PEGASOS Refinement Project

Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites

Volume 1

- Summary Report -

by

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Abstract

The PEGASOS Project, a new state-of-the-art probabilistic seismic hazard assessment for the nuclear power plant sites in Switzerland, was carried out from 2000 to 2004. The quantification of the epistemic uncertainty and aleatory variability in seismic hazard at the four Swiss nuclear power plant sites was the key aspect of the PEGASOS Project. After the completion of the project, the Swiss utilities decided to perform a refinement of the study by collecting additional data and using new advances in earthquake science, especially in the field of ground motion modelling, to further reduce the identified epistemic uncertainties. The PEGASOS Refinement Project (PRP) started in 2008 and was completed in 2013. This report provides an overview of the different components of the project and the approaches used and also identifies some new challenges for the earthquake science community. An important aspect of the ground motion characterization that had a significant impact on the PSHA results is the adjustment of ground motion prediction equations to make them applicable to the site conditions in the study region.

Keywords

Probabilistic Seismic Hazard Assessment (PSHA), Nuclear Power Plant, SSHAC, Seismic Source Characterization, Ground Motion Prediction Equation (GMPE), Site Amplification, Switzerland

Executive Summary

Motivation and Objective

The PEGASOS study carried out from 2000 to 2004, documented the scientific knowledge related to the occurrence of earthquakes in Switzerland, ground motion models for Switzerland, and site response at the four nuclear power plant (NPP) sites that was available in 2004. The study has since become known under the name of the 'PEGASOS Project' (Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-StandOrte in der Schweiz).

A key aspect of the PEGASOS study was the quantification of the aleatory variability and epistemic uncertainty in seismic hazard at the four Swiss NPP sites. The epistemic uncertainties are due to the very limited data for (i) ground motions from large magnitude earthquakes, and (ii) soil properties at the NPP sites. After completion of the PEGASOS Project, the review team of the Swiss Federal Nuclear Safety Inspectorate and the Project sponsor found that the uncertainty range was rather broad, and that this spread could possibly be reduced by further investigations. Thus, the PEGASOS Refinement Project (PRP) represents an update of the PEGASOS Project, with the objective of improved quantification of the epistemic uncertainties in the hazard through the collection of new data and use of improved models and methods. This interdisciplinary Project – which started in 2008 – involved 25 key experts from 8 European countries and the USA and was completed in 2013.

The PRP sought to produce results that would be stable and have high longevity. By carrying out the Project on the highest SSHAC Level 4, the NPP operators followed the requirements of the Swiss Federal Nuclear Safety Inspectorate and aimed also to achieve a high degree of regulatory assurance in the process and end-product.

Project Organization and Structure

The main components of the Refinement Project organization are based on the PEGASOS study and consist of five technical subprojects: SP1 – Seismic source characterization, SP2 – Ground motion characterization, SP3 – Site response characterization, SP4 – Hazard computation, and SP5 – Earthquake scenario development. Overseeing the development of the expert models for input into the PRP and the integration task was the responsibility of the Technical Facilitator/Integrator (TFI). The subproject experts were supported by the Project Management Team (PMT), the Computing Modeling and Database Center (CMD) and numerous resource experts who carried out specific technical studies on behalf of the experts. Administrative support was provided by the sponsor swissnuclear and the role of the project QA representative was taken on by an external consultant familiar with the technical subject. The Swiss Federal Nuclear Safety Inspectorate (ENSI) performed a participatory peer review of the project and was supported by a team of recognized experts forming the ENSI Review Team (ENSI-RT). The Project was designed to allow for optimal involvement of all stakeholders, as transparency, communication of interfaces and a continuous exchange of information between the TFI and the utilities regarding the results of the different technical studies was identified from the previous PEGASOS Project as a key element for acceptance.

Hazard Results

State-of-the-art seismic hazard studies calculate ground motion exceedance probabilities using earth science hypotheses about the sizes, rates, and locations of earthquakes in the region being studied. The multiple interpretations defined by the experts are propagated through the hazard analysis, resulting in a suite of hazard curves and their associated weights. Finally, the hazard results are presented as curves showing statistical summaries (e.g. mean, median, fractiles) of the annual exceedance probability for each ground motion amplitude. The hazard curves are developed for both site-specific reference rock and the site-specific surface soil. The hazard curves are computed for probabilities down to 10^{-7}.

At ground motion levels corresponding to low probability levels (e.g. annual probability of exceedance of 10^{-6}/yr), the hazard for higher frequencies at all four sites is dominated by $M5.5$ – $M6.5$ earthquakes at short distances (0–20 km). This is a common result for hazard analyses conducted for regions lacking known high activity faults with the seismicity described by areal source zones. This range of controlling magnitudes and distances is consistent with the previous results from PEGASOS.

The change in the epistemic uncertainty in the hazard between the PEGASOS and PRP studies was evaluated through sensitivity analyses. The uncertainty in the soil UHS, measured in terms of the 5%–95% range at annual exceedance of 10^{-4} to 10^{-6} were reduced from factors of near 6 in PEGASOS to factors near 3 in the PRP for high frequencies ($>$5 Hz). The PEGASOS and PRP results can also be compared in terms of the uncertainties resulting from the SP1, SP2, and SP3 experts, separately.

The SP1 contribution to the epistemic uncertainty in the rock hazard for a hazard level of 10^{-4} and 100 Hz is slightly higher for the PRP than for PEGASOS. The main change for SP1 is the result of the update of the earthquake catalog which included a change in the magnitude conversion. The use of the new catalog lead to a reduction of the hazard for the PRP as compared to the PEGASOS hazard.

The SP2 contribution to the epistemic uncertainty in the rock hazard was reduced significantly in the PRP as compared to PEGASOS, but the rock ground motion model remains the largest contributor to the total uncertainty in the hazard. The largest reduction in uncertainty in the PRP was for low frequencies (near 1 Hz). The reduction in rock hazard uncertainty is due to use of improved candidate GMPEs that are more applicable to Swiss conditions. Uncertainty in the median rock ground motion models (selection of the GMPEs) and the associated adjustments to make them applicable to the NPP site conditions in Switzerland dominate the hazard uncertainty.

The SP3 contribution to the epistemic uncertainty is the smallest of the three subprojects, but the uncertainty was larger for the PRP than it was for PEGASOS. The uncertainty was increased due to inconsistencies between different types of data collected (down-hole, cross-hole, ambient noise, etc.). The interpretation of the new data led to different possible interpretations and the candidate soil profiles and material properties are the main contributor to the increased uncertainty within SP3. At annual probabilities of exceedances between 10^{-3} and 10^{-5} the uncertainty could slightly be reduced, while for probabilities smaller than 10^{-5} the new models increased the uncertainty by a factor of up to 3. Due to the improved characterization of the hard rock conditions at the NPP sites, the frequency content of the Uniform Hazard Spectra (UHS) changed significantly compared to PEGASOS, shifting the peak to higher frequencies in the rock ground motion.

Beside the main project report, which contains more than 3000 pages, the PRP has produced a large database of additional documentation material which supports the assessments and provides background information. There are 490 presentations shown at the occasions of workshops and meetings, 435 technical notes and 90 technical reports. Over 50 scientific journal papers emerged directly or indirectly from the work of the PRP.

Conclusions

The results show that the uncertainties expressed by an individual expert ("within-expert" component of uncertainty) are the dominant contributors to the total hazard uncertainties, rather than the uncertainties among multiple experts ("expert-to-expert" component). This is a positive result and supports the conclusion that each expert has made a concerted attempt to consider the views of the larger technical community in their expressions of uncertainty.

The Project spent a large effort on, and was successful in, developing consistent models and results in order to eliminate previously identified items of double counting of uncertainties. The experts' models represent today's state-of-knowledge of the scientific community and the evaluations performed span the range of credible technically defensible interpretations.

The PRP encountered various challenges and shifted, for certain technical issues, from a pure application project to a project with extended research character, which also caused some schedule delays. Early in the project, the SP2 experts recognized the fundamental and critical limitations of the available ground motion models. To improve the identified critical issues, additional research was required to develop new methods and models to reduce the uncertainties and increase the quality of the results. In particular, a new state-of-the-art was developed by the project in the areas of target κ assessments, $V_S - \kappa$ correction methods and, V/H models for hard rock. These new methods and models are now used by several other major seismic hazard studies around the world.

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Chapter 1

Introduction

In the original PEGASOS Project, carried out from 2000 to 2004, seismic hazard was evaluated considering the available knowledge of the broad international expert community in earthquake science and geotechnical engineering. The PEGASOS Project documented the available scientific knowledge related to the occurrence of earthquakes in Switzerland, ground motion models for Switzerland, and site response at the four Swiss nuclear power plant sites. A key aspect of the PEGASOS Project was the complete treatment of ground motion aleatory variability and quantification of the uncertainty in seismic hazard at these four sites. The large epistemic uncertainties resulted from the very limited data on strong earthquakes, ground motion attenuation, and soil properties at the sites. After completion of the Project, the review team of the Swiss Federal Nuclear Safety Inspectorate and the Project sponsor found that the uncertainty range was rather broad, and that this spread could possibly be reduced by further investigations. Thus, the PEGASOS Refinement Project represents an update of the PEGASOS Project, with the intention of reducing epistemic uncertainties through the collection of additional data and use of improved models. In particular, improvements in the rock ground motion models and the site response models, including new data collection, were identified as potential approaches which could lead to a noticeable reduction in the overall uncertainty of the hazard in the short term. In the PEGASOS Refinement Project, new earthquake data were collected, the updated Earthquake Catalogue of Switzerland was incorporated, improved empirical ground motion models were considered, and site-specific investigations were performed to collect new soil property data. Particular attention was paid to interface issues in order to achieve consistency across the various subproject model interpretations and thereby eliminate (or minimize) the unintended contributions to uncertainty that can stem from introducing inconsistent combinations of interpretations. Post-processing of the hazard results was performed in an additional fifth subproject to produce seismic hazard outputs that can be directly incorporated into the nuclear power plants' probabilistic safety assessments.

1.1 Initial Situation

The Swiss Nuclear Power Plants (NPPs) are designed and built to resist strong earthquakes. They are amongst the structures with the highest seismic safety in Switzerland. Nevertheless, earthquakes continue to represent a significant hazard to the Swiss NPPs. Therefore, the owners of the NPPs and the Swiss Federal Nuclear Safety Inspectorate (ENSI[*]) attach great importance to the most comprehensive and accurate assessment of the seismic hazard at the four NPP sites in Switzerland. In order to assess the seismic hazard for the original design of the Swiss NPPs, historical earthquake data were gathered. In the mid 1970s, these data were evaluated statistically and presented in earthquake intensity maps, which still form the basis for the seismic hazard assessment at dam sites. With the introduction of the Probabilistic Safety Assessments (PSA) for NPPs, the requirements for the seismic hazard analysis were enhanced. Since then, the aleatory variability and epistemic uncertainty range, which is caused by the inherent scatter of the recorded data and the range of alternative analysis models, has had to be included in the seismic hazard analysis. In 1999, HSK[†] required that the licensees assess seismic hazard according to state-of-the-art methodology for NPPs, including appropriate and realistic evaluation of uncertainties.

1.1.1 The PEGASOS Project

The PEGASOS Project (Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites) [NAGRA 2004] was based on a method developed in the U.S.A. in which seismic hazard was evaluated considering the broad knowledge of the international expert community in earthquake science and geotechnical engineering. The PEGASOS study, carried out from 2000 to 2004, documented the available scientific knowledge related to the occurrence of earthquakes in Switzerland, ground motion models for Switzerland, and site response at the four NPP sites. A key aspect of the PEGASOS study was the quantification of the aleatory variability and epistemic uncertainty in seismic hazard at the four Swiss NPP sites. The epistemic uncertainties are due to the very limited data on (i) strong earthquakes, (ii) ground motion attenuation, and (iii) soil properties at the NPP sites. The original PEGASOS Project was divided into 4 subprojects (SP):

- SP1: Seismic Source Characterization (SSC);
- SP2: Ground Motion Characterization (GMC - for reference rock conditions);
- SP3: Site Response Characterization (SRC); and
- SP4: Seismic Hazard Computation.

The PEGASOS Project was conducted in accordance with the "Senior Seismic Hazard Analysis Committee" Level 4 approach Budnitz et al. [1997] (NUREG/CR-6372).

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[*] named HSK until 31.12.2008

[†] Since 1.1.2009 renamed ENSI

Project Review by the Swiss Regulator (HSK)

HSK established a team of experts – the HSK-Review Team (HSK-RT), which conducted a review of the PEGASOS Project. In the final review report [HSK 2004], the HSK-RT concluded that the methodological requirements had been accomplished and that the results of the PEGASOS Project currently represented the best available basis for the specification of seismic hazard parameters in the PSA applications and for seismic design issues for nuclear facilities. However, the HSK-RT also found that the documented uncertainty range was rather broad and that this range could possibly be reduced by further investigations. The HSK-RT report identified areas for potential refinement. The category 1 items were defined as

> ”open items that were not found to be explicitly addressed during the course of the Project or in the PEGASOS final report, and which may have a meaningful impact on the PSHA results and are therefore considered as candidates for potential refinements to the PEGASOS study”.

These items are:

1. Assessments of maximum magnitude;
2. Lower-bound magnitude;
3. SP2/SP3 integrated assessments;
4. SP1/SP2/SP3 interface issues.

Swiss NPP Reviews

Unfortunately, the NPP representatives were not actively involved in the technical discussions held during the PEGASOS workshops and were therefore surprised by the large increase in the estimated seismic hazards compared to the earlier hazard studies by Basler & Hofmann [1984, 1989, 1991, 1996]. To address their concerns, the NPP representatives performed their own review of the project [Klügel 2004, 2006c] and launched several studies (e.g. ABS Consulting [2004]; Klügel [2005a]; Proseis [2005b, a, c]) to evaluate in detail the PEGASOS seismic source and ground motion models as well as the overall PSHA approach.

In early 2005, several papers were published from the side of the Swiss utilities questioning the PEGASOS results and PSHA in general [Klügel 2005b, e, c, f, d, g, 2006b; Klügel et al. 2006; Klügel 2006a, 2007b, a, 2008]. The experts involved in the PEGASOS Project disagreed with the criticisms and published a series of papers defending their PEGASOS results and methods used [Budnitz et al. 2005; Lomnitz 2005; Musson et al. 2005; Wang 2005; Bommer and Abrahamson 2006, 2007]. Retrospectively, it can be seen that this situation probably occurred, because the Swiss utilities were not sufficiently involved in the process in order to fully acquire the technical expertise to understand the results and the associated uncertainties. Within the PEGASOS Refinement Project, this interface improved through having in-house technical expertise in PSHA and continuous exchange of information between the TFI and the utilities regarding the results of the technical studies.

In summer 2005, the NPP representatives postulated a possible reduction of the hazard by further investigations and proposed a reduction of the PEGASOS ground motions by 20%.

HSK agreed that this reduction could be used temporarily until the end of 2007, but that the appropriateness of the reduction needed to be demonstrated and a follow-up study had to be conducted [HSK 2007].

PEGASOS Follow-Up Workshops

A PEGASOS review meeting, organized by swissnuclear, was held in Baden in 2004 (Specialists meeting, 9.-10. November 2004). The workshop participants (who were not all involved in the PEGASOS Project) identified some potential issues needing further clarification regarding the source characterization, rock ground motion models, the treatment of ground motion variability, and the basic methodology used in PSHA.

A second workshop was held in November 2006 in Üetliberg [Rizzo 2007] to discuss the issues raised in the past about the PEGASOS Project and the PSHA methodology in general. During that meeting, HSK made it clear that only a risk-informed approach using PSHA would be considered for nuclear power plants, and that a change to a deterministic approach would not be considered. This shifted the focus of the workshop to identifying which additional studies and new data would have the best potential to reduce epistemic uncertainties in the hazard in a short time period. Although much of the discussion at the Üetliberg workshop was focused on the source models and how they could be improved through an updated earthquake catalogue, maximum magnitudes, and non-Poisson models of earthquake occurrence, the workshop conclusions were that improvements in the rock ground motion models (SP2) and in the site-specific soil properties (SP3) had the greatest potential to lead to reductions in the epistemic uncertainty of the hazard. Furthermore, it was recommended that a new earthquake catalogue for Switzerland be developed. These potential improvements are the basis for the PEGASOS Refinement Project and will be presented in the following chapter.

1.2 Project Objectives and Scope of Work

Based on the conclusions developed at the PEGASOS Follow-Up Workshops, swissnuclear established the PEGASOS Refinement Project (PRP) with the objective of improved quantification of the epistemic uncertainties in the hazard through the collection of new data and use of new models, leading to more robust PSHA results. It is understood that reduction of epistemic uncertainty does not necessarily lead to a reduction in the mean hazard. As the uncertainties are reduced, they could be centered on the low, middle, or high range of the fractiles of the PEGASOS hazard curves.

The general structure of the PEGASOS Refinement Project (PRP) is based on the PEGASOS Project [NAGRA 2004]. It has five subprojects (SP), each of them including different tasks. Figure 1.1 outlines the general procedure and the main steps of the PRP. As a first step, seismic sources (source zones) are defined based on the available earthquake data. Then, magnitude-frequency relationships and ground motion models are derived for the different sources and spectral frequencies. Rock hazard curves are then computed from the source characterization and ground motion characterization. Using site-specific amplification factors, the rock hazard curves are converted into soil hazard curves. Finally, site-specific hazard and scenario spectra are developed from the hazard curves, and scenario time histories are generated from the defined scenario spectra.

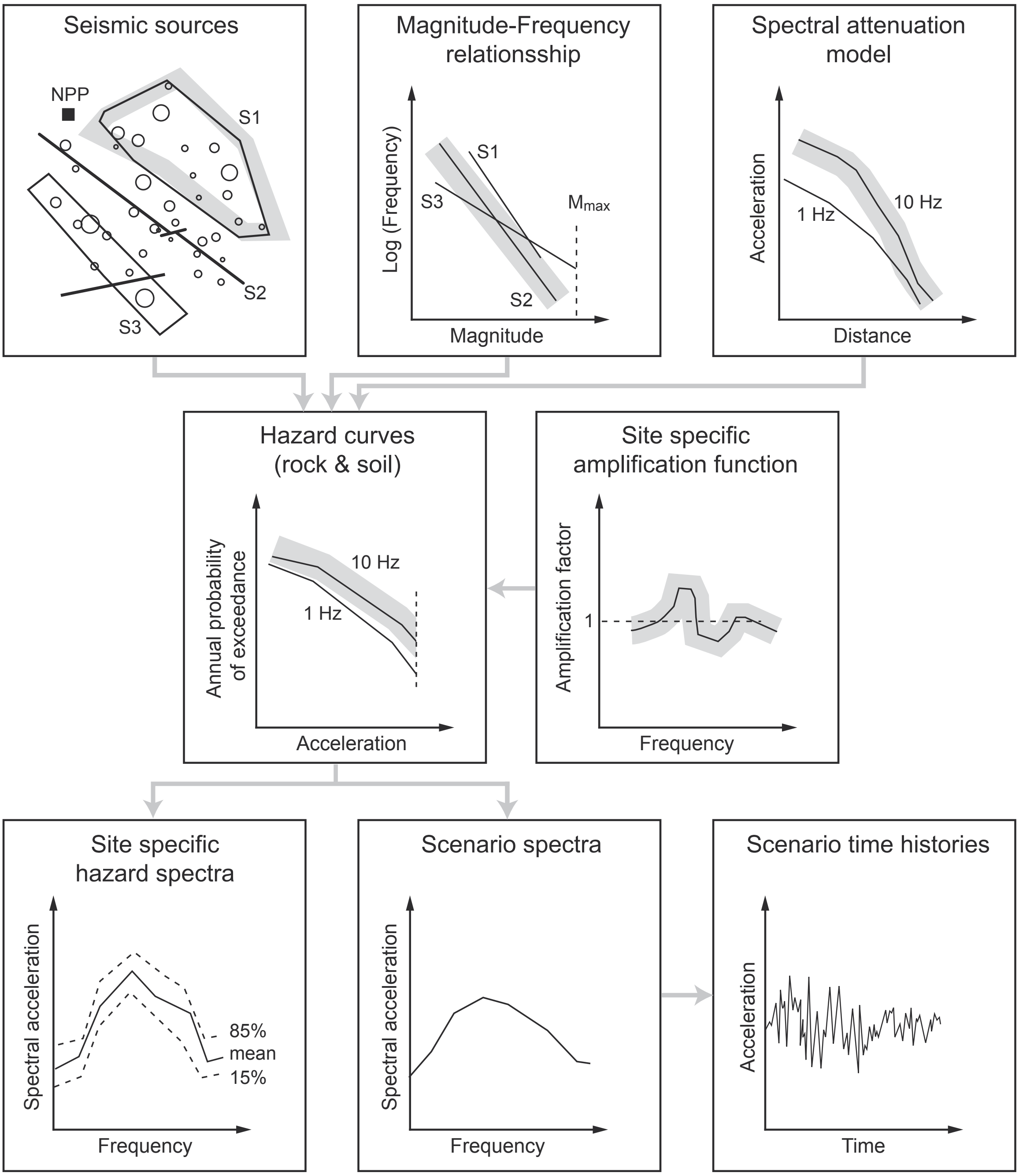


Figure 1.1: Schematic illustration of the procedure of probabilistic seismic hazard assessment (resulting in the hazard curves) and the post-processing steps (hazard spectra and scenarios).

Swissnuclear submitted the project plan (Ver. 3) to ENSI on 27. June 2008; this was accepted by ENSI with a letter of 25. August 2008. Subsequently, there was a revision of the project plan (Ver. 4.2.1) in order to account for some changed boundary conditions, and the revised version was submitted on 12. December 2011 to ENSI together with a status report [Renault and Biro 2011] (PMT-AN-1119); this received positive feedback with ENSI's letter of 27. March 2013. To address the changes in the implementation and execution of the project compared to the initial version of the project plan, swissnuclear added a report to the submitted project plan. The status report [Renault and Biro 2011] reflects how the project evolved and summarizes all changes to the project plan (Ver. 3) which were previously discussed with the ENSI Review Team (RT) in the course of the regular workshop debriefings.

To better capture the hazard from smaller earthquakes, a lower-bound magnitude of 4.5 was used in the hazard calculations of the PRP, as compared to a lower hazard based on a minimum magnitude of 5 used in PEGASOS. Two basic hazard result sets are prepared; one for a lower-bound magnitude of 4.5 and the other for a lower-bound magnitude of 5, which allows a comparison with the PEGASOS results. The NPPs will individually have to justify their choice of result set ($M4.5$ or $M5.0$) for further calculations and implementations. One possible way, for example, to account for the effects of different-magnitude events in a seismic PSA would be to develop magnitude-dependent hazard and fragility curves.

1.3 Background

Conventional seismic hazard maps, as used as a basis for the modern seismic design codes of conventional buildings, are based on a $2.1 \cdot 10^{-3}$ annual probability of exceedance, which corresponds to 10% exceedance probability in 50 years and can thus be interpreted as approximately a 475 year return period. The hazard map shown in Figure 1.2 is just for reference, but shows the location of the four NPP sites. According to the current state-of-the-art [IAEA 2008, 2009], the seismic design of NPPs is expected to fulfill a performance goal of 10^{-5} per year (i.e. the probability of failure of any structure/system/component due to a seismic event must be less than 10^{-5} per year). For the safety analysis of an NPP, this requires the definition of acceleration probabilities of exceedance up to at least 10^{-7} per year (10 million year return period). The Swiss Federal Nuclear Safety Inspectorate has defined these boundary conditions in the guideline ENSI-A05 [ENSI 2009], which also implies that a PSHA in Switzerland needs to be performed under SSHAC Level 4 [Budnitz et al. 1997; Panel on Seismic Hazard Evaluation et al. 1997].

The PEGASOS Refinement Project (PRP) Plan [swissnuclear 2009] describes the situation that prevailed at the conclusion of the PEGASOS Project in 2004 with regard to the four subprojects that comprised the Project. The review of the Project by the HSK-Review Team, which served as the Participatory Peer Review Panel (PPRP) for the Project, concluded that the SSHAC methodology had been followed properly and that the results of the PEGASOS Project currently represented the best possible basis for the specification of seismic hazard parameters in the probabilistic safety analysis (PSA) applications and for seismic design issues for nuclear facilities. However, the HSK-RT also found that the documented uncertainty range was rather broad and that this could be reduced by further investigations.

The PEGASOS Project was conducted using a SSHAC Level 4 process, which is the most elaborate of the four Study Levels described in the SSHAC guidelines (NUREG/CR-6372,

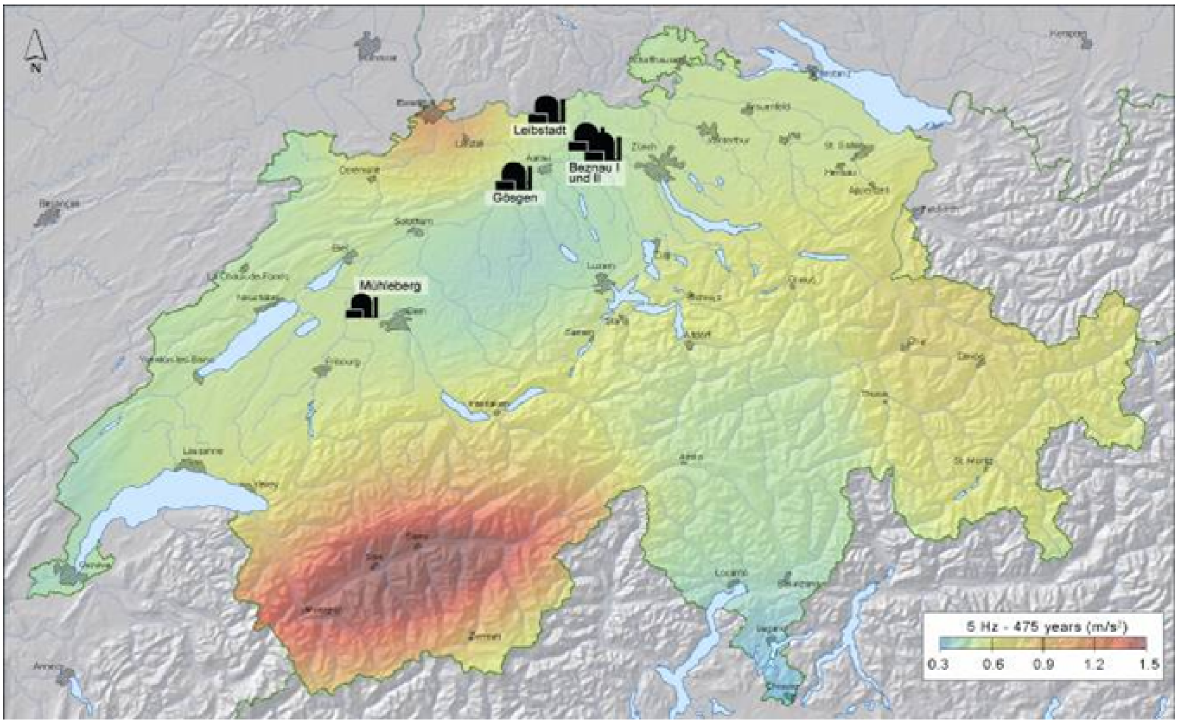


Figure 1.2: NPP locations and seismic hazard map of Switzerland for a return period of 475 years (in [cm/s^2] units for 5% damped acceleration response spectrum at 5 Hz frequency) [Giardini et al. 2004], `http://www.seismo.ethz.ch/prod/haz_map/10000years`. The map is calibrated for a rock ground condition (V_S approximately 1500 m/s).

[Budnitz et al. 1997] and NUREG-2117, [Kammerer and Ake 2012]). The SSC assessments were made by four expert teams, which each included the necessary expertise to characterize seismic sources. The GMC and SRC assessments were performed by four individual experts each. As described in the regulatory guidance Kammerer and Ake [2012], the expert teams serve as ”evaluator experts” who are responsible for carrying out both the evaluation and the integration activities associated with the project. During the evaluation phase, the expert teams are responsible for evaluating the full range of available data, models and methods that have been developed or proposed by the larger technical community. They do this by identifying applicable data, interacting with resource experts and proponent experts in structured workshops, and conducting working meetings with members of the TFI team. During the integration phase of the Project, the expert teams develop their models in the light of their evaluations of the views of the larger technical community. The goal is to develop an SSC and GMC model that represents the Center, Body, and Range of technically defensible interpretations. This means that each team's knowledge and uncertainties must be properly captured. A key element of a SSHAC process is the function of a participatory peer review panel that monitors both the technical assessments and the process being followed. The peer review function was carried out by the ENSI-RT and a number of review meetings were held between the TFI and the RT throughout the Project. In this way, advice was provided to the Project in a timely manner so that improvements could be made during the course of the Project.

The PEGASOS Refinement Project (PRP) has been defined as a ”refinement” because the PEGASOS assessments are a starting point and only those aspects are updated that have the potential to significantly reduce the uncertainties in the hazard results. Sensitivity studies for the PEGASOS hazard results (Section 8.4.1 of the PEGASOS 2004 report) show that the most important contributor to uncertainty in seismic hazard is uncertainty in the rock ground motions, followed by uncertainty in site response, and then uncertainty in seismic source characterization. This situation is common for hazard results in regions with limited strong motion data. A sensitivity study on the assessment of M_{max} was conducted by swissnuclear in 2007 to address the HSK review team recommendation that the maximum magnitude was one of the candidates for potential refinement. It was found that reducing the uncertainty in the maximum magnitude M_{max} has almost no impact on the mean hazard [Interoil 2007]. On the other hand, the sensitivity study showed that a truncation of the M_{max} distributions in the vicinity of the plants could lower the mean hazard slightly, but the effect remains very small and developing the technical basis for such a truncation would require a major effort. It was therefore concluded that the focus of the PRP would not include the SP1 models because of the lesser possibility of reducing hazard uncertainties. However, because the entire hazard model would be updated during the course of the PRP, it was decided that the study should allow for updates of any key data that could significantly influence the SP1 models. The most fundamental database of this kind is the earthquake catalogue and a considerable effort was devoted to updating this. In addition, the SP1 expert teams were free to identify other data that could potentially influence their models and these were evaluated for their potential influence.

SP1/SP2/SP3/SP4/SP5 Interface Issues

Great attention was paid to interface issues between all SPs in order to ensure a proper and efficient knowledge exchange between the different subprojects. During the PEGASOS Project, three subprojects were run in parallel, which made some of the interface issues difficult. Since there was little change to the SP1 and SP3 in terms of the general approach and overall structure of the logic trees, it was easier in the PRP to address the interface issues. A series of dedicated workshops were held during the PRP to address these issues. To address the interface issues right from the start of the new project, all project partners were invited to attend the three kick-off meeting days.

New NPP Projects

After the start of the PRP, swissnuclear decided to incorporate the new NPP projects into the revised version of the PRP plan as it was also the intention to use the PRP results for purposes other than just the Probabilistic Safety Assessment (PSA) of the existing plants, for example for safety analyses for new site permits. Thus, the new NPP sites were treated in the same way as the existing ones. As a consequence, the site investigations and site response calculations for the three new NPP sites were also included in the SP3 review and modeling. Even though the new sites would have been close to the existing ones, it might have been necessary to compute separate rock hazards for the new sites if the shear-wave velocity for the selected reference rock condition for a new site, obtained through site investigations, was different from the one used for an existing site. The soil hazard would have been computed for the new sites using the appropriate specific local site conditions. Nevertheless, the overall scope of the PRP is to provide PSHA results without a specific focus on the new NPP projects.

After the Fukushima Daiichi NPP accident the new NPP projects in Switzerland were stopped and thus are no longer part of the final results provided within this report.

1.4 Project Organization

The overall project organization and the different tasks of the PRP are shown in Figure 1.3. In the following subsections, the different roles and duties of the experts and representatives shown in the organizational chart are described, as specified in the project plan.

1.4.1 Regulator (ENSI)

The regulator is responsible for the official, independent participatory peer review as well as the final review in accordance with the procedure in the PEGASOS Project [HSK 1999, 2004]. ENSI is supported by a team of recognized experts forming the ENSI Review Team (ENSI-RT). These experts are:

- S. Brosi (ENSI),
- D. Giardini (ETH Zürich),
- R. Sewell (R.T. Sewell Associates) and
- P. Zwicky (Basler & Hofmann).

This team participated in all PRP workshops as observers and prepared written comments after discussion with the PMT and the TFI. The ENSI-RT could request project data and documents at any time and had permanent access to all project documents through the online project database managed by the PMT.

1.4.2 Project Management Team (PMT)

The Project Management Team (PMT), represented by P. Renault, M. Johnson and Y. Alpay-Biro (formerly also S. Heuberger), was responsible for the overall management and execution of the project. Within the allocated budget and time frame, the team made decisions, in agreement with the TFI, on all issues with a significant impact on the project's course and progress and assumed responsibility for achieving the project's ultimate goal. This involved overseeing and coordinating the scientific, engineering and technical work in the subprojects and identifying project needs. On a non-technical level, it involved the organization of workshops, technical meetings, information flow, preparation and review of reports, and accounting. It was within the PMT's competence to handle experts requests pragmatically (e.g. request for additional technical studies). Swissnuclear made the final decision as to whether an additional work package was carried out during the project. However, the TFI could commission a sensitivity study in order to make a well-founded decision on whether an additional work package had to be carried out during the project or not. This procedure was transparently documented by the PMT according to the QA standards. The PMT participated in all workshops and kept the minutes. During the workshops, the PMT provided descriptions of the status of the technical tasks. The PMT was responsible for detailed planning of all project activities and regular reviews of the work progress, the maintenance of the project

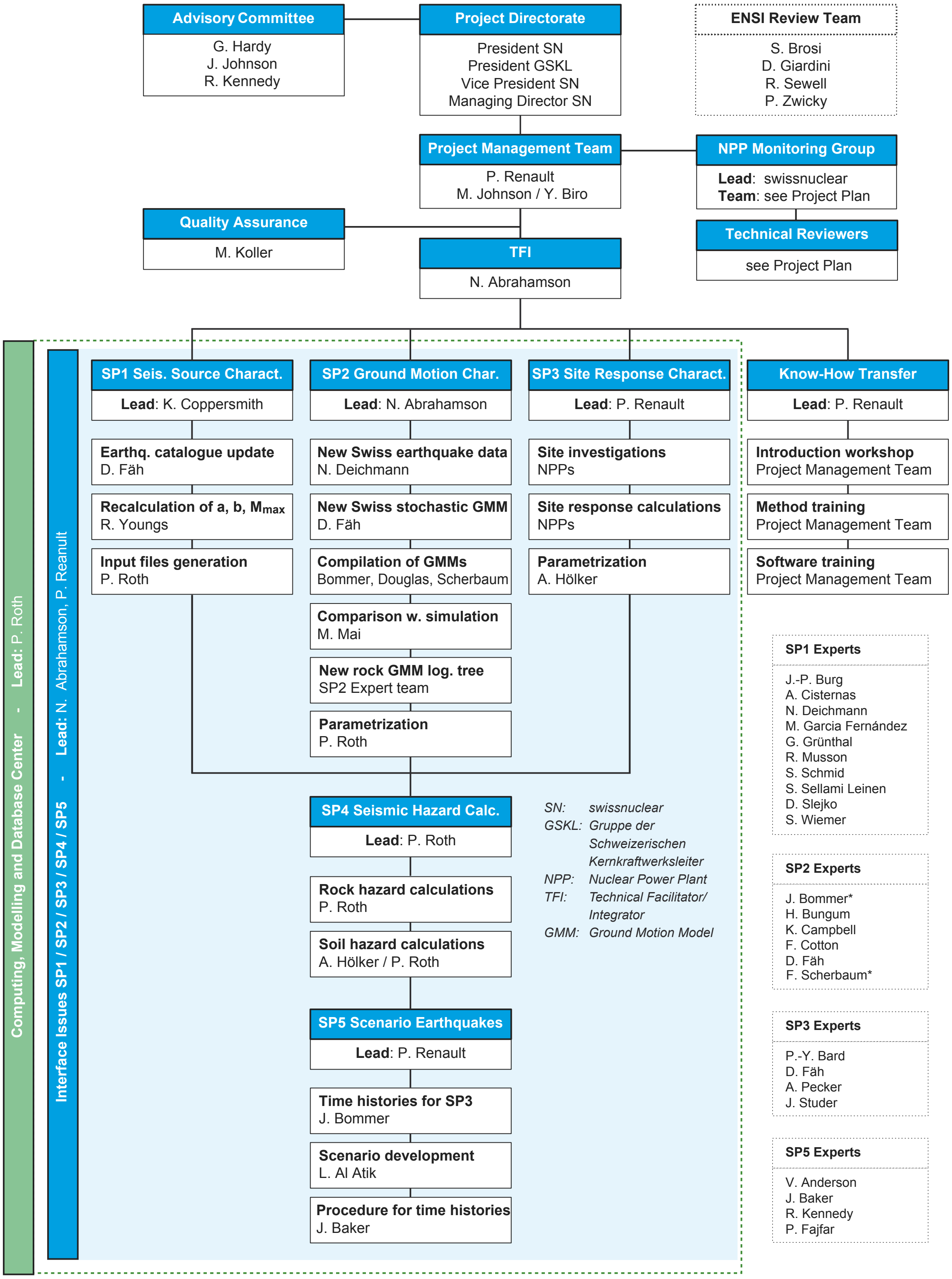


Figure 1.3: Project Organization Chart

data and document database, the schedule and the budget situation. The PMT reported regularly to the Project Directorate.

1.4.3 Technical Facilitator/Integrator (TFI)

The Technical Facilitator/Integrator (TFI), represented by N. Abrahamson, is a single entity who is responsible for:

- Overseeing the development of the expert models for input into the PRP
- Bringing together the technical experts and proponents of various hypotheses for discussion and interaction
- Supporting the evaluation of aleatory variabilities and epistemic uncertainties
- Ensuring appropriate treatment of interface issues
- Documenting the process.

The TFI has the overall technical responsibility for the project. As stated in the SSHAC guidelines [Budnitz et al. 1997] (NUREG/CR-6372), the TFI will aggregate the expert models so that they represent the Center, Body, and Range of the ITC. In addition to the roles specified by the SSHAC guidelines, the TFI has the following responsibilities in the PRP: (1) the TFI can commission a sensitivity study in order to make a well-founded decision on whether an additional work package has to be carried out during the project or not; and (2) in the case of an incomplete expert team during a workshop (or part of a workshop), the TFI can decide whether the workshop remains relevant for the project and can thus be implemented or if it must be repeated.

In addition to facilitation, the TFI is also an integrator, integration being defined as ”the process of combining multiple experts’ evaluations into an aggregate assessment across all experts’. The SSHAC process emphasizes the need to consider, at the outset of a project the strategy for integration of the experts’ evaluations. From the beginning of the PEGASOS Project, a strategy was defined to combine the evaluations of the experts using equal weights, which was maintained in the PRP. The key procedural components of the project, ranging from the selection of the experts to the dissemination of data, were designed to allow the equal-weights strategy to be implemented in a defensible manner. As noted by the SSHAC guidelines [Budnitz et al. 1997], the goal of a multi-expert evaluation of inputs to a PSHA is to capture and express the range of uncertainty such that the aggregated hazard reasonably represents the uncertainty of the informed technical community.

1.4.4 Subproject Experts

To enable a proper continuation of the PEGASOS procedures, the same experts participated in the PRP. Exceptions are two SP1 experts (M. Burkhard, W. Brüstle) and one SP2 expert (F. Sabetta) who either had work-related reasons for not being able to participate or passed away (M. Burkhard). Table 1.1 lists the subproject experts and the corresponding Resource Experts (the affiliations of the evaluator experts are given in Table 1.2). The two SP1 Experts (M. Burkhard, W. Brüstle) have not been replaced. F. Sabetta has been replaced by D. Fäh. The SP5 team was composed of V. Andersen, J. Baker, P. Fajfar and R. Kennedy.

Table 1.1: List of experts per subproject.

	SP1	SP2	SP3	SP4	SP5
Evaluator Experts	J.-P. Burg A. Cisternas N. Deichmann M. Garcia F. G. Grünthal R. Musson S. Schmid S. Sellami L. D. Slejko S. Wiemer	J. Bommer H. Bungum K. Campbell[*] F. Cotton D. Fäh F. Scherbaum	P.-Y. Bard D. Fäh A. Pecker J. Studer		V. Andersen J. Baker P. Fajfar R. Kennedy
Supporting Resource Experts	K. Coppersmith D. Fäh P. Roth R. Youngs	L. Al Atik N. Deichmann J. Douglas B. Edwards D. Fäh N. Gregor N. Kühn M. Mai V. Poggi A. Rodriguez-Marek P. Roth P. Stafford F. Strasser	NPPs A. Asfura A. Pecker P. Roth V. Poggi M. Ryan W. Silva	A. Hölker R. McGuire P. Roth G. Toro	A. Asfura N. Gregor G. Hardy J. Johnson SP2 Experts SP3 Experts

[*] K. Campbell joined the project in August 2011 and replaced the experts J. Bommer and F. Scherbaum.

1.4.5 Resource Experts

The subproject experts or the TFI can ask any specialist from inside or outside the project to contribute their knowledge on a specific topic. Such specialists are called Resource Experts here. A Resource Expert is a specialist with particular technical expertise and knowledge of specific data, methods or models of importance for the PSHA evaluations at the four NPP sites. In addition to presenting data and/or models to the experts, Resource Experts may participate in the workshop discussions based on the needs determined by the TFI. The resource experts used in the PRP are listed in the bottom half of Table 1.1.

1.4.6 Project Directorate

The Project Directorate represents the sponsor (swissnuclear) and has, through property rights, ownership of the overall PRP report, data and results. It is formed by:

- President of swissnuclear
- President of GSKL (German ”Gruppe der Schweizerischen Kernkraftwerksleiter”)
- Vice president of swissnuclear

Table 1.2: Panel of experts and affiliations.

Subproj.	Name[*]	Affiliation
TFI	Dr. Norman A. Abrahamson	Norman A. Abrahamson Inc. Piedmont, CA, USA
SP1, EG1a	Dr. Nicolas Deichmann	Schweizerischer Erdbebendienst, ETHZ, Zürich, Switzerland
	Prof. Dr. Stefan Schmid	Geologisch-Paläontologisches Institut der Universität Basel, Basel, Switzerland
	Dr. Dario Slejko	Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy
SP1, EG1b	Dr. Armando Cisternas	Université Louis Pasteur Inst. Physique du Globe, Strasbourg, France
	Dr. Gottfried Grünthal	Deutsches GeoForschungsZentrum (GFZ) Potsdam, Germany
SP1, EG1c	Dr. Roger Musson	British Geological Survey, Edinburgh, United Kingdom
	Dr. Souad Sellami	Schweizerischer Erdbebendienst, ETHZ, Zürich, Switzerland
SP1, EG1d	Prof. Dr. Jean Pierre Burg	Geol. Institut der ETHZ, Zürich, Switzerland
	Dr. M. Garcia-Fernandez	Agencia Estatal Consejo Superior de Investigaciones Cientificas (CSIC), Spain
	Prof. Dr. Stefan Wiemer	Geologisches Institut der ETHZ, Zürich, Switzerland
SP2	Prof. Dr. Julian J. Bommer	IC Consultants Ltd., Imperial College, London, UK
	Prof. Dr. Hilmar Bungum	NORSAR, Kjeller, Norway
	Dr. Kenneth W. Campbell	EQECAT Inc., Beaverton, Oregon, USA
	Prof. Dr. Fabrice Cotton	Laboratoire de Géophysique Interne et Tectonophysique (LGIT), Univ. Louis Fournier, Grenoble, France
	Prof. Dr. Frank Scherbaum	Universität Potsdam, Institut für Geowissenschaften, Potsdam, Germany
SP3	Dr. Pierre Yves Bard	Laboratoire de Géophysique Interne et Tectonophysique (LGIT), Univ. Louis Fournier, Grenoble, France
	Prof. Dr. Donat Fäh	Schweizerischer Erdbebendienst, ETHZ, Zürich Switzerland
	Dr. Alain Pecker	Géodynamique et Structure, Bagneux, France
	Dr. Jost Studer	Studer Engineering, Zürich, Switzerland

[*] in the rest of the report without academic titles

- Managing director of swissnuclear.

The Project Directorate acts as the supervisory board and is responsible for the following tasks:

- Preparation of "Project Directives", comprising:
  - Strategic and conceptual planning of project implementation
  - Project goals
  - Internal cost budget
  - Authorization and approval of procedures
  - Project reporting requirements.
- Approval of the Project Plan, comprising
  - Cost budget
  - Organization and staffing
  - Subcontractors
  - Time schedule.
- Regular Project Reviews, comprising
  - Progress and status
  - Project budget and achievement forecasts
  - Appraisal of achievement of project goals.
- In case of deviations from cost budget and time schedule, approval of recovery measures to bring the project back on track.

1.4.7 Advisory Committee

Objective

The Advisory Committee is an international and independent group of technical engineers which provides advice to the Project Directorate. Such advice is mainly envisaged as assisting in instances of strong disagreement among the Project Partners and the sponsor. The advice is limited to consultancy and support and does not necessarily lead to modifications in the project activity. The Advisory Committee focuses on the interface for the implementation of the results into the PSA. This interface is mainly SP5. The Advisory Committee is provided with all of the workshop summaries, but only attends a limited number of workshops. Constitution and Organization The Advisory Committee is composed of three experts, each being a senior engineer with an excellent reputation and very broad experience in international multidisciplinary projects in the field of seismic hazard and earthquake engineering. The three committee members were selected by the Technical Facilitator/Integrator (TFI) and the Project Management Team (PMT). The members are:

- G. Hardy

- J. J. Johnson
- R. P. Kennedy

The committee acts only at the request of the Project Directorate and PMT and reports to the Project Directorate. The three members can act and express themselves individually or as a team. The Advisory Committee is invited by the PMT to a selection of workshops in order to obtain a good overview of the project, forming the basis for its potential advisory duties. Furthermore, the PMT will regularly inform members on the project progress. The committee members only have the status of workshop observers, like all the other workshop participants who are not part of a subproject expert team.

Competence and Duties

The Advisory Committee's scope of activity is defined as follows:

- Participation in selected project workshops as observers
- No interaction with the subproject experts during the workshops, other than at the explicit request of the TFI, or if they are requested to act as Resource Experts
- Keeping track of the project and being aware of mid- and long-term downstream interface issues (e.g. applicability of PRP results in NPP-specific risk analysis)
- Providing consultancy to the Project Directorate if required. The Advisory Committee's duties are:
- Being familiar with the project plan content and project goals
- Participating in selected workshops based on the suggestion of the PMT
- Participating in selected debriefing meetings with the PMT and the TFI after workshops
- If requested, providing feedback and strategic advice to the Project Directorate via the PMT by written reports.

Documentation

Any relevant information exchange between the Advisory Committee and the Project Directorate or the PMT must be transparently documented and submitted to the PMT in order to be archived. Information is defined as relevant if it contains scientific or technical comments related to the PRP, has an impact on project duration or budget, or reflects a comment/feedback or a suggestion of the Advisory Committee that is relevant for the success of the PRP. This documentation is necessary to provide the possibility of tracing and reproducing the decision-making process. Workshop participation Table 1.3 gives an overview of the workshops which the Advisory Committee attended.

Table 1.3: Advisory Committee's workshop participation.

Date	Workshop
31.08.-03.09.2008	Introduction WS, Kick-Off meeting and WS1/SP1, WS1/SP2, WS1/SP3
08.-10.12.2008	SP1-SP2-SP3-SP4-SP5 Interface Workshops
08.07.2011	Knowledge Transfer SP5
14.-17.05.2013	WS2/SP5 and Summary Meeting

1.4.8 NPP Monitoring Group

Objective

The NPP Monitoring Group's (NPP MG) role within the PRP is to provide feedback to the PMT and to ensure that the specific needs of the NPPs are met. Therefore, the Monitoring Group is involved, if necessary, in the subproject "Interface Issues" (SP3-SP4-SP5) or in separate internal meetings to ensure and define the output requirements of the seismic hazard calculations. Members of the NPP MG can also act as Resource Experts in SP3 and SP5. The PMT prepares written responses to issues raised by the NPP MG and shares them with the TFI.

Constitution and Organization

The NPP MG is composed of representatives of the five existing Swiss Nuclear Power Plants (at four sites and at at the beginning of the project included also representatives of the three potential new plants) and monitors the progress of the project. The NPP MG is provided with information about the workshop agenda and preliminary results prior to the main workshops and prior to the release of the final documents. The members of the monitoring group have access to all project data and information stored in the project database.

Competence and Duties

The NPP MG can ask technical questions and communicate wishes/requests by submitting them in written form to the PMT. The PMT discusses the issues raised with the TFI. The TFI decides whether or not the issues raised (questions, requests) should be discussed among the SP experts during a workshop. In either case, the NPP MG receives a written response from the TFI addressing their requests. This whole procedure is documented by the PMT according to the QA standards. During project workshops, the NPP MG has an observer status. As for all project and workshop participants other than SP experts, comments to the experts and other responsible project participants can be made during the short session "comments from observers" which is held at the end of each workshop day. The NPP MG has the opportunity to complete training courses in PSHA methods. With this improvement of knowledge regarding the technical issues in seismic hazard assessment, the NPP MG representatives can act as a valuable interface between the PRP and the NPPs' PSA and fragility experts.

1.4.9 Technical Reviewers (of the sponsor)

Objective

The Technical Reviewers represent an international, independent group of seismic hazard specialists and technical engineers specialized in earthquake engineering that conduct partial technical reviews of selected project tasks, including corresponding data and documents. This technical review is only performed on behalf of the NPP Monitoring Group (NPP MG) and is managed by the Project Management Team (PMT). Where discrepancies are found by the Technical Reviewers, the results are communicated to the NPP MG and brought to the attention of the PMT. The PMT discusses the issue with the TFI and the TFI then determines if this issue needs to be addressed by the experts.

Constitution and Organization

The Technical Reviewers are six seismic hazard and earthquake engineering experts. They were selected by the NPP MG and accepted by the Technical Facilitator/Integrator (TFI) and the PMT. These reviewers are:

- M. Faber
- A. Gürpinar
- P. Labbé
- P. Rizzo
- T. Schmitt
- G. Woo

The reviewers act only at the request of the NPP MG via the PMT and report to the NPP MG through the PMT. The Technical Reviewers are invited by the PMT to a selection of workshops, especially those dealing with the project task they have to review. The Technical Reviewers only have the status of workshop observers, like all the other workshop participants who are not part of a subproject expert team.

Competence and Duties

The Technical Reviewers' scope of activity is defined as follows:

- Participation in selected project workshops as observers
- No interaction with the subproject experts during the workshops, except on explicit request of the TFI, or if they are requested to act as a Resource Expert
- Monitoring the progress of the project and being aware of technical issues having to do with the project task they have to review
- The PMT and the NPP MG define individual project tasks that the Technical Reviewers should review in detail. These tasks are listed in Table 1.4
- The technical review consists of analyzing and checking data and performing spot checks on model calculations

- The Technical Reviewers are not charged with reviewing the overall project process or the implementation of the SSHAC methodology. These roles are the responsibility of the ENSI Review Team.

The Technical Reviewers' duties are:

- Being familiar with the project plan content and project goals
- Participating in selected workshops based on the requests of the NPP MG or the PMT
- Reviewing task-specific documents and data submitted by the PMT and providing written feedback to the NPP MG through the PMT.

Table 1.4: Technical Reviewers responsible for different project plan tasks.

Project plan §	Task	Reviewer(s)
2.5.1	Earthquake catalogue update (ECOS09)	T. Schmitt
2.6.1.1	Source studies	G. Woo
2.6.1.2	Process ground motion data + NPP recordings	P. Rizzo
2.6.1.3	Site information for Swiss seism. stations	P. Rizzo
2.6.2	New Swiss stochastic ground motion model	A. Gürpinar
2.6.3.1	New Ground Motion models (NGA)	A. Gürpinar
2.7.1	Site investigation	P. Labbé
2.7.2	Site response calculation	T. Schmitt
2.8	Hazard Calculations (HID check)	M. Faber, G. Woo
2.9	Scenario Earthquakes	P. Labbé
-	Interface Issues	M. Faber, A. Gürpinar

Documentation

Any relevant information exchange between the Technical Reviewers and the NPP MG or the PMT must be documented and submitted to the PMT in order to be archived. Information is defined as relevant if it contains scientific or technical comments related to the PRP, has an impact on project duration or budget, or reflects a comment/feedback or a suggestion of a Technical Reviewer that is relevant for the success of the PRP. This documentation is necessary to provide the possibility of tracing and reproducing the decision-making process. Where there is doubt about the relevance of the information, the information should be documented.

Workshop Participation

Table 1.5 gives an overview of the workshops which the Technical Reviewers attended.

1.4.10 External Contractors

To satisfy all expert requests for special studies and supporting computations, a considerable volume of work had to be assigned to outside contractors other than the initially defined

Table 1.5: Technical Reviewers' workshop participation.

Date	Workshop	Faber	Gürpinar	Labbé	Rizzo	Schmitt	Woo
31.08.-03.09.2008	Intro WS & Kick-Off & WS1/SP1,2,3	X	X	X	X	X	X
08.-10.12.2008	Interface WS SP1-2-3-4-5	X	X				
27.-28.04.2009	WS2/SP2, WS2/SP1 & SP1-2 IF WS		X				
22.10.2009	WS2a/SP3	X		X	X		
03.-04.11.2009	WS3/SP2	X	X		X		X
19.11.2009	WS2b/SP3	X					
23.02.2010	WS3/SP1		X			X	
24.02.2010	WS-FFS		X			X	
25.-26.02.2010	WS4/SP2	X	X				
05.+07.05.2010	WS2c/SP3			X			
07.-08.07.2010	WS5/SP2		X		X		
06.10.2010	SP2-3 Interface WS		X				
07.-08.10.2010	WS6/SP2		X				
04.-05.11.2010	WS3a/SP3	X				X	
01.12.2010	WS7/SP2		X				
02.-03.12.2010	WS3b/SP3		X				
16.-18.03.2011	WS4/SP3	X				X	
12.05.2011	WS8/SP2			X			
06.-07.07.2011	WS5/SP3		X				
08.07.2011	Know-How Transfer SP5		X	X			
30.08.-01.09.2011	WS9/SP2		X				X
19.-20.12.2011	WS6/SP3		X	X			
9.-11.05.2012	WS10/SP2 & WS1/SP5 (IF WS)		X				X
16.-18.01.2013	WS11/SP2 & SP2-3 IF WS						
14.-17.05.2013	WS2/SP5 & Final Meeting		X	X	X		X

Resource Experts. The following Table 1.6 lists the most important of these contractors in European countries and the US.

Table 1.6: List of resource experts and external contractors who supported the PRP and their scope of work...."without academic titles".

Subproj.	Name/Company	Scope of Work
SP1	R. Youngs, AMEC Geomatrix Inc.	Support of SP1 experts in their model re-evaluation (completeness, a- & b-values, M_{max}, sensitivities for SP1)
SP1, SP2	P. Roth & B. Steiner, Interoil E&P Switzerland AG	Support of SP1 and SP2 experts in their model evaluations, ECOS comparisons, auxiliary software development for comparison plots
SP2	W. Frei & L. Keller, GeoExpert AG,	Field investigation and data evaluation for site characterization of selected SED stations
	J. Douglas, BRGM	Selection and comparison of GMPEs, development of a simplified empirical model for Switzerland
	U. & M. Kuhlmann, TK Consult AG	Development of software codes for GMPE evaluation and comparison
	O. Ktenidou, Université Joseph Fourier	Kappa evaluation at SED stations, comparison of Kappa estimation methods
	P. Stafford & J. Bommer, Imperial College Consultants London	Small magnitude adjustments for GMPEs
	F. Strasser, Council for Geoscience	Maximum ground motion database and plotting tool
	N. Kühn & F. Scherbaum, Universität Potsdam	Visualization of GMPEs, iterative $V_S - \kappa$ correction, intensity testing, mixture model approach
	M. Mai & L. Dalguer, SED	Finite Fault Simulations (FFS)
	A. Rodriguez-Marek, VirginiaTech	Single-Station Sigma model
	S. Akkar, METU	Single-Station Sigma data, V/H model development
	A. Michelini & L. Faenza, INGV	Development of Intensity-SA correlation
	B. Chiou	Swiss stochastic model parameterization
	T. Schmitt, SDA engineering	Comparison of FFS with GMPEs and PSSM for specific scenarios

Continued on next page...

Table 1.6 – continued from previous page

Subproj.	Name/Company	Scope of Work
	N. Vaidya & R. Quittmeyer, Paul C. Rizzo Associates	Hazard comparison study based on preliminary expert models
	J. Anderson	Single-Station Sigma data, Kappa estimation
SP2, SP3	B. Edwards & V. Poggi, SED,	Kappa evaluation at SED stations, $V_S - \kappa$ corrections for PSSM, QWL functions for SED stations, V/H models, processing of signals recorded at the NPP sites, simulation of GM for SP5, miscellaneous on-demand evaluations
SP2, SP3	W. Silva, Pacific Engineering and Analysis	Site response computations, sensitivities, horiz. and vert. κ evaluations, $V_S - \kappa$ corrections, approach comparisons
SP2, SP5	L. Al Atik, L. Al Atik Consulting	Single-Station Sigma, IRVT approach, empirical κ evaluations, dataset processing, small magnitude adjustments, conditional spectra software
SP2, SP5	N. Gregor	Swiss station residual evaluations, spectral matching for SP3 input time histories, spectral matching and comparison plots for SP5
SP3	A. Hölker, Geophysical Technologies & Consulting GmbH	Support of SP3 experts in their model evaluations, auxiliary software development
	G. Toro, Lettis Consultants International	V_S-profile randomization
	M. Pelli, Geodeco	NL site response computations
	A. Pecker, Géodynamique et Structures	NL site response computations, liquefaction assessments
	M. Ryan & A. Behan, AMEC Geomatrix Inc.	Site response computations and sensitivities
	S. Thomassin, Résonance SA	V_S-profile selection based on dispersion curves
	J. Régnier, CETE Méditeranée, LRN,	Evaluation of non-linear site response for Kiknet stations
	E. Rathje, University of Texas	RVT comparisons
	E. Thompson & D. Boore	SMSIM runs and assessment of Peak-to-RMS factors for RVT

Continued on next page...

Table 1.6 – continued from previous page

Subproj.	Name/Company	Scope of Work
SP3, SP5	A. Asfura, APA Consulting	RVT site response computations, SSI & fragility curve consultancy
SP4	R. McGuire, Lettis Consultants International	Hazard consultancy, V_S-profile randomization
SP5	S. Godey, EMSC	Development of a RESORCE flatfile and access to the database

1.5 Project Activities

Preparation work for the PRP began already in January 2008 and the site investigations started in March 2008. The PRP activities and milestones are shown in Figure 1.4 and Table 1.7. Figure 1.4 shows all the PRP SSHAC workshops in chronological order on a time axis from 2008 to 2013. Compared to the original project plan, many more workshops were held than initially planned. Formal workshops were preferred over working meetings in order to provide full transparency on the decisions with a chance for the observers to follow the process and evolution of models. Table 1.7 summarizes only the most important milestones within the project together with an overview of all SSHAC workshops.

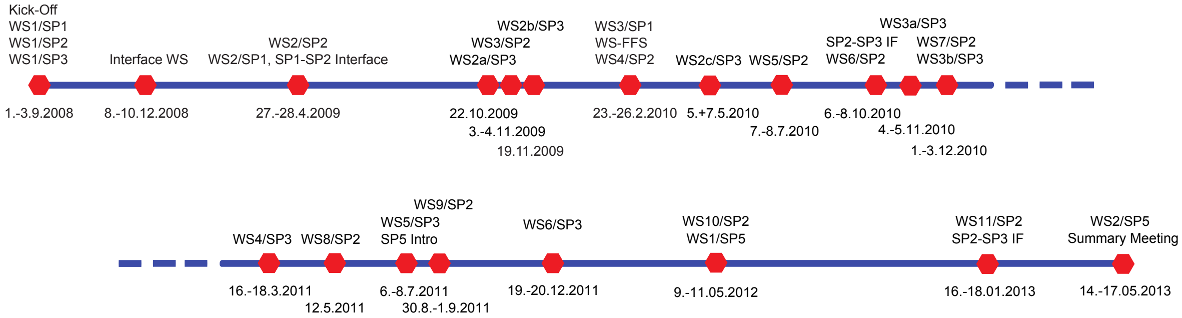


Figure 1.4: PRP schedule and dates of all PRP SSHAC workshops.

Due to several schedule extensions, requested mainly by the SP2 experts, the original project schedule was revised a couple of times during the course of the project. The four main schedule extensions were made to improve quality in the evaluation and results of the PRP:

- Consideration of new NPPs (July 2009)
- Consideration and evaluation of new Swiss stochastic model of the SED (October 2010)
- Review and evaluation of the intended $V_S - \kappa$ corrections (July 2011)
- Review and evaluation of NGA-West2 GMPEs and new information on $V_S - \kappa$ corrections (September 2012)

This led to a completion of the PRP by the end of 2013 and the total duration of the project was thus 63 months instead of the initially planned 30 months.

1.5.1 Knowledge Transfer

The main motivation for an extended knowledge transfer was to increase knowledge on all issues of seismic hazard assessment in swissnuclear and at the NPPs. Thus, there was a continuous technical and managerial know-how transfer from the project to the PMT and the NPP experts during the entire duration of the project. This also guaranteed longevity of know-how and expertise in Switzerland in this specific discipline, which is still evolving and is in many regards a subject for research. Workshops and training seminars were held, including:

- Kick-off meeting for all PRP participants: During the kick-off meeting, sensitivity studies already performed before 2008 were presented, thus enabling the experts to identify the issues that contribute most to a reduction of all the uncertainties.

Table 1.7: PRP milestones

Date	Milestone
31. Aug. & 1.–3. Sept. 2008	PRP Kick-Off Meeting
8.–10. December 2008	Interface Workshop
27.–28. April 2009	Workshop 2 for SP1 and SP2, SP1-SP2 Interface WS
22. October 2009	Workshop 2A for SP3
September 2009	Delivery of new earthquake catalogue to the project
1.–2. November 2009	Review of earthquake catalogue
3.–4. November 2009	Workshop 3 for SP2
19. November 2009	Workshop 2B for SP3
October 2009	Delivery of SP3 site investigation data to the project
26. January 2010	Final review of earthquake catalogue and evaluation
23. February 2010	Workshop 3 for SP1
24.–26. February 2010	Workshop 4 for SP2
March 2010	Completion of SP3 site investigations
5. March 2010	Workshop 2C for SP3
7.–8. July 2010	Workshop 5 for SP2
6.–8. October 2010	SP2-SP3 Interface Workshop & Workshop 6 for SP2
November 2010	Delivery of SP3 site response amplification results to the project
4.–5. November 2010	Workshop 3A for SP3
1.–3. December 2010	SP2-3-4-5 Interface Workshop & Workshop 3B for SP3
February 2011	Delivery of re-computed a, b and M_{max}
16.–18. March 2011	Workshop 4 for SP3
10.–12. May 2011	Workshop 5 for SP3 & Workshop 8 for SP2
6.–8. July 2011	Workshop 6 for SP3 & Know-How Transfer SP5
July 2011	SP2 Experts J. Bommer and F. Scherbaum resigned from PRP
31. Aug.–2. Sept. 2011	Workshop 9 for SP2 & Workshop 6 for SP3
19.–20. December 2011	Workshop 6 for SP3
9.–11. May 2012	Workshop 10 for SP2, Workshop 1 for SP5 & Interface
8. January 2013	Death of SP3 expert J. Studer
16.–18. January 2013	Workshop 11 for SP2, Interface Workshop for SP2-3
February–April 2013	Re-computation of SHAKE and RVT with new consistent κ
14.–15. May 2013	Workshop 2 for SP5
16.–17. May 2013	Project Summary Meeting
19.–20. September 2013	Additional SP2 Workshop on κ
20. December 2013	Submission of Results and Reports to ENSI

- Introductory workshop for new project members who were not involved in the PEGASOS project.
- Training (methods) for swissnuclear staff and NPP experts in applying methods of seismic hazard assessment, seismic design, and seismic safety analysis. Additionally, training also included the further use of hazard results for PSA and fragility analyses and procedures for developing time histories for scenario earthquakes.
  - March 2009: Crash Course on "Probabilistic Seismic Hazard Analysis" with F. Scherbaum
  - June 2009: Crash Course on "The art of deriving seismotectonic input models for PSHA" with S. Wiemer
  - July 2011: "Geological evidences to constrain seismic source characterizations in seismic hazard assessments" with L. Serva
  - July 2011: "Input for the development of fragility curves and their application in PSA" with A. Asfura, J. Baker, G. Hardy, R. Kennedy, S. Rao, N. Vaidya
- Training (software) for swissnuclear staff in using seismic hazard assessment software and tools. The software training was intended to enable swissnuclear staff to independently perform sensitivity studies and future hazard calculations for swissnuclear's own internal purposes, including after the completion of the project. Such calculations will allow swissnuclear to evaluate the potential impacts of new data and models, but these hazard results will not replace the PRP results.
  - January 2012: Crash Course on "Extremwertstatistik für Naturereignisse (ProGUMBEL)" with W. Rosenhauer, H. Meidow, H.-J. Niemann, J. Jensen
  - April 2012: Crash Course on "Soil hazard computations" with A. Hölker

1.5.2 Supporting Computations and Special Studies

In the framework of the PRP, numerous supporting computations were commissioned by the experts in order to provide additional evaluations of data, perform simulations or modeling under their specific advice. On several occasions, when confronted with a novel or poorly understood problem, such as the host-to-target ($V_S - \kappa$) corrections, special studies were tasked to renowned specialists to propose research and modeling work with the potential benefit of providing a better understanding of the problem and the underlying phenomena. In total, 60 key supporting computations were carried out (not including special work packages which were performed by the TFI or some experts themselves), documented and provided to the experts for their evaluation before being stored in the project database. This large amount of additional contract work resulted in a significant re-allocation of budget.

1.6 Quality Assurance

Quality Assurance (QA) in the PRP is based on the QA-Guidelines of PEGASOS and has three major goals:

- To minimize the possibility of errors occurring (or remaining undetected);

- To guarantee the reproducibility and traceability of all project results (traceability will be extended to the reasoning behind decisions if these decisions have an impact on the results), and
- To maintain or increase the same level of technical and procedural quality as achieved during the PEGASOS Project.

The procedures are to be simple and practical without unduly impeding the normal flow of work. The QA procedures for the PRP [Renault et al. 2009] (PMT-TB-1017) are adapted from the PEGASOS QA-Guidelines and were only slightly revised based on the lessons learned from PEGASOS. Based on this experience, the following processes were subjected to QA procedures:

- Management of project documents;
- Management of project data;
- Acceptance and entry of basic data into the project database;
- Conversion of expert models into hazard computation input;
- Software verifications;
- Preparation of hazard software input files;
- Rock and soil hazard computations; and
- Development of scenario earthquakes.

The site investigations and site response computations had a special status in the PRP. The QA for the site investigations and site response calculations were the responsibility of the NPPs. This was done under their QA program and the results were then forwarded to the project. This was judged to be a pragmatic solution with respect to the necessary logistics and accounting issues which had to be addressed individually by each plant. Furthermore, this also implied ownership of the utilities of the site investigations and site response calculation results.

The model parameterizations performed by SP4 for SP1-3 were additionally reviewed by members of the technical review team before starting the hazard calculations. Furthermore, at least 5% of the hazard calculations were performed by an independent contractor (G. Toro) to check the computations of the main contractor (Proseis AG).

According to the PRP QA guidelines, independent audits of their implementation were performed by the designated project QA representative (M. Koller). M. Koller was preferred compared to a professional auditor, as it was learned from the PEGASOS project that the auditor needs a minimum technical understanding of the subject in order to be able to fulfill the expected task. These audits were carried out on 29. October 2008, 14. December 2009, 19 October 2011, and 18. July 2013. During these audits, the QA representative verified strict adherence to the rules and provisions of the guidelines on behalf of the PMT and also issued audit reports.

1.6.1 Software QA

According to the PRP plan and its QA guideline, formal verification of the PSHA software used to compute hazard results is required and needs to meet the specified criteria. Software used in PRP supporting computations on behalf of the experts was not subject to the formal software verification requirements. In total, 14 auxiliary software packages were developed within the PRP. As some developed codes, which were not directly used to calculate hazard, formed a major basis for the expert evaluations, the project management decided to perform several additional software quality assurance assessments. These are for example:

- RDZ-ASW-1003 SP3 Database and Plotting Tool for Site Response Analyses
- TP3-ASW-1004 V/H Model Comparison Tool (used by SP2 and SP3)
- TP2-WAF-1012 Maximum Ground Motion Database and Plotting Tool (used by SP2 and SP3)
- RDZ-ASW-1006 $V_S - \kappa$ Database and Plotting Tool

In order to accommodate all the features of the PRP expert models, modifications of the FRISK88M software had to be made. The QA of these changes to the hazard software is documented in Toro [2013] (QA-TN-1282) (see also Section 7.3.1). Within SP3, complete QA of the expert model parameterization was performed by Thomassin [2013] (QA-TN-1281) and the soil hazard software was independently checked by Baker [2012] (QA-TN-1249) (see also Section 7.3.2).

Recently, within the SSHAC Level 3 PSHA for Thyspunt in South Africa a comparison of hazard results for some cases between FRISK88 and OpenQuake was performed [Bommer et al. 2013] and showed very good agreement when reproducing the functionalities of FRISK in OpenQuake [GEM 2013].

1.7 Report Organization

This final PRP report comprises five volumes. Volume 1 describes and summarizes all project activities and presents illustrative examples of project results. The complete compendium of hazard results for all four NPP sites is represented in Volume 2 as figures and tabulated numerical values (CD-ROM). Volume 3 contains the evaluation summaries of the SP1 seismic source characterization teams, together with the corresponding HIDs and HID QA certificates. The corresponding evaluation summaries and supplementary information of the SP2 ground motion and SP3 site response experts are contained in Volumes 4 and 5 respectively. The workshop summaries are compiled as an appendix to Volume 1 and are available on request.

Volume 1 is made up of twelve main chapters. Chapter 1 consists of this introduction, a review of the initial situation, the project organization and a summary of all activities. The subproject-specific activity reports follow in chapters 2, 4 and 6. These chapters start with a brief methodological introduction (e.g. seismic source characterization methodology) and then proceed to a summary of the subproject's workshops and evaluation meetings, emphasizing highlights and course-setting decisions. The development of the expert models is reported in chronological order, followed by a more comparative discussion of the salient features and, finally, by a subproject-specific summary of the assessments. Chapter 3 and 5 are dedicated to the interfaces between the subprojects 1, 2 and 3 and the topics which needed special attention.

Chapter 7 covers the hazard computations. It includes the list of result specifications, the software tools and detailed accounts of how the rock and soil hazard computations were performed. A sample presentation of hazard results is given in Chapter 8. The different project products correspond to the site-specific content of Volume 2 and include: rock hazard curves and rock hazard spectra for a number of specified frequencies, soil hazard curves and soil hazard spectra for the specified frequencies and three elevation levels (incl. surface), deaggregations and a selection of other sensitivity products, such as sensitivities to upper ground motion estimates, seismic sources and expert models. These sensitivity results and the contributions to hazard, as well as the epistemic uncertainties are discussed as part of Chapter 8.

A special chapter (Chp. 9) is dedicated to additional ground motion parameters for structural evaluations. This Volume 1 concludes with a discussion of the SSHAC consistency (in Chapter 10) and the lessons learned, with an outlook for further improvements in Chapter 11.

The description of the work performed within subproject 5 and the results are not part of this report, but are documented in a separate PRP technical report.

Chapter 2

Seismic Source Characterization - SP1 Summary

The key elements for the SP1 component of the PRP included the following:

- Updating the project database, with particular emphasis on the earthquake catalogue, based on the expert teams' identification of new data
- Evaluation of new data, models, and methods that pertain to seismic source characteristics in the PEGASOS study region
- Workshops to allow for expert interactions and to ensure that interface issues with the other subprojects are addressed
- Integration/model-building based on a number or exploratory analyses conducted to assess the impact of various issues on seismic source models
- Revision, as needed, of elements of the SP1 models or affirmation that no revisions are needed
- Feedback regarding the hazard implications of potential changes to the models as well as revisions to the earthquake catalogue
- Finalization and documentation of the expert assessments

The goal of this analysis is to ensure that the updated SP1 models continue to represent the center, body, and range of technically defensible interpretations.

2.1 Scope of SP1 for the PRP

As itemized in the Project Plan (p. 12), the principal activities for the SP1 component of the PRP consisted of three primary tasks: (1) update of the earthquake catalogue, (2) calculations of recurrence parameters and M_{max} using the new catalogue and (3) affirmation that the logic trees do not need modification, as well as conducting SP1 workshops. The actual work followed these principal activities, but involved considerably more effort than originally envisaged. For example, the catalogue development activity, carried out by the Swiss Seismological Service (SED), involved updating the ECOS02 (Earthquake Catalogue of Switzerland) [SED 2002] and was originally slated for completion prior to the time of the second workshop. The intention was that the new catalogue could be used to calculate M_{max} and recurrence parameters such that these could be discussed and decisions made regarding the need for revision of the logic trees. In reality, the catalogue (termed in the project the ECOS09 catalogue, as only events up to the year 2009 have been considered) was not available until well after the second workshop. It was provided in preliminary form prior to the third workshop and only completed at the time of the finalization of the SP1 expert models. The new catalogue was officially published in 2011 as SED [2011].

Likewise, the need for working meetings among the expert teams was not originally envisaged, but the significant issues associated with the catalogue revision necessitated two working meetings devoted entirely to catalogue revision issues (e.g., conversions of various earthquake size measures to a uniform moment magnitude and associated implications for the seismic source models) and a third working meeting for each team to identify any required revisions to their logic tree models or additional desired sensitivity analyses.

Rather than merely affirm the existing PEGASOS SP1 models, the expert teams decided that the catalogue issues would require extensive consideration. This resulted in multiple requests for a variety of sensitivity calculations to allow each expert team to assess the full impact of the new catalogue on their models. These requests included a wide range of calculations, including calculations of completeness, comparisons of the location, size, and depths of earthquakes in the ECOS09 [SED 2011] and ECOS02 [SED 2002] catalogues, a variety of recurrence calculations using different input and modeling assumptions, and M_{max} calculations based on specified inputs and multiple approaches. The project specialty contractors were able to honor all such requests from the expert teams.

Despite the schedule and scope expansion, the SP1 component of the PRP made every effort to maintain the SSHAC goals of considering the data, models, and methods proposed by the larger technical community and representing the center, body, and range of technically defensible interpretations [Kammerer and Ake 2012] through the expert assessments. As a result, many of the issues explored by the expert teams through sensitivity calculations did not prove to be hazard-significant (the changes in locations of earthquakes in the catalogue is a good example), but all avenues requested by the experts were explored. In this way, the experts were able to finally arrive at informed decisions regarding the structure of their models (logic trees) and to endorse their respective components of the Hazard Input Document (HID).

An overall summary of the principal SP1 activities of the PRP are given in Sections 2.1.1, 2.1.2 and 2.1.3 below, followed by a detailed summary of these activities in Section 2.2. Section 2.3 summarizes the revisions made by the SP1 teams to the original PEGASOS models. The conclusions of the SP1 component of the PRP are given in Section 2.4.

2.1.1 Earthquake catalogue update

The scope description for the update to the PEGASOS earthquake catalogue (ECOS09) is given in the Project Plan (Section 2.4.1):

> ”To ensure the compatibility of the PRP results with the new generation of seismic hazard for Switzerland, the SED will synchronize the ongoing catalogue revision with the PRP implementation so that the PRP can benefit from the latest data and results.
> The following tasks are included:
>
> - Complete the revision of the Earthquake Catalogue Of Switzerland (ECOS09), in time to be used in the PRP hazard assessment.
> - Improve the procedure for the assessment of location and magnitude for historical events, including better assessment of uncertainties and better assessment of source depths.
> - Improve knowledge of the reference soil/rock condition of the macroseismic attenuation model.
> - Recompute the earthquake parameters across the entire revised ECOS on the basis of the updated macroseismic database and of the new instrumental data.
> - Recalibrate instrumental magnitudes for events in border regions derived from seismological agencies in neighboring countries.
> - Re-evaluate the procedures and calibrations for the evaluation of instrumental magnitudes for Switzerland.
> - Implement a formulation for site regionalization and depth-dependence compatible between the different attenuation models used for the macroseismic and instrumental parts of the catalogue.”

As can be seen in the scope specifics, some of the catalogue development activities—such as the work related to the macroseismic database and regionalization and depth-dependence using macroseismic data—were designed to benefit the ground motion modeling (SP2) parts of the Project, as well as SP1.

It was originally envisaged in the Project Plan that the earthquake catalogue work would be completed in September 2009 and, after review, would be available for calculations at the end of 2009. A variety of issues led to delays in completing the catalogue, but the basic sequence of activities that required the catalogue as input was carried out as planned (see Section 2.2 below). The authors of the new ECOS09 and the SP1 expert considered the new catalogue to be an update and replacement of the older ECOS02. The improvements in ECOS09 were not considered by the SP1 experts to be alternative interpretations, but rather addressing deficiencies in the ECOS02.

2.1.2 SP1 Workshops, Interface Workshops and Working Meetings

A key part of the SSHAC process entails interactions amongst the experts to exchange data and ideas. These interactions occur in structured workshops and working meetings, each with a set of clearly identified goals. The goals were defined together with the invitation in the workshop agenda so that the participants could prepare ahead of time. The purpose of each of these meetings is summarized briefly below. The timing and sequence of the SP1 workshops and interface workshops including SP1 are shown along a timeline in Figure 2.1.

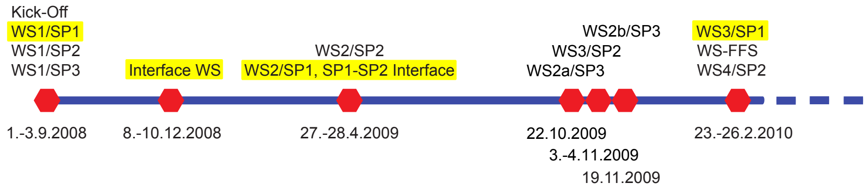


Figure 2.1: Summary timeline of SP1 workshops and interface workshops that included SP1, shown relative to other PRP workshops.

SP1 Workshops:

- Kick-Off Workshop
  The kick-off meeting was intended to provide the participants in all subprojects with an opportunity to understand the reasons for carrying out the PRP, the work that had been conducted since the time of the original PEGASOS Project, and the work that was anticipated to be conducted during the PRP.

- Workshop #1 WS1/SP1
  Workshop #1 (WS1) for SP1 was held on 2. September 2008 with the objectives of reviewing the planned update of the earthquake catalogue (ECOS09), reviewing sensitivity studies regarding maximum earthquake magnitude (M_{max}), making recommendations for sensitivity studies that address other new models and data identified for seismic source characterization, and reviewing the applicability of the existing PEGASOS SP1 models and whether the same structure of the logic tree could be maintained, given the new catalogue.

- Workshop #2 WS2/SP1
  The three main purposes of the WS2/SP1 workshop held on 28. April 2009 were to provide an update on the status of development of the ECOS09 earthquake catalogue, to present and discuss the results of several sensitivity studies identified in previous meetings, and to identify any remaining potential interface issues between SP1 and SP2.

- Workshop #3 WS3/SP1
  The purpose of the third SP1 workshop (WS3) held on 23. February 2010 was to review the updated earthquake catalogue and the new activity rates, b-values, and maximum magnitudes calculated from the new catalogue. The teams were asked to provide their views regarding whether, —in the light of the new ECOS09 catalogue, —they considered that their models of the source zones and spatial smoothing were still applicable, their M_{max} values were still applicable and whether the same structure of the SP1 logic tree could be maintained.

Interface Workshops: Interface workshops were conducted with the specific purpose of ensuring communication between the various subprojects of the PRP. They were also a means of making decisions about the manner in which common technical issues would be addressed.

- SP1-SP2-SP4 Interface Workshop A
  Held on 8. December 2008, the SP1-SP2-SP4 Interface workshop focused on major interface issues including the need to achieve consistency between the ECOS09 earthquake

catalogue and the ground motion models, the rupture dimension models, the style-of-faulting classification and consistency in the definitions used in SP1 and SP2, distance metrics with regard to conversions used in the composite ground motion model, reducing M_{min} in the hazard calculations to 4.5, and the extrapolation of ground motion models to the largest M_{max} coming from SP1.

- SP1-SP2 Interface Workshop B
  Held in conjunction with workshop #2 on 28. April 2009, the SP1-SP2 interface workshop focused on consistency in the attenuation from isoseismals being developed as part of the catalogue activity and used in the ground motion models, consistency between SP1 and SP2 in the source models (e.g., area-magnitude scaling, definitions), and the implications of a sensitivity study showing strong sensitivity of high frequency hazard to M_{max}, thus pointing to the need to consider magnitude scaling of median ground motion and σ at high fractiles.

- SP1-SP2 Interface Workshop C
  An SP1-SP2 interface workshop was held on 24. February 2010 to discuss and resolve the last remaining interface issues, including the current state of the ECOS09 catalogue and its changes from the ECOS02 catalogue, changes in the characteristics of the earthquakes such as focal mechanisms, focal depths, and dips, the Swiss stochastic ground motion model and its reliance on magnitude estimates and hazard sensitivity to the depth distribution.

Working Meetings: Working meetings provided the opportunity for the expert teams to consider available data and to work towards developing assessments and models as a team. The PRP SP1 working meetings were held both as joint meetings across all teams and as closed sessions with each team working on their own.

- ECOS/SP1 Working Meeting I
  A working meeting was held on 1.-2. November 2009 to allow international external reviewers to understand the progress being made in the development of the ECOS09 earthquake catalogue, to discuss some key issues that had emerged during catalogue development, and to describe suggestions by the SP1 experts regarding tasks that could be carried out during the catalogue development process.

- ECOS/SP1 Working Meeting II
  The SP1 experts were assembled on 26. January 2010 for a working meeting devoted to the ECOS09 catalogue, discussions of the potential implications for the elements of the SP1 models, and the identification of additional activities that the experts needed to finalize their assessments. The most significant changes from the ECOS02 catalogue were the inclusion of available instrumental data for the period 2002-2008, non-linear scaling between M_L and M, revised moment magnitude assessments of historical events, and the inclusion and analysis of uncertainties in both location and magnitude.

- Individual SP1 Working Meetings
  In the light of the several studies conducted at the request of the SP1 experts, the SP1 teams met in individual working meetings on 22. February 2010, just prior to WS3.

> The goal of the meetings was to review the new parameters in the light of ECOS09 and the supporting documents provided. Furthermore, before the workshop, the group members were expected to convene and prepare a common position of the group to be presented during the workshop. If modifications to the models were necessary because significant issues related to the ECOS09 were found, the experts were asked to prepare proposals and justifications for the modifications.

2.1.3 Team Evaluations of the Implications of the Earthquake Catalogue for SP1 Models

In terms of SP1, the PRP was designed to include the comprehensive update of the earthquake catalogue, to provide a forum for the active consideration and analysis of the impacts of the new catalogue on the PEGASOS SP1 models, and to refine the SP1 models such that they provide an up-to-date assessment of knowledge and uncertainties in the light of current information. The four resulting SP1 models are captured as logic trees and associated parameters that are given in the Hazard Input Document. The HID was reviewed and endorsed by each of the four SP1 teams as faithfully capturing their assessments. As such, the HID is endorsed for subsequent use in PSHA calculations.

In general, the structure and the weights of the source characterization logic trees of the PEGASOS Project were maintained for the PRP and no changes were made to seismic source geometries. The new catalogue data were used for calculation of the new activity rates (a-values), b-values, and maximum magnitudes for each source zone following the procedures described by each expert team in the PEGASOS elicitation summaries. Unless the M_{max} values were directly assessed by the experts, they were recalculated using the M_{max} approaches identified by the team using the earthquake catalogue (e.g., the EPRI approach [Johnston et al. 1994], [Kijko and Graham 1998]). During the course of the PRP, the SP1 experts specified numerous sensitivity studies and analyses as a means of identifying the implications of various aspects of their models for the calculated results (i.e., M_{max} and recurrence) such that they were able to provide informed final assessments of their models, including the seismic source zonation and logic trees, given the new earthquake catalogue.

2.2 Summary of Key SP1 Activities

The key activities conducted by the SP1 expert teams took place through a series of SP1 workshops, interface workshops with other subprojects, working meetings, and analyses conducted by each team as office studies. This section of the report works through the key activities and findings over the course of the Project in order to explain the procedure followed, demonstrate the avenues followed by the expert teams during their deliberations, and to provide a context for the key conclusions of the study that are presented in the SP1 HID.

2.2.1 Kick-off Meeting, 1. September 2008

The kick-off meeting was intended to provide the participants in all subprojects with an opportunity to understand the reasons for carrying out the PRP, the work that had been conducted since the time of the original PEGASOS Project, and the work that was anticipated to be conducted during the PRP. It was explained in the common session of the workshop that, in the original PEGASOS Project, carried out from 2000 to 2004, seismic hazard at the four nuclear power plant sites in Switzerland was evaluated considering the broad knowledge of the international expert community in earthquake science and geotechnical engineering. After completion of the Project, the review team of the Swiss Federal Nuclear Safety Inspectorate (HSK) and the Project sponsor (swissnuclear) found that the uncertainty range was rather broad, and that this could be reduced by further investigations. Thus, the PRP represents an updating of the PEGASOS Project with the intention reducing uncertainties. All PRP experts, technical reviewers, and advisory committee members were invited to the kick-off meeting in order to obtain an overview of the planned Project work and the new subprojects with their different tasks. Following the joint introduction, the first subproject workshops were held, marking the official start of the PRP.

In the summary presentation of the plans for the PRP, the Technical Facilitator/Integrator (TFI) N.A. Abrahamson indicated that there were essentially two key activities that were to be conducted for SP1. The first was to identify parts of the SP1 models for which there are new data, models, or methods. The new earthquake catalogue being developed by the Swiss Seismological Service (SED) is an example of such new data. The other activity was to conduct sensitivity studies to evaluate the potential impacts on hazard of the new information. If there is a significant impact on uncertainty, then revisions to the SP1 models would be made. Only those parts of the SP1 models that are impacted would need to be updated; if there is no impact, the original SP1 models would be used without modification. It was noted that in the interest of greatly reducing the extensive calculation times required to exercise the full PEGASOS source model, the sensitivity studies would be based on a simplified seismic source model that captures the essential elements of the SP1 models and that is sufficiently accurate for assessing mean hazard and fractiles within certain tolerances according to the Quality Assurance Guidelines [Renault et al. 2009] (PMT-TB-1017). Although the simplified model would be used throughout the PRP, the final hazard calculations would be conducted using the full SP1 models, as defined in the SP1 HID for the PRP.

SP1-SP2 interface issues were also identified at that time. This included the need to convert all earthquakes in the catalogue to moment magnitude, and it is particularly important that a consistent magnitude conversion be used for earthquakes that are common to the two subprojects. Distance conversions also need to be consistent, which depends on depth and dip distribution. Depths of seismogenic sources, style-of-faulting, and magnitude-area scaling were also identified as interface issues which, once the SP1 models are fully defined, SP2 will need to consider in the evaluation of the candidate ground motion models. An interface workshop was scheduled for December 2008 to review the progress related to this and other interface issues.

2.2.2 Workshop #1 WS1/SP1, 2. September 2008

Workshop #1 (WS1) for SP1 was held on 2. September 2008 with the objectives of reviewing the planned update of the earthquake catalogue (ECOS09), reviewing the sensitivity studies regarding maximum earthquake magnitude (M_{max}), making recommendations for sensitivity studies that address other new models and data identified for seismic source characterization, and reviewing the applicability of the existing PEGASOS SP1 models, as well as determining whether the same structure of the logic tree could be maintained, given the new catalogue. In the event that new data, models, or methods were identified, the full group of SP1 experts would have to prioritize the new data and models to be evaluated through sensitivity studies. Based on the discussion during the workshop, the Project Management Team (PMT) would, together with the TFI, evaluate the recommended sensitivity studies and select the ones to be implemented.

The bulk of the workshop entailed a discussion of the earthquake catalogue update that was just beginning to be carried out. The state of the catalogue prior to the PEGASOS Project was discussed, as well as the number of improvements that were made in the ECOS02 that was developed to service the PEGASOS Project. The new update would be called ECOS09 and a number of refinements and updates were discussed. The discussions included the question of whether or not the development of the catalogue update would have a significant effect on the SP1 models, beyond the simple and anticipated need to recalculate the recurrence rates to include the additional years of observation between the time of the ECOS02 and the ECOS09 catalogues. In general, the SP1 experts concluded that the update of the ECOS could potentially have a significant effect on the hazard calculations since there could be changes in the magnitudes calculated from intensities in the previous catalogue used in the PEGASOS Project. Most experts reserved judgment until the catalogue was completed, but suggested that they would not expect the geometry of seismic sources identified in the PEGASOS Project to differ as a result of the new catalogue.

Because of the potential importance of the new catalogue in general and the intensity-conversion issue specifically, it was decided that an SP1 working meeting devoted to the earthquake catalogue should be held in conjunction with WS2 on 28. April 2009. In reality, due to delays in the development of the catalogue, the ECOS09 working meeting took place on 1.-2. November 2009 and a second working meeting related to the earthquake catalogue was added on 10. January 2010.

Sensitivity studies were then presented regarding M_{max} in the host source. As is common in stable continental regions, the findings of the PEGASOS study indicate that the mean hazard at the sites is dominated by the contribution of the host zone. The sensitivity study examined the potential impact of being able—perhaps through detailed and extensive surface geological studies—to limit M_{max} in the host zones to magnitudes smaller than M 6.5 within a box of 10 km by 10 km centered around the site. The calculations carried out for the example site Beznau indicate that the impact of limiting M_{max} in this manner is small, due to the relatively small contribution that M_{max} makes to the mean hazard.

Because all of the expert teams relied to some extent on the earthquake catalogue to estimate M_{max} for all source zones, the experts noted that their M_{max} estimates could be affected by the revisions made as part of ECOS09. The decision was made that, once the ECOS09 catalogue was available, the M_{max} estimates would be re-calculated for each team using the approaches that they had specified earlier as part of the PEGASOS study. The teams would then each be provided with the revised M_{max} distributions in order to make a decision regarding whether or not they would require modification.

The next part of the workshop entailed a discussion of new information that could potentially have an influence on the SP1 seismic source models. Each topic was first introduced and discussed, followed by a decision regarding the manner in which the new information could be incorporated into sensitivity studies to evaluate the potential influence of the findings on seismic hazard. The topics and planned sensitivity analyses were the following:

1. Fribourg Fault:
   The depth of the earthquakes has been revised to shallower depths (2 km as compared to 7 km), which means that the sources of the observed earthquakes are now in the sediments that overly the basement rock. The limited downdip dimensions could affect the depth distribution that was assessed by the expert teams for the Fribourg fault source and a sensitivity analysis on the impacts was proposed.

2. Subaqueous Landslides:
   A recent study by Strasser et al. [2006] found evidence for synchronous landslide events in Lake Zurich and Lake Lucerne that occurred during the past 15,000 years. These landslides are interpreted to have been seismically triggered and the timing of the events is used to estimate the recurrence of large seismic shaking events in the region. To evaluate the impacts of the subaqueous, earthquake triggered landslides, a study was proposed to check if the M_{max} distributions for sources that include the landslides is consistent with M6.5-M7 earthquakes that are implied if these subaqueous landslides are considered to be seismically triggered. Also, the recurrence of $M > 6.5$ earthquakes can be compared to the recurrence for the zones that contain the events to determine if these could have an impact on rates. If either the M_{max} or recurrence rates are found to be inconsistent with the values implied if the subaqueous landslides are assumed to be seismically triggered, then a sensitivity study on the impact on the hazard for these parameters was proposed.

3. Permo-Carboniferous Troughs:
   Geomorphic evidence for possible geologically recent uplift and folding in the Besancon area was described by Prof. Stefan Schmidt, suggesting evidence for ongoing folding along an ENE-WSW axis. This indicates that the recent stress is characterized by transpression, rather than strike slip or transtension, as is the case in Basel, based on earthquake fault plane solutions. Such transpression implies that the hypothesis of thick-skinned reactivation of the Permo-Carboniferous troughs, which would be reactivated in compression, might be more probable than assessed by the SP1 teams. A sensitivity study on the effect of changing the probability of activity of the troughs to 100% was proposed.

Also discussed at the workshop were potential SP1/SP2 interface issues, which were planned for discussion at the December 2008 interface workshop. These included:

- Magnitudes: SP1 and SP2 must both convert magnitudes to moment magnitudes. A check should be made on the consistency of this conversion. In particular, the moment magnitude for any common earthquakes used by SP1 and SP2 datasets should be equivalent.

- Distances: The distance conversion used by SP2 to convert the ground motion models to Joyner-Boore distance depends on the depth and dip distribution. The plan for the PRP is to not implement such a conversion, but rather to leave the ground motion models in their native distance metrics. Therefore, this interface issue is not critical as it was in PEGASOS.

- Depths, style-of-faulting, magnitude-area scaling relations: The definitions and scaling relations used by SP1 will be compared to the definitions and implied scaling relations from the earthquakes used to develop the ground motion models.

2.2.3 SP1-SP2-SP4 Interface Workshop, 8. December 2008

Experience with PSHA projects has shown that it is important for issues that lie at the interfaces between various components of the hazard model to be addressed such that there is common knowledge and agreement on the manner in which the interfaces will be addressed. Accordingly, the PRP held the SP1-SP2-SP4 interface workshop with the specific goal of ensuring communication among the subprojects and as a means of making decisions that would affect multiple components of the hazard model. By doing so early, potential problems that could emerge later in the Project due to different assumptions being made by different subprojects are mitigated.

The major interface issues discussed at the workshop consisted of the following: First is the need to achieve consistency between ECOS09 and the ground motion models. The main focus is on attenuation (isoseismal attenuation, ground motion attenuation, regional differences) and magnitude conversions (conversion to M used in ECOS02, conversion to M used for ground motion models). Second is the rupture dimension models, where dimensions are derived from (a) models used in SP1, (b) from ground motion data, and (c) from numerical simulations. Another interface issue is the style-of-faulting classification and consistency in the definitions used in SP1 and SP2. Distance metrics were discussed with regard to conversions used in the composite ground motion model. Reducing M_{min} in the hazard calculations to 4.5 was discussed as an interface affecting both SP1 and SP2, as well as the largest M_{max} that would come from SP1 and extrapolation of ground motion models to that M_{max}.

A summary of the hazard computations performed during PEGASOS and planned for the PRP was also given by SP4 in order to better understand how the models were simplified and combined for the hazard calculations. For SP1, the models were simplified by tree trimming and moment based pinching following the PEGASOS QA guidelines [Renault et al. 2009] that limited the degree of model simplification based on the impacts on the mean hazard, σ and the fractiles. For sensitivity feedback of the SP2 and SP3 models in the PRP, the existing SP1 model was recently further pinched. This model represents a TFI model, similar to the TFI models used during PEGASOS, and is intended for sensitivity calculations only. The simplified source model does not replace the full PEGASOS SP1 models. The purpose of this model is to allow feedback to be provided to the SP2 and SP3 experts in a timely manner. It was presented to the SP1 teams merely to ensure complete communication.

Decisions regarding the interface issues that have an impact on SP1 were the following: Regarding magnitude conversions, it was noted that all events in the catalogue are defined by a moment magnitude and the ECOS09 conversions are being updated. For the ground motion models, it is suggested that SP2 avoid conversions when possible, otherwise there is still the issue of conversions used to develop the ground motion dataset. Where possible, SP2 should check for consistency with the ECOS09 conversions. Regarding rupture dimensions, the area-magnitude scaling from the SP1 models is consistent with the scaling from the NGA data used to develop some of the candidate ground motion models. If the information is available, the scaling for other ground motion datasets should be checked. Distance conversions should be avoided by using the native distance metric from the ground motion models and the applicable source geometries given by SP1. Because SP1 will be specifying sources out to distances of 500 km, the ground motion models will need to extrapolate to these large distances. The contribution to hazard of sources at these large distances is expected to be very low. A review of the SP1 definitions of style-of-faulting, and associated fault dip angles shows that the range of dips from earthquakes in the ground motion dataset are consistent with dips for SP1 style-of-faulting classes. There are no issues associated with reducing M_{min} in the hazard calculations to 4.5 and the ground motion models will need to be extrapolated to M_{max} as large as 8.0.

Immediately following the workshop, decisions were made by the TFI regarding sensitivity studies that would be carried out with the particular purpose of addressing the hazard significance of new data or new interpretations of data that could have an influence on SP1 models. The topics to be addressed were based on items identified at either the SP1 WS1 or the SP1-SP2-SP4 Interface workshop, requests made by the SP1 expert teams, or requests from the PRP sponsors. Only those issues that were judged to have a significant potential impact on seismic hazard were deemed to be worthy of pursuit. The sensitivity studies to be conducted were the following:

- The impact of the new catalogue ECOS09 on calculated M_{max} and recurrence rates for each seismic source (this was planned to be conducted as part of the PRP anyway and does not require a separate sensitivity study).

- The impact of the hypothesis of thick-skinned reactivation of the Permo-Carboniferous troughs, given a transpression scenario. This hypothesis is captured by making the assessment that the Permo-Carboniferous troughs are active with a probability of 1.0. This assessment was already part of past sensitivity analyses, as shown in the tornado diagrams in the PEGASOS report. There is virtually no impact, but the result will be extracted from the report and identified to the expert teams for their information.

- The impact of the presence and timing of the subaqueous landslides will be evaluated by comparing their reported magnitudes and locations with the magnitudes and recurrence rates for the SP1 seismic sources that include the landslides.

- Regarding M_{max} assessments, a suggestion was made by the sponsors to use two approaches (bootstrap paradigm and Generalized Extreme Value (GEV)) to limit the M_{max} in the vicinity of the NPP sites. It was agreed that the methods would be investigated, but, like all methods of assessing M_{max} that are based entirely on the observed earthquakes, their numbers are low and statistically-based assessments are usually unconstrained. It was also decided to present the results of the recent special USGS conference on M_{max} assessments to the SP1 experts and to summarize the conclusions relative to the approaches that had been selected by the SP1 experts.

- The approach used in the PEGASOS SP1 models involves the smoothing of recurrence rates (a-values) over various regions specified by the expert teams. Concern was raised by a sponsor technical reviewer that this process might lead to over-prediction of rates in the local site vicinities around each of the NPP sites. A sensitivity study was identified that would compare the recurrence rates derived from smoothing within these local vicinities with the observed rate of earthquakes from the earthquake catalogue.

It should be noted that the SP1 experts were asked to provide their assessments in writing of whether or not they were aware of any new data, models, or methods that would change their assessments that were present within the PEGASOS model. With the exception of the new earthquake catalogue and the planned sensitivity studies, the SP1 experts concluded that they were not aware of any other new information that would change their SP1 models (TP1-TN-1020).

2.2.4 Workshop #2 WS2/SP1 & SP1-SP2 Interface Workshop, 28 April 2009

The three principal purposes of the WS2/SP1 workshop held on 28. April 2009 were to provide an update on the status of development of the ECOS09 earthquake catalogue, to present and discuss the results of several sensitivity studies identified in previous meetings, and to identify any remaining potential interface issues between SP1 and SP2. These activities are consistent with the notion of evaluating the impact of new data, models, and methods developed since the conclusion of the PEGASOS Project, and allowing for the revision of the models by the expert teams if the impacts are significant.

Because of differences in the approaches being taken, the update given by the SED on the ECOS09 catalogue [SED 2011] consisted of a discussion of the historical part (derived from the update of the macroseismic catalogue MECOS08) and the instrumental part. The update of the macroseismic catalogue (MECOS08) was completed, including new studies and investigations of the last 5 years and the reports were planned to be finalized in May/June 2009. The procedure for the calibration of historical events (for the years 205-1975 A.D.) was discussed along with its challenges. The main issues were the selection of the intensity attenuation relation, the use of a site correction term and the overall calibration method to be applied. Issues were raised and discussed by the SP1 experts regarding how consistency can be obtained between the M estimates in the catalogue, which have large scatter, and the estimates given in the catalogues for adjacent countries. In addition, the experts requested a clear description of the treatment of uncertainties in the new catalogue and to have more information about the differences between locations and magnitudes in the new catalogue with respect to the previous version. It was noted that only systematic changes in magnitude and associated changes in a-values would impact the hazard results.

Regarding the instrumental part of the catalogue update, the procedure consisted of three steps:

1. Revise the SED catalogue,
2. Merge that catalogue with the applicable part of foreign catalogues, and
3. Convert all magnitudes to a homogeneous magnitude.

In the discussion of the incorporation of the new data recorded since 2000, it was pointed out that the relation between M_L and M cannot be modeled by just a constant shift at all magnitudes as was done in ECOS02. At small magnitudes ($M_L = 2$), the slope between M

and M_L increases to 1.5 from a slope of 1.0 for moderate magnitudes ($M_L = 4$). This means that there could be a significant impact on the b-values that result from using the revised $M_L - M$ scaling at small magnitudes, if magnitudes as small as $M = 2$ are used for computing the b-value. This uncertainty in the magnitude conversion was not explicitly considered in the original PEGASOS SP1 models.

Given the status and plans for the ECOS09 catalogue, as presented at the workshop, the issue was discussed regarding whether or not the revised catalogue would lead to a revision of the PEGASOS SP1 models (logic tree structures). In general, the experts concluded that there was no need to change the basic structure of their logic trees. The principal impact identified by the experts was the need to recompute the recurrence parameters (a- and b-values) and the M_{max} estimates, and to then provide the new results to the teams for their review. M_{max} is affected because the EPRI approach [Johnston et al. 1994] incorporates the size of the largest observed event within a seismic source and the counts of earthquakes to define the likelihood function. In addition, those teams that used the Kijko and Graham [1998] approach could be affected because the approach relies entirely on the observed earthquake counts within the seismic source. Related to the recurrence issue, some of the experts identified catalogue completeness as a potential issue that might need to be revisited in the light of recent studies, particularly the work on the historical record. Because the ECOS09 catalogue also is planned to provide a description of the uncertainties associated with the magnitude of each event, it was noted that there is a need to understand how those uncertainties were arrived at.

In addition to the earthquake catalogue, other potentially significant data, models, and methods had been identified in previous workshops, along with sensitivity analyses that would provide insight into the potential impact on site hazard. A series of presentations and discussions were carried out to provide the experts with an opportunity to thoroughly understand the sensitivity analyses and their potential implications for hazard. A brief summary of each sensitivity case is given below.

- Impact of reactivation of the Permo-Carboniferous Troughs
  Discussions at WS1 had raised the issue of the potential for the Permo-Carboniferous Troughs to have a higher probability of being active than previously assessed in the PEGASOS SP1 models. Because this assessment was part of the original logic trees, its impact could be assessed by varying the assessment from a probability of 1.0 to 0. The sensitivity of the hazard to this range was evaluated by considering the impact on the epistemic uncertainty as shown in the tornado diagrams. It was shown that the global variables linked to the potential activity of the Permo-Carboniferous Troughs have little impact on the total epistemic uncertainty.

- Impact of revised Fribourg Fault Zone depth distribution
  Recent work presented at WS1 on the depth distribution of earthquakes within the Fribourg Fault Zone showed that the depths of hypocenters are shallower than assessed during the original PEGASOS Project. The depth distributions of future earthquakes are assessed by each of the teams on the basis of the depths of all observed earthquakes within the seismic source of interest or, in some cases, across broad regions. Sensitivity to the revised depths along the Fribourg Fault Zone was assessed by looking at the change in the mean depths and standard deviation for sources that include the Fribourg Fault Zone. In all cases, the change in mean and standard deviation is minor, leading

to the conclusion that this new data would not have a significant effect on the depth distributions and, in turn, on the calculated seismic hazard.

- Slip-depth distribution (see TP1-TN-1039)
  Part of the assessments made by the SP1 teams that is used in modeling future earthquakes is the expected depth distributions of future earthquakes. All of the SP1 teams used a magnitude-dependent depth distribution. The magnitude dependence was modeled by requiring the hypocenter to be in the lower half of the fault rupture and for the area of rupture along the fault plane to be magnitude-dependent. A question was asked regarding what the impact of using a magnitude-dependent depth distribution (SP1 models) would have on the coseismic slip distribution with depth. Representative cases with shallow and deep hypocenter distributions, and with steep and shallow dips, were considered. For the moderate magnitudes ($M5$), the slip distribution with depth is similar to the hypocentral distribution. For the large magnitudes ($M7$), the slip distribution with depth is nearly uniform for the lower part of the fault and is tapered at the upper part of the fault. This result matches the experts' expectations and does not affect the SP1 models, but it may be useful for the SP2 models.

- Assessment of spatial smoothing of seismicity near the NPP sites and alternative methods for assessing M_{max}
  In response to questions raised by a sponsor technical reviewer, a sensitivity study was conducted to assess whether the spatial smoothing approach used might be over-predicting or otherwise inconsistent with the local recurrence from observed seismicity within the local area near the NPP sites. The study showed that the rates of earthquakes predicted by the PEGASOS SP1 models in areas of 10, 20 and 30 km around the NPP sites are not inconsistent with the observed rates of earthquakes in these regions. This indicates that the SP1 models did not include excessive smoothing that could be rejected by the observed data.
  Another question had been raised regarding what M_{max} estimates would be obtained by utilizing two alternative approaches to assessing M_{max} within the local region within 25 km of the sites. The claim was that the M_{max} approaches used by the SP1 teams were resulting in higher M_{max} estimates than would result from using the alternative approaches in the local region around the sites. The two M_{max} approaches were the bootstrap approach of Dargahi-Noubary [2000], and a generalized extreme value model. These methods were applied to the catalogue of earthquakes within 25 km of each plant site, which is considerably smaller than the typical sizes of seismic sources identified by the SP1 teams. Because of the relatively few events and the reliance of the two approaches solely on the observed earthquakes, both approaches result in relatively wide ranges in the confidence intervals for the M_{max} estimates. After discussion, the experts concluded that they found no reason to modify either the approach to smoothing or to assessing M_{max} based on these sensitivity analyses.

- Summary of USGS M_{max} workshop (see TP1-TN-1032)
  In the spirit of identifying and evaluating new data, models, and methods that may have become available since the PEGASOS Project was completed, the issue of what M_{max} approaches were currently considered to be appropriate for use within stable continental regions was identified. In response, a summary was given of the issues and approaches

discussed at the NRC-USGS workshop on M_{max} in the CEUS (Central and Eastern United States) held on 8.-9. September 2008 [Wheeler 2009]. The major finding was that there is no significant change in methodologies compared to what the SP1 experts considered and chose to apply in PEGASOS. The Bayesian or EPRI approach [Johnston et al. 1994] taken by the SP1 expert teams is consistent with the approaches that are widely endorsed by the technical community for seismic hazard studies within stable continental regions. Further evidence of the viability of this approach is its use in the CEUS SSC Project for nuclear facilities [EPRI et al. 2012].

- Impact of new paleoseismic data (subaqueous landslides) on M_{max} and recurrence (see TP1-TN-1033)
  Paleoseismic data are completely independent of the data given in the earthquake catalogue that are used to assess the recurrence rates and M_{max} of seismic sources. Hence, the issue was raised previously regarding whether the paleoseismic observations of subaqueous landslides in central Switzerland [Strasser et al. 2006] might lead to the need to modify the recurrence rates or M_{max} estimates for the seismic sources in that region. A comparison was presented of the estimated sizes and recurrence rates for the paleo-earthquakes and the M_{max} estimates and recurrence rates developed by each of the expert teams. The results show that the assessments by the SP1 experts include the potential for earthquakes having magnitudes as large as $M6.5$ to $M7.0$. In addition, the recurrence rate for these events based on paleoseismic evidence is generally consistent with the predicted rates developed by the teams from observed seismicity. Therefore, there is no discrepancy and the experts concluded that there is no need to modify their source characterizations to account for the new paleoseismic data.

- Impact of M_{max} variation (see TP1-TN-1038)
  An M_{max} sensitivity study was carried out with the purpose of seeing how important a one-half magnitude variation in mean M_{max} is for calculated hazard. The results showed a significant and surprising impact of the M_{max} variation on the final hazard. Further analysis of the results and comparisons showed that the effect is related to the ground motion model. Thus, the SP2 expert team was made aware of the importance of the epistemic uncertainty in the median ground motion and its relation to M_{max} when developing their new SP2 logic tree. The implication for the SP1 experts is that they should be aware that the M_{max} assessments are important to the hazard calculations, but there is no particular need to alter the approaches that they might be considering in the light of these sensitivity results.

2.2.5 ECOS/SP1 Working Meeting, 1.-2. November 2009

A working meeting was held on 1.-2. November 2009 to allow international external reviewers to understand the progress being made in the development of the ECOS09 earthquake catalogue, to discuss some key issues that had emerged during catalogue development, and to describe suggestions by the SP1 experts regarding tasks that could be carried out during the catalogue development process. Discussions included the issues associated with merging of catalogues for adjacent countries, especially in the light of the need for a uniform moment magnitude in the ECOS catalogue. This involves the identification of duplicate entries for the same earthquake. The work has shown that the use of an automatic procedure for identifying duplicates can be problematic and often manual procedures are needed to define the duplicates. Priority ranking for various regions is needed in the cases where multiple catalogues may include the same earthquakes. Discussions focused on the issues associated with estimating location and magnitude uncertainties. A key issue identified is the relationship between M_L and M, which shows a non-linearity below M_L smaller than about 3. This was not seen the ECOS02 catalogue. Depending on whether smaller earthquakes are used to constrain earthquake recurrence, this non-linearity can affect the b-value of recurrence curves. The experts provided their input on these issues and made suggestions that would help them in their evaluation of the usefulness of the catalogue.

2.2.6 ECOS/SP1 Working Meeting, 26. January 2010

The SP1 experts were assembled for a working meeting devoted to the ECOS09 catalogue, discussion of the potential implications for the elements of the SP1 models, and identification of additional activities that the experts needed to finalize their assessments. The most significant changes from the ECOS02 catalogue are the inclusion of available instrumental data for the period 2002-2008, non-linear scaling between M_L and M, revised moment magnitude assessments of historical events, and the inclusion and analysis of uncertainties in both location and magnitude.

Discussions were held regarding the impacts of the new catalogue for the key elements of the SP1 assessments, including the potential need to modify seismic source zone boundaries, catalogue completeness, recurrence rates, M_{max}, and depth distribution. In all cases, sensitivity studies were identified that would allow the various teams to examine the effect that the new catalogue would have on their model, if any. For example, three of the teams concluded that the new catalogue would not affect their source zone boundary locations. However, one team concluded that the position of a particular cluster of seismicity had an influence on a source zone boundary and, if the location of the cluster had moved in the new catalogue, their boundary would also need to be moved. A number of sensitivity cases were identified to test the sensitivity of the existing SP1 recurrence models to the new relationship between M_L and M. Also, requests were made to recalculate the M_{max} distributions in light of the new catalogue. Finally, plans were made to conduct hazard sensitivity analyses to assess whether or not the potential changes would result in significant changes to the calculated hazard at the NPP sites.

In response to the requests made by the SP1 experts, a number of studies were carried out by specialty contractors for the Project. The purpose of these studies was to provide insights to the experts regarding whether or not the new catalogue would lead to significant changes to their SP1 PEGASOS models. Although the judgment regarding whether or not the catalogue information would lead to changes in the SP1 model components was left to the expert teams, the significance of the model changes, in turn, for the calculated hazard at the site would need to be evaluated based on additional seismic hazard calculations at the NPP sites.

The studies that were conducted at the request of the SP1 expert teams consisted of the following:

- A systematic comparison of the magnitudes, locations, and depths (MRZ) of earthquakes in the ECOS02 and ECOS09 catalogues [Roth and Farrington 2010] (TP1-TN-1063).

This request was made with the particular interest of seeing whether systematic shifts in location might be present, which could lead to possible changes in seismic source boundaries, or systematic shifts in magnitude, which could lead to possible changes in earthquake recurrence.

- A summary of the five largest earthquakes that have occurred within each seismic source zone based on the ECOS02 and ECOS09 catalogues [Roth 2010a] (TP1-TN-1065). The request was made to examine whether there were any systematic shifts in location or magnitude, which could potentially affect the geometry of seismic sources. Also, the sizes of the largest observed earthquakes are used to constrain the likelihood function used in estimating M_{max} using the EPRI 1994 [Johnston et al. 1994] approach.

- Earthquake focal depth distributions in Switzerland based on ECOS02 data and earlier studies are very different below the Alps and below the Alpine foreland. An update was carried out using focal depth statistics that take into account the earthquake data acquired since then. The updated results essentially confirm the significant focal depth differences seen along a NNW-SSE profile across Switzerland [Deichmann et al. 2000b]. Below the foreland, earthquakes occur throughout the whole crust all the way down to the Moho at depths of more than 30 km. Below the Alps, on the other hand, where the Moho reaches depths of more than 50 km, seismicity and thus brittle deformation is restricted mainly to the top 15 km of the crust.

- An evaluation of potential impacts that changes to the earthquake catalogue may have on estimates of catalogue completeness, including the magnitude of completeness (Mc) as a function of time and space. Issues identified include the influence of the observed non-linearity in the M_L to M conversion, differences in completeness in adjacent countries, and the influence of the newly reassessed intensity on M conversions. The goal of this discussion was to clarify the issues and to provide a focus for the assessments that the SP1 teams must make.

- Calculations of catalogue completeness (”Stepp plots”), recurrence rates, and M_{max} for the SP1 seismic sources using the approaches specified by the PEGASOS models and using the ECOS09 catalogue. Comparisons were provided between the values for the ECOS02 and the ECOS09 catalogue. These results were intended to provide an indication to each expert team of whether or not the recurrence or M_{max} assessments have changed as a result of the new catalogue.

2.2.7 SP1 Working Meetings, 22. February 2010

In the light of the several studies conducted at the request of the SP1 experts, identified above, the SP1 teams met in individual working meetings on 22. February 2010, just prior to WS3. The purpose of the meetings was to review the new parameters in the light of ECOS09 and the supporting documents provided. Furthermore, before the workshop the group members were expected to convene and prepare a common position of the group to be presented during the workshop. If modifications to the models were necessary because significant issues related to the ECOS09 were found, the experts were asked to prepare proposals and justifications for the modifications.

2.2.8 Workshop #3 WS3/SP1, 23 February 2010

The purpose of the third SP1 workshop (WS3/SP1) was to review the updated earthquake catalogue and the new activity rates, b-values, and maximum magnitudes calculated from the new catalogue. The plan was for the catalogue to be finalized and presented to the SP1 experts to be used in the framework of the PRP. The teams were asked to provide their views regarding whether, in the light of the new ECOS09 catalogue, they considered that their models of the source zones and spatial smoothing are still applicable, their M_{max} values are still applicable, and if the same structure of the SP1 logic tree can be maintained.

A description was given of the progress being made on the ECOS09 catalogue, which was slated for completion in March 2010. It was noted that several activities had been conducted that would address concerns raised by the SP1 experts. For example, concerning the historical part of the catalogue, the calibration for some key events had been checked, a listing was being prepared of all fake or explosions/induced events, and events that showed large differences in location and magnitude between ECOS02 and ECOS09 had been checked. Concerning the instrumental part of the catalogue, particular events in the border region had been studied such that the best solution could be selected, duplicates had been identified, and events outside of the area of the network had been used to locate the events.

At the workshop, a summary was provided of the several studies conducted at the request of the expert teams to assist the experts in their evaluation of the influence that the ECOS09 catalogue has on their SP1 assessments (described above). The assessments presented included completeness assessments that take into account the new non-linear relationship between M_L and M, recurrence relationships using alternative magnitude distributions and minimum magnitudes, and recalculations of M_{max} using the approaches specified by the experts. These results were presented and discussed with the experts, but the experts noted that they would need to spend time following the workshop to study the results in more detail.

Following these presentations, a representative from each of the SP1 expert teams made a presentation summarizing their team's position regarding the expected effects that the ECOS09 catalogue would have on seismic source geometry, M_{max} assessments, earthquake recurrence, or any other aspect of the logic tree structure. The assessments by each team are summarized in the following:

- Team EG1a

  There is no need to change seismic source boundaries. There is no new evidence to identify linear sources or faults, based on the seismotectonics. The overall assessment of the seismotectonic environment is unchanged.

  There is no need to change the depth distribution previously used.

  Regarding M_{max}, it is unlikely that there will be big differences. The team would like to see the results that come from a recalculation using the Kijko and Graham [1998] approach, once the recurrence parameters are available. Also, the team will consider a possible geological basis for an upper magnitude cut-off (the upper tail of the M_{max} distribution).

  Regarding recurrence, the team would like to use the same procedure for assessing recurrence, including the various approaches for deriving b-values. The team plans to review the Stepp plots provided to them and to decide if the Mc approach is the way to go, and to explore the use of the new model proposed to account for the $M_L - M$ conversion.

It was noted during the discussions that the experts should realize that they are providing input to a hazard analysis and that they need to be pragmatic in providing those assessments that are important to the hazard calculations. It is unlikely that all technical issues, such as the non-linearity of the $M_L - M$ relationship, will be "solved" as part of the PRP.

- Team EG1b

There is no need to revise the source zone boundaries for either the large or small zones. There is no systematic shift in the location of earthquakes, which would lead to a possible change in source locations.

There is no need to change the earthquake depth distribution.

Regarding M_{max}, the team will consider a different discretization of the posterior distribution into five bins. The team will look at the issue of having uncertainty in the largest observed magnitude. The team will have a new maximum cut-off based on the largest earthquakes in the ECOS09 catalogue as well as physical considerations (fault length, etc.). A report has been written with a short section on this (EG1-ES-1008, EG1-EXA-1010 & 1012).

Regarding earthquake recurrence, there is no change in the declustering approach. The team would like to see the recurrence plots with and without the $M_L - M$ conversion taken into account. To avoid many of the problems at low magnitudes, the team would like the recurrence curves to begin at $M2.7$, which will lead to more stability in b-values.

- Team EG1c

Regarding the source zone model, the team does not need to revise source zones. The basis for the zones is that there is a homogeneous spatial distribution within the sources. It was thought that there might be some clustering when declustering was run for the ECOS09 catalogue, but with further review it was seen that the seismicity was not becoming more spatially clustered.

Regarding the depth distribution, the team may want to skew the distribution based on a new approach, as well as account for shallower earthquake focal depths along the Fribourg source. There is no change to the style-of-faulting or associated geometries.

The team would like for M_{max} to be re-calculated with the new catalogue using the same approach as specified for PEGASOS. For the largest observed magnitude, the team will use the same procedure with new input provided by the new catalogue.

Completeness needs to be reconsidered and the team will study the materials provided before giving its assessment.

Regarding recurrence, the team will consider all three cases given in the Stepp plots, but the procedure that will be used is not statistical; it is based on the team's judgment in the light of the calculations.

- Team EG1d

There is no need to adjust the geometry of the seismic source zones.

Regarding the depth distribution, there is no new evidence that would lead to the need to make a change.

Regarding M_{max}, the team will be asking for additional feedback to assist with making its assessments. This includes looking at the lower magnitude truncation, which is controlled by the largest observed earthquakes, the sensitivity to binning, and the upper magnitude truncation in the light of the largest events in the catalogue.

Regarding recurrence, there are a number of issues that the team plans to consider. For completeness, options include calculating Mc automatically, using the new conversion, or using the conversion only at the higher magnitudes. The team needs to look at the Stepp plots. A big change in instrumentation occurred in 2001 and the team needs to consider the effect on completeness. Looking at the density recurrence plots for the ECOS02 and ECOS09 catalogues shows that there is a difference in b-value for all events, but this stabilizes above about $M2.7$. It might be pragmatic to use $M > 2.7$ for recurrence purposes, but the team would like to see the effect on calculated hazard before making a decision on the b-value issue.

Evaluation of additional data and information published in the course of the PRP

All publications discussed in the framework of workshop WS1/SP1 at the start of the PRP are documented in PMT-TN-1088. During the WS3/SP1, the SP1 experts were elicited again as to whether any new data or information had become available that would change their interpretation of the actual SP1 models. This was not the case and the technical note TP1-TN-1020 of the SP1 experts thus summarizes their evaluation of new additional data and information to be potentially considered for the PRP. The publications of Kock et al. [2009], Ziegler and Fraefel [2009] and Fraefel [2008] (from the University of Basel) only became publicly available in late 2009. However, the data and technical conclusions from those studies were summarized at the workshop and were therefore considered by the SP1 experts during their evaluations, even if not cited in PMT-TN-1088 directly. These publications were also evaluated in detail by NAGRA within the framework of another Project and did not show any inconsistency with the PRP SP1 models.

Evaluation of criticism of the Bayesian Approach (modified extract from EPRI et al. [2012])

Kijko [2010] has criticized the use of the Bayesian approach for estimation of M_{max} as producing results that are biased low. He demonstrates the issue by performing simulations of catalogues of earthquakes generated from an exponential distribution with a known M_{max} (set at the mean of a hypothetical M_{max} prior distribution) and then estimating the M_{max} using the posterior distribution generated from the product of the prior with the sample likelihood function. Discussions with the lead author (A. Kijko, pers. comm., 2011) indicate that Kijko [2010] uses the mode of the posterior as the point estimate of M_{max}. However, the application of the Bayesian approach for M_{max} estimation in the PRP uses the full posterior distribution. A better point estimate of this result is the mean of the posterior rather than the mode.

The effect of the use of the mode versus the mean has been investigated within the framework of the CEUS-SSC Project (EPRI et al. [2012], Section 5.2.1.1.5) by comparing the posterior distributions. Comparison of posterior distributions with a small sample size shows that the posterior distribution has a shape very similar to the prior with only a minor shift in the mode. The shift in the mean between the prior and the posterior is even less. When using a large sample size, the likelihood function dramatically affects the shape of the posterior such that the mode occurs at the maximum observed value. However, the posterior distribution does extend to magnitudes larger than the maximum observed such that the mean would be a larger value.

The effect of using the mode of the posterior, as in Kijko [2010], versus the mean of the posterior, a more appropriate point estimate of the results used in the CEUS SSC Project, is illustrated in Figure 2.2. A prior distribution for maximum magnitude with a mean of 6.9 and a standard deviation of 0.5 was assumed. Various size samples of exponentially distributed earthquakes were then simulated from an exponential distribution of magnitudes truncated at the mean of the prior, 6.9. For each sample, the likelihood function was used to develop a posterior distribution. The mean and the mode of this posterior were then computed. The process was repeated for 1000 simulations of each sample size. The average values of the mean and mode for each sample size are plotted on Figure 2.2. These results confirm the conclusion of Kijko [2010] that the mode of the posterior is a biased estimate of M_{max}, with the bias to smaller values. However, the mean of the posterior does not display any significant bias. Therefore, it is concluded that the application of the Bayesian approach using the full posterior distribution should not lead to biased estimates of M_{max}.

2.2.9 SP1 - SP2 Interface Workshop, 24. February 2010

An SP1-SP2 interface workshop was held on 24. February 2010 in order to discuss and resolve the last remaining interface issues. The workshop included presentations describing the current state of the ECOS09 catalogue and its changes from the ECOS02 catalogue, a summary of the changes in the characteristics of the earthquakes such as focal mechanisms, focal depths, and dips, a summary of the Swiss stochastic ground motion model and its reliance on magnitude estimates and a study of the hazard sensitivity to the depth distribution.

The interface issues that were identified in the workshop were the following:

- Linearity of the Gutenberg-Richter (recurrence) relation
  The update of the $M_L - M$ conversion based on the new catalogue shows non-linearity between the larger magnitudes and the smaller magnitudes (less than about $M2.7$). As a result, the recurrence relationships also show non-linearity (changes in b-value). It was pointed out that the Swiss stochastic ground motion model is based on small-magnitude earthquakes and that detailed studies might be of help in assessing the non-linearity of the Gutenberg-Richter relations.

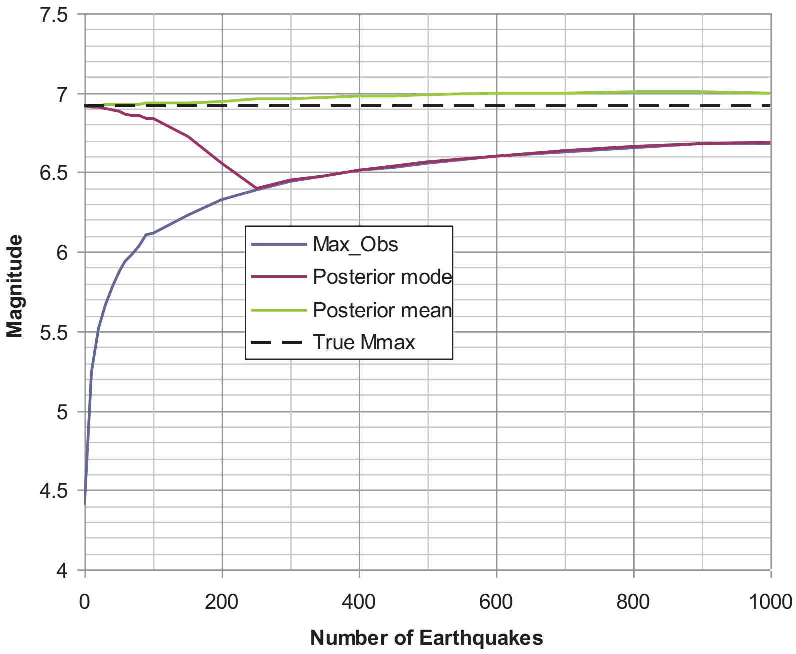


Figure 2.2: Comparison addressing the criticism of the Bayesian Approach (Figure 5.2.1-10 from EPRI et al. [2012]). Results of simulations of estimates of M_{max} using the Bayesian approach for earthquake catalogues ranging in size from 1 to 1000 earthquakes. True M_{max} is set as the mean of the prior distribution.

- Swiss Small Magnitude Model
  The ECOS09 catalogue results in changes to the moment magnitude estimates for many earthquakes used in the Swiss stochastic model and the Swiss small magnitude empirical model. The final Swiss stochastic model will be developed after the ECOS09 catalogue is finalized, but it is important for the magnitudes to be consistent between the Swiss small magnitude model and ECOS09. SP2 can either wait for the catalogue before the model is finalized or proceed to finalize the model and then demonstrate that the adjusted ground motion models are consistent with the final Swiss small magnitude model.

- Hypocenter Location on Rupture Plane
  The SP1 models specified the probability of the hypocenter location on the rupture plane. For example, the hypocenter might have been assessed to be located in the lower half of the rupture plane. Based on the finite fault simulation work for SP2, the available simulated ruptures could be used to check (or constrain) the assumed distribution of the hypocenter locations on the rupture plane.

2.2.10 Analyses Conducted for SP1 Teams to Assist in Finalizing Models

From the time of the workshop in February 2010 until the development of the final SP1 models that are included in the final HIDs, a series of exploratory assessments and analyses were made at the request of the various SP1 teams by the specialty contractor R. Youngs. The particular parameters and models that were explored in these analyses were specified by each team and, based on these specifications and requests, a series of calculations were conducted in order to provide useful feedback to each team. In some cases, the teams devoted considerable time and effort to exploring a particular aspect of their model only to decide that a particular avenue of inquiry was not worthy of further pursuit. In other cases, a line of inquiry might have been deemed important at the outset but, upon consideration of the calculations, the team might have concluded that the significance for the important SSC parameters was too small to merit a change in the SSC model. This give and take of exploratory analyses followed by consideration of the calculational results is a valuable part of a SSHAC process, whereby the careful consideration of multiple cycles of feedback provides a confident basis for fully understanding and finalizing the models. This extended evaluation phase was completed in March-June 2011 (see TP1-TN-1091 and TP1-KS-1052 for all the requested sensitivities and exchange between the experts and the speciality contractor). The last round of hazard feedback provided by SP4 on 8. August 2011 was the basis for the experts to sign their HIDs in September and November 2011.

The analyses that were conducted for each SP1 team at their specific request are documented in the chapters on the supporting calculations performed by R. Youngs in Volume 3 of this report.

2.3 Summary of PRP Refinements to SP1 Models and Implications for the Calculated Seismic Hazard

2.3.1 Summary of Changes to SP1 Models

In the light of the extensive series of analyses and feedback calculations provided to the SP1 teams, each team made decisions regarding whether or not changes should be made to their SSC models and, if so, exactly what those changes should entail. The Evaluation Summaries for each team (EG1-ES-1001 to 1004) that describe their final models are provided in Volume 3 together with the Hazard Input Documents (EG1-HID-1001 to 1004). The hazard calculations made in the light of the revised models are given in the appendix of Volume 3. The final concurrence provided by each team in the representation of their final assessments is indicated by their signing of the final HIDs. This section describes the changes that were made to the SP1 models for each team.

- Team EG1a:

  Seismic source zonation was unchanged along with the characteristics of seismicity in each zone.

  The approach for assessing M_{max} was unchanged. Two approaches were used, the Bayesian and the Kijko approach. The M_{max} distributions were updated to reflect the updated ECOS09 earthquake catalogue.

  The approach for assessing earthquake recurrence parameters was unchanged. Earthquake catalogue completeness was unchanged, with the exception of adding the additional 8 years to the length of the catalogue. Regional b-values were assessed for the "macro" zones based on analysis of the catalogue. These b-values and their assessed uncertainties were then used to develop earthquake recurrence rates for the individual source zones. Alternative earthquake recurrence rates were based on using the assigned b-values for each zone and fitting earthquake recurrence relationships to alternative earthquake counts based on different portions of the catalogue (e.g. post 1975, pre 1975, larger magnitudes) in a similar fashion to what was done for PEGASOS. The issue of the non-linearity in the relationship between M_L and M was dealt with by basing earthquake recurrence calculations on earthquakes of magnitude $M2.7$ and larger.

- Team EG1b:
  Seismic source zonation was unchanged along with the characteristics of seismicity in each zone. Due to new findings, the "fuzzy boundaries" of the originally defined N-S elongated SSZ Fribourg zone AE-7 have been removed from the model.

  The general approach for assessing M_{max} was unchanged. The Bayesian approach was used for both large and small zones. One change in application was that some grouping of small zones was used to develop a single M_{max} distribution for a collection of small zones with very similar characteristics and geographical locations. Another change in application was to use a discrete 5-point approximation to the posterior distribution produced by the Bayesian approach instead of binning the posterior into 0.5 magnitude unit bins.

  The approach for assessing earthquake recurrence parameters was unchanged. Earthquake catalogue completeness was unchanged, with the exception of adding the additional 8 years to the length of the catalogue. Recurrence parameters were assessed for the large zones based on analysis of the catalogue and the resulting b-values were used as priors in fitting the truncated exponential model to the data for the small zones. The issue of the non-linearity in the relationship between M_L and M was dealt with by basing earthquake recurrence calculations on earthquakes of magnitude $M2.8$ and larger.

- Team EG1c:
  Seismic source zonation was unchanged along with the characteristics of seismicity in each zone.

  In the PEGASOS Project, the EG1c team developed three global branches for assessing maximum magnitude and earthquake recurrence rates. Branch A was to use a globally assigned M_{max} distribution directly assessed and use maximum likelihood to assess earthquake recurrence rates using a global prior b-value. Branch B was to use the Bayesian approach for assessing M_{max} with a uniform prior between a minimum value of M_{max} and $7^1/_4$ (rounded to 7.3 for the analysis). The M_{max} minimum was set at 5.5 or the maximum observed magnitude rounded up to the nearest $^1/_2$ magnitude unit, whichever was larger. Branch C was to simulate jointly M_{max} and recurrence parameters from joint distributions developed from the other methods. For the PRP, Team EG1c dropped the Branch C approach based on the argument that it represented redundant information. They retained Branch A and Branch B and re-weighted these two approaches. The issue of the non-linearity in the relationship between M_L and M was dealt with by basing earthquake recurrence calculations on earthquakes of magnitude $M3.0$ and larger.

- Team EG1d:
  Seismic source zonation was unchanged along with the characteristics of seismicity in each zone.

  The general approach to maximum magnitude assessment and earthquake recurrence assessment was unchanged from that used in the PEGASOS Project. Multiple estimates of regional b-values were obtained based on different portions of the catalogue and the possibility of differences in recurrence rates for the pre-instrumental and instrumental periods (pre 1975 and post 1975, respectively). Various approaches for addressing the issue of the non-linearity in the relationship between M_L and M were investigated, including the incorporation of the non-linear shape in the truncated exponential recurrence model. Ultimately, the issue was addressed by considering two alternative ranges for assessing earthquake recurrence parameters for the truncated exponential model, magnitudes larger than the minimum magnitude of completeness in each region, and magnitudes larger than $M3.007$. The total complexity of the logic tree increased as a second set of branches for the assessment of the catalogue completeness was added to the first level of the logic tree. Thus, in total, four completeness scenarios were implemented compared to the original two.

M_{max} distributions were assessed using the Bayesian approach. Two alternative approaches were explored for representing the posterior distributions, either binning in 0.5 unit magnitude bins or using a 5-point discrete approximation. Based on a review of the resulting predicted recurrence relationships developed using the two approaches, the team settled on the use of only one, the 0.5 magnitude unit binning approach.

2.3.2 Seismic Hazard Calculations and Sensitivity Results

After completing and reviewing various analyses to assess the implications of various revisions to their models (see Section 2.2.10 and the supporting computations), each team finalized their assessments and they were documented in their final HIDs. These HIDs provided the inputs to the final round of hazard calculations conducted for the SP1 Project. Note that because these calculations were intended to illustrate the impact of changes in the SP1 models and not the impact of changes to the SP2 models, the calculations are based on the SP2 ground motion models from the original PEGASOS Project. Final hazard calculations that use both the PRP final SP1 and SP2 models are presented in Volume 2 of the report.

In general, the sensitivity analyses show essentially the same results as for the original PEGASOS study in terms of sensitivity to various elements of the logic trees and contributions to uncertainty in the hazard results. The only significant difference between the PRP models and the PEGASOS models is the change in the earthquake catalog. The new catalog made use of a non-linear conversion between M_L and M_W (Fig. 2.3) [Bethmann et al. 2011; Goertz-Allmann et al. 2011]. This new magnitude conversion was discussed extensively at the SP1 workshops. The non-linear conversion was accepted by all SP1 teams to derive rates and b values for magnitudes that were not strongly affected by the non-linear term, using lower magnitude limits between $M2.7$ and 3.0. The use of the non-linear conversion removed a 0.1 magnitude bias in the conversion for the magnitudes > 3, resulting from using a linear conversion over a larger magnitude range (e.g. > 2), as was applied in ECOS02 (Fig. 2.4). Previously in ECOS02, M_W estimates were derived from moment tensor solutions based on broadband waveform fitting of local earthquakes with $M_L > 2.4$. In this magnitude range, a 1:1 scaling of $M_W = M_L - 0.2$ was found. Above $M_L = 4$, the newly obtained M_W estimates are consistent with the previously used scaling relation.

The new dataset used for the development of the ECOS09 is representing an expanded dataset of M_L-M_W compared to the data available for ECOS02. The new data indicate that there is

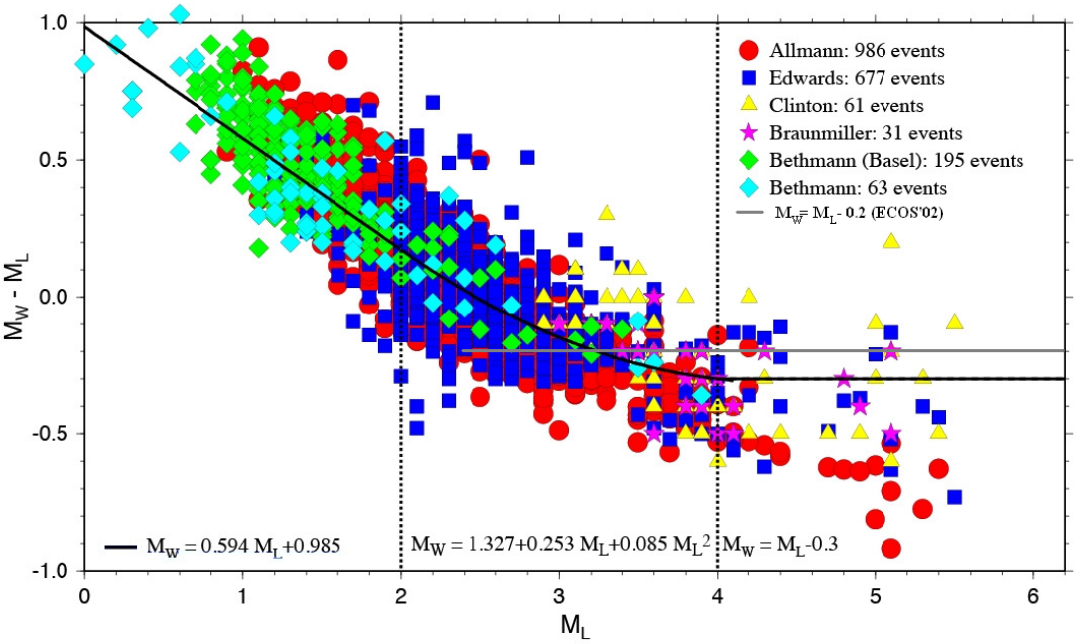


Figure 2.3: Difference between M_L and M_W versus M_L of different datasets (different shaped and colored symbols). The black solid line shows the combined scaling relation from three different segments. The dataset of Bethmann has been shifted up by 0.28 for a better visual comparison. The grey solid line shows the M_L to M_W relationship used for the ECOS02.

Modified from [Fäh et al. 2011a].

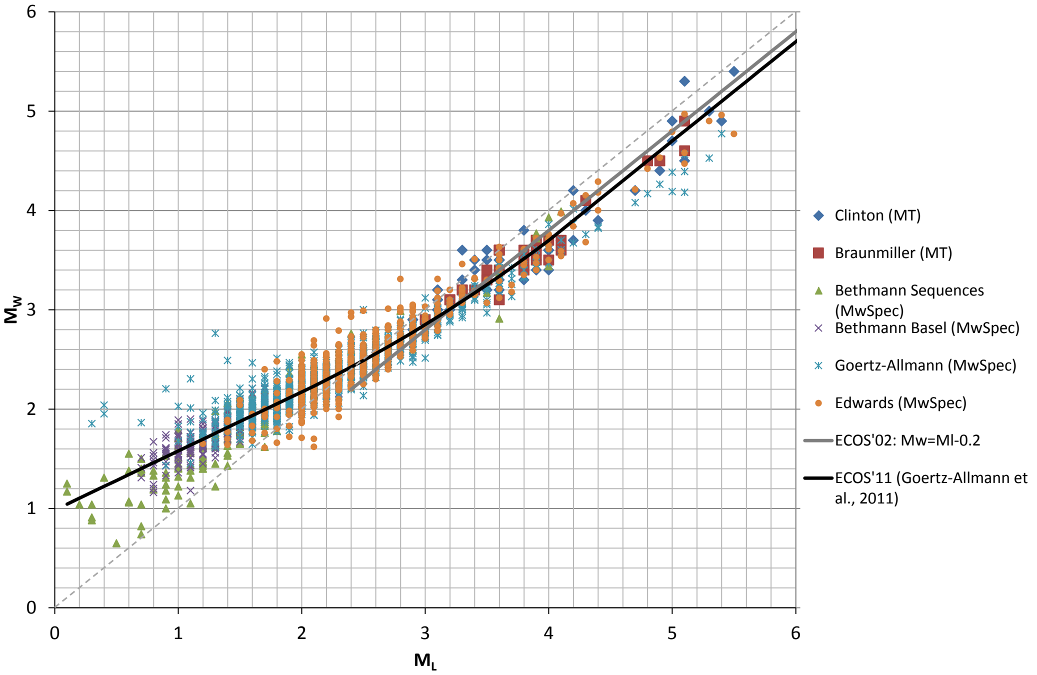


Figure 2.4: Comparison of old (ECOS02) and new (ECOS09) M_L-M_W relationship on top of the available data. The black solid line shows the new ECOS09 relationship. The grey solid line shows the M_L to M_W relationship used for the ECOS02.

a bias in the higher magnitudes and that there should be a curvature in the M_L-M_W scaling relationship. Avoiding the curvature by considering magnitudes above 3.5, there is still a systematic bias in the M_W values computed using ECOS02 conversion of about 0.1 magnitude unit. Even if with the new ECOS09 model there is a slight overprediction of the magnitudes above 4, as shown also in Figure 2.4. The new model (black curve) represents an improved model over PEGASOS which corrects the overprediction of M_W in the ECOS02 and is based on a much larger dataset.

This shift in magnitudes and the associated shift in recurrence for a given magnitude (larger than $M \approx 3$) results in lower calculated hazard. This effect is seen in the various plots comparing hazard curves for the PRP and PEGASOS.

2.3.3 Comparison of Recurrence Rates Between the SP1 Models

A comparison of the forecast recurrence rates provided by each SP1 team is compared in Figure 2.5, based on the models used in PEGASOS. The considered area for this comparison is limited to the vicinity of the NPPs (50 km). The changes due to the use of the new ECOS09 can be seen in Figure 2.6, which shows the team comparison for the refinement project. Further comparison plots can be found in the appendix (Fig. A.1 - A.8)

2.3.4 Comparison of M_{max} Distribution of the SP1 Models

The final M_{max} distributions by team are compared in terms of mean values for Switzerland and the neighboring countries considered and also the largest value of M_{max} (tail of the distribution). As can be seen from Figure 2.7, the mean values by team are very different according to the individual zones. The largest M_{max} value is defined by team EG1d with $M_{max} = 8$, compared to team EG1a and EG1b with $M_{max} = 7.2$ in the Swiss Foreland (see Figure 2.8.)

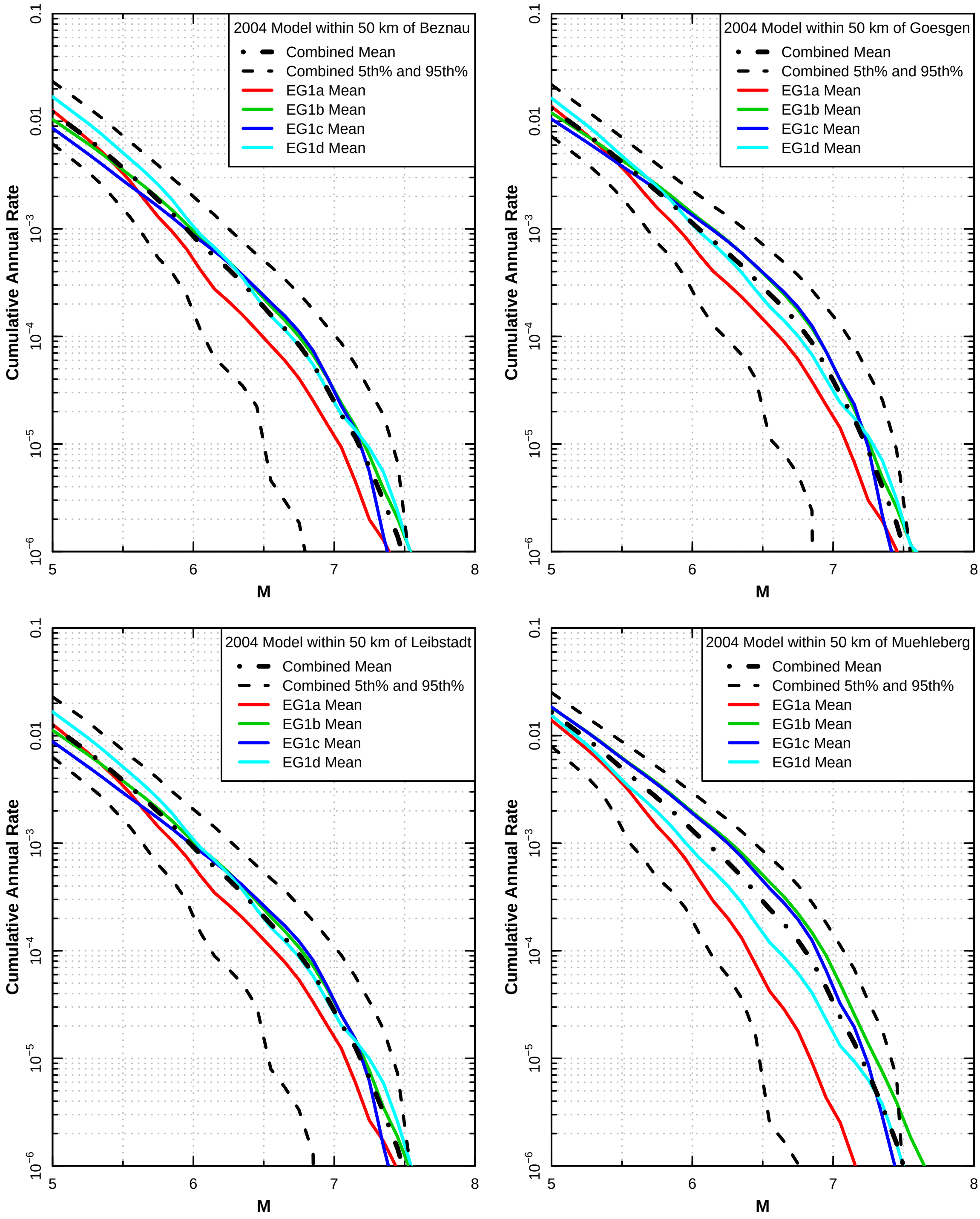


Figure 2.5: Comparison of forecast earthquake recurrence rates of PEGASOS for the four SP1 teams. The comparison includes only a zone of 50 km radius around each NPP.

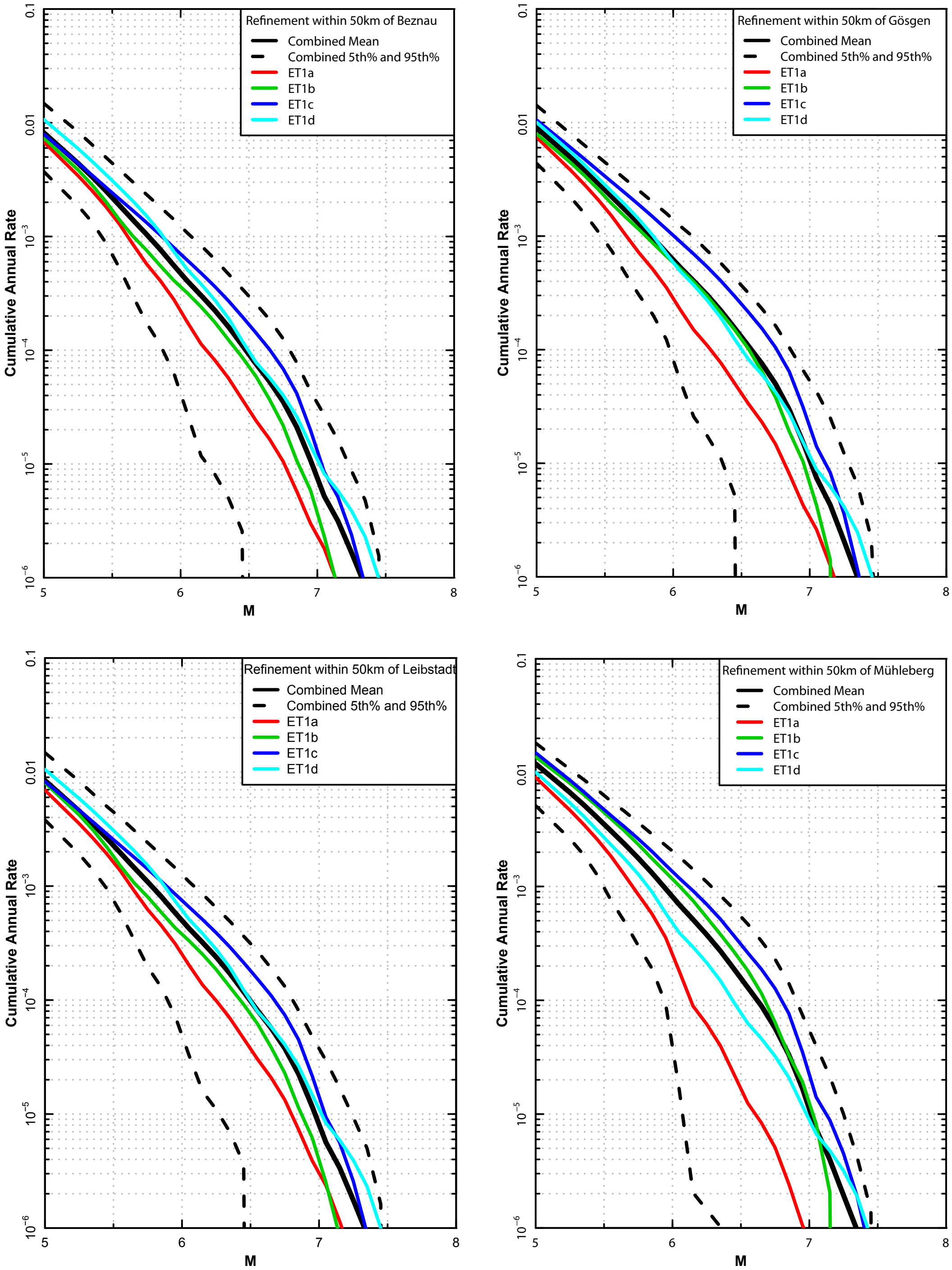
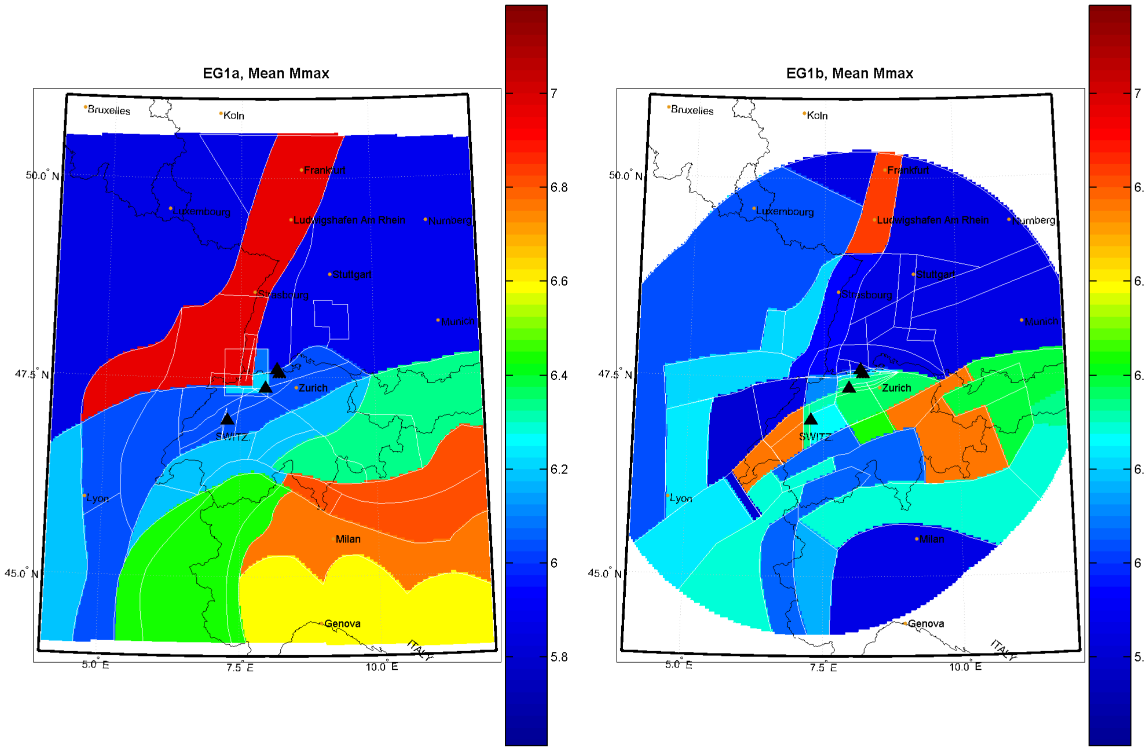
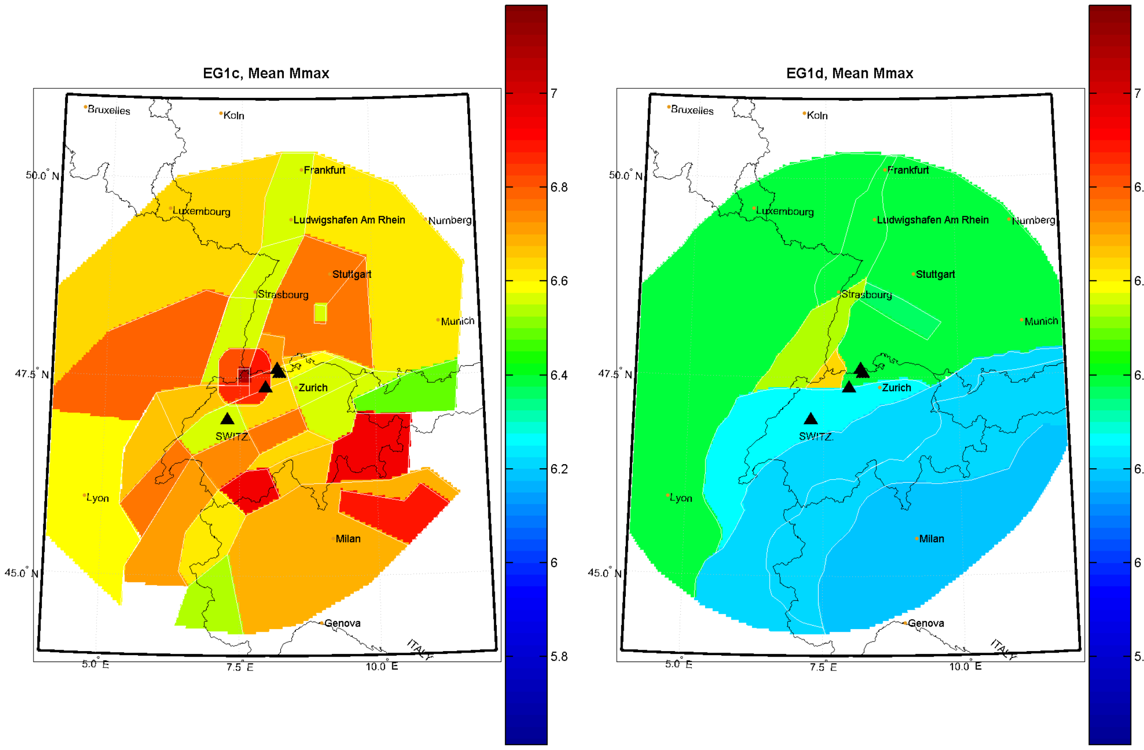


Figure 2.6: Comparison of forecast earthquake recurrence rates of PRP for the four SP1 teams. The comparison includes only a zone of 50 km radius around each NPP.



(a) EG1a Team

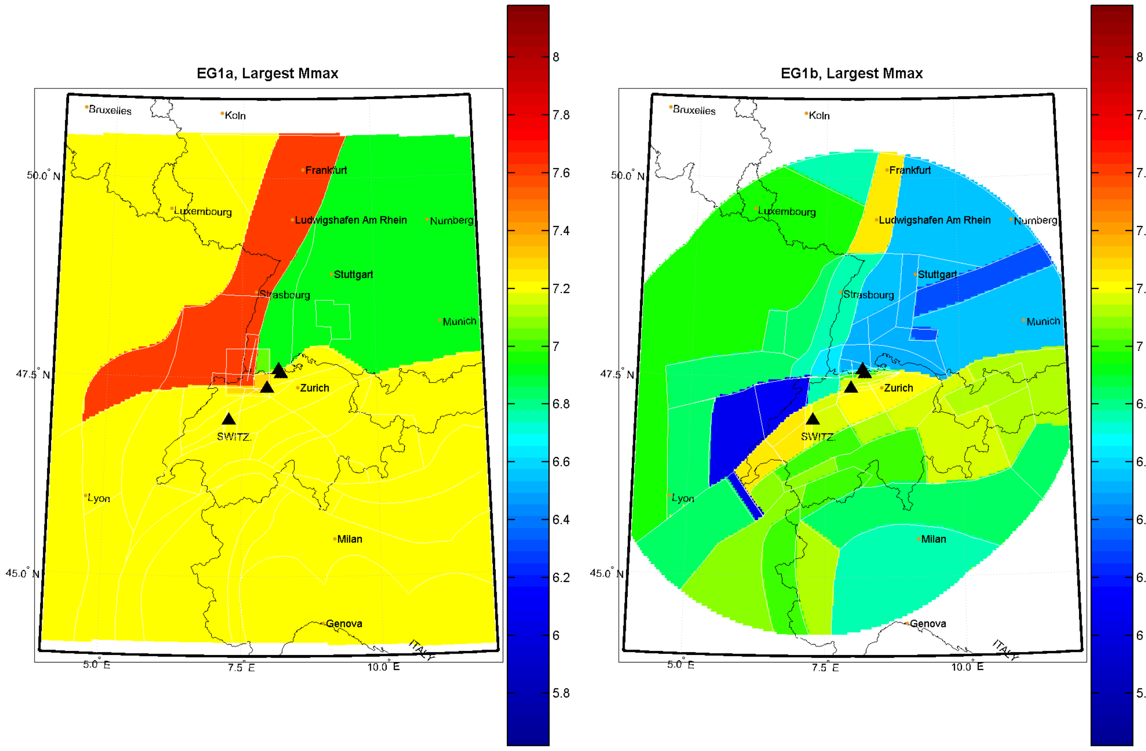
(b) EG1b Team



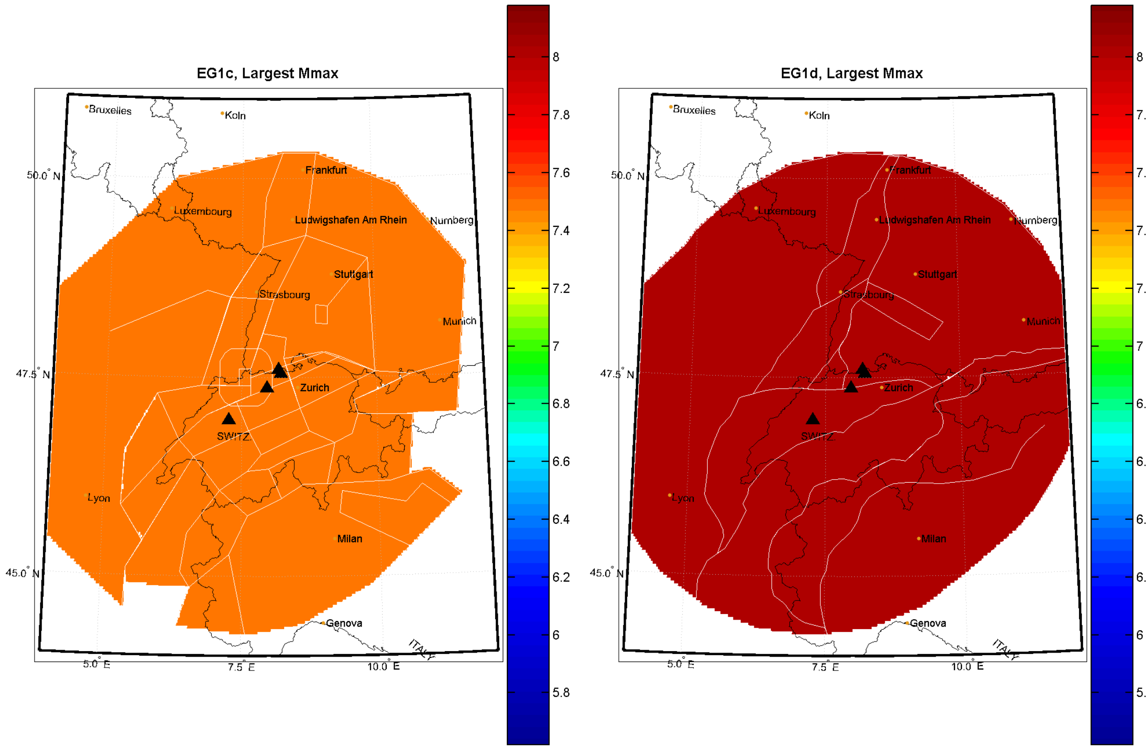
(c) EG1c Team

(d) EG1d Team

Figure 2.7: Comparison of mean M_{max} values for Switzerland and neighboring countries for the four SP1 teams.



(a) EG1a Team (b) EG1b Team



(c) EG1c Team (d) EG1d Team

Figure 2.8: Comparison of largest M_{max} values for Switzerland and neighboring countries for the four SP1 teams.

2.4 Conclusions on SP1 Model Revisions in the PRP Across All SP1 Teams

As discussed previously, during the evaluation phase of the PRP the SP1 teams were exposed to new data, models, and methods that could potentially lead to revisions to their PEGASOS models. During the integration phase, the teams identified a number of exploratory calculations and analyses designed to test the sensitivity and importance of potential model revisions. In the end, each team made decisions regarding whether and how their SP1 models should be revised. The team-by-team summary of model revisions is given in Section 2.3 and the general summary across all teams is given below:

- New Data, Models, and Methods: Of all the information considered by the teams, only the updated earthquake catalogue was considered to be significant for updating the existing PEGASOS SP1 models. New geological and seismological models were considered by the teams (e.g., focal depths of the Fribourg fault, geomorphic evidence of activity of Permo-Carboniferous troughs, paleoseismic interpretations for prehistoric earthquakes in the Basel area), but it was concluded by all teams that these new findings would not result in revisions to their SP1 models.

- Seismic Source Boundaries and their Properties: None of the SP1 teams concluded that the new catalogue or other information would lead to changes to seismic source zone boundaries or the properties of those boundaries relative to future earthquake ruptures. The teams were provided with plots that showed how earthquake locations and magnitudes had changed from the ECOS02 to the ECOS09 catalogue. Although changes occurred, none were considered significant or systematic enough to lead to the need to adjust source boundaries. Likewise, no changes were deemed necessary to earthquake depth distributions or their magnitude dependency.

- Maximum Earthquake Magnitude: In general, none of the teams changed their general approach to assessing maximum earthquake magnitude. Some teams made minor changes in the implementation of their approaches (e.g., specifying a five-point approximation for the posterior distribution) and one team (EG1c) eliminated one of three implementation approaches that they deemed to be redundant from their logic tree. The new ECOS09 catalogue was used in the calculation of M_{max} distributions for all sources given the approaches specified by each team, but differences in the resulting M_{max} distributions were minor.

- Earthquake Recurrence: The general approaches taken to assessing earthquake recurrence for the seismic sources were unchanged. The most significant issue faced by all teams was the curvature of the $M_L - M$ conversion at the lower magnitudes [Bethmann et al. 2011; Goertz-Allmann et al. 2011], as shown in Figure 2.9. In general, the teams dealt with the issue by considering the linear part of the relationship above a minimum magnitude specified by each team (generally larger than about $M3$).

- Calculated Seismic Hazard: The calculations of seismic hazard at the NPP sites show that the PRP SP1 models lead to somewhat lower calculated hazard than the SP1 models for the original PEGASOS Project. This result for SP1 can be mainly attributed to the approximately 0.1 magnitude shift downwards between the ECOS02 and ECOS09 catalogues at magnitudes larger than about 3 (Fig. 2.9).

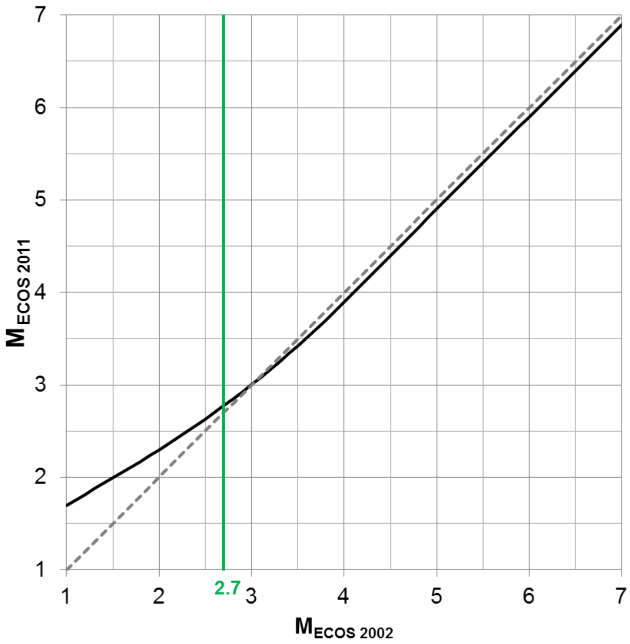


Figure 2.9: Relationship between moment magnitudes in the ECOS02 and ECOS09 earthquake catalogues. The vertical green line indicates the magnitude range above which SP1 considered the relationship to be acceptable.

Chapter 3

Interfaces between SP1 and SP2

3.1 Overview

Interface issues between the seismic source characterization (SP1) and the ground motion characterization (SP2) are implicitly handled by the hazard computation. The most relevant interface topics, for example the depth distribution and the distance metric, were discussed in the PRP on the occasion of dedicated interface workshops between the SP1 and SP2 experts. In the following sections, the interface issues identified as the most important for the hazard are discussed briefly.

3.1.1 Interface Workshop: Interface Issues Between SP1, SP2, SP3 and SP4

The interface workshop was held on 8.-9. December 2008 in Zurich. The first day of the workshop addressed the SP1/SP2 interface and the SP1/SP2/SP4 interface. The second day addressed the SP2/SP3/SP4 interface.

The key interface issues for SP1/SP2/SP4 discussed at the workshop are listed below:

- Consistency of ECOS with ground motion models: The magnitudes in the ECOS catalogue are based on models of the attenuation of intensity measurements. The assumptions and models used for the ECOS catalogue should be compared to GMPEs to check for consistency between the attenuation used in the two sets of models. The magnitude scale (e.g. M_W) used by the GMPEs needs to be consistent with the magnitude definition used in the earthquake catalogue and the magnitude-frequency distributions. Compile an intensity and ground motion dataset for earthquakes with both types of data available. Develop relations between EMS and spectral acceleration (Sa). Evaluate regional variations in the EMS-Sa relations.

- Magnitude conversions: The ECOS catalogue uses magnitude conversions to convert M_L to M_W and M_S to M_W. These conversions should be checked against the conversion used in developing the GMPEs. The new GMPEs are based on M_W so a conversion within PRP is not needed, but there may have been conversions done in developing the database for the GMPEs.

- Rupture dimensions: The Area(M) scaling relations are used by SP1 and by the finite-faulting simulations. The GMPEs are based on a subset of earthquakes with a given Area(M) distribution. The Area(M) scaling used by SP1 and SP2 should be consistent. The Area(M) scaling for the NGA dataset is consistent with the SP1 Area(M) models, but the Area(M) model used in the finite-fault simulation is inconsistent with larger areas in the FFS. Evaluate whether the area for the FFS should be revised.

- Distance conversions: Distance conversions are not applied by SP2. They are addressed in the hazard code using the native distance measures of the ground motion models.

- Distance extrapolation: SP1 includes sources out to 500 km, but, in PEGASOS, ground motion models were only defined to 250 km. SP2 models need to be defined out to 500 km. This does not have a significant effect on the hazard, but should be addressed for consistency.

- Style-of-faulting and dip definitions: SP1 defines the style-of-faulting categories by dip whereas SP2 uses rake. These different definitions of style-of-faulting and dip need to be consistent. The range of dips in the ground motion dataset were found to be consistent with the dips for the SP1 style-of-faulting classes.

- Reducing M_{min}: The hazard calculation will include a case with the M_{min} reduced from 5.0 to 4.5. For SP1, there is no issue with reducing M_{min}. For SP2, the available ground motion models may not extrapolate well to smaller magnitudes. The ground motion models will need to be adjusted for smaller magnitudes using the Swiss ground motion data as a constraint.

- M_{max}: The M_{max} values from SP1 are as high as $M8$. The SP2 models need to be checked for how they extrapolate to $M8$.

3.1.2 Depth Distribution of Earthquakes in Switzerland

As shown in Figures 3.1 and 3.2, earthquake focal depth distributions in Switzerland are very different below the Alps and below the Alpine foreland [Deichmann et al. 2000a]. These differences were taken into account within the framework of the SP1 expert elicitations in the original PEGASOS Project and the statistics were updated in the PRP, taking into account the earthquake data acquired since then [Deichmann 2010] (TP1-TN-1066). The SP1 experts

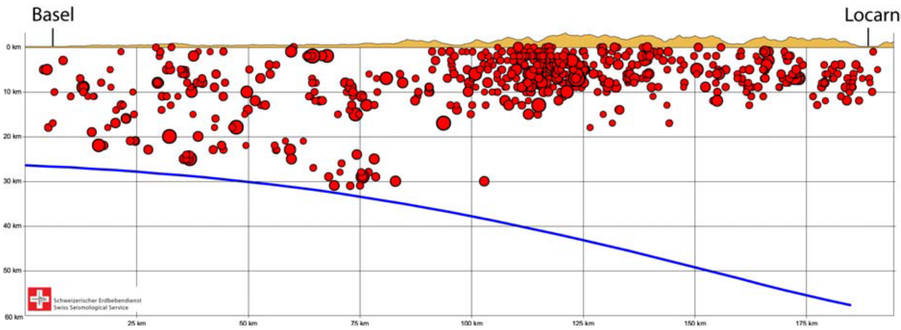


Figure 3.1: Focal depth cross-section of selected earthquakes along a NNW-SSE trending profile from Basel to Locarno for the time period 1975-2007 [Deichmann 2010] (TP1-TN-1066).

concluded that the updated information essentially confirmed the significant focal depth differences seen along a NNW-SSE profile across Switzerland. Earthquakes occur throughout the whole crust in the foreland, all the way down to the Moho until 30 km. Below the Alps, where the Moho reaches depths of more than 50 km, seismicity mainly occurs in the top 15 km of the crust.

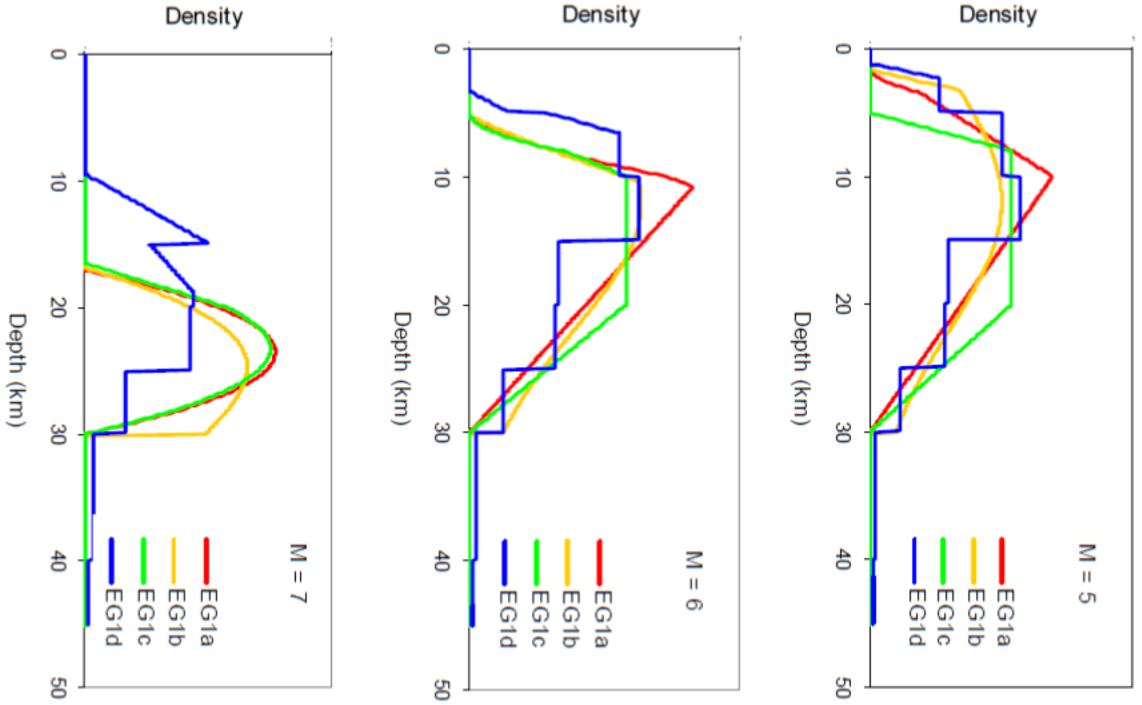


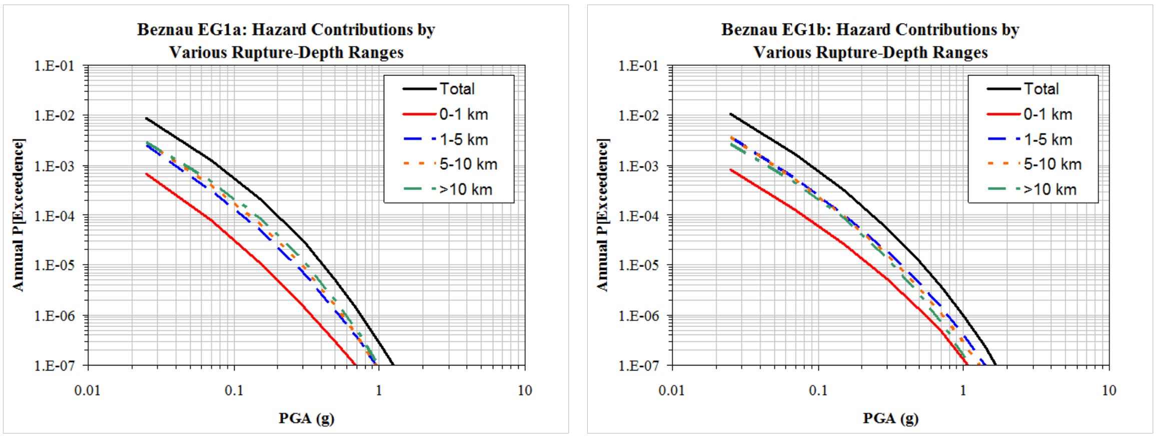
Figure 3.2: Magnitude-dependent depth distributions used by the SP1 experts.

An evaluation of slip and strain rates for Swiss area sources was performed by Toro [2009]. Toro [2010] (TP4-TN-1075) assessed the depth distribution for small earthquakes and presented it at WS3/SP1 (TP1-RF-1178). The conclusions were that similar results were found for all four teams and the contribution from events that rupture near the surface (0-1 km) is less than 10% at amplitudes of interest, and increases to 15% for very high amplitudes. Figures 3.3 and 3.4 illustrate the findings for the example of the Beznau site.

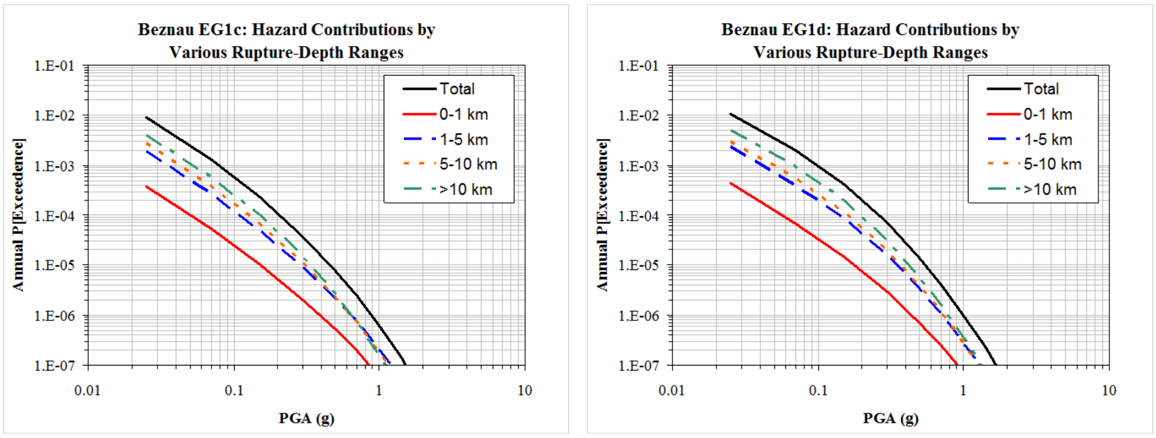
A direct evaluation of surface faulting was not part of the PRP. Within the PRP only the ground motion hazard was evaluated. Surface faulting potential was investigated by the Swiss new build projects in 2011 within the framework of the site applications [ENSI 2010a, b, c].

3.1.3 Distance Metric

In PEGASOS, the ground motion models were all converted to a common distance metric, which also caused some issues. In the PRP, the GMPEs are used with the native distance metrics. The different distance metrics are handled as part of the hazard calculation. Distance conversions are only used to make comparison plots of the GMPEs. For general purpose use, the approach proposed by Bommer and Akkar [2012] can be evaluated.



(a) EG1a (b) EG1b



(c) EG1c (d) EG1d

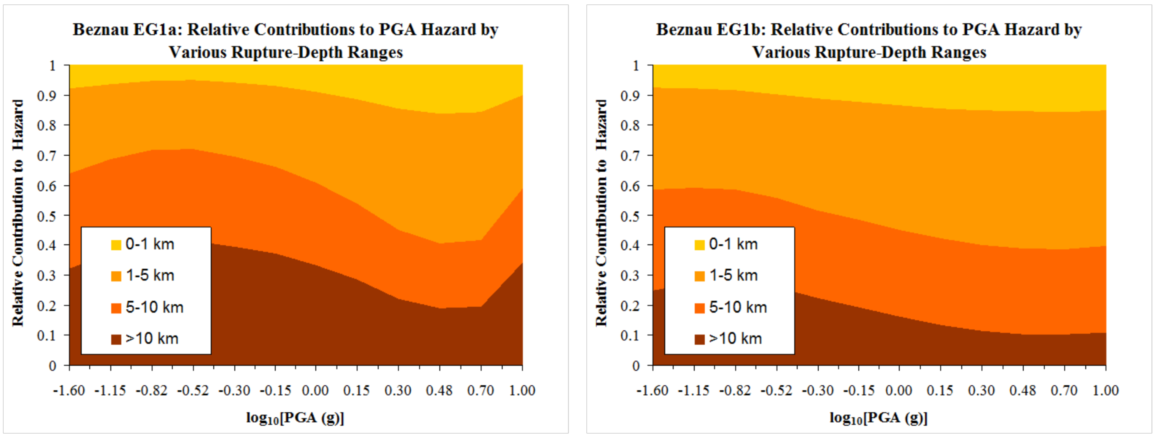
Figure 3.3: Contributions of different depth ranges to the hazard for Beznau (from TP1-RF-1178).

3.1.4 Style-of-Faulting

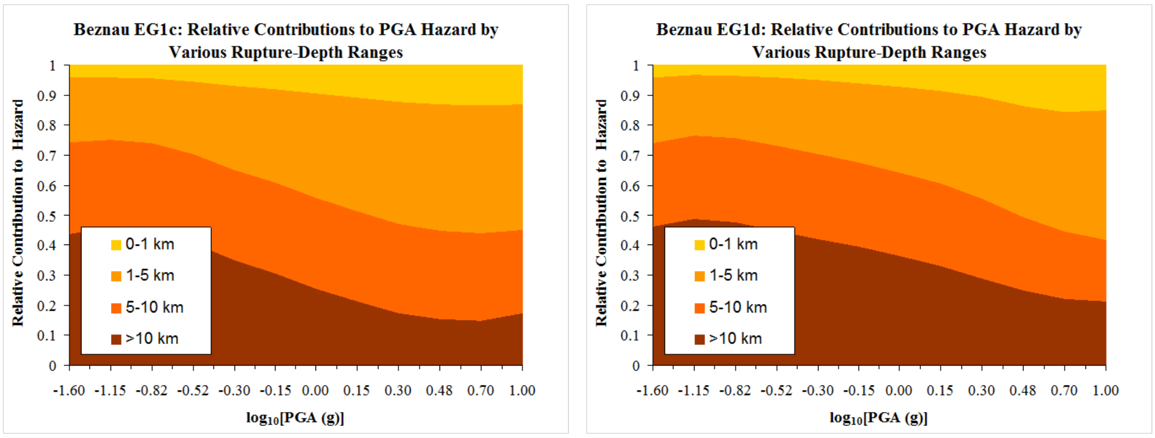
Both SP1 and SP2 classify sources into bins based on the style-of-faulting. SP1 classified the sources based on the dip angle, whereas SP2 classified the sources based on the rake angle. With these different classification schemes, the consistency between the SP1 and SP2 style-of-faulting categories is an interface issue. To address this issue, the range of dips for earthquakes within each rake-based style-of-faulting category was compared to the range of dips used by SP1. At the December 2008 interface workshop, it was shown that the range of dips from earthquakes in the rake-based classification scheme were consistent with the range of dips used for the SP1 classifications.

3.1.5 Magnitude-Area Scaling

SP1 specifies scaling relations between area and magnitude as part of the source characterization. For SP2, the area-magnitude relation is implied by the subset of data used to derive the empirical GMPEs. The 2008 NGA-West1 database includes estimates of the rupture dimensions and can be used to quantify the area-magnitude relation implicit in the GMPEs. At the December 2008 interface workshop, it was shown that the area-magnitude scaling



(a) EG1a (b) EG1b



(c) EG1c (d) EG1d

Figure 3.4: Contributions of different depth ranges to the PGA for Beznau (from TP1-RF-1178).

relations used in SP1 are consistent with the area-magnitude scaling implicit in the GMPEs.

3.1.6 Overview of Fault Style, Dip Angles and Depth Distributions

Table 3.1 lists the weights assigned by the four EG1 teams to the different fault styles in some selected seismic sources (see Roth [2012] (TP4-TN-1254)). Table 3.2 lists the dip angles associated with these fault styles in these particular seismic sources. Note that EG1d introduced uncertainty in this parameter in the form of alternative dip angles. These angles are averaged here for a given fault style. In both tables the numbers in the last row give the site-specific mean fault style weight and dip angle over the four equally-weighted EG1 teams.

The SP1 expert groups have specified different forms of hypocentral depth distribution: trapezoidal, triangular (a special form of trapezoidal distribution), truncated normal and multiple uniform (histogram) distributions. Table 3.3 lists these distributions together with the parameters that characterize them. For trapezoidal distributions, the p1, p2, p3 and p4 are the corner depths (where p2 = p3 for a triangular distribution). For the truncated normal distributions of EG1b, p1 and p4 are the lower and upper truncation depths, while p2 and p3 are the mean and sigma of the untruncated normal distribution, respectively. EG1d specified two histogram distributions, one for the seismic sources located north of the Alpine front ("N" in Table 3.3) and one for the sources in the Alps ("S").

Table 3.1: Weighting associated with the different fault styles in the selected seismic sources of the four SP1 models. The last row shows the mean weights per NPP site and fault style (from Roth [2012]).

Group	KKB	SS	NM	RV	KKG	SS	NM	RV	KKL	SS	NM	RV	KKM	SS	NM	RV
EG1a	E3A	0.5	0.5	0	E3A	0.5	0.5	0	F3A	0.25	0.75	0	E2D	1	0	0
	E3B	0.5	0.5	0	F2F	0.4	0.4	0.2	E3A	0.5	0.5	0	FF	1	0	0
	E3AF2F	0.5	0.5	0	E2F	0	0	1					E2F	0	0	1
EG1b	AE02	0.7	0.1	0.2	AE02	0.7	0.1	0.2	AE02	0.7	0.1	0.2	AE	0.8	0.1	0.1
	AE	0.8	0.1	0.1	AE	0.8	0.1	0.1	AE	0.8	0.1	0.1	AE07	0.9	0.05	0.05
	AE03	0.7	0.2	0.1	RG1_AE1	0.7	0.2	0.1	RG1_AE1	0.7	0.2	0.1	AE06	0.8	0.1	0.1
	SG5_6_8	0.8	0.15	0.05	AE04	0.8	0.1	0.1	SG5_6_8	0.6	0.15	0.25				
EG1c	DBASL	0.5	0	0.5	DBASL	0.5	0	0.5	DBASL	0.5	0	0.5	FRIB	0.35	0	0.65
	BLAF	0.5	0	0.5	MOMI	0.35	0	0.65	BLAF	0.5	0	0.5	FRIB	0.35	0	0.65
	NSPG	0.2	0	0.8	DBASL	0.5	0	0.5	NSPG	0.2	0	0.8	HELV	0.15	0	0.85
EG1d	E	0.85	0.05	0.1	J	0.75	0.05	0.2	E	0.85	0.05	0.1	J	0.75	0.05	0.2
	E-NRG	0.85	0.05	0.1	E	0.85	0.05	0.1	E-NRG	0.85	0.05	0.1	J	0.75	0.05	0.2
					B_LG	0.75	0.2	0.05					XHHA	0.7	0.15	0.15
		0.62	0.18	0.20		0.58	0.13	0.28		0.59	0.17	0.24		0.63	0.04	0.33

Table 3.2: Dip angles [°] associated with the different fault styles in the selected seismic sources of the four SP1 models. The last row shows the mean dip angles per NPP site and fault style (from Roth [2012]).

Group	KKB	SS	NM	RV	KKG	SS	NM	RV	KKL	SS	NM	RV	KKM	SS	NM	RV
EG1a	E3A	90	60	30	E3A	90	60	30	F3A	90	60	30	E2D	90	60	30
	E3B	90	60	30	F2F	90	60	30	E3A	90	60	30	FF	90	60	30
	E3AF2F	90	60	30	E2F	90	60	30					E2F	90	60	30
EG1b	AE02	90	60	45	AE02	90	60	45	AE02	90	60	45	AE	90	60	30
	AE	90	60	30	AE	90	60	30	AE	90	60	30	AE07	90	60	45
	AE03	90	60	45	RG1_AE1	90	60	45	RG1_AE1	90	60	45	AE06	90	60	45
	SG5_6_8	90	60	45	AE04	90	60	45	SG5_6_8	90	60	45				
EG1c	DBASL	90		45	DBASL	90		45	DBASL	90		45	FRIB	90		45
	BLAF	90		45	MOMI	90		45	BLAF	90		45	FRIB	90		45
	NSPG	90		45	DBASL	90		45	NSPG	90		45	HELV	90		45
EG1d	E	80	60	30	J	80	60	30	E	80	60	30	J	80	60	30
	E-NRG	80	60	30	E	80	60	30	E-NRG	80	60	30	J	80	60	30
					B_LG	80	60	30					XHHA	80	60	30
		88.3	60.0	37.5		87.7	60.0	36.9		88.2	60.0	38.2		87.5	60.0	36.2

Table 3.3: Parameters of the small magnitude hypocentral depth distributions in the four SP1 models (see text for details). The last row shows the median hypocentral depth per NPP site. Abbreviations: Trpz: trapezoidal, Tn: truncated normal, MU: multiple uniform (from Roth [2012]).

	KKB	p1	p2	p2	p4	KKG	p1	p2	p2	p4	KKL	p1	p2	p2	p4	KKM	p1	p2	p2	p4
EG1a	E3A	1	10	10	30	E3A	1	10	10	30	F3A	1	10	10	25	E2D	1	10	10	30
Trpz.	E3B	1	10	10	30	F2F	1	1	10	20	E3A	1	10	10	30	FF	1	1	27.3	27.3
	E3AF2F	1	10	10	30	E2F	1	10	10	30						E2F	1	10	10	30
EG1b	AE02	0	12	10	30	AE02	0	12	10	30	AE02	0	12	10	30	AE	0	12	10	30
Tn.	AE	0	12	10	30	AE	0	12	10	30	AE	0	12	10	30	AE07	0	12	10	30
	AE03	0	12	10	30	RG1_AE1	0	13	5	26	RG1_AE1	0	13	5	26	AE06	0	12	10	30
	SG5_6_8	0	9	3	20	AE04	0	12	10	30	SG5_6_8	0	9	3	20					
EG1c	DBASL	5	8	20	30	DBASL	5	8	20	30	DBASL	5	8	20	30	FRIB	5	8	20	30
Trpz.	BLAF	5	8	15	30	MOMI	5	8	20	30	BLAF	5	8	15	30	HELV	3	6	12	20
	NSPG	3	8	20	30	DBASL	5	8	20	30	NSPG	3	8	20	30	FRIB	5	8	20	30
EG1d	E	N				J	N				E	N				J	N			
MU	E-NRG	N				E	N				E-NRG	N				J	N			
						B_LG	N									XHHA	S			
		13.0					13.1					12.8					12.3			

Chapter 4

Ground Motion Characterization - SP2 Summary

4.1 Ground Motion Characterization Requirements

The SP2 experts were tasked with developing ground motion models for the horizontal spectral acceleration and the V/H response spectral ratio at 5% damping as a function of earthquake magnitude, site-to-source distance, and style-of-faulting. The models were required to be applicable to the NPP-specific rock condition. Furthermore, the SP2 models were required to be applicable to the magnitude range of 4.5 to 7.5, distances up to at least 200 km, and all styles-of-faulting (strike-slip, reverse, and normal). Nine spectral frequencies were specified: 0.5 Hz, 1.0 Hz, 2.5, 5 Hz, 10 Hz, 20 Hz, 33 Hz, 50 Hz and 100 Hz.

The SP2 experts were required to develop models for the median spectral acceleration, the aleatory variability, and the maximum spectral acceleration. Here, the horizontal component is defined as the geometric mean of the two horizontal components. The aleatory variability of the two horizontal components about the geometric is captured in the set of time histories and is part of the SP5 tasks (not described here).

For the vertical component, the experts were required to develop models for the median V/H ratio, the aleatory variability in the vertical component (in terms of the increased variability as compared to the horizontal component) and the maximum vertical spectral acceleration

From the PEGASOS study, it was noted that, although the SP2 experts used very different approaches to their evaluations, their logic trees had a similar structure. Therefore, a master logic tree is used for SP2 which is fully documented in Volume 4.

4.2 Approaches for Ground Motion Characterization for Median Ground Motion

There are four basic approaches that are used to develop ground motion models: empirical GMPEs, point source stochastic simulations, finite-fault simulations (FFS), and the hybrid empirical method (HEM).

4.2.1 Empirical GMPEs

Empirical GMPEs have the advantage that they are calibrated by data but they have the disadvantage that they often need to be extrapolated beyond the range that is well constrained by the empirical data, such as short distances and large magnitudes. To expand the empirical dataset for large magnitudes and short distances, empirical GMPEs are often based on global datasets, but these global GMPEs may not capture the region-specific attenuation in Switzerland. In addition, they may not be applicable to the Swiss hard-rock site conditions as most of the empirical data are for soil or soft-rock site conditions. The corrections required to adjust the empirical GMPEs to Swiss site conditions, in particular κ, are not straightforward and are one of the main contributors to the uncertainty in the SP2 models.

4.2.2 Point Source Stochastic Model

The point source stochastic model [Boore 2003] is the simplest numerical simulation method available based on seismological theory. Models are developed for the Fourier amplitude spectrum and the duration of shaking. Random vibration theory is then used to convert the Fourier amplitude spectrum and the duration to response spectral values. Because random vibration theory is used, these numerical simulations are called stochastic models.

There are six main input parameters for the point source model: earthquake magnitude, stress-drop ($\Delta\sigma$), geometrical spreading, Quality factor (Q), crustal amplification, and high frequency attenuation (κ). Region-specific models of the geometrical spreading and Q are often determined empirically using recordings from smaller earthquakes in the region of interest. The duration is either computed using simple analytical models or using region-specific models based on empirical observations.

The small magnitude region-specific data do not provide constraints on the stress-drops of larger magnitude earthquakes, which is the major source of uncertainty in the application of the stochastic model. The site-specific κ value is also a key contributor to the uncertainty.

4.2.3 Finite-Fault Simulations

Finite-fault simulations (FFS) provide a physical basis for the extrapolation from small magnitudes to larger magnitudes by incorporating finite-fault effects; however, they have a much larger number of input parameters and therefore require greater calibration before the FFS can be reliably applied to engineering applications. At the time of the PRP, the FFS methods had not been adequately calibrated, particularly for the high frequencies of interest to nuclear power plants. Therefore, in the PRP, the FFS were not used as an alternative method for the median ground motions. Instead, a limited set of FFS were conducted to allow the SP2 experts to check the short distance and large magnitude scaling of the median values from the empirical GMPEs and point source stochastic models. The science behind the FFS is improving rapidly and FFS will likely be sufficiently far advanced to allow them to be included as alternative models in the next 10 year update of the seismic hazard evaluation.

Currently, FFS are sometimes used to develop ground motion models as an alternative to empirical GMPEs. The FFS represent ”Technically Defensible Interpretations” if all necessary input parameters can be reasonably well constrained. Such simulations were also performed within the framework of the PRP by SED (Dalguer and Mai [2010], TP2-TB-1028 and

TP2-TB-1057). The SP2 experts evaluated the state of FFS for Switzerland and reached a consensus that the results could be useful in checking the range of the selected empirical GMPEs (see Section 4.8.1), but that they were not sufficiently developed to be included as a branch in the master logic tree for SP2, the main reason being that the FFS still lack a successful benchmark and wide acceptance due to the difficulties in defining all the necessary input parameters. Furthermore, there are correlations between many of the parameters which, at the time, had not been properly identified and modeled.

The FFS per se do not require a κ-value, but the broadband simulation methods apply a κ filter such that the simulated ground motion will match the specified target κ. In that respect, the FFS results for high frequency remain empirically constrained.

4.2.4 HEM Models

The hybrid empirical model [Campbell 2003] is a mixture of the empirical GMPE approach and the point source stochastic model approach. In the HEM method, point source stochastic models are developed for both the host GMPE region and the target site region capturing the region-specific parameters for both regions (stress-drop, geometrical spreading, Q, crustal amplification, and κ). The stochastic model is then used to compute the response spectral scale factors from the host region to the target region for a given magnitude and distance. These factors are then applied to the host region GMPE.

A key assumption for this method is that response spectral scale factors for the point source model are applicable to the GMPE. Because response spectral scale factors at a given frequency depend on the underlying spectral shape, this assumption is only valid if the spectral shape of the GMPE is similar to the spectral shape of the point source model. This issue is addressed further in the κ correction section.

4.2.5 Conversions

In the PEGASOS study, the available GMPEs were based on different magnitudes, distance metrics and horizontal component definitions. A series of conversions were developed to convert the GMPEs to moment magnitude, R_{JB}, and the geometric mean of the two horizontal components. In the PRP, these conversions are not required. The selected candidate GMPEs (see Section 4.8.1) all use moment magnitude and the horizontal component is representative of the average (geometric mean) of the two horizontal components. Different distance metrics are used in the GMPEs, but these differences are addressed in the hazard calculation, treating them in a way consistent with the source characterization.

Note: In PEGASOS, the GMPEs were evaluated for their range of applicability and only used over that range. The original candidate GMPEs were replaced with a suite of composite GMPEs that considered the weights for the GMPEs and the limited M-R range. A result of this approach was that the GMPEs had to be converted to a single distance metric to allow the different GMPEs to be combined [Scherbaum et al. 2004].

4.2.6 Testing and Sammon's and Self-Organizing Maps

Within the PRP, the SP2 experts used new techniques [Delavaud et al. 2009; Scherbaum et al. 2009; Kühn and Scherbaum 2010; Scherbaum et al. 2010; Riggelsen et al. 2011;

Scherbaum and Kühn 2011] to support the selection and quantitative comparison of ground-motion prediction models for seismic hazard analysis. Scherbaum et al. [2010] proposed the use of Sammon's maps and self-organizing maps (SOMs) from the field of high-dimensional information visualization to evaluate the candidate GMPEs. Both techniques allow the projection of high-dimensional vectors onto two-dimensional maps such that the mutual distances between these vectors and even their topological neighborhood can be preserved. These techniques allowed the experts to make more objective decisions during the selection and evaluation phase.

Furthermore, Kühn [2011c, b, a, 2012]; Kühn and Renault [2012] tested the preselected GMPEs against the Swiss macroseismic intensity observations. These comparisons were mainly based on building a so-called mixture model (see Section 4.8.1). The comparison with intensity data was not used to discard models, but rather to support the experts in their evaluation of weights for the candidate GMPEs.

4.3 Approaches for the Vertical Median Ground Motion

There are two approaches that can be used for the vertical component ground motion: develop separate GMPEs for the vertical or develop V/H ratios that are applied to the horizontal component GMPEs. Following the approach used in PEGASOS, the vertical ground motion is developed in the PRP using the V/H approach. There are two main advantages to this approach:

- There are many more horizontal GMPEs than vertical GMPEs, so using the V/H ratio allows the range of horizontal GMPEs to be captured in the vertical model,
- Using the V/H ratio leads to a vertical ground motion that goes with the horizontal ground motion so that it is appropriate to combine the horizontal and vertical loading in the application of the ground motions to the NPP sites as part of the structural analyses.

4.4 Standard Deviation Models

In the PRP, the SP2 logic tree separates the median and standard deviation (σ) models into separate models. The basis for this decision is that the models may have different strengths and weaknesses of the median and standard deviation. Some models may have a well-derived median model, whereas the standard deviation might not be as well constrained. For example, a very simple standard deviation model such as using the average standard deviation from smaller magnitudes may be found in some models.

In addition, the use of single-station σ to improve the SP2-SP3 interface, described in Chapter 5, also leads to this separation of the median and σ, because most of the published GMPEs include a standard deviation based on the traditional ergodic σ. Therefore, all of the GMPEs require an adjustment of the published standard deviations to convert them into single-station σ models.

The technical basis behind the single-station σ concept is that each site has an average site amplification that is not captured by the simple dependence on the V_{S30} value. By using ground motions from sites with multiple recordings, the average residual at a site provides an estimate of the site-specific site term. If the site-specific site term (mean residual) for each site is removed from each residual, then there is a reduction in the overall standard deviation. This reduced standard deviation is called the "single-station σ".

The advantage of the single-station σ approach over the traditional ergodic approach is that it properly treats the mean site amplification as a fixed value with epistemic uncertainty (part of the logic tree) rather than assuming that the mean site-specific amplification is a random sample from the distribution of site amplification of all sites with a similar V_{S30} value. The single-station σ approach provides a framework for improving the site-specific amplification estimates, through the collection of additional data or by improved modeling.

If the single-station σ approach is used (reduced aleatory variability), then the epistemic uncertainty in the estimate of the site-specific site term must be included as part of the logic tree in the application of the model to a site-specific hazard estimate. This is the penalty for using the single-station σ approach. The SP3 models explicitly address this epistemic uncertainty in the site-specific site amplification through their logic trees for the velocity profiles and non-linear material properties. Therefore, the single-station σ approach is well suited to addressing the interface between the SP2 rock ground motion models and the SP3 site amplification models.

4.4.1 Horizontal Aleatory Variability

The PRP uses single-station σ to avoid the double counting of uncertainty that is included in the SP3 logic trees. At the start of the PRP, the single-station σ was a well established concept that had a strong empirical basis, but there were no well developed global models for single-station σ available.

Much of the basic research work to derive a robust single-station σ model was conducted as part of the PRP. The PRP sponsored research [Rodriguez-Marek et al. 2013] to collect data from around the world that could be used for single-station σ estimates and develop the model based on global data [Ancheta et al. 2013].

4.4.2 Vertical Aleatory Variability

In the PEGASOS Project, the vertical aleatory component was not considered directly. The approach for the vertical hazard is to scale the horizontal hazard curves by the median V/H ratio for the controlling M and R identified by the deaggregation. This method leads to the correct vertical hazard if the aleatory variability of the vertical component is equal to the aleatory variability of the horizontal component. However, empirical GMPE studies that have developed both horizontal and vertical models have shown that the standard deviation of the vertical is larger than for the horizontal [Abrahamson and Silva 1997; Campbell 1997, 2000, 2001; Campbell and Bozorgnia 2003d, a, b, c]. To account for this increased aleatory variability of the vertical component, models for the additional aleatory variability, called σ_{VADD}, were developed by the SP2 experts (see Section 4.8.4).

4.5 Maximum Ground Motion on Rock

There are two main approaches to the estimation of the maximum ground motion (max. GM): largest empirical recordings of ground motions and numerical simulations for worst-case conditions. In the empirical approach, the largest recorded ground motions are summarized as a function of magnitude and distance. Because the empirical database represents the maximum from an existing set of observations, this is a lower limit to the maximum possible; however, the empirical data are from a wide range of path and site conditions that may include conditions that lead to large ground motions which are not applicable to the Swiss NPP sites.

As an alternative to empirical data, numerical simulations based on kinematic models have the advantage that they can use specified path and site conditions and they can consider earthquakes that have not yet been recorded, but the results are sensitive to the assumptions of the source input parameters.

For the PRP, an updated empirical evaluation of the maximum ground motion was conducted including the expanded ground motion datasets [Strasser and Zulu 2010] (EXT-TB-1067). An updated model of the dependence of the recorded largest ground motion on the earthquake magnitude and distance were provided to the experts. An example plot of the largest recorded spectral acceleration at 10 Hz is shown in Figure 4.1.

Numerical simulations for the maximum ground motion using kinematic models had been conducted as part of the PEGASOS Project based on linear models of the source and site response. Since the completion of the PEGASOS Project, additional studies for the maximum ground motion were conducted as part of the Extreme Ground Motion Project - ExGM [Hanks et al. 2013]. The ExGM Project used dynamic rupture models with non-linear source (off-fault damage) and non-linear rock site material properties to evaluate the maximum ground motion for the Yucca Mountain site [Andrews et al. 2007].

They found that while the fully non-linear models lead to lower maximum ground motions than the linear models (such as those used in PEGASOS), the maximum values remained very large (Fig. 4.2) and would not have a significant effect on the rock site hazard. Therefore, no additional numerical simulations were conducted for the maximum ground motion for the PRP. Instead, the SP2 experts had access to the kinematic simulations from PEGASOS and the dynamic rupture models from Andrews et al. [2007].

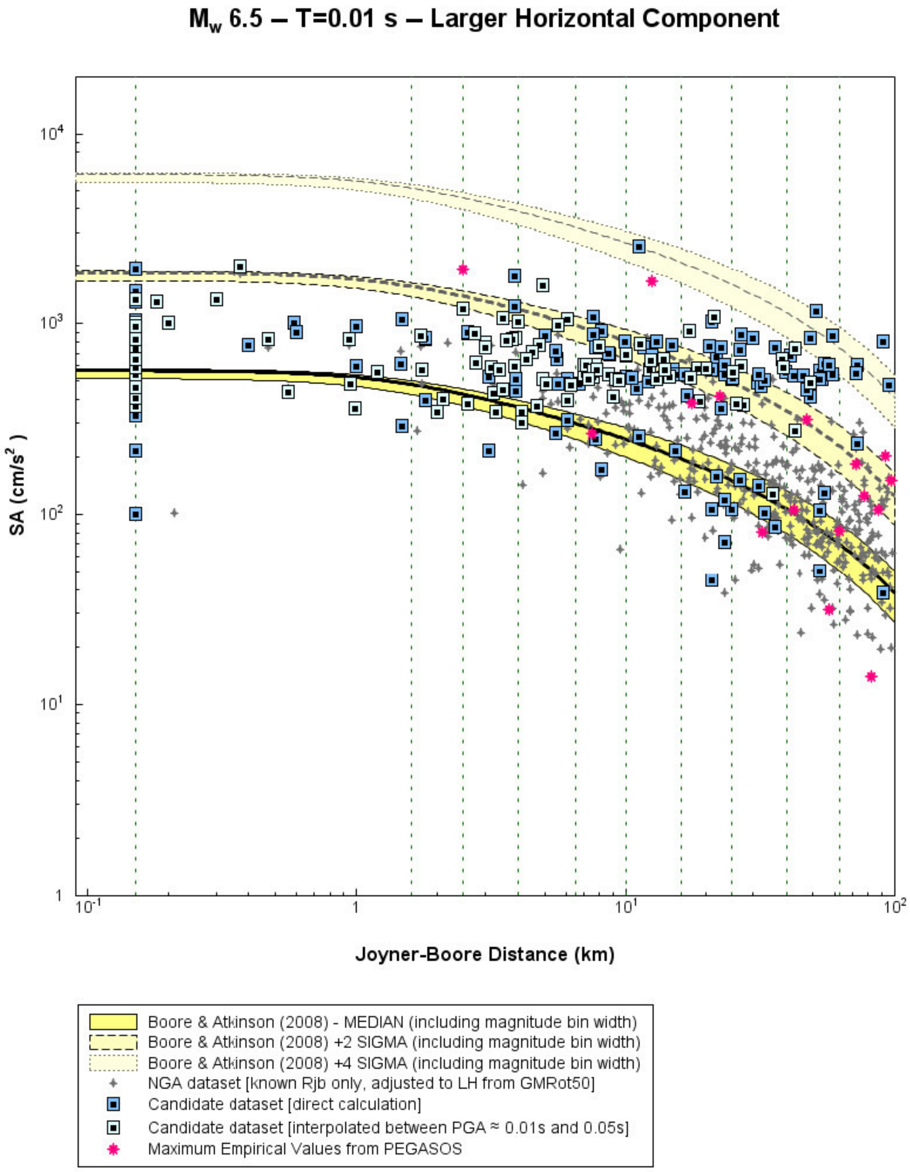


Figure 4.1: Example of maximum ground motions for magnitude 6.5 [Strasser 2012].

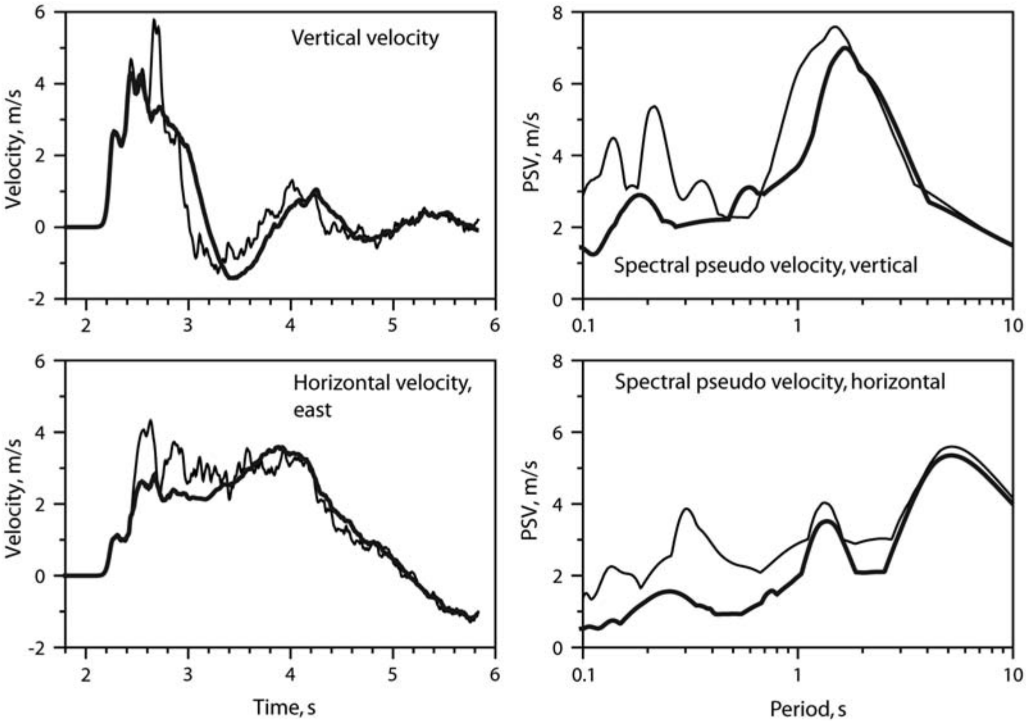


Figure 4.2: Ground motion at the repository depth at 1 km east of the Solitario Canyon fault with 15 m fault slip with and without yielding. Elastic calculation, light curves; calculation with Coulomb yielding, heavy curves. Left-hand panels: velocity. Right-hand panels: spectral pseudovelocity. Top panels: vertical component. Bottom panels: horizontal component (Figure 20 from Andrews et al. [2007]).

4.6 Workshops and Elicitation Meetings

As part of the PRP, eleven workshops were held for SP2 and six interface workshops. This greatly exceeds the three workshops that are required for SSHAC Level 3 or Level 4 studies [Kammerer and Ake 2012]. The additional workshops were needed for the PRP because of technical issues that were only identified during the PRP and that were poorly constrained and led to large uncertainties. The Project Management decided that rather than simply evaluating the large uncertainties, additional research would be conducted to improve understanding and possibly reduce the uncertainties. In this section, only the key outcomes of the workshops are given. The full workshop summaries are contained in the appendix to this report. The overview of workshops and milestones is summarized in Table 4.1.

Table 4.1: Overview of SP2 workshops and key contents

Date	Number	WS type	Topic
1.-3. Sept. 2008	WS1	Kick-Off, SSHAC WS1 Data Collection	Available new data and models (e.g. Swiss Stoch. Model), Sensitivity studies, Interfaces
8.-9. Dec. 2008	Interface WS	General interfaces between SP1, SP2, SP3, SP4	Interface topics and necessary logic tree considerations (e.g. ECOS parameters, rupture geom., distance metric, reference bedrock, upper bound, V/H, site investigations, PSA inputs)
27.-28. April 2009	WS2	SSHAC WS1 Data Collection, Interface with SP1	Progress review of SED tasks, SP2 logic tree components (e.g. SSM vs. GMPE, Single-station σ), Interface on ECOS09 and sensitivities
3.-4. Nov. 2009	WS3	SSHAC WS2 Evaluation	Candidate GMPEs, implementation of new research results, testing procedures, new earthquake data, Swiss stochastic model
24.-26. Feb. 2010	WS4	SSHAC WS2 Evaluation, Interface with SP1	Finite-Fault Simulations, Interface with SP1, Sigma, Small Mag adjustments, Upper bound, Host-to-target conversion, V/H models
7.-8. July 2010	WS5	SSHAC WS2 Evaluation	Swiss stochastic model revision, GMPE adjustments, SP2 logic tree structure, Single-station σ
6.-8. Oct. 2010	WS6	SSHAC WS2+3 Evaluation & Feedback, Interface with SP3	Interface topics with SP3, testing results, preliminary rational for LT weights, hazard feedback
1. Dec. 2010	WS7	SSHAC WS3 Feedback	Comparison of PSSM and GMPEs, hazard feedback on Max GM, extended testing
12. May 2011	WS8	SSHAC WS3 Feedback, Interface with SP3	Interface topics with SP3, $V_S - \kappa$ corrections, Intensity Testing, SP2 logic tree review, hazard feedback
30. Aug. - 1. Sept. 2011	WS9	Restructuring of SP2, SSHAC WS1 Data Collection	Introduction of new SP2 expert, overview all available proponent models, testing results, $V_S - \kappa$ corrections, hazard feedback
9.-11. May 2012	WS10	SSHAC WS2 Evaluation, Interface with SP3+SP5	Hazard feedback, GM logic tree models and weights justification, Interface topics with SP3 and SP5
16.-18. Jan. 2013	WS11	SSHAC WS3 Feedback, Interface with SP3	Hazard feedback, supplementary investigations on Swiss data, κ estimates, GM logic tree models and weights justification, Interface topics with SP3 and SP5
16.-17. May 2013	Summary Meeting	SSHAC WS3 Feedback	Preliminary hazard results, testing of $V_S - \kappa$ corrections
19.-20. September 20013	WS12 κ-Workshop	SSHAC WS3 Feedback	Review of requested additional investigations on centering of the approach

4.6.1 Workshop #1: Kick-Off and Data Needs

The SP2 data needs workshop (WS1/SP2) was held on 1.-2. September 2008 in Zürich. The first day of the workshop reviewed the data collection and modeling efforts being conducted by SED in support of the PRP. The topics and identified data needs are described below:

- Meta data for Swiss earthquakes with recorded ground motions: Consider earthquakes since 1998 with high quality data. Prepare a dataset for $M \leq 4$ and, if possible, extend to $M > 3.5$. Estimate the following source parameters for each earthquake: moment, rupture area, mechanism, and depth. In addition, compute the stochastic model stress parameter using geometrical spreading and Q that are consistent with the stochastic model being developed.

- Compilation of new Swiss ground motion data: The dataset should include all earthquakes with $M \geq 4$ and all earthquakes recorded at NPP sites. Specifications for the processing (filtering and baseline corrections) need to be developed. The response spectra and CAV should be computed for each component. For recordings at the NPP sites, a summary of the seismic instrumentation at the site is needed.

- Collect site condition information for SED stations: Collect information on the velocity profile at 25 SED stations. Only consider stations in the foreland. The site characterization should include the V_S profile, including V_{S30}, and its uncertainty. Additionally, information on the site period should be provided if available from previous investigations. The stations with multiple recordings will be most useful. Indentify the stations with more than 14 recordings for use in the selection of the 25 stations for site characterization.

- Development of a new Swiss stochastic model: The development of the new Swiss stochastic model should focus on Swiss-specific parameters: Q, κ, geometrical spreading, stress-parameter, and duration. To address the strong trade-off in the model parameters, estimate the correlations of the parameters. This model will be used as an alternative GMPE and as a target region model for the hybrid-empirical approach.

- Compile/evaluate improved GMPEs: The compilation of new GMPEs should include NGA models, new European models, the CEUS-EPRI (2004) model, new NGA-East models if available, and Japanese models. Compare the Swiss small magnitude ground motion data with GMPEs from California, Japan and Europe that are applicable to small magnitudes to determine if the Swiss data are systematically lower, as seen in PEGASOS. Evaluate the models by comparing the model predictions with the PRP dataset using the likelihood approach and potentially the information theory approach suggested by Scherbaum et al. [2009].

- $V_{S30} - \kappa$ correlations: Compile new $V_{S30} - \kappa$ correlations for use in estimating κ for the hybrid empirical method.

- Finite-fault modeling: The finite-fault simulation plan described by M. Mai is acceptable. The results of the finite-fault simulations will be compared to the GMPEs, but not used to derive new ground motion models.

- CAV model for Europe: If the NPPs and the PMT decide to use CAV filtering, then a new CAV model would need to be developed for Europe.

During the second day, interface issues between SP1, SP2 and SP3 were discussed. It was decided that a full workshop on interface issues was needed (see Section 3.1.1)

4.6.2 Interface Workshop: Interface Issues Between SP1, SP2, SP3 and SP4

The interface workshop was held on 8.-9. December 2008 in Zürich. The first day of the workshop addressed the SP1/SP2 interface and the SP1/SP2/SP4 interface and is summarized in Section 3.1.1. The second day addressed the SP2/SP3/SP4 interface and is summarized in Section 5.1.1.

4.6.3 Workshop #2: Data needs, Candidate GMPEs

The second SP2 workshop was held on 27. April 2009 in Zürich. The workshop addressed the data needs tasks being conducted by the SED and other contractors, the compilation of the empirical ground motion models and the approach to building a unified SP2 logic tree. Key topics and data needs discussed at the workshop are given below.

- Swiss ground motion data: The ground motions are low-pass filtered at 25 Hz which can affect the κ estimate. The trade-off between filter corner and κ should be evaluated.

- Source studies: What stress-drops to use for the Swiss stochastic model? How should stress-drop be defined given that the stress-drops for Swiss earthquakes are dominated by $M2 - M3$.

- Use of finite-fault simulations: Compare with the empirical GMPEs and the stochastic model for the following scaling: magnitude-dependence of the geometrical spreading term, median ground motion at short distances for large magnitudes, and distance-dependence of the standard deviation (does it change at short distances?).

- Site amplification variability: Previously agreed that SP2 will remove the median site term from the rock standard deviation. There are several datasets that can be used to estimate single-station σ. Need for an SP2 working meeting to develop the single-station σ models.

- Selection of candidate ground motion models: The pre-selection criteria presented were adopted with the exception that criteria 6 and 7 (model has an inappropriate functional form and regression method or coefficients are inappropriate) were dropped as they involve significant judgment that should be the SP2 experts' responsibility.

- Building the SP2 unified logic tree: Reconsider the decision to keep the median and σ for each ground motion model as correlated inputs. Use of single-station σ requires all of the σ models to be adjusted. This issue was discussed again at the SP2 working meeting.

- Hybrid models: Two alternatives were discussed: use of a full host-to-target conversion and use of a site (V_S and κ) only conversion. The discussion of the two alternatives was postponed to the November 2009 workshop.

4.6.4 Workshop #3: Initial Expert Evaluations

The third SP2 workshop was held on 3.-4. November 2009 in Zürich. The workshop was a combination of a data needs and evaluation workshop. It addressed the selection of candidate GMPEs, new approaches to visualizing and quantifying epistemic uncertainty, status of the data needs tasks related to Swiss ground motions and the Swiss stochastic model, datasets that can be used to constrain the single-station σ, relation between V_{S30} and κ, and testing of the candidate GMPEs against intensity data. The key decisions made and issues identified by the SP2 experts are listed below:

- All of the candidate GMPEs should be adjusted so that they extrapolate to small magnitudes consistent with the Swiss data.
- Check if the pre-selected GMPEs capture the full range of the technically defensible interpretations. The SP2 exerts considered expanding the set of candidate models to include Zhao et al. [2006], McVerry et al. [2006], and Cotton et al. [2008].
- The SP2 experts agreed that the σ models from the GMPEs should be converted to single-station σ to remove the site variability that is covered by SP3 (part of the SP2/SP3 interface). The aleatory variability of the site response will remain in the SP2 σ. The available data to constrain the single-station σ were presented. The currently available ground motion data for single-station σ are not yet treated consistently around the world.
- Updates on the Swiss earthquake data studies were presented by SED.
- Stochastic model: There is a strong trade-off in the stochastic parameters. The extrapolation of the Swiss stochastic model to large magnitudes is not well constrained.
- The SP2 experts agreed that pre-selected GMPEs all needed to be adjusted to the Swiss κ values.
- How should the κ be estimated for the NPP sites? The $V_{S30} - \kappa$ correlation was the only available approach considered.
- The testing procedure based on the intensity data has large uncertainties due to the conversion from intensity to ground motion, but these data provide the only check on the GMPEs for larger magnitudes. The SP2 experts agreed that the intensity testing should be considered despite the limitations of the intensity data.
- Finite-fault simulations can be used as a check on the median and sigma of the GMPEs at large magnitudes and for short distances.

4.6.5 Workshop #4:

The fourth SP2 workshop was held on 25.-26. February 2010 in Zürich. The workshop was an evaluation workshop. It addressed two main topics: finite-fault simulation results and datasets for estimating single-station σ. In addition, the SP2 experts also discussed the development of the SP2 master logic tree, host-to-target conversions, and extrapolation to small magnitudes. The key decisions made and issues identified by the SP2 experts are listed below:

- The initial structure of the SP2 master logic tree for the median and σ was discussed. The master logic tree will be updated by J. Bommer and F. Scherbaum for discussion at the July 2010 workshop. A key issue is the vertical model for both the median and the σ. The range of the horizontal models will be compared with the range of the V/H models to allow the SP2 experts to determine if the resulting range of the vertical (Horiz. × V/H) is appropriate. The approach for single-station σ for the vertical component has not yet been addressed.

- New data for constraining the upper bound ground motions were discussed. A proposed SP2 master logic tree structure for the maximum ground motion will be developed by J. Bungum for discussion at the July 2010 workshop.

- Host-to-target conversions remain a key issue. Estimation of host κ based on fitting the GMPEs to the point-source model suffers from trade-offs between point-source model parameters (e.g. stress-drop and κ). The correlations can be reduced using normalized spectral shapes. Updated $\kappa - V_{S30}$ corrections for the GMPEs will be developed using the normalized spectral shapes.

- A consensus methodology for extrapolation to small magnitudes has been selected by the SP2 experts.

- The methods and notation used for the evaluation of the components of the standard deviation from different datasets has not been consistent. A consistent notation and approach will be developed. Repeat the σ evaluations for Swiss and Japanese data using consistent methods. Add data from other regions as appropriate: California, Taiwan, Italy, and Turkey. Organize a separate workshop to address single-station σ including possible magnitude and distance dependence.

- The FFS conducted by M. Mai were reviewed. There are inconsistencies between the reference site and crustal models used for the FFS and those of the GMPEs adjusted to Swiss rock site conditions. The FFS results should be adjusted to be consistent with the reference velocity profile and the SED Q model by applying factors to the simulated ground motions.

- The FFS show a stronger dependence of the near-fault ground motions on fault mechanism than in the empirical GMPEs. The FFS need to be checked against two validation earthquakes with data at short distances to confirm that the FFS methodology is valid at short distances before these results are considered reliable.

- The FFS can be used to check for a distance dependence of large magnitude ground motions for comparison with the empirical models.

4.6.6 Workshop #5

The fifth SP2 workshop was held on 7.-8. July 2010 in Zürich. The workshop addressed four main topics: revised Swiss stochastic model, host-to-target adjustments to the GMPEs, proposed structure of the SP2 master logic tree, and single-station σ. The key decisions made and issues identified by the SP2 experts are listed below:

- The SP2 experts concluded that the suite of pre-selected GMPEs with the revised Swiss stochastic model provided a broad enough range of candidate models that no additional epistemic uncertainty was needed.

- Three of pre-selected GMPEs (Zhao et al. [2006] , Toro et al. [2002] , and Atkinson & Boore [2006]) did not include style-of-faulting (SOF) factors for all of the mechanisms. The SP2 experts made a consensus decision to add a single SOF to these three models based on the Akkar & Bommer [2010] model as this model had a simple functional form similar to the functional forms used by the three GMPEs.

- The proposed master logic tree for the maximum ground motion proposed by H. Bungum is flexible enough to be used by all of the SP2 experts.

- A key issue for the Swiss stochastic model is the stress-drop for large magnitudes.

- The host-to-target corrections depend on the methodology for the site factors (quarter wave length method or SH wave propagation method). The SP2 experts made a consensus decision that the quarter wave length method, which leads to smooth amplification, should be used. The SP2 experts also agreed that the target κ should be based on the Swiss correlations between κ and V_{S30}.

- To facilitate the SP2 evaluation, hazard feedback using a fixed σ of 0.65 was requested. This helps to show the sensitivity of the hazard to the median GMPE models. In addition, to aid the visualization of the uncertainty in the medians, the SP2 experts requested the SOM map using the same constant σ of 0.65.

- Single-station σ values were presented based on datasets from California, Taiwan, Japan, Turkey, and Mexico. Initial candidate models for the single-station σ will be developed and presented at the October 2010 workshop.

4.6.7 Workshop #6

The sixth SP2 workshop was held on 7.-8. October 2010 in Zürich. The workshop addressed three main data needs topics: single-station σ, magnitude dependence of stress-drop in the Swiss stochastic models and testing of candidate models using the mixture model method. In addition, the SP2 experts also presented their initial approach for developing their weights for the SP2 logic tree. The SP2 expert approaches are discussed later in Section 4.7.2. The key decisions made and issues identified by the SP2 experts are listed below:

- Three candidate models for the V/H ratio were selected by the SP2 and SP3 experts as part of the interface workshop.

- Single-station σ results for the combined datasets were presented and discussed. A bias in the residuals for small magnitudes and short distances was observed and should be removed. After correcting the GMPEs to remove this bias, a set of alternative candidate models for single-station σ will be developed including period dependence and possible magnitude and distance dependence of the within-event and between-event standard deviation terms.

- Estimate the epistemic uncertainty of within-event single-station σ (ϕ_{SS}). Check whether there is a regional dependence of the uncertainty.

- The distribution of the upper tail of the ground motion variability was evaluated using a Pareto distribution rather than log-normal. If the correlations are properly considered, there is no significant difference between these two distributions. The SP2 experts concluded that no additional work was needed for the distribution of the upper tail.

- A key issue for the application of the Swiss stochastic model is the stress-drop for large magnitudes. Several alternative versions of the magnitude dependence of the Swiss stochastic model will be developed and included in the SP2 master logic tree. This provides the SP2 experts with a wider range of candidate models for evaluation.

- The SP2 experts requested additional testing of the candidate GMPEs, including the suite of Swiss stochastic models, using the mixture model approach but using high initial weight on one model at a time to see if the testing pushes the model out, showing a stronger case for rejection of a model.

4.6.8 Workshop #7

The seventh SP2 workshop was held on 1. December 2010 in Zürich. The workshop was mainly focused on the Swiss stochastic models. In addition, hazard feedback on the alternative models for the maximum ground motion was provided. The completion of the single-station σ models and additional testing of the GMPEs were also discussed. Finally, the approach to developing NPP-specific $V_S - \kappa$ adjustments was discussed. The key decisions made and issues identified by the SP2 experts are listed below:

- The suite of Swiss stochastic models was discussed, including the alternative models for the magnitude dependent stress-drop and the alternative models for the effective point-source distance for large magnitudes. The final set of Swiss stochastic models will be completed by January 2011.

- Comparison of PSSMs and GMPEs showed a systematic offset between both groups even after correction of the GMPE to Swiss site conditions. The difference between the GMPEs and PSSMs is a key contributor to the uncertainty in the hazard.

- The hazard feedback showed that the initial SP2 experts models for the maximum ground motion had a negligible effect on the hazard.

- An additional outstanding issue was identified. The $V_S - \kappa$ adjustment for NPP-specific application could be made in one of two ways: (1) first adjust to the Swiss reference rock model and then adjust from the reference rock model to the NPP-specific rock model; or (2) adjust the GMPEs directly to the NPP-specific rock model. An evaluation of the effects of the two different approaches will be made.

4.6.9 Workshop #8

The eighth SP2 workshop was held on 12. May 2011 in Zürich. The workshop addressed five topics: host-to-target $V_S - \kappa$ corrections, intensity testing, V/H ratios for rock sites, SP2 expert evaluations, and hazard feedback. The SP2 expert evaluations are discussed later in Section 4.7.2. The key decisions made and issues identified by the SP2 experts are listed below:

- The available $V_S - \kappa$ correction methods for developing response spectral scale factors have been found to be unstable and continue to be a major source of uncertainty for the hazard in Switzerland at high frequencies. A new $V_S - \kappa$ correction method, called the iterative approach, was develop by F. Scherbaum and discussed by the SP2 experts at the workshop. This new method still needs to be finalized, but looks promising.
- An alternative simplified method for estimating κ for the host GMPEs based on the high frequency normalized spectral shape was presented.
- Addressing an open issue from SP2 WS#7, the SP2 experts reached consensus that the NPP-specific $V_S - \kappa$ corrections should be computed in one step directly from the GMPEs.
- The new intensity testing results were presented. One shortcoming of the current methodology is that the standard deviation of the ground motions estimated from intensity were assumed to be the same as the standard deviation of the GMPEs. The intensity testing methodology will be revised to use the appropriate standard deviation, accounting for the larger variability of the spectral values estimated from intensity values.
- The available V/H ratio models are not well constrained for rock sites. The SED is developing a new V/H ratio model that is specifically for rock sites, but this model is not currently available. The SP2 master logic tree will be modified to include an additional branch for the uncertainty in the extrapolation of the V/H ratio models to rock sites with $V_{S30} > 1000$ m/s.
- The site-to-site uncertainty in the ϕ_{SS} values is not captured in the current SP2 master logic tree. An additional branch will be added to the SP2 master logic tree to allow for a scale factor on ϕ_{SS} to capture this uncertainty.
- The hazard feedback showed that the initial SP2 experts models for the maximum ground motion had a negligible effect on the hazard.

4.6.10 Workshop #9

Unlike PEGASOS, in which the SP2 experts evaluated the models and methods that were available, in the PRP significant new work was conducted to develop improved rock ground motion models for Switzerland. In particular, the κ correction has a large effect on the high frequency ground motions and it was found that the available methods were not robust, leading to very large uncertainties. To address the short-comings of the available models and methods, new research was conducted on the $V_S - \kappa$ corrections. Significant improvements to the models and methods were made, but addressing these issues led to delays in the schedule and the planned SP2 evaluation phase was repeatedly postponed. With the extensions of the SP2 schedule, F. Scherbaum and J. Bommer felt that they would not be able to complete their evaluations due to prior commitments made when the PRP schedule was expected to have been completed by this time. As a result, F. Scherbaum and J. Bommer resigned as SP2 experts, but F. Scherbaum was able to continue to participate as a Resource Expert.

The SSHAC guideline does not set the number of evaluator experts required for a SSHAC Level 4 study, but the other two subprojects (SP1 and SP2) each have four experts or expert groups. To be consistent with the other subprojects, a fourth SP2 evaluator expert was added. K. Campbell was selected as the additional SP2 expert based on his familiarity with the SSHAC process and his experience with κ corrections, which are a key issue for the PRP.

The addition of a new SP2 expert into the PRP provided the opportunity to evaluate the stability of the results if a different set of experts were to conduct the study. This is discussed further in Section 4.7.

The ninth SP2 workshop was held on 30. August - 1. September 2011 in Zürich. With the addition of a new SP2 expert, this workshop was structured to address both the data needs and proponent models (e.g. SSHAC workshop type 1 and type 2) to allow the new SP2 expert to understand the evaluations previously made by SP2 and also to allow the new SP2 expert to provide his inputs to the selected candidate proponent models. Hazard feedback was provided early in the workshop to help focus the discussions with the new SP2 expert on the issues that lead to the largest uncertainties in the rock hazard at the NPP sites: median ground motion model, uncertainty of single-station sigma, the stress-drop for large magnitudes in the Swiss stochastic model, and the pseudo depth used for the stochastic model. The proponent models presented and discussed at the workshop are listed below along with the key additional data needs identified. As shown below, significant additional data needs were identified during the workshop.

- Structure of the SP2 master logic tree for the median ground motion. Additional candidate GMPEs that were not available during the initial SP2 pre-selection or models that were updated after the initial selection. In all, four new GMPEs and three updated GMPEs were added to the suite of candidate models for consideration.

- New ground motion datasets: Although the NGA-West2 GMPEs are not available yet, the NGA-West2 dataset should be used to estimate the expected change in the medians using the mean residuals based on the NGA (2008) models. The ground motion data from the 2011 Mineral (Virginia) earthquake should be compared to the pre-selected GMPEs (EUS and other regions) as well as the Swiss stochastic models.

- Proponent Swiss stochastic models: The selection of the method to compute the effective point source distance has a large effect on the hazard. An additional branch will be added to the SP2 master logic tree to include alternative effective distance models.

- Proponent consensus model for small-magnitude adjustments for GMPEs: The application of the model should include both increases and decreases as needed to be consistent with the Swiss ground motions from small magnitudes. Also check the behavior of the adjustments at larger distances.

- Proponent methods for $V_S - \kappa$ corrections for GMPEs: Three methods were presented: $V_S - \kappa$ corrections using the hybrid empirical method (HEM), Scherbaums' iterative method, and empirical scale factors.

- Proponent models for host and target V_S-profiles and κ values. Three approaches for the velocity profiles were identified: WUS V_S-profiles for GMPEs, Swiss V_S-profiles for GMPEs, and estimation of V_S-profiles by inversion. Three alternative κ values for the GMPEs based on the spectral shape were discussed. Estimates of the target κ based on the FAS of recordings at the NPP sites are not well constrained.

- Proponent method for GMPE testing using intensity data: Consideration of the new Michelini and Faenza (2011) model for converting intensity to spectral acceleration was added to the data needs. Additional testing cases were requested using the updated small magnitude adjustment and $V_S - \kappa$ corrections. Also make traditional plots of the residuals of intensity versus magnitude and distance.

- Proponent models for single-station σ. Additional ground motion data for California at all periods will be available as part of the NGA-West2 dataset. Compare the standard deviation of ϕ_{SS} from global datasets with those from Swiss data in the M3-M4 range. Check if the ϕ_{SS} is dependent on V_{S30} for rock sites. Check the distance dependence of σ from the finite-fault simulations by M. Mai. Revise the frequency interpolation scheme to favor linear rather than spline methods.

- SP2 master logic tree for maximum ground motions: No additional models were considered based on the lack of hazard sensitivity to the maximum ground motion model.

- Proponent models for V/H ratios: Add the new SED V/H model for hard rock sites as a new candidate V/H model. Evaluate the dependence of V/H on kappa for short distances. Plot V/H rations for Japanese rock sites. Compare with V/H ratios used by G. Atkinson for hard rock sites in the Eastern US.

4.6.11 Workshop #10

The tenth SP2 workshop was held on 9.-10. May 2012 in Zürich. This workshop was an evaluation workshop (SSHAC workshop type 3), with each SP2 expert providing the technical basis for his evaluation of the center, body, and range of the technically defensible interpretations for the median horizontal ground motion, the median V/H ratio, the maximum horizontal and vertical, and the single-station sigma for the horizontal and vertical. The workshop also included hazard feedback to focus the discussion among the SP2 experts on the parts of the models that have the largest effect on the uncertainty in the hazard. The discussion was focused on how the SP2 experts can check if their evaluation is properly centered and if it has the full range of technically defensible interpretations. The difference evaluation approaches presented by the SP2 experts at this workshop are discussed in Section 4.7.2.

4.6.12 Workshop #11

The eleventh SP2 workshop was held on 16.-17. January 2013 in Zürich. This was an evaluation workshop and addressed the following topics: Hazard feedback using the updated SP2 expert models, comparison of NGA-West2 data and Swiss data for comparable magnitude ranges, evaluation of the Swiss stochastic model approach through application to Japanese data, κ estimates for Switzerland, presentation of the updated SP2 expert evaluations and the technical basis for their logic tree weights. The hazard feedback was used to identify the differences in the SP2 experts' models that lead to the largest differences in hazard so that the discussions of the technical bases of the expert evaluations would be focused on the most important parts of the models. Estimation of κ remains a key source of uncertainty. Additional presentations on κ estimation were made by the Resource Experts J. Anderson, O. Ktenidou, and B. Edwards. Key issues are removal or avoidance of site response effects and the Q effects on κ (constrained from regional models or estimated from distance dependence of κ). The discussions of the SP2 expert models focused on the technical basis for the centering of the model and ensuring that the full range of technically defensible interpretations is captured. The difference evaluation approaches presented by the SP2 experts at this workshop are discussed in Section 4.7.2 and are presented in detail in the expert summaries in Volume 4.

4.6.13 Summary Meeting

The May 2013 project summary workshop included the presentation of hazard results and a discussion of the outstanding technical issue of the centering of the $V_S - \kappa$ correction. The discussion addressed initial additional evaluations that could be used to test the centering of the $V_S - \kappa$ correction based on the newly available NGA-West2 models and data. The SP2 experts indicated that having this additional analysis to test the centering of the $V_S - \kappa$ corrections would be useful and it was therefore agreed to organize an additional SP2 workshop on κ later in the year to allow for a more in-depth discussion of the $V_S - \kappa$ centering.

4.6.14 Workshop #12 - Additional κ Workshop

The new methods for centering the $V_S - \kappa$ corrections presented in May 2013 were presented as a set of methods that would provide constraints on the effective target κ values as part of the $V_S - \kappa$ corrections. The constraints on target κ could be used to explain high frequency ground motions, but they did not provide improved centering of the $V_S - \kappa$ correction for low frequencies (see Abrahamson [2013] (TFI-TN-1272)). These new $V_S - \kappa$ correction centering methods were considered by the SP2 experts in their final revision of their SP2 models.

4.6.15 Working, Web-meetings and Individual Elicitation Meetings

In addition to the 11 SP2 workshops, there were also 7 working meetings, 8 web-meetings, and individual elicitation meetings between the SP2 experts and the TFI. Tables 4.2, 4.3 and 4.4 summarize the SP2 working meetings, web-meetings and individual elicitation meetings, respectively.

Table 4.2: Overview of SP2 working meetings.

Date	Location	Topic
11.06.2009	Potsdam	Pre-selection of existing ground-motion models
27.-28.08.2009	London	Review of candidate models, Need for frequency interpolation, Style-of-faulting adjustments, Approach for the vertical component, Testing procedure,
21.-22.01.2010	London	Revision of SP2 schedule, Discussion on κ estimation of the GMPEs, Small magnitudes, Discrepancy between Swiss stochastic model and simplified Douglas model and hazard contributions from small magnitude events, Revision of GMPE candidate models, Host-to-target region conversion, Rejection to adopt USGS approach for PRP to cover epistemic uncertainty, Upper bound for rock ground motion for SP2, Single station sigma, Comparisons with Finite Fault Simulations
12.-13.04.2010	London	$V_S - \kappa$ adjustment of GMPEs to the SED reference rock profile, Final Swiss stochastic model and revised empirical model comparison, Extension of GMPEs to Swiss small magnitudes, Draft logic tree for GMPE median models, Testing task, Single-station σ, Maximum ground motions, Vertical models, Need for FFS validation
27.08.2010	Zürich	Preliminary results of GMPE testing, Further GMPE adjustments, Maximum ground motion logic tree, Single-station σ progress
24.01.2011	Zürich	Proposed models for τ, ϕ_{SS} (and total σ_{SS}), SP2/SP3 interface issues related to $V_S - \kappa$ correction factor, Hazard feedback on maximum ground motion
30.01.2012	Zürich	Generic $V_S - \kappa$ corrections, NPP specific $V_S - \kappa$ corrections, GMPE testing – 2 new GMPEs vs. 8 PRP GMPEs, V/H logic trees (Median, Variability and MaxGM), Interface to SP3 – Separation of vertical variability, Amplitude differences of PSSM and GMPEs

Table 4.3: Overview of SP2 web-meetings.

Date	Topic
24.10.2011	$V_S - \kappa$ correction – Determination of "central estimates" for small magnitude adjustments and testing
23.11.2011	Additional GMPE evaluation , $V_S - \kappa$ corrections
04.07.2012	$V_S - \kappa$ corrections, NPP κ estimates
17.09.2012	$V_S - \kappa$ corrections, Mixture model comparisons, GMPE weights
31.10.2012	Review of $V_S - \kappa$ corrections, Intensity testing results, V/H models, Hazard feedback
13.11.2012	Hazard feedback, V/H models, Open items
01.02.2013*	Testing of the $V_S - \kappa$ scaling based on the residual analysis comparing the observations at selected SED stations with the expert specific predictions (PMT-SUP-1084)
11.11.2013	Review of $V_S - \kappa_0$ corrections necessary to produce centered models (TFI-TN-1272)

* K. Campbell could not participate on 1. February. Another dedicated web-meeting between the TFI and K. Campbell was held on 4. February 2013.

Table 4.4: Overview of elicitation meetings between the TFI and individual SP2 experts.

Date	Location	Expert
12.03.2012	Zürich	F. Cotton
13.03.2012	Zürich	D. Fäh
13.03.2012	Zürich	H. Bungum
16.03.2012	Berkeley	K. Campbell
13.06.2012	Web-meeting	H. Bungum
29.06.2012	Web-meeting	F. Cotton
27.08.2012	Zürich	K. Campbell
07.-09.09.2012	Berkeley	K. Campbell
19-20.09.2012	Berkeley	K. Campbell
11.12.2012	Berkeley	K. Campbell
07.01.2013	Berkeley	K. Campbell

4.7 Expert Model Development

4.7.1 Master Logic Tree

In the PEGASOS study, each expert provided a description of his logic tree in his own elicitation summary. The structures of the logic trees used by the five PEGASOS SP2 experts had many similarities. To take advantage of these similarities, the PRP SP2 experts agreed to develop a single master logic tree structure that could be used by all of the SP2 experts for their evaluations. The use of a master logic tree structure did not require the SP2 experts to include every branch in their model. The SP2 experts were free to exclude branches and they developed their own individual weights and justifications for the weights.

4.7.2 Development of Logic Trees Weights

During the PRP, there were four workshops in which the SP2 experts evaluations were discussed, as shown in Table 4.5. The first two, conducted in 2010 involved the original five SP2 experts and the last two in 2012 and 2013 involved the final four SP2 experts.

Table 4.5: Workshops with discussion of the SP2 experts' evaluations and hazard feedback.

Date	Bommer	Scherbaum	Bungum	Cotton	Fäh	Campbell
June 2010	X	X	X	X	X	
Oct. 2010	X	X	X	X	X	
May 2012			X	X	X	X
May 2013			X	X	X	X

The influence of the expert interaction and the hazard feedback on the expert evaluations of the Center, Body, and Range of the ground motion models can be seen by comparing the mean and fractiles of the hazard for the initial and final expert models. The hazard from the preliminary expert models in July 2010 shows a wide range of interpretations. Based on the interaction of the experts during the workshop the revised interpretations shown in the October 2010 workshop had greater consistency between the experts. This was observed again in the May 2012 workshop when Campbell's initial evaluation was compared to the other expert models and showed a much narrower range. The interaction among the SP2 experts and the hazard feedback caused K. Campbell to broaden the range of his model. His final model shown in Chapter 8.4.1 covered a range comparable to the other SP2 experts.

Approaches Used by the SP2 Experts

The objective of the expert evaluation is the capture the Center, Body, and Range of the technically defensible interpretations of ground motion models for Switzerland. This objective applies to the outcome of the experts' models and does not require that each expert consider every model. That is, there may be different approaches that lead to different sets of models that still capture the desired Center, Body, and Range. The details of the SP2 expert evaluations are given in the expert summaries in Volume 4. To illustrate the differences in the evaluation methods, short descriptions of the different approaches to developing the logic tree weights for the median horizontal component (GMPEs and PSSMs) used by the SP2 experts are given below.

J. Bommer considered that all of the models that passed the pre-selection criteria were credible models and applied selection criteria based on the similarity of the tectonic region for the GMPE and the tectonic region for Switzerland. Based on feedback from other experts and the initial testing results, J. Bommer rejected the EUS GMPEs as applicable models for Switzerland; however, he was concerned that the remaining candidate GMPEs would not provide a broad enough range and that additional models should be considered. In a change from the selection criteria used to pre-select the models, J. Bommer suggested that the additional models should not be constrained to published models. Rather, scaled versions of the pre-selected models should be considered. This approach, which has recently been adopted by other projects, is now called the "scaled backbone" approach.

F. Scherbaum considered all of the models that passed the pre-selection criteria to be of acceptable quality. F. Scherbaum's concept for developing weights for the logic tree was to use "degree of belief" weights rather than weights that represent the quality or robustness of the model. The ranking of the models considered only tectonic/regional proximity and empirical regression versus stochastic simulation. A key feature of F. Scherbaum's approach is that he concentrated the weights on a small number of models rather than giving some weight to all models.

F. Cotton's initial evaluation of the GMPE weights was based on comparisons of the distance attenuation of macroseismic data and weak motion data in Switzerland with similar data for other stable and active regions. He also compared ground motion data from moderate magnitude earthquakes to the GMPE predictions. From these comparisons, he concluded that Switzerland is more similar to active regions and gave higher weight to active region models. He also used the Sammon's map to provide information on the similarity/differences of the GMPEs. F. Cotton rejected the EUS models and replaced the suite of GMPEs for active regions with the scaled backbone approach proposed by J. Bommer. A key difference from the other SP2 experts was that F. Cotton selected scale factors for the backbone model and large magnitude stress-drops for the Swiss stochastic model that spanned a similar range of ground motions. He selected the Abrahamson and Silva [2008] GMPE and then scaled the model to create four alternative scaled versions of the AbSi08 model. In this way, the GMPE and PSSM approaches lead to similar ground motion values. Therefore, F. Cotton assigned the GMPEs and PSSM models equal weights.

H. Bungum used an approach similar to F. Scherbaum. He considered that the pre-selection criteria only passed models that were of high quality. He relied on the intensity testing and mixture model weights to rank the models and used the Sammon's maps and SOMs to evaluate the redundancy of the models. He followed the approach that the model weights should represent degree-of-belief weights where tectonic criteria are used together with a general consideration of the Center, Body and Range and mutually exclusive and collectively exhaustive (MECE) criteria. He also used the approach of limiting the number of models to avoid smearing out the weights too much. The relative weighting between the GMPEs and the PSSMs was based on the reliability of the models in the large magnitude range that dominate the hazard. Using this approach, he assigned a much lower weight to the PSSM class than to the GMPE class.

D. Fäh used the more traditional approach to evaluation of the candidate GMPEs, focused on the quality of the metadata and size of the database used to derive the model. Other factors considered were the range of validity given by the authors of the models, the redundancy of the datasets used to derive the GMPEs, and the consistency with the central Europe intensity data attenuation. He developed weights for each of the evaluation metrics and combined them into a single GMPE weight. D. Fäh constrained the range of stress-drops in the PSSMs based on the comparisons with the intensity data. The relative weighting between the GMPEs and the PSSMs was based on the reliability of the models in the large magnitude range that dominate the hazard. Due to the lack of large magnitude data used to develop the PSSM, he gave slightly higher weight to the empirical GMPEs than to the PSSMs.

K. Campbell considered the pre-selection criteria as a method to eliminate GMPEs that were not clearly applicable based on their general properties and characteristics. He then applied additional screening of the pre-selected GMPEs in terms of their applicability to the tectonic environment of Switzerland and their appropriateness for the magnitude and distance range of most interest in the PRP seismic hazard analysis. In particular, he focused on the extrapolation of the models to higher magnitudes. He used the Sammon's maps and SOMs to evaluate the redundancy of the GMPEs. He also evaluated the models against the intensity data using the traditional approach of evaluation of residuals for individual models rather than the mixture model weights approach. The intensity residuals were the basis for constraining the stress-drops for the Swiss stochastic model. The relative weighting between the GMPEs and the PSSMs was based on the reliability of the models in the large magnitude range that dominate the hazard. He gave much higher weight to the GMPE class of models than to the PSSM class based on the lack of large magnitude data used to derive the PSSM model.

With the change in the composition of the SP2 expert group due to the loss of two SP2 experts and the addition of a new expert, there was an issue as to the effects of this change on the results. In particular, were the approaches advocated by J. Bommer and F. Scherbaum captured in the evaluations of the new SP2 expert group? As noted above, the key aspect of J. Bommer's approach, the scaled backbone approach, was captured in Cotton's evaluation and the key aspects of F. Scherbaum's approach, use of degree-of-belief weights and limiting the number of models to a small subset, were captured in H. Bungum's evaluation. Other key contributions by J. Bommer and F. Scherbaum (small magnitude adjustments, mixture model weights, and $V_S - \kappa$ correction methods) were captured in the SP2 master logic tree. Thus, with the change in the composition of the experts in the SP2 group, the project was still able to capture the range of approaches that could affect the evaluation of the center, body, and range of the ground motion models.

Documentation of Final Expert Models (Evaluation Summaries and Hazard Input Documents)

The expert models are fully documented in the Evaluation Summaries given in Volume 4. These summaries give the quantitative model parameters (parameters in the logic tree branches and branch weights) and also describe the technical basis for the selected models and weights. The condensed information describing the expert models necessary for SP4 to implement them in the hazard code are provided through the hazard input documents (HID), which are also part of Volume 4. The HIDs are reviewed by the SP2 experts and signed when accepted.

4.8 Features and Comparison of the SP2 Expert Models

In this section, the main features of the SP2 models are described and the center and range of the experts' models are compared for the median horizontal, median V/H, aleatory variability of the horizontal additional aleatory variability of the vertical, maximum ground motion for the horizontal, and maximum ground motion for the vertical. The center is given by the weighted average of models of each expert's logic tree. The range is given by the highest and lowest branch with non-zero weight in the expert's logic tree.

The expert models are developed for each NPP site condition. The magnitude and distance scaling are similar for all four NPP sites, so the comparisons are mainly shown for just the Beznau site. The frequency content of the rock motion changes for each NPP site due to different $V_S - \kappa$ corrections, so the spectra are compared for each of the four NPP sites.

4.8.1 Median Horizontal

The master logic tree is shown in Figure 4.3. The main branches of the logic tree are:

- Model class (GMPE or PSSM)
- Candidate GMPEs
- Magnitude scaling of the stress-drop for PSSM
- $V_S - \kappa$ correction

These main branches are briefly discussed below. The model class branch is discussed following the candidate GMPE and PSSM stress-drop scaling.

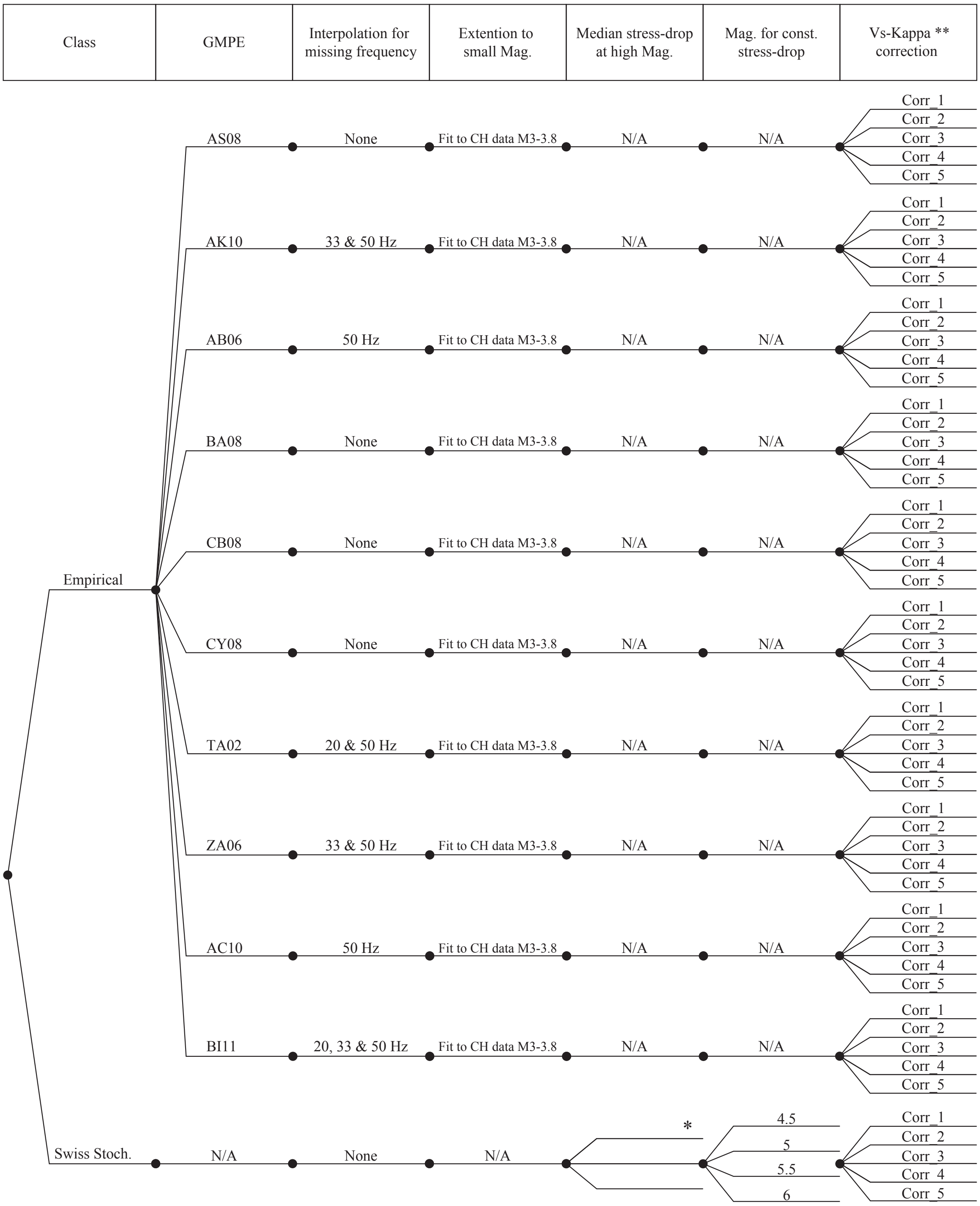
Candidate GMPEs

Ten candidate GMPEs passed the selection criteria (Section 4.6.3). The experts selected different subsets of the candidate GMPEs to include in their models using different methods for the evaluations. The subsets of the GMPEs that were selected by each expert are summarized in Table 4.6. All of the experts rejected the ENA ground motion models [Toro 2002; Atkinson and Boore 2006] based on testing of the models using intensity data. As a substitute, the SP2 team decided to use the stochastic model developed for Switzerland by Edwards et al. [2010], published as Edwards and Fäh [2013] (TP2-TB-1024, respectively TP2-RF-1453). In addition, none of the experts included the Bindi et al. [2011] model for a variety of reasons, one of which was the sparse dataset for $M > 6$ (only three earthquakes).

The technical basis for the approach used by each expert is briefly described below.

$V_S - \kappa$ Corrections

The interface between SP2 and SP3 is the site-specific reference rock, which is categorized as very hard rock. The interface reference rock condition is interpreted as rock outcrop. The site response (always modeled as the ratio of outcropping soil over outcropping rock) is then added on top of this reference rock interface to come up with the hazard at the surface. The GMPEs are first evaluated for their best estimate rock shear wave velocity (e.g. 620 m/s for



* Note: Median stress-drops are to be set by SP2 experts
(model includes SD parameter)

** Note: The frequency dependent correction factors
are to be set by SP2 experts

Figure 4.3: Logic tree for the median of the horizontal component.

Table 4.6: Candidate GMPEs and selection by expert

GMPE	Region	Bungum	Campbell	Cotton	Fäh
Abrahamson & Silva (2008)	Global		X	X(*)	X
Boore & Atkinson (2008)	Global		X		X
Campbell & Bozorgnia (2008)	Global	X	X		X
Chiou & Youngs (2008)	Global	X	X		X
Akkar & Bommer (2010)	Europe	X	X		X
Toro (2002)	ENA				
Atkinson & Boore (2006)	ENA				
Zhao et al. (2006)	Japan	X	X		X
Akkar & Cagan (2010)	Europe	X			
Bindi et al (2011)	Italy				

(*) Four scaled versions are used.

the NGA-West models) and then modified through the $V_S - \kappa$ correction to provide hard rock ground motion. Within SP2, the V_{S30} is understood as the average shear wave velocity in the 30 m below the defined rock surface (rock-soil interface), not the V_{S30} measured at the surface. To differentiate between the rock and soil V_{S30}, the project plan introduced for the rock the term $V_{S30,rock}$, but, for the sake of simplicity, only the term V_{S30} will be used in the following.

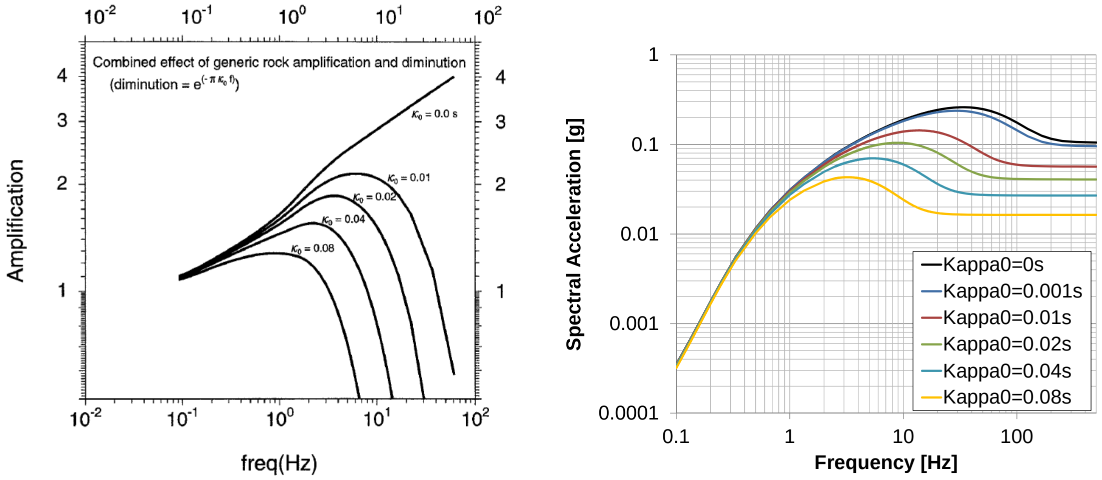
All of the experts applied V_S and κ corrections to the candidate GMPEs. While the V_S corrections are relatively straightforward, the κ corrections were more difficult with large uncertainty.

The scaling of the Fourier amplitude spectrum (FAS) with κ was shown by Boore and Joyner [1997] and is presented in Figure 4.4(a). The scaling of the response spectrum with κ is shown in Figure 4.4(b). The strong effect of κ on the high frequency response spectral values is clearly seen: at 20 Hz, there is a factor of 4 difference between the spectral acceleration for κ=0.04 s (typical for rock sites in California) and the spectral acceleration for κ=0.016 s (similar to the κ estimated by Edwards et al. [2010] for rock sites in Switzerland).

Given this strong sensitivity of the high frequency ground motions to κ (see Renault [2011b]; Biro and Renault [2012c, 2013b]), additional studies were conducted to evaluate how well the κ values are constrained and how well the κ scaling values are known.

These studies led to three key findings:

- The κ scaling for FAS is understood and well constrained, but the κ scaling for response spectral values is very sensitive to the shape of the high frequency shape of the GMPE-based response spectrum.
- The estimation of κ for a recording site is sensitive to the methodology used, leading to large differences in κ estimates [Ktenidou et al. 2012, 2014a].
- There is large variability in the estimated κ values for a given V_{S30}, indicating that V_{S30} alone does not provide a good constraint on the high frequency content of the rock ground motion [Laurendeau et al. 2013; Ktenidou et al. 2014b].



(a) Amplification effect given by $\exp(-\pi\kappa_0 f)$, (Fig. 8 from Boore and Joyner [1997])

(b) Effect on response spectra (here for a M=6, R=20 km, using site amplification for the Swiss generic rock conditions with V_{S30}=1000 m/s).

Figure 4.4: The combined effect of the generic rock amplification and the attenuation.

An initial evaluation showed that the traditional hybrid empirical method (HEM) [Campbell 2003] for κ scaling did not work well with the candidate GMPEs selected for the PRP. To address the short comings of the κ scaling of the response spectral values in the available methods, the PRP supported the development of new methods for scaling the spectra from GMPEs to account for differences in rock κ values. Three approaches were developed: an iterative approach, an empirical approach, and an inverse random vibration theory (IRVT) approach [Al Atik et al. 2013]. The development of these new approaches represents a significant improvement in the field of ground motions. Recently, the IRVT approach has been adopted as the main method for κ corrections for several other major seismic hazard studies around the world (e.g. NGA-East, SWUS GMC, BC Hydro for Dams).

The methodologies for estimating κ were also reviewed as part of the PRP [Ktenidou et al. 2014a]. κ is traditionally measured by the slope of the log(FAS) at high frequencies, but the estimated value can be strongly dependent on the frequency band used. In addition, the κ can also be estimated as part of the point-source model that fits the full frequency band. These two approaches can lead to very different estimates of κ. The SP2 experts considered multiple methods for κ estimation as part of their evaluations.

Despite the improvements made during the PRP (e.g. Ktenidou [2012]; Ktenidou and Van Houtte [2013]; Ktenidou et al. [2013]), the κ estimation and κ corrections remain one of the key uncertainties in the estimation of the high frequency seismic hazard for the Swiss NPP sites. More details on the approaches and issues for this topic are documented in Volume 3.

Small Magnitudes

One of the key issues identified from the PEGASOS report was the very low ground motions from Swiss small magnitude ($M3 - M4$) earthquakes as compared to the ground motions computed by extrapolating the GMPEs to small magnitudes. The difference was about a factor of 3 as shown in Figure 4.5. This led to the key question: do these low ground motions from small magnitude earthquakes indicate that the ground motions from large magnitude earthquakes will also be smaller than from GMPEs?

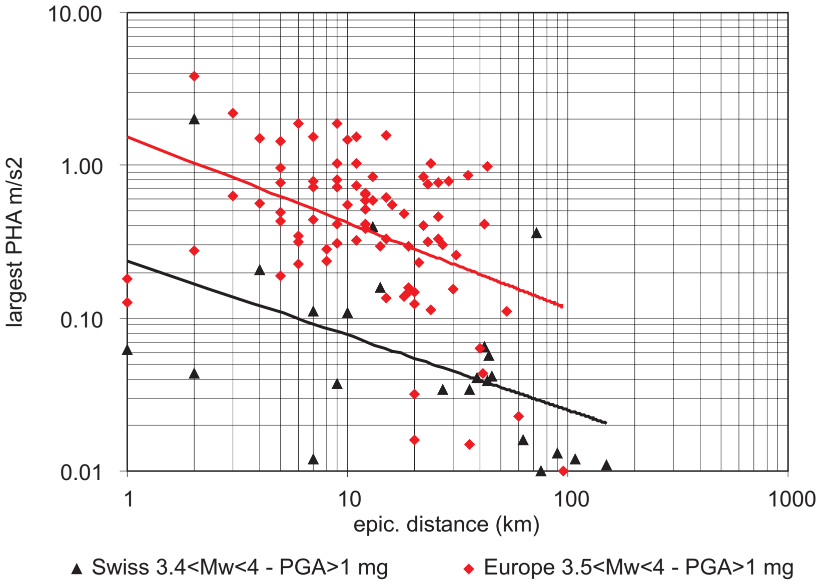


Figure 4.5: Comparison of PGA values between Switzerland and Europe in the magnitude range 3.4 to 4.0. No site selection applied. Straight lines represent the regression performed on the data (from Sabetta's elicitation summary, see Vol. 4 of the PEGASOS report).

In the course of the PRP, a new NGA database (hosted by PEER: `http://peer.berkeley.edu/peer_ground_motion_database`) was also built up and served as the basis for developing new GMPEs, the so called NGA-West2 models. The completion of the NGA-West2 Project was foreseen for early spring 2013, and a preliminary results workshop was held on 15. November 2012. This gave the opportunity to review preliminary versions of the GMPEs and compare them to the GMPEs selected for the PRP, even if the completion of the NGA-West2 Project was delayed and the final models were not ready until the end of the PEGASOS Refinement Project. This preliminary comparison was presented at workshop WS11/SP2 on 16. January 2012 (see TP4-RF-1451 and Biro and Renault [2013a], PMT-TN-1260). The conclusion was that the GMPEs selected for the PRP including all the adjustments (small magnitude adjustment, $V_S - \kappa$ correction) fall within the range of the existing and future NGA-West models. This suggests that the PRP results will not be significantly different if the NGA-west2 models are used in place of the 2008 NGA models.

Within the framework of an assessment of stress-drops and their implications for ground motion prediction equations, Baltay et al. [2013] also performed a comparison with the Swiss data. Baltay and Hanks [2013] (EXT-TN-1262) investigated the magnitude-dependence of Swiss strong motion data in comparison to NGA-West2 data. This comparison demonstrated that the Swiss data appear to be a reasonable extension of the NGA-West2 dataset towards smaller magnitudes (see Figure 4.6 and 4.7; figures for 1 s can be found in EXT-TN-1262). Furthermore, the proposed point source model with constant stress-drop over all magnitudes is not rejected by the data. Baltay and Hanks also note that the strong correlation between κ and stress-drop for small magnitude earthquakes makes it difficult to constrain the stress-drop for $M < 3$ earthquakes.

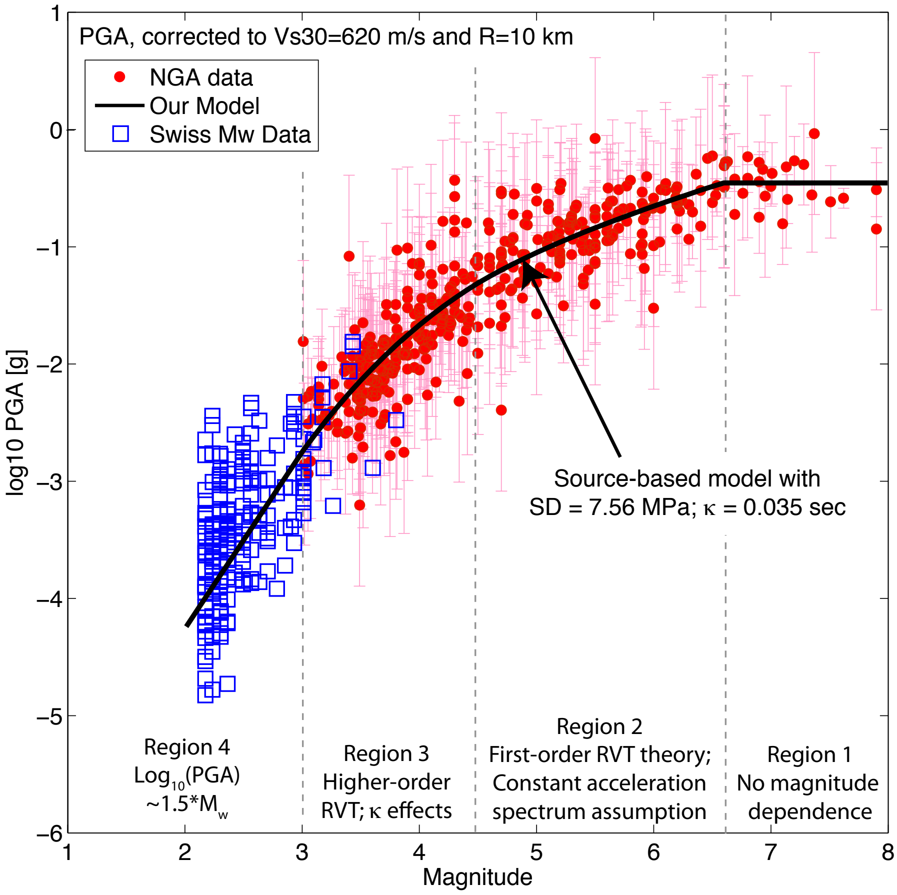


Figure 4.6: PGA of NGA-West2 data (red dots) and Swiss data (blue squares) for data within 20 km [Baltay et al. 2013]. NGA data are corrected to 10 km with $1/R$ geometrical spreading and to V_{S30}=620 m/s using Boore and Atkinson (2008); Swiss data with $1/R^{1.29}$ and amplification factors provided. Black line shows the source-based model developed for NGA-West2 with a stress-drop of 11.5 MPa and a κ of 0.035 s. The four regions of the model, based on different source behavior at close recording distances, are indicated with the dashed grey lines.

These recent efforts to expand the ground motion datasets from small magnitudes in the regions from which the GMPEs are derived help to address this issue. Figure 4.6 shows the magnitude scaling of ground motions from the NGA-West2 data with a large number of small magnitude earthquakes from California, corrected to a distance of 10 km and a reference V_{S30} of 620 km/s. The rapid steepening of the magnitude scaling from $M6$ down to $M3$ can be seen in these data. Also shown in this figure are the small magnitude data from Swiss earthquakes, treated in the same manner. The figure shows that the Swiss data are not significantly lower than the Californian ground motions, indicating that there is not a large discrepancy between the observed ground motions in Switzerland and the GMPEs from other active regions. This observation was used by the SP2 experts to justify the application of large magnitude scaling from other regions to Switzerland, once the site term differences are addressed through the $V_S - \kappa$ corrections.

At the time of the PRP selection of candidate GMPEs, the new GMPEs that included the small magnitude data were not available. Many of the candidate GMPEs were focused on the scaling from magnitude 5 to 8 and did not properly capture the changing magnitude scaling

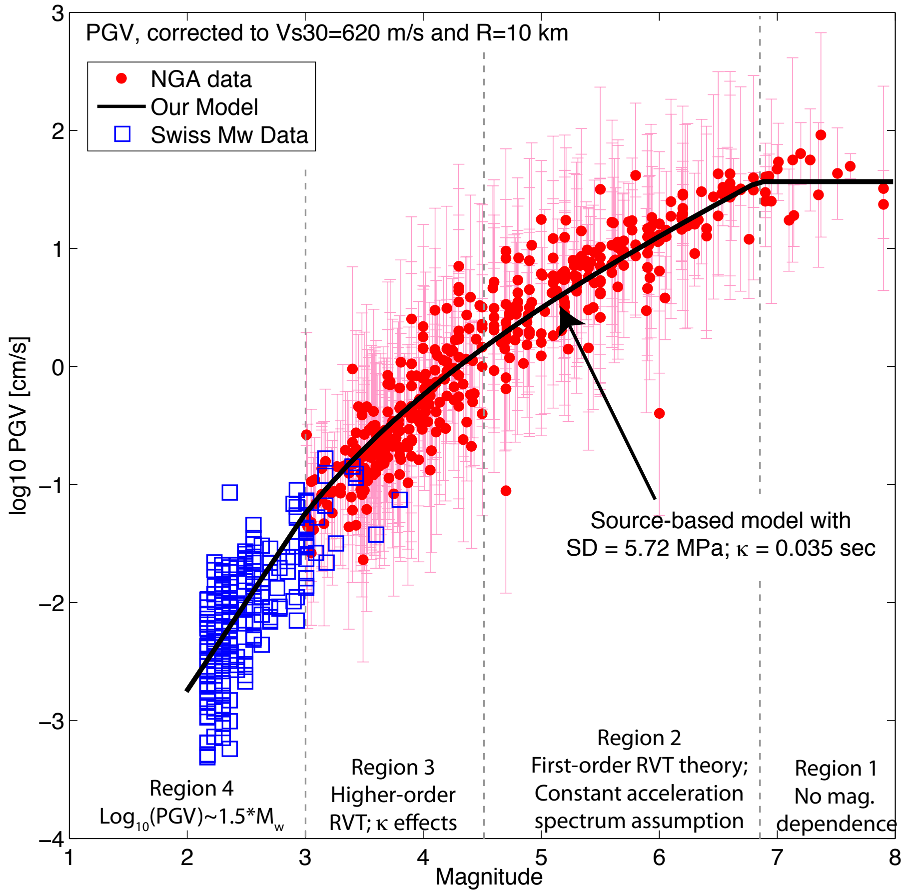


Figure 4.7: PGV of NGA-West2 data (red dots) and Swiss data (blue squares) for data within 20 km [Baltay et al. 2013].NGA data are corrected to 10 km with $1/R$ geometrical spreading and to V_{S30}=620 m/s using Boore and Atkinson (2008); Swiss data with $1/R^{1.29}$ and amplification factors provided. Black line shows the source-based model developed for NGA-West2 with a stress-drop of 4.3 MPa and a κ of 0.035 s. (Note: the difference in stress drop for the model between PGA and PGV is still an artifact of the model parameters and constants which is being investigated. Thus, only relative values of stress drop should be considered.) The four regions of the model, based on different source behavior at close recording distances, are indicated with the dashed grey lines.

below $M5.5$ shown in Figure 4.6. Therefore, the magnitude scaling of the candidate GMPEs below $M5.5$ was modified [Bommer 2010; Bommer and Stafford 2010; Stafford 2011, 2012] so that they would be consistent with the Swiss small magnitude ground motions (see also Volume 4, Chapter 4 of this report for further details). This modification led to scaling that is similar to that magnitude scaling seen in Figure 4.6. For example, the magnitude dependence of the PGA from one of the small magnitude adjusted NGA GMPEs is compared to the magnitude scaling from the corresponding NGA-West2 model in Figure 4.8. Both the adjusted model and the NGA-West2 model show a string break in the magnitude scaling near $M5$.

Figure 4.9 shows the procedure applied within the PRP for the evaluation of the small magnitude adjustments and the $V_S - \kappa$ corrections. The small magnitude adjustments are only evaluated for the generic Swiss rock conditions. For this case, the generic $V_S - \kappa$ corrections are applied to the models and then the remaining misfit at small magnitudes is evaluated to

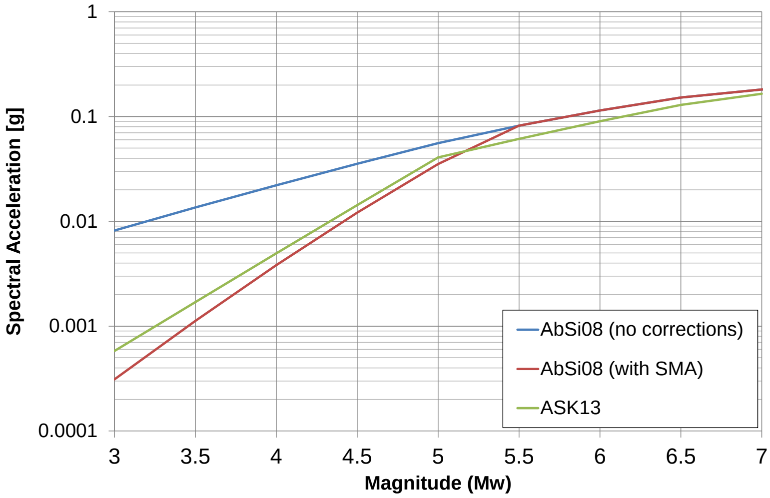


Figure 4.8: Comparison of magnitude scaling of NGA-West2 ("ASK13"), original NGA-West1 ("AbSi08 (no corrections)") and small magnitude adjusted NGA-West1 model ("AbSi08 (with SMA)"). Here as an example the Abrahamson & Silva [2008] model for R_{JB}=20 km and V_{S30}=1000 m/s at PGA (an average hypocentral depth of 12 km and strike-slip is assumed).

define the necessary adjustments.

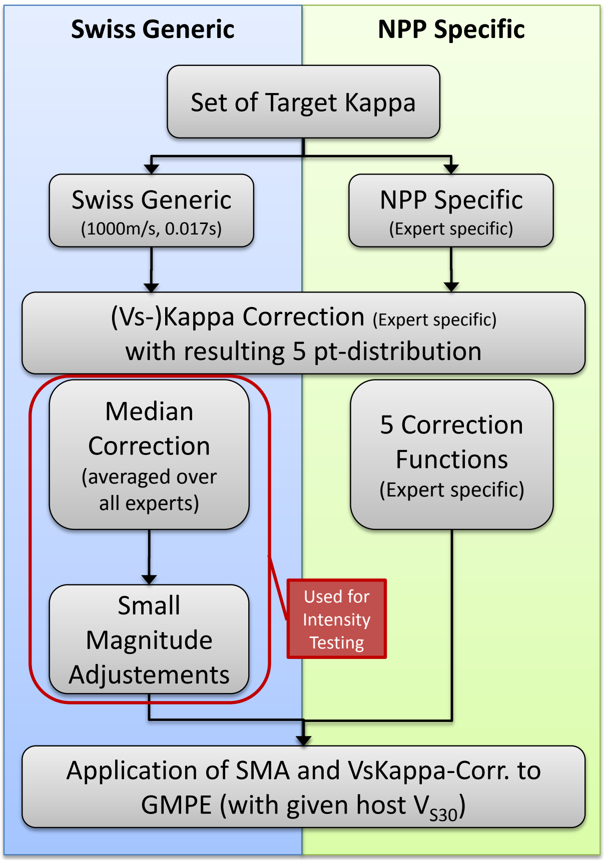
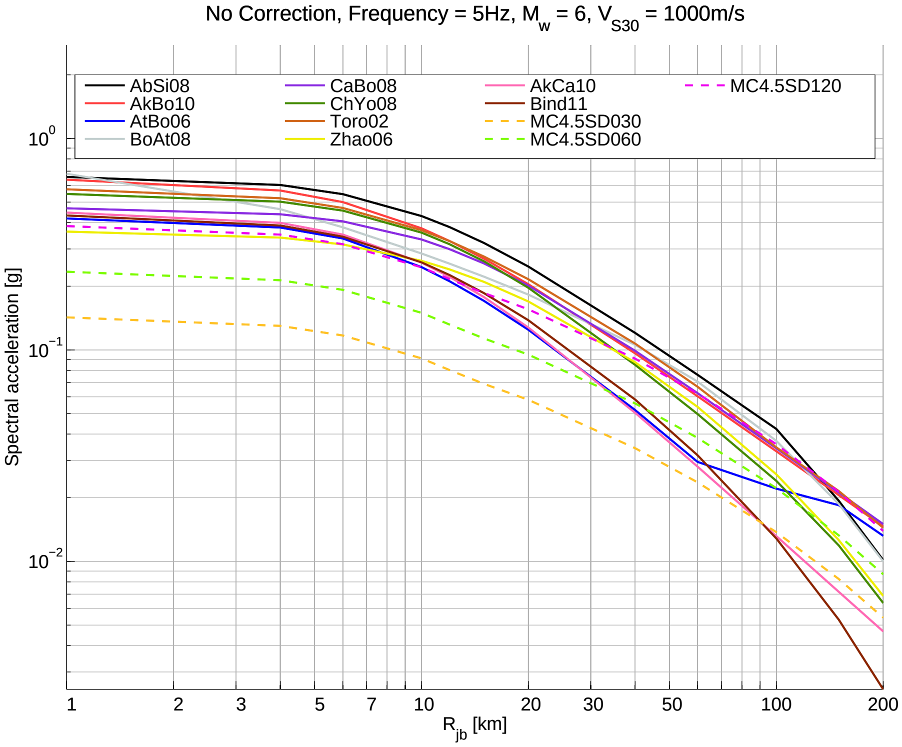


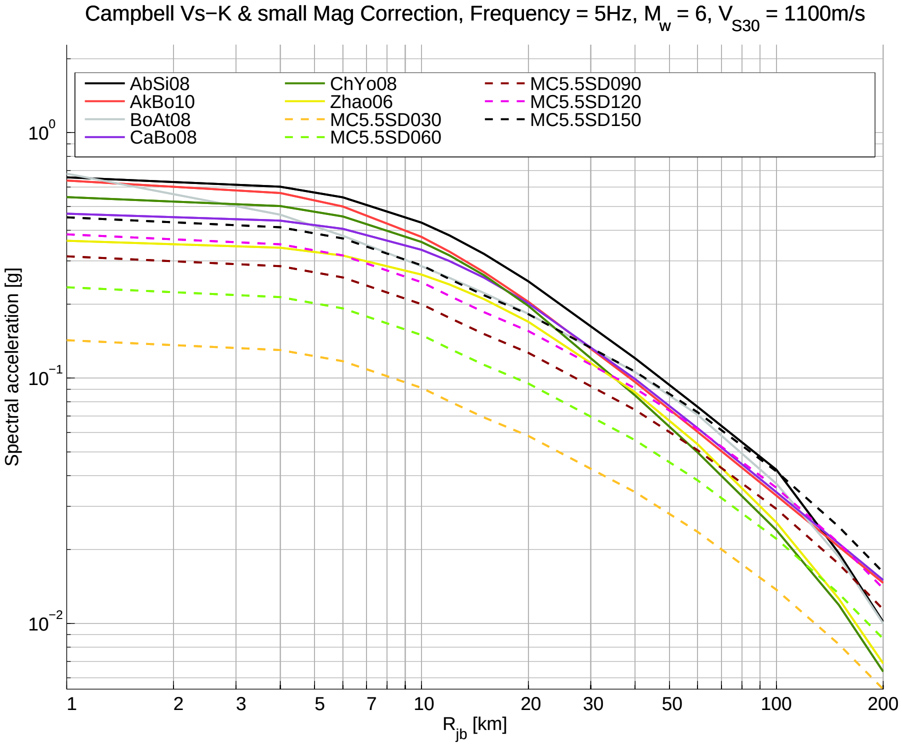
Figure 4.9: Flowchart for the small magnitude adjustment and $V_S - \kappa$ correction evaluation within PRP.

Model Class

The two main approaches to the median horizontal ground motion are the GMPEs and the paramterized Swiss stochastic model (PSSM). In general, the PSSM leads to much lower ground motions than the GMPEs even after the GMPEs are adjusted to the V_S and κ for Switzerland. For example, the distance scaling for 5 Hz spectral acceleration for the unadjusted and adjusted GMPEs and the PSSM are compared in Figure 4.10 (Figure A.9 in the appendix shows a similar comparison for 100 Hz). This difference between the two classes remains one of the main contributions to the epistemic uncertainty in the experts' models.



(a) Without corrections



(b) With corrections

Figure 4.10: Comparison of distance scaling for all considered candidate GMPEs and PSSMs for magnitude 6 at 5 Hz. Note: At the end of the project, corrections were not available for all candidate GMPEs, as they were only developed for the NPP-specific conditions based on the individual expert estimates. Here as an example, for the plot with $V_S - \kappa$ corrections and small magnitude adjustments the corrections for Campbell at KKM were used (Ver. May 2013).

Comparison with Finite-Fault Simulations

The magnitude and distance scaling from the Finite-Fault Simulations (FFS) [Dalguer and Mai 2010] (TP2-TB-1028 and TP2-TB-1057) were compared to the scaling from the GMPEs in the November 2009 workshop. For the PRP simulations, two different values for site κ were considered as input parameters for the broad band ground motion simulations: 0.01 s and 0.03 s, based on Edwards et al. [2009], who performed a detailed study at the beginning of the project on the site κ values at or close to the NPP-sites of interest.

An example of this comparison is shown in Figure 4.11 for a magnitude ∼6.5 strike-slip earthquake and κ=0.010 s. For this example, the median curves from the FFS are within the range of the SP2 expert models for frequencies greater than 1 Hz, but are much lower at 1 Hz. The distance scaling from the FFS tends to be stronger from 5-50 km but similar for distances less than 5 km. For another case of a M6.75 earthquake (not shown), the 1 Hz curve is within the range of the SP2 expert models, so the 1 Hz difference is not systematic. The SP2 experts did not directly use the FFS results as it appears that additional calibration of the method is needed.

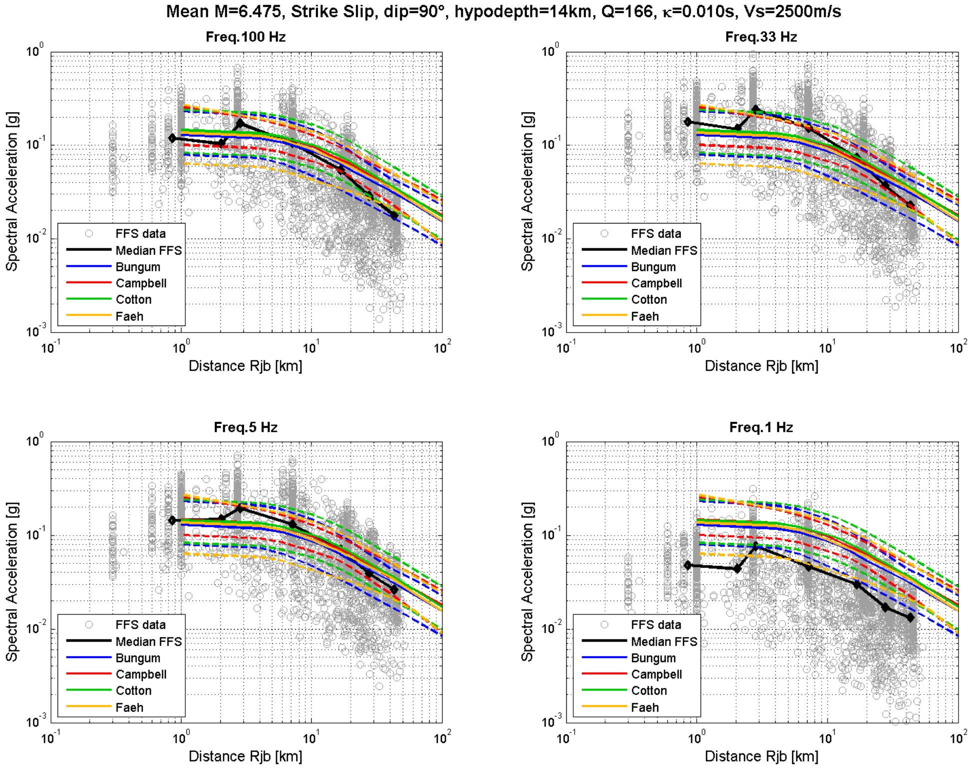


Figure 4.11: Comparison of FFS results with the range of SP2 expert models for 100 Hz, 33 Hz, 5 Hz and 1 Hz, for events with M ∼6.5.

Testing and Centering of Models

A key evaluation tool for checking the centering of the weighted logic trees is the intensity testing and the mixture model. The available ground motion data from Switzerland are for $M < 5$ earthquakes, mostly in the range of $M2 - M3$. The historical intensity data provide a rough measure of the ground motion from large historical earthquakes. This provides a method to test the logic tree to check if the model is centered on the observed large magnitude data. Although there are large uncertainties when converting intensity data to spectral accelerations, these data are important because they allow testing of the large magnitude scaling.

Intensity testing

The testing is based on comparisons of Swiss intensities [Fäh et al. 2009] with the predictions of the GMPEs (including the Swiss stochastic model). Conversion between spectral accelerations and intensities are done using the relations of Faenza and Michelini [2010b, 2011]. For testing, it is assumed that the selected models form a so-called "mixture model" $p(y|x)$:

$$p(y|x) = \sum_{i=1}^{N} w_i p_i(y|x), \tag{4.1}$$

where N is the number of tested models and the w_i are the individual weights with $\sum_i w_i = 1$, which are estimated using Bayesian inference. In this notation, y is the target variable (i.e. intensity), and x are the predictors such as magnitude, distance, spectral acceleration and so on. The mixture model is a weighted average of the GMPEs and PSSMs that best fit the observed intensity data. In total, more than 1000 sets of weights were calculated, for different magnitude/distance ranges, period combinations and priors. To compare different models and distributions, the so-called LLH value (from log-likelihood value) is often calculated (see Scherbaum et al. [2009] for details). It is defined as

$$LLH := -\frac{1}{N} \sum_{i=1}^{N} \log_2 g(x_i), \tag{4.2}$$

where N is the number of data and g is the probability density function defined by the GMPE. The LLH value is a measure of how much information is lost if "reality" (i.e. the data generating distribution) is replaced by the GMPE. It can be used as a ranking criterion for GMPEs, with a larger LLH value implying a better model. The testing was done in two different ways [Kühn 2011a, c] (EXT-TB-1086, TP2-TB-1078). First, residual plots were evaluated for each of the tested models. Then, mixture weights were calculated, with different values for the prior distribution, different period combinations and different data ranges (see Figure 4.12). The testing was done for four period combinations: using all periods but PGA (i.e. T=0.3, 1, 2 s), and using each PGA, 0.3 s, 1 s and 2 s individually. Four data ranges were considered, which are shown in Table 4.7.

Table 4.7: Data ranges and scenarios used for the testing

Scenario	SC1	SC2	SC3	SC4
Magnitude range	3-7.5	4-5.5	5-7.5	5.5-7.5
Distance range [km]	0-200	10-100	10-100	100-200

Mixture model comparisons

The goal of the mixture model comparison was to check to what degree the observed macroseismic intensity data are consistent or inconsistent with the set of candidate ground motion

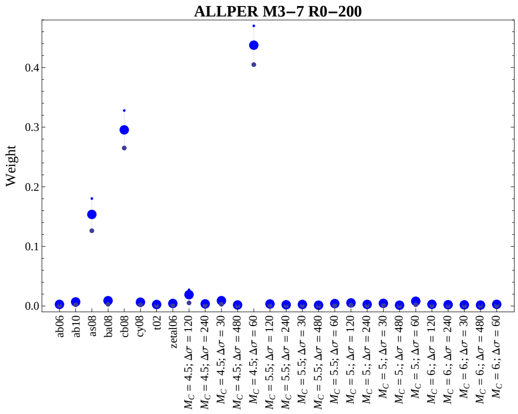


Figure 4.12: Example plot for means and interquartile range for the posterior distribution of the weights for the GMPEs and different PSSMs given a subset of the converted intensities. Here the weights were calculated using all periods, for the full M and R range.

models of each expert. The comparisons are only available for the periods 0.01 s, 0.3 s, 1 s and 2 s, as these are the periods for which the Faenza and Michelini [2010a, 2011] relationship, relating spectral acceleration to intensity, is defined. The mixture model and the intensity testing is based on the generic Swiss rock conditions (V_S=1000 m/s, κ=0.017 s) and there is, therefore, no NPP-specific dependence in the presented results and NPP-specific small magnitude adjustments of the GMPEs are not needed.

In this approach, a new GMPE is generated that is a linear combination of the candidate GMPEs that are centered on the observed intensity data. The weighted ground motion models from the experts can then be compared to the mixture model to help evaluate if the model is properly centered.

In order to evaluate the robustness of the mixture model, it was tested using four different sets of magnitude and distance ranges shown below [Kühn and Renault 2012] (EXT-SUP-1078):

- M_W=5.5-6.6; R=100-200 km
- M_W=5.5-6.6; R=10-100 km
- M_W=4.0-5.5; R=10-100 km
- M_W=4.0-6.6; R=10-200 km

The sets of magnitude and distance ranges listed above were selected for use in determining the average mixture model and are slightly different to the magnitude distance ranges used to evaluate the weights for the candidate models shown in Table 4.7.

The intensity to spectral acceleration conversions were defined by the SP2 experts in August 2010. The different strategies are repeated here:

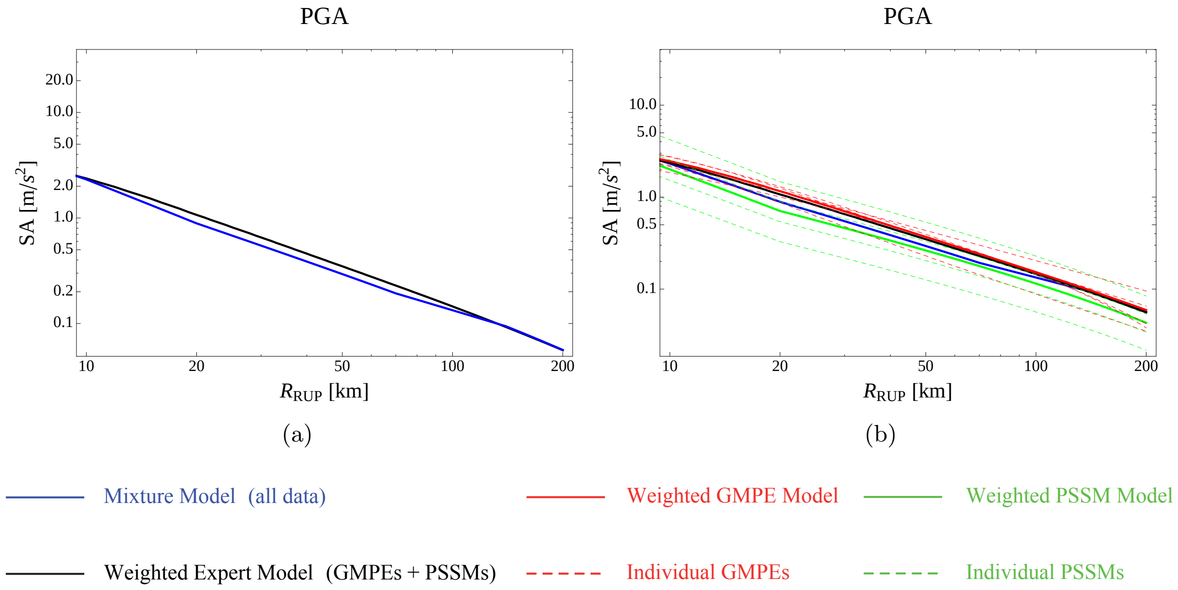
- Assuming Italian intensity is equivalent to Swiss intensity (raw intensity data)
- Assuming Italian intensity needs to be adjusted to Swiss intensity on rock using an average value of 0.38 intensity units (converted intensities are 0.38 units lower)

- Applying site condition corrections from the site geology to rock site conditions to the raw intensity data (providing a ”rock intensity”).

For the final mixture model approach, the converted intensities adjusted by -0.38 intensity units have been used.

Figure 4.13 shows an example of the expert-specific weighted mean model compared to the mixture model versus distance for H. Bungum. The expert-specific weighted mean model is based on the evaluation of the GMPEs and PSSMs used by the expert with their corresponding V_S-κ corrections and weights. The weighted average of the GMPE and PSSM (shown by the black line) is similar to the mixture model (shown by the blue line), indicating that the expert model is centered with respect to the intensity data. The expert model was decomposed into the GMPE and PSSM parts in order to see if the two groups are systematically low or high compared to the mixture model. For this example, the average PSSMs are lower than the mixture model and average GMPEs are higher than the mixture model

A sensitivity to the median, lower and upper bound V_S-κ corrections (out of the five branches of the 5-point distribution), as specified by the individual expert approach can be found in Kühn and Renault [2012]. Furthermore, these plots were later updated by also splitting the GMPEs and PSSMs into their individual models in order to check if certain stress-drop and target κ combinations could be identified as extreme cases not supported by the data. An example plot of Biro and Renault [2012a] (PMT-SUP-1082) comparing different alternative mixture models to the individual GMPEs and PSSMs as a function of the expert-specific target κ is shown in Figure 4.14.



(a) (b)

Figure 4.13: Example plots for mixture model comparisons of H. Bungum. (a) Comparison of the mixture model (blue) with the expert's average (black) at PGA as spectral acceleration versus distance. (b) Comparison of the mixture model (blue) with the expert's average (black) and the different GMPEs (red) and PSSMs (green) at PGA as spectral acceleration versus distance.

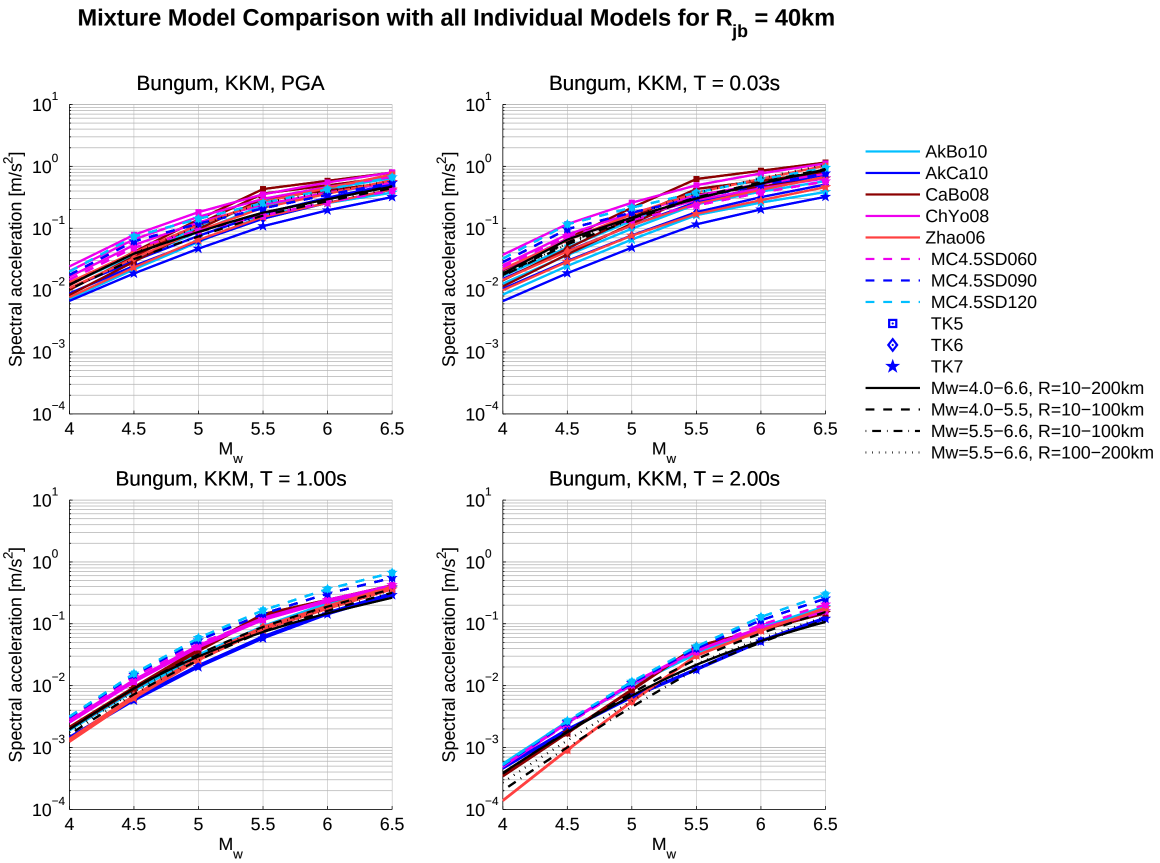


Figure 4.14: Example plot for H. Bungum comparing different alternative mixture models to the individual GMPEs and PSSMs in dependence of the expert-specific target κ.

Another approach is to compute the residuals of the intensity data by GMPE or PSSM directly. This allows for a check of the centering of the models in a similar, but different, way. An example of the residuals from the intensity data from the Campbell & Bozorgnia [2008] model adjusted GMPE is shown in Figure 4.15.

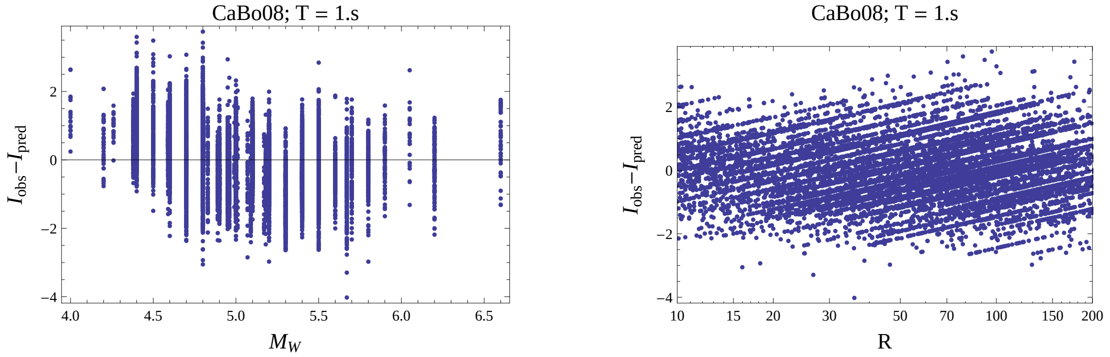


Figure 4.15: Example plot for residuals of the intensity data and the Campbell & Bozorgnia [2008] model at 1 Hz.

The SP2 experts used the comparisons between the GMPE and the intensity data in very different ways. Some experts used the intensity data to constrain the mixture model and then evaluated the candidate GMPEs in terms of their consistency with the mixture model. Other

SP2 experts evaluated the residuals from the intensity in the traditional method of residual analysis.

All of the SP2 experts found that the EUS models were inconsistent with the intensity data (either checking the mixture model or checking the residuals), so these models were not part of the range of technically defensible interpretations. This led all of the SP2 experts to set the logic weights for the EUS models to zero.

The SP2 experts also used the intensity data testing to constrain the stress-drops for large magnitude for the PSSM. Overall, this led to an increase in the stress-drop for the PSSM from near 60 bars from the initial proponent model [Edwards et al. 2010] to an average close to 90 bars.

Testing and Centering of the $V_S - \kappa$ Adjustments

There are no direct target κ estimates available at the NPP sites. Thus, target κ values had to be inferred by the SP2 experts based on global κ estimates and values evaluated for the Swiss network stations. This led to a large range of κ estimates for the NPP sites and a large uncertainty range for the hazard at high frequencies. The $V_S - \kappa$ corrections were based on the application of alternative methods for computing the correction. Initially, there was no means for the SP2 experts to check if their $V_S - \kappa$ correction models were centered as intended. The intensity data discussed above were useful for testing the intermediate and low frequencies, but the intensity data did not provide a constraint on the high frequency ground motion.

There are ground motion data from small magnitude earthquakes in Switzerland recorded for hard-rock site conditions that could be used to test the methodology used to compute the $V_S - \kappa$ scale factors; however, the methods could not be directly tested using the candidate GMPEs because these had been adjusted to fit the small magnitude ground motions in Switzerland for an assumed $V_S - \kappa$ correction. Testing these adjusted GMPEs against the ground motions from small earthquakes at Swiss hard-rock sites would be a circular check and would provide no new information.

To provide a check of the $V_S - \kappa$ correction method, a set of global GMPEs applicable to small magnitudes without being adjusted to the Swiss data is needed. The recently developed NGA-West2 GMPEs are applicable down to $M3$ based on small magnitude events in California and meet this requirement. The NGA-West2 models were evaluated consistent with the approach used to modify the global GMPE to Swiss conditions used by the IRVT method.

In May 2013, the TFI used one of the newly available NGA-West2 GMPEs to test the centering of the $V_S - \kappa$ adjustment procedure by evaluating the residuals between the observed and predicted ground motions at the hard rock stations of the SED network (Fig. 4.16). The results and findings are documented in Renault and Biro [2013]; Abrahamson [2013].

A set of 11 hard-rock sites in Switzerland was selected for which the velocity profile was measured and recordings from earthquakes at distances less than 70 km (to limit the effects of Q) were available. The κ was estimated at these stations using a range of methods. These estimated κ values served as target κ values, consistent with the target κ values evaluated for the NPP sites. An example of applying the $V_S - \kappa$ corrections to the NGA-West2 GMPEs is shown in Figure 4.17. This figure shows that the adjusted high frequency (20–40 Hz) ground motions for the GMPEs are similar to the observed values (residuals near zero) using a set of high target κ values withan overprediction of the observed ground motions (negative residuals) by a factor of 2.5 to 3 when using a set of low target κ values. This check of the residuals indicated that the methodology for adjusting the global ground motion models to Swiss conditions could be overestimating the high frequency adjustment. In the moderate frequency range (2–10 Hz), the adjusted ground motions were factors of 1.5 to 2 above the observed values (negative residuals), indicating that the methodology is overestimating the moderate frequency adjustment. There are several possible causes for these differences, but κ is the main factor affecting the high frequency ground motion. If the high frequency difference is attributed to the $V_S - \kappa$ correction, then the $V_S - \kappa$ adjustment can be modified so that it captures the center of the range, but it does not explain the overestimation at moderate frequencies.

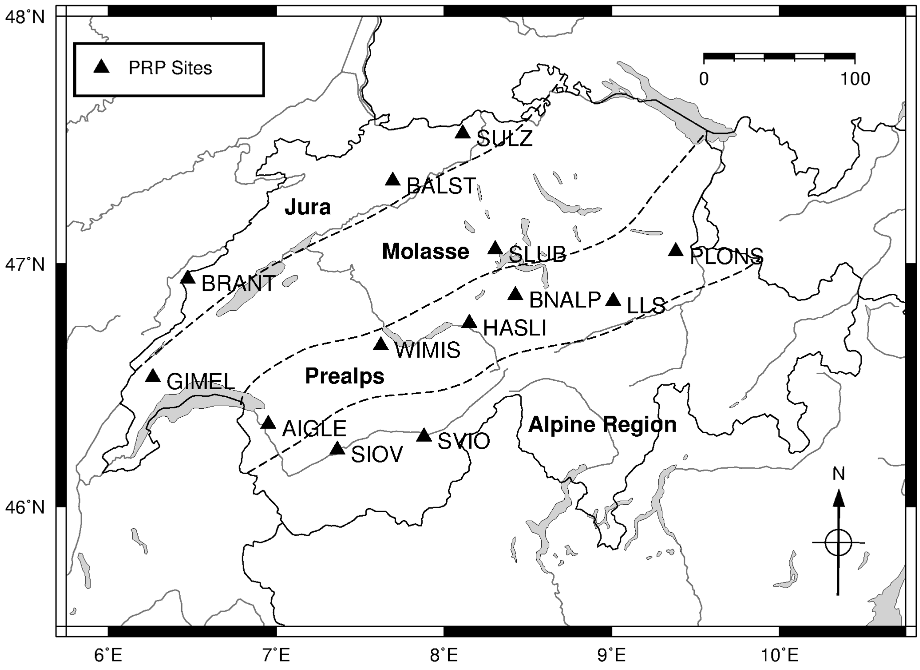


Figure 4.16: Map of Switzerland showing the locations of the SED hard rock stations used for the residual testing.

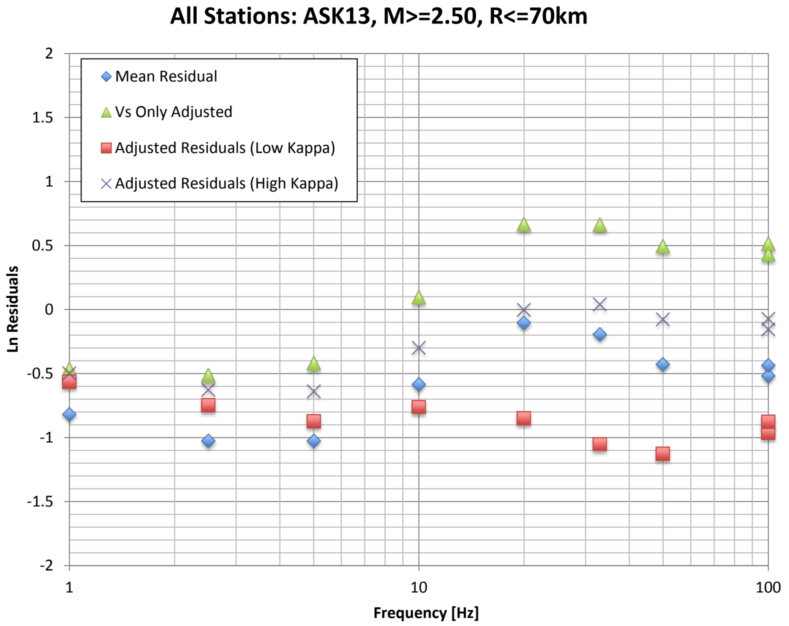
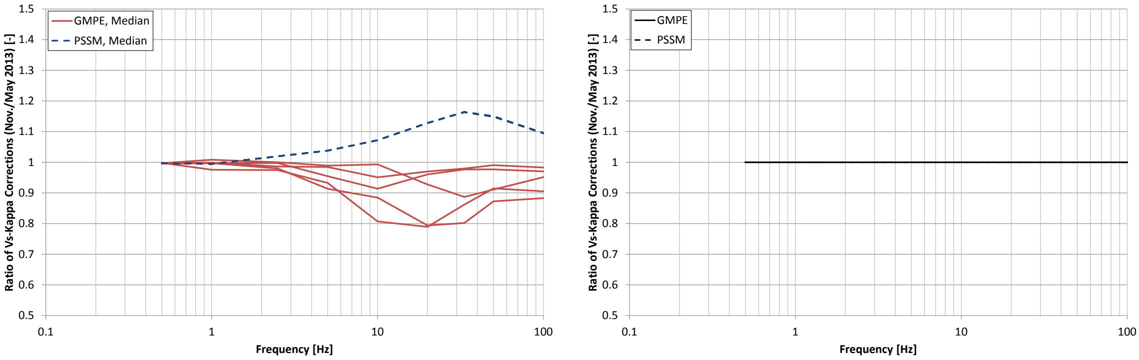
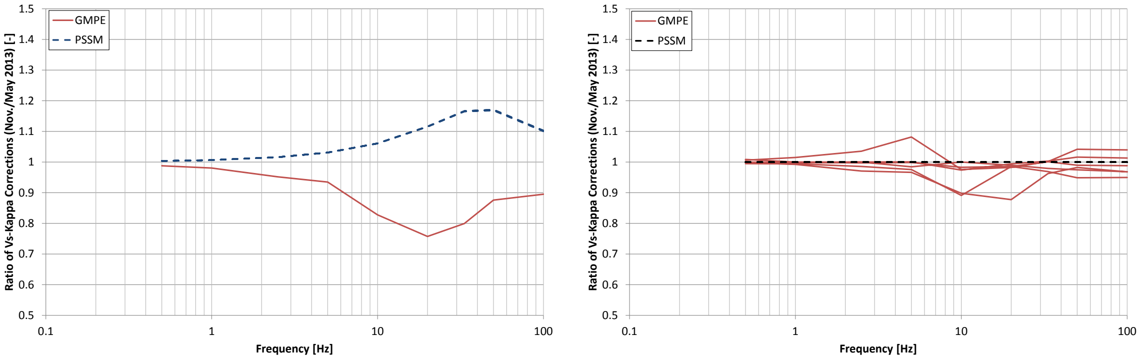


Figure 4.17: Example plot of residuals (Obs.-Pred.) for the Abrahamson et al. [2013] model against frequency [Abrahamson 2013].

The high frequency residuals from the Swiss hard-rock sites can be centered by defining a new target κ that is scaled from the directly estimated κ. Thus, a fictitious κ is defined that is used in the $V_S - \kappa$ methodology. This does not mean that the estimated κs were wrong, but rather that the entire method for adjusting the global GMPEs to Swiss hard-rock conditions needs a different κ to lead to unbiased residuals at high frequencies. An additional workshop (19.-20. September 2013) was dedicated solely to evaluating and discussing the centering of the $V_S - \kappa$ and was followed by a web-meeting on 11. November 2013. The SP2 experts reached different conclusions regarding the approach to centering the $V_S - \kappa$ correction. Two experts adopted higher target κ values for their final model based on the additional feedback, while the other two experts kept their $V_S - \kappa$ correction values as defined in April/May 2013 (see Fig. 4.18).



(a) Bungum (b) Campbell



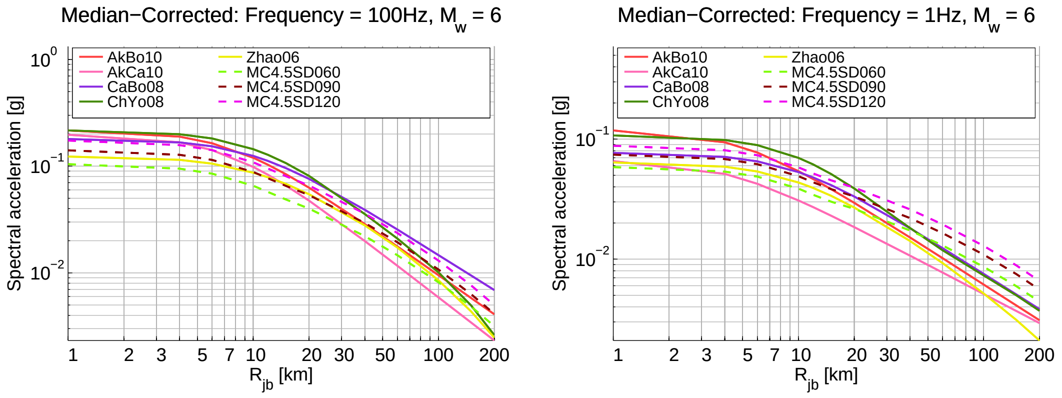
(c) Cotton (d) Fäh

Figure 4.18: Comparison of changes in the $V_S - \kappa$ corrections from May to November 2013.

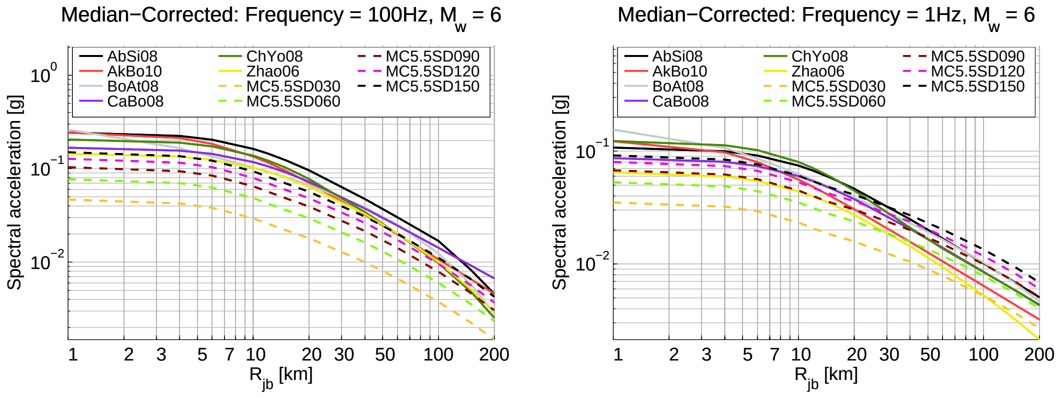
Comparison of Median Horizontal Models

The center and range of the distance dependence of the median horizontal ground motion for f=100 Hz and 1 Hz spectral acceleration for magnitude 6 earthquakes are compared in Figure 4.19 for the Beznau site. The candidate models lead to a range of factors of 3 to 5 depending on the expert.

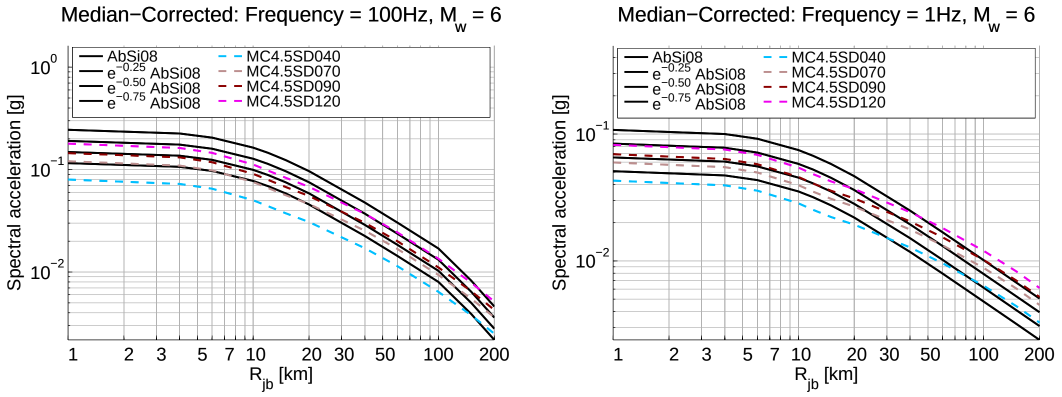
The center and range of the magnitude scaling of the median horizontal ground motion for f=100 Hz and 1 Hz spectral acceleration for a distance of 10 km are compared in Figure 4.20 for the Beznau site.



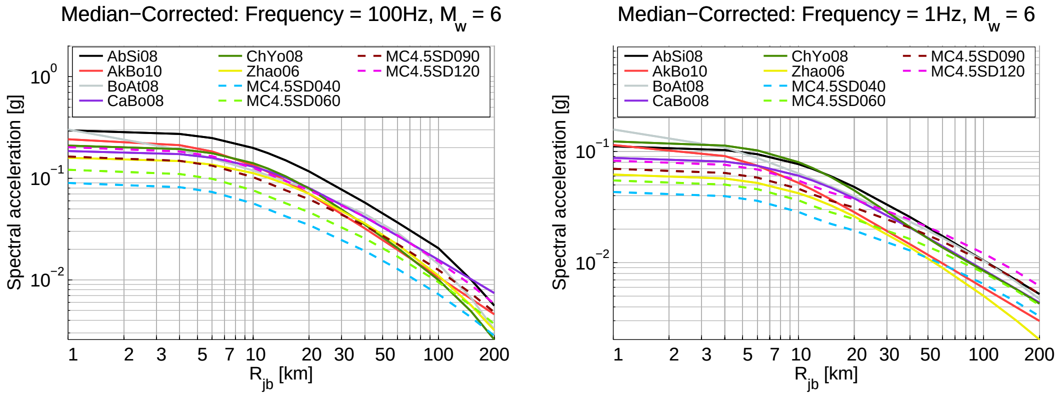
(a) Bungum



(b) Campbell

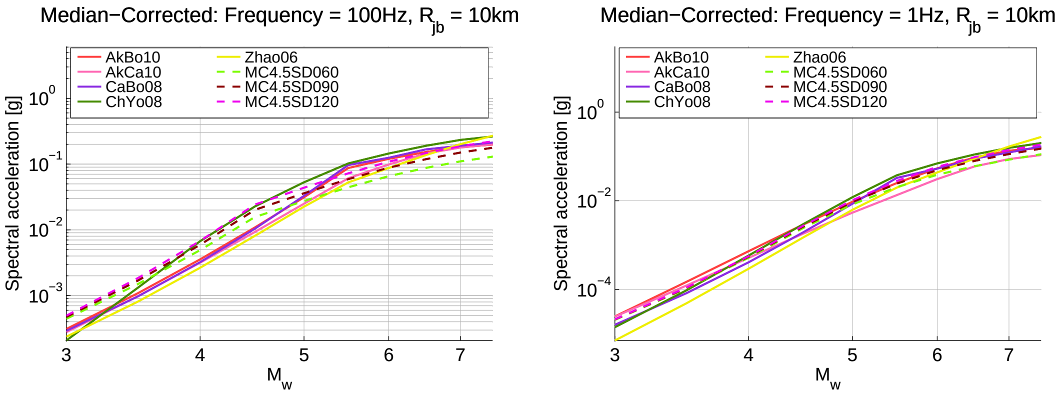


(c) Cotton

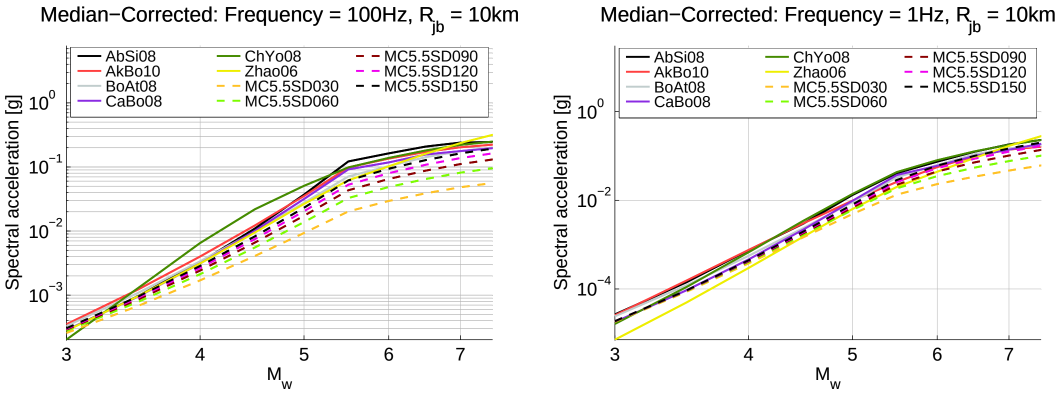


(d) Fäh

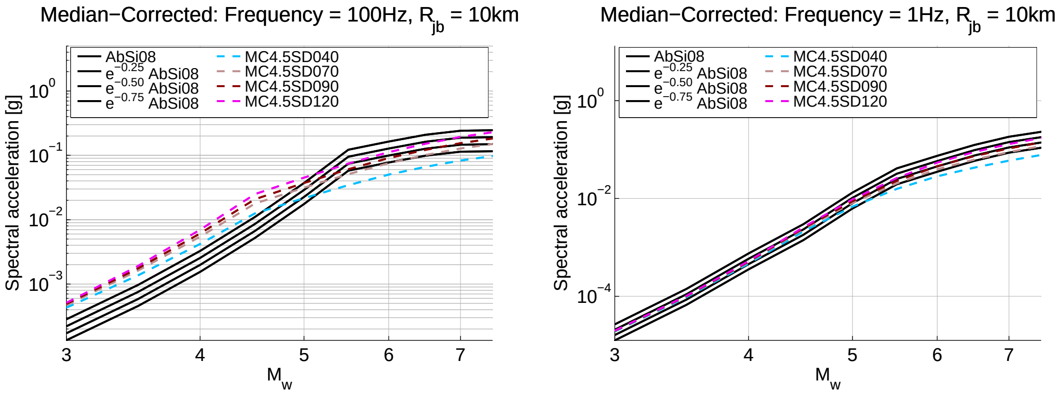
Figure 4.19: Comparison of the expert-specific median horizontal ground motions for 100 Hz (left) and 1 Hz (right) for M=6 at Beznau, based on $V_S - \kappa$ corrections of May 2013.



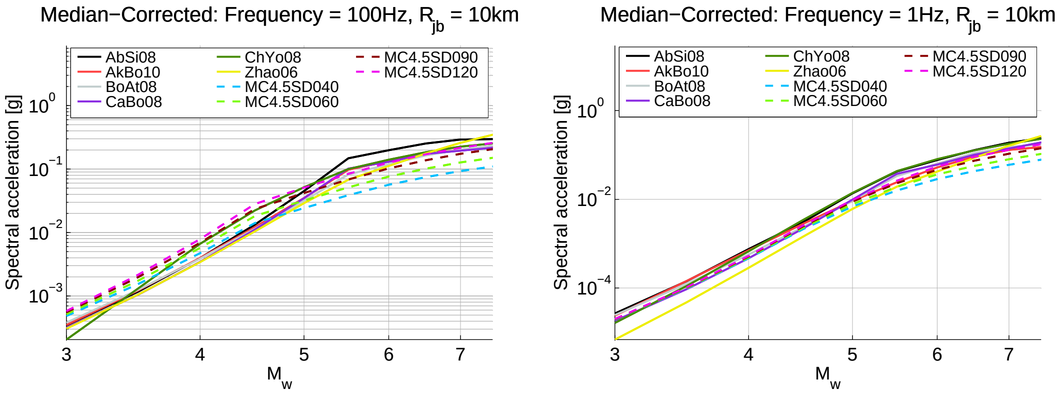
(a) Bungum



(b) Campbell



(c) Cotton

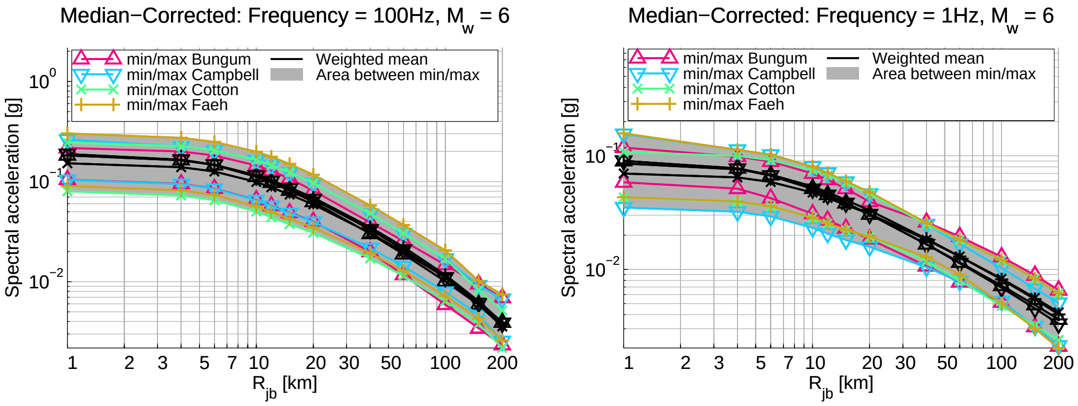


(d) Fäh

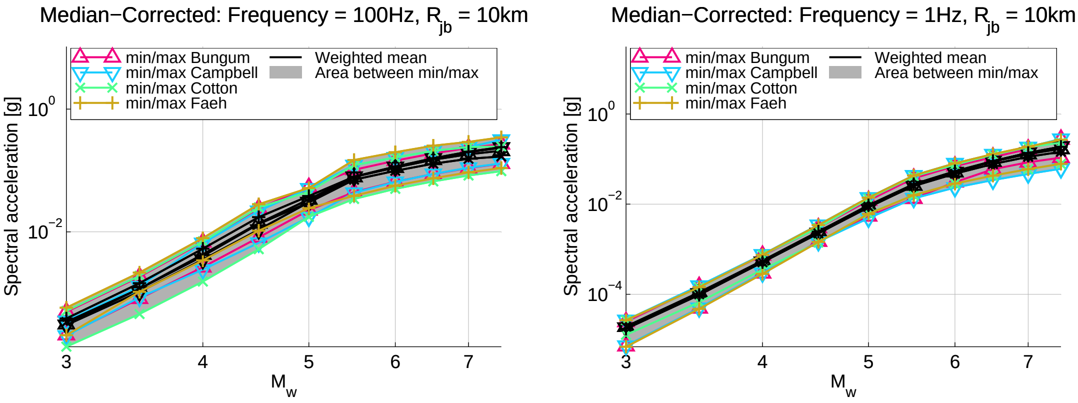
Figure 4.20: Comparison of the expert-specific median horizontal ground motions for 100 Hz (left) and 1 Hz (right) for R=10 km at Beznau, based on $V_S - \kappa$ corrections of May 2013.

Figure 4.21 compares the weighted mean expert models and their range for the Beznau site as a function of distance (for M=6) and magnitude (for R=10 km). Comparisons for the other sites are shown in Figures A.14 to A.16. The magnitude and distance scaling in Figures 4.19 and 4.20 show that the distance scaling for the PSSM is generally consistent with the distance scaling for the GMPEs. The magnitude scaling for the PSSM depends on the selected high-magnitude stress-drop. The GMPEs tend to have a stronger magnitude scaling from $M5$ to $M6$ than the PSSM. Overall, the PSSMs give lower ground motions than the GMPEs. For F. Cotton, the PSSM models are higher in some cases than the GMPEs due to the lower κ values that F. Cotton assigns to the PSSMs and the approach that he used to set the range of the GMPEs with scaled backbone models that are lower than the reference GMPEs.

The range of medians, shown in Figure 4.21, spans about a factor 3 and is, therefore, a significant contributor to the hazard uncertainty. The range of the mean values between the SP2 experts is much smaller, about a factor of 1.2. Therefore, the epistemic uncertainty in the hazard is mainly caused by the uncertainty within each expert's model and is not due to differences between the experts' evaluations.



(a) Comparison of Sa vs. R for M_W=6

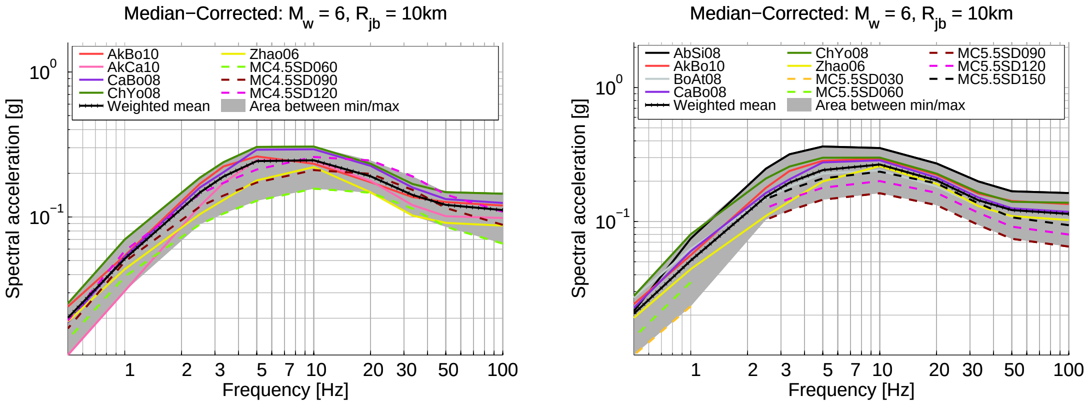


(b) Comparison of Sa vs. M_W at R=10 km.

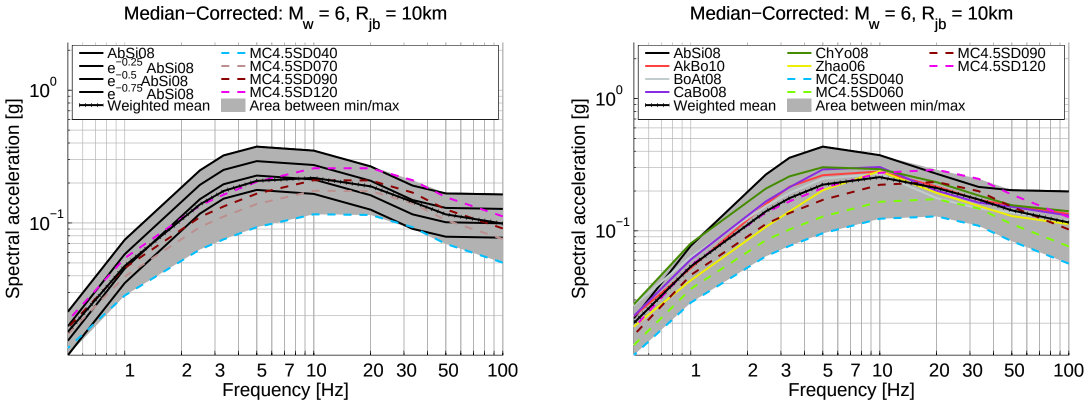
Figure 4.21: Comparison of the expert weighted mean and range of horizontal ground motions for 100 Hz (left) and 1 Hz (right) at Beznau, based on $V_S - \kappa$ corrections of May 2013.

The center and range of the response spectra for a magnitude 6 earthquake at a distance of 10 km are compared for each of the four NPP sites in Figure 4.22. Additional comparisons for all four NPP sites are shown in the figures A.10 to A.13. These additional figures also compare the spectral shape from the Boore & Atkinson [2008] model for a site with an average velocity of 1000 m/s for reference. The effect of the lower κ for the Swiss NPP sites can be seen by the shift in the peak of the spectra to higher frequencies compared to the global Boore & Atkinson [2008] model.

The range of the experts' models is larger for higher frequencies due to the large uncertainty in the $V_S - \kappa$ corrections.



(a) Bungum (b) Campbell



(c) Cotton (d) Fäh

Figure 4.22: Comparison of median horizontal ground motions for M=6 and R=10 km at Beznau and all four SP2 experts, based on the $V_S - \kappa$ corrections (November 2013). The expert specific weighted mean of all models is represented by a thick black chain dotted line.

The comparison of the spectra in Figure 4.22 for M6 at 10 km shows that the range in the median spectral values is larger for F. Cotton and D. Fäh in the 3 to 10 Hz frequency range due to the inclusion of a smaller minimum stress-drop (40 bars) for the PSSM. At 5 Hz, the uncertainty for F. Cotton and D. Fäh spans a range of up to a factor of 5, whereas the uncertainty range for H. Bungum and K. Campbell remains near a factor of 3 at all frequencies.

As seen previously for 100 Hz and 1 Hz, the range of the mean values between the SP2 experts is much smaller than the uncertainty range within a single expert's model.

Target κ comparison

The target κ values selected by each SP2 expert are compared for the group of GMPEs in Figure 4.23(a) and for the PSSMs in Figure 4.23(b). As can be seen, two experts decided to define a site-independent target κ, whereas the other two introduced a decay of target κ with increasing shear wave velocity. The ranges for the PSSM are narrower than for the GMPE, except for K. Campbell who has the same κ values for the GMPE and PSSM.

4.8.2 Median V/H Ratio

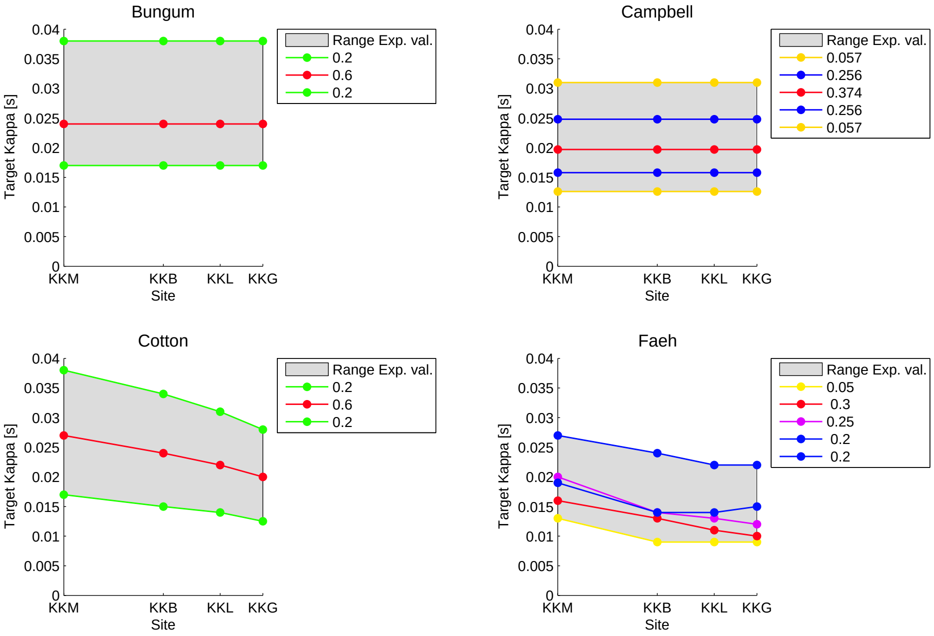
The V/H ratio candidate model included empirical GMPEs for the V/H ratio as well as statistical models for rock sites. The final set of candidate V/H models for rock is as follows:

- Bommer et al. [2011]
- Campbell and Bozorgnia [2003d]
- Gülerce and Abrahamson [2011]
- Edwards et al. [2011b] without correction above 7 Hz
- Edwards et al. [2011b] with correction above 7 Hz
- US-West Median [Biro and Renault 2012a] (PMT-TN-1257)
- US-East Median [Biro and Renault 2012a] (PMT-TN-1257)

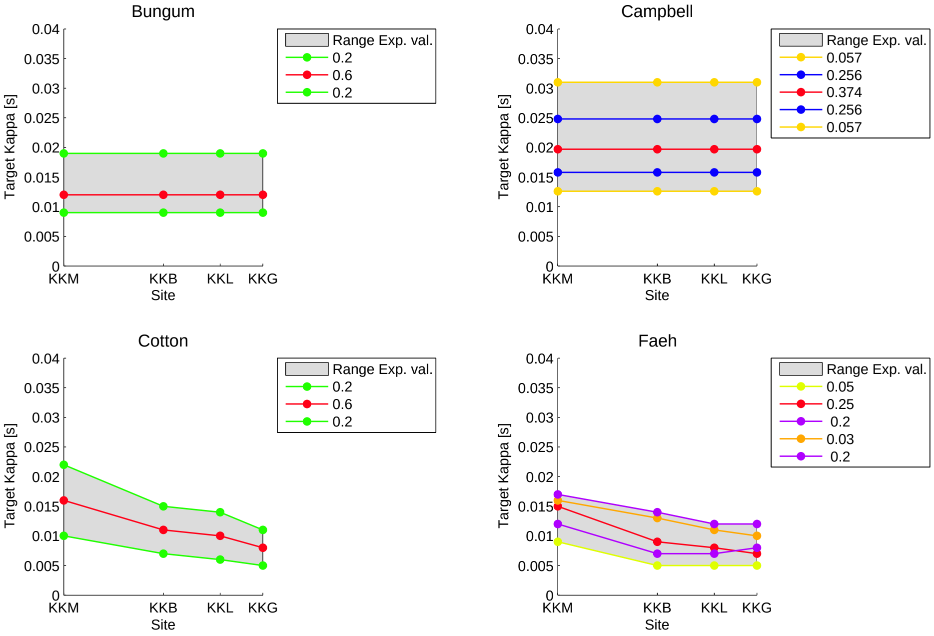
An example of the candidate V/H models are shown in Figure 4.24 for magnitude 6 earthquakes at a distance of 10 km. The V/H GMPEs for rock sites are primarily controlled by soft-rock site conditions. For the SP2 evaluation, a key issue is the applicability of the candidate V/H ratios to the NPP rock site conditions. Siddiqqi and Atkinson [2002] (and also Biro and Renault [2012b], PMT-TN-1218) give evidence that, for hard rock conditions, a more or less flat V/H ratio can be expected over the whole frequency band. This was further supported by the work of Edwards et al. [2011b], Edwards and Fäh [2011] and Edwards et al. [2012].

In particular, the effect of κ on the V/H ratio is not captured by the V/H GMPEs. To address this limitation, the range of candidate models was expanded to include simple empirical V/H ratios developed for rock sites in the WUS and for rock sites in the EUS. The EUS model represents the V/H ratio for smaller κ values. Figure 4.24 shows that the empirical WUS data are consistent with the V/H GMPEs and the Edwards et al. (2011) V/H ratio for rock sites, but that the EUS empirical model has a much flatter V/H ratio.

The center and range of the experts' V/H models for a magnitude 6 earthquake at a distance of 10 km are compared in Figure 4.25 for the example of Beznau. The V/H ratio models span a range of 1.5 to 2.0, which is smaller than the range from the horizontal models. Figures A.17 to A.20 show the individual expert ranges for all the four NPP sites.



(a) GMPE target κ value comparison.



(b) PSSM target κ value comparison.

Figure 4.23: Comparison of target κ values defined by the SP2 experts to be used for the GMPE (top) and PSSM (bottom). The NPP sites are arranged increasingly according to their V_{S30} values. The grey shaded area spans the range of the used target κ values and the colored dots/lines indicated the associated weights.

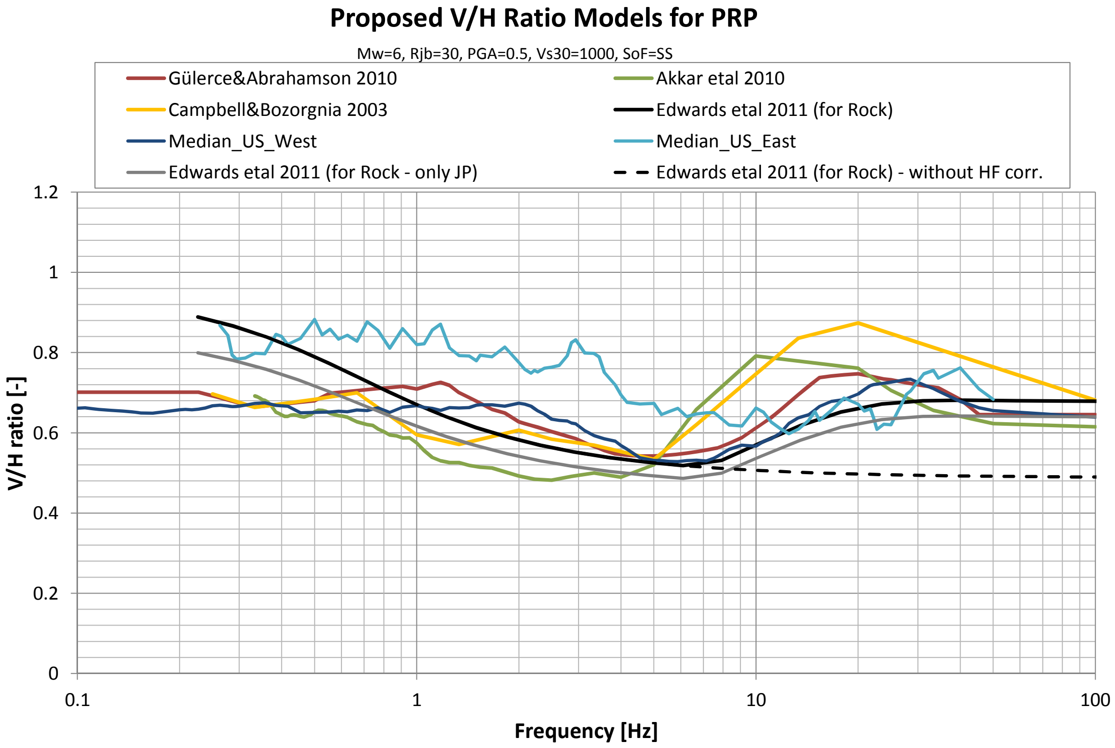


Figure 4.24: Comparison of median V/H ratio for the candidate models for M=6 and R=30 km for Swiss generic hard-rock site condition.

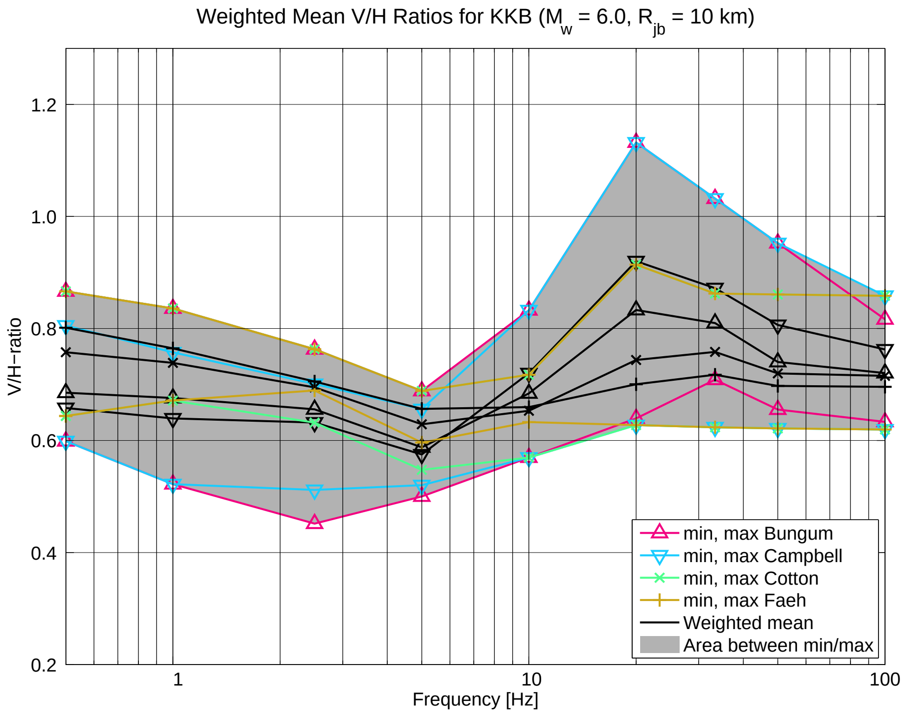


Figure 4.25: Comparison of the range of V/H models at Beznau for the four PRP SP2 experts.

4.8.3 Aleatory Variability for Horizontal

The aleatory variability logic tree set up by SP2 is illustrated in Figure 4.26. According to the nomenclature in Al Atik et al. [2010] the aleatory variability (σ) is divided in the two parts: Tau (τ), being the between-event model and Phi (ϕ), as within-event model. The center and range of the magnitude scaling of the aleatory variability of horizontal ground motion for 1 Hz and 100 Hz spectral acceleration for a distance of R=10 km and M=6 are compared in Figures 4.27 and 4.28. For all four experts, there is only a weak dependence on magnitude and distance.

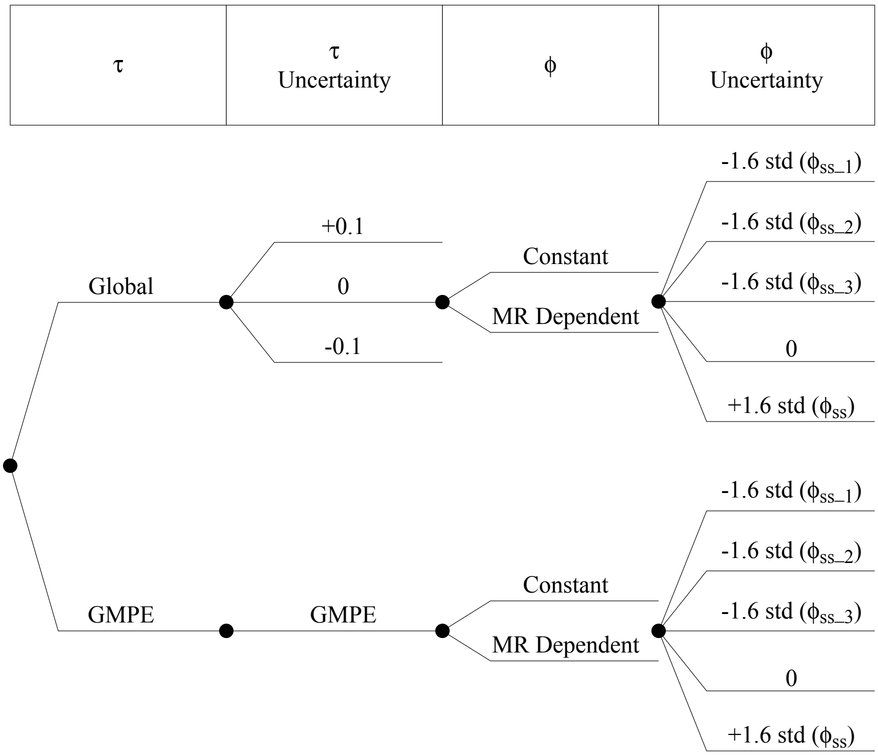


Figure 4.26: Logic tree for the aleatory variability of the horizontal component.

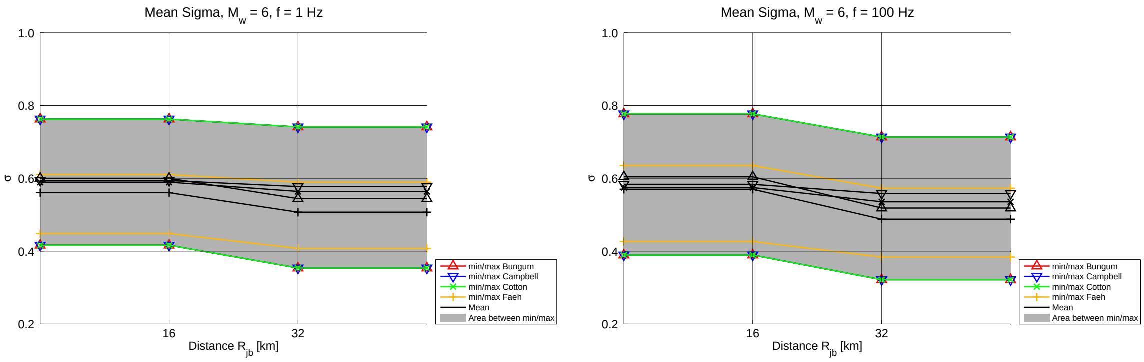


Figure 4.27: Comparison of the single-station σ models in dependence of distance for 1 Hz (left) and 100 Hz (right) by SP2 expert.

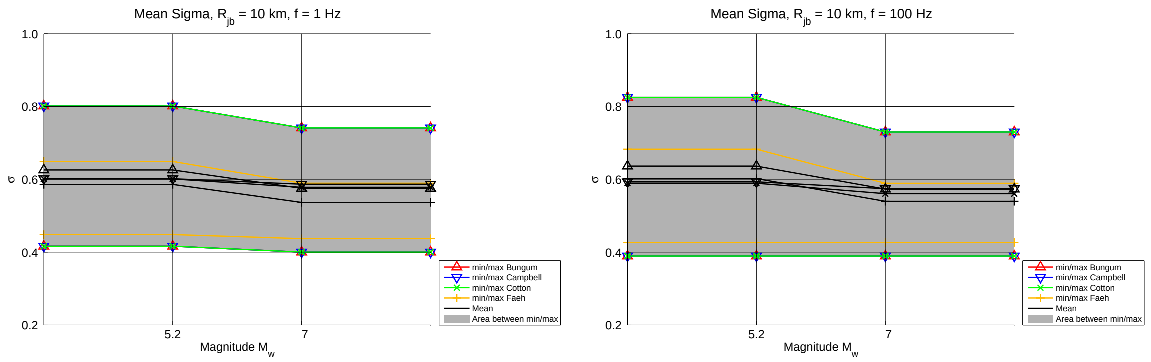


Figure 4.28: Comparison of the single-station σ models in dependence of magnitude for 1 Hz (left) and 100 Hz (right) Hz by SP2 expert.

Figure 4.29 shows the comparison of the single-station σ models for each expert as a function of frequency for the case of M=6 and R=20 km. The weighted mean of H. Bungum, K. Campbell and F. Cotton are very similar, near 0.6, and have identical ranges spanning sigma values from about 0.4 to 0.73. The weighted mean for D. Fäh is slightly lower than the other three models. The key difference is that the range of the σ for D. Fäh's model is much narrower. This difference in the uncertainty range would affect the slope of the hazard curves at the high fractiles, but, as will be shown in the results section, the effect of the different expert models for the uncertainty range on σ is small.

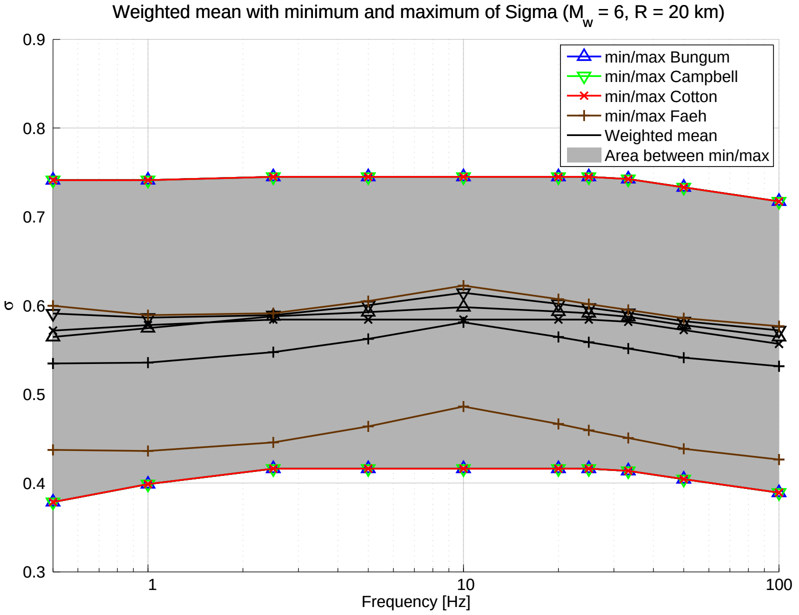


Figure 4.29: Comparison of the weighted mean and range of single-station σ models for the four PRP SP2 experts. As an example the case for M=6 and R=20 km is shown.

In PEGASOS, the aleatory variability model was truncated by some of the experts at 4σ and by some at 6σ. In PRP, the new aleatory variability logic tree has no explicit truncation of the ground motion distribution at a fixed number of σ. It is only truncated at the maximum ground motion level (see Section 4.8.5 and 4.8.6).

4.8.4 Aleatory Variability for Vertical

The additional vertical variability (σ_{VADD}) is the same for all four NPP sites and no uncertainty range around it was used because this term has only a small effect on the hazard. The additional aleatory variability models for a magnitude 6 earthquake at a distance of 10 km of the four SP2 experts are compared in Figure 4.30.

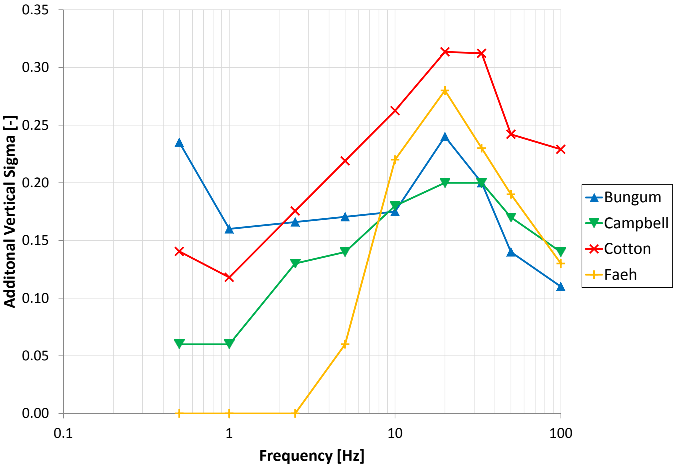


Figure 4.30: Comparison of the additional vertical aleatory variability models (σ_{VADD}) of the four PRP SP2 experts.

4.8.5 Maximum Ground Motion for the Horizontal Component

The maximum ground motion truncation model for rock was developed based on a new compiled database of maximum ground motions [Strasser and Zulu 2010] (EXT-TB-1067). Based on the trends in the empirical data (see e.g. Fig. 4.1), two models were proposed: a distance-independent model and a distance-dependent model. The distance-independent model set a maximum ground motion applicable to all distances for a given magnitude based on magnitude scaling of the Boore and Atkinson [2008] model evaluated at a distance of 1 km. This corresponds to physical limits on ground motion. The distance-dependent model set a maximum based on a scaling of the Boore & Atkinson [2008] median ground motion at a given magnitude and distance. This second model corresponds to a limit on the energy generated at the source and then attenuated to the site distance. For both models, a set of alternative scale factors that range from 7.5 to 100, equally spaced on the log scale, were proposed. For the vertical component, two alternative approaches considered for the reference ground motion were proposed: (1) using the Boore & Atkinson [2008] horizontal model and adjust with different scale factors for the vertical component, and (2) scale the Boore & Atkinson [2008] horizontal model by a V/H ratio.

The maximum rock ground motion is the same for all four sites. The center and range of the distance-dependence and magnitude-dependence of the maximum horizontal ground motion for 1 Hz spectral acceleration for magnitude 6 earthquakes and at a distance of 10 km are compared in Figure 4.31. A comparison for 100 Hz is shown in Figure 4.32. A comparison of all the individual branches of the maximum ground motion models is shown in Figures A.27 and A.28. The upper constant range in the distance plot is for the branch with the distance-independent maximum ground motion model. The second branch with the distance-and magnitude-dependent model shows the decay with distance in the upper part of the plot. The weighted means of the experts are quite comparable. Compared to the other experts, K. Campbell has only defined a single truncation limit with no epistemic uncertainty due to the minor effect on the hazard (shown later). The range of F. Cotton and D. Fäh is narrower, but falls within the broader range of the other experts. As seen from Figure 4.31, the model of K. Campbell is at the lower end of the range of SP2 experts for the distance dependence, but in the middle for the magnitude dependence.

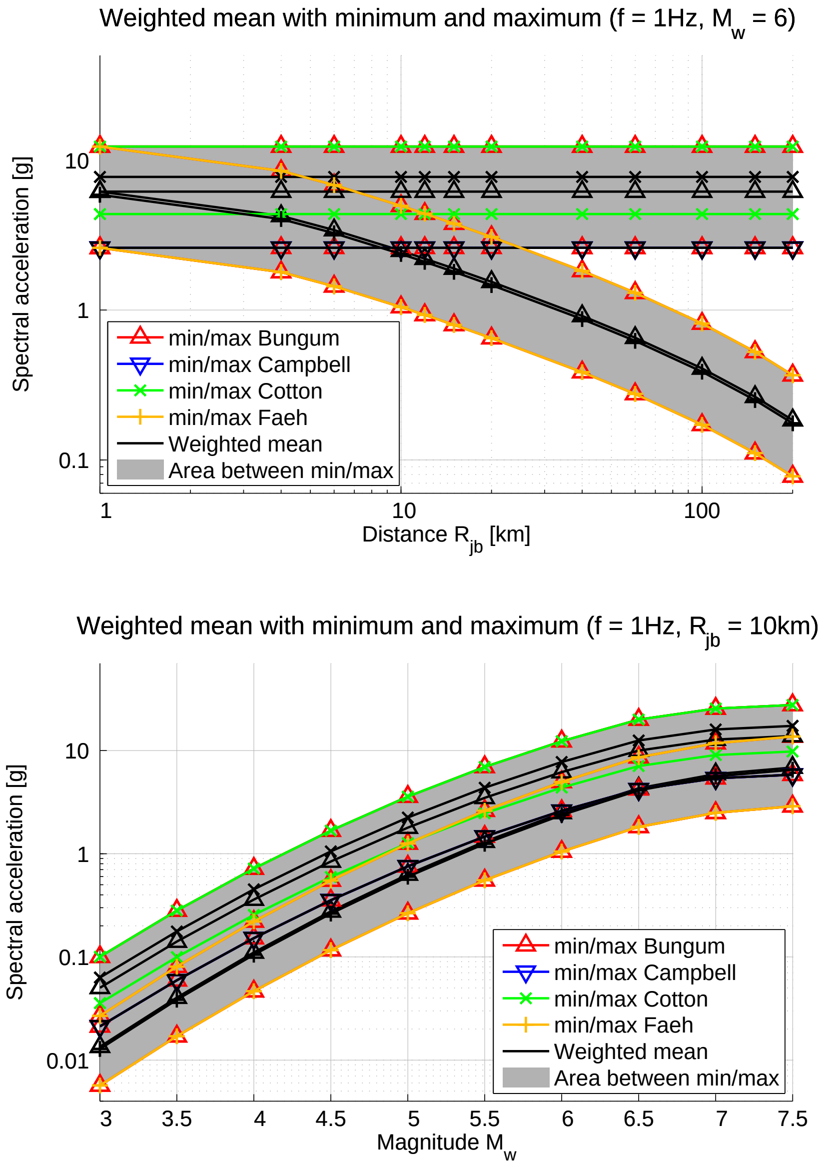


Figure 4.31: Comparison of the horizontal maximum ground motion truncation models for all four experts showing the distance-dependence (at R=10 km, top) and magnitude dependence (for M=6, bottom) for 1 Hz.

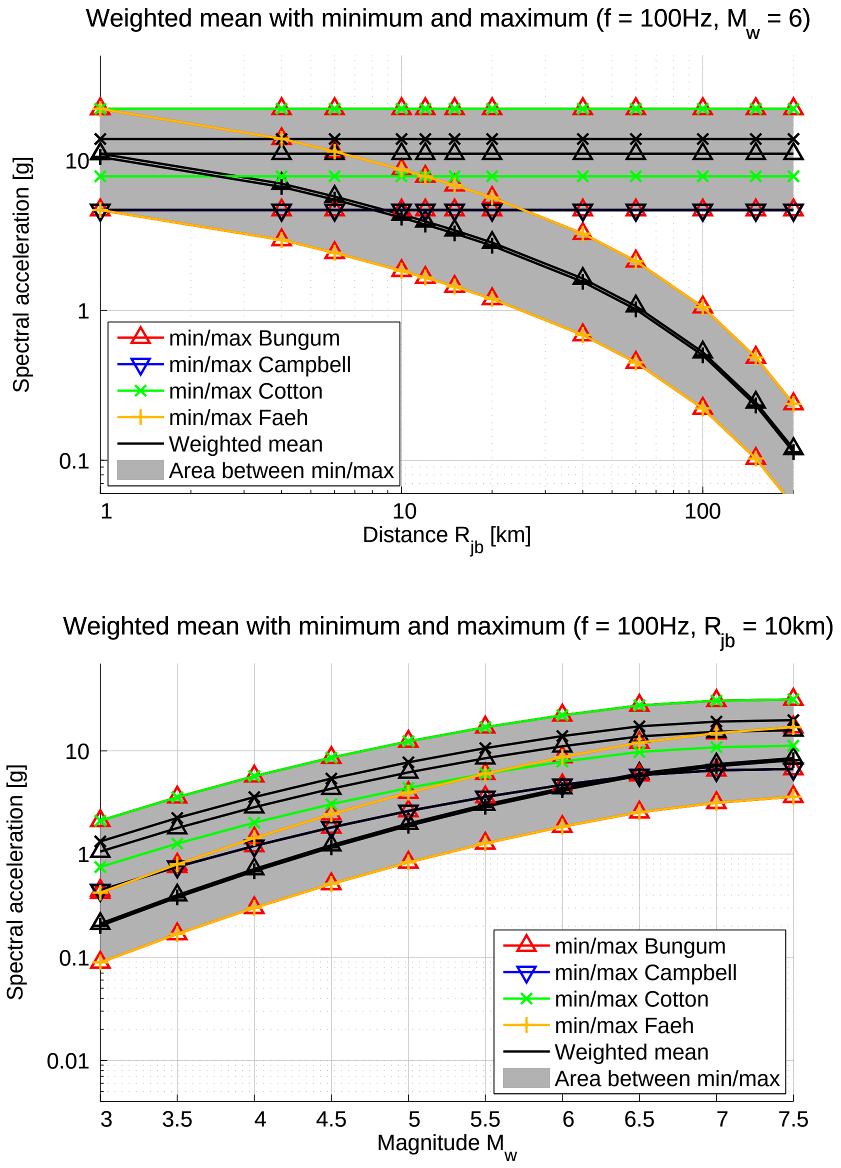


Figure 4.32: Comparison of the horizontal maximum ground motion truncation models for all four experts the distance-dependence (at R=10 km, top) and magnitude dependence (for M=6, bottom) for 100 Hz.

The hazard feedback showed on various occasions, that the maximum ground motion truncation models, as defined by the PRP SP2 experts, have almost no effect on the hazard results. Even though the SP2 experts defined their ”scientific logic trees” to include maximum ground motion truncation, the Project decided to perform the final hazard calculations without maximum ground motion truncation model for rock for the sake of computational efficiency. As an example for the quantification of the effect of this decision, Figure 4.33 shows the comparison of the mean hazard for all four SP2 experts with and without the MaxGM truncation model for Beznau at 5 Hz.

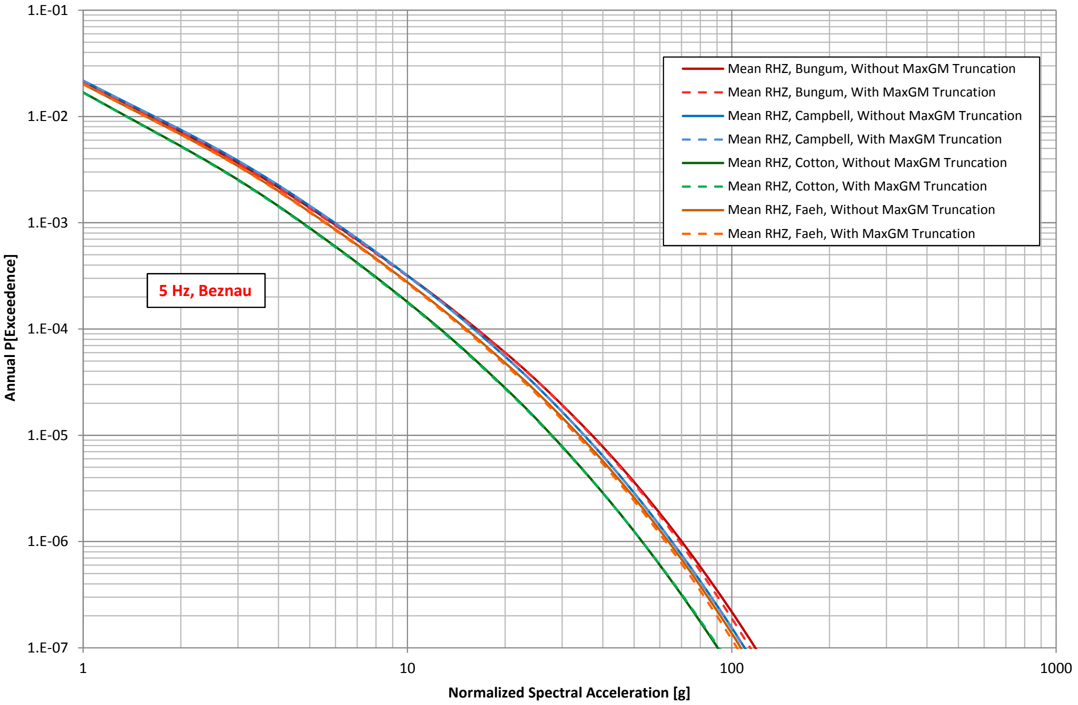


Figure 4.33: Comparison of the effect of the maximum ground motion truncation models for the four SP2 experts. Mean rock hazard with and without MaxGM truncation for the Beznau site at 5 Hz.

4.8.6 Maximum Ground Motion for the Vertical Component

The maximum ground motion is the same for all four sites. As the experts have chosen the vertical maximum ground motion model to be the same as for the horizontal component, the center and range of the distance and magnitude-dependence of the maximum vertical ground motion for peak acceleration are the same as in Figures 4.31 and 4.32.

Chapter 5

Interfaces between SP2 and SP3

5.1 Overview

In the PRP, considerable attention was paid to the careful and clear handling of interfaces between the ground motion characterization (SP2) and the site response characterization (SP3). The key issues that have to be addressed in order to avoid double counting of uncertainties are:

- Partition of aleatory variability,
- V/H models,
- κ and consistency with site amplification models,
- Maximum ground motion.

It should be mentioned that the maximum ground motion truncation models are handled differently by both expert groups (rock vs. soil) and there was not really any issue that had to be discussed. Nevertheless, both teams had access to the same empirical database [Strasser and Zulu 2010; Strasser 2012] (EXT-TB-1067 and EXT-WAF-1012) and made use of it for the development of their individual models.

In the following, the formal SP2-SP3 interface workshops are briefly summarized.

5.1.1 SP2-SP3-SP4 Interface Workshop A

The first interface workshop was held on 9. December 2008 in Zurich. The key interface issues for SP2/SP3/SP4 discussed at the workshop are listed below:

- Reducing M_{min}: The hazard calculation will include a case with the M_{min} reduced from 5.0 to 4.5. For SP3, this requires a check that the non-linear site effects can be extrapolated to $M4.5$.
- Reference rock for each NPP: Checking the consistency of the rock velocity profiles at the NPP sites with the rock profiles for the GMPE datasets.

- Avoid double counting of site amplification variability: A key issue for the SP2/SP3 interface is the treatment of the variability. The variability of site amplification (between sites with the same V_{S30} and within a single site for different input motions) is included in SP2 if the traditional standard deviations for GMPEs are used. It is also included in the epistemic uncertainty of the site profile for SP3 and in the variability of amplification from different input time histories. Approaches to address this double counting were reviewed. The experts supported having SP2 remove the epistemic part by switching to a single-station σ approach and having SP3 not add the variability from different input time histories for the linear range of input ground motions. The Japanese data may be useful for evaluating the reduction in the SP2 σ. The final decision on the separation of the aleatory variability terms was postponed to a later workshop.

- Non-linear effects in SP2 models: The SP3 models incorporate non-linear effects. The ground motion models used by SP2 also include non-linear effects. These non-linear effects should be consistent for the PRP application. Because the NPP reference rock condition will be greater than 700 m/s, the non-linearity in the ground motion model will be very small. The differences in the non-linear models between SP2 and SP3 will therefore not cause a significant effect.

- 2D/3D-effects on the variability: There are 2D and 3D-effects in the SP3 models. Some of the variability due to 2D and 3D-effects is captured in the SP2 aleatory terms. It is not clear how much double counting exists due to this issue. This will need to be addressed at a later interface workshop.

- Maximum ground motions: Both SP2 and SP3 use empirical values for the largest recorded ground motions as one of the inputs for the maximum ground motions. A single updated dataset that can be used by both SP2 and SP3 should be developed so that SP2 and SP3 are using consistent maximum values.

- Frequency content of rock ground motions: SP3 uses times histories to define the input rock motion. The stochastic model from SP2 also produces a Fourier spectrum of the input rock motion. Check the consistency of the frequency content (spectral shape) of the Fourier spectra of the input rock motions used by SP3 with that from the Swiss stochastic model.

- Ground motion parameters: SP5 may need additional ground motion parameters such as Sa averaged over a frequency band. There is an interface with the ground motion models developed by SP2 and SP3, the hazard calculation (SP4) and the needs of SP5.

- It was discussed whether the information theory approach (presented by F. Scherbaum) is applicable to the SP3 models.

5.1.2 SP2-SP3 Interface Workshop B

The second interface workshop was held on 6. October 2010 in Zurich.

- Partition of aleatory variability between SP2 and SP3: The use of single-station σ by SP2 removes the average site response uncertainty from the SP2 model, but the aleatory variability of the site amplification is still part of the σ in the SP2 models. To address this interface issue, SP3 will only include the aleatory site amplification term to the extent that it exceeds the variability implicitly included in the SP2 models. The epistemic uncertainty in the average site amplification will be captured by the SP3 logic trees.

- Maximum ground motion: Both SP2 and SP3 use empirical data as one approach for estimating the maximum ground motion. For consistency, a common database of large ground motions was developed for both SP2 and SP3, but with different subsets selected by the SP2 and SP3 experts based on the application.
- $V-S$-profile amplification effects: SP2 uses $V-S$ correction factors based on the QWL method to adjust the spectra from GMPEs for a reference profile to the rock site conditions at the NPP sites. SP3 uses site amplification factors based on vertically propagating SH waves to scale the rock spectra to the ground surface. The use of different site amplification methodologies by SP2 and SP3 leads to an interface issue. The QWL method leads to a smoothed amplification, whereas the SH wave method includes resonances. As shown in TP2-TN-1135, the amplification from the QWL method is consistent with the average (smoothed) amplification from the SH method.

5.1.3 SP2-SP3 Interface Workshop C

The interface workshop originally scheduled for 11. May 2011 was canceled and SP3 elicitation meetings were held instead. Nevertheless, the following interface issues between SP2/SP3 were discussed individually with the SP3 experts based on the material prepared in advance and then with the SP2 experts on 12. May 2011:

- Kappa for input rock motion: The updated SP2 models have led to a significant change in the frequency content of the input rock motion due to changes in the κ from SP2. A new set of amplification factors for SHAKE and RVT methods will be computed using updated input rock motion that has a frequency content consistent with the UHS for rock.
- Vertical aleatory variability: The SP2 experts include additional aleatory variability for the vertical components (σ_{VADD}). The SP3 experts will be provided with the σ_{VADD} values so that they can evaluate the effect on their vertical aleatory models.
- V/H ratios: To allow for a consistency check of the full process for vertical, the SP3 experts will be provided with comparisons of the empirical V/H and the $\mathrm{UHS}_V/\mathrm{UHS}_H$ ratios.

5.1.4 SP2-SP3 Interface Workshop D

The last interface workshop was held on 18. January 2013 in Zurich, immediately after workshop WS11/SP2. The key items discussed during this workshop are presented below.

- Treatment of damping for the Gösgen deep and shallow profiles: SP2 will use the κ applicable to the shallow rock profile for both the shallow and deep profiles. The damping in the deep part of the rock profiles (P1-P3) will be set to zero.

- Kappa for input rock motion: The updated SP2 models have led to a significant change in the frequency content of the input rock motion due to changes in the κ from SP2. A new set of amplification factors for SHAKE and RVT methods was computed using the updated input rock motion that had a frequency content consistent with the UHS for rock. As part of the SP2-SP3 interface, the SP3 experts evaluated the effect of the change in the spectral content on their amplification factors and concluded the change was not significant.

5.2 NPP-Specific Rock Interface

The reference rock interface between SP2 and SP3 is treated as outcropping rock in the PRP, as this is consistent with the interpretation of the GMPE prediction, and as the SP3 amplification is modeled as the ratio of outcropping soil over outcropping rock. In the PRP, the rock interface was defined for each NPP site at a different depth level in order to account for the site-specific properties and the new detailed knowledge on the soil based on the site investigations performed. This is considered as an improvement compared to PEGASOS, where a generic rock interface was defined (based on an assumed generic V_{S30} of 2000 m/s). Figure 5.1 illustrates the site-specific rock interface with the assumed generic rock velocities below and the different site-specific soil profiles above. Nevertheless, this also implies that the rock hazard results obtained by the PRP are no longer directly comparable to the old PEGASOS rock hazard results and are also different from site to site.

For Mühleberg, the generic rock profile was modified in order to account for the special situation at the site [Roth 2010b] (EXT-TN-1110). The SP3 soil models only consider the uppermost 44 m. The underlying unweathered Molasse is considered as rock. The total thickness of the Molasse at Mühleberg is about 1300 m underlain by 1700 m thick Mesozoic sediments. Applying the same method to merge the profiles as for the other site, one would almost end up with the basic Swiss generic rock profile (SGVsP). This is not reasonable for Mühleberg as, at a depth of e.g. 900 m for the Molasse at Mühleberg, about the same velocity is already reached (ca. 3100 m/s) as for the granite basement at the same depth at Beznau and Leibstadt. In a seismic interpretation project covering western Switzerland, a compressive wave velocity V_P of 3750 m/s has been assessed for the entire Molasse section in the region of Mühleberg. Assuming a V_P/V_S ratio of $\sqrt{3}$, an average V_S value of 2165 m/s is obtained. One way to reach such an average value for the entire Molasse interval (from 0 to 1300 m) would be to keep the $V_{S30,rock}$ value of 1100 m/s constant down to 375 m and shift the SGVsP vertically to this point. However, such a velocity increase with depth is not realistic in the Molasse where compaction is known to be the main factor responsible for the velocity increase with depth [Roth 2010b]. As the compaction is known to be best modeled with an exponential increase, a profile was proposed which starts with 1100 m/s and stops at 1300 m (the base of the Molasse unit) with 2700 m/s. The resulting interval velocity for the entire Molasse interval is approximately 2150 m/s. At 1300 m, the top of the high-velocity Malm limestones, the velocity increases rapidly to join to SGVsP (Fig. 5.1(d)).

5.2.1 NPP-Specific κ

Figure 5.2 illustrates the different portions of κ and soil damping (ζ) and how the subprojects partitioned them. The $\kappa_{0,ObservedSurface}$ which is evaluated based on recordings at the surface reflects κ_0 (where the index "0" means at zero distance) of the base rock which includes the effects of the source and the crustal damping and also the damping due to the overlying soil. In the PRP, SP2 took ownership over κ_0 as it is interpreted as a rock parameter, even if κ is defined on a site-specific basis. The use of site-specific κ_0 is justifiable based on the large differences in the rock V_{S30} at the four sites. Nevertheless, κ_0 was also regarded by some experts as a regional parameter and thus independent of V_{S30} for rock sites. The geotechnical damping in the soil layers ($\zeta_{Profile}$) and its scattering ($\zeta_{Scatter}$) are handled by SP3 which captures the epistemic uncertainty in the soil profiles and material damping and can be included in the expression of κ_0 by using the terms $\kappa_0(\zeta_{Profile})$ and $\kappa_{Scatter}$.

5.2.2 Average Site-Specific κ_0 for Site Amplification

For the evaluation of the site response, the RVT input spectra were initially based on the site-specific κ_0 estimates by SED. After re-evaluation of κ_0 by SP2 in 2012, new values were defined which led to the need for a revision of the RVT input spectra. In order to be fully consistent, the re-analysis of the site response by the equivalent linear (EQL) methods (SHAKE and RVT) was performed with the new target κ_0 values. The time histories used for SHAKE were adjusted in frequency content to be consistent with the spectral shape of the RVT input spectra. This also removed the inconsistency in the 2010 site amplification for SHAKE and RVT which had used different spectral shapes.

The SP2 experts have defined a range of target κ_0 values per site to be used for the evaluation of the $V_S - \kappa$ corrections on rock. SP3 used only one target κ_0 value per NPP site as input for the sake of simplicity. This averaged κ_0 value was obtained by evaluation of the mean κ_0 based on the high frequency slope of the rock UHS for each site. These mean κ_0 values are shown in Table 5.1 for the horizontal and vertical component.

Table 5.1: Average κ_0 values based on rock UHS used for the definition of the site response input (rounded to two significant digits) [Renault 2013a] (PMT-AN-1132).

	Horizontal	Vertical
KKB	0.022	0.016
KKG	0.020	0.016
KKL	0.021	0.016
KKM	0.025	0.016

5.3 Treatment of Deep and Shallow Soil Profiles for Gösgen

For Gösgen, the SP3 experts defined shallow (28 m) and deep (560 m) soil profiles which have a shear-wave velocity of 2500 m/s at the bottom of the profile. The deep profiles capture the case of a weathered rock layer in the 532 m below the soil. There are three interface issues associated with having shallow and deep profiles in the computation of the site amplification, which are discussed below.

The first issue is the damping in the part of the deep profile between 28 and 560 m depth. The damping in the deep part of the profile is implicitly captured in the κ_0 used by SP2. If the damping in the deep part of profile was included in the geotechnical site response model, then these effects of damping would need to be removed from the SP2 rock motion to avoid double counting the effects of damping. This would require developing SP2 rock ground motions for two different κ_0 values (one for the shallow profile input motions and one for the deep profile input motions). A simpler approach, applied in the PRP, is to use the same SP2 rock motion as inputs to both the shallow profile and the deep profile but assign zero damping in the geotechnical model for the deep part (28-560 m) of the profile. This avoids double counting the damping in the deep part of the profile without having to develop a second set of SP2 rock motions for the Gösgen site (decision made at workshop WS11/SP2 (January 2013)). See also Figure 5.2 for illustration of the different portions of κ_0.

The second issue is the V_S correction for the GMPEs. The V_S correction accounts for differences between the host velocity profile and the NPP target profile. For the SP2 models, the V_S correction was computed including the 532 m weathered layer, which results in a small increase in the computed target amplification at low frequencies. Applying this V_S correction to both the shallow and deep profiles results in a slightly conservative correction for the deep profile case because the amplification from the deeper part of the profile is included twice.

The third issue is the application of the V/H models for hard rock by Edwards et al. [2011b] and for soil of Fäh et al. [2011b]. In these two models, the V/H ratio depends on the QWL velocity, which will be different for the deep and shallow profiles. As a result, the V/H ratio model should be different for the shallow and deep profiles; however, the effect is small with differences in the V/H ratios of less than 5%. Both sets of V/H ratios (based on the shallow and deep QWL velocities) were applied to the SP2 rock motion which was based on the shallow profile.

5.4 V/H Models for Rock and Soil

Implementation

In SP2, the rock V/H ratios are evaluated and weighted separately from the horizontal median models. In the rock site hazard calculation, the V/H ratios are applied to the combined fractiles of the hazard curves for the horizontal component for all four SP2 experts. That is, the V/H ratio from an individual SP2 expert is not combined with only his own horizontal component hazard. Therefore, the sensitivity of the vertical hazard by expert isolates the sensitivity to the V/H ratio of the individual SP2 experts.

In SP3, two approaches are used to provide V/H ratios and amplification factors, which scale the horizontal rock ground motion to vertical soil ground motion: (1) V/H ratios for soil and amplification factors for horizontal motion are developed by the SP3 experts and are combined, and (2) V/H ratios for rock by the SP3 experts and amplification factors for vertical motion by the SP3 experts are combined. For the first approach, the SP3 expert-specific soil V/H ratios are combined on a per-expert basis with the expert-specific horizontal motion amplification. For the second approach, the V/H rock ratios of all four SP2 experts are combined with the SP3 vertical motion amplification factors. Both approaches cover horizontal-to-vertical motion scaling and amplification. The results of both approaches are combined into a single soil input file per site. This soil input file is used to compute the vertical soil motion hazard on the basis of the horizontal rock motion hazard, which is always the "full" (all fractiles, complete SP1 and SP2 models) horizontal motion rock hazard. Approach 2 above is similar to the computation of the vertical motion rock hazard in that the full horizontal motion rock hazard is combined with all four SP2 V/H models, i.e. there is no correlation between (but full combination of) the SP2 expert-specific rock hazard subsets and the SP2 expert-specific V/H rock ratios.

Candidate Empirical Models

The same candidate empirical V/H models were evaluated by SP2 and SP3, as their range of applicability with respect to V_{S30} fits the rock conditions as well as the soil conditions. The SP2 experts selected the V/H models considered to be applicable for hard rock with corresponding $V_{S30,rock}$ or site class respectively. SP3 evaluated the available V/H models for the surface V_{S30}. As the range of available hard rock V/H models was judged to potentially not cover the full range, additional empirical hard rock models were added (see Section 4.8.2). Within SP3, the experts added two soil-specific V/H models developed by SED [Fäh et al. 2011b] (TP3-TB-1084). The candidate V/H models used by the SP2 and SP3 experts are compared in Table 5.2.

Table 5.2: Comparison of V/H models used by the SP2 and SP3 experts.

SP2 (Rock)	SP3 (Soil)
Bommer et al. [2011]	Bommer et al. [2011]
Campbell and Bozorgnia [2003d]	Campbell and Bozorgnia [2003d]
Gülerce and Abrahamson [2011]	Gülerce and Abrahamson [2011]
Edwards et al. [2011b] without correction above 7 Hz	Poggi et al. [2012] (Method 1 in TP3-TB-1084)
Edwards et al. [2011b] with correction above 7 Hz	Edwards et al. [2011a] (Method 2 in TP3-TB-1084)
Biro and Renault [2012a] US-West Median	Kawase et al. [2011]
Biro and Renault [2012a] US-East Median	

Table 5.3 summarizes the average (mean) shear wave velocity (V_{S30}) over all defined site-specific soil profiles, as defined within SP3 and the rock values used by SP2.

Table 5.3: V_{S30} in [m/s] for the NPP sites at the surface and the sub-surface levels.

Site (depths)	Surface	Sub-Surface 1	Sub-Surface 2	Rock
Beznau (0/-15 m)	516	774	-	1800
Gösgen (0/-9 m)	467	692	-	2500
Leibstadt (0/-10 m)	526	656	-	2200
Mühleberg (0/-7/-14 m)	490	784	906	1100

Kappa

Within the PRP, no specific adjustment of the V/H models with respect to (vertical) κ was performed. The issue of κ for V/H models was already discussed in Section 4.8.2.

Non-linear site amplification effects

A technical note by Abrahamson and Hölker [2012] (TFI-TN-1235) was prepared to address the SP3 experts request to support their evaluation of the V/H models with respect to their applicability within SP3 in terms of non-linear site response effects. The emphasis of this technical note was on the consistency of the horizontal and vertical response with respect to the non-linear site effects, as the V/H GMPEs are applied by multiplying them by the horizontal SP3 soil ground motion which explicitly includes non-linear effects.

The first issue is the consistency of the non-linear scaling in the candidate V/H models and the site-specific non-linear scaling in the horizontal amplification. The Gülerce and Abrahamson [2011] V/H model (GA10) assumes linear site response for the vertical component and non-linear response for the horizontal component (the horizontal component non-linearity is based on the Abrahamson & Silva [2008] model). As a result, the site response for the GA10 V/H model includes non-linear effects. In contrast, the other V/H models assume the site response for the V/H ratio is linear. If the expected vertical amplification is linear, then the non-linearity in the V/H ratio will only be consistent with horizontal soil motion if the same degree of non-linearity for the horizontal component is used in the V/H model. The vertical amplification for soil sites computed using the V/H method is given by:

$$\frac{V_{Soil}}{V_{Rock}}(PGA_{Rock}) = \frac{H_{Soil}}{H_{Rock}}(PGA_{Rock}) \cdot \left(\frac{V}{H}(PGA_{Rock})\right)_{Soil} \cdot \left(\frac{H}{V}(PGA_{Rock})\right)_{Rock} \tag{5.1}$$

which corresponds to:

$$VMAF = HMAF(PGA_{Rock}) \cdot \left(\frac{V}{H}(PGA_{Rock})\right)_{Soil} \cdot \left(\frac{H}{V}(PGA_{Rock})\right)_{Rock} \tag{5.2}$$

Using this relationship, the amplification for the V/H ratio models can be compared to the analytical vertical amplification models.

The vertical amplification from RVT is compared to the vertical amplification from the V/H approach in Figure 5.3. The vertical amplification from the RVT approach is constant (linear). The vertical amplification based on the GA10 model shows a larger vertical amplification and a slight slope. The non-zero slope occurs because the generic non-linearity in the horizontal component for the GA10 model is not as strong as the non-linearity in the PRP horizontal site-specific response calculations. The vertical amplifications for the other V/H models have a large slope because they assume the same non-linearity applies to both the horizontal and vertical components, which is not consistent with PRP analytical models. The issue of inconsistency in the non-linearity in the horizontal component can be avoided by using the linear amplification. The dashed lines in Figure 5.3 show the linear amplification.

A second issue is the inconsistency between the linear amplification from the vertical site response (RVT VM AF) and the linear amplification from the V/H ratio approach. Figure 5.3 shows that the linear amplification from the RVT runs is lower than the V/H models other than the SED1 model. The inconsistency is due to different site conditions at the PRP sites as compared to the sites used in the empirical V/H ratios. The horizontal component site response has a resonance at 6 - 10 Hz, while the vertical component site response has a resonance at 30 - 40 Hz. These site-specific resonances are at higher frequencies than typical sites in the ground motion datasets used for the empirical V/H ratios. The global empirical data show peaks in the horizontal soil ground motion near 5 Hz and peaks in the vertical soil motion near 10 Hz. This leads to a higher linear vertical amplification at 10 Hz than seen for the site-specific RVT calculation. This comparison shows the importance of considering the consistency of the V/H model and the site-specific site conditions for the NPP sites.

5.5 Consistency of Treatment of Aleatory Variability Between SP2 and SP3

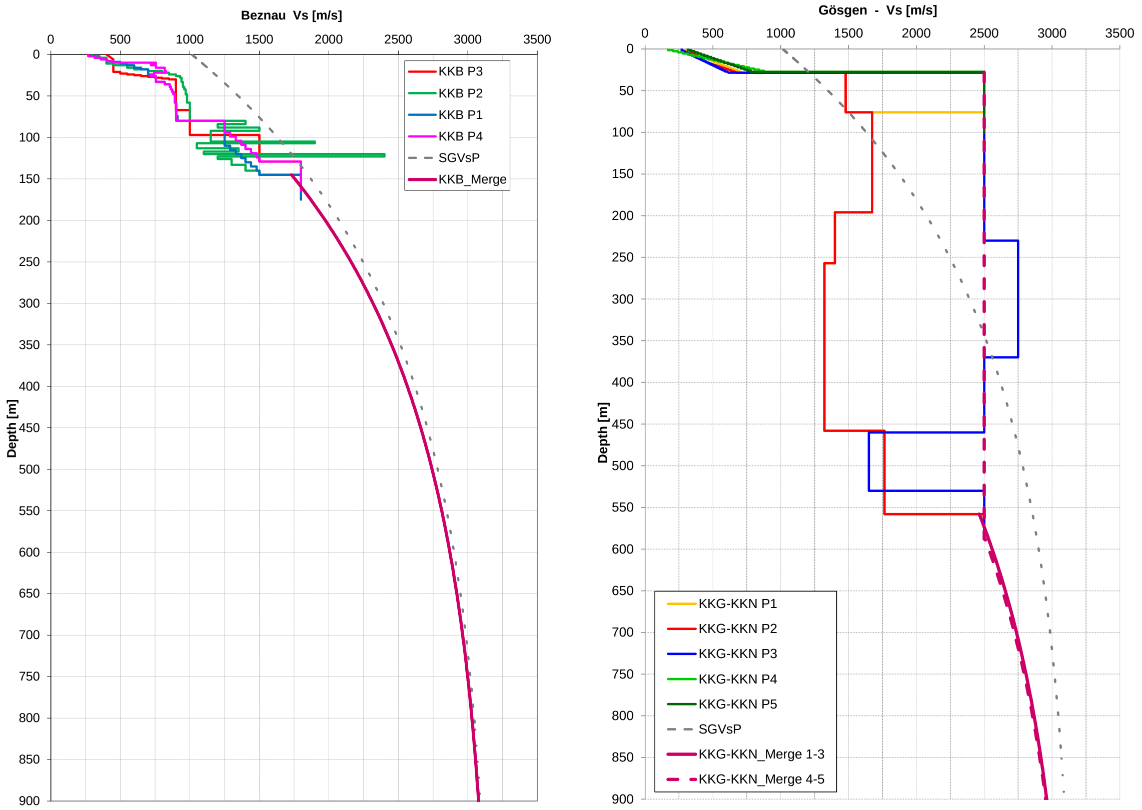
The candidate aleatory σ models used by SP2 are based on GMPEs that use both soil and rock data to estimate the standard deviation for rock sites. Therefore, in a traditional ergodic σ both differences in the average site-specific site amplification and the variability of the soil amplification about this average are included in the rock site σ.

The use of single-station σ removes the effect of site-to-site differences in the average amplification from the rock σ, but the variability of the soil amplification (due to different input time histories, for example) is still included in the single-station rock σ values. The empirical datasets used to estimate σ are dominated by ground motions in the linear range, so the site amplification variability for linear response is mainly included in the rock site single-station σ. The site amplification variability for cases with highly non-linear site response is not represented in the rock site single-station σ.

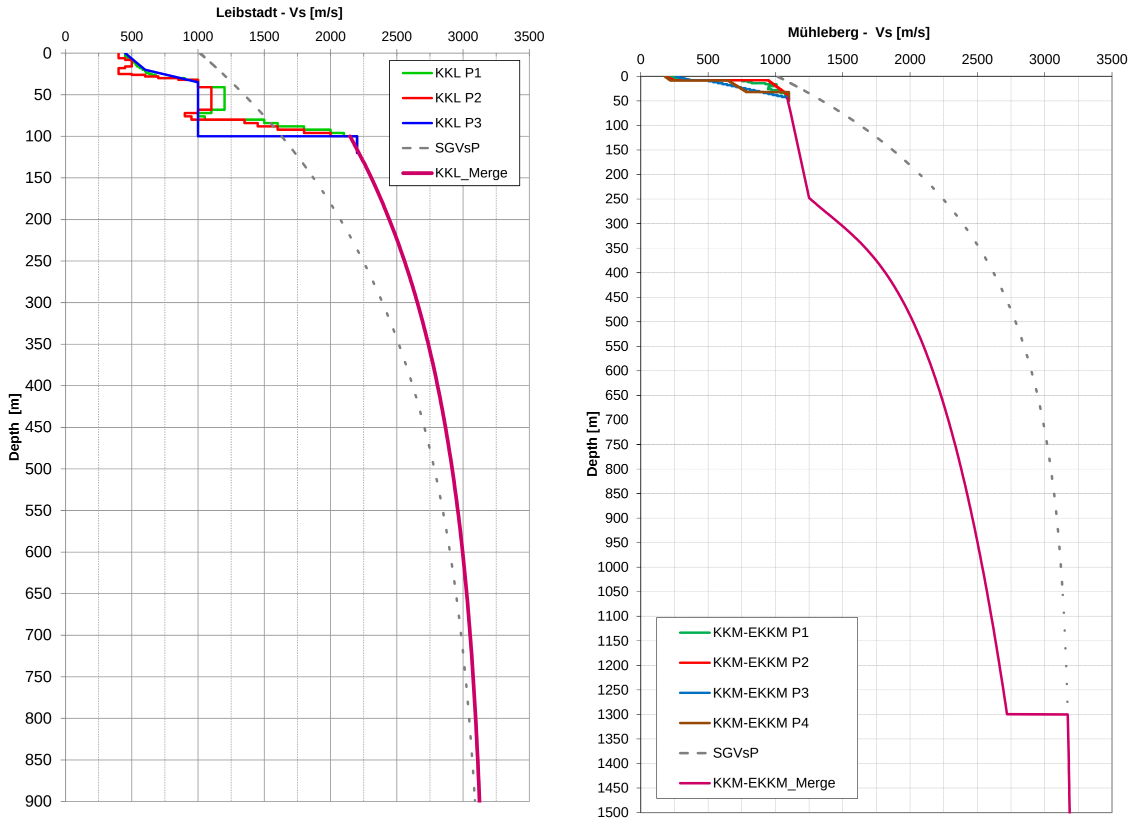
To avoid double counting the site amplification aleatory variability, the aleatory variability of the site amplification resulting from the variability of the input time histories is not included in the SP3 model. However, if there is additional aleatory variability of the site amplification at high levels of shaking, then this is added to the SP3 variability model.

The use of single-station σ requires that the epistemic uncertainty in the site-specific site amplification is captured in the logic tree model. The epistemic uncertainty in the site-specific site amplification is captured in the SP3 logic trees through the alternative models for the V_S-profile and the non-linear properties.

The above-mentioned concept applies to the horizontal ground motion as well as to the vertical. See Section 4.4.1 for the motivation behind using the single-station σ concept.



(a) Beznau (b) Gösgen



(c) Leibstadt (d) Mühleberg

Figure 5.1: Illustration of the merged rock (magenta curve) and the different soil V_S-profiles for all NPP sites (EXT-TN-1110, see also Figure 5.2). The grey dashed line represents the Swiss generic rock profile, as assumed for the development of the Swiss stochastic model and is shown for comparison purposes here.

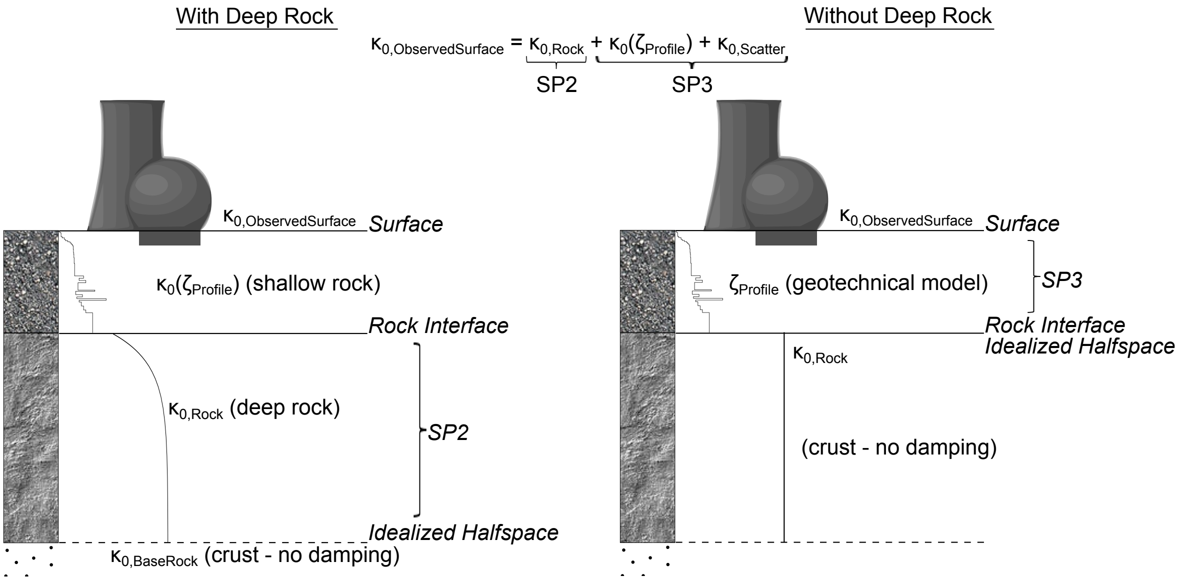


Figure 5.2: Sketch of portions of Kappa (κ_0) / damping (ζ) and its treatment by subproject.

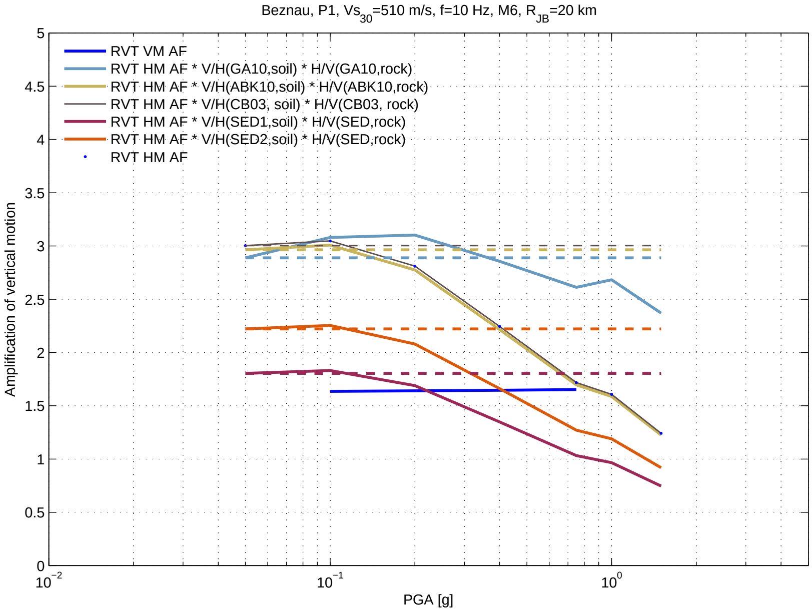


Figure 5.3: Comparison of the vertical amplification factors from RVT with the vertical amplification implied by the V/H models for 10 Hz spectral acceleration. The dashed lines show the vertical amplification based on the V/H models assuming linear amplification for the vertical component (constant at the amplification computed for PGA=0.05 g).

Chapter 6

Site Response Characterization - SP3 Summary

6.1 Summary of Key SP3 Activities

As part of the PRP, nine workshops were held for SP3 and three interface workshops. This greatly exceeds the three workshops that are required for SSHAC Level 3 or Level 4 studies [Kammerer and Ake 2012]. In this section, only the key outcomes of the workshops are given. The full workshop summaries are contained in the appendix to this report. The overview of workshops and milestones is summarized in Table 6.1.

6.1.1 Workshop #1: Kick-Off and Data Needs

The SP3 data needs workshop (WS1/SP3) was held on 3. September 2008 in Zürich. The workshop reviewed the new data collection and modeling efforts proposed by the utilities to support the PRP. The topics and identified data needs are described below:

- The workplan and schedule for SP3 was presented.
- The structure and concepts of the existing SP3 logic trees were discussed and the potential impact of the new site soil data was evaluated in order to determine if the logic trees needed to be updated.
- The following interface issues between SP2 and SP3 were discussed: Definition of site-specific reference rock for each NPP, avoid double counting of aleatory variability in making clear separation of σ between SP2 and SP3, consistent inputs for SHAKE and RVT, necessary additional ground motion parameters, review of new V/H ratio models.
- The site response calculation specifications were revised in order include more soil profiles to capture uncertainty and also more calculation cases for RVT and NL. Furthermore, constraints on the soil profiles were added by consideration of dispersion curves. For the vertical ground motion it was proposed to use the same three methodes as in PEGASOS for the EQL approaches.

Table 6.1: Overview of SP3 workshops and key contents

Date	Number	WS type	Topic
1.-3. Sept. 2008	WS1	Kick-Off, SSHAC WS1 Data Collection	Available new data and models, Sensitivity studies, Interfaces
9.-10. Dec. 2008	Interface WS	General interfaces between SP1, SP2, SP3, SP4	Interface topics and necessary logic tree considerations (e.g. reference bedrock, upper bound, V/H, site investigations, PSA inputs)
22. Oct. 2009	WS2A	SSHAC WS1+2 Data Collection & Evaluation	Assessment of the new site data and revision of the proposed models for Gösgen and Mühleberg, Development of profiles and material models incl. uncertainties
19. Nov. 2009	WS2B	SSHAC WS1+2 Data Collection & Evaluation	Assessment of the new site data and revision of the proposed models for Beznau and Leibstadt, Development of profiles and material models incl. uncertainties
5.+7. May 2010	WS2C	SSHAC WS2 Evaluation	Evaluation of revised soil and material models for all NPPs, Review of input response spectra and time histories for site amplification computations
6. Oct. 2010	Interface WS	SSHAC WS2+3 Evaluation & Feedback	Review of interface topics with SP2
4.-5. Nov. 2010	WS3A	SSHAC WS2 Evaluation	Evaluation of EQL and RVT amplification factors for all NPP sites
2.-3. Dec. 2011	WS3B	SSHAC WS2 Evaluation	Evaluation of NL amplification factors for all NPP sites and several comparisons
16.-18. Mar. 2011	WS4	SSHAC WS2+3 Evaluation	Review of the available data and models for the vertical motion (median, maximum ground motion and σ), Presentation of the draft revised logic trees for the horizontal motion and concept for the weighting of the branches, Peak-to-RMS scale factors approach, Interface issues with SP2 (e.g. κ)
6.-7. Jul. 2011	WS5	SSHAC WS3 Feedback	Hazard Feedback, Logic trees and weights justification, Issues with vertical ground motion models for soil, SP2-SP3 interface on $V_S - \kappa$ corrections
19.-20. Dec. 2011	WS6	SSHAC WS3 Feedback	Hazard Feedback, Revised logic trees and weights justification for vertical component
16.-18. Jan. 2013	Interface WS	SSHAC WS3 Feedback	Interface with SP2 (κ, V/H, σ) and SP5, Soil Hazard Feedback, Treatment of deep soil profiles for KKG, Recalculation of site amplifications for consistency with SP2 κ and input ground motions

6.1.2 Interface Workshop: Interface Issues Between SP1, SP2, SP3 and SP4

The interface workshop was held on 8.-9. December 2008 in Zurich. The first day of the workshop addressed the SP1/SP2 interface and the SP1/SP2/SP4 interface and is summarized in Section 3.1.1. The second day addressed the SP2/SP3/SP4 interface and is summarized in Section 5.1.1.

6.1.3 Workshop #2A: Data Needs and Evaluation of Site Investigations at Gösgen and Mühleberg

The second SP3 workshop was held on 22. October 2009 in Zürich. The workshop addressed the evaluation of the new site data and their associated uncertainties. Key topics and data needs discussed at the workshop are given below.

- Velocity profile interpretation: Alternative velocity profiles for V_S and V_P based on the available measurement data and the utilities interpretation were evaluated. The evaluation by SP3 lead to further data requests, mainly to investigate the dispersion curves. The reference rock shear wave velocity was defined as 2000-2500 m/s for Gösgen and as 1100 m/s for Mühleberg.

- Non-linear material property interpretation: Additional data request on G/G_{max} were issued for Gösgen. As no laboratory testing results were available for Mühleberg, the use of theoretical material models (e.g. Menq [2003] and Rollins et al. [1998]) were discussed and comparisons with the Gösgen data were requested.

- Reference rock velocity: The V_{S30} for Gösgen was evaluated and sensitivity studies on the effect of lower rock velocities at depth were requested by the experts. In order to constrain the different interpretations on the V_S profiles additional data requests and re-interpretations were issued by the experts. Potential reasons for the resonance at 0.6 Hz for the Gösgen site were discussed.

- Velocity profile for KKM: Alternative velocity profiles for Mühleberg were evaluated in addition to the ones proposed by the utilities. Additional evaluations on H/V data, dispersion curves and downhole data were requested by the experts.

6.1.4 Workshop #2B: Data Needs and Evaluation of Site Investigations at Beznau and Leibstadt

The third SP3 workshop was held on 19. November 2009 in Zürich and represents the continuation of the previous workshop. The workshop addressed the evaluation of the new site data and their associated uncertainties for the two sites which were not covered by the previous workshop. Additional key topics and data needs discussed a the workshop are given below.

- Velocity profile interpretation: Alternative velocity profiles based on the available measurement data and the utilities interpretation were evaluated. The reference rock shear wave velocity was defined as 1800 m/s for Beznau and as 2200 m/s for Leibstadt. Based on the measurement data different alternative V_S-profiles for KKB and EKKB were defined. Neverthless, requests for additional evaluations were also requested in order to better constrain the candidate models (e.g. based on dispersion curve constraints).

- Non-linear material property interpretation: Even if additional data request were issued for defining the material models at Beznau, preliminary material curves could be defined. At the Leibstadt site the data showed very large scatter in the testing results and thus, additional information on the minearlogy of material at the site were requested.

- It was decided to held a SP3 working meeting in January 2010 in order to evaluate the requested dispersion curve comparisons at all sites in order to revise the soil profiles.

6.1.5 Workshop #2C: Final Evaluation of Site Investigation Data

The fourth SP3 workshop was held on 5. and 7. May 2010 in Zürich. The workshop had the aim to finalize the soil profiles and material models for all NPP sites to be used for the site response analyses. As one of the SP3 experts was not available on the 6. May, this day was used as a working meeting by the rest of the SP3 experts to finish the reports on the site investigation interpretations. A brief summary of the workshop is provided in the following.

- The development of the soil profiles and material models was based on consensus models by the SP3 experts and the subsequent individual weighting on the logic tree branches will allow the experts to represent their evaluations.
- The boundary conditions for the soil profile randomization, to be used as input to the RVT computations, were defined as the bounds on the dispersion curves distribution and the fundamental frequencies.
- A benchmark test case for the EQL methods for the external contractors was defined by the experts.
- A revision of the V_P profiles for all sites was proposed for the layers below the water table. For all for sites the soil profiles and material models were completed at the end of the workshop. The damping in the rock was defined to be 0.5% for the sites KBB, KKL and KKM. For Gösgen it was decided to have no damping in the rock in order to be consistent with the SP2 approach.
- The specification of the site response analysis was revised. For the non-linear runs the issue of element size were explicitly addressed and the maximum reliable frequency for the non-linear runs was reduced to 50 Hz.
- The issue of time history scaling for various PGA levels was discussed and the requirements for the input ground motion for RVT to be used by the contractors were defined.
- The SP3 schedule until 2011 was presented and the deadlines for the submission and review of the site response calculation results were set.

6.1.6 Workshop #3A: Evaluation of EQL Site Response Results

The fifth SP3 workshop was held on 4.-5. November 2010 in Zürich. The workshop was an evaluation workshop. It addressed two main topics: The review of the new available SHAKE and RVT site amplification results and the identification of missing information and data necessary for the revision of the SP3 logic trees. Beside the presentation of the available information the following key items were discussed:

- Empirical maximum ground motions are available from a database prepared for SP2 rock maximum ground motions. The need to calculate maximum soil ground motions was identified and the analytical models were reviewed: 1) Betbeder, 2) Pecker, 3) scaled spectral shapes. To support the evaluation additional non-linear runs were requested.
- V/H models: The candidate models and information availalbe for the vertical soil hazard evaluation were reviewed: V/H from performed site response calculations, global V/H ratio models based on V_{S30}, Swiss network data for sites similar to the NPPs and also ratios from the KiK-net.
- Based on the available information the SP3 experts concluded that no new calculations for 2D & 3D effects were necessary.

- The following observations were made based on the evaluation of the site response results:
  - Beznau: A shift in the fundamental frequency due to the influence of the lower bound material model.
  - Gösgen: The missing RVT GM levels (0.3 and 1 g) will be interpolated. The NL results have much higher strains than RVT and a large scatter of results at the surface was observed, while the results at 1 m below the surface looked reasonable and are stable. Furthermore, the RVT base case was identified to be inconsistent with respect to the EQL results.
  - Leibstadt: Increase in amplification at depth as compared to the surface.
  - Mühleberg: Randomized RVT is removing all the peaks at higher levels of shaking compared to RVT base case and SHAKE.
  - For all sites: The high frequency amplification for RVT is much lower than for SHAKE.
- Based on the findings of above, additional evaluations were requested by the SP3 experts in order to understand the PGA dependence of the amplification factor and the cause of the differences between the high frequency amplification for SHAKE and RVT.
- The database and plotting tool to evaluate the site response results needed extended capabilities in order to enable the SP3 experts to perform a comparison and evaluation of the large datasets available for each site.

6.1.7 Workshop #3B: Evaluation of Non-linear Site Response Results

The sixt SP3 workshop was held on 2.-3. December 2010 in Zürich. The workshop was an evaluation workshop and aimed on the review of the new non-linear site amplification results for all four sites. Beside the presentation of the available information the following key items were identified:

- The evaluation of the cross-check runs revealed a good agreement for the sites, except for KKM at 0.75 g.
- Higher damping in the non-linear soil models compared to the EQL was observed and based on this the experts requested a compilation of past studies with high strains in order to better understand the results.
- The reliability of the non-linear runs at the surface for KKM were discussed, as there are liquefiable lenses in the first 7 m, but this layer has been removed during the construction of the NPP. Results with suppressed liquefaction showed that there is an impact on the results at 7 m depth. The SP3 experts suggested to use the SHAKE and RVT results for 7 m depth, as the strains in the Molasse are small and thus, the EQL methods are applicable.
- A Resource Expert presented the evaluation of non-linear effects based on Japanese data. The SP3 experts asked for additional clarifications and plots showing the resulting model of non-linear amplification for gravel sites vs. amplification for the NPP sites.

6.1.8 Workshop #4: Logic Tress for Soil Models

The seventh SP3 workshop was held on 16.-18. March 2011 in Zürich. The workshop was an evaluation workshop and its goal was to present the draft logic trees for the horizontal motion and the justification for the weights. The second key item was to review the available data and models for the vertical motions and identify potential interface issues. The following items were addressed at the workshop:

- The single-station σ concept used by SP2 was presented and the related SP2-SP3 interface issues to avoid double counting were discussed. In order for the SP3 experts to evaluate if additional variability would be necessary to be applied within the soil hazard computation comparison plots were reviewed and additional ones requested. The epistemic and aleatory parts were treated and compared to the SP2 data.

- Vertical models: The approach used by SP2 was presented (the vertical rock hazard is based on V/H ratios): Using only the median V/H implies that the same aleatory in the rock vertical as is in the rock horizontal is assumed. The SP3 experts have two approaches to determine the vertical soil hazard: using the computed vertical soil amplifications applied to the vertical rock hazard or using V/H ratios for soil applied on the horizontal soil hazard. The available empirical models were reviewed and SED introduced two new candidate V/H models developed specifically for Switzerland and hard rock conditions, respectively.

- The separation of vertical aleatory variability was discussed and the interface to SP2 was addressed.

- The two approaches to the vertical soil ground motion models were discussed: No maximum, or largest empirical PGA together with application of spectral shapes.

- During the second day the SP3 experts presented their horizontal logic trees and the rational for the preliminary weights. During the workshop the experts and the TFI identified items to be improved in the justifications of each expert and the details are documented in the meeting minutes.

- The third day was dedicated to discuss the open items for SP3 and interface issues: 1) Evaluation of usability of NL behavior of KiK-net data, 2) Approach for the development of Peak-to-RMS scale factors, 3) Consistency of SP2 $V_S - \kappa$ approach with the SP3 models, 4) Comparison of site amplification computations with observed data at the NPP sites. For the interface on the V_S correction by SP2 the SP3 experts concluded that SP3 supports to make the V_S correction from the generic Swiss profile to the NPP specific V_{S30} for rock by removing the top layer of the generic Swiss profile and match the corresponding target V_{S30}. This approach is supported from the geological point of view and has a physical background. The only identified exception was the V_S correction for Mühleberg where the site specific defined V_S-profile needed to be used, as high V_S values were only found at larger depth. Furthermore, the V_S-profiles need to match at larger depth with the base rock to avoid an impedance difference in the half space.

6.1.9 Workshop #5: Hazard Feedback and Logic Tree Revisions

The eighth SP3 workshop was held on 6.-7. July 2011 in Zürich. The workshop was an evaluation and hazard feedback workshop and addressed the following topics: Identification of the relevant parts of the SP3 models based on the preliminary hazard feedback; presentation of the final revised logic trees for the horizontal motion; maximum ground motions and their uncertainties, including the rational for the attributed weights; review of the available vertical and V/H models to be used by SP3. At the occasion of the workshop the TFI presented again the concept of the partitioning of the components of σ between SP2 and SP3. The following items summarize the conclusions from the workshop:

- Based on the provided hazard feedback the experts requested additional feedback plots (among which e.g. more detailed tornado plots) and sensitivity studies to support the SP3 experts in their choices for weights on specific branches.
- During both days, the experts presented and discussed their individual logic trees and weighting schemes. Some further improvements in the justifications were identified and required to be appropriately documented in the individual evaluation summaries.
- Different approaches on how to define relative weights between SHAKE and RVT at high frequencies were evaluated. In order to be consistent with the latest developments in SP2 on the $V_S - \kappa$ corrections the possibility to adjust the existing amplifications at higher frequency were evaluated by the SP3 experts.
- The final SED V/H models for hard rock were evaluated to be applicable to the site conditions at the NPPs and thus, considered by the SP3 experts in their update of the vertical soil logic tree. Based on the discussion at the workshop it was agreed to provided hazard feedback on the vertical later and to discuss the results at the occasion of a web-meeting.
- At the end of the workshop the SP3 experts discussed possible approaches and recommendations on how to select profile and material properties for engineering purposes. Definitive conclusions could not be reached on this topic, as it would have required to also include deterministic approaches, which are out of scope of the project.

6.1.10 Workshop #6: Hazard Feedback

The ninth SP3 workshop was held on 19.-20. December 2011 in Zürich. The workshop was a hazard feedback workshop. The content of the workshop can be summarized as follows: After a summary and discussion on the key SP2/SP3 interface issues (κ, σ of site amplification due to input motion and V/H models) hazard feedback was presented to each expert based on his models. The horizontal feedback was only a summary and update—where necessary—of the hazard feedback previously shown at workshop #5. The focus of the workshop was on the vertical hazard feedback and evaluation of the vertical expert models. During the two workshop days the SP3 experts presented and defended their choices on the weights for the logic tree branches for the median, maximum ground motion truncation and aleatory variability. As one SP3 expert was not available on the morning of the second day, this time was used by the other SP3 experts as working meeting to re-assess the liquefaction potential at the NPP sites, as this had been stressed by the review team as a topic which was not sufficiently addressed. It was decided to exchange about the mentioned interfaces issues with SP2 during the May 2012 interface workshop and to then finalize the SP3 evaluation summaries.

6.1.11 Working, Web-meetings and Individual Elicitation Meetings

In addition to the workshops, there were six working meeting and three web-meetings held for the SP3 experts. The meeting dates and topics discussed are listed in Tables 6.2 and, 6.3 for the working meetings and web-meetings, respectively. There were also expert elicitation meetings between the individual experts and the TFI which are listed in Table and 6.4.

Table 6.2: Overview of SP3 working meetings.

Date	Location	Topic
19.-20.01.2010	Zürich	Review of the additional requested data and development of the velocity models and the non-linear soil properties to be used for the site response calculations.
02.02.2010	Zürich	Discussion of the soil profiles and material parameters to be used for each of the three calculation methods and documentation of the models in a technical note.
05.03.2010	Zürich	Revision of proposed velocity profiles for KKM/EKKM (Dispersion curves, Eigenfrequency, Profile for NL and V_P profile, Measured data vs. velocity profiles and variability). Evaluation of KKG/KKN comments on velocity profiles. For Beznau and Leibstadt final definition of V_S-profiles and NL material properties.
06.05.2010	Zürich	Evaluation and revisions of reports: Finalization of site reports describing rationales, Revision and evaluation of spectra for RVT computation, Revision and finalization of output formatting specification. For the KKB/EKKB site revision of the profile P3 and material models.
03.11.2010	Zürich	Discussion with Resource Experts undertaking NL calculations on the preliminary results. Differences due to the Peak/RMS models used in the different codes (two alternative models used). Vertical component for NL runs.
19.-20.01.2011	Zürich	Maximum ground motion models for soil, Understand the PGA dependence of the amplification factors, Understanding causes for the differences between high frequency amplification for SHAKE and RVT, Comparison of EQL and RVT input spectra, Differences in RVT base case and EQL result for Gösgen: Test case with same layer thicknesses, Evaluation of different Peak-to-RMS models used in RVT, Review of non-linearity of amplification factor using KiK-net data, Effect of including vertical component for NL runs, Plots of non-linear amplification using PGA and SA as measure of strength of input motion, SP3 hazard sensitivity with both approaches using EQL results, Initial evaluation of liquefaction potentials, Additional aleatory variability to add to σ covered by SP2, Issues with $V_S - \kappa$ correction of SP2.

Table 6.3: Overview of SP3 web-meetings.

Date	Topic
08.02.2011 & 24.02.2011	Use of strain information to set threshold for transition between EQL and NL (PMT-RF-1339)
26.10.2011	Discussion of hazard feedback for horizontal motion logic trees of SP3 (TFI-RF-1424)
15.04.2013	Evaluation of new amplification functions for all sites after revision of SP2 Kappa (PMT-RF-1450)

Table 6.4: Overview of elicitation meetings between the TFI and individual SP3 experts.

Date	Location	Expert
03.05.2010	Zürich	A. Pecker & J. Studer
04.05.2010	Zürich	D. Fäh & P.-Y. Bard
29.11.2011	Zürich	J. Studer
30.01.2012	Zürich	J. Studer
17.02.2012	Zürich	A. Pecker
02.04.2012	Zürich	J. Studer
19.04.2012	Zürich	D. Fäh
03.09.2012	Zürich	P.-Y. Bard

6.2 New Site Investigations

6.2.1 Introduction

Initial situation and objectives

The PEGASOS site studies relied primarily on the original geotechnical data from the stage of reactor construction. The soil profiles were developed based on the velocity and density data contained in the original documents of that time. Only a few additional geophysical field measurements were undertaken within the framework of PEGASOS. The behavior of shear modulus (G) and damping values as a function of shear strain were taken from scientific publications, except for Beznau where specific laboratory data from the stage of reactor construction were available. No additional laboratory tests were performed within the framework of PEGASOS. Given the limitations of the available data, the range of uncertainty was relatively high for all parameters relevant to site response characterization.

The objective of the PRP was to significantly reduce the uncertainties of key model parameters. Before starting the PRP, each NPP performed a large site characterization campaign to better constrain the local soil parameters. The investigation program of the PRP focused on geophysical and soil dynamics investigations. This was done by means of field measurements, mainly for wave velocities, as well as laboratory testing, mainly for the non-linear behavior of the soil materials.

General Site Investigation Approach

The PRP management edited specifications for the geotechnical and geophysical investigations [Renault et al. 2008] (PMT-TB-1013) that had to be followed by the utilities so that types of available data would be consistent between the four sites.

First, the project representative of each utility had to compile and analyze existing documents and data. These data then had to be reviewed by one to three independent experts, who were not part of the PRP SP3 expert panel. These experts were hired by the utility and are, henceforth, referred to as "utility experts". The key questions to be answered were: What is the reliability of the existing data? Do more recent methods exist which allow more reliable data to be obtained? Are sufficient data available to allow uncertainties to be quantified? Which additional investigations could reduce or at least better constrain these uncertainties? The outcome of this first step was the development of a detailed site investigation program.

The investigation program had to allow the project responsible and the utility experts to:

- Compile an integrated shear wave velocity profile (V_S-profile) for the controlling site(s) considering all available (old and new) test results;
- Define the average shear wave velocity value in the upper 30 m of bedrock ($V_{S30,rock}$);
- Develop a relationship for G/G_{max} (normalized dynamic shear modulus) and the damping as function of the shear strain for the different soil types;
- Evaluate the potential of significant earthquake-induced pore water pressure increases and their effect on the relationship of G/G_{max} and the damping as a function of the shear strain;
- Analyze and quantify the uncertainties for all parameters (V_S-profile, non-linear parameters, ...).

Once the various investigations had been carried out, the project representative within the NPPs and utility experts interpreted the raw data in workshops and defined all the parameters mentioned above. All the data and their interpretations, in particular the velocity profiles, were delivered to the PRP SP3 experts for evaluation and review.

The following section devoted to the NPP Beznau ("KKB") serves as an example. It provides an overview of the site investigations and discusses many details of the interpretation of the measurement results. The objective is to illustrate the difficulties encountered in developing shear wave velocity profiles, based on the interpretation of inconsistent measurement results from different methods. These results diverged despite the fact that all field measurements and laboratory tests were carried out, by experienced and highly qualified teams.

Similar investigation programs to that at Beznau were conducted for the other NPP sites, and similar discussions about the measurement results took place among the experts. For the other NPP sites, only a very concise description of the most important aspects will be given in the present summary. For further details, the reader is referred to the corresponding detailed site-specific reports and Volume 5. All site characterization studies conducted at the four sites are listed in the following:

- Crosshole seismics
- Downhole and uphole measurements
- MASW (Multichannel Analysis of Surface Wave)

- SASW (Spectral Analysis of Surface Waves)
- Ambient vibration H/V and array measurements
- Laboratory testing (static and dynamic)*

* Mühleberg did not perform new laboratory testing.

6.2.2 Beznau

NPP Beznau ("KKB") is situated on the island of Beznau, in the river Aare. At the beginning of the PRP, a new replacement NPP ("EKKB") was also planned on the island. In what follows, only the KKB site is presented.

Site Investigations

A total of eight destructive jetted wells (SB1 to SB8) and three core drillings (KB1 to KB3) were executed covering both sites [NOK 2009]. An extensive measurement program was carried out in these boreholes as well as across the island (Fig. 6.1). Only the most important aspects of this will be mentioned here.

Figure 6.1: Island of KKB with all investigated seismic lines and boreholes.

At the Bezanu site, there is a superficial layer of coarse-grained fluvial deposits (essentially a compact gravel, with the water table at 5 m depth) with a thickness of about 9 m. Underneath, a relatively soft rock called the "Opalinus Clay" (a clayey marl) can be found down to a depth of around 80 m. The Opalinus Clay rests on a harder rock of the Lias formation. Top

Lias corresponded to the main impedance contrast in all three PEGASOS soil profiles for this NPP.

The geophysical borehole measurements were:

- S-wave crosshole measurements with horizontally polarized shear waves and P-waves, using 3 boreholes;
- Uphole measurements using small explosive charges (i.e. without significant shear waves);
- Downhole measurements with shear waves produced with the aid of horizontal hammer blows in opposite directions, allowing a reasonably good identification of the shear waves due to phase changes of 180°;
- Several borehole loggings (acoustic logging, gamma-ray logging and full wave sonic logging).

Ultrasonic laboratory measurements on several rock samples completed the borehole measurements. The main objective of the ultrasonic measurements was to capture the rock anisotropy.

Furthermore, geophysical surface measurements were carried out across the Beznau island and its surroundings. On the one hand, hybrid active seismic surveys, combining reflection and refraction seismics, were performed; the recorded data were then analyzed in a classical way as well as according to the MASW (”Multichannel Analysis of Surface Waves”) technique. On the other hand, single-station H/V as well as array ambient vibration measurements were carried out.

Extensive laboratory testing was also undertaken. From the three core drillings, samples of the coarse-grained gravel, as undisturbed as possible, had been taken every two meters in depth. In addition, four large samples had been taken from a trench located nearby. From these samples, the specific gravity was determined and the particle size distribution was obtained with the aid of 30 sieve analyses. Four large isotropically consolidated static triaxial compression tests on reconstituted samples of the fluvial deposits were also carried out. In addition, four large cyclic triaxial tests and four resonant column tests were performed in order to obtain the shear modulus and damping as a function of deformation.

With respect to the Opalinus Clay, a minimum of two undisturbed samples had been taken from each borehole. These samples had been protected against drying with a paraffin cover. The laboratory program consisted of four undrained static triaxial compression tests with multi-stage testing, i.e. each sample specimen was tested for several initial hydrostatic stress states, increasing from 1 MPa to 10 MPa. No new cyclic triaxial tests were performed, since the tests of the 1980s were considered to be reliable.

Site Investigation Results

All over the island of Beznau, almost identical H/V-curves were found at numerous measurement points, although the thicknesses of the gravel layer and the Opalinus Clay vary significantly (at KKB: 9 m of gravel and about 70 m of Opalinus Clay; at EKKB: 22 m of gravel and 34 m of Opalinus Clay). These H/V-curves show a first peak between 2.5 and 2.9 Hz (2.5 Hz according to Fäh's analysis procedure, 2.9 Hz according to a classical procedure). This peak was very stable locally and was consistent with results from previous measurements in 2001.

Whereas all the PEGASOS models assumed the main impedance contrast at top Lias, the 2009 crosshole measurements of V_S showed only a very modest jump in velocity, from 1400 m/s at the lower end of the Opalinus Clay to about 1550 m/s in the uppermost layer of Lias (Jurensis marl). The jump in V_P, however, was more pronounced at this depth, from about 3100 m/s to more than 4000 m/s.

The V_S values resulting from different measurement techniques varied enormously. The most striking example was the velocity in the Opalinus Clay. Values of 790 m/s (KB1) and 680 m/s (KB2) were measured downhole at 25 to 40 m depth, whereas values of 1450, 1810 and 2017 m/s were found for the same depth ranges in ultrasonic laboratory tests for vertically propagating waves. This is a discrepancy of more than a factor of 2. The 2009 crosshole tests gave values between 1200 and 1400 m/s at 25 to 30 m depth, whereas the crosshole tests carried out in 1980 showed values of only 700 to 800 m/s.

MASW measurements were carried out in the region between the sites of KKB and EKKB, where top Opalinus Clay is at about 20 m depth. A relatively strong impedance contrast was found at top Opalinus Clay, with V_S jumping from 700 m/s to 1300 m/s. Although the velocities in the Opalinus Clay might not be very reliable due to the depth limitations of MASW measurements, the estimated V_S value is in agreement with the 2009 crosshole results.

The difference between downhole and crosshole measurements in the Opalinus Clay can partly, but only partly, be explained by its strong anisotropy. NAGRA showed with laboratory tests on Opalinus Clay from the Benken borehole that V_P and V_S horizontal are 33% higher than V_P and V_S vertical, respectively [NAGRA 2001]. Essentially the same result was found for the same Opalinus Clay formation in the "Mont Terri Rock Laboratory" (horizontal 30% higher than vertical, measurements exist only for V_P).

The top of the Gipskeuper formation was considered as the base rock level; however, only two of the boreholes on the island of Beznau reached the Gipskeuper formation, and no crosshole measurements were performed at these depths because, at the beginning of the PRP, it was believed that the main impedance contrast was situated at the top of the Lias. To define the $V_{S30,rock}$ measured 30 m into the rock. Therefore, the mean velocity within 30 m the below top Gipskeuper was deduced from the V_P log of the nearby NAGRA Beznau borehole. V_P was transformed into V_S with the aid of the formation-dependent V_P/V_S ratios measured by NAGRA in the Benken borehole. However, since at smaller depths, for which crosshole results exist, the resulting V_S values were systematically 10% above the 2009 anisotropy-corrected crosshole V_S values, the V_S values deduced from the V_P were further multiplied by a fudge factor of 0.9. A value of $V_{S30} = 1800$ m/s was finally found.

As an alternative, the main impedance contrast was assumed to be at top Lias, and the velocities from the crosshole measurements were lowered by 10% within the gravel and the Opalinus Clay (in addition to the correction for anisotropy). This was done primarily in order to achieve a better match between the fundamental frequency of the transfer function and the H/V fundamental frequency. However, this also meant that the results of the downhole measurements, that gave significantly lower V_S values, were taken into account to some small extent.

Interpretations Proposed by the Utility Experts

The utility experts interpreted the results of the site characterization study and developed alternative candidate models for the velocity profiles and material properties. These utility expert interpretations served as proponent models to be evaluated later by the SP3 experts in the SSHAC evaluation procedures. Three shear wave velocity profiles were developed, mainly based on the 2009 crosshole results, corrected for anisotropy. The profile called "KKB MK-1" represents their best estimate median profile. Two alternative V_S-profiles, called "KKB MK-2" and "KKB PM" were developed (see Figure 6.2). The KKB PM model was based more on geological considerations than on pure measurement data.

The V_S of the model MK-2 is 0.9 times the V_S of the MK-1 model down to the base of the Opalinus Clay. Below this, the deep structure is not modeled in detail. MK-2 assumes the main impedance contrast is at the top of the Lias. The V_S at depth for MK-2 is increased to match the 1800 m/s for the MK-1 and PM models so that there is a single reference rock velocity.

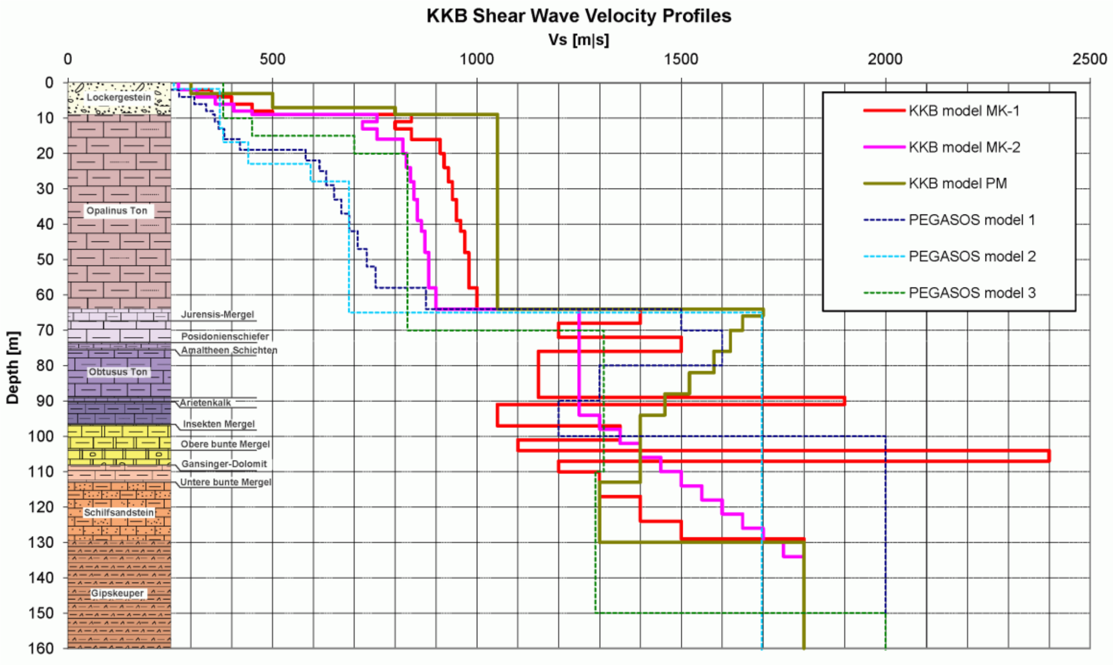


Figure 6.2: Shear wave velocity profiles for NPP Beznau as proposed by the utility experts, in comparison with the original PEGASOS profiles (from part 3 of NOK report KKB-213-D0016).

The utilities developed a single compression wave (P-wave) velocity profile based on the model MK-1 and, as far as possible, on measured V_P/V_S ratios. From top Opalinus Clay downwards, the ratio of V_P/V_S was determined with the aid of the 2009 crosshole measurements. A value of 2.25 was found within the Opalinus Clay, whereas a value of 2.5 or slightly more could be deduced below top Lias. However, since NAGRA had measured an average Lias V_P/V_S value of 2.0 in the Benken borehole, a value of 2.25 was also used for all formations below top Lias.

Within the gravel layers, no V_P values could be found by the 2009 crosshole measurement campaign. Therefore, a standard value of V_P/V_S of 2.5 was used to estimate V_P from V_S within the gravel.

With respect to the material models, the utility experts considered the new laboratory results for the gravel to be consistent with the old test data from 1980. They recommended using the old $G/G_{max}(\gamma)$ and $D(\gamma)$ curves as best estimate curves and to delimit the lower and upper bound curves enveloping all available test results.

No new tests had been conducted for the Opalinus Clay. Therefore, it was recommended that the results from 1980 should be used, considering an uncertainty range analogous to the one used for the gravel.

SP3 Candidate soil models

The PRP SP3 experts worked together to develop a consensus suite of candidate velocity profiles and non-linear material property models. Using the same set of candidate models allows for efficiency in the site response calculations. The goal in defining the consensus set of models was to cover the range of models that were considered applicable by any of the experts. The SP3 experts will later assign their own weights to the alternative models.

Candidate Shear wave velocity profiles determined by the SP3 experts

The SP3 experts, evaluated the suite of proponent velocity profiles proposed by the utility experts. To help constrain the profiles and to address the inconsistencies between the different measurements, the SP3 experts used the resonance frequencies from V/H ratios and dispersions curves from both MSAW and ambient vibration (AMV). The main reason for relying on the MASW and AMV techniques is that they capture the behavior of a site in an average sense, as it would be relevant to seismic waves, whereas crosshole measurements may be affected by very small scale heterogeneities that are not significant for seismic waves with wave lengths of several tenths or hundreds of meters.

Based on the observed data, the SP3 experts defined limits on the dispersion curves and required that the theoretical dispersion curves for the profiles fall within this range (see Figure 6.4). They found that the PM model was not consistent these data and it was rejected. For the other two utility expert proponent profiles, they found that the Rayleigh wave velocities were too high at intermediate to high frequencies. This could be corrected by the introduction of some weathering in the upper part of the Opalinus Clay and using lower velocities in the superficial gravels. The proponent profiles MK-1 and MK-2 were modified by trial and error so that they were consistent with the dispersion curves and resonance frequencies. In addition, the SP3 experts modified the depth of the top of Lias.

The utility experts assumed top Lias at a depth of 64 m, as was the case for two out of the three PEGASOS profiles (see Figure 6.2). In fact, none of the well reached the top of Lias below the reactors. In the four wells situated around the reactors, the top of Lias was found at depths varying from 59 m to 90 m. The interpolation of these values led to depths of 85 m and 76 m for reactors 1 and 2, respectively. Therefore, the SP3 experts assumed an average depth of 80 m for the top of Lias (see Figure 6.3).

In the end, the SP3 experts defined four new velocity profiles, denoted P1 to P4. Figure 6.3 shows the four profiles, together with the new measurement data. The basis for these four models are discussed below.

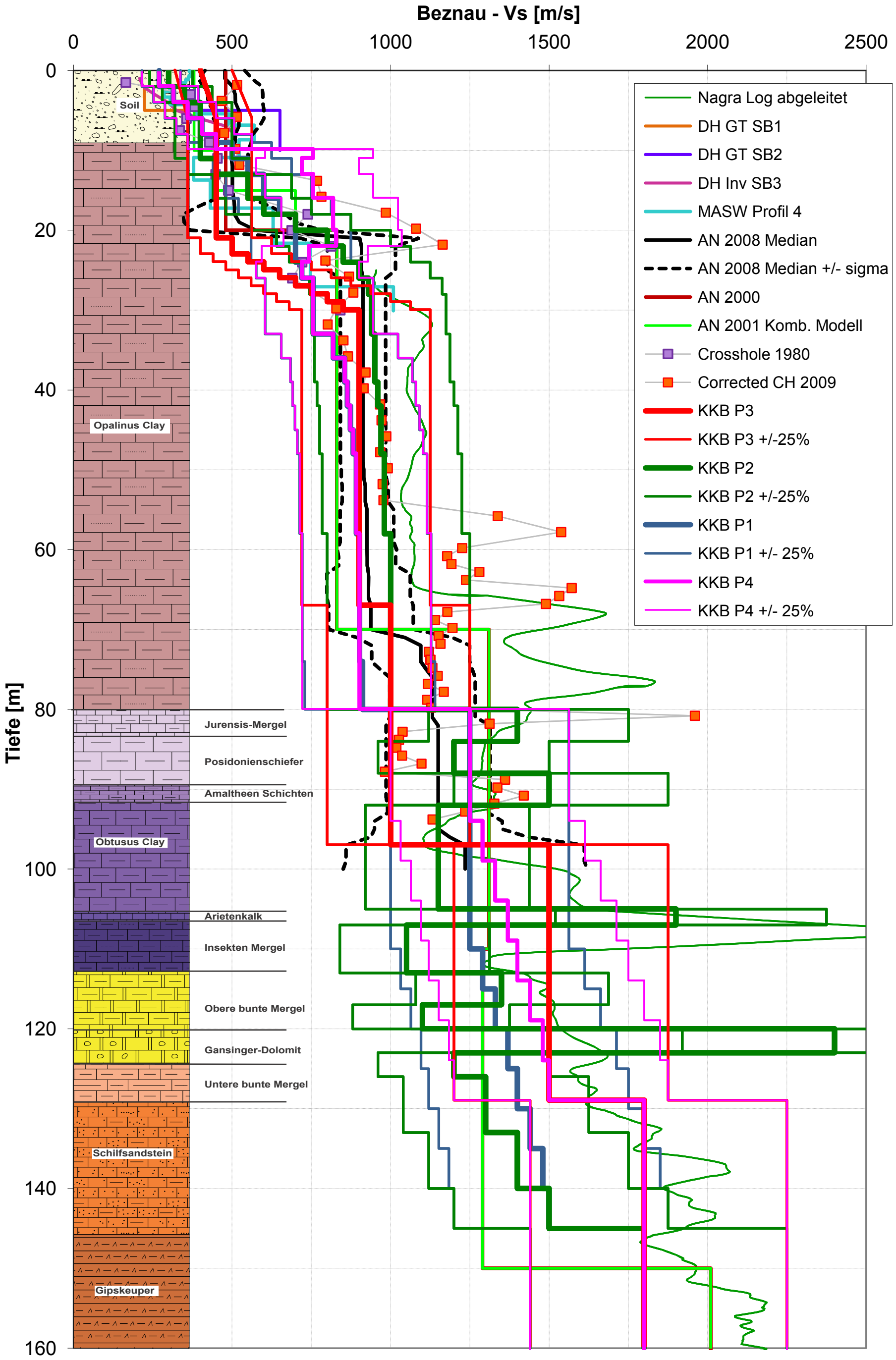


Figure 6.3: The KKB profiles P1 to P4 developed in the PRP in comparison with measurement results.

Model P1 is based on model MK-2, which does not take into account the short wavelength vertical heterogeneities associated with thin lithographic layering below top Lias. The main modification to model MK-2 concerns the upper 15 m of Opalinus Clay: the velocity was significantly reduced between 9 and 24 m depth, and there is no longer a low velocity zone in the uppermost Opalinus Clay. The dispersion curves of P1 are consistent with the AMV dispersion curves at intermediate frequencies and the high frequency low MASW velocities (low surface velocities in the gravel).

Model P2 is based on MK-1 with the "complex" velocity profile below the top of Lias, following the crosshole data. Again, the main modifications were reductions in the velocities in the gravel layer and in the upper Opalinus Clay. In the gravel layer, the velocity varies from 270 to 450 m/s (instead of 400 to 500 m/s) in order to match the MASW results. In the Opalinus Clay, there is an almost linear velocity gradient down to 26 m, without any velocity jump at the interface between gravel and Opalinus Clay. Again, the rationale behind these modifications was a better matching of measured dispersion curves at intermediate (AMV) and high (MASW) frequencies (see also Figure 6.4).

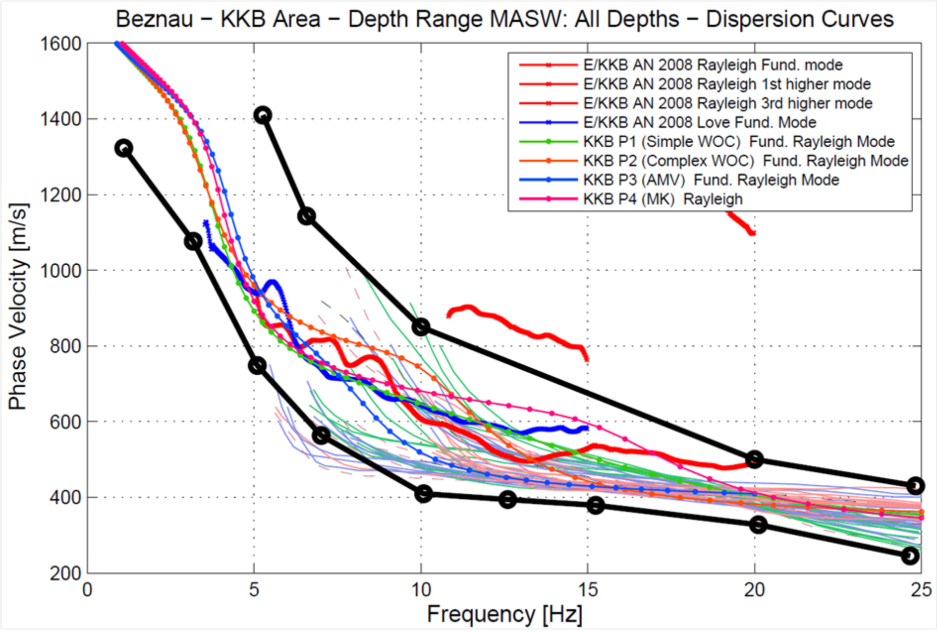


Figure 6.4: Dispersion curves for Beznau in comparison with bounds fixed by the SP3 experts.

Model P3 is the simplest model as it is essentially derived from the inversion of dispersion curves, which does not allow the resolution of thin layers. The base model was the model proposed by SED on the basis of array recordings of ambient vibrations, with some simple extrapolation at large depth on the basis of borehole data, and some reduction in the upper part of the Opalinus Clay to better fit the MASW results not taken into account in the original inversion. The main impedance contrast of this model, i.e. top of bedrock, is situated at a depth of 97 m, i.e. well below the top of Lias.

Model P4 is very similar to the initial MK-2 model with only slight adaptations.

The utility experts and two of the SP3 experts initially considered the shear wave velocities of model P3 to be too low, particularly in the gravel layer. In extensive discussions, the experts tried potential alternatives with higher V_S in the soil layers which also satisfy the eigenfrequency and dispersion curve criteria. However, no viable alternative was found. Finally, the shear wave velocities in the soil layers in profile P3 were accepted because the criteria eigenfrequency, dispersion curve and rock velocities were all satisfied.

Figure 6.5 shows the four profiles P1 to P4 in comparison with the three original PEGASOS models. In addition to the median values, Figure 6.5 also contains ±25% boundaries which were considered as corresponding to ± two standard deviations. This assumption was based on pure expert judgment, the value of 25% being slightly lower than that proposed by the utility experts (30%).

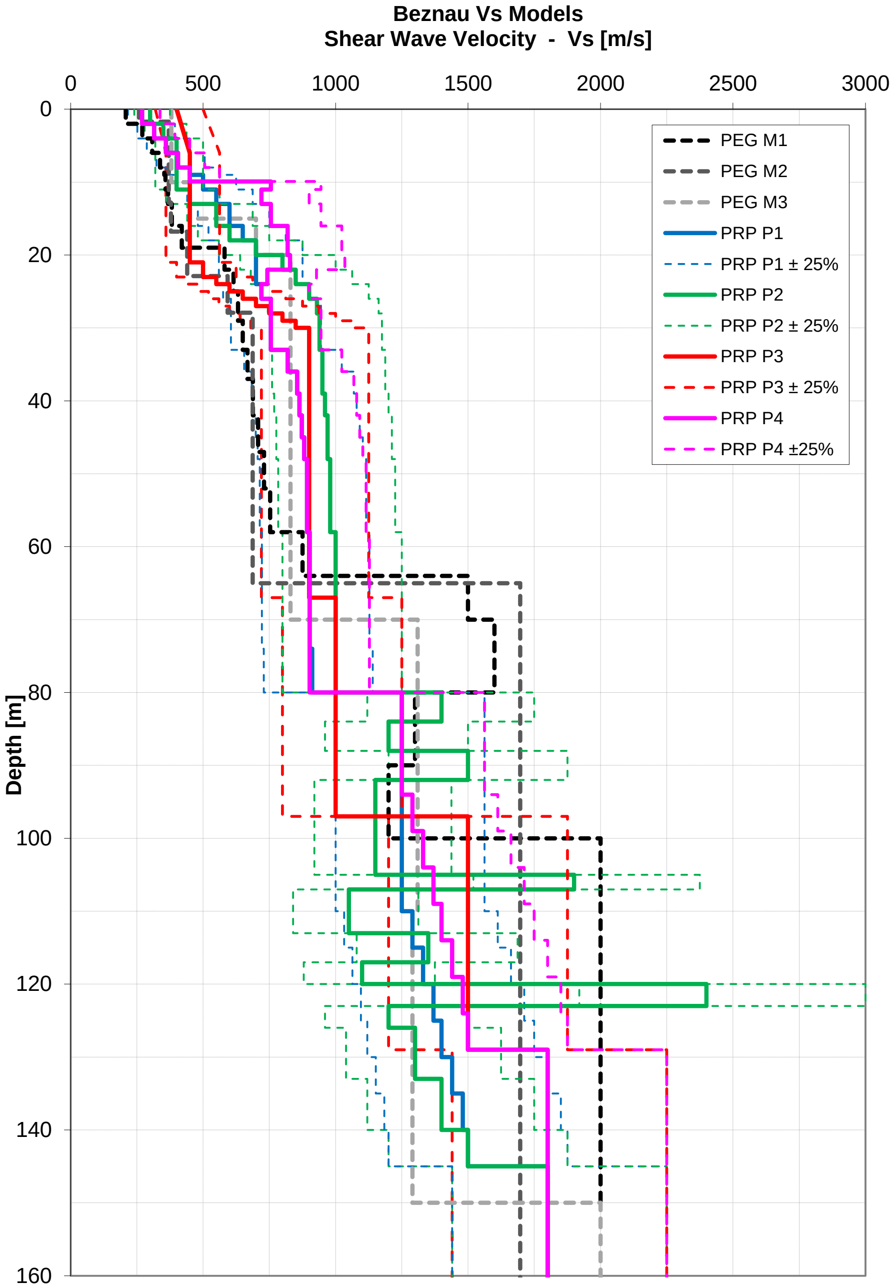


Figure 6.5: KKB velocity profiles (median values and ±25% boundaries) in comparison with the original PEGASOS profiles.

Candidate Compression Wave Velocity Profile Determined by the SP3 Experts

A single V_P profile was developed. The V_P profile was derived by taking the preferred model (P1) and applying a V_P/V_S ratio of 2.5 in the loose soil above the water table, and the square root of 3 in the rock; this is equivalent to assuming a Poisson's ratio of 0.4 in the loose soil and of 0.25 in the rock. Below the water table in loose soils, the compression wave velocity was calculated based on the theory of a two-phase material, soil and water; a compression wave velocity higher than 1500 m/s resulted from this if the water was assumed to be perfectly de-aired.

The variability of the V_P profile was defined as ±25% above the water table and in the rock, but only ±10% in the soil below the water table.

Candidate Material Models Selected by the SP3 Experts

The selected non-linear material property models were based on laboratory testing results and on the results published by Rollins et al. [1998] and Menq [2003]. Menq's curve takes into account a dependence of G/G_{max} on the confining stress, while Rollins' curve does not. Furthermore, Menq's curve corresponds to a weaker material compared to Rollins.

The examination of the G/G_{max} curves showed that Menq's mean curve coincided with the lower bound of the test data and Rollins' mean to the upper bound. Therefore, the mean curve was defined by the SP3 experts as the average between the lower and upper bound curves. As lower bound for the damping, Rollins' mean damping curve was used, while Menq's mean curve was used for the upper bound. Those curves were slightly modified to better fit the observed data.

Based on observations as well as on theory, it is known that a stiffer material exhibits lower and a softer material higher material damping. Therefore, a negative correlation was introduced, meaning that higher stiffness values had to be combined with correspondingly lower damping values, and vice versa.

The rock layers below top Lias were treated as being visco-elastic, with a constant damping ratio of 0.5%.

6.2.3 Gösgen

The Gösgen site consists of well graded, highly compacted gravel on top of a relatively "hard" bedrock whose top is at ∼28 m depth. No distinction was made between the sites of the NPP Gösgen ("KKG") and its replacement NPP ("KKN"), since the geological and geotechnical situation is very similar for both sites. Therefore, all measurement data were merged together for the elaboration of velocity profiles.

Similar problems of very divergent measurement results arose, as in the case of Beznau. In particular, downhole velocities were much lower than the corresponding crosshole values. A special aspect at Gösgen, however, is worth mentioning: Whereas all H/V measurements led to a peak around 4 to 5 Hz, the amplitude changed considerably across the site, and some H/V diagrams showed an additional lower frequency peak around 0.6 Hz. This was interpreted by the SP3 experts as the fundamental frequency of the entire structure down to about 660 m depth, which would then result in V_S values below 2000 m/s over thick layers in the rock, whereas crosshole measurements indicated V_S values of about 2500 m/s at shallow depths below top bedrock. In total, six V_S profiles were defined for the Gösgen site.

In order to account for the uncertainties in the measured shear wave velocities in rock, several models for the rock were proposed that explain some of the observed features. No model explains all observations. The models that explain the H/V peak at 0.6 Hz and the dispersion curves from ambient vibration observations are the models P1 and P2, which are characterized by a velocity inversion at greater depth. Model P2 takes into account the slow average shear waves in rock obtained from downhole measurements at different borehole sites, whereas model P1 considers the measurements from crosshole and sonic logs in the uppermost rock layer. Both models consider an average soil velocity profile with a total thickness of 28.5 meters. The rock reference velocity is defined as 2500 m/s, which is reached at a depth of 558 m.

Additional models with high shear wave rock velocities were included (models P3, P4 and P5), as originally proposed by the utility experts. These rock models were derived mostly from crosshole measurements and the sonic logs. Model P3 is based on measurements performed by NAGRA [2001] in the Benken borehole. In the soil layer, an average soil-velocity profile is taken with a total thickness of 27.5 m. The rock reference velocity of 2500 m/s is reached at a depth of 80 m.

Models P4 and P5 are selected to cover the range of measured velocities in the soil layer, as defined by the measured dispersion curves. The rock layer is chosen assuming a constant velocity in the uppermost layer that corresponds to the rock reference velocity of 2500 m/s, which is reached at a depth of 27.5 m.

For the true non-linear (NL) calculations, only one of the velocity models, namely P1, considered to be the best estimate model, was selected. However, since non-linear computations are restricted in model size and can barely treat models of a depth of 500 to 600 m, a new shorter model was defined (called P6) that combined the soil profile from model P1 with the constant rock velocity of models P4 and P5.

6.2.4 Leibstadt

Roughly speaking, the site of the NPP Leibstadt consists of a gravel layer of 41 m thickness above relatively hard bedrock (top Wellenmergel at 41 m depth).

Three shear wave velocity profiles were defined by the SP3 experts (Volume 5 contains figures with all V_S profiles). Profile P1, is mainly based on AMV and MASW data, whereas profile P2 is based on crosshole data, with corrections taking into account anisotropy (higher horizontal than vertical velocities). The third profile, P3, is a hybrid; surface wave data have been used for the gravel layer, and crosshole data in the bedrock.

The degree of cementation of the gravel layer beyond 30 m depth was a topic of to discussions in the SP3 workshops and meetings. Inspection of a trench indicated that only individual lenses were cemented. However, all attempts to have reduced velocity to mimic the absence of a cemented layer did not provide any acceptable match with observed dispersion curves. Therefore, all three profiles consider relatively large shear-wave velocities for the deep gravel.

It turned out that the PEGASOS profiles had been erroneous by a height mismatch of 7 m. All the measurements carried out before the construction of the reactor were referenced with respect to the natural surface, whereas during construction, a layer of gravel of 7 m was removed. This removal had not been taken into account by the original PEGASOS models.

With respect to the material models, smaller damping values were assumed within the cemented layer at low strain levels, but essentially the same damping values as for the uncemented layer were taken into account for larger strain levels, assuming that the cementation would be broken at these strain levels.

6.2.5 Mühleberg

The site of the NPP Mühleberg consists of a gravel layer of about 8 m thickness above a relatively "soft" Molasse bedrock.

As for Gösgen, no distinction was made between the sites of the NPP Mühleberg ("KKM") and its replacement NPP ("EKKM"). Therefore, all measurement data were merged together for the elaboration of velocity profiles. Local variability in the measurement results was taken into account with the aid of four velocity profiles. The four velocity profiles for KKM are illustrated in Volume 5 of this report.

The first profile, P1, is a kind of "composite" model, based on MASW and H/V measurements for the gravel, and on downhole and crosshole data in the underlying Molasse; it was proposed by the utility and is considered as the "best estimate" profile. Additional profiles were derived mainly from the surface wave measurements, which could be interpreted in different ways, depending on the identification of some dispersion curves as corresponding to the fundamental or the first higher mode of Rayleigh waves. P2 is defined as low velocity gravel over an only weakly weathered Molasse. P3 assumes a high velocity gravel layer overlying a significantly weathered Molasse. A fourth profile , P4, was finally defined that gave a better match with the relatively low phase velocities observed in the western part of the site; it includes both a gravel layer with very low velocity (around 200 m/s) and a 20 m thick, significantly weathered Molasse layer.

6.3 Site Response Evaluations

Based on the proposed site-specific soil profiles and material properties, 1D site response computations were performed according to the technical specification in Renault and Abrahamson [2010] (PMT-TB-1014) and Renault [2013a] (PMT-AN-1132). Three types of computations were performed:

- SHAKE type [Schnabel et al. 1972]
- RVT* (base case and with randomized profiles) [Vanmarcke 1972, 1975; Der Kiureghian 1980; Boore 1983]
- True non-linear

The time histories to be used for the site response computations were defined by Bommer [2009] (TP5-TB-1020) and subsequently modified by Abrahamson [2010b] (TP5-SUP-1007) to match the SP3 requirements. The RVT input response spectra were developed by Abrahamson [2010a] (TP3-SUP-1009). Based on the SP2 reevaluation of κ in 2013, a new set of input records was defined (see Renault [2013a]; Gregor [2013], PMT-AN-1132, EXT-TN-1265 and TP3-WAF-1023) to be consistent with the high frequency content for the final κ values.

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*Random Vibration Theory

Renault [2011a] provides an overview of all computations performed per site for each type. All results from the different contractors were gathered by the project and compiled into a database [Hölker 2013a], which facilitated the comparison and uniform plotting of the results for the SP3 experts.

The different software codes used by the contractors are listed in Table 6.5. Various comparisons and quality assurance runs were performed and are documented in: QA-TN-1118, TP3-TN-1123 and TP3-TN-1169.

Table 6.5: Software codes used for the site response analyses.

Site	SHAKE	RVT	Non-Linear
KKG	SHAKE-AR by R. Attinger	APASHAKE by A. Asfura	Dynaflow (SUMDES for cross check)
KKB & KKL	SHAKE91 by. Idriss & Sun (1991)	RASCALS by W. Silva	SUMDES (Dynaflow for cross check)
KKM	SHAKE 10 modified version of SHAKE [Schnabel et al, 1972] by AMEC Geomatrix	STRATA by A. Kottke and E. Rathje	SUMDES (Dynaflow for cross check)

The ground motion results at surface and depth are provided as outcropping motion.

6.4 Candidate Models for Very Strong Rock Ground Motion - Maximum Ground Motion on Soil

There is no well-established method for estimating the maximum ground motion that a soil profile can transmit to the ground surface. However, it is recognized that the soil cannot transmit arbitrarily large motion due to its limited shear resistance capacity. This maximum motion can be estimated from numerical analyses such as those carried out for the five NPP sites with increasing input motions, from theoretical models based on an assumed soil constitutive behavior and from experimental evidence gathered during actual earthquakes. All three approaches were evaluated by the SP3 experts.

- Basically, two fundamentally different approaches were discussed:
    - A mechanical approach: estimating the maximum PGA from the maximum resistance of the soil material, and associating a normalized response spectrum
    - An empirical approach: estimating the maximum spectral ordinate for each frequency on the basis of observed maximum ground motion throughout the world
- Three different mechanical approaches were considered:
    - the theoretical model of Pecker [2005];
    - the theoretical model of Betbeder-Matibet [1993];
    - the non-linear site response analyses carried out for the derivation of the amplification functions.

Pecker Method

The model of Pecker [2005] allows the study of a soil layer of finite thickness overlying a stiff bedrock, considered as a rigid boundary. A simpler precursor of this model was previously used in PEGASOS.

The S-wave velocity is assumed to vary with depth according to some power law:

$$V(z) = V_s \left(\frac{z+d}{h+d}\right)^{\frac{p}{2}} \tag{6.1}$$

The parameter d has been introduced to allow for a non-zero shear wave velocity at the ground surface.

The motion of the soil layer—the ground surface acceleration as well as the shear strain as a function of depth—was calculated by means of a modal superposition. The spectrum of the rock input motion was taken as the mean response spectrum calculated over the ten time histories that were used in the PRP to represent a magnitude 6 event. This mean spectrum was computed for 20% damping and scaled to 10 $\mathrm{m/s^2}$. Since the model deals with large strains, close to soil failure, it is reasonable to assume that the soil damping ratio is at least equal to 20%.

A linear elastic, perfectly plastic constitutive equation was used for the soil layer, fully defined by two parameters, the shear strength τ_{max} and the yield strain γ_f.

The shear strength was assumed to be of the form

$$\tau_{max} = \sigma_v' \tan\phi + c, \tag{6.2}$$

where σ_v' is the effective vertical stress, ϕ is the soil friction angle and c the cohesion. The yield strain is given by

$$\gamma_f = \frac{\tau_{max}}{G}. \tag{6.3}$$

Because τ_{max} is essentially proportional to σ_v' and G to the square root of σ_v', the yield strain is also nearly proportional to the square root of σ_v' (in PEGASOS, the yield strain was assumed to be independent of depth). For very shallow depth, it is assumed that γ_f is at least 1%.

The calculated shear strain can be compared with the yield strain over the whole depth of the soil layer. The input motion can then be scaled until the curve of the shear strain touches, at some critical depth, the curve of the shear strength. Then, the ground surface acceleration corresponding to this scaled input motion can be considered as the maximum possible ground motion above the critical depth. Figure 6.6 shows the application of this procedure to the Beznau site. At the Swiss NPP sites, which are all gravel sites, the critical depth was between 2 to 3 m with corresponding maximum surface accelerations between 1.8 and 2.5 g.

Betbeder-Matibet Method

The model of Betbeder-Matibet [1993] was previously used in the PEGASOS Project; it is similar to Pecker's model, but simpler. The shear modulus is assumed to be constant with depth, whereas the constitutive equation of the soil is given by the hyperbolic model. Only

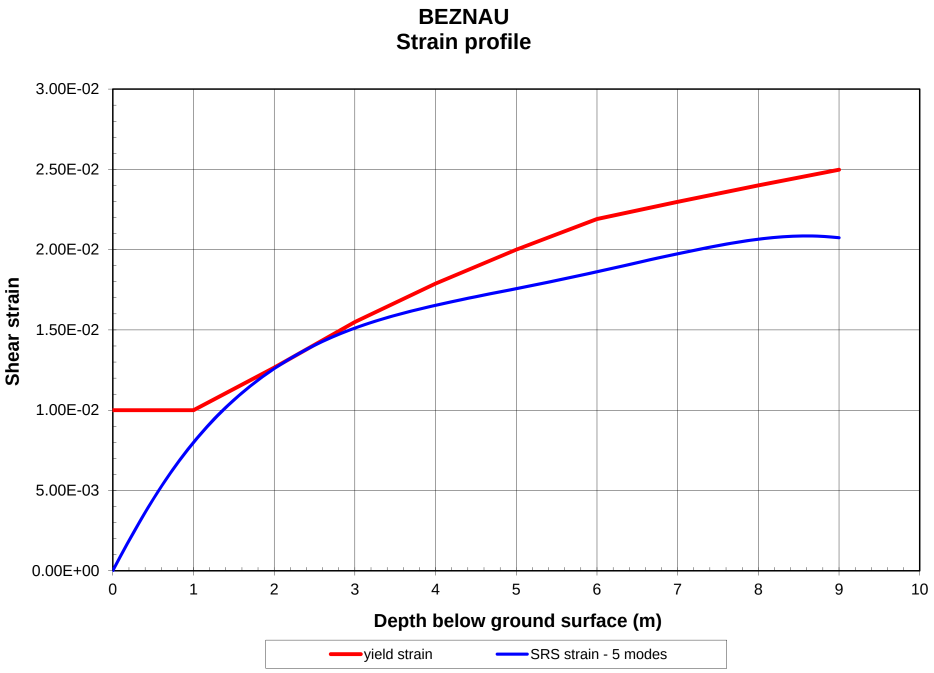


Figure 6.6: Determination of the maximum ground motion at the KKB site using Pecker's method; the critical depth where the shear resistance is first reached is about 2.5 m for a surface acceleration of 2.5 g (24.6 m/s^2). For this example Sa* are equal to 4.84 m/s^2 (first mode) and 15 m/s^2.

the fundamental mode of the soil column is considered. The average soil column acceleration is limited by the available shear strength τ_{max} at the base of the profile divided by the mass of the soil column. Finally, the surface ground acceleration is deduced from the average soil column acceleration based on the fundamental "non-linear" mode shape. The maximum accelerations calculated with Betbeder-Matibet's model are up to 40% smaller than those obtained with Pecker's model.

Non-linear Site Response Method

The non-linear site response analyses conducted for the site amplification can also be used to estimate the maximum surface ground motions. At high levels of input motion, as the input rock motion increases, there is only a small increase in the short period surface ground motions on soil. Figure 6.7 illustrates this limit on the surface ground motion with the example of the mean ground surface accelerations at Gösgen for 30 Hz as a function of the PGA of the input rock motion. Although the input rock PGA increases from 0.75 g to 2.5 g,the resulting soil acceleration is nearly constant.

The non-linear site response analysis used 10 input time histories. An upper bound of acceleration had to be determined from this set of analyses. The 85% fractiles of the results for the upper bound soil properties was selected. Use of the upper bound soil properties maximize the soil strength. Because most non-linear calculations are unreliable for frequencies above 30 to 40 Hz, the spectral accelerations at 30 Hz were used as proxies for the PGA. Potentially, this slightly overestimates the true PGA.

The resulting maximum ground surface accelerations are almost site independent. This could

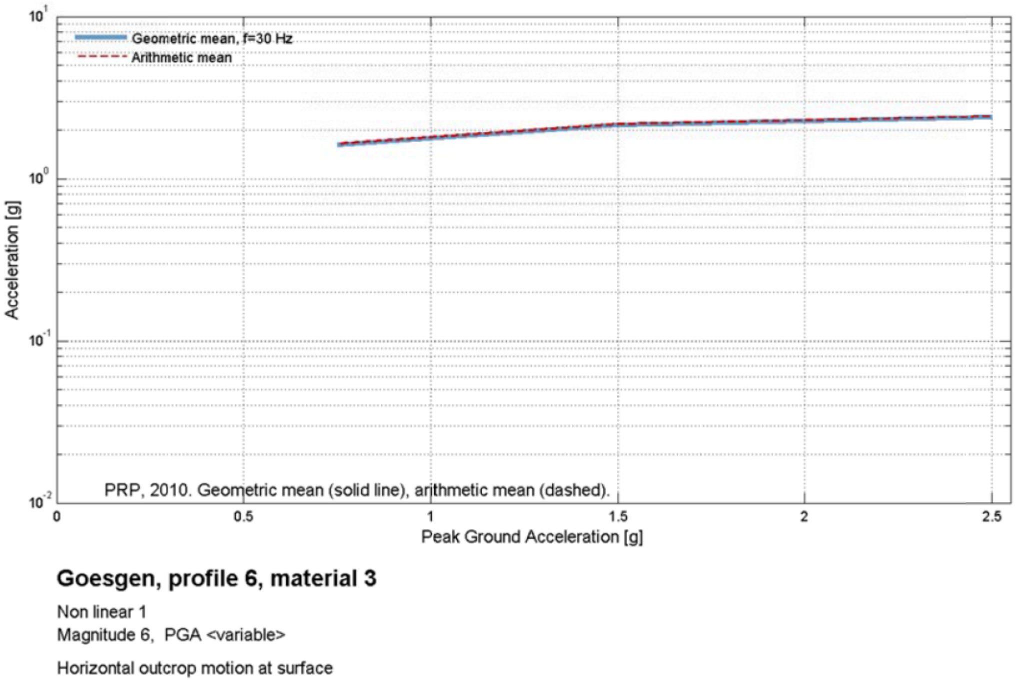


Figure 6.7: Variation of spectral acceleration at 30 Hz with PGA on rock (Gösgen).

Table 6.6: Maximum ground surface accelerations [g] according to different methods of estimation. The two values stemming from the NL site calculations correspond to the mean value and the upper 85% fractile, respectively. The Pecker (2005) model is listed as the "Theoretical model".

	KKG	KKB	EKKB	KKL	KKM
Theoretical model	2	2.5	2.2	1.8	2.1
Betbeder's model	1.4	2	1.5	1.5	1.5
Non-linear site Response analyses	2.5 - 3.0	2.3 - 3.0	2.1 - 2.7	2.2 - 2.8	2.1 - 2.7
Proposed range of values	2.5 - 3.0	2.5 - 3.0	2.2 - 2.7	2.3 - 2.8	2.1 - 2.6

be explained by the fact that all sites have similar strength characteristics and that, according to the results of Pecker's model, the thickness of the soil layer does not seem to play a major role because the maximum shear strength at shallow depth is what is most relevant.

Table 6.6 shows the maximum ground surface accelerations resulting from the three different methods applied, together with the range of values that were used by the SP3 experts. The non-linear site calculations led to the highest values: 2 to 3 g, but all three methods lead to results within a factor of 2 of each other.

Empirical Approach

The empirical approach simply looks at the maximum ground motion ever recorded for each frequency. Clearly, such an approach can only provide a "lower bound", since such "maximum" motions can only increase with the increasing number of instruments and seismic events. In fact, Figure 6.8, based on a compilation by Strasser and Zulu [2010], shows how the maximum values ever measured have increased with time; no ”saturation” has been identified yet. Therefore, larger values might be expected to be observed in the future.

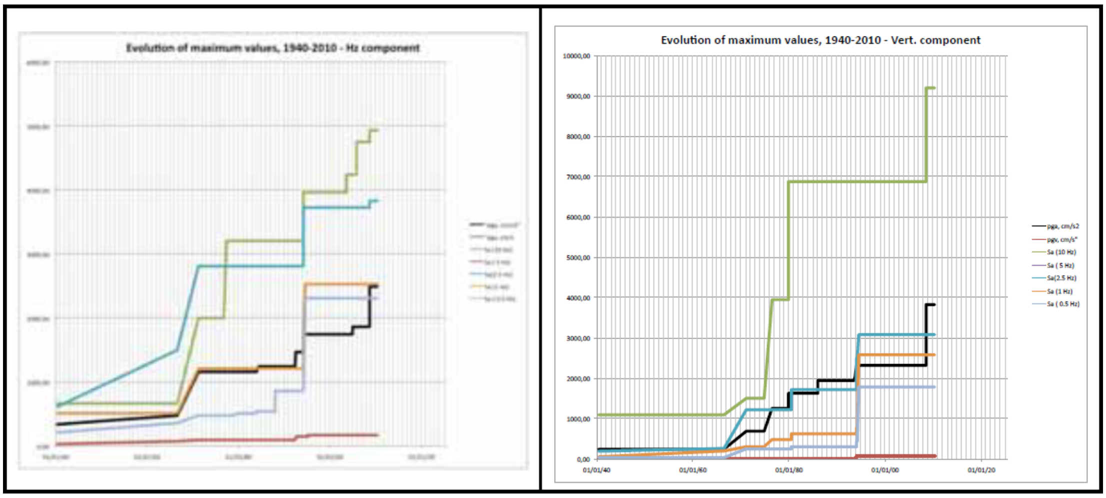


Figure 6.8: Evolution of maximum values for PGA, PGV and different spectral accelerations as a function of time (1940 - 2010). Left: horizontal component; right: vertical component.

Simply looking at the strongest values ever measured is not site-specific, since sites are grouped in very rough site categories. However, this approach has the advantage of being totally free of any underlying model, and may, therefore, reflect the level of maximum ground motion that one may reasonably anticipate, irrespective of any other considerations on the regional seismic hazard and local site conditions.

6.5 Expert Models

The different expert models—essentially the SP3 logic trees—are described in detail in the experts' Evaluation Summaries (EG3-ES-1014 to EG-ES-1017, see Volume 5). In what follows, an attempt is made to present the most relevant aspects, highlighting and explaining the diverging views of the experts as far as this is feasible in a concise way. The emphasis is on the median amplification of horizontal ground motion. Since the expert models are quite differently structured, in many respects, any concise overview must necessarily remain incomplete. A discussion of how the individual SP3 models represent the Center, Body and Range of the technically defensible interpretations is given in Section 10.5.

In the present summary, essentially only ground motions at surface level are addressed. The chapter on horizontal ground motion contains some indications about ground motion at depth.

6.5.1 Median Amplification of Horizontal Ground Motion

The approaches and overall structure of the logic trees of all four SP3 experts are different. Therefore, the structure of the logic tree of each expert are described briefly in a first step. Then, the principal weights for each NPP site are presented in a second step.

Logic Tree of P.-Y. Bard

The basic logic tree is presented in Figure 6.9. It includes the following branches:

- Velocity profile
- Non-linear properties of the soil deposits
- Computation approach
- Uncertainty sub-branch for the NL calculations
- Amplification factor (AF) interpolation and extrapolation schemes
- 2D/3D effects; the branches take into account epistemic uncertainty with respect to these effects

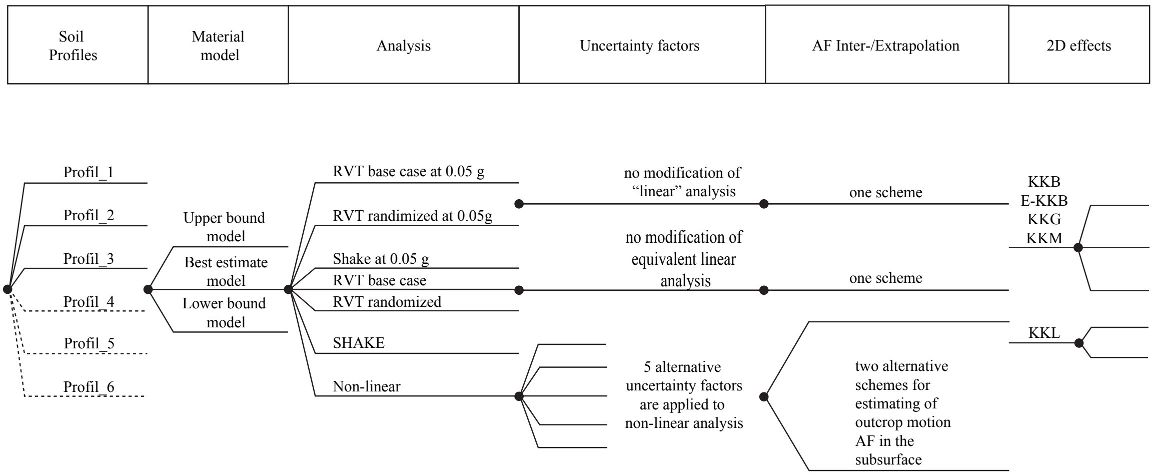


Figure 6.9: Basic logic tree of P.-Y. Bard for the amplification of horizontal ground motion.

Further, for ground motions at depth:

- Estimation of the "outcropping" AF for NL calculations where only "within" AF are readily available (included at the interpolation scheme level)
- Estimation of 2D/3D effects at depth, different from those at the surface

In his evaluation summary, P.-Y. Bard discusses the advantages and shortcomings of borehole and non-invasive wave velocity measurements, the latter providing direct estimates of the surface wave dispersion curves. He points out that "while the present practice in the geotechnical earthquake engineering community is to rely more on borehole measurements, I consider both types should be given an equal weight." This concept is his main criterion for assigning weights to the velocity profiles (see site-specific chapters).

At the second branching level, the weights for lower bound (LB), best estimate (BE) and upper bound (UB) material models depend on the site.

The weights of the different AF calculation approaches are given in Figure 6.10. They depend on the strain γ, normalized by the reference strain γ_{50} at which the shear modulus is reduced to half of its initial value. In order to calculate the PGA values corresponding to the strain levels considered, the results of the RVT base case calculations are used; the reason is that these calculations cover the full domain of interest of the input parameters.

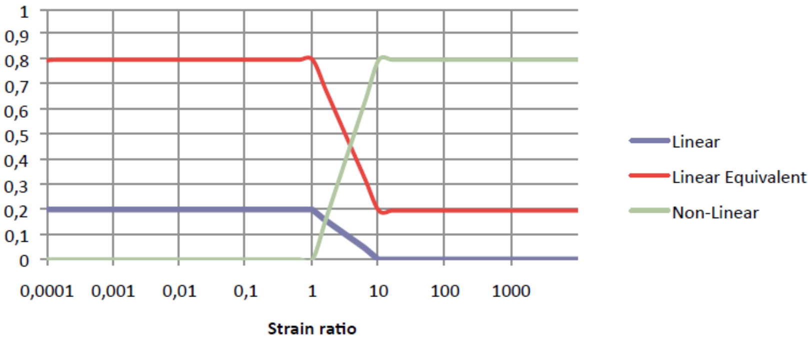


Figure 6.10: Relative weights of the linear, equivalent linear and non-linear results of amplification function calculations as a function of strain ratio.

The relative weighting between SHAKE and RVT results exhibits strong frequency dependence; it is essentially governed by the following considerations:

On the one hand, the computation of response spectra through the RVT approach is reliable at intermediate and high frequencies (large number of cycles), but it is not reliable at low frequencies (few cycles) because of the approximation used for the peak values, which is only satisfactory for a large number of cycles.

P.-Y. Bard assigns a relative weight of 1 to SHAKE results below 0.5 Hz. Between 1 Hz and 15 Hz, he gives equal weights to SHAKE and RVT results (except for Leibstadt where the weight is 0.6 for RVT). Finally, above 30 Hz, the relative weights of SHAKE and RVT results depend on the high frequency content of the input rock motion for each NPP site. Between the indicated frequencies, the weights are linearly interpolated on a logarithmic frequency scale.

Since the parameters to be used in fully non-linear calculations were not 100% constrained by the available information, and since only relatively few NL calculations were carried out, Bard adds a sub-branch that introduces five alternative additional uncertainty factors. For each site, the values of these uncertainty factors are estimated by judgment based on the differences between the NL results obtained by different computer codes and contractors (primary analysis and cross check analyses).

For interpolations of available amplification functions for PGA and magnitude values where calculations are "missing", an interpolation (and extrapolation) scheme is used that is based on RVT base case calculations. This scheme consists of piecewise one or two-dimensional linear interpolation on a log scale for PGA, and a linear scale for magnitude.

With truly NL calculations, only "within" motions can be obtained; it is no longer evident to differentiate up-going and down-going wave trains. Therefore, "outcrop" motion at depth is estimated in analogy to the equivalent-linear (EQL) case. Two different schemes are proposed. The first one assumes that the variations with depth are similar for the NL and EQL approaches; the NL AF at the surface is reduced at depth as it would result from an analogous EQL calculation. The second one assumes that the differences between outcrop and within motions are similar for the NL and EQL (SHAKE) approaches. Scheme 1 leads to more stable results, but does not take into account possible localizations of deformation in NL calculations. Therefore, a slightly higher weight (0.6) is assigned to scheme 2 compared to scheme 1 (weight 0.4).

The subsoil/surface topography structures always exhibit some amount of lateral variation. A few 2D-computations for Leibstadt were carried out in the PEGASOS Project. The results indicate the possibility of significant geometrical effects due to nearby lateral heterogeneities, in relation—in that particular case—to the topography of the river terrace. A survey of the cross-sections for each NPP site showed the existence of such lateral heterogeneities, at variable distances and with variable geometrical characteristics.

A simplified model has been built to account for these geometrical effects. Its formulation is based on the interpretation of 2D/3D effects as surface waves diffracted by the main lateral heterogeneities, which means that 2D effects decrease for increasing levels of strain (and therefore increasing damping). The model's quantitative parameters have been calibrated on the results obtained for Leibstadt; they are strongly site-dependent. Since considerable uncertainties exist in these estimates, a sub-branching is introduced with different parameter values, and different weights.

Logic Tree of D. Fäh

The basic logic tree is presented in Figure 6.11. D. Fäh's fundamental concept is based on four levels of ground motion, defined as a function of PGA and magnitude, and the possible physical models that approximate the behavior of the soils at these different ground motion levels. The ground motion levels and the related physical models are as follows:

- Level 1: The physical model is based on the EQL theory.
- Level 2: NL and EQL models are used.
- Level 3: Mostly non-linear behavior of the soil is expected, which cannot be captured by EQL models.
- Level 4: The soil column is expected to fail.

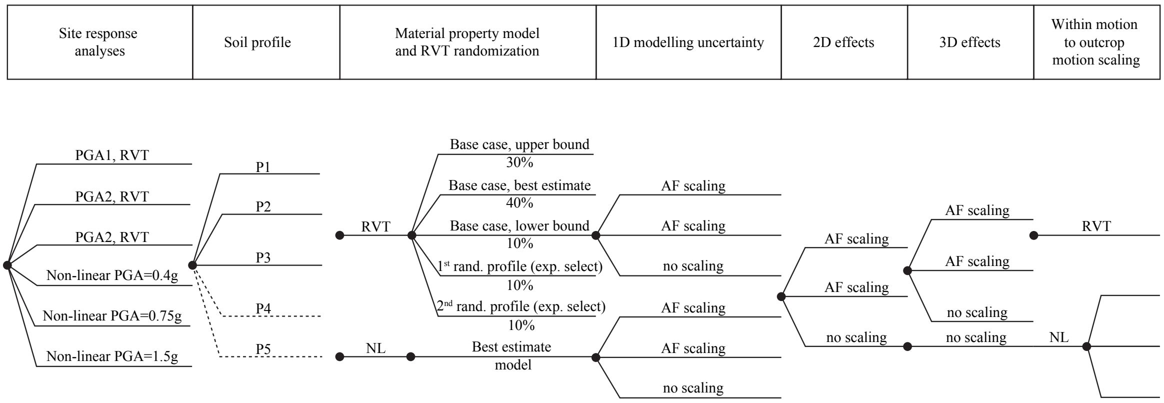


Figure 6.11: Basic logic tree of D. Fäh for the amplification of horizontal ground motion.

D. Fäh provides a table of PGA / magnitude values in his Evaluation Summary that define the transitions from one ground motion level to the other. These transitions are site-dependent. Roughly speaking, he assumes the limit of reliable results for EQL modeling in the range of PGA on rock of 0.4 to 0.7g.

In contrast to the logic trees of all other SP3 experts, D. Fäh's first branching differentiates between different specific site response analyses (SRA), i.e. RVT and NL analyses, depending on the ground motion level. At this stage, no SHAKE results are used. For level 1 ground motions, and PGA values for which no AF have been calculated, the AF obtained for the next lower existing ground motion level are used. For level 2 and 3 ground motions, for any given PGA value, AF from RVT and NL calculations for different PGA at, above and below the given PGA value are used, with different weights. An example: at Beznau, for a given PGA of, say, 0.6 g, for magnitude 6, weights of 0.4 and 0.2 are assigned to the NL results for 0.4 g and 0.75 g, respectively; furthermore, weights of 0.1 are given to the RVT results for 0.2 g and 0.3 g as well as a weight of 0.2 to the RVT results for 0.4 g.

Branching level 2 differentiates the soil profiles; their weights are given in the site-specific chapters. D. Fäh's tendency is to weight velocity profiles deduced from surface wave dispersion curves at least as much as profiles mainly based on borehole measurements.

Branching level 3 is devoted to the material models and occurs only on the RVT branches, since NL results are exclusively available for BE material models. This branch uses the RVT base case results for upper bound (UB weight 0.3), best-estimate (BE weight 0.4) and lower bound (LB weight 0.1) material models, as well as the RVT results for two expert-selected velocity models, issued from the randomization process, with BE material models (weight 0.1 each). The expert-selected additional velocity profiles are characterized by features of observed dispersion curves not covered by the base case.

D. Fäh argues that profile randomization leads to a reduction in the amplification factor due to the averaging of results from different velocity structures. This is why he only uses RVT results for the base cases and individual profiles selected from the set of randomized profiles, without soil randomization. D. Fäh's rationale for using asymmetric weights of the material models for the RVT base cases is that errors in laboratory testing have the effect of generally producing lower G/G_{max} curves, and therefore pushing the values to lower bounds. For these reasons, less weight is given to the LB material properties, and weights are mainly distributed between the BE and UB curves.

At branch level 4, 1D modeling uncertainty factors are introduced, separately for RVT and NL branches. On the RVT branches, these uncertainty factors are based on SHAKE/RVT and NL/RVT ratios; the main objective here is to correct for the fact that RVT results are less reliable at low frequencies than SHAKE results. Therefore, for $f < f_0/2$, (f_0 being the site's natural frequency obtained from H/V measurements), a weight of 0.6 or 0.65 is given to the sub-branch applying a SHAKE/RVT correction factor. On the NL branches, SHAKE/NL correction factors are applied that account for the "missing" runs in the NL computations for the different profiles. At ground motion level 3, further uncertainty factors are introduced to take into account the differences between the NL calculations carried out by different codes and contractors.

Branch level 5 introduces a general correction factor for the possibility of 2D effects. As already mentioned before, 2D effects were calculated in the PEGASOS Project, and no additional calculations have been carried out during the PRP. For all sites except Leibstadt, D. Fäh assigns a weight of 0.2 that 2D effects similar to those calculated for Leibstadt occur and a weight of 0.8 that 2D effects remain negligible. For Leibstadt itself, a weight of 0.7 is given to the existence of significant 2D effects. In contrast to P.-Y. Bard, D. Fäh assumes 2D correction factors that are independent of the ground motion level.

Because 2D effects depend on the direction and incidence angle of the wave fields, these parameters should principally be known. However, this is not possible within the framework of the PRP, since the hazard computations are performed in two steps. Source and attenuation are treated together in a first step- and site-effects separately in a second step. Therefore, D. Fäh estimates the probabilities for the different directions and angles for the incoming waves from the deaggregation of the PEGASOS hazard computations.

Branch level 6 adds a further correction for possible 3D-effects to the cases where 2D-effects were assumed to occur. These factors are purely based on expert judgment.

Finally, branch level 7 defines alternative ways of defining within motion to outcrop motion scaling factors, which are applicable only to branches based on NL analyses, for motions at depth.

Logic Tree of A. Pecker

The basic logic tree is presented in Figure 6.12. The first branching level is related to the velocity profiles. A. Pecker's approach is to assign higher weights to the velocity profiles that are mainly based on borehole measurements and lower weights to profiles solely deduced from surface wave dispersion curve inversions.

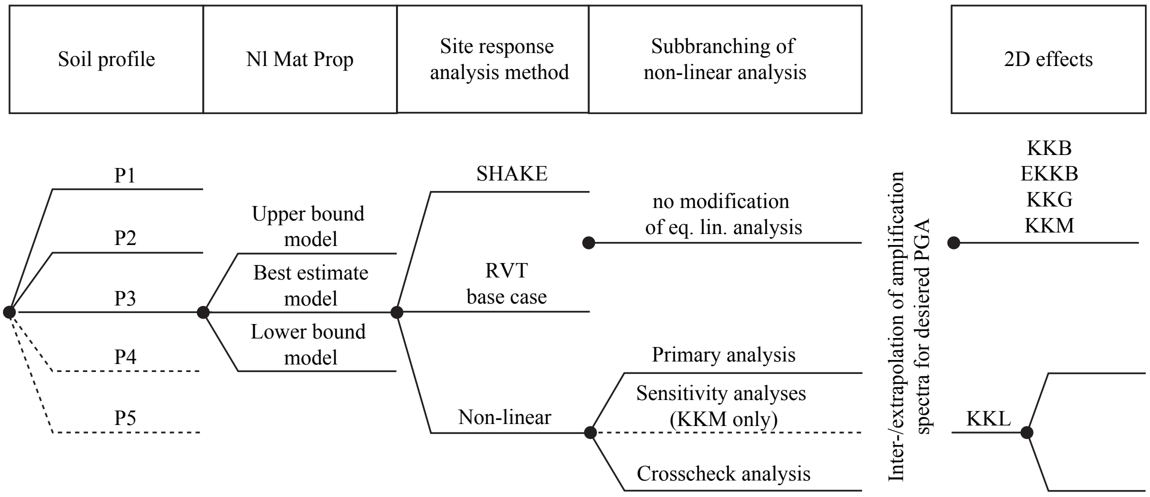


Figure 6.12: Basic logic tree of A. Pecker for the amplification of horizontal ground motion.

The second branching level captures the epistemic uncertainty of the material models. The weights assigned to each of the three material models (BE, LB and UB) are site-dependent, but independent of the different velocity profiles. The weights are chosen after careful examination of the corresponding laboratory data. In doing this, A. Pecker judges the plausibility of the "distance" of the LB and UB models from the BE model essentially based on his own geotechnical experience. The chosen weights are given in the site-specific chapters.

Branch level 3 differentiates the site response analysis (SRA) methods: SHAKE, RVT base case and NL. The RVT results for randomized velocity profiles are rejected as being unrealistic based on the study of Assimaki et al. [2003]. The weights assigned to the SRA methods are conditional on the strain level, expressed as a PGA level, as well as on the spectral frequency.

Two PGA thresholds are defined. Below the first threshold, the EQL methods are considered to be fully reliable and the NL results are not used. Beyond the second threshold, only the NL methods are trusted (a total weight of 0.2 is nevertheless given to the EQL methods). In-between, A. Pecker weights the EQL results from 0.5 to 0.7 and the NL results from 0.5 to 0.3. The first PGA threshold corresponds to a normalized strain γ usually assumed to be of the order of 1 (normalized by the reference strain γ_{50} for which the shear modulus is reduced to half of its initial value). The second threshold corresponds to the strain where the shear stress reaches the maximum shear stress (shear resistance) τ_{max}; this strain depends on the G/G_{max} curve and the soil resistance (depending, for gravels, on the overburden stress) and is therefore site- and depth-dependent. The strain for which τ_{max} is reached, at relevant depths, varies enormously. A. Pecker found, for instance, threshold strain values of 15 for Beznau, but only 1.0 for Leibstadt. The strain thresholds are "translated" into PGA thresholds based on the RVT base case results.

Four frequency ranges are distinguished with the aid of three frequencies f_1, f_2 and f_3. f_1 is taken as half the frequency of the first peak identified in the amplification functions for magnitude 6 and all PGA values; f_2 corresponds to twice the frequency of the peak with the highest frequency in these amplification functions. Finally, f_3 designates the limit frequency above which the results of none of the site response analysis methods are considered to be reliable; f_3 is estimated to be at 30 Hz (for Beznau and E-Beznau at 40 Hz). Below f_1, RVT results are disregarded. Between f_1 and f_2, equal weights are assigned to SHAKE and RVT results. Above f_2, the relative weights of SHAKE and RVT results are 1/3 and 2/3, respectively.

No magnitude-dependence of the amplification function is taken into account. Two reasons are given for this decision. Firstly, even the most recent GMPEs do not include any magnitude dependence of the site-specific terms. Secondly, the calculated AF do not show any significant magnitude-dependence; all other parameters are kept equal.

At branch level 4, an additional sub-branching is implemented for NL branches, where differences between primary and crosscheck NL analyses are used to capture the epistemic uncertainty of these simulations.

AF are interpolated for arbitrary PGA levels by piecewise cubic interpolation on a log scale for PGA. Estimation of AF for non-available parameter sets is based on ratios derived from AF by other analyses. For example: extrapolation of a SHAKE analysis for PGA 1.2 g (maximum PGA computed is 0.75 g) would utilize RVT analyses by evaluating SHAKE(1.2 g) = SHAKE(0.75 g) · RVT(1.2 g) / RVT(0.75 g). For the missing NL runs, with the same profile but different material types (LB, UB), the ratio of the AF of NL(LB or UB) to NL(BE) is calculated for 0.75 g (where all AF are available) and applied to NL(BE) at the requested PGA. This is justified by the small impact of the material type on the AF in the NL calculations.

Finally, a frequency-dependent 2D correction factor, with a maximum value of 1.2 independent of PGA, is taken into account for Leibstadt only, with a weight of 0.2. The alternative is no 2D effect, with a weight of 0.8.

Logic Tree of J. Studer

The basic logic tree is presented in Figure 6.13. The first branching level differentiates the velocity profiles. J. Studer assigns slightly higher weights to the velocity profiles that are mainly based on borehole measurements in comparison with the profiles deduced solely from surface wave dispersion curve inversions.

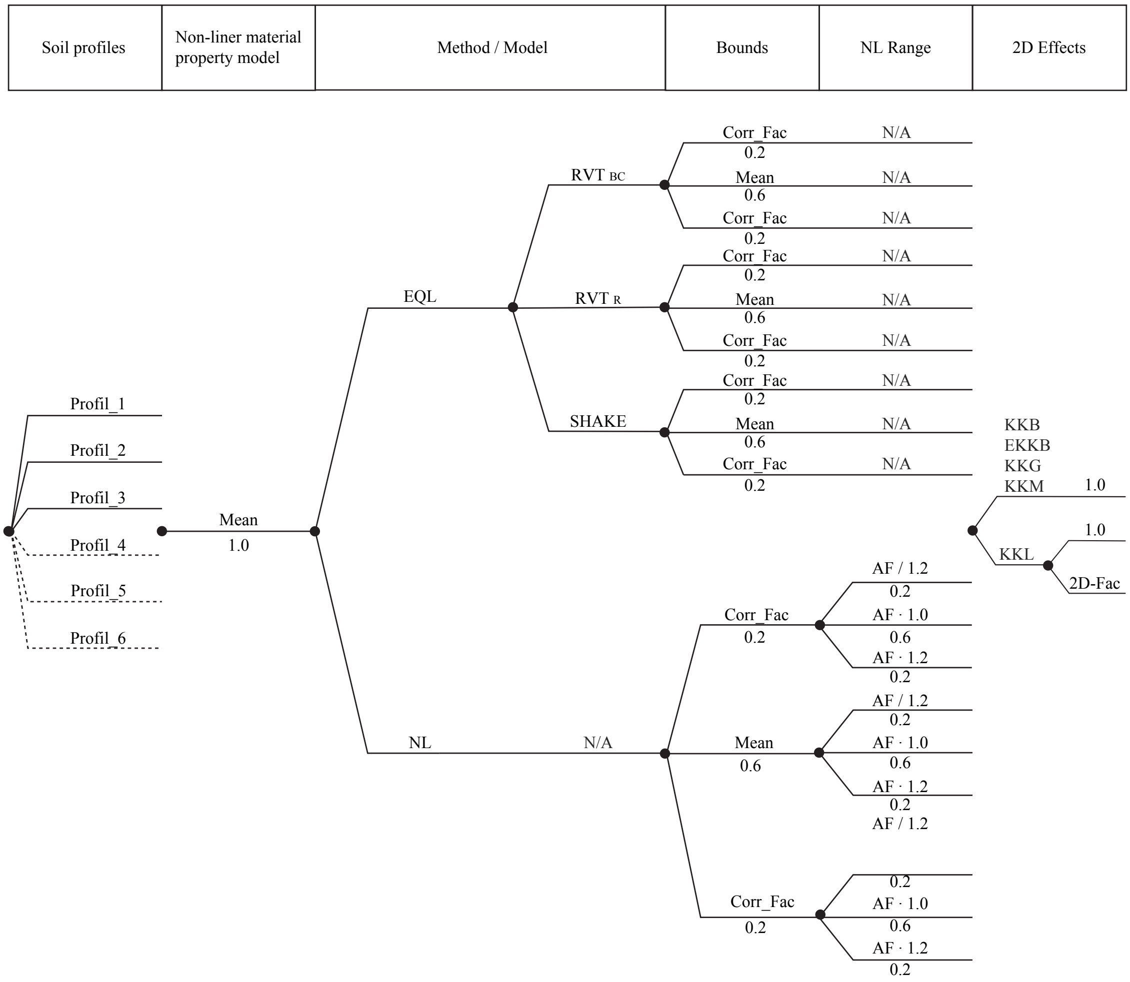
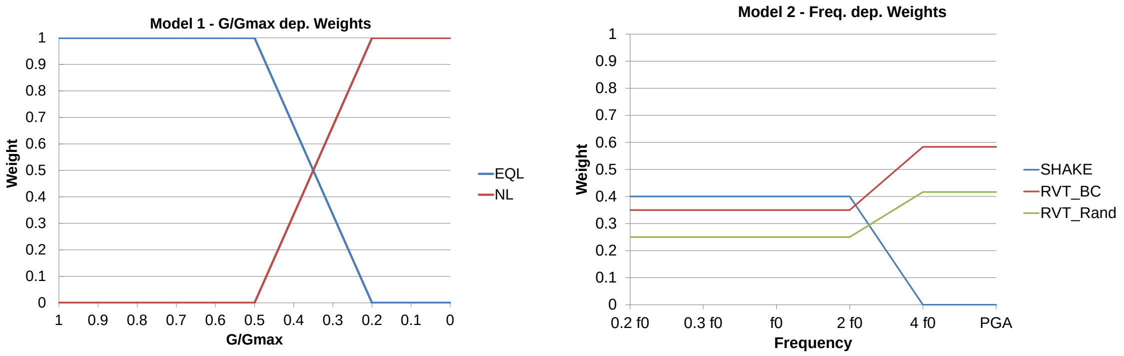


Figure 6.13: Basic logic tree of J. Studer for the amplification of horizontal ground motion.

In principle, the second branching level would be related to the material models. However, only BE material models are used. As a compensation for this simplification, the resulting AF will later be modified by the standard deviations from the randomized RVT calculations.

At the third branching level, weights are assigned to the different site response analysis methods, conditional, at first, on the decay of the shear modulus as well as on the spectral frequency. The weight distribution between EQL and NL methods as a function of G/G_{max} as well as the relative weights for the different EQL methods as a function of frequency are shown in Figure 6.14. The transition from G/G_{max} to PGA levels is different for each site and, within a site, for each velocity profile.

Interpolation for missing PGA is done in the simplest possible way, usually by means of linear interpolation.



(a) Model 1 EQL vs. NL (b) Model 2

Figure 6.14: Weights of the SRA methods as a function of G/G_{max} and frequency.

At the fourth branching level, in addition to the unmodified AF, branches with ± 1.6 standard deviations (σ) are taken into account in order to capture the epistemic uncertainty of the AF. At the fifth level, an additional sub-branching is introduced to allow for the higher epistemic uncertainty of the NL calculations; the unmodified branch is completed by branches where the AF are multiplied or divided by a factor of 1.2, interpreted as $\pm 1.6\sigma$ of log(AF). These sub-branches are weighted accordingly with 0.2/0.6/0.2.

Finally, a frequency- and PGA-dependent 2D-correction factor is taken into account for Leibstadt only. This correction factor corresponds to the geometric mean of the results of P.-Y. Bard's calculations carried out for the PEGASOS Project. Its maximum value is about 1.4 for a PGA of 0.1 g and 1.15 for a PGA of 0.4 g. The weight of the branch with this correction factor is 0.7, 0.3 being the weight of having no significant 2D effects.

Weights for Beznau Velocity Profiles and Material Models

Table 6.7 presents the weights assigned to the different velocity profiles for Beznau. Profiles P1, P2 and P4 are mainly based on borehole data, whereas profile P3 was deduced from the inversion of dispersion curves of ambient vibration and MASW measurements. Three out of the four experts assign a lower weight to profile P3 in comparison with the others, whereas D. Fäh weights all profiles equally. The relatively low weight of P.-Y. Bard for P3 is due to the fact that the corresponding dispersion curve is towards the lower end of the acceptable range. For A. Pecker und J. Studer, they consider the borehole data (crosshole and downhole measurements) to be more reliable than in inversions of measured dispersion curves.

Table 6.7: Weights for the velocity profiles for Beznau.

Profile	Bard	Fäh	Pecker	Studer
Beznau P1	0.30	0.25	0.35	0.40
Beznau P2	0.30	0.25	0.25	0.25
Beznau P3	0.15	0.25	0.15	0.10
Beznau P4	0.25	0.25	0.25	0.25

Table 6.8 presents the weights for the LB, BE and UB material models. D. Fäh and J. Studer use the same weights for all sites; their weights are discussed in the Volume 5 chapters

devoted to these experts. Interestingly, P.-Y. Bard gives a higher weight to the UB model than to the BE model, meaning that the so-called BE model is not really a best estimate in his view. P.-Y. Bard first observes that the laboratory data for the shear modulus, for moderate strains ($\gamma/\gamma_{50} < 1$), are closer to the UB than to the BE curve. Then, his rational is as follows: "Considering the fact that at large strains, the largest weight is given to fully NL computations, for which the shear modulus degradation is only approximated, and the damping values could be extremely different from the laboratory tests, the weights have been assigned in view mainly of linear equivalent computations used at small and intermediate strains."

Table 6.8: Weights for the material models used for Beznau and E-Beznau.

Material Beznau	Bard	Fäh	Pecker	Studer
Lower Bound (LB)	0.20	0.10	0.22	0
Best Estimate (BE)	0.35	0.40	0.45	1
Upper Bound (UB)	0.45	0.30	0.33	0

Site-Specific Aspects for Gösgen

Table 6.9 presents the weights assigned to the different velocity profiles for Gösgen. P1 to P3 correspond to very deep velocity profiles, and P4 to P6 to shallow profiles down to a bedrock considered as very hard (2500 m/s) and homogeneous below 30 m depth (see Figure 5.1). The deep profiles P1 and P2 were introduced with the objective of explaining the "bump" at a frequency of 0.6 Hz that appears in the H/V ratios; indeed, this bump cannot be explained with a homogeneous base rock whose top is at slightly less than 30 m depth (see Section 6.2.3). P6 is identical to P1 within the gravel layer, but has a homogeneous base rock.

It is most interesting to compare how the different experts distribute their weights between the deep and the shallow profiles. P.-Y. Bard assigns only one third to all the deep profiles and two thirds to the shallow ones. Conversely, D. Fäh weights the deep profiles with 0.8 and the shallow ones with only 0.2. Finally, A. Pecker and J. Studer weight the deep and shallow profiles equally.

P.-Y. Bard's reasoning for weighting the deep profiles less is as follows: the aleatory variability associated with deep bedrock characteristics is already taken into account in the empirical GMPE used to compute the rock hazard. Therefore, including the deep profiles could lead to some double counting of this variability "by adding some epistemic uncertainty to the aleatory variability built in the rock hazard estimate". D. Fäh, in contrast, considers it important to explain the site resonance at 0.6 Hz and, therefore, assigns higher weights to the deep profiles.

Looking at individual profiles, it is striking that P.-Y. Bard and A. Pecker both give the lowest weight (0.05 and 0.10) to profile P2, whereas D. Fäh assigns the highest weight (0.40) to this profile. Profile P2 is based on down hole measurements that yielded much lower V_S values than the crosshole measurements. P.-Y. Bard and A. Pecker consider this velocity to be too low with respect to the rock description. Consequently, P.-Y. Bard and A. Pecker assigned a low weight to that profile. In contrast, D. Fäh considers in the downhole measurements to be more reliable than in the crosshole measurements within the deep rock.

Table 6.9: Weights for the velocity profiles for Gösgen.

Profile	Bard	Fäh	Pecker	Studer
Gösgen P1	0.10	0.20	0.25	0.20
Gösgen P2	0.05	0.40	0.10	0.20
Gösgen P3	0.20	0.20	0.15	0.10
Gösgen P4	0.20	0.10	0.25	0.20
Gösgen P5	0.15	0.10	0.25	0.20
Gösgen P6	0.30	- (*)	- (*)	0.10

(*) D. Fäh and A. Pecker consider P6 to be essentially identical to P1 (P6 is in fact identical to P1, but with homogeneous base rock); therefore, they do not use this profile in their logic tree as a separate profile.

Table 6.10 presents the weights for the LB, BE and UB material models. P.-Y. Bard and A. Pecker, who assign site-specific weights, weight the different models fairly equally. They argue that the models coincide well with the most probable range of G/G_{max} curves.

Table 6.10: Weights for the material models used for Gösgen.

Material Gösgen	Bard	Fäh	Pecker	Studer
Lower Bound (LB)	0.25	0.10	0.33	0
Best Estimate (BE)	0.45	0.40	0.33	1
Upper Bound (UB)	0.30	0.30	0.33	0

Site-Specific Aspects for Leibstadt

Table 6.11 presents the weights assigned to the different velocity profiles for Leibstadt. Velocity profile P1 was mainly deduced from ambient vibration and MASW measurements, whereas profile P2 is based on crosshole data, with corrections taking into account anisotropy (higher horizontal than vertical velocities). Finally, P3 is a hybrid profile; surface wave data have been used for the gravel layer and crosshole data in the bedrock.

The experts' weights differ only slightly from each other. Some tendency, though, can be observed in accordance with the fact that A. Pecker and J. Studer have more confidence in crosshole data (basis of P2) than P.-Y. Bard and D. Fäh.

Table 6.11: Weights for the velocity profiles for Leibstadt.

Profile	Bard	Fäh	Pecker	Studer
Leibstadt P1	0.40	0.40	0.40	0.40
Leibstadt P2	0.25	0.20	0.40	0.30
Leibstadt P3	0.35	0.40	0.20	0.30

Table 6.12 shows the weights for the material models. The LB, BE and UB models include almost all measured data points. There is some concentration of data close to the BE model,

and no asymmetry or bias can be seen. Consequently, P.-Y. Bard and A. Pecker, who define site-dependent weights, assign symmetric weights in a very similar way to each other.

Table 6.12: Weights for the material models used for Leibstadt.

Material Leibstadt	Bard	Fäh	Pecker	Studer
Lower Bound (LB)	0.20	0.10	0.25	0
Best Estimate (BE)	0.60	0.40	0.50	1
Upper Bound (UB)	0.20	0.30	0.25	0

Site-Specific Aspects for Mühleberg

Table 6.13 presents the weights assigned to the different velocity profiles for Mühleberg. There are four velocity profiles. P1 is the profile that was derived with the largest weight on borehole data and has been considered to be the best estimate profile by the utility. P2, P3 and P4 were mainly based on dispersion curves which could be interpreted in very different ways. P2 corresponds to a low velocity gravel layer over an only weakly weathered Molasse, whereas P3 has a high velocity gravel layer overlying a significantly weathered Molasse. Finally, P4 is a rather "extreme" profile with very low velocities in the gravel, with only a poor agreement with most in-situ data.

P.-Y. Bard gives clearly the highest weight to profile P1 and the lowest to P4 because he is not confident in the very low velocities in the gravel layer. Similarly, A. Pecker and J. Studer consider the velocities in the gravel layer to be unusually low in the profiles P2 and P4. Therefore, they give a slightly lower weight to these profiles than to the profiles P1 and P3. Finally, D. Fäh assigns equal weights to all four profiles, arguing that the spatial variability of the weathered Molasse makes it difficult to prefer one profile over the others.

Table 6.13: Weights for the velocity profiles for Mühleberg.

Profile	Bard	Fäh	Pecker	Studer
Mühleberg P1	0.40	0.25	0.30	0.30
Mühleberg P2	0.25	0.25	0.20	0.20
Mühleberg P3	0.25	0.25	0.30	0.30
Mühleberg P4	0.10	0.25	0.20	0.20

There are no specific laboratory measurements of the non-linear material behavior for either the gravel layer or the weathered Molasse for Mühleberg. The consequence is that the LB and UB models were chosen to span a wider range about the BE model as compared to the other three sites than had site-specific laboratory testing results. As can be seen from Table 6.14, P.-Y. Bard skews the weight distribution towards the UB model, arguing that the chosen curves for G/G_{max} show a stronger decay with strain than what is often reported in the literature [Hardin and Drnevich 1972; Ishibashi and Zhang 1993]. In contrast, A. Pecker assigns equal weights to the LB and UB models.

Table 6.14: Weights for the material models used for Mühleberg.

Material Mühleberg	Bard	Fäh	Pecker	Studer
Lower Bound (LB)	0.15	0.10	0.27	0
Best Estimate (BE)	0.45	0.40	0.46	1
Upper Bound (UB)	0.40	0.30	0.27	0

6.5.2 Aleatory Varability of Horizontal Ground Motion

The aleatory variability is assumed to arise from the variability in the input signal waveform, from the variability in the soil profile across the site associated with the random location of the earthquake, from the variability arising from different incidence angles and from potential 2D or 3D effects. The experts agreed that all these factors are already accounted for by SP2, at least as long as a linear or nearly linear behavior for the soil dominates. Therefore, in order to avoid double counting, the only component that possibly needs to be added to the aleatory variability of the rock ground motion is the variability associated with the (strongly) non-linear soil behavior.

It is well known that non-linear calculations may be sensitive to small details in the input motion or small changes in the constitutive model. On the one hand, it might therefore be expected that the variability in the ground surface response would be increased with respect to the variability obtained assuming quasi linear behavior. On the other hand, the ground motion variability should decrease with higher input motion because the response is increasingly controlled by strength properties that are less subject to epistemic uncertainty than the moduli.

P.-Y. Bard looked carefully into the development of the variation of the non-linear AF and response spectra with increasing PGA in comparison with the linear AF and response spectra (calculated for 0.05 g). He identified two sites, Gösgen and Leibstadt, where the aleatory variability is clearly reduced with respect to the linear case for intermediate frequencies (typically 1 - 8 Hz). However, at low frequencies, all sites except Mühleberg exhibit a slight trend towards increased variability. Since rock hazard is computed first in the PRP, independently of soil behavior, it is not easy to ”take out” part of the rock aleatory variability afterwards when computing the soil hazard. Therefore, the TFI decided for practical reasons to not reduce aleatory variability in the rock model.

D. Fäh states that non-linear computations become less reliable the more PGA is increased. The epistemic uncertainty is therefore increased in his logic tree with increasing input ground motion, assuming also a wide range of different non-linear behavior, and ”simulating” an increased variability of soil behavior. Adding additional aleatory uncertainty therefore carries the risk of counting the same effect twice. For these reasons, no additional aleatory variability for non-linear behavior is included in his model.

A. Pecker evaluated the standard deviation of the spectral accelerations at very low PGA levels, where linear elastic behavior governs the response, and at high PGA levels (1.5 g) available from the NL computations. He observed no definite trend in the standard deviation. Sometimes, the linear AF show more variability than the NL AF and sometimes it showed less variability. He finally uses physical reasons (the response being increasingly controlled by strength properties) to conclude that the aleatory variability in the NL domain of soil behavior should, in general, be less or equal to the variability in the linear range. Therefore, A. Pecker does not include additional aleatory variability for the soil hazard.

J. Studer compares the aleatory variability of the site AF calculated in the PRP with the aleatory variability evaluated with the SP2 single-station standard deviation of KiK-net data (for low PGA values). He concludes that the additional variability at high PGA levels is justified for Leibstadt and Mühleberg.

6.5.3 Median Amplification of Vertical Ground Motion

As previously mentioned in Section 5.4, the SP3 experts defined several empirical V/H models as candidates for the evaluation of the vertical ground motion. At the very beginning, a V_{S30} dependent V/H ratio based on McGuire et al. [2001] (NUREG/CR-6728) was also considered. This V/H ratio was developed by interpolation of the CEUS and WUS recommended V/H ratios defined in Table 4-4 (for V_{S30}=520 m/s) and Table 4-5 (for V_{S30}=2800 m/s) of NUREG/CR-6728. This model was dropped for the final evaluation by the SP3 experts and not considered to be an applicable model for Switzerland.

The logic trees of the different experts are quite similar. In principle, all experts use three different ways of computing the vertical ground motion hazard at the NPP sites. At the first level, there are three branches:

- A branch where V/H ratios are applied to the horizontal ground motion hazard on soil, according to different V/H models (henceforth referred to as the "V/H approach")
- A branch without any amplification with respect to the vertical rock motion (this branch is discussed by all experts, but often given a zero weight)
- A branch where AF for vertically incident compression waves, calculated with SHAKE or RVT, are applied to the vertical rock hazard

The main differences between the experts are the relative weights that they give to the different approaches. Furthermore, they give very different weights to the candidate V/H models that are available in the literature, and they give different weights to SHAKE or RVT based vertical AF. The different weights either depend or do not depend on frequency and/or PGA.

Logic Tree of P.-Y. Bard

Figure 6.15 shows P.-Y. Bard's logic tree for the vertical ground motion. He dropped the "no amplification" branch because the EQL site-specific compression wave analyses lead to significant amplifications, although all sites are relatively stiff. He assigned a weight of 0.6 to the V/H approach and a weight of 0.4 to the EQL compression wave AF; these global weights are independent of frequency and PGA.

On the V/H branch, P.-Y. Bard takes into account four different models: GA10 [Gülerce and Abrahamson 2011], BAK11 [Bommer et al. 2011], PEF11 [Poggi et al. 2011] and KSSM11 [Kawase et al. 2011]. The first two models are classical GMPEs, with rather detailed descriptions of earthquake and distance, but an "elementary" site description in terms only of V_{S30}-continuous dependency for GA10 and discrete site classes for BAK11. The third model is much more site-specific, using frequency-dependent quarter wavelength velocities and

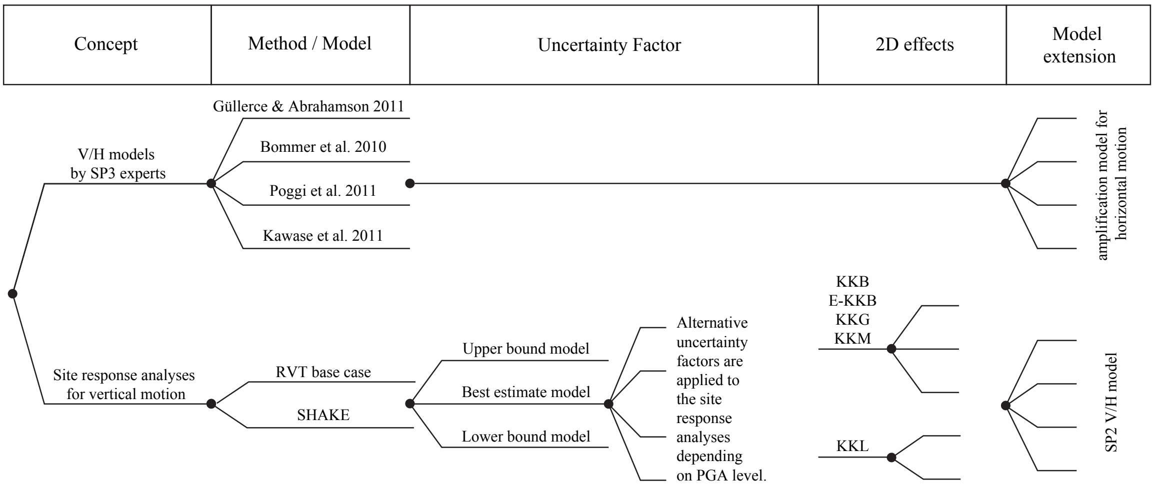


Figure 6.15: Logic tree of P.-Y. Bard for the amplification of vertical ground motion.

impedance contrasts, while having an elementary earthquake and distance descriptor. The fourth model is a purely theoretical one, associated with the latest findings on the V/H ratio from the diffuse wave field theory. It offers the possibility to directly link an "average" V/H ratio to the ratio of the site-specific S to the compression wave transfer function, modulated by the square of the S/P wave velocity ratio in the underlying half-space.

P.-Y. Bard's weighting is influenced by the models' ability to account for the site-specific characteristics, the PGA dependence, and the existence of a background theory. He assigns the highest absolute weight (0.25) to KSSM11 since it uses the vertical and horizontal, site-specific, PGA-dependent AF for vertical and horizontal ground motion (P.-Y. Bard uses the AF from the SHAKE calculations). Therefore, it automatically corrects for the large differences in the amount of NL behavior on the horizontal and vertical components. An only slightly lower absolute weight (0.20) is given to PEF11 since this model also captures the site characteristics quite well. Finally, lower absolute weights of 0.1 and 0.05 are assigned to GA10 and BAK11, respectively, because the site descriptions of these models are rather crude. The cited weights are valid at surface level; they are slightly different at depth. The V/H approach is directly applied to the results of the logic tree model for horizontal ground motion.

On the site response analyses branch, P.-Y. Bard uses equal weights for the AFs derived from the SHAKE and RVT base case computations at frequencies up to 15 Hz. For higher frequencies, he assigns a higher weight to the RVT base case results. The weights on the material models sub-branch are the same as those used for the computation of the horizontal ground motion.

At a further branching level, P.-Y. Bard introduces an additional "uncertainty factor". The main reason is that, on some strong motion recordings, it can be observed that non-linear effects result in increased vertical amplification, essentially beyond the fundamental natural frequency of vertical motion. Finally, he adds possible 2D-3D effects because observations as well as computations on "canonical" models have shown that 2D-3D effects generate Rayleigh waves that affect the vertical component at frequencies around the vertical component natural frequency. This 2D-3D correction is only applied to the site response analyses branch because the V/H branch is applied to the horizontal motion which already takes into account the

2D-3D effects.

Logic Tree of D. Fäh

Figure 6.16 presents D. Fäh's logic tree for the vertical ground motion. There are three main branches:

- A branch based on empirical relations for V/H spectral ratios and on the results for the median amplification of the horizontal motion ("V/H approach"), with by far the largest weight;
- A branch with no amplification of the vertical component with respect to the rock motion;
- A branch based on the computation of AF performed with RVT assuming vertically propagating compression waves (the site-specific AF for PGA values of 0.4 g and 0.75 g are averaged).

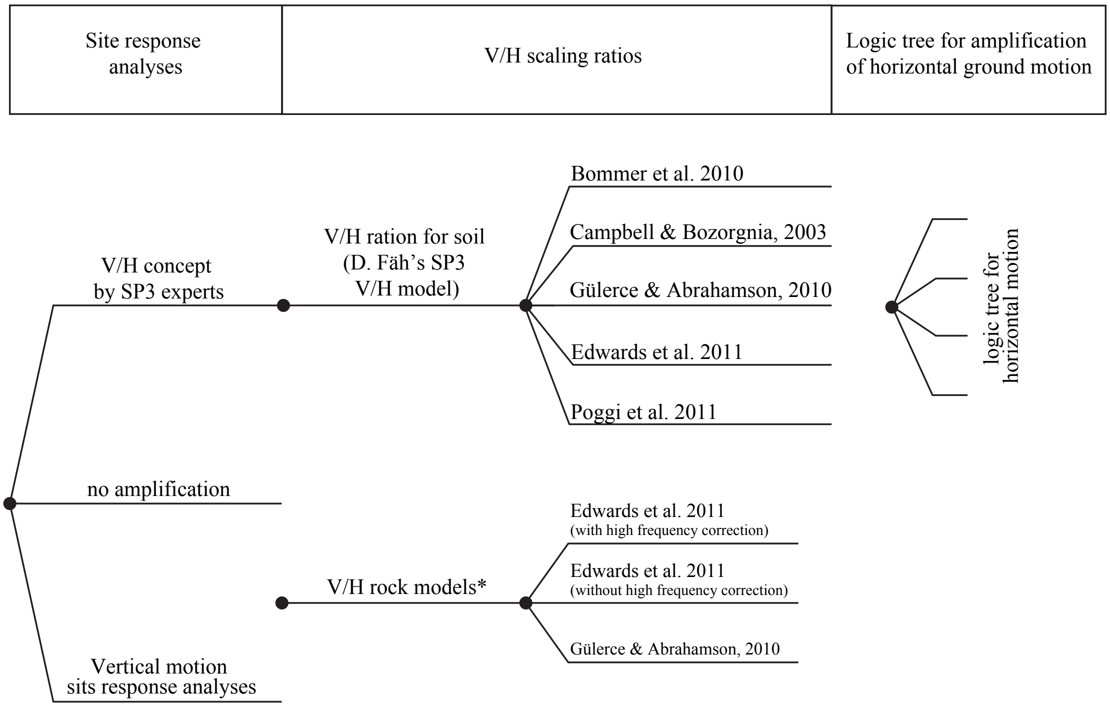


Figure 6.16: Basic logic tree of D. Fäh for the amplification of horizontal ground motion.

The first branch is connected to the horizontal motion soil hazard results. The second and third branches are applied to the estimate of the vertical rock hazard proposed by D. Fäh himself in SP2 using V/H spectral ratios for rock condition.

For the ground motion levels 1 and 2 (see chapter on D. Fäh's logic tree for the median horizontal ground motion), the total weight is on the first branch. For the ground motion level 3 and distant sources (further away than 20 km), the first and second branches have weights of 0.8 and 0.2, respectively. Only for close sources, the third branch receives a non-zero weight of 0.1, the first and second branches having weights of 0.7 and 0.2, respectively.

For the V/H approach, worldwide empirical V/H models as well as site-specific V/H concepts are used with equal relative weights. The empirical models are: GA10 [Gülerce and Abrahamson 2011], BAK11 [Bommer et al. 2011], CB03 [Campbell et al. 2003]. The site-specific concepts have recently been developed by SED; they are based on observed V/H ratios from earthquake recordings combined with measured velocity profiles and, in one method, also with ambient vibration recordings. Both methods make use of the specific velocity profiles at the NPP sites and V/H ratios are therefore site-specific. The first method (method 1, Poggi et al. [2011]) is based on observed V/H ratios from earthquakes recorded at the KiK-net sites, using the quarter-wavelength representation of the velocity profiles. A predictive equation to obtain the V/H ratio for sediment sites has been established, accounting for resonance phenomena at soft sediment sites. A parameter is directly derived from the quarter-wavelength velocity and represents the frequency-dependent seismic impedance contrast at the site. The second method (method 2, Edwards et al. [2011a]) is based on observed ambient vibration V/H ratios and V/H ratios from earthquake recordings at the stations of the Swiss seismic network. Ambient vibration data for Japanese sites were not available, limiting the generality of the second method. At NPP sites, ambient vibration measurements are used to estimate V/H ratios of earthquake recordings.

The weights of the sub-branches of the V/H approach depend on D. Fäh's "ground motion levels":

- For ground motion level 1, GA10, BAK11 and CB03 are weighted 0.30, 0.10 and 0.10, respectively. The two SED methods have weights of 0.40 (method 1) and 0.10 (method 2).
- For ground motion level 2, GA10, BAK11 and CB03 are weighted 0.10, 0.20 and 0.20, respectively. The two SED methods have weights of 0.45 (method 1) and 0.05 (method 2).
- For ground motion level 3, GA10, BAK11 and CB03 are weighted 0, 0.25 and 0.25, respectively. The two SED methods have weights of 0.50 (method 1) and 0 (method 2).

D. Fäh assigns a relatively high weight to the GA10 model at low ground motion level since he considers the meta-data on which the model is based to be of higher quality than for the other empirical models. However, he gives a low or even zero weight to GA10 at higher ground motion levels because this model explicitly takes into account non-linear soil behavior, but only on the horizontal component. D. Fäh states that this leads to very high V/H ratios, particularly for frequencies above 10 Hz, a feature that he cannot observe in the KNet and KiK-net data. On the contrary, he argues that horizontal and vertical motions are due to (inclined) shear wave arrivals so that it can be assumed "that non-linear soil response should act in a similar manner on the vertical and horizontal components, and that V/H ratios derived from the linear range of the soil response can be extrapolated into the non-linear range".

Logic Tree of A. Pecker

Figure 6.17 presents A. Pecker's logic tree for the vertical ground motion. A. Pecker differentiates between the same fundamental approaches as do the other experts. However, the difference is that, in A. Pecker's logic tree, the overall weights between the different fundamental approaches are frequency- as well as PGA-dependent.

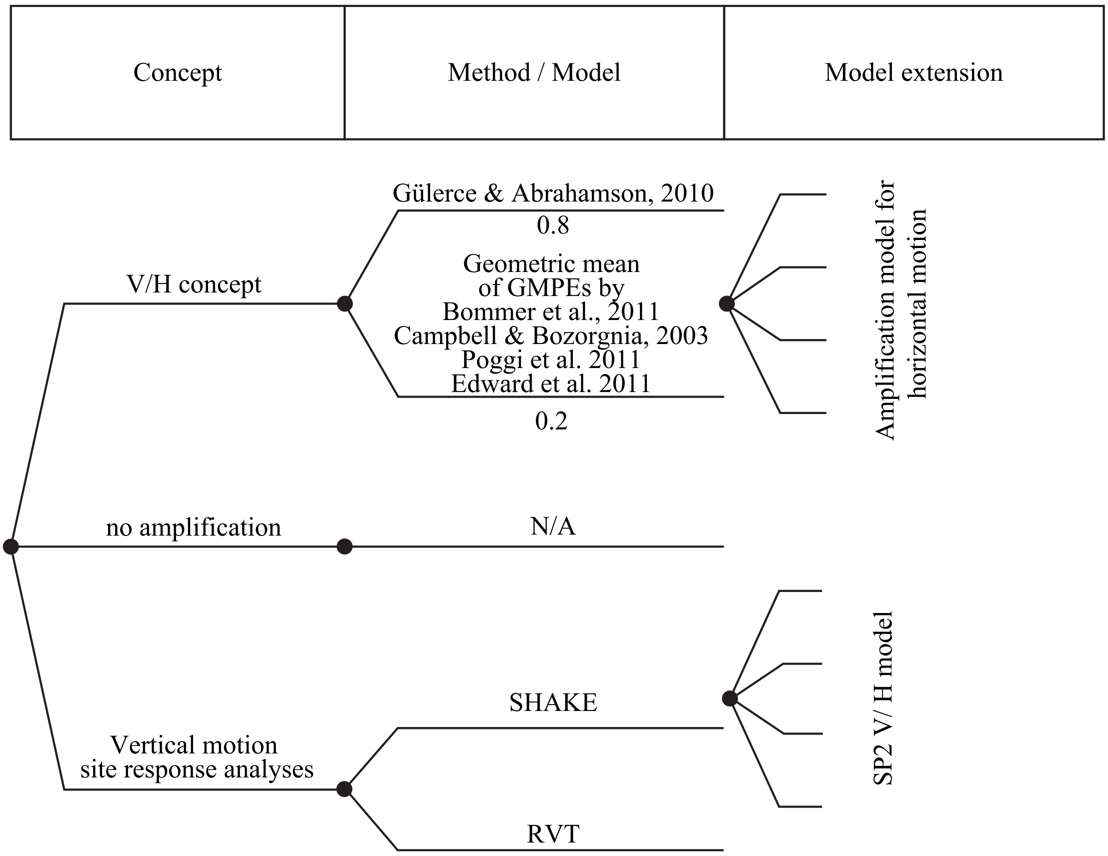


Figure 6.17: Logic tree of A. Pecker for the amplification of vertical ground motion.

In order to understand A. Pecker's weights, it is helpful to follow his approach to the problem. In saturated soils, the compression waves travel through the water; the bulk modulus of the soil skeleton may be slightly affected by the induced shear strain, but the overall bulk modulus, which is the sum of the soil skeleton bulk modulus and the water bulk modulus, will be almost unaffected. Furthermore, the compression wave velocity is large and consequently the natural frequency of the soil column is high.

In a dry soil, the propagation of compression waves is controlled by the skeleton properties:

$$\rho V_P^2 = K + \frac{4}{3}G. \tag{6.4}$$

These properties are influenced by the shear strain, but the bulk modulus K to a lesser extent than the shear modulus G. This compression wave velocity is smaller than in a saturated layer and consequently the natural frequency of vibration of the soil column is lower.

Therefore, amplifications will depend on the natural frequency of the soil column and will be much less dependent on the PGA input amplitude than for the horizontal motion (governed by the shear wave velocity). Below the natural frequency, almost no amplification of compression waves will take place; therefore, a no-amplification branch is introduced in the logic tree.

Nevertheless, vertical motion is not induced only by vertical propagation of compression waves, but also by P-SV waves; this is reflected in the logic tree by the introduction of a branch based on experimental V/H ratios, which inherently contain the contributions of all wave types. The third branch in the logic tree is based on numerical 1D amplifications obtained with equivalent linear calculations for vertically incident compression waves. Above the natural frequency defined above, amplification can be calculated either from the SHAKE or RVT base case runs, or from empirical relations of the V/H ratios.

Amongst the published empirical relations, only the model GA10 depends on the level of input motion. All other correlations, aside from a design spectra oriented NUREG/CR-6728 correlation not considered here, exhibit no such dependence. However, according to the previous statements regarding the relative dependence of the S and P wave velocities on the induced strain, an increase in the input motion should result in a similar increase in the vertical motion, whereas the increase in the horizontal motion should be weaker due to the soil non-linearities. Consequently, the V/H ratio should depend on the amplitude of the input motion. Therefore, much more weight is attributed by A. Pecker to the GA10 V/H model than to other empirical V/H models.

The frequency- and PGA-dependence of A. Pecker's weights is kept simple by assigning different weights to, on the one hand, two different frequency ranges and, on the other hand, two different PGA ranges (the PGA ranges are site dependent):

- $f < f_1$ and $f > f_1, f_1$ being about a factor of 2 below the lowest natural frequency of vertical motion at the site
- PGA<PGA$_1$ and PGA>PGA$_1$, PGA$_1$ being in the range of 0.1 to 0.2 g

The natural frequencies were read off the AF calculated by RVT and SHAKE for all material models and input motions of 0.1 g, 0.4 g and 0.75 g; it turned out that the frequency was only slightly dependent on the input motion amplitude, confirming that the vertical motion is not really affected by the non-linearities as long as only compression waves are considered. Table 6.15 gives an overview of A. Pecker's frequency thresholds f_1 for the different sites. The relatively low value for Leibstadt reflects the much greater depth of the water table (∼25 m) in comparison to all other sites.

Table 6.15: Pecker's frequency thresholds f_1 for the different sites.

Site	Beznau	E-Beznau	Gösgen	Leibstadt	Mühleberg
f_1 [Hz]	8	10	10	4	15

A. Pecker's weights are different for all sites. In order to show the general trend, the weights for Beznau are presented in Table 6.16. The weights for the "no amplification" branch, for $f < f_1$, are 0.3 for the stiffer sites, i.e. Gösgen and Mühleberg, and only 0.1 for Leibstadt, a softer site, because of the low water table. Above f_1, the weight of the "no amplification" branch is zero at all sites. All weights within the V/H branch are also the same for all sites; the total weight of this branch is 0.5 for PGA<PGA$_1$, but only 0.1 (solely on GA10) for PGA>PGA$_1$. This is very different from D. Fäh's logic tree where, even for high ground motion levels, the total weight on the empirical V/H models is still 0.7 or 0.8.

Table 6.16: Pecker's weights for the example of Beznau.

	$f < f_1$					$f_1 < f$				
	AF		No amp	V/H		AF		No amp	V/H	
	SHAKE	RVT		GA10	Others	SHAKE	RVT		GA10	Others
PGA $<$ PGA$_1$	0.15	0.15	0.2	0.4	0.1	0.15	0.35	0	0.4	0.1
PGA$_1$ $<$ PGA	0.35	0.35	0.2	0.1	0	0.35	0.55	0	0.1	0

Logic Tree of J. Studer

J. Studer's logic tree is shown in Figure 6.18. J. Studer differentiates between the same fundamental approaches as do the other experts. The weights of the V/H approach, the "no amplification" branch and the branch with the AF calculated with vertically propagating compression waves are 0.35, 0.1 and 0.55, respectively.

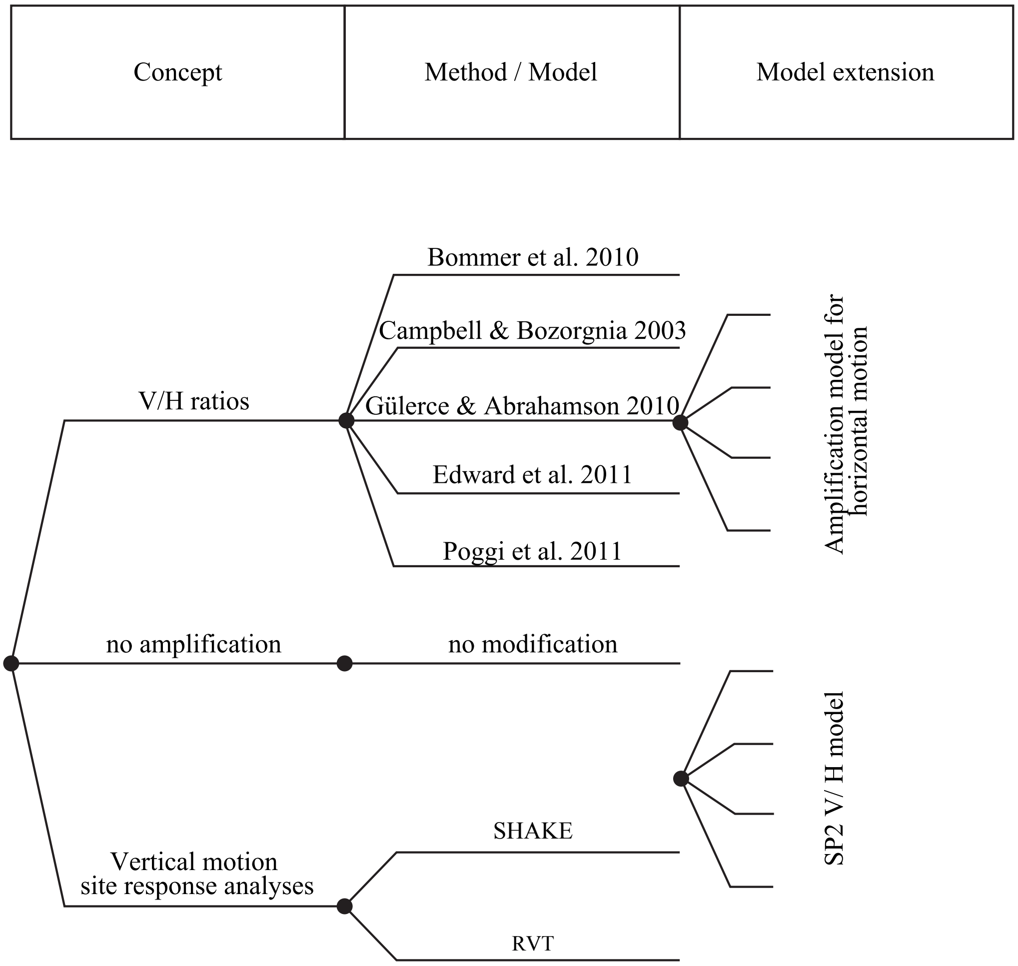


Figure 6.18: Logic tree of J. Studer for the amplification of vertical ground motion.

In the V/H approach, J. Studer uses five different empirical V/H models: BAK10, CB03, GA10, SED method 1 and SED method 2. Their respective weights are 0.15, 0.15, 0.2, 0.05 and 0.45 for the vertical ground motion at the surface. For the cases at depth within a soft rock (Beznau and Mühleberg), the weights of the SED methods 1 and 2 are 0.3 and 0.2, respectively.

6.5.4 Aleatory Variability of Vertical Ground Motion

All experts agree that no aleatory variability has to be added to the aleatory variability of the vertical rock ground motion, and all experts essentially give the same arguments. P.-Y. Bard formulates this as follows: For the horizontal motion, it was considered that only the non-linear behavior of soft soil could involve some additional aleatory variability in relation with the site response. As a consequence, since the non-linear behavior is much less pronounced for vertical motion, it is simply assumed that the site response does not imply any additional aleatory variability on the vertical motion.

6.5.5 Maximum Ground Motion

Logic Tree of P.-Y. Bard

Figure 6.19 presents P.-Y. Bard's logic tree for the maximum horizontal ground motion. This logic tree starts with two main branches, one for the mechanical and one for the empirical approach.

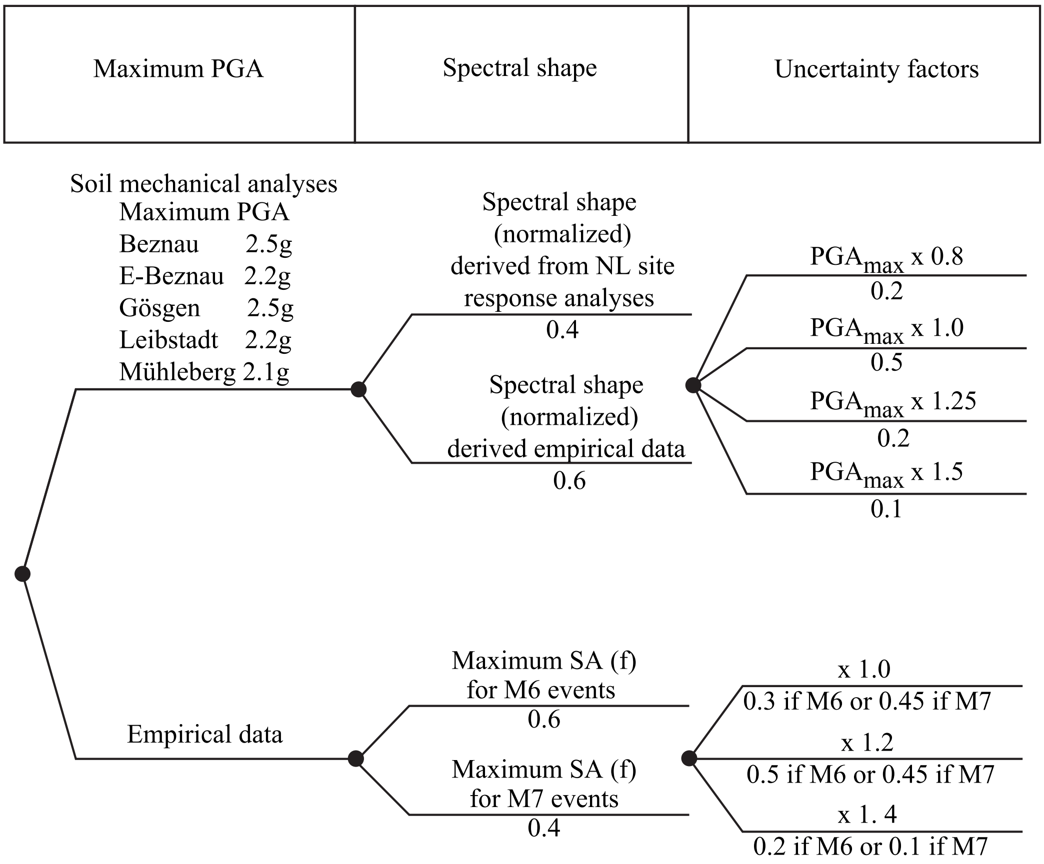


Figure 6.19: Logic tree of P.-Y. Bard for the maximum horizontal ground motion.

For the mechanical model branch, P.-Y. Bard uses as maximum PGA value the maximum of the estimates from A. Pecker's theoretical model [Pecker 2011] (TP3-TB-1074) and from the non-linear site amplification computations. Being aware of the simplicity of the mechanical model and considering its results as "highly uncertain", P.-Y. Bard assigns a weight of only 1/3 to this branch. Furthermore, he introduces a sub-branching with four branches of different scaling factors in order to capture the epistemic uncertainty. The scaling factors are 0.8, 1.0, 1.25 and 1.5 with weights of 0.2, 0.5, 0.2 and 0.1, respectively. Finally, to estimate the maximum ground motions at the spectral frequencies, a spectral shape has to be anchored to the given PGA. For this, P.-Y. Bard uses two approaches: a normalized spectrum derived from the non-linear computations at 2.5 g, different for each site, and a normalized spectrum deduced from the geometrical mean of normalized spectral shape observed for all the "extreme" recordings selected in Strasser and Zulu [2010] (EXT-TB-1067); the respective weights of these approaches are 0.4 and 0.6.

Arguing that the empirical approach directly provides estimates over the whole spectrum, based on present day observations without any theoretical considerations, P.-Y. Bard assigns a weight of 2/3 to this branch. He further introduces two sub-branches for spectral shapes originating from magnitude 6 and magnitude 7 events. However, since at high frequencies, the $M7$ maxima ever observed are lower than the $M6$ maxima, he raised the observed $M7$ maxima to the $M6$ maxima. The shape for magnitude 6 has to be used predominantly for events with magnitudes lower than 6.5, and the magnitude 7 shape for events with magnitudes above 6.5, if this is technically possible (i.e. if track is kept of the magnitudes in the hazard computations). Otherwise, P.-Y. Bard suggests a weight of 0.6 for the magnitude 6 shape and 0.4 for the magnitude 7 shape.

In order to account for the fact that the presently obtained maximum spectra are a lower-bound estimate of the "true" maximum spectra, a further sub-branching into three branches is introduced, where the spectral ordinate values are multiplied by scaling factors of 1.0, 1.2 or 1.4. The respective weights of these branches are 0.3, 0.5 and 0.2 for the magnitude 6 spectral shape and 0.45, 0.45 and 0.1 for the magnitude 7 spectral shape. Slightly larger weights for the larger scaling factors are assigned for the magnitude 6 spectral shape because of the smaller source size and, consequently, the lower probability of having had, in the past, a station at very close proximity to the most energetic part of the rupture.

For the maximum vertical ground motion, only one main branch is considered: the one of the empirical approach; there are no "theoretical" upper bounds. Otherwise, the logic tree is identical with the one described for the maximum horizontal ground motion.

Logic Tree of D. Fäh

Figure 6.20 presents D. Fäh's logic tree for the maximum horizontal ground motion; it contains no site-specific element. D. Fäh argues that no significant difference between the sites can be seen, either from the results of A. Pecker's model or from the non-linear runs. He concludes that, in view of the considerable uncertainty of all these results, a site-specific maximum ground motion is not justified. Therefore, D. Fäh starts with a maximum PGA of 2.5 g for all sites. However, in order to account for additional effects, such as possible 2D / 3D effects, or when the soil failure introduces a solid-liquid interface able to trap shear wave energy, D. Fäh introduces an alternative branch with a PGA of 5.0 g. The respective weights are 0.7 and 0.3.

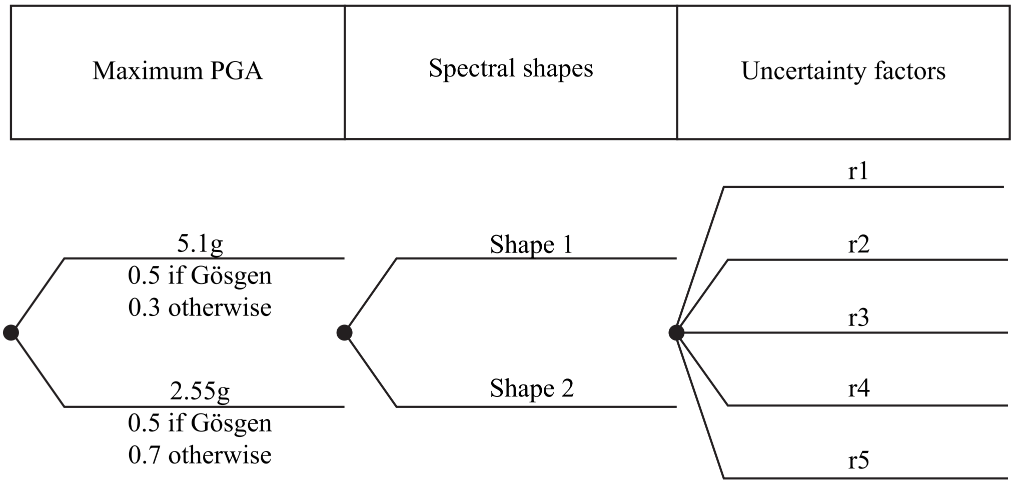


Figure 6.20: Logic tree of D. Fäh for the maximum horizontal ground motion.

At the second branching level, the PGA values are used to scale two alternative spectral shapes taken from PEGASOS: shape 1 with a plateau amplification of 2.5 and shape 2 with a plateau amplification of 4.0. For the 2.5 g branch, D. Fäh assigns weights of 0.3 and 0.7, respectively, to these spectral shapes. For the higher PGA of 5.0 g, the flatter shape 1 is preferred, with a weight of 0.8, and shape 2 is assigned a weight of 0.2.

Finally, in order to smooth the influence of his four upper bound models, D. Fäh introduces a third branching level with five different reduction factors, going from 80% to 100% within the 2.5 g branch and from 60% to 100% within the 5 g branch.

For the maximum vertical ground motion, D. Fäh's logic tree is essentially the same as for the horizontal component, with the same maximum PGA values of 2.5 g and 5.0 g. The reason is that he assumes similar shear wave energy on the vertical component as on the horizontal one. However, the weights of 0.7 and 0.3 of the first branching level are now inverted, with the higher weight for the 5.0 g branch. This is justified by the fact that compression wave energy can still pass through a liquefied layer. A further difference is that the spectral shapes for the vertical component are different from their horizontal counterparts. Again, one shape (shape 3) is flatter than the other (shape 4). Otherwise, identical weights are used: for shape 3 as for shape 1 and for shape 4 as for shape 2. Finally, the third branching level is strictly identical to the corresponding level of the logic tree for the horizontal component.

Logic Tree of A. Pecker

Figure 6.21 shows A. Pecker's logic tree for the maximum horizontal ground motion. This logic tree starts with two main branches defining values for the maximum PGA, one based on A. Pecker's analytical soil mechanical model, with a weight of 0.4, and one on the results of the non-linear soil amplification computations, with a weight of 0.6. A somewhat larger weight has been given to the non-linear calculations with respect to A. Pecker's analytical model, because the numerical models are more accurate and flexible for representing the true behavior of the soil; analytical models inherently contain simplified modeling assumptions.

No branch exists for the empirical models. A. Pecker states that the empirical data represent

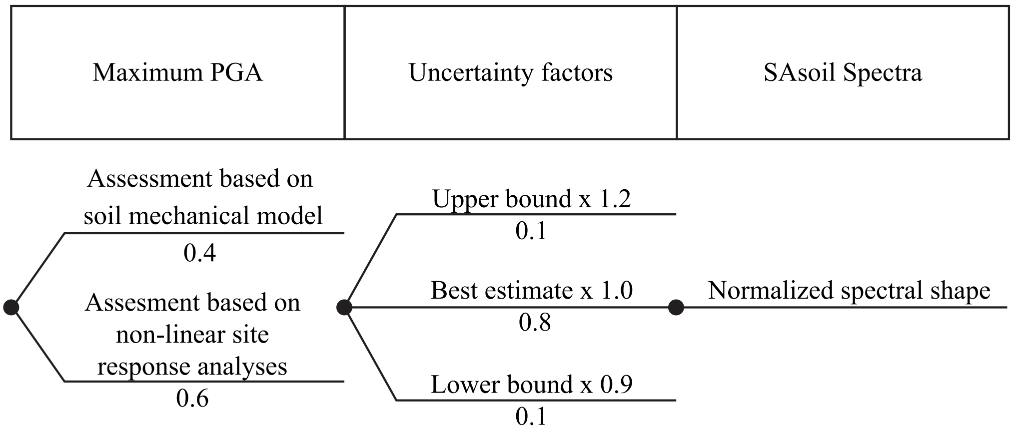


Figure 6.21: Logic tree of A. Pecker for the maximum horizontal ground motion.

the maximum recorded motion on a given site, but not necessarily the maximum ground motion that the site can sustain.

In order to reflect the uncertainty in the determination of the soil resistance, three sub-branches are added: the main sub-branch corresponds to the maximum PGA listed in Table 6.17. The two additional sub-branches correspond to maximum PGA values equal to 0.9 and 1.2 times the tabulated values.

Table 6.17: Maximum horizontal PGA values used by A. Pecker.

Model / Site	Beznau	E-Beznau	Gösgen	Leibstadt	Mühleberg
Pecker	2.5 g	2.2 g	2.0 g	1.8 g	2.1 g
NL runs	2.8 g	2.5 g	2.8 g	2.6 g	2.4 g

Finally, normalized spectral shapes are anchored to the resulting PGA values. These spectral shapes were determined from the non-linear soil amplification computations for a PGA of 2.5 g with upper (stiff) bound material properties.

A. Pecker finds that there is no reason for limiting the maximum vertical ground motion.

Logic Tree of J. Studer

J. Studer's logic tree for the maximum horizontal ground motion can be seen in Figure 6.22. Its first branching is identical to A. Pecker's one: weights of 0.4 and 0.6 are given to Pecker's mechanical model and to the non-linear soil amplification computations, respectively. There is no branch using the empirical data. J. Studer's arguments are that these data provide lower bound values and that the corresponding site characteristics are not known in detail.

For the branch of A. Pecker's model, Studer introduces a sub-branching in order to capture the epistemic uncertainty in the soil resistance. He assigns weights of 0.1 to PGA values multiplied or divided by a factor of 1.2, whereas a weight of 0.8 is given to the unmodified values of Table 6.17.

Finally, normalized spectral shapes are anchored to the resulting PGA values. These spectral shapes were determined from the non-linear soil amplification computations for a PGA of 2.5

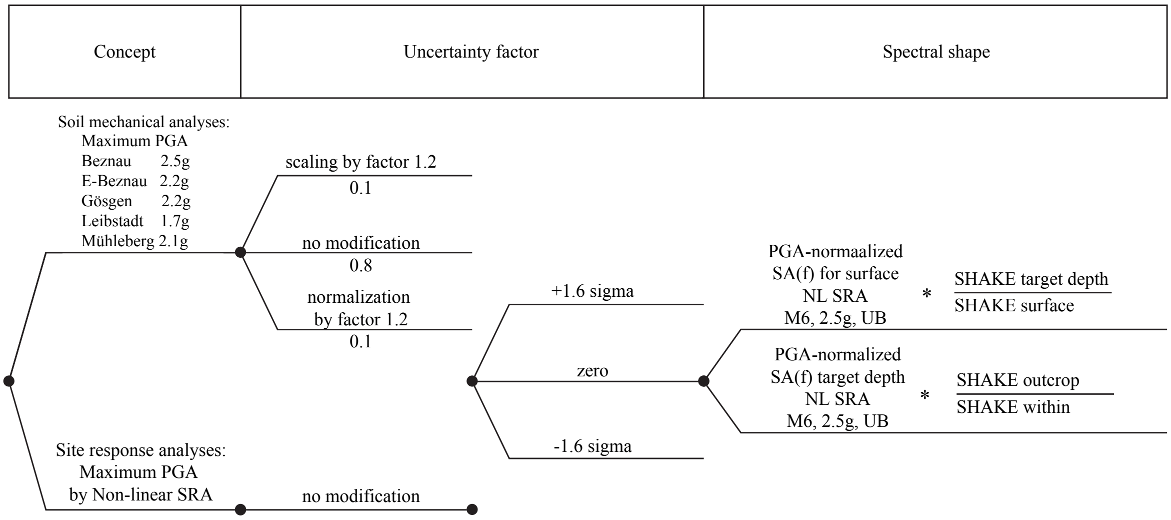


Figure 6.22: Logic tree of J. Studer for the maximum horizontal ground motion.

g with upper bound (stiff) material properties. J. Studer uses the site-specific mean spectral shapes, with a weight of 0.6, as well as the spectral shapes that correspond to ±1.6 times the (log-normal) standard deviation, with a weight of 0.2 each.

With respect to the vertical ground motion, J. Studer argues that the strength of a soil element under normal loads is significantly larger than under shear loading. Therefore, he assumes the maximal vertical ground motion to be virtually ”unbounded”. Nevertheless, he considers some limit for Leibstadt, the only site with a low water table, by introducing three branches: no bound with a weight of 0.5, a spectrum according to TP3-TN-0359 with a weight of 0.25 and, finally, 1.4 times this spectrum, also with a weight of 0.25.

6.6 Comparison of the SP3 Expert Models

6.6.1 Median Horizontal Amplification

The range of amplifications for the median horizontal component for the four expert models at the four sites are shown in Figure 6.23 for rock PGA of 0.05 g. (The median is evaluated as the mean of the log values, which corresponds to the median under the assumption of a log normal distribution.) For this level of shaking the site response is nearly linear. The range of models have different resonances. The resonance frequencies based on the used V_S profiles and the ”apparent” resonance frequencies after averaging over all profiles, materials and methods for the median amplification are listed in Table 6.18. The median amplification for the four experts at these low levels of input motion are similar: they differ by less than a factor of 1.2 of each other. The epistemic uncertainty in the amplification, shown by the dashed lines, spans about a factor of 4 to 8 near the resonance frequencies.

The amplifications for median horizontal component for a higher level of input motion (0.75 g) are compared in Figure 6.24. The non-linear effects on the amplification for high frequencies is seen in this figure with amplification less than unity for some of the models. The resonance frequencies are not as clear for the higher level of input motion. There is a larger difference between median amplification for the four experts at this higher level of input motion as

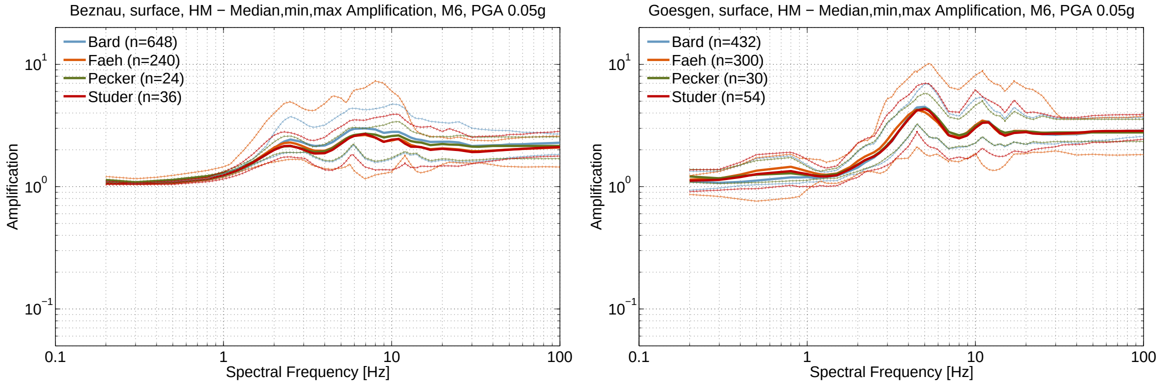
Table 6.18: Resonance frequencies for median amplification for low ground motion levels.

(a) Resonance frequencies according to the V_S profiles.

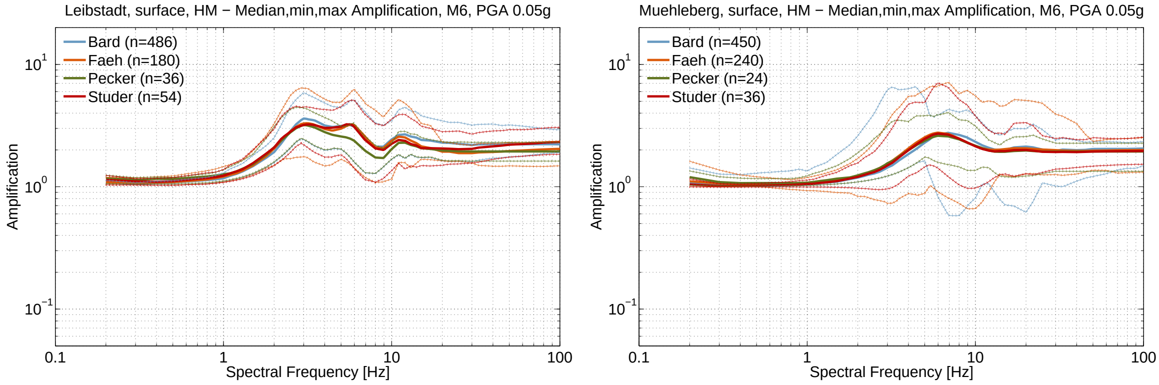
Site	Frequencies [Hz]
Beznau	2.3 2.5
Gösgen	4.4 5.3 5.4 5.7
Leibstadt	2.3 2.9 3.4
Mühleberg	5.6 5.9 6.9 8.9

(b) "Apparent" resonance frequencies after evaluation of the site amplification.

Site	Frequencies [Hz]
Beznau	2.5 6
Gösgen	4.5 11
Leibstadt	3 5.5 11
Mühleberg	6



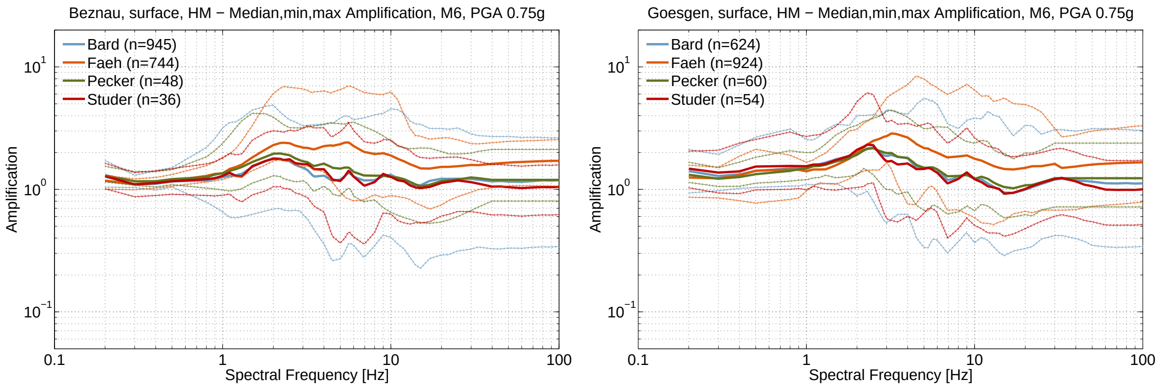
(a) Beznau (b) Gösgen



(c) Leibstadt (d) Mühleberg

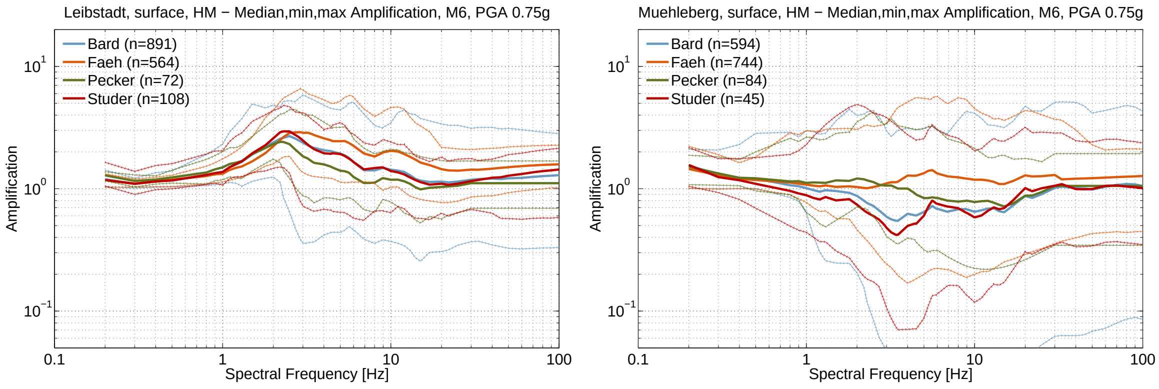
Figure 6.23: Comparison of the horizontal soil surface amplification for PGA=0.05 g at all four sites. In bold lines the median per expert is shown and the thin crossed lines represent the minimum and maximum curves by expert.

compared to the 0.1 g case. The median amplifications span a range of up to a factor of 2. Due to the uncertainty for the non-linear behavior of the soil, the range of the amplification is much wider (over a factor of 10) at the mid frequency range.



(a) Beznau

(b) Gösgen



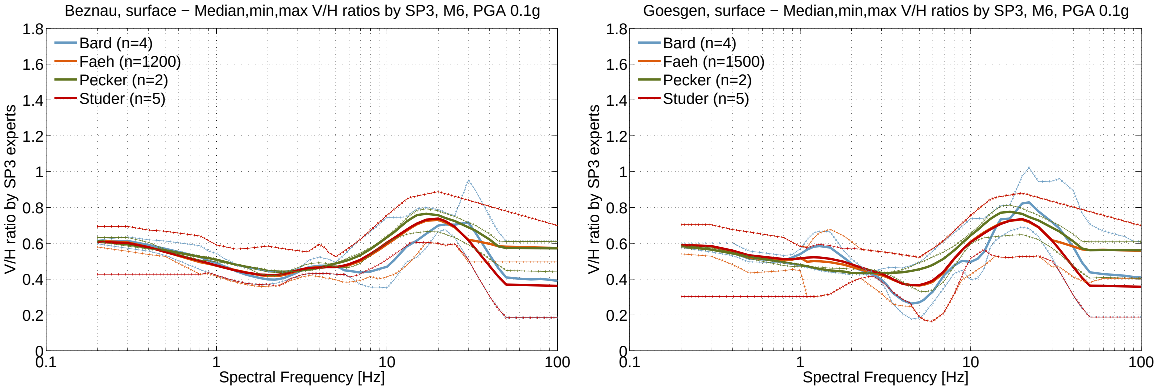
(c) Leibstadt

(d) Mühleberg

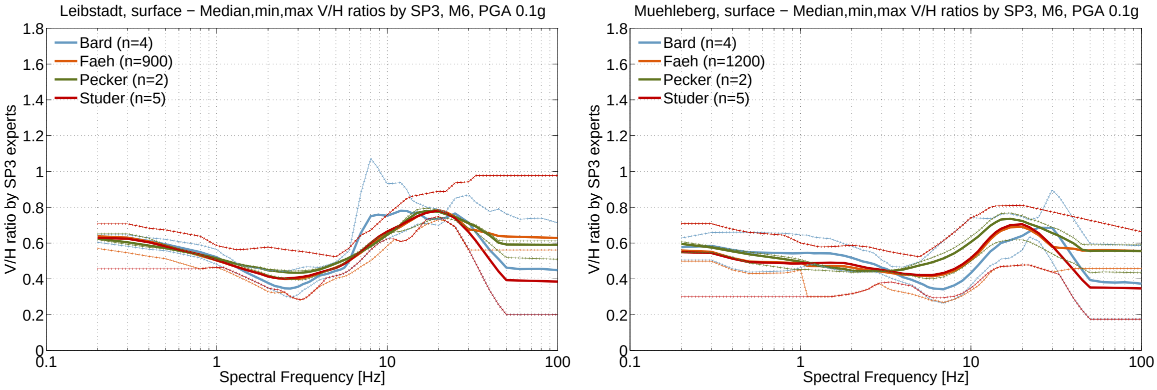
Figure 6.24: Comparison of the horizontal soil surface amplification for PGA=0.75 g at all four sites. In bold lines the weighted median per expert is shown and the thin crossed lines represent the minimum and maximum curves by expert.

6.6.2 Median Vertical V/H Ratios

The median and range of the V/H ratios for an input PGA of 0.1 g is shown in Figure 6.25. For this low range of input motions, the V/H ratios have similar spectral shapes with a peak near 20 Hz and the median ratios are below 0.7 at all frequencies. The median and range for the V/H ratios for higher rock input PGA of 0.75 g are shown in Figure 6.26. There is a much larger range of the V/H ratios in the 10 - 30 Hz range which reflects the different assumptions of the non-linear behavior of the V/H ratios in the candidate models. The higher end of the range, with V/H ratios between 1.2 and 1.8 for the four sites and four experts are due to the V/H models that include non-linear behavior for the horizontal component, but linear behavior on the vertical component. The lower end of the ranges, near 0.5 at 20 Hz, reflects models that assume the non-linear is the same for the horizontal and vertical ground motions.



(a) Beznau (b) Gösgen



(c) Leibstadt (d) Mühleberg

Figure 6.25: Comparison of the soil surface V/H ratios for PGA=0.1 g at all four sites.

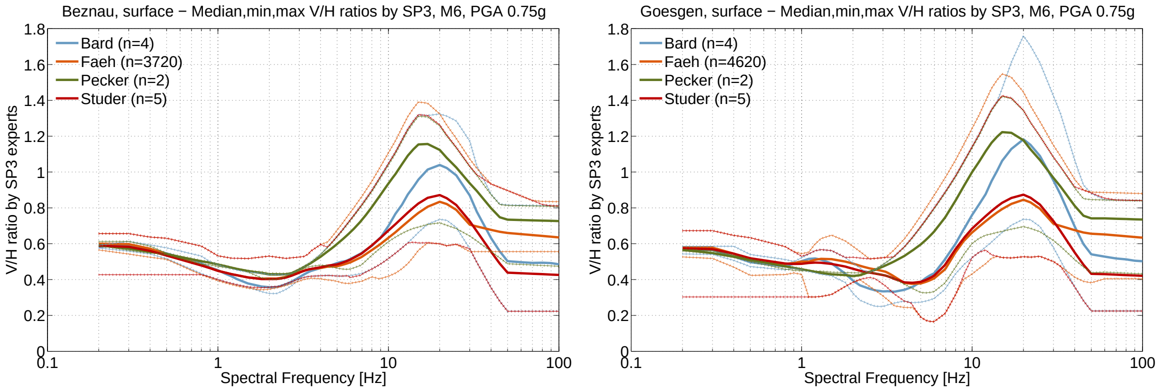
6.6.3 Aleatory Variability for Horizontal and Vertical

The aleatory variability for SP3 is only the additional aleatory variability for the non-linear range of the site response. Two of the SP3 experts include additional variability – P.-Y. Bard and J. Studer –, but it is relatively small. The other two experts – D. Fäh and A. Pecker – do not include any additional variability.

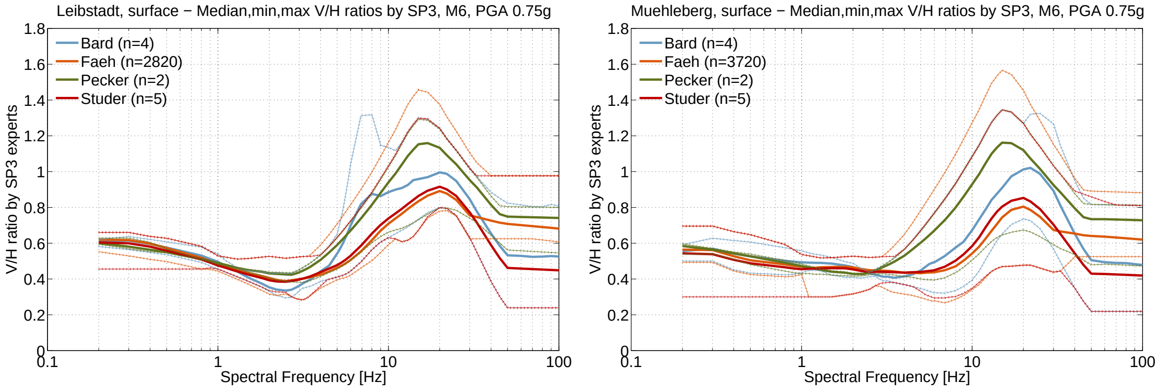
6.6.4 Maximum Ground Motions for Soil

The median and range for the maximum ground motions for soil for the four sites are shown in Figure 6.27 as a function of frequency. At the low frequencies, there are two different sets of spectral shape for the maximum ground motion: the shapes that decrease strongly at low frequencies and the shapes that remain high at low frequencies. The shapes with the strong decay are based on the spectral shape of the non-linear runs.

The median values of the maximum ground motion are similar between the four SP3 experts at high frequencies, except for the Mühleberg site in which J. Studer's model leads to much lower maximum values. At all four sites, J. Studer has a much smaller maximum soil ground motions for the lower end of the range. The hazard is most sensitive to this lower end of the range, so the truncation at the maximum ground motion from J. Studer has a stronger effect than from the other three SP3 experts.

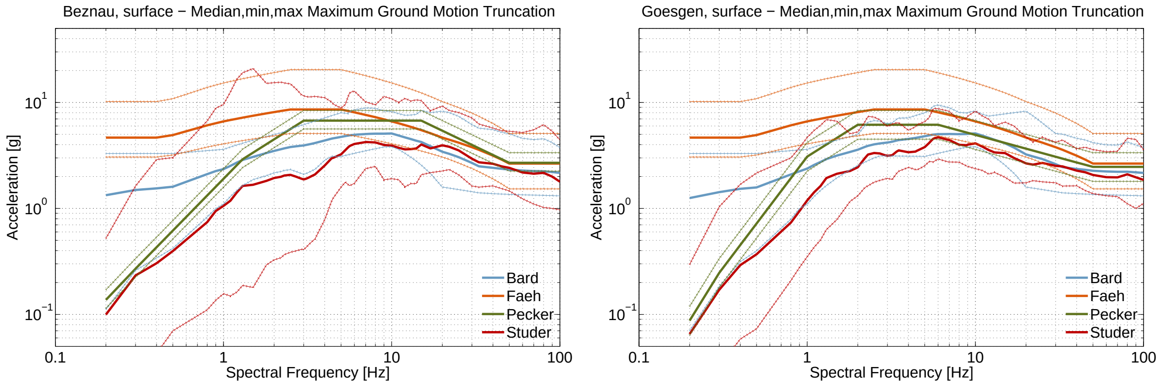


(a) Beznau (b) Gösgen

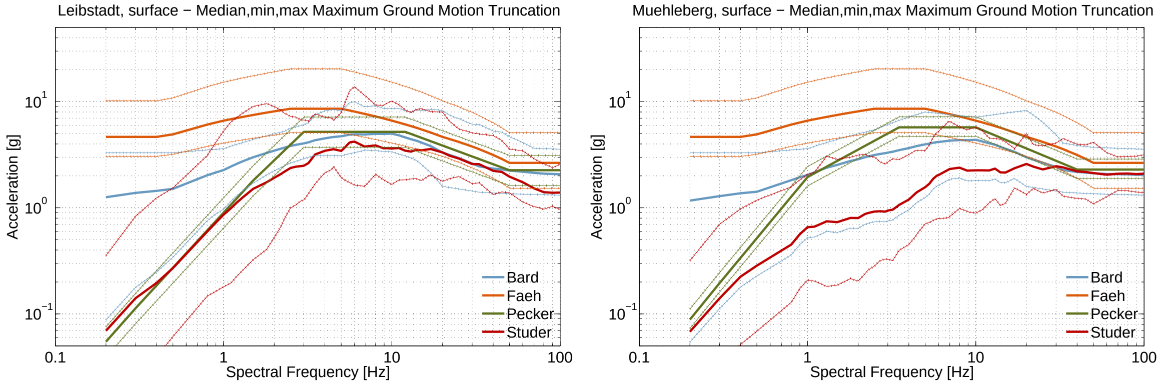


(c) Leibstadt (d) Mühleberg

Figure 6.26: Comparison of the soil surface V/H ratios for PGA=0.75 g at all four sites. In bold lines the weighted median per expert is shown and the thin crossed lines represent the minimum and maximum curves by expert.



(a) Beznau (b) Gösgen



(c) Leibstadt (d) Mühleberg

Figure 6.27: Comparison of the maximum ground motion spectra at all four sites. In bold lines the weighted median per expert is shown and the thin crossed lines represent the minimum and maximum curves by expert.

6.7 Liquefaction

The possibility of liquefaction was investigated for all the NPP sites [Pecker and Studer 2013] (EXT-TN-1270). This was done, on the one hand, by means of 1D non-linear soil amplification calculations with effective stresses and, on the other hand, with the aid of empirical relations, e.g. [Youd and Idriss 2001].

At Gösgen, for instance, a few time histories triggered liquefaction at some depth for very strong input motion (PGA on rock $\geq$0.75g) despite the strong dilative behavior of the gravel as long as perfectly undrained conditions were assumed. However, as soon as a realistic permeability was taken into account in a 2-phase model, the excess pore pressure became negligible. This clearly showed that the gravel permeability is high enough to permit pore water redistribution. In finer materials, a certain pore water pressure increase will occur, but this material is located in lenses so the stability of the entire soil body is not affected and earthquake induced pore water increases will dissipate rapidly into the neighboring previous soil.

Because the soil is composed of essentially dense and well compacted gravel at all the NPP sites, the result cited for Gösgen holds good for all sites where incompetent soil layers were removed below the relevant structures (e.g. below the reactor building). Therefore, liquefaction turned out to be highly improbable, at most limited to lenses of finer materials for very strong input motion.

For the Mühleberg site, the conclusions are twofold. Liquefaction is most likely to take place in the silty sand layer at or very near the ground water table (located in the layers at a depth of 3-4.5 m) for earthquake magnitudes equal or larger than 6.0 and peak rock accelerations equal or larger than 0.4 g. At deeper depths, the gravelly layer located below the silty sand layer (>4.5 m) is dense enough to prevent liquefaction, even for large magnitudes and high accelerations. Based on the review of the design drawings, construction photographs and subsurface conditions, it was concluded that most of the critical plant structures are founded on the dense gravel or Molasse bedrock. Other structures resting on a shallow foundation might be affected by liquefaction of the silty sand layer which, in absence of underground sloping conditions and existence of a free surface towards which the soil could flow, will experience vertical settlements and possibly some tilt because liquefaction will not be uniform under a given structure.

For all four NPP sites, the parameters entering the constitutive equations used for the liquefaction evaluation have not been derived from actual measurements; several are based on experience or derived through correlations with some index parameter. Thus, the assessment carried out for all four NPP sites is subject to significant uncertainties and does not replace site-specific investigations and expert judgment that would be required for the evaluation of a specific structure. More details can be found in Volume 5.

Chapter 7

Seismic Hazard Computation - SP4 Summary

The SP4 hazard analysts performed the implementation of the models provided by SP1, SP2 and SP3 and ran hazard computations. Following the procedure and understanding of PEGASOS, the hazard analysts were not supposed to make any interpretations and judgments about the models to be implemented. Besides the computation of the hazard, the key element of the work of SP4 was the development of Hazard Input Documents (HID). The TFI is responsible for reviewing the technical content of the HID. These were developed at the interface between the expert elicitation and SP4. The HID are self-contained and complete in terms of inputs required for the hazard computations. The SP4 hazard analysts attended all expert workshops in order to be aware of the details behind the model implementations and to be able to clarify any technical issues. Any interface issues in terms of the implementation of the SP1, SP2, or SP3 models by SP4 were explicitly addressed in the HIDs and thus, no formal SP4-interface workshops waere necessary. Based on the HIDs, SP4 prepared the rock hazard input files (RIFs) for the rock hazard software and soil hazard input files (SIFs) for the soil hazard software.

Because the hazard software must not limit the freedom of the experts to capture the range of technically defensible interpretations, it had to be modified several times to accommodate non-standard features of the experts' models and their parameterization. In the PRP, the rock hazard software was modified to sample large source model logic trees in a computationally efficient manner (see Section 7.5.2) and thus avoided excessive use of pinching of logic tree branches, as was necessary in PEGASOS.

7.1 Hazard Result Specification

The output specification of the PRP is based on the output specifications applied in the PEGASOS Project. The main outputs were prepared for both lower-bound magnitude result sets (magnitudes 4.5 and 5.0). Additionally, scenario earthquakes have been identified and scenario spectra (conditional spectra) were developed accordingly in SP5, but these are not part of this report. The detailed output specification, as defined in the PEGASOS Refinement Project plan (PMT-TB-1012), is presented below.

7.1.1 Basic Requirements

Elevations

In the PEGASOS Project, the ground motion at each plant was presented for the site-specific soil condition at the different elevation levels. Table 7.1 lists the plant-specific elevation levels for which the output in terms of soil hazard is presented. The ground motions at depth are given as outcropping motion.

Table 7.1: Elevation levels for outcropping ground motion at NPP sites.

Plant	Terrain Elevation (asl)	Elevation 1 (free surface)	Elevation 2 (relative to ground surface)	Elevation 3 (relative to ground surface)
Beznau	327 m	0 m	-15 m (reactor building)	
Gösgen	382 m	0 m	-9 m (reactor building)	
Leibstadt	332 m	0 m	-10 m (reactor building)	
Mühleberg	466 m	0 m	-7 m (turbine and radwaste building)	-14 m (reactor building)

Components of motion

The hazard is computed for the geometric mean of the two horizontal components and for the vertical component. The standard deviation of the horizontal component-to-component variability that can be used for the development of time histories is discussed in Chapter 9.

Vibration frequencies for hazard analysis

The rock hazard results are computed for the following nine spectral frequencies: 0.5 Hz, 1 Hz, 2.5 Hz, 5 Hz, 10 Hz, 20 Hz, 33 Hz, 50 Hz and 100 Hz ($\approxeq$ PGA). The soil hazard is computed at the nine spectral frequencies given above for the rock hazard plus one or more additional frequencies, so that the site-specific soil resonance is adequately represented.

7.1.2 Common Hazard Results

Seismic hazard curves for reference rock site condition

The reference rock site seismic hazard for the horizontal components for each frequency at each plant is supplied at the following ground motion levels: 0.025 g, 0.05 g, 0.07 g, 0.1 g, 0.15 g, 0.2 g, 0.25 g, 0.3 g, 0.35 g, 0.4 g, 0.5 g, 0.65 g, 0.7 g, 0.8 g, 1 g, 1.25 g, 1.4 g, 1.5 g, 2 g, 2.5 g, 3 g, 4 g, 5 g, 6 g, 8 g, 10 g and higher g-values (2 g increments) until the mean annual hazard level falls below 10^{-7}/yr.

The epistemic uncertainty in the reference rock site hazard curves is presented for the horizontal and vertical components for each frequency and each plant in plots of the 5%, 16%, 50%, 84% and 95% fractile levels and the mean hazard (tables of the fractiles at 99 equally weighted levels). The fractile curves are depicted (extended to small annual probabilities of exceedance respectively) until they reach the PGA level where the mean annual hazard has the annual probability of exceedance of 10^{-7}/yr.

Seismic hazard curves for the soil site condition

The soil site hazard for the horizontal and vertical components for each frequency at each plant are supplied at the ground motion levels specified in Section 7.1.2 until the mean annual hazard level falls below 10^{-7}/yr.

Epistemic uncertainty the soil hazard curves

The epistemic uncertainty in the soil site hazard curves is presented for the horizontal and vertical components for each frequency and each plant as follows: Plots of the 5%, 16%, 50%, 84% and 95% fractile levels and the mean hazard (tables of the fractiles at 99 equally weighted levels).

Upper limit of the ground motion

The upper limits of the ground motion were re-elicited and provided for both rock and soil. Logic trees were developed by SP2 and SP3 to account for a complete integration in the hazard curve estimation. The maximum ground motions for the reference rock sites were high so that they had a negligible effect on the hazard. For computational purposes, the upper limits on the rock ground motion were not applied in the hazard calculation; however, the upper limits were applied to the soil hazard by truncating the hazard at the upper limit ground motion for individual hazard curves at each branch tip of the logic tree. The sensitivity of the computed mean hazard curves for the reference rock and soil site condition to the estimates of the upper limit of the ground motion was shown at the occasion of hazard feedback workshops.

Uniform hazard spectra

Uniform hazard spectra (UHS) for the horizontal and vertical components for the soil site condition were computed and plotted for each plant for the following annual exceedance frequencies, provided that no extrapolation of the hazard curves to these levels is necessary: 10^{-2}/yr, $2.1 \cdot 10^{-3}$/yr, 10^{-3}/yr, 10^{-4}/yr, 10^{-5}/yr, 10^{-6}/yr, 10^{-7}/yr. The ground motions for the UHS are determined by linear interpolation in log-log space between the ground motion levels defined in Section 7.1.2. The epistemic uncertainty in the UHS is shown in terms of the mean and the 5%, 16%, 50%, 84%, and 95% fractiles.

Deaggregation

To be consistent with the representation of the UHS, the mean horizontal component rock hazard is deaggregated in terms of magnitude, distance, and ϵ (number of standard deviations) at the following levels of annual exceedance frequency: 10^{-2}/yr, $2.1 \cdot 10^{-3}$/yr, 10^{-3}/yr, 10^{-4}/yr, 10^{-5}/yr, 10^{-6}/yr, 10^{-7}/yr. The deaggregation plots are generated for the frequencies 1 Hz, 5 Hz, 10 Hz and 100 Hz. A deaggregation for additional frequencies is done on an NPP-specific basis. The deaggregation is used to determine the controlling earthquakes in terms of magnitude, distance and ϵ.

7.1.3 Additional Parameters

Ground motion duration

Ground motion durations were defined for the different earthquake scenarios. SP5 reviewed available duration models (including global models for large magnitudes and Swiss-specific models for small magnitudes) and determined which models are applicable to large magnitudes in Switzerland and consistent with the models defined by SP2. The applicable models were used to define the range of durations for the scenario earthquakes.

Peak ground velocity

In the past, there were few ground motion models for PGV, so simplified scaling relations between PGV and spectral acceleration were often used to estimate the PGV. Many, but not all, of the new ground motion models include models for PGV. The simplified PGV scaling relations developed within PEGASOS can be used to estimate the PGV for a given UHS. The peak ground velocity (PGV) hazard will be computed only at the explicit request of an NPP. If the PGV hazard is requested, then for GMPEs that include a PGV model, the PGV models can be used for the GMPEs in the hazard calculation.

Average spectral acceleration

A simplified procedure for computing attenuation relations for spectral acceleration averaged over a specified frequency band was developed in the PEGASOS Project. This procedure was based on scaling of the attenuation relation for one of the spectral frequencies given in Section 7.1.1 and will be revised if necessary. The scaling relation includes scaling of both the median ground motion and the aleatory variability of ground motion. The simplified procedure will only be applied at the explicit request of an NPP to estimate hazard curves for average spectral acceleration.

7.1.4 SP5 Outputs

The subproject 5 is not part of this report, but for the sake of consistency with the project plan the specified outputs are repeated here.

Scenario hazard curves

The scenario hazard curves were developed by SP4 for the frequencies 1, 5 and 100 Hz (PGA). For each of these frequencies, the total hazard was decomposed into scenario hazard curves in terms of magnitude and distance. The decomposition was done for the rock and, if necessary, soil hazard. A table of representative earthquake scenarios in terms of a response spectrum, magnitude, distance and rate of occurrence was developed on request for an NPP. The configurations of hazard curves requested by each NPP are summarized in Renault [2013b] (PMT-TN-1146).

Scenario earthquakes

Representative scenario earthquakes in terms of spectral acceleration response spectra and time histories were developed by SP5. The development of scenario earthquakes for rock was done for all sites, whereas for soil it would be done on a site-by-site basis as requested by each NPP. The scenarios requested by the NPPs and the NPP-specific amount are summarized in the technical note PMT-TN-1146.

All the common hazard results (Section 7.1.2) are contained in Volume 2 of this report. The additional parameters (Section 7.1.3) are discussed in Chapter 9 of this volume. The scenario spectra and time histories developed within SP5 (Section 7.1.4) are documented in a separate report [Renault and Abrahamson 2013].

7.2 Hazard Software and Tools

7.2.1 FRISK88MP

The FRISK88MP* package consists of four programs for the calculation of seismic hazard on rock, namely PREP88, FRISK88M, POST88 and MRE88. Program PREP88 is a preprocessor that prepares input to FRISK88M, using information about the logic tree, the attenuation equations, the seismic source parameters and geometry and – if specified – the Monte Carlo input parameters. Program FRISK88M calculates the seismic hazard curves for each combination of source parameters. FRISK88M is also used in dedicated runs to produce deaggregated seismic hazard results. Typically, PREP88 and FRISK88M are run separately for each seismic source, delivering the seismic hazard by source. Program POST88 computes the total seismic hazard at the site (i.e. the seismic hazard from all seismic sources) and sensitivity results, using the logic tree and the seismic hazard results from the various seismic sources. Another post-processor, MRE88, calculates marginal and joint probability distributions and summary statistics of magnitude, distance and ground motion ϵ for one or more seismic sources, using the deaggregated results produced by multiple FRISK88M runs. Figure 7.1 summarizes the flow of information among these programs.

POST88 delivers the total seismic hazard at the site for one particular combination of one SP1 and one SP2 model. There are 16 such combinations in the PRP. The integration of all combinations from multiple expert groups is performed by the small CMB-FRAC post-processing utility. The integrated mean and fractile hazard curves computed with CMB-FRAC (which embody all SP1 and SP2 information and associated uncertainties) are passed to the soil hazard software (see Section 7.6) for the calculation of soil hazard curves and uniform soil hazard spectra.

The FRISK88MP package (including its predecessors [McGuire 1976]) is the most widely used PSHA software for critical facilities. It has been reviewed and qualified for use in a number of seismic hazard studies subject to the US-NRC and US-DOE QA requirements (US Code of Federal Regulations, Section 10, Part 50, Appendix B, and Section 10, Part 830). These studies include the Rocky Flats nuclear site, the Yucca Mountain Nuclear Waste Repository, the Paducah Gaseous Diffusion Plant, the North Anna and Grand Gulf early site permit applications. Furthermore, the FRISK88MP package was also used in the PEGASOS Project. In order to maintain continuity/comparability and the Swiss know-how on FRISK88MP, the project management team of the PRP decided to use FRISK88MP again for the PRP.

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[*] FRISK88MP is the name used for the PEGASOS-specific version of the FRISK88M software

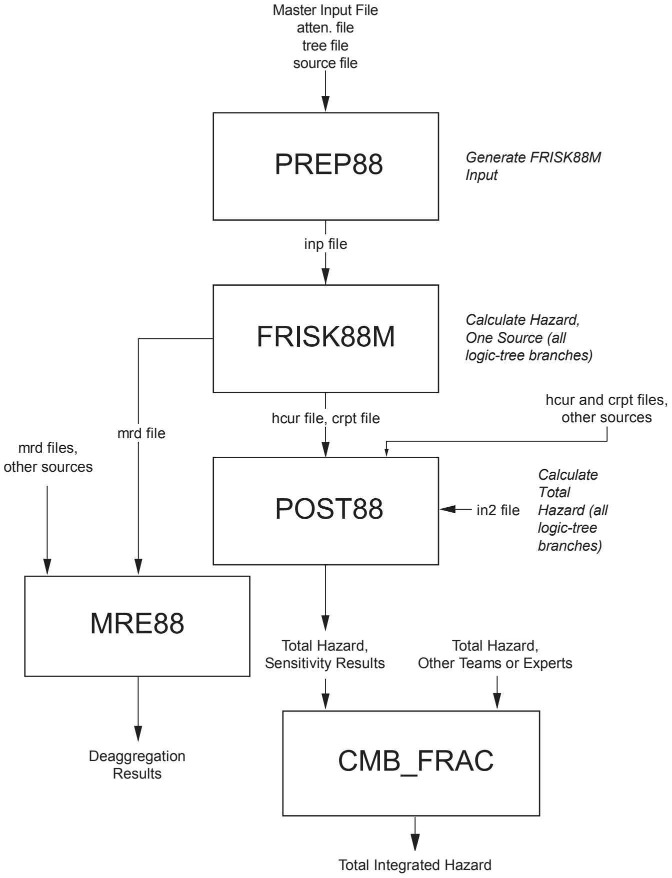

Figure 7.1: Organization of programs and flow of information in the FRISK88M software package

7.2.2 SHZeval and SOILHAZP

The SOILHAZP [McGuire 2004] and SHZeval [Hölker 2012a] tools are two alternative software solutions, which establish hazard-consistent combinations of a set of seismic hazard results with a set of scaling models, where each scaling model is associated with uncertainty, and a set of maximum ground motion truncation models. Practically, the software is used for the computation of:

- the horizontal motion hazard at or near the surface (soil hazard[†]) given the horizontal motion hazard on rock (rock hazard) and the results of the horizontal motion SP3 (site response) assessments;
- the vertical motion soil hazard given the horizontal motion rock hazard and the combined SP3 site response models, SP2 and SP3 V/H models; and
- the vertical motion rock hazard given the horizontal motion rock hazard and the results of the SP2 V/H scaling assessments.

The kernels of the SOILHAZP and SHZeval software tools likewise implement the methodology described in McGuire et al. [2002] (NUREG/CR-6769) as "Approach 2a/3". The kernel

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[†] In this context, "soil" is the unconsolidated sediment which covers the "rock" as defined in Section 5.2

functionality is to re-evaluate the probability of exceeding a spectral acceleration considering a scaling of the acceleration, where the scaling follows a log-normal distribution, which is specified by the median scaling value and the standard deviation. This kernel functionality is applied per spectral frequency and per spectral acceleration, which samples the hazard results.

Generally, all input quantities (hazard results, scaling models, truncation models) are represented by multiple scenarios and associated weights. The software develops the combinations of all scenarios and computes a hazard curve per combination using the kernel functionality. The resulting hazard curves are summarized into discrete fractiles taking into account the weights. This operation is performed sequentially per spectral frequency. Uniform hazard spectra are computed by interpolating the hazard curve fractiles.

The output of SOILHAZP and SHZeval are likewise discrete hazard fractiles, which are formatted twofold: as hazard curves per spectral frequency and as uniform hazard spectra per annual probabilities of exceedance.

7.3 Project-Specific Software Modifications

7.3.1 FRISK88MP

In order to accommodate all the features of the PRP expert models, a number of modifications were introduced in the FRISK88M software. The most significant modification relates to the sampling of the individual logic tree branches. For the simplest SP1 × SP2 expert model combination (EG1c and Faeh's models), the number of branches to calculate for each individual frequency and site exceeds 10^{60} [‡]. The FRISK package is designed to sequentially compute each individual combination, but allows for some algorithmic simplifications to be made in the POST88 runs under the analyst's control: the so-called moment-based pinching of the source logic tree. In the PEGASOS Project, intensive use was made of this type of pinching, as well as of a second type, the logic tree trimming. The effort to first iteratively develop pinching schemes and to then show their compliance with the project accuracy criteria is enormous. Partly because of this, and partly because the most complex experts' model was further enlarged with respect to the PEGASOS Project, it was recognized early in the PRP that another sampling approach had to be chosen. Monte Carlo sampling of the logic tree was added to the FRISK88M package [Toro 2011] (TP4-TN-1172). Section 7.5.2 summarizes the use of pinching and Monte Carlo in the PRP.

The main modifications to the software were done at the beginning of the PRP and led to version 66 of the core package FRISK88M. In the course of the PRP, some additional features were identified by the PMT which might be useful in the long term and were incorporated into version 76-66.

Modifications to FRISK88MP v.66 include the following:

- Implementation of the PRP ground motion prediction equations (parametric representations of all models)

[‡] In this case, the number of branches to calculate in FRISK88M per seismic source amounts to only' 2.10^6; the number explodes in POST88 when each branch of each source has to be combined with all branches from all other sources present in the model.

- Addition of options to adjust the published equations to Swiss conditions (maximum ground motion truncation, tabular input for a new single-station sigma, small magnitude adjustment and $V_S - \kappa$ scaling of the models)
- Arrays extension in order to accommodate larger logic trees
- Implementation of Monte Carlo sampling in PREP88 (ver. 109g) and POST88 (ver. 112l)

Additional modifications to FRISK88MP v.76-66 include the following:

- Implementation of a common and consistent distance metric (R_{JB} or R_{RUP}) for the deaggregation
- Addition of an optional hanging wall factor for the ground motion prediction equations considering this effect
- Addition of a mean distance, mean magnitude and coarse magnitude deaggregation in the FRISK88M output

7.3.2 SHZeval

SOILHAZP was implemented for the PEGASOS Project and used in 2002 to 2004. It is written in Fortran77, is designed as a stand-alone application, and has a static functionality and a somewhat cumbersome data input/output interface. SOILHAZP is described in McGuire [2003] (TP4-AN-0182). The SOILHAZP software was only used to qualify a new software package (SHZeval) to evaluate the soil hazard.

The SHZeval software is a set of routines bundled into a toolbox for MATLAB[§] or GNU Octave. The routines are written in MATLAB and C languages, where the latter use parallelization via multi-threading. The toolbox has a modular design and features data input from, and output to, the MATLAB workspace, which provides a certain flexibility concerning setup and purpose of the hazard calculations. The SHZeval software was implemented for the PRP in 2010 and was used throughout the PRP for soil hazard and vertical motion rock hazard computations. SHZeval provides data import and export routines, which maintain full compatibility with SOILHAZP. An overview of SHZeval is given in Figure 7.2 and a description can be found in Hölker [2013b] (TP4-TN-1264). The latter includes an algorithmic description of the methodology.

A twofold QA of the SHZeval software was undertaken: The plausibility of results was verified using simple generic models. Furthermore, one set of PEGASOS soil hazard computations was redone and compared with the original SOILHAZP-based result. J. Baker of Stanford University independently reviewed the source code for compliance with the methodology described in McGuire et al. [2002] (NUREG/CR-6769). The former QA is described in Hölker [2013b] and the latter is reported in Baker [2012].

[§] MATLAB©is a registered trademark of MathWorks, Inc. in the U.S.A. protected by U.S. and international patents.

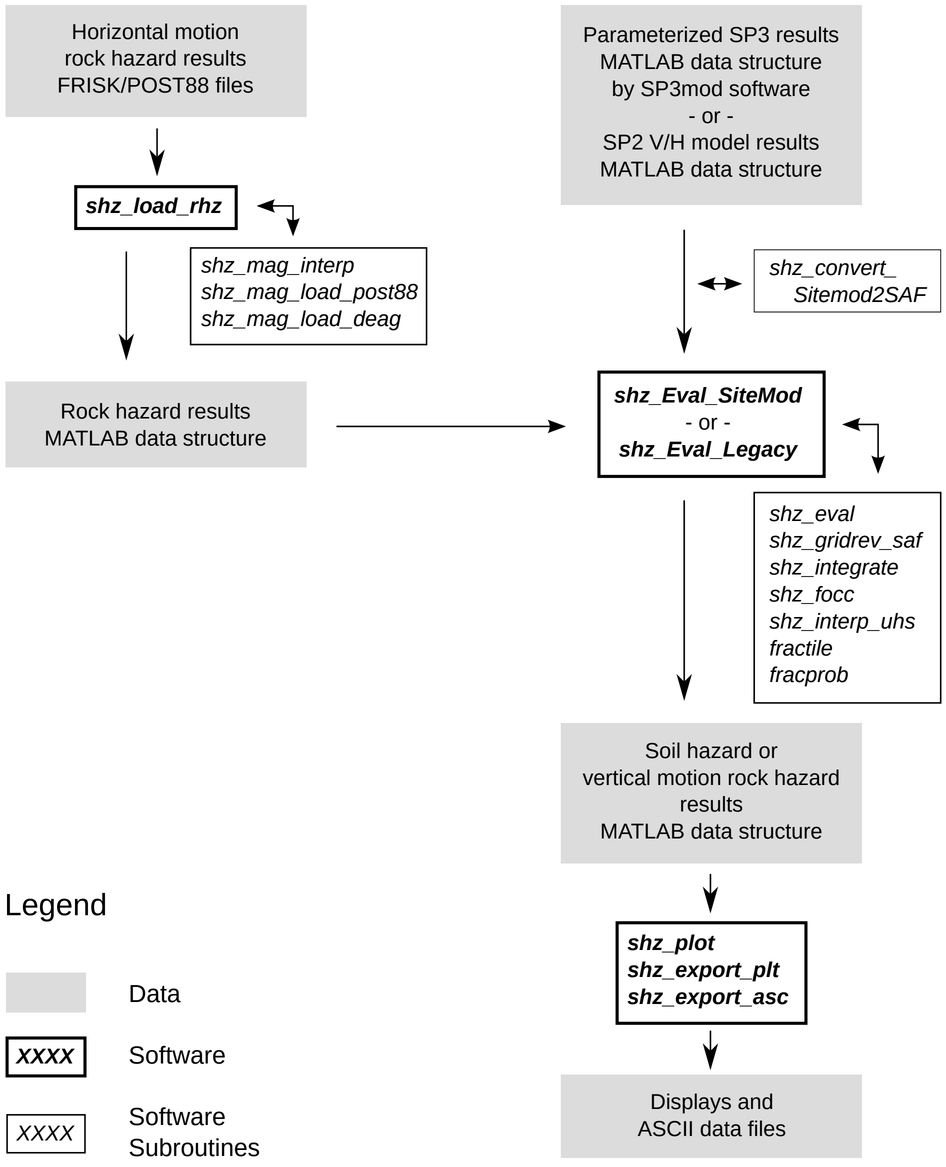


Figure 7.2: Schematic representation of the core functionality of the SHZeval toolbox and simplified display of the hazard evaluation workflow. A more complete and detailed display of this scheme can be found in figure 1 of Hölker [2013b].

7.4 Project-Specific Boundary Conditions and Decisions

Applicability of GMPEs at large distances: The selected GMPEs have a range of applicability which is at maximum 200 km. Some of the GMPEs are only well constrained up to 150 km. The source models of SP1 extend up to 300 km and thus the GMPEs are used at large distances outside their range of applicability. From the hazard deaggregation it is known that earthquakes at large distance have a negligible contribution to the hazard at the levels of interest. Extrapolating the GMPEs to large distances within the hazard code will not significantly affect the end results.

The $V_S - \kappa$ corrections were developed and calibrated for the mid-distance range which dominates the hazard. Some of the spectral shapes of the $V_S - \kappa$ corrected GMPEs would not be appropriate at large distances; however, because the large distance earthquakes do not significantly affect the hazard, the short distance $V_S - \kappa$ corrections are applied to all distances.

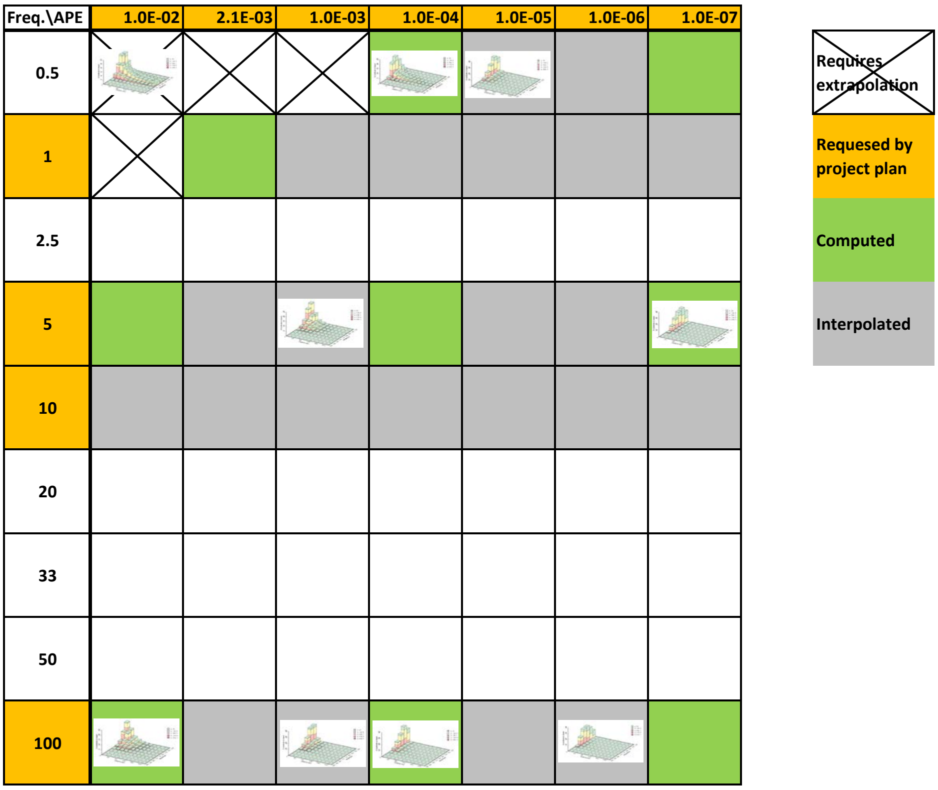
Maximum ground motion truncation: As already discussed in Section 4.8.5, the project decided to perform the final rock hazard calculations without the maximum ground motion truncation part, for the sake of computational efficiency and in the light of the marginal impact of this part of the models. The maximum ground motion truncation is applied to the soil ground motion.

Deaggregation: In terms of computing efficiency, the deaggregation calculation for a given frequency and hazard level in FRISK88M is as time-consuming as the main calculation for the given frequency. The project specifications (see Section 7.1) list 28 (4 x 7) combinations of spectral frequency and PGA or annual probabilities of exceedance (APE) at which deaggregation results should be delivered, see Figure 7.3. Four such combinations are rejected because the mean spectral acceleration associated with the mean hazard at the relevant APE and frequency for all the sites is lower than the smallest spectral amplitude for which hazard is calculated (0.025 g). In other words, an extrapolation of the hazard would have been necessary for these four combinations before the deaggregation could have taken place. Considering the smooth distribution of magnitude, distance and ϵ contributions in the frequency-APE space, nine carefully selected combinations were chosen (green cells in Figure 7.3) for which deaggregation was calculated. For the remaining cells, deaggregation results were interpolated (grey cells in Figure 7.3).

Lower magnitude integration limit: In most PSHA conducted for nuclear power plants, hazard integration starts at magnitude 5, contributions from smaller earthquakes being considered irrelevant from an engineering perspective. To obtain a better control on the impact of this parameter on the seismic hazard, and because the PEGASOS study had shown the seismic hazard at the Swiss plants to be dominated by contributions from low to moderate magnitude, near-field earthquakes, the PRP decided to quantify the seismic hazard using both the traditional $M_{min} = 5.0$ value and a reduced $M_{min} = 4.5$ limit.

The recurrence parameters provided by the experts for $M_{min} = 5.0$ were scaled to $M_{min} = 4.5$ according to an exponential distribution:

$$N_{4.5} = N_{5.0}\, e^{0.5\beta} \tag{7.1}$$



Freq.\APE	1.0E-02	2.1E-03	1.0E-03	1.0E-04	1.0E-05	1.0E-06	1.0E-07
0.5	☒	☒	☒	🟩	▨	▨	🟩
🟧 1	☒	🟩	▨	▨	▨	▨	▨
2.5							
🟧 5	🟩	▨	▨	🟩	▨	▨	🟩
🟧 10	▨	▨	▨	▨	▨	▨	▨
20							
33							
50							
🟧 100	🟩	▨	▨	🟩	▨	▨	🟩

☒ Requires extrapolation

🟧 Requesed by project plan

🟩 Computed

▨ Interpolated

Figure 7.3: Table of the requested, calculated and interpolated combinations of spectral frequencies and annual probabilities of exceedance (APE) for the mean hazard deaggregation. The small deaggreagtion plots superposed on some cells of the matrix indicate approximatively the few corresponding cases evaluated for PEGASOS. Note that for PEGASOS the deaggregation cases were defined in terms of spectral acceleration level and not APE.

Where $N_{4.5}$ and $N_{5.0}$ are the rates of occurrence, expressed as numbers of earthquakes per year with $M \geq M = 4.5$ and $M \geq M = 5.0$ respectively and $\beta = ln(10)\, b$ (b is the b-value in the Gutenberg-Richter relationship).

Starting the hazard integration at $M_{min} = 4.5$ for this site-specific study means that the results may not be directly comparable to the results from other studies that use the traditional $M_{min} = 5.0$.

Software version: The final hazard computations and the deaggregation made use of the FRISK88MP version 66 [Risk Engineering, Inc 2013]. The project made this decision as the additional features of the version 76-66 were not used in the final expert models and this newer version proved to be much slower than the version 66, which makes a considerable difference when considering the number of runs necessary to produce all outputs.

7.5 Rock Hazard Computations

7.5.1 Transformation of SP1/SP2 HIDs into Rock Hazard Input Files (RIFs)

The development of the rock hazard input files (RIFs) begins with the hazard input document (HID). The HID, together with its electronic attachments, contains a complete parameterization of the SP1 and SP2 expert models in a form that is consistent with the hazard computation methodology described in the original PEGASOS report volume 1, section 2.

The PRP process for the development, approval and usage of the HID formalizes the flow of information from experts to TFI to SP4; this flow had been more ad-hoc in past pre-PEGASOS studies. Benefits from this process include a more clear delineation of responsibilities, better documentation of the inputs and lower chances for misinterpretation of the expert models. The introduction and implementation of the HID process constitutes a significant contribution of the PEGASOS and PRP studies to PSHA practice.

The RIFs consist of three groups of files, as follows:

- Files containing the characterization of seismic sources. This group consists of source files (extension ”src”) and logic tree files (extension ”tree”). There is one source file for each seismic source in an SP1 expert model, but more than one source may use the same logic tree file. In addition, the source file may incorporate source coordinate files and variable seismicity files by reference. There is also another (global) logic tree file, which serves as input to POST88. This file contains information about the alternative ground motion models and about the global variables in the logic trees for all sources in the SP1 expert models.

- Files containing attenuation information. This group of files includes the rock ground motion attenuation files (extension ”att”) and the files containing the single-station sigma component values (extension ”csv”). The attenuation files contain alternative GMPE-specific parameters, scaling factors ($V_S - \kappa$ corrections), indices pointing to the appropriate sigma values for the alternative ground motion models and all the associated weights. The attenuation files also contain other control information not related to attenuation or to source characterization (i.e. codes controlling the type of calculations, step sizes, spectral accelerations to consider, site coordinates, etc.).

- Intermediate input files. The control input files to POST88 (extension ”in2”) contain the list of source hazard files to read, calculation options, etc. They also include the Monte Carlo parameters. The control input files to MRE88 (extension ”mri”) provide similar information for MRE88.

7.5.2 Rock Hazard Computation Scheme

Figure 7.4 illustrates how the four SP1 models are individually combined with the four SP2 models to produce an SP1 expert group and SP2 expert-specific rock hazard and how these 16 sets of hazard results are then combined into the final rock hazard. The figure also shows where Monte Carlo sampling had to be introduced.

For three of the four SP1 expert groups, EG1a, EG1b and EG1c, Monte Carlo sampling was applied when combining the hazard of the different seismic sources, thus at the POST88 level. For these three groups, the source-by-source hazard was computed considering each individual logic tree branch and therefore the entire uncertainty. A number of 10’000 realizations was chosen for all the POST88 runs in accordance with the conclusions of previous tests carried out on these models by Toro [2011] (TP4-TN-1172). The introduction of Monte Carlo sampling

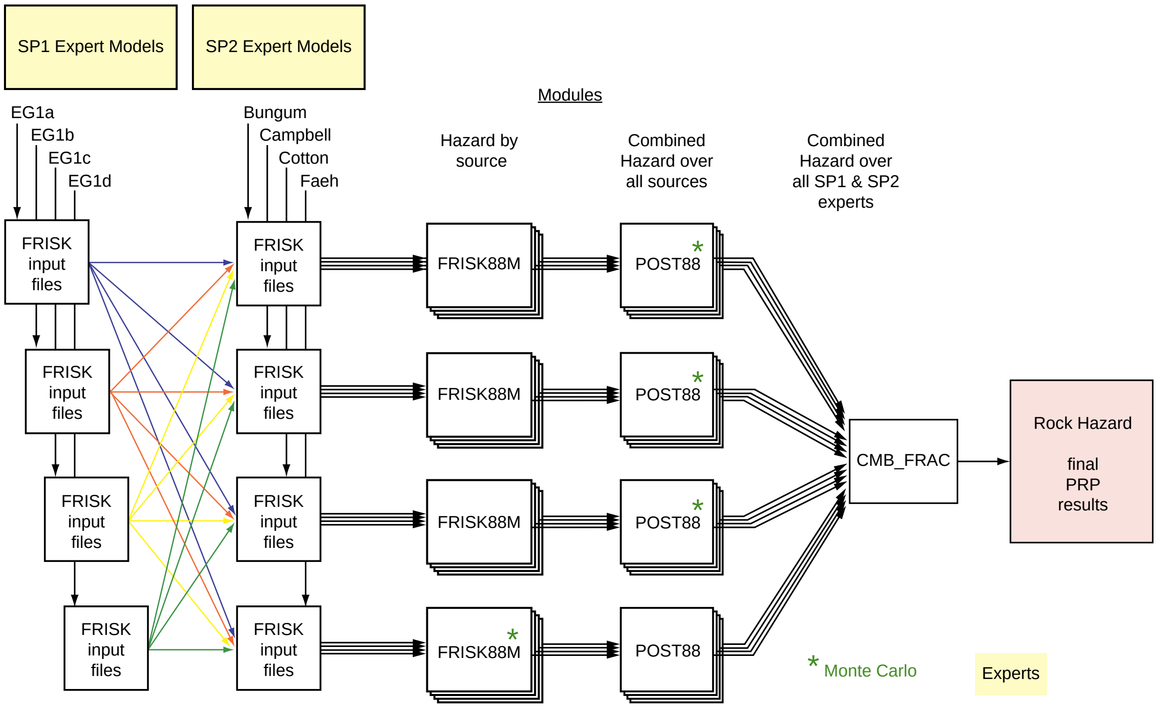


Figure 7.4: Rock hazard computation scheme for a given spectral frequency and site.

allows for a complete abdication of both moment-based pinching and tree trimming (see Section 7.3.1).

The model of expert group EG1d has a degree of complexity which is more than 1'000 times larger than the second most complex model (approx. 245'000 global logic tree branches vs. 219 branches for EG1a). It would have taken more than a month of CPU time, for a single frequency, site and SP2 model, to calculate the source-by-source hazard with a complete sampling of all logic tree branches, as was performed for the other three SP1 teams' models. Furthermore, OS memory limitations would have made these calculations almost impossible. Three options were available: (a) introduce some heavy logic tree trimming as was done in PEGASOS, (b) use Monte Carlo already in FRISK88M or (c) use a combination of both. Logic tree trimming implies a lot of accessory calculations to show the compliance of each individual trimming decision with the accuracy criteria. Therefore, it was decided to use Monte Carlo on the untrimmed EG1d logic tree for the individual sources, not just on the combination of sources as implemented for the other three SP1 groups. Here also 10'000 realizations were selected, relying on the code developer's recommendations [Toro 2011]. For EG1d, the entire FRISK88M output was used as input for the POST88 runs (no additional Monte Carlo sampling in POST88).

7.5.3 Vertical Rock Hazard Evaluation

There are two approaches that are commonly used for computing vertical ground motions in a PSHA. In the first approach, the vertical component is computed independently of the horizontal motion using vertical component ground motion equations in place of the horizontal component ground motion equations in the PSHA calculation. In the second approach, the vertical ground motion is computed conditional on the horizontal ground motion from the

PSHA; the vertical ground motion amplitude is the vertical amplitude that is expected to occur given the occurrence of the horizontal amplitude associated with the exceedance probability of interest. If the first approach is used (independent vertical component), then the vertical component may correspond to a different earthquake than the horizontal component, so that the combination of the loads from the horizontal and vertical components would be physically unrealistic. Because the horizontal motion is generally more damaging than the vertical component, the main impact of the vertical component is to modify the amount of damage from the horizontal component. Therefore, the approach selected in the PRP was to develop the vertical component conditional on the horizontal component (approach 2).

The SP2 experts delivered median V/H models (see Section 4.8.2) together with their assessment of the additional vertical component to the aleatory variability (see Section 4.8.4). The former are based on published ground motion prediction equations for the V/H ratio, which typically require magnitude, distance, depth, dip angle and V_{S30} as input parameters. When the horizontal rock hazard is scaled with the V/H models, it is necessary to consider an associated magnitude and distance to feed the V/H ground motion equations. These values were extracted from the interpolated hazard deaggregation for each frequency and APE. Rather than taking a single M, R based on the mode from the deaggregation (the magnitude and distance of the highest column in the deaggregation figure), the V/H ratios in all individual M-R bins and their weighted average were calculated, the weights being given by the hazard contributions of each bin.

The distance deaggregation is performed for a single distance metric. However, the set of candidate V/H models use both R_{JB} and R_{RUP} distance metrics. Therefore, a conversion of the deaggregated R_{JB} to R_{RUP} distance is required. This conversion depends on the depth distribution. The hypocentral depth is obtained through an analysis of the SP1 low magnitude depth distributions in the host sources, calculating a mean distribution over all SP1 teams, scaling it for higher magnitudes in the same way as FRISK88M does (TP4-TN-0373) and computing the median depth as a function of magnitude for a given dip angle. This is repeated in each deaggregation M-R bin and, as above, the weighted average is calculated over all bins. The SP1 expert groups specify in their model the dip angles for each individual seismic source and fault mechanism. The values for the host seismic sources of each SP1 expert team at a given site are averaged over the four teams and used in the calculation of the individual V/H values. Finally, a mean V/H ratio is built averaging over the fault mechanisms (using the ratios of fault mechanisms specified by the SP1 expert teams as weights) and equally weighting the SP1 and SP2 experts. For more details about the evaluation of the averaged site- and source-dependent style-of-faulting, dip angle and hypocentral depths, as well as the tabulated values, the reader is referred to Roth [2012] (TP4-TN-1254).

Inputs to the vertical motion rock hazard computations are the results of the V/H assessments by the SP2 experts and the aggregated horizontal motion rock hazard results. The latter are loaded by means of 23 discrete fractiles (1, 2, 5, 10, 15, . . . , 90, 95, 98, 99%). These horizontal motion rock hazard fractiles are assigned weights according to the bin width considering the percentages as bin centers. The (SHZeval) software treats these 23 fractile hazard curves as weighted scenarios, which reflect the epistemic and aleatory variability of the horizontal motion rock hazard.

The other input to the rock hazard are the V/H scaling models evaluated for discrete spectral frequencies and APE levels according to the description above. The APE levels in this context are synonymous with peak ground acceleration levels, which are scaled to spectral accelerations using the site-specific horizontal motion mean rock uniform hazard spectrum as a relation. An association with spectral accelerations replaces the association of the V/H model results with APE levels, so that the V/H model results become associated with the same parameter space as the input hazard results. Given four SP2 experts providing weights for nine candidate GMPEs, 36 V/H model scenarios (some of which are zero-weighted) are input to the hazard computations. These scenarios reflect the epistemic uncertainty of the V/H assessment.

The V/H scaling factors are considered to follow a log-normal distribution. Per scenario, per spectral frequency and per spectral acceleration, they are specified by the median V/H ratio and by the standard deviation $\sigma(\log(V/H))$. The $\sigma(\log(V/H))$ value is non-zero in the PRP and reflects the aleatory variability, which will be additional in the vertical motion rock hazard as compared to the horizontal motion rock hazard. If $\sigma(\log(V/H))$ were zero, the vertical motion rock hazard could simply be obtained via scaling of the spectral acceleration of the horizontal motion rock hazard by the V/H ratios. However, given the probabilistic specification of V/H and non-zero aleatory variability, the problem of computing vertical motion rock hazard and the problem of computing soil hazard become technically identical. They differ only in terms of scaling model input (V/H ratios versus amplification) and a disabled maximum ground motion truncation input. Thus, the soil hazard software SHZeval (Section 7.2.2) is used for vertical motion rock hazard calculation. A detailed description of the SHZeval software and the hazard evaluation procedure (by means of the flow of the soil hazard computation) is provided in Hölker [2013b] (TP4-TN-1264), but this description is also appropriate for the vertical motion rock hazard evaluations.

7.6 Interfaces between Rock and Soil Hazard Calculations

The principal inputs to the soil hazard computations are the horizontal motion rock hazard results and the parameterized results of the SP3 assessments. The latter are referred to as SIFs ("Soil Hazard Input Files"). The interface between rock and soil hazard calculations concerns:

- the aggregation and up-sampling of the rock hazard with respect to spectral frequency and amplitude (where strictly speaking the aggregation of the 16 combinations of the SP1 and SP2 models is required anyway for the rock hazard output) and
- the dependencies of the SIFs on the rock hazard results.

The horizontal motion rock hazard is the main input to the soil hazard calculations. The SIFs for the vertical motion case implicitly include V/H scaling among the results of the site effect and maximum ground motion assessments, but the input for the soil V/H models is dependent on the aggregated rock hazard information, as described in Section 7.6.2.

This section concerns the procedural interface between the rock and soil hazard calculations. There is also the physical interface between "rock" and "soil", i.e. the boundary between the two media, which is defined by a minimum stiffness of the "rock" medium (Section 5.2). This physical interface is relevant to the procedures insofar as all rock hazard results and SIFs must be calibrated to the same physical interface.

7.6.1 Aggregation and Up-Sampling of the Rock Hazard Results

The horizontal motion rock hazard is evaluated for the 16 combinations of SP1 and SP2 assessments, for 12 ground motion amplitudes (accelerations) at 8 spectral frequencies and for PGA. The results of the SP1/SP2 model-specific evaluations are aggregated into the full rock hazard. The amplitude/frequency discretization with 12 by (8+1) nodes (bold printed values in Table 7.2) adequately samples the rock hazard, but the soil hazard requires a finer discretization: otherwise patterns contained in the SP3 results would not be adequately represented in the soil hazard results. Most prominently this concerns the site-specific resonance effects and the spectral troughs between the fundamental resonance frequencies. For this reason, the rock hazard results are up-sampled to 57 spectral frequencies. The up-sampling to 173 amplitudes is required for resolution issues (crucially maximum ground motion truncation) and for numerical reasons[¶]. The up-sampled discretization is given in Table 7.2.

Up-sampling is achieved by linear interpolation of the rock hazard (exceedance probabilities) on log-frequency–log-amplitude space. Extrapolation to amplitudes exceeding 10 g (as are part of the soil hazard discretization and listed in Table 7.2) is not required, because such amplitudes do not occur in the rock hazard for annual probabilities of exceedance up to 10^{-7}/yr. PGA is handled like an additional spectral frequency and, for interpolation purposes, it is assigned the numerical value 100 Hz. All rock hazard results are associated with mean magnitudes. These magnitudes are interpolated likewise.

7.6.2 Dependencies of SIFs (SP3 models) on Rock Hazard Results

Dependencies of the SIFs on the rock hazard results exist. This requires attention with respect to the sequence of rock hazard, SP3 model and soil hazard calculations and links some but not all SIFs to the corresponding set of rock hazard results. While the SIFs for horizontal motion can be considered independent of the rock hazard results for practical purposes (but not from a principal point of view), the SIFs for vertical motion are generally linked to the rock hazard results.

The SIFs for horizontal motion quantify amplification, aleatory variability of amplification and maximum ground motion. All SP3 assessments of the aleatory variability and maximum ground motion and 3 of 4 assessments of amplification are self-consistent, i.e. they are independent of rock hazard, SP1 or SP2 results. The assessment of amplification by one SP3 expert (D. Fäh) contains a dependency on the mean site-to-source distance. This distance is obtained from the deaggregation of the rock hazard results. Thus, 1 of 4 horizontal motion SIFs is not independent of the rock hazard results. However, the effect of this dependency is minor. It concerns the change of a scaling factor from 1.25 to 1.26, if a distance threshold of 20 km is exceeded. Furthermore, this scaling factor is applicable in a model subset only:

[¶] The soil hazard computation internally requires occurrence frequencies rather than exceedance probabilities. The former are derived from the latter by differencing over amplitudes. If the amplitude sampling is too coarse, the soil hazard results become inaccurate. This issue is discussed in Hölker [2013b] (TP4-TN-1264). While the SHZeval software (Section 7.2.2) performs the up-sampling of input and down-sampling of output internally, the SOILHAZP software does not. The set of 173 amplitudes was defined in the PEGASOS Project when using SOILHAZP. It was adopted formally to the PRP, but the SHZeval software employed internally uses a denser amplitude sampling with 291 nodes defined on $\log_{10}$ [g] scale by first node at 1.7, increment of 0.01 and last node at 1.2 (in $\log_{10}$(g) unit).

Table 7.2: Discretization of spectral frequencies and ground motion amplitudes (accelerations) in soil hazard calculations. The rock hazard is evaluated at values printed in bold font and is interpolated otherwise.

Spectral frequencies (Hz)											
0.5	0.8	0.9	**1.0**	1.1	1.2	1.3	1.5	1.8	2.0	2.2	2.3
2.5	2.7	2.9	3.0	3.1	3.2	3.4	3.5	4.0	4.4	4.5	**5.0**
5.3	5.4	5.5	5.6	5.7	5.75	5.9	6.0	6.9	7.0	8.0	8.9
9.0	**10**	11	12	13	14	15	17	**20**	22	25	30
33	40	45	**50**	60	70	80	90	**100**			

Ground motion amplitudes (Hz)						
0.0250	0.0269	0.0289	0.0300	0.0311	0.0335	0.0360
0.0387	0.0400	0.0417	0.0448	0.0482	0.0500	0.0519
0.0558	0.0600	0.0645	0.0694	**0.0700**	0.0747	0.0800
0.0803	0.0864	0.0900	0.0930	0.1000	0.1061	0.1125
0.1194	0.1266	0.1343	0.1425	**0.1500**	0.1512	0.1604
0.1701	0.1805	0.1914	0.2000	0.2031	0.2154	0.2285
0.2424	0.2500	0.2572	0.2728	0.2894	**0.3000**	0.3070
0.3257	0.3455	0.3500	0.3665	0.3888	0.4000	0.4125
0.4375	0.4642	0.4924	**0.5000**	0.5223	0.5541	0.5878
0.6000	0.6236	0.6500	0.6615	**0.7000**	0.7017	0.7444
0.7897	0.8000	0.8377	0.8886	0.9000	0.9427	**1.0000**
1.0350	1.0710	1.1080	1.1470	1.1870	1.2280	1.2500
1.2710	1.3160	1.3610	**1.4000**	1.4090	1.4580	1.5000
1.5090	1.5610	1.6160	1.6720	1.7310	1.7910	1.8530
1.9180	1.9850	**2.0000**	2.0540	2.1260	2.2000	2.2770
2.3560	2.4380	2.5000	2.5230	2.6110	2.7020	2.7970
2.8940	2.9950	**3.0000**	3.0990	3.2070	3.3190	3.4350
3.5550	3.6790	3.8070	3.9400	4.0000	4.0770	4.2200
4.3670	4.5190	4.6770	4.8400	**5.0000**	5.0080	5.1830
5.3640	5.5510	5.7440	5.9450	6.0000	6.1520	6.3670
6.5890	6.8180	7.0000	7.0560	7.3020	7.5570	7.8200
8.0000	8.0930	8.3750	8.6680	8.9700	9.0000	9.2830
9.6060	9.9410	**10.0000**	10.2900	10.6500	11.0000	11.0200
11.4000	11.8000	12.0000	12.2100	12.6400	13.0000	13.0800
13.5300	14.0000	14.0100	14.4900	15.0000		

on 70% of the logic tree model branches in the case of Leibstadt and 20% otherwise. Given the limited impact of this dependency, the horizontal motion SIFs may be considered as independent of the rock hazard for practical purposes.

The SIFs for vertical motion quantify V/H scaling, amplification, aleatory variability of amplification and maximum ground motion. With respect to amplification, aleatory variability and maximum ground motion, the above statements also apply. In contrast, the V/H scaling component has a wide dependency on rock hazard results, because V/H ratios are modeled via GMPEs, which require a source-to-distance fault mechanism and fault dip in addition to the SP3 parameter space (magnitude, amplitude (PGA) and spectral frequency). Secondary dependencies occur, such as distance-dependent spectral frequency or hypocenter depth and fault dips being required for source-to-distance adjustments. The results of rock hazard deaggregation provide weights, which are used to compute the weighted means of those parameters that are not members of the SP3 parameter space. V/H ratios are then modeled on the basis of these mean parameter values. Therefore, the vertical motion SIFs are principally linked to a specific set of rock hazard results.

The SIFs for vertical motion include the SP2 V/H results in addition to the results of the SP3 assessments. The technical background is discussed in Section 7.7.2. These SP2 V/H results depend on rock hazard results as described above but the dependency on magnitude is additionally collapsed. The included SP2 V/H results are specific to the mean magnitudes associated with the rock hazard results, while per se magnitude is an independent parameter space dimension within the SIFs. This introduces an additional dependency on the rock hazard results.

7.6.3 SP4-Internal Interface Procedures

The horizontal motion rock hazard results, the SP2 V/H model results and source parameters (SP1 results) were handed over within SP4 from the rock hazard analyst to the soil hazard analyst.

The rock hazard files are MATLAB data structures and contain the results aggregated over the experts and up-sampled to 57 spectral frequencies and 173 amplitudes. The SP2 V/H model results are provided as MATLAB data structure per SP1/SP2 combination for the 8 spectral frequencies plus PGA for which the rock hazard is evaluated. The source parameters are transferred as plain numbers.

The SP2 V/H results and the source parameters are integrated into the SP3mod software [Hölker 2013c] (TP4-TN-1197) and become part of the database underlying the software. They are used in the SP3 model parameterization and are processed into the SIFs. The rock hazard files are directly input to the soil hazard computations.

7.7 Soil Hazard Computations

Soil hazard computations were performed using the SHZeval software (Hölker [2012a], see also Section 7.2.2). Inputs are the rock hazard results and the results of site effect (SP3) assessments, where the latter are compiled into so-called SIFs.

The soil hazard is computed separately for horizontal and vertical motion. Correspondingly, SIFs for horizontal and vertical motion exist. As the vertical motion SIFs include (in addition to the results of site effect assessments) the complete results of V/H scaling models, the soil hazard calculations generally require only horizontal motion rock hazard as input. Thus, the results of vertical motion rock hazard evaluations (see Section 7.5.3) are not utilized in the context of soil hazard computations.

The following subsections discuss the preparation of the input files for soil hazard computations and summarize the soil hazard computation scheme.

7.7.1 Preparation of Rock Hazard Results as Input for Soil Hazard Computations

Generally, the aggregated horizontal motion rock hazard results (output of CMB-FRAC in Figure 7.3) are input to soil hazard computations. The SHZeval software toolbox [Hölker 2012a] provides a routine for loading the FRISK/POST88/CMB-FRAC output files (hazard results and associated mean magnitude) into a MATLAB data structure, which are saved as MATLAB data files to become direct input for the soil hazard calculations.

To meet resolution and sampling requirements, the rock hazard results are up-scaled with respect to spectral frequency and ground motion amplitude. The details and reasoning are discussed in Section 7.6. Procedurally, the up-scaling of the finer rock hazard is performed right after running the CMB-FRAC software and and part of the code loading the files into MATLAB.

7.7.2 Transformation of SP3 Assessments into Soil Input Files (SIFs)

The SP3 experts have quantified and described their assessments of:

- amplification of horizontal ground motion on rock,
- maximum horizontal ground motion on soil,
- amplification of vertical ground motion on rock,
- V/H scaling of ground motion on soil,
- maximum vertical ground motion on soil, and
- aleatory uncertainty of the above amplifications and V/H scaling

by means of logic tree models discussed in their Evaluation Summaries (EG3-ES-1014 to EG-ES-1017). Evaluation of the logic tree models yields a large number of amplification and maximum ground motion scenarios and associated weights. The parameter space of the SP3 models is spectral frequency, peak ground acceleration (PGA) and source magnitude. The distributions of the SP3 model results (amplification and maximum ground motion scenarios separately) are summarized into 17 discrete fractiles per node of the parameter space, taking into account the weights of the scenarios. In this context, aleatory uncertainty is treated as an extension of the logic trees for amplification. The 17 fractiles are: 0.13, 0.62, 2.28, 5, 10, 20, …, 90, 95, 97.72, 99.38, 99.87%.

The parameter space of hazard evaluations is spectral frequency and spectral acceleration. Magnitude occurs as a variable depending on spectral acceleration on rock. Thus, the SP3 parameter space and the hazard parameter space differ with respect to the ground motion amplitude. In order to utilize the SP3 results in soil hazard calculations, the association of amplification with PGA must be changed to an association of amplification with spectral acceleration. The same applies to V/H scaling factors, but not to maximum ground motion amplitudes, because the latter effectively depend only on spectral amplitudes.

The relation between PGA and spectral acceleration is given by the spectral shapes of the waveforms, which were input to the site response analyses underlying the SP3 assessments. Conceptually, any amplification factor is based on a certain site response analysis, for which spectral acceleration is known as a function of spectral frequency and PGA.

The SIFs for vertical motion include V/H scaling in addition to amplification and maximum ground motion assessments. V/H logic tree models are implemented as an extension of the amplification logic tree models and V/H scaling factors and amplification factors are multiplied. This yields a combined scaling factor accounting for amplification and V/H scaling. The distribution of these combined factors is summarized to fractiles as listed above. Technically, the vertical motion SIFs contain two generic types of combined scaling factors: (1) amplification factors for horizontal motion are combined with "SP3" V/H scaling factors applicable to ground motion on soil and (2) amplification factors for vertical motion are combined with ”SP2” V/H scaling factors applicable to ground motion on rock. Thus, the vertical motion SIFs contain not only the results of SP3 assessments but also include the SP2 results concerning V/H scaling.

SIFs are produced per SP3 expert, per site and target layer and per ground motion component. These SIFs are described on a per-expert basis in the hazard input documents (HIDs) (EG3-HID-1005 to EG3-HID-1008). The entire process (SP3 assessment to SIF) is implemented in the SP3mod software [Hölker 2012b]. This software and the technical details of the processing are described in Hölker [2013c] (TP4-TN-1197). Figure 7.5 gives an overview of the SP3mod software and processing flow.

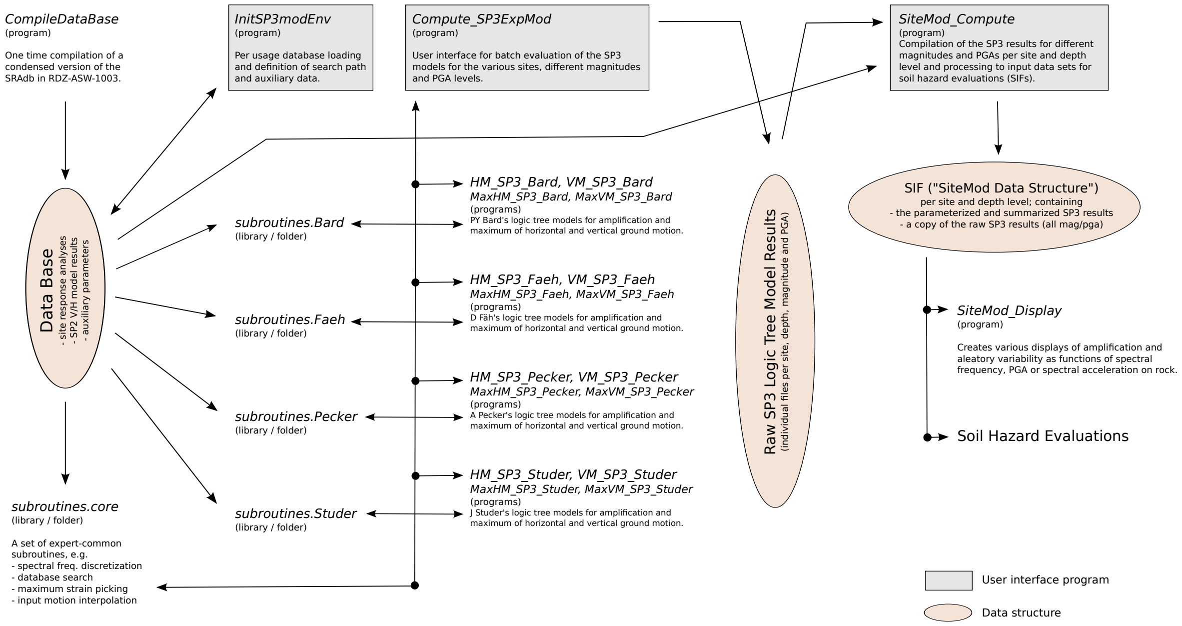


Figure 7.5: Overview of the SP3mod software, which implements the SP3 assessments and which produces input files for soil hazard computations.

7.7.3 Soil Hazard Computation Scheme

Given the rock hazard results and the SIFs, the soil hazard is calculated per spectral frequency (Tab. 7.2), per SP3 expert, per site and target layer for horizontal and vertical ground motion. The SP3 expert-specific results are aggregated and the aggregated hazard distributions are sampled by 103 discrete fractiles (0.1, 0.5, 1, 2, 3, . . ., 98, 99, 99.5, 99.9 %). The schematics of the procedure are illustrated in Figure 7.6.

The distributions of the input rock hazard are originally sampled by 99 fractiles (1, 2, . . ., 99 %). This set is decimated to 15 fractiles (1, 2, 5, 10, 20, . . ., 90, 95, 98, 99 %) for the purpose of soil hazard computations. No information is lost, because the distributions of the rock hazard are smooth, but the CPU time required for soil hazard computations is reduced by a factor of 6.6.

The expert-specific soil hazard results (an intermediate product) are saved twofold: (1) summarized into the above 103 fractiles and (2) as ”raw” soil hazard curves that are the individual hazard curves resulting from the combination of the rock hazard model fractiles, amplification model fractiles and truncation model fractiles. The raw soil hazard curves of all SP3 experts are then aggregated into the final soil hazard, which is again summarized by the 103 fractiles.

The entire process of the soil hazard calculation, i.e. the scheme illustrated in Figure 7.6, is coded into a MATLAB script (batch file), which generally exists in two versions (horizontal and vertical motion) for every soil hazard calculation performed for the project. This script takes care of looping over the NPP sites and target layers, calls the relevant SHZeval software and is part of the delivered soil hazard results.

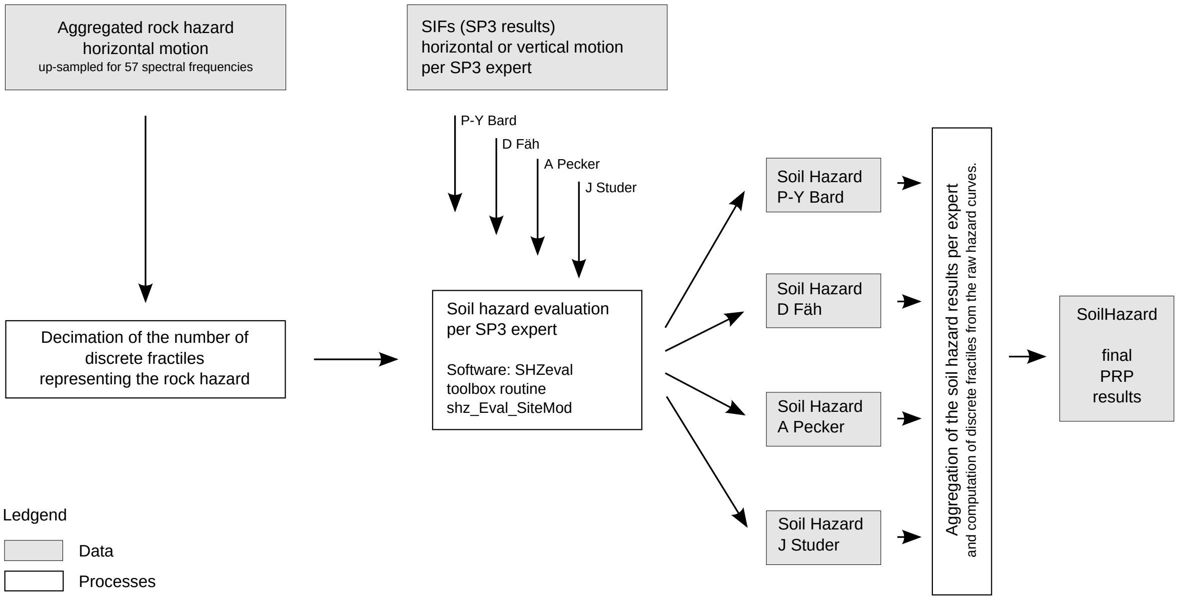


Figure 7.6: Soil hazard computation scheme for a given site, target layer and ground motion component.

7.7.4 Deaggregation of Soil Hazard Results

Deaggregation in the context of soil hazard is a somewhat ambiguous term, because it may refer to the ”conventional deaggregation” of the hazard for magnitude and distance or it may refer to deaggregation of the soil hazard for SP3 parameters such as soil profile or material.

Deaggregation of the soil hazard for source magnitudes and source-to-site distances is not possible given the procedures used. This is because all soil hazard computations are based on the aggregated rock hazard results. One could argue that the rock hazard deaggregation results likewise represent the soil hazard results, because the scaling models within the SIFs are only weakly dependent on magnitude and distance. However, from a principal point of view, this statement is incorrect, because such dependencies do exist. Conceptually, it would be possible to flip the sequence of computations: The parameterized SP3 results could be used to scale the rock hazard results, before the latter are aggregated. Aggregation (over source zones) would then be done on a soil hazard basis, thus allowing a soil hazard deaggregation for magnitudes and distances (as done for the rock hazard).

Within the PRP, a deaggregation of the soil hazard in the sense of SP3 parameter sensitivity analyses was performed and discussed as soil hazard sensitivity analyses. They are based on SIFs, which contain subsets of the SP3 models specific to certain parameter sets (soil profiles, soil models, truncation models, variability models, uncertainty factors) yielding different hazard results, which are compared to a base case (hazard results based on the full model). This is particularly helpful with respect to the engineering application and SP5, where this information can be used to issue a preferred choice of SP3 parameters, based on the knowledge of which ones contribute the most to the soil hazard.

7.7.5 Vertical Soil Hazard Evaluation

The procedure for the soil hazard evaluation has already been explained in the context of the vertical rock hazard computation, as the same approach is used (see Sections 7.3.2 and 7.7.2).

7.8 Summary of Computational Effort

Despite the introduction of Monte Carlo sampling in the rock hazard calculations the amount of calculations remains large, even when only the median $V_S - \kappa$ correction branch is considered in SP2. To calculate the source by source rock hazard requires 29 billion logic tree branches (combinations of SP1 and SP2 model branches) to be computed. This effort has to be repeated for the nine project frequencies at each of the four sites. The total computational effort for the horizontal rock hazard calculation (using the single median $V_S - \kappa$ correction branch) is approximately 4930 CPU hours on modern, high-end personal computers. As FRISK88M requires separate runs for the assessment of the hazard deaggregation, another 4340 CPU hours have to be planned. Since the deaggregation runs can only be started when the mean hazard is known, a rough total of 10 CPU days had to be planned in the 68-processor environment used. The computation of the vertical rock hazard is comparatively fast as in essence the approach chosen in PRP scales the horizontal rock hazard results with the V/H ratio models of SP2 and does not require an actual full hazard calculation.

The SP3 assessments of amplification, V/H scaling, aleatory uncertainty and maximum ground motion were formulated as logic tree models. These models were evaluated for 17 PGA levels, 3 magnitudes and 60 spectral frequencies. The effective number of logic tree branches (scenarios) depends on the NPP sites and the PGA/magnitude combination considered. For the Beznau site, the maximum numbers of scenarios are 2112 for horizontal motion amplification, 10'410 for V/H scaling and vertical motion amplification, 52 for maximum horizontal ground motion and 28 for maximum vertical ground motion. The cumulative computational effort of evaluating and parameterizing the SP3 models is approximately 40 CPU hours assuming a single core of a Xeon X56xx series CPU at 3.3 GHz. Effectively this task takes about 6 hours given some parallelization.

The soil hazard evaluations were performed sequentially for 57 spectral frequencies. Per frequency N, hazard curves are evaluated, where the number N is given by the combinations of the input rock hazard curves, the amplification (incl. V/H scaling) models, the aleatory uncertainty models and the maximum ground motion (truncation) models. For example 70'380 soil hazard curves are evaluated for horizontal motion at the Beznau site and 121'380 soil hazard curves for vertical motion. The full set of soil hazard evaluations includes horizontal and vertical motion each at 9 combinations of site and target layer. The cumulative computational effort of the full set of soil hazard evaluation is 120 CPU hours for horizontal motion and 610 CPU hours for vertical motion, assuming a single core of a Xeon X56xx series CPU at

3.3 GHz. The hazard evaluations partially make use of multi-threading and parallelization requiring an effective CPU time of approximately 4 days on a 16 CPU system.

Chapter 8

Hazard Results

8.1 Final Hazard Results

The integrated hazard results provide a representation of seismic rock hazard and its uncertainty at the four NPP sites, based on the four SP1 expert teams' and four SP2 experts' models. Separate rock hazard results are obtained for spectral accelerations at 0.5, 1, 2.5, 5, 10, 20, 33, 50 and 100 Hz. These rock hazard results, combined with the site-specific SP3 expert models, provide a representation of seismic soil hazard and its uncertainty at the four NPP sites. For each site, soil hazard results are obtained for the aforementioned ground motion measures and, in addition, for spectral accelerations at one or more site-specific resonance frequencies. Volume 2 of this report contains the full catalogue of hazard results, without any comment or interpretation. Here, we present and discuss a subset of the results. The same subset of plots are shown for all four NPP sites in Volume 2.

The issue of the effect of κ on ground motions was addressed as part of the PRP. The methods for κ adjustments available at the start of the PRP were found to have significant problems so the PRP made a large effort to develop improved methods to adjust GMPEs for the effect of different κ values. The new methods represent the state-of-the art for $V_S - \kappa$ adjustments; however, there is an implicit assumption that the other predictive parameters are not correlated with κ. After the final PRP meeting, additional investigations and evaluations on this issue were performed by the project and presented to the SP2 experts in the framework of an additional SP2 workshop in September 2013 (see TFI-TN-1272 and TP2-TN-1279). As the findings were not completely conclusive at this stage, the experts decided to not fully make use of this additional information for the finalization of their models. In light of these results, new evaluations of the κ scaling were made in 2014 using the expanded ground motion datasets from Eastern North America as well as the global ground motion datasets from active regions [Kishida et al. 2014; Ktenidou et al. 2015, 2016]. This study used residuals to evaluate the κ scaling which has the advantage that the effects of correlations in the parameters are implicitly contained in the residuals. The main issue is that the slope of the FAS ($\pi\kappa$) is not just due to damping, but can also affected by other parameters including stress-drop and site amplification. The study showed that while lower κ values tend to lead to larger high-frequency ground motions, the scaling with κ is weaker than computed using the PRP methods, indicating that there is a correlation between the estimated κ and other parameters. That is, the effect of low κ values are offset by the trade-off with other parameters. If this correlation is ignored, then there is double counting of the ground motion uncertainty. This becomes a key issue when a large range of $\Delta\kappa$ values (differences between the host GMPE κ and the target site κ) is used. To fully address this issue of correlation will require additional studies over the next few years. To reduce the double-counting of uncertainty in the PRP and to lead to a more robust estimate of the site-specific ground motion, only the median $V_S - \kappa$ corrections (by GMPE and expert) from the SP2 experts are used. This topic will be monitored and re-evaluated in the next years as improvements are made in the constraints on κ scaling.

Figures 8.1 and 8.2 show the mean rock and soil hazard at surface for 100 Hz, while Figures 8.3 and 8.4 show the uniform hazard spectra (UHS) for an annual probability of exceedance of 10^{-4}/yr, for rock and soil conditions, respectively. In all the figures, the mean and median hazard curves convey the central tendency of the computed exceedance probability, while the separation between the remaining fractiles conveys the effect of epistemic uncertainty on the computed exceedance probability.

The epistemic uncertainty is high, even at low ground motion amplitudes. This reflects the uncertainty about the parameters (recurrence rate, stress-drop, κ, etc.) associated with the moderate magnitude earthquakes that dominate the seismic hazard in this part of Europe (see below). The epistemic uncertainty is larger at low frequencies, because the hazard at low frequencies is more sensitive to M_{max}. Figures 8.5 and 8.6 show the deaggregation of the mean hazard for annual probabilities of exceedance of 10^{-4}/yr and two frequencies: 0.5 Hz in Figure 8.5 and 100 Hz in Figure 8.6. The figures show the deaggregation into magnitude-distance-ϵ bins in the upper part of the figure and into the three components separately in the lower part. ϵ is the difference between the logarithm of the UHS spectral acceleration and the logarithm of the median spectral acceleration for the magnitude and distance pairs contributing to the hazard, normalized by the standard deviation of the GMPE. ϵ gives the number of standard deviations above the median ground motion required to reach the UHS ground motion. Figure 8.6 shows that the 0.5 Hz spectral accelerations are mainly caused by moderate earthquakes ($M < 7.0$) located at distances less than 20 km from the site. As will be shown in the following plots, this is valid for all the NPP sites.

A comparison of the rock and soil UHS and their ratio of the horizontal and vertical component was shown as part of the hazard feedback during the SP2/SP3 interface workshop on January 18, 2013 (TP4-RF-164a) and is reproduced in Figure 8.7 for the Beznau site.

Figures 8.8 through 8.28 show the same type of results for the other three sites.

Some general observations regarding the results are listed below:

- In the 10^{-4} range, the mean UHS lies between the 50% and 85% fractile for both soil and rock for all sites. For all cases other than the soil UHS for Mühleberg, the mean is near the 60% fractile. For the soil UHS for Mühleberg, the mean UHS is close to the 75% fractile due to the larger uncertainty of the SP3 site amplification models for Mühleberg.

- The epistemic uncertainty range is such that the 95th fractile UHS is about a factor of 3 larger than the 5th fractile UHS. This range increases to about 7 for the soil UHS for Mühleberg.
- The modal magnitude, distance, and epsilons are nearly the same for all four sites: modal magnitude near $M5.5$, modal distance between 5 and 10 km, and modal epsilon near 1.5.
- The V/H ratios of the UHS in the 20 - 30 Hz range show a large change between 10^{-4} and 10^{-6} annual hazard levels. The ratio increases for the 10^{-6} hazard level due to non-linear site effects on the horizontal component with linear site effects on the vertical component.

8.1.1 Beznau Site

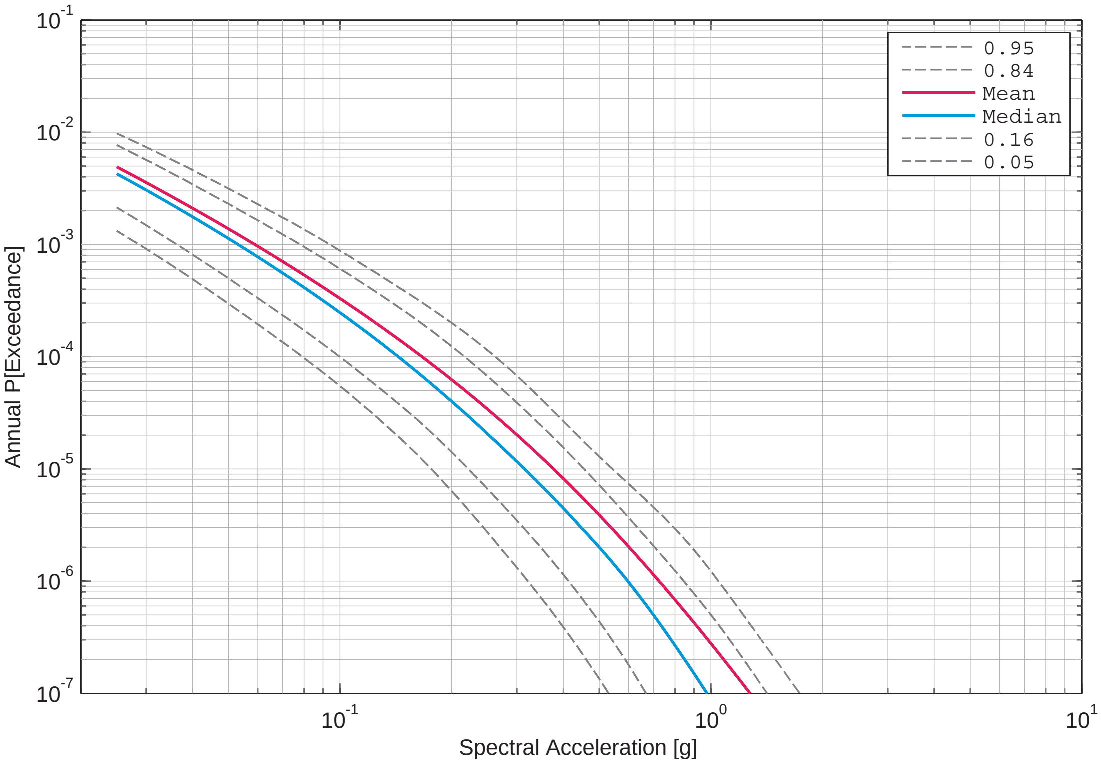


Figure 8.1: Beznau, horizontal component, rock, mean hazard and fractiles, 100 Hz.

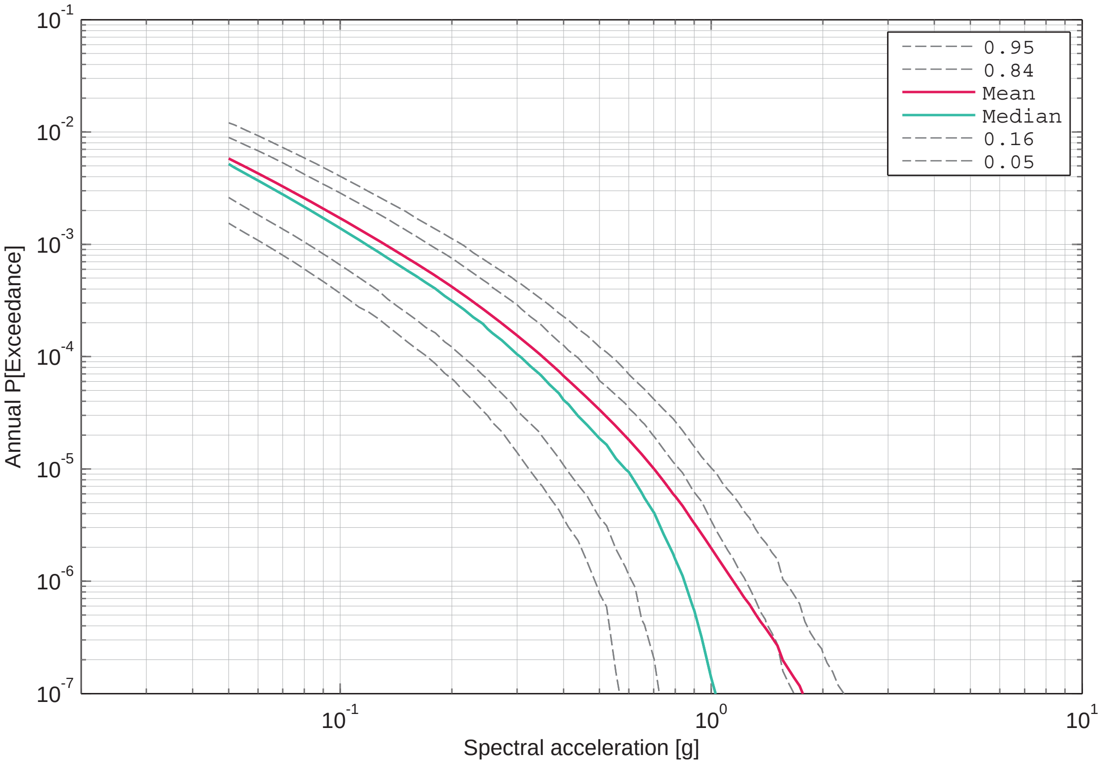


Figure 8.2: Beznau, horizontal component, soil, surface, mean hazard and fractiles, 100 Hz.

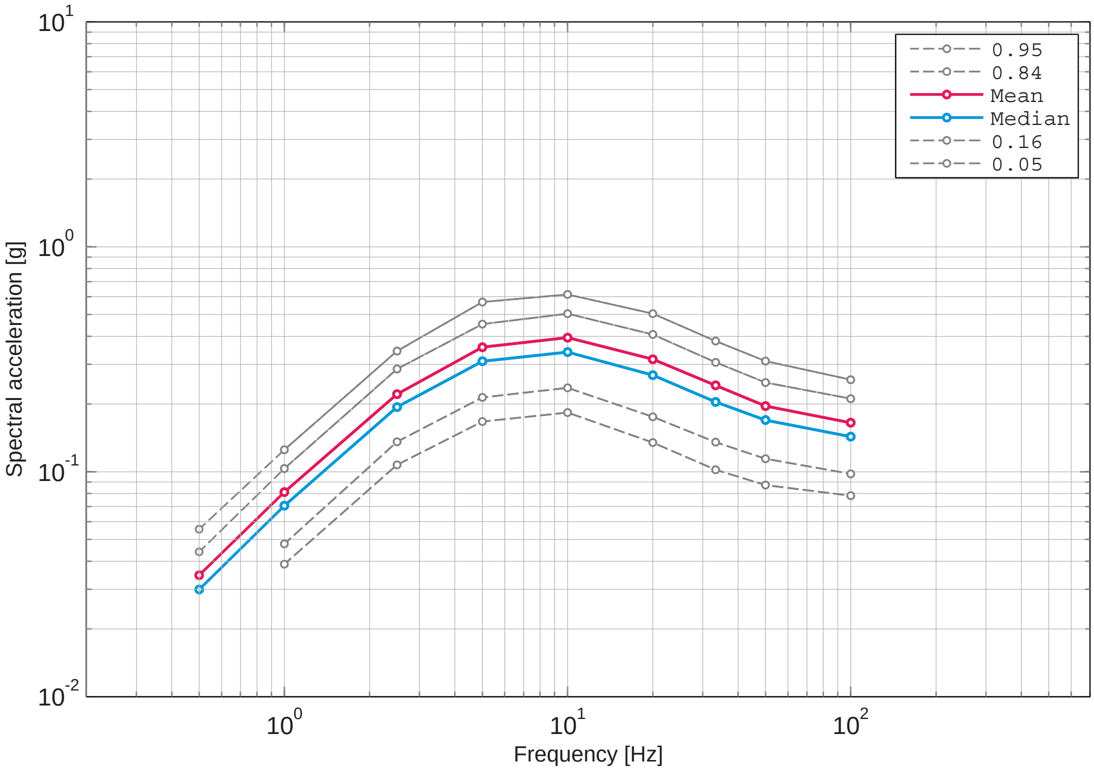


Figure 8.3: Beznau, horizontal component, rock, uniform hazard spectra for an annual probability of exceedance of 1E-4 and 5% damping.

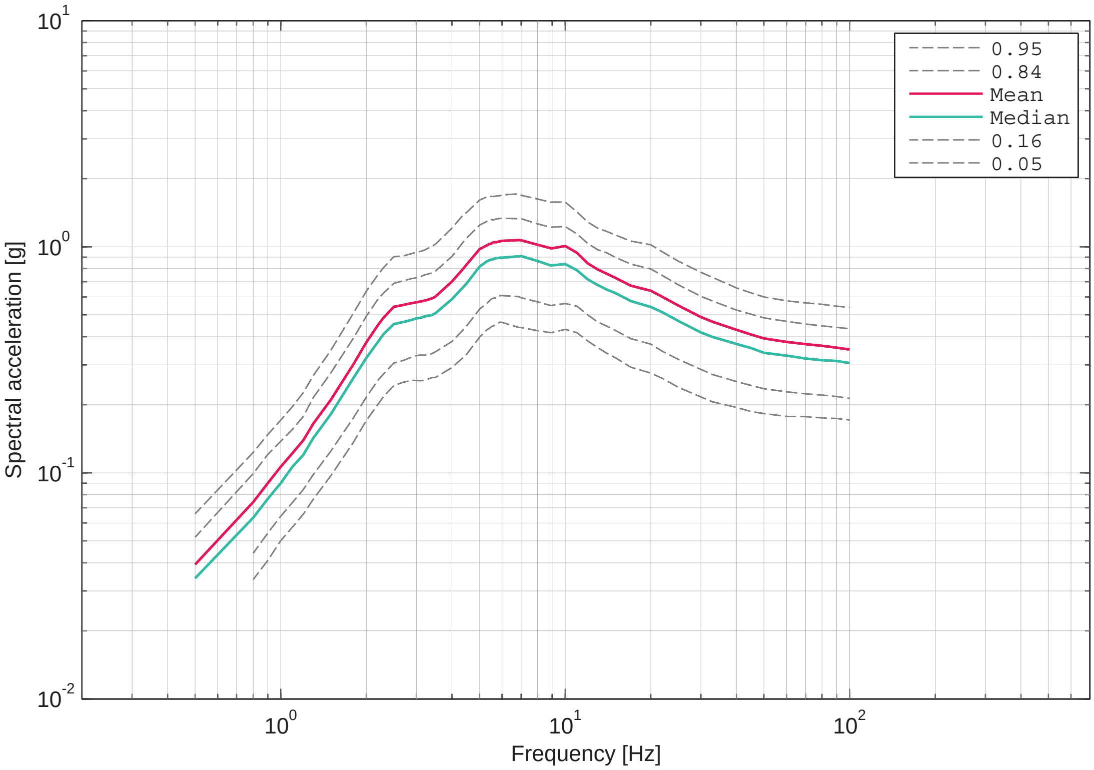


Figure 8.4: Beznau, horizontal component, soil, surface, uniform hazard spectra for an annual probability of exceedance of 1E-4 and 5% damping.

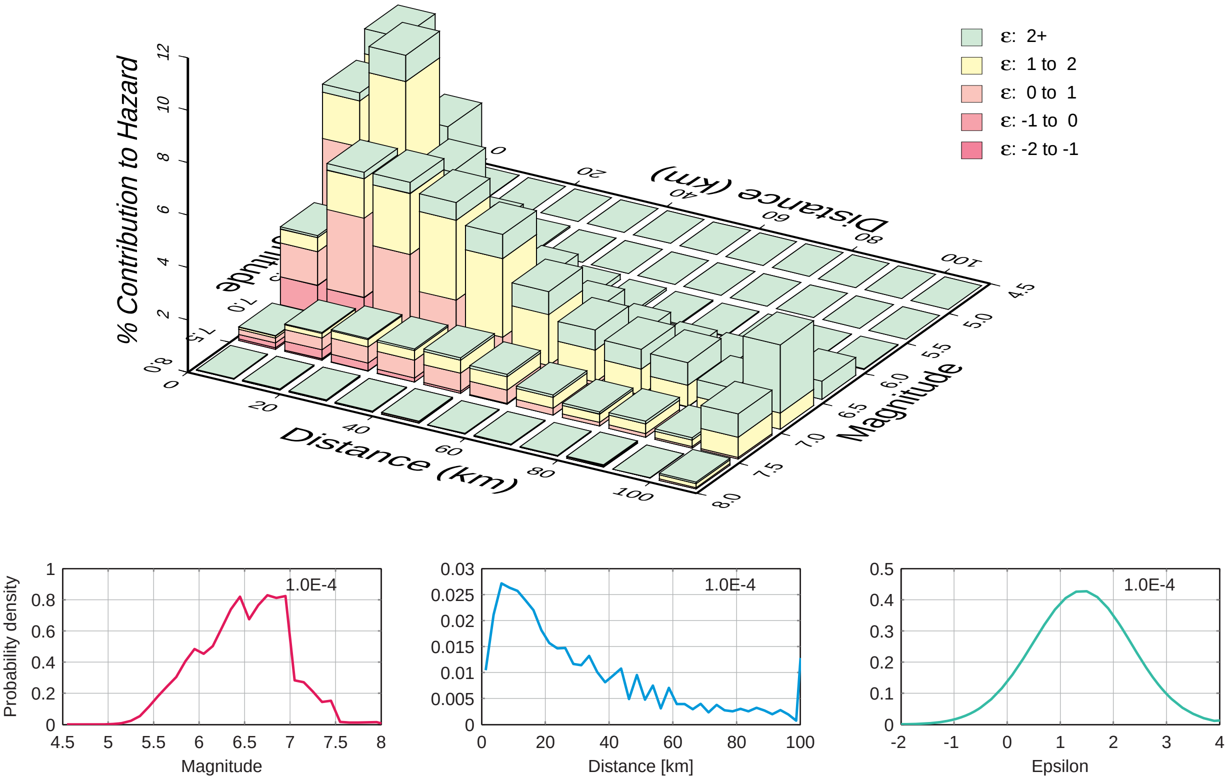


Figure 8.5: Beznau, horizontal component, rock, hazard deaggregation by magnitude, distance and ϵ for annual probability of exceedance of 1E-4, 0.5 Hz.

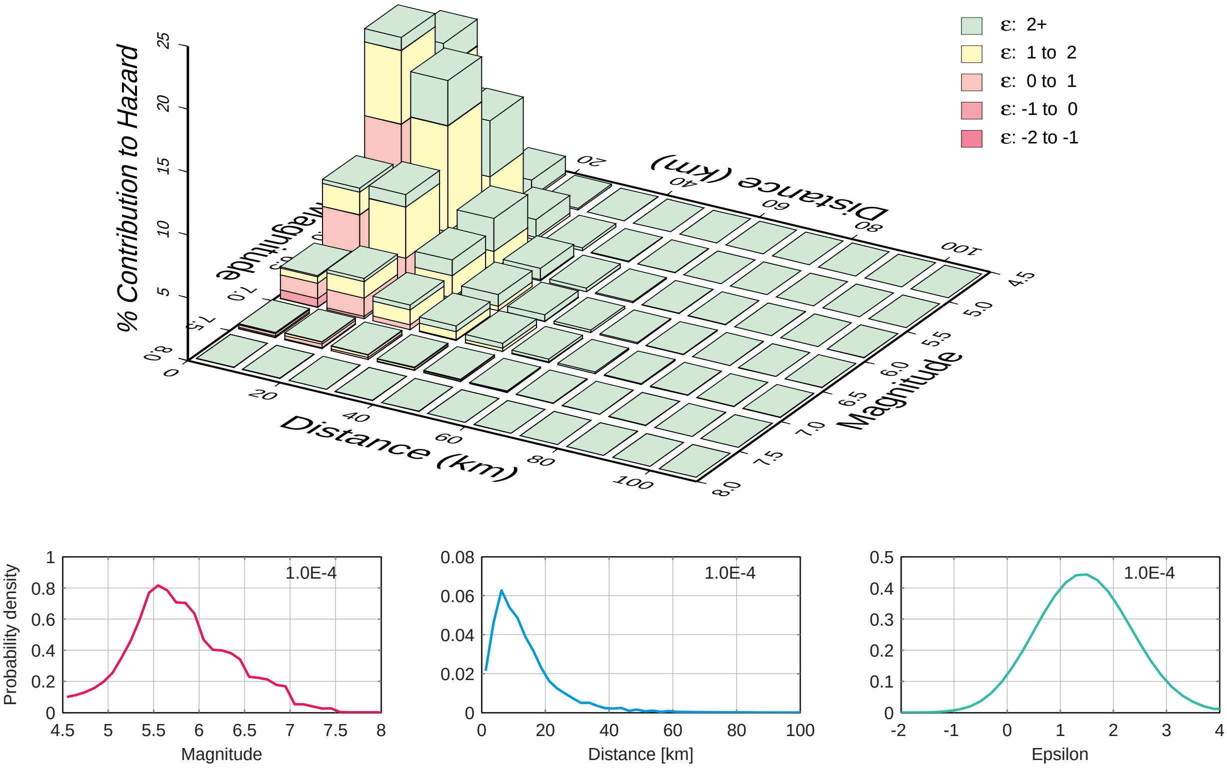


Figure 8.6: Beznau, horizontal component, rock, hazard deaggregation by magnitude, distance and ϵ for annual probability of exceedance of 1E-4, 100 Hz

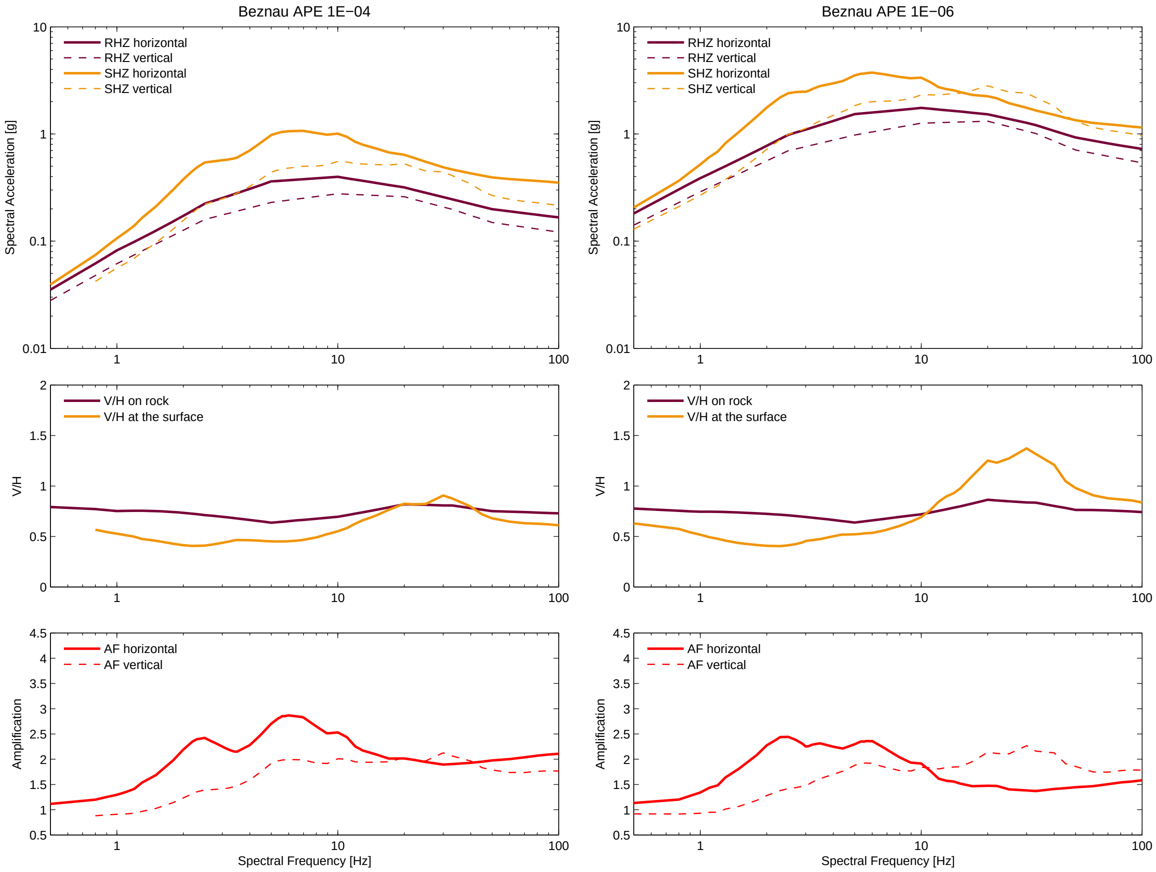


Figure 8.7: Comparison for Beznau of rock and soil UHS (top), V/H ratio resulting from the horizontal and vertical UHS (middle) and the horizontal and vertical soil amplification (bottom) for an annual probability of exceedance of 10^{-4} and 10^{-6}.

8.1.2 Gösgen Site

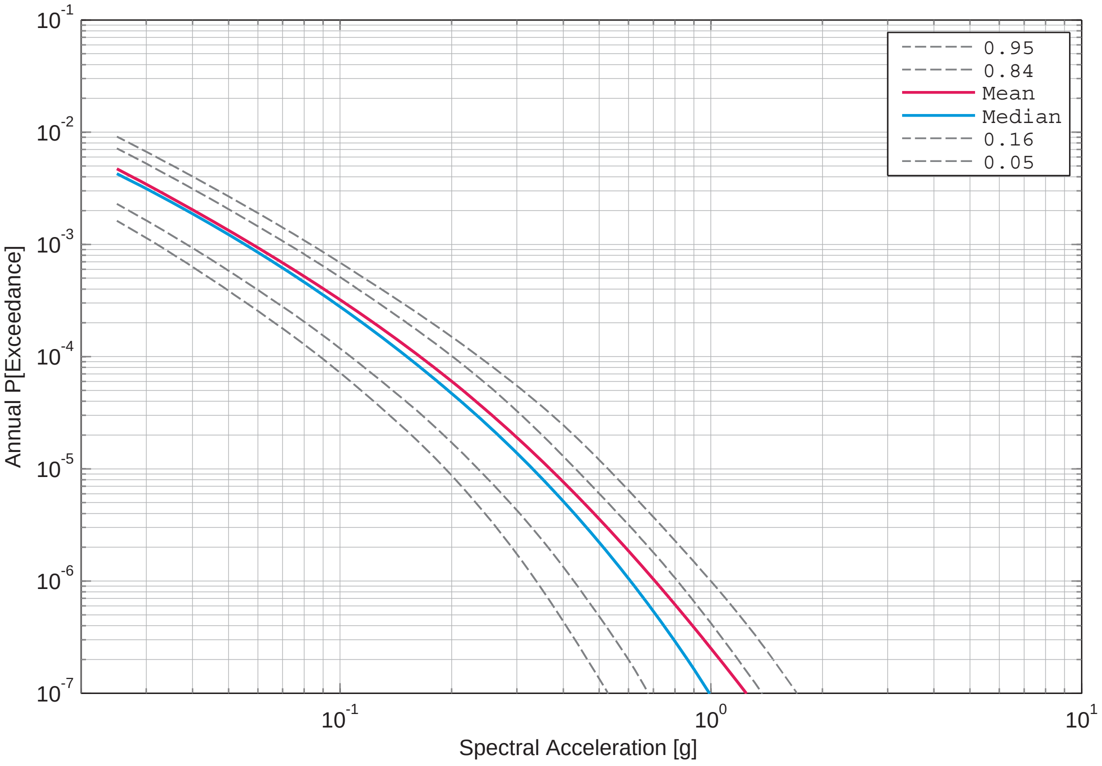


Figure 8.8: Gösgen, horizontal component, rock, mean hazard and fractiles, 100 Hz.

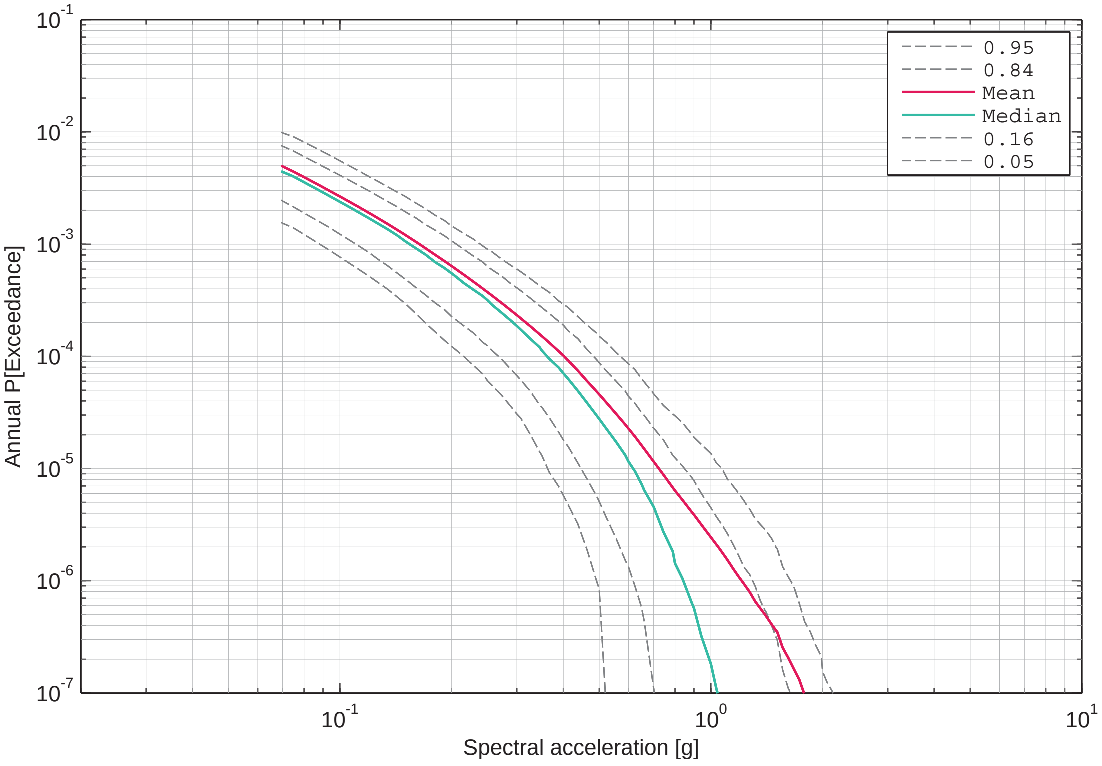


Figure 8.9: Gösgen, horizontal component, soil, surface, mean hazard and fractiles, 100 Hz.

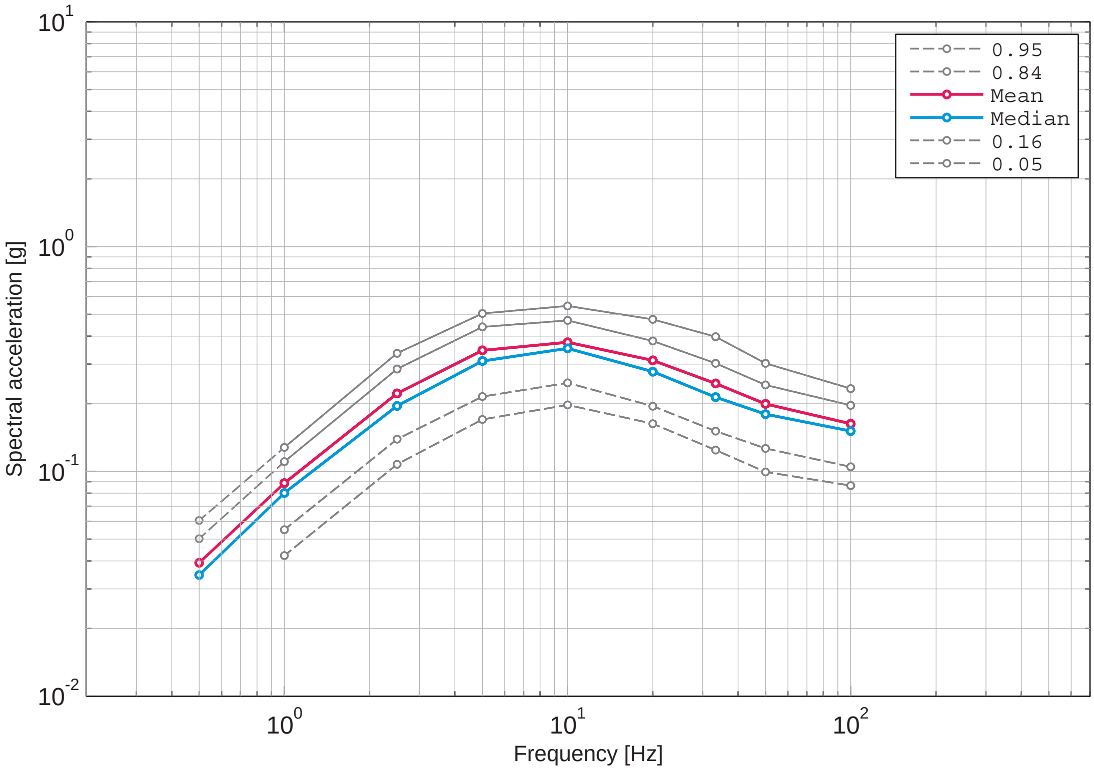


Figure 8.10: Gösgen, horizontal component, rock, uniform hazard spectra for an annual probability of exceedance of 1E-4 and 5% damping.

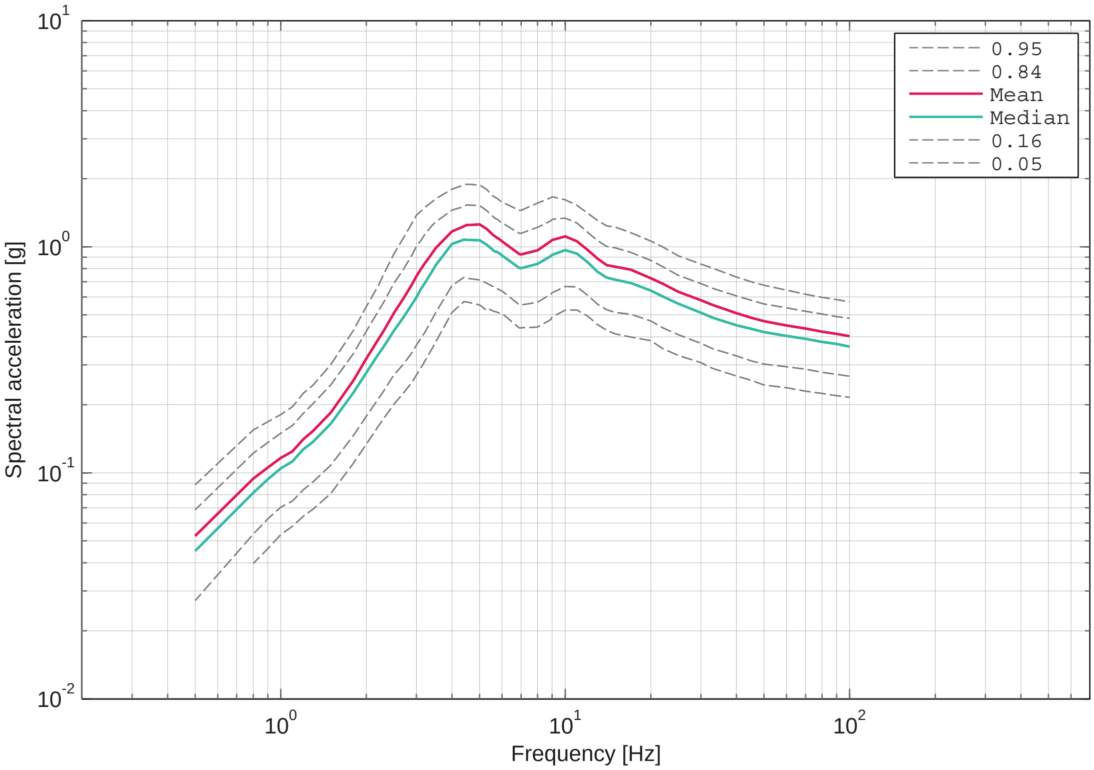


Figure 8.11: Gösgen, horizontal component, soil, surface, uniform hazard spectra for an annual probability of exceedance of 1E-4 and 5% damping.

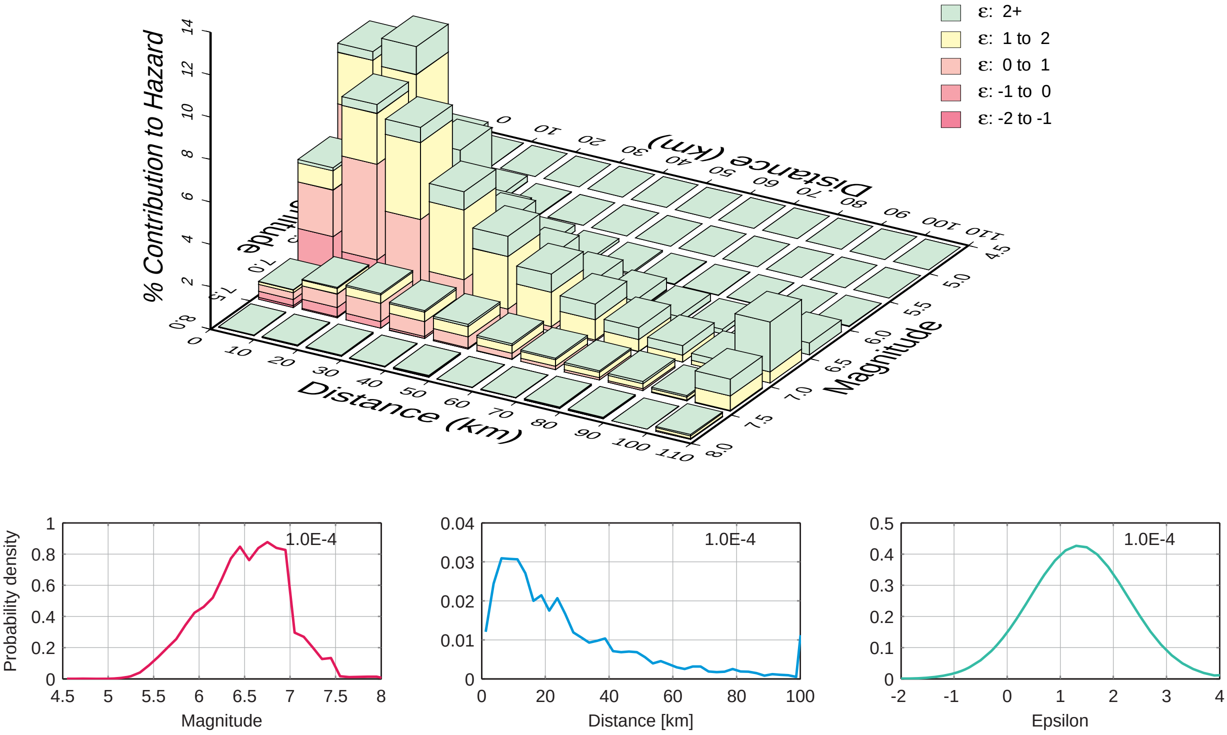


Figure 8.12: Gösgen, horizontal component, rock, hazard deaggregation by magnitude, distance and ϵ for annual probability of exceedance of 1E-4, 0.5 Hz.

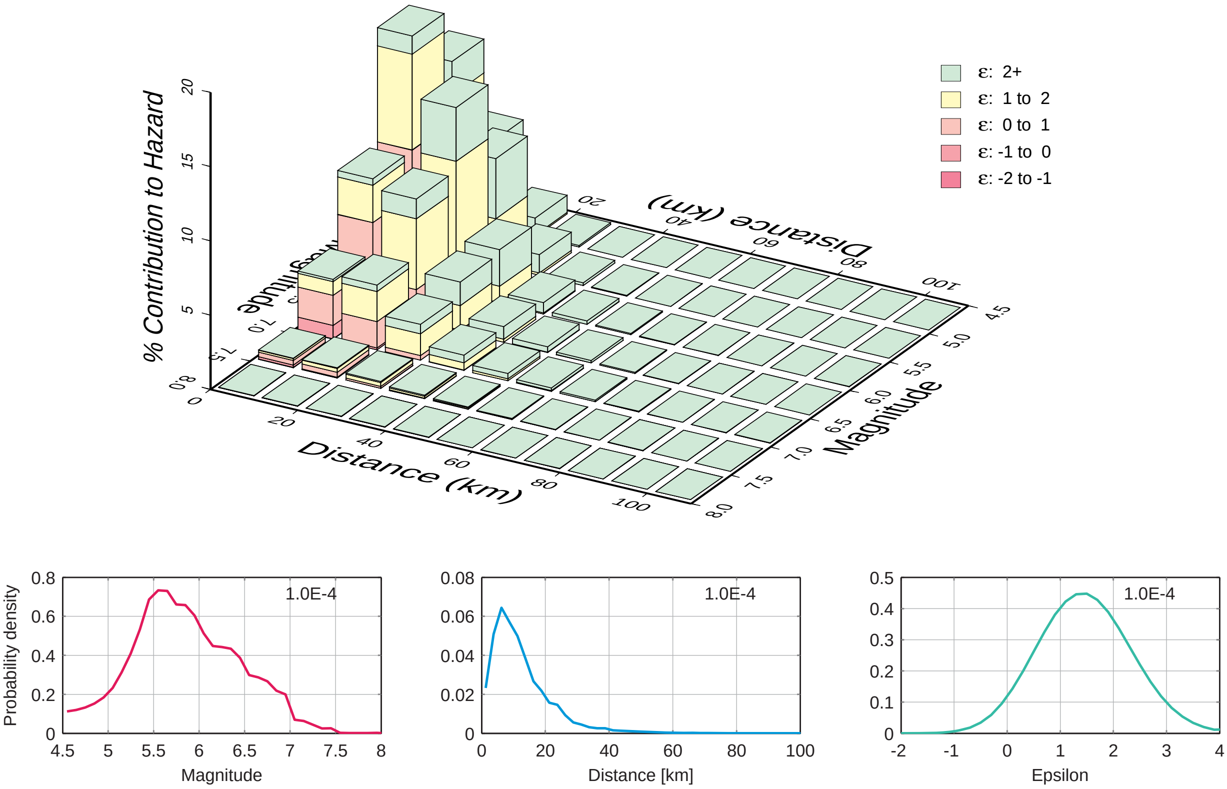


Figure 8.13: Gösgen, horizontal component, rock, hazard deaggregation by magnitude, distance and ϵ for annual probability of exceedance of 1E-4, 100 Hz

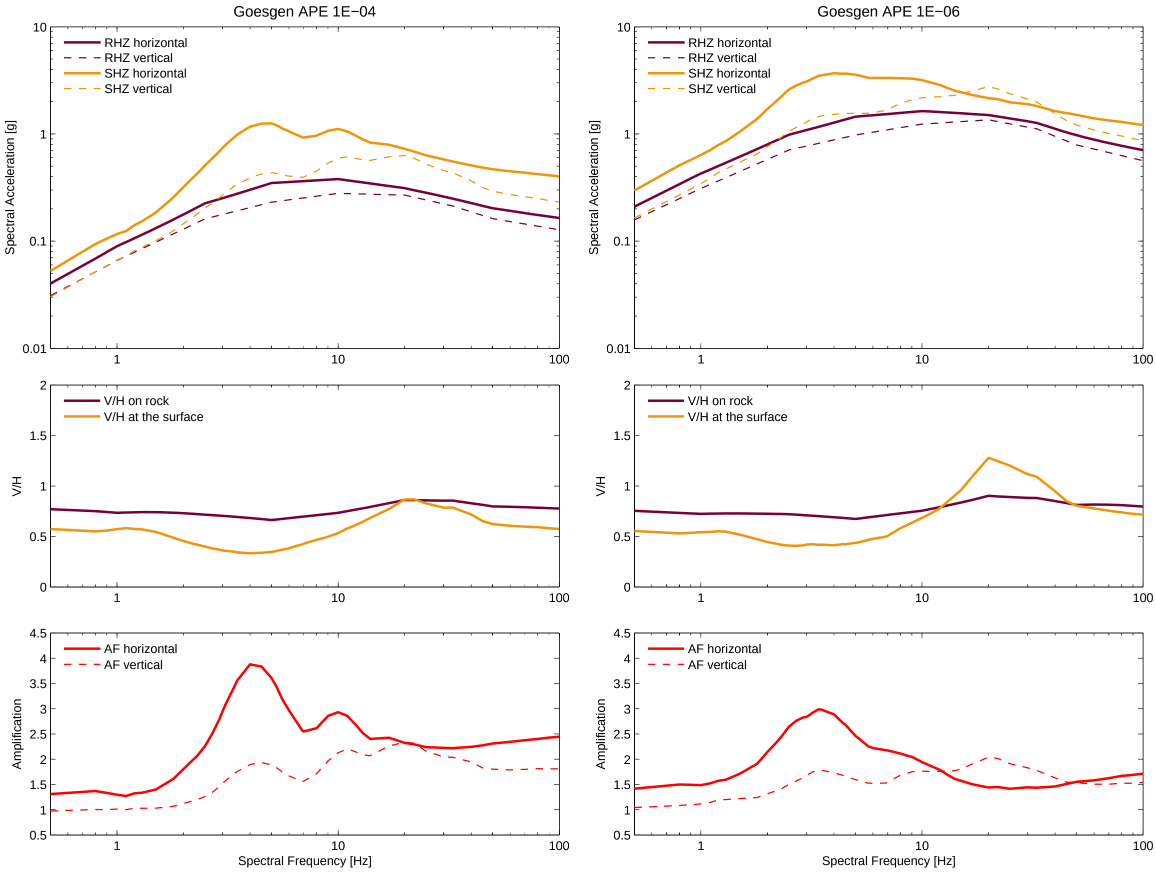


Figure 8.14: Comparison for Gösgen of rock and soil UHS (top), V/H ratio resulting from the horizontal and vertical UHS (middle) and the horizontal and vertical soil amplification (bottom) for an annual probability of exceedance of 10^{-4} and 10^{-6}.

8.1.3 Leibstadt Site

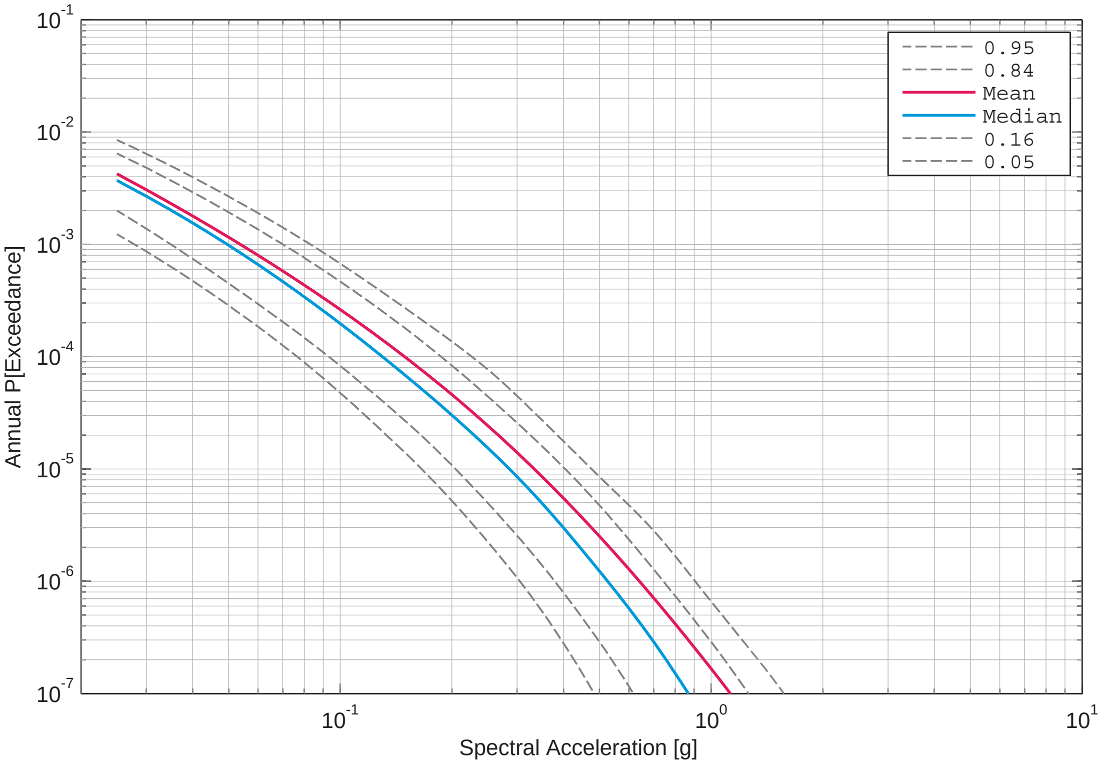


Figure 8.15: Leibstadt, horizontal component, rock, mean hazard and fractiles, 100 Hz.

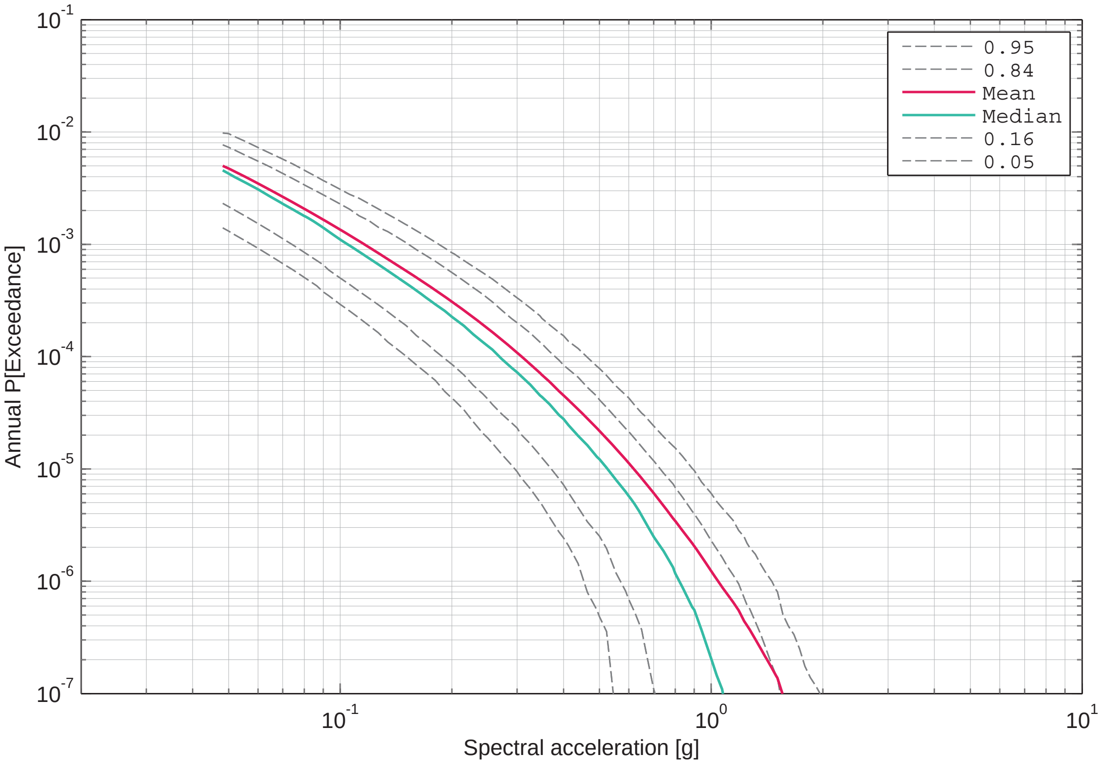


Figure 8.16: Leibstadt, horizontal component, soil, surface, mean hazard and fractiles, 100 Hz.

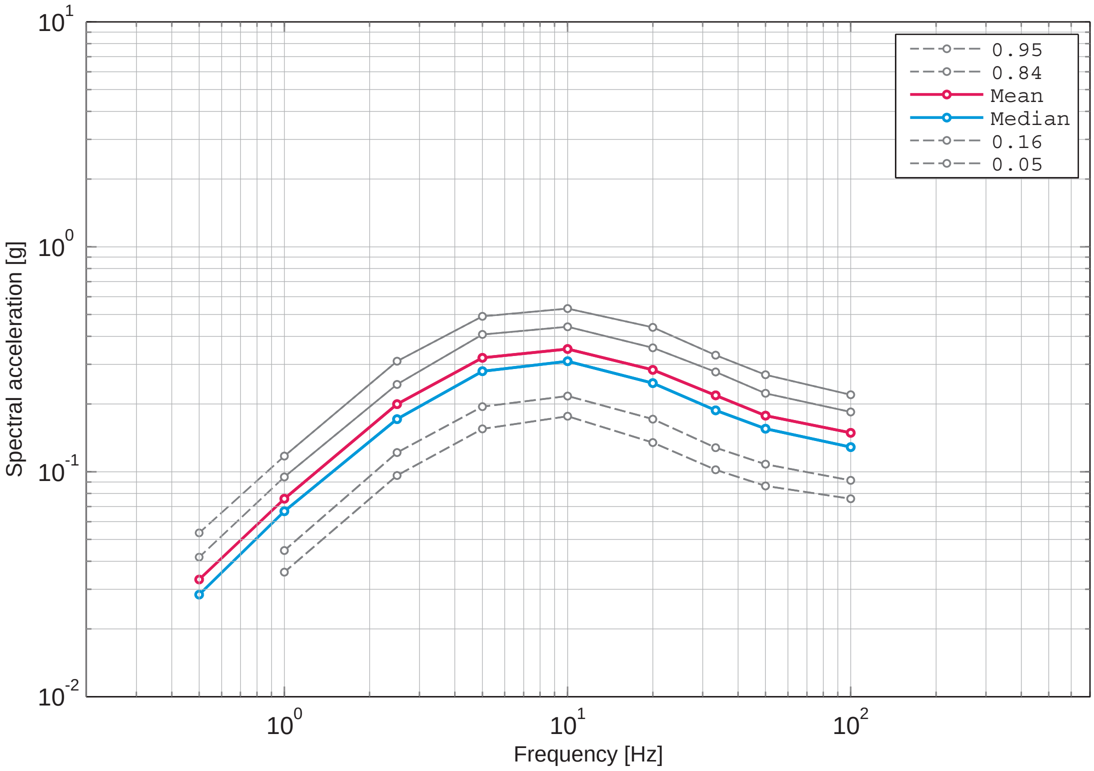


Figure 8.17: Leibstadt, horizontal component, rock, uniform hazard spectra for an annual probability of exceedance of 1E-4 and 5% damping.

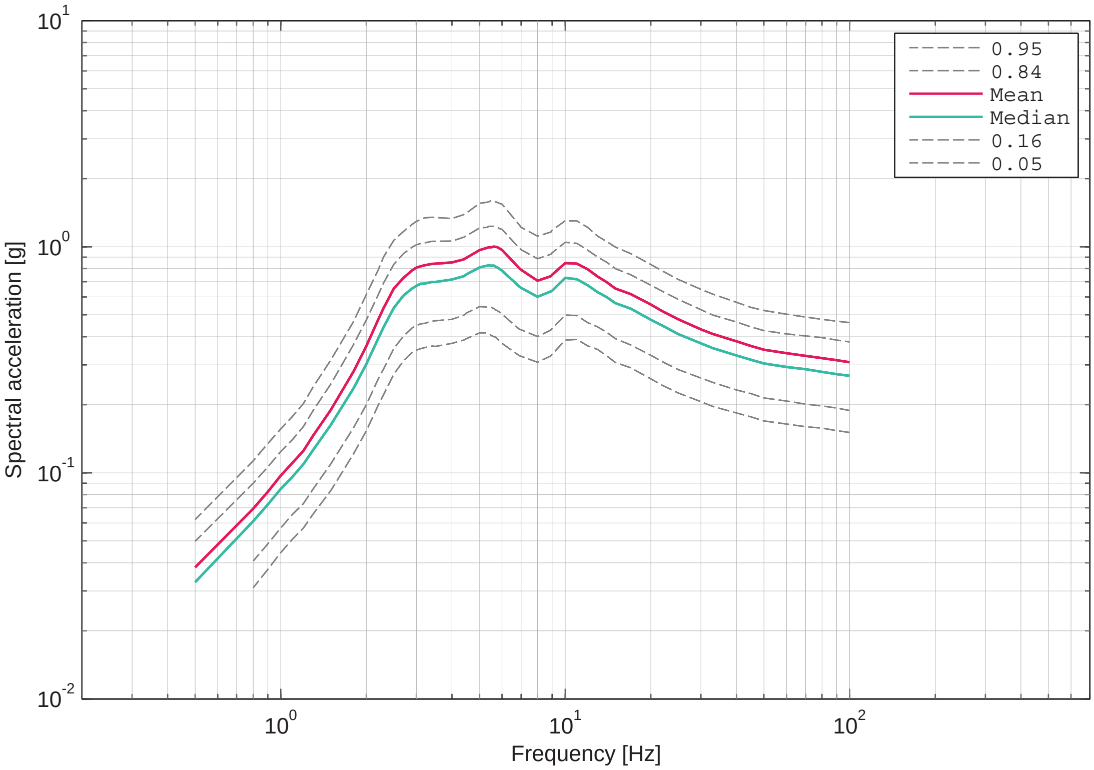


Figure 8.18: Leibstadt, horizontal component, soil, surface, uniform hazard spectra for an annual probability of exceedance of 1E-4 and 5% damping.

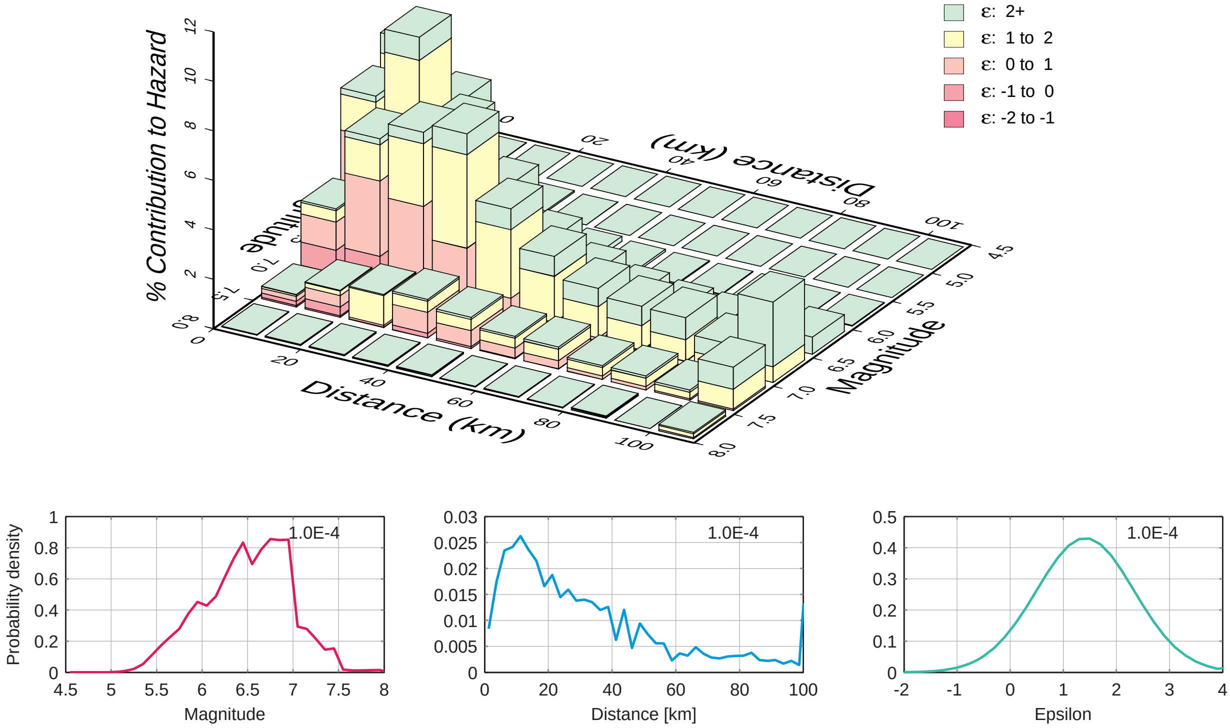


Figure 8.19: Leibstadt, horizontal component, rock, hazard deaggregation by magnitude, distance and ϵ for annual probability of exceedance of 1E-4, 0.5 Hz.

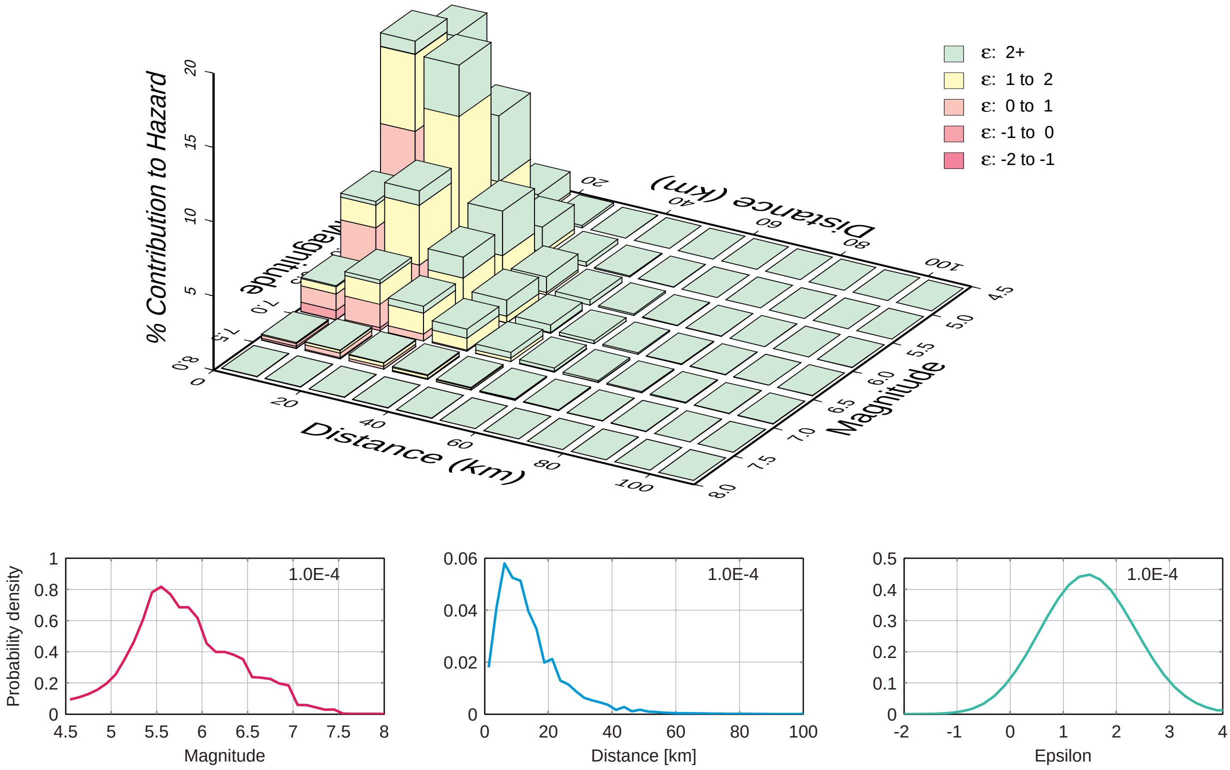


Figure 8.20: Leibstadt, horizontal component, rock, hazard deaggregation by magnitude, distance and ϵ for annual probability of exceedance of 1E-4, 100 Hz

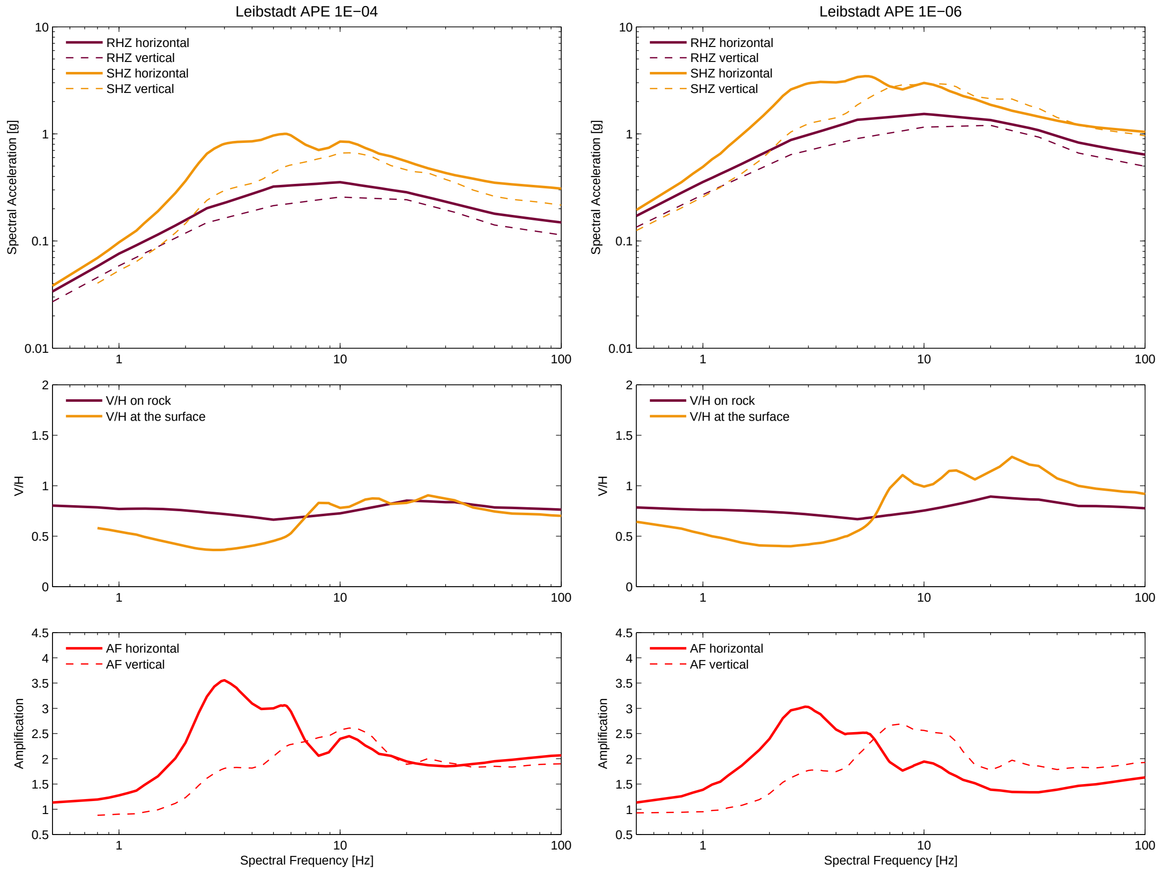


Figure 8.21: Comparison for Leibstadt of rock and soil UHS (top), V/H ratio resulting from the horizontal and vertical UHS (middle) and the horizontal and vertical soil amplification (bottom) for an annual probability of exceedance of 10^{-4} and 10^{-6}.

8.1.4 Mühleberg Site

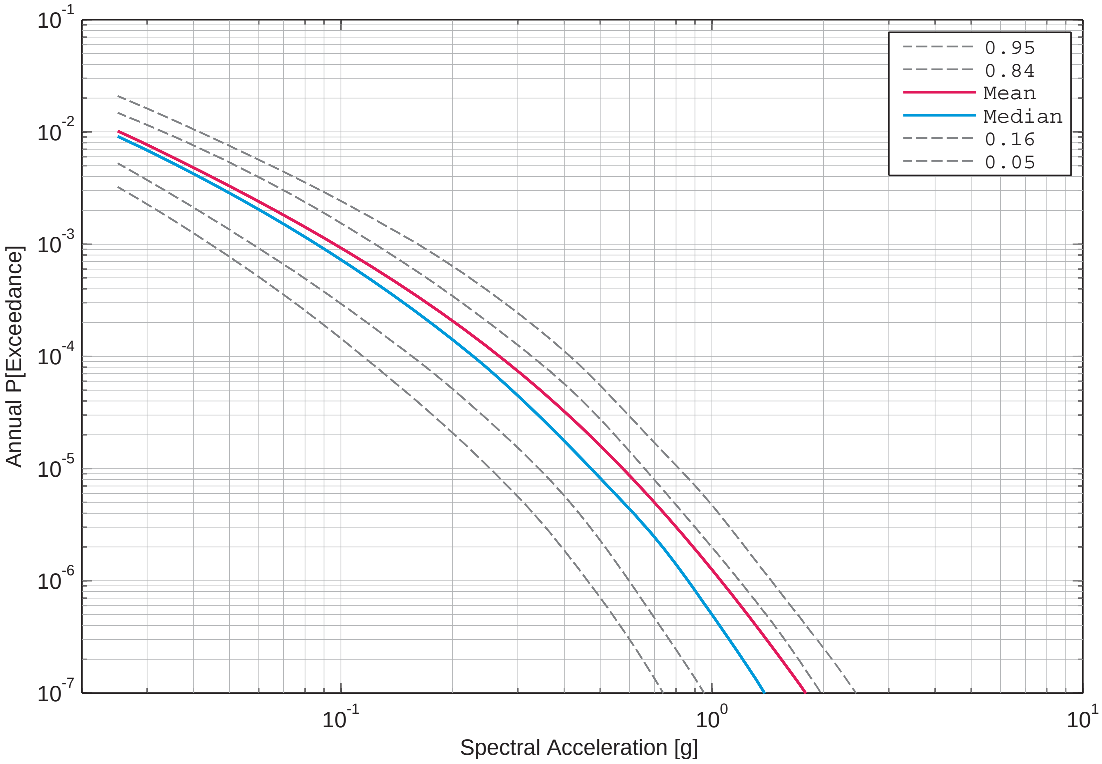


Figure 8.22: Mühleberg, horizontal component, rock, mean hazard and fractiles, 100 Hz.

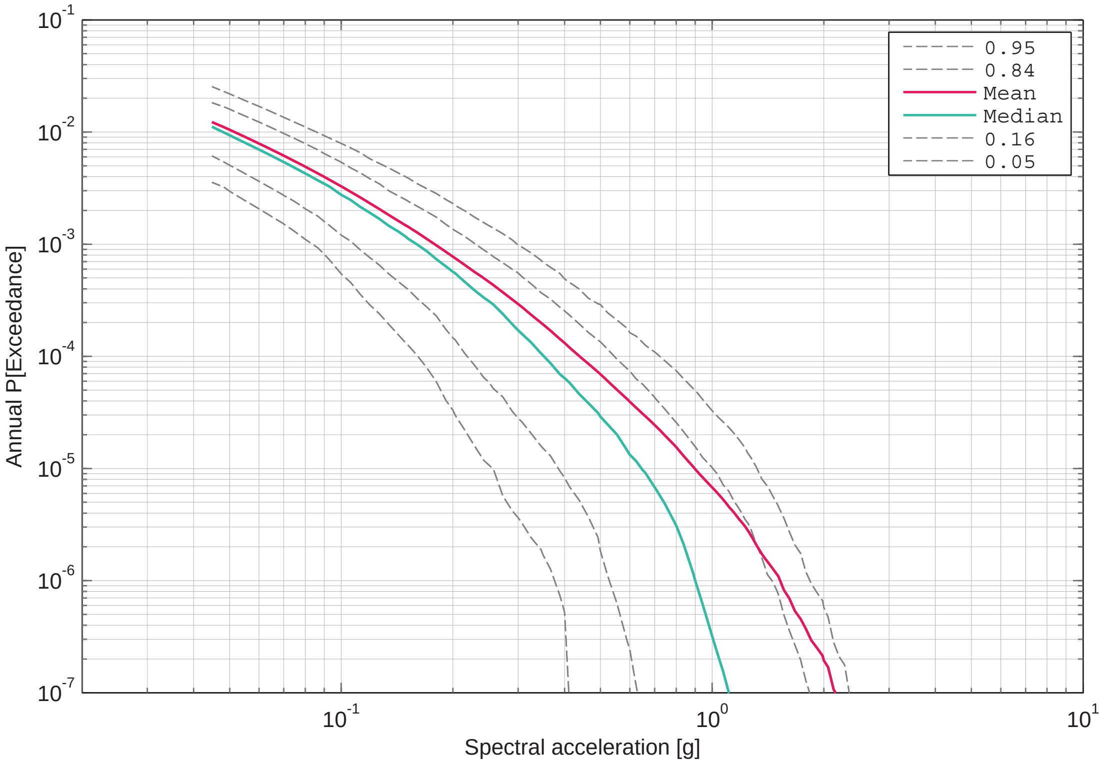


Figure 8.23: Mühleberg, horizontal component, soil, surface, mean hazard and fractiles, 100 Hz.

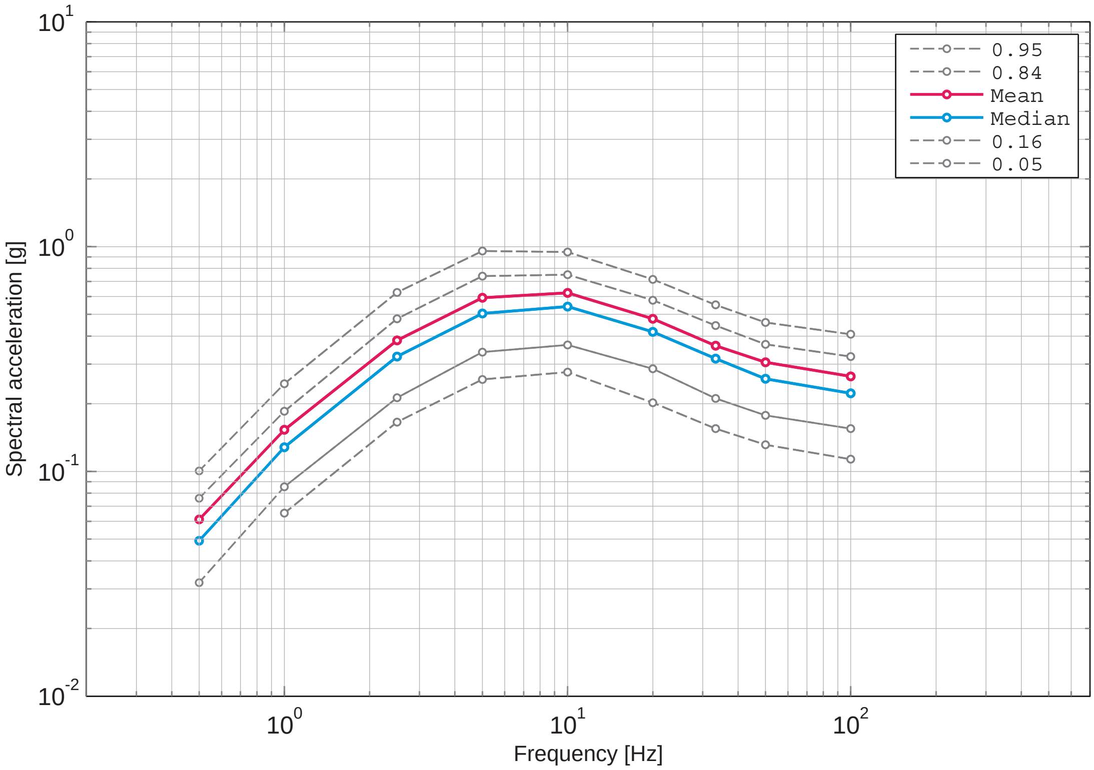


Figure 8.24: Mühleberg, horizontal component, rock, uniform hazard spectra for an annual probability of exceedance of 1E-4 and 5% damping.

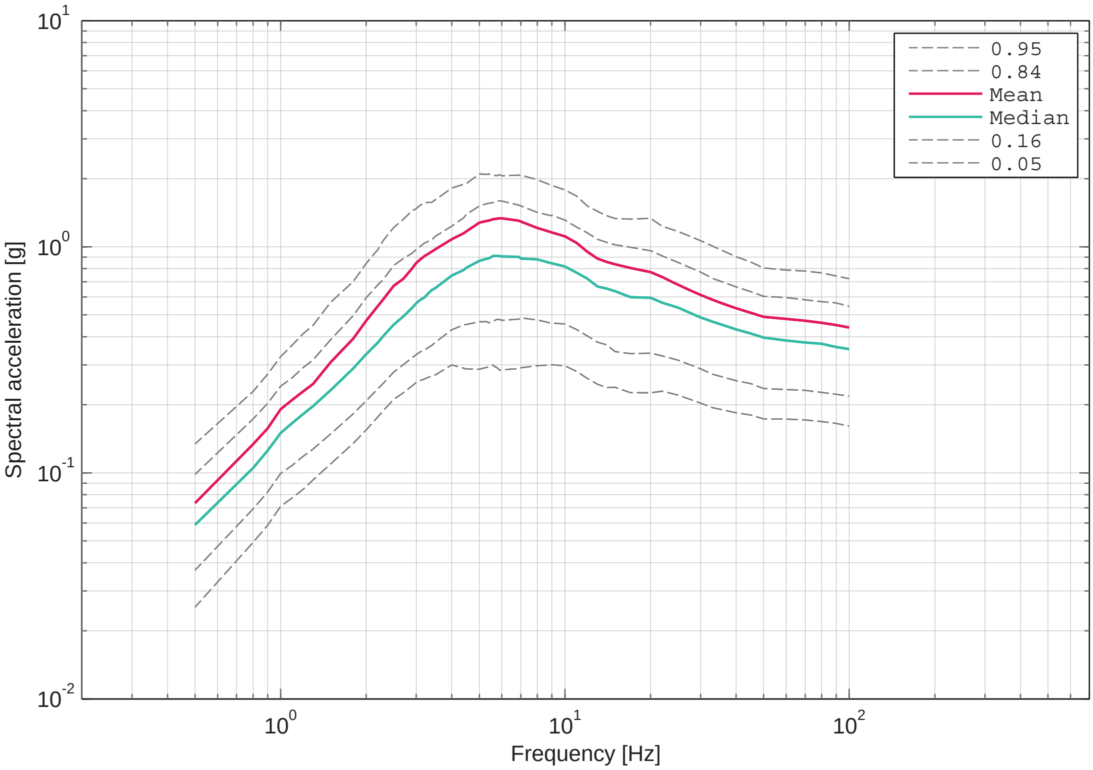


Figure 8.25: Mühleberg, horizontal component, soil, surface, uniform hazard spectra for an annual probability of exceedance of 1E-4 and 5% damping.

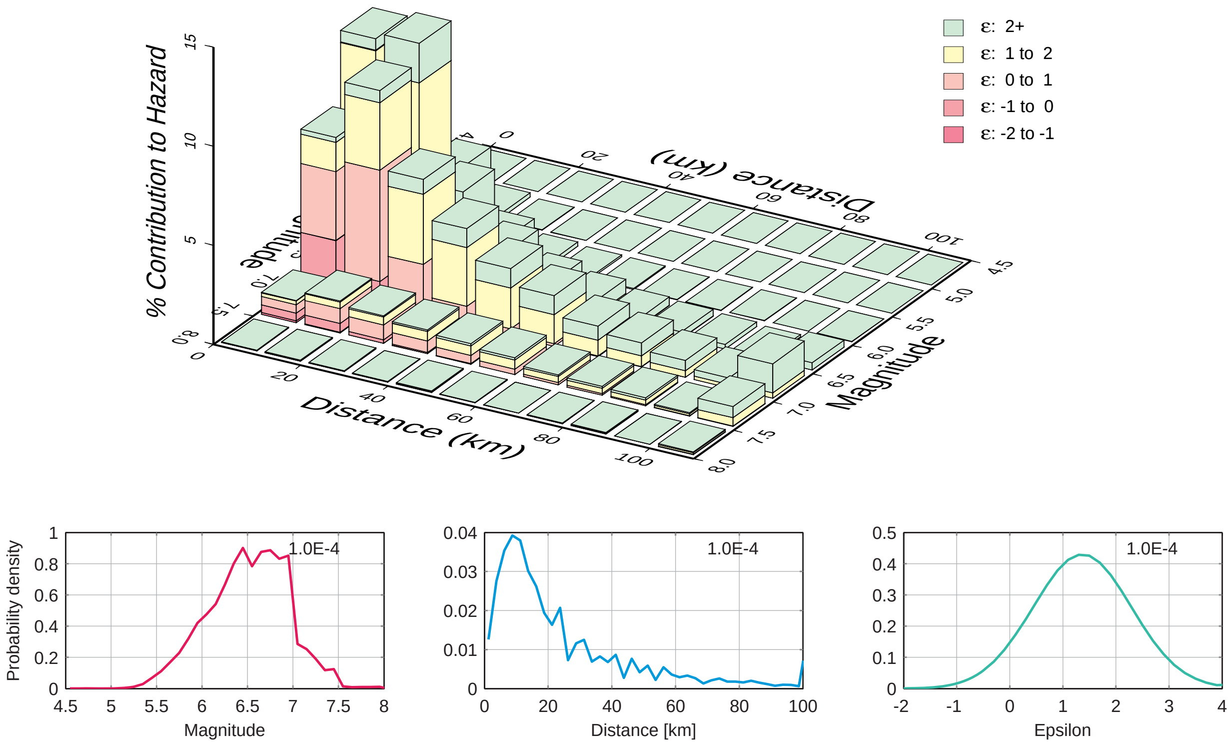


Figure 8.26: Mühleberg, horizontal component, rock, hazard deaggregation by magnitude, distance and ϵ for annual probability of exceedance of 1E-4, 0.5 Hz.

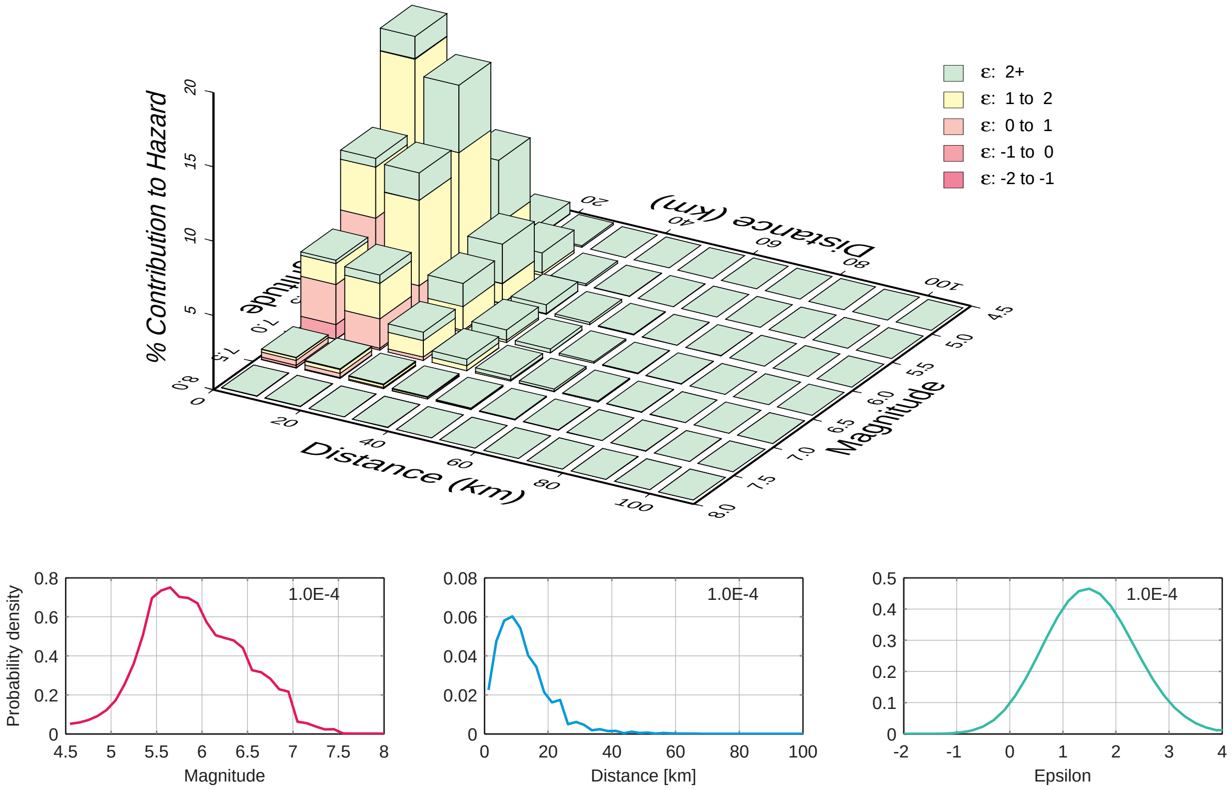


Figure 8.27: Mühleberg, horizontal component, rock, hazard deaggregation by magnitude, distance and ϵ for annual probability of exceedance of 1E-4, 100 Hz

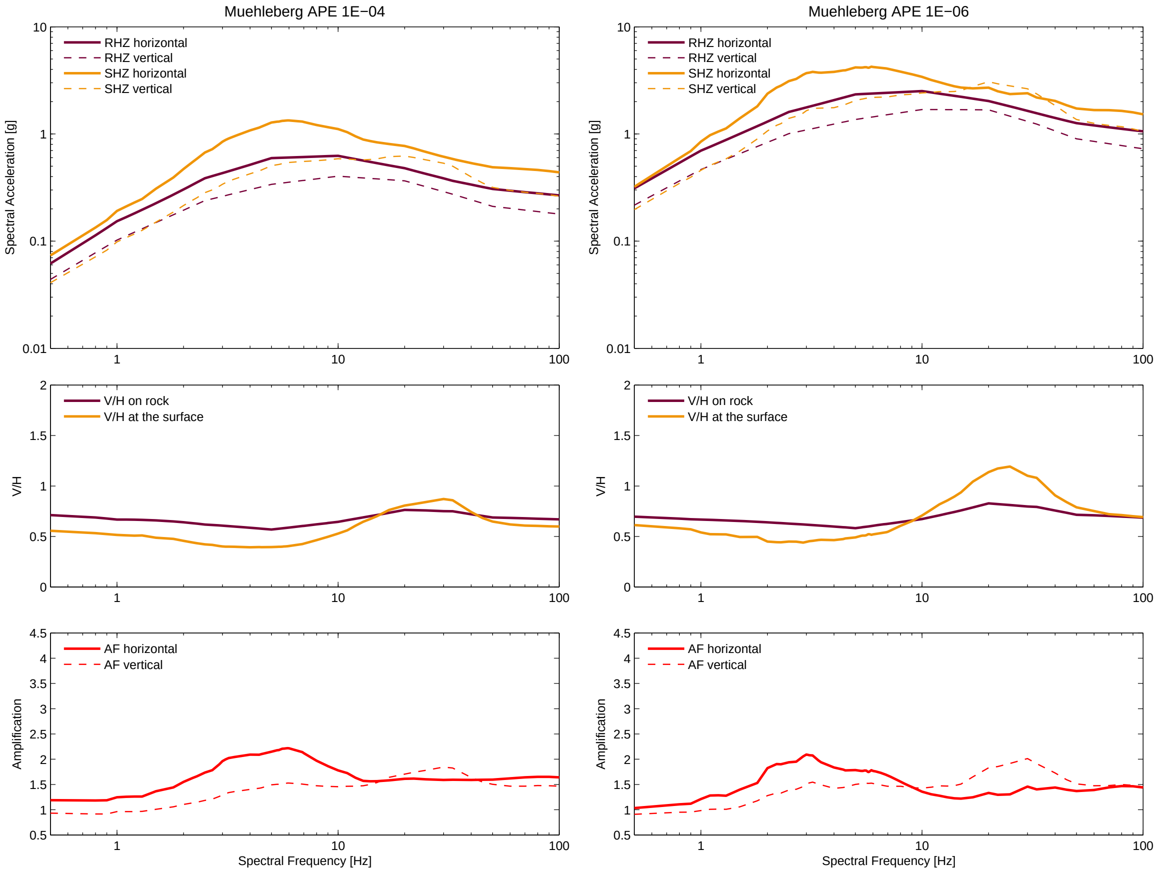


Figure 8.28: Comparison for Mühleberg of rock and soil UHS (top), V/H ratio resulting from the horizontal and vertical UHS (middle) and the horizontal and vertical soil amplification (bottom) for an annual probability of exceedance of 10^{-4} and 10^{-6}.

8.1.5 Comparison of Lower Bound Magnitude Integration Limit

Figures 8.29 and 8.30 show the comparison of the effect of considering a lower bound magnitude of 4.5 as the integration limit for the example of Gösgen and Mühleberg at 1 and 100 Hz, respectively. As can be seen from the hazard curves and the deaggregation plots (Section 8.1.4), the impact of considering M_{min}=4.5 has only a minor effect on the hazard and the differences only occur at low ground motion levels where we expect the smaller earthquakes may contribute to the hazard.

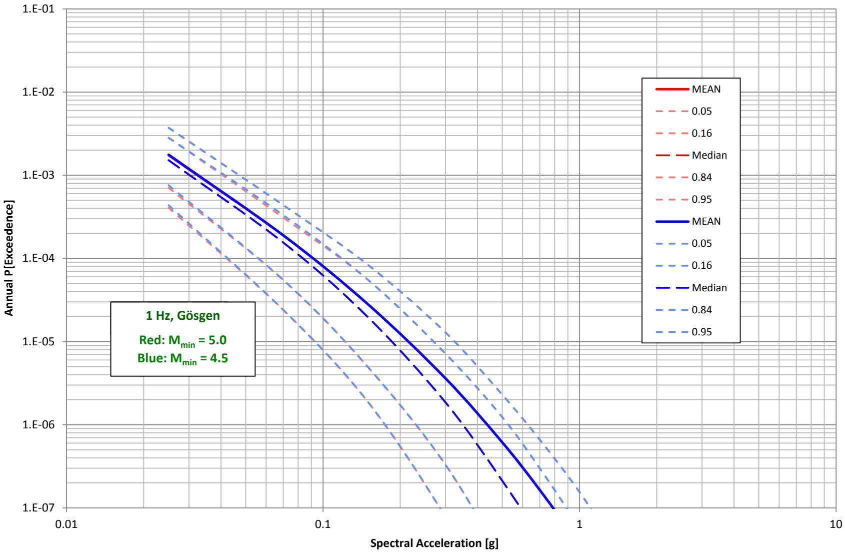


Figure 8.29: Hazard comparison for Gösgen based on lower bound integration magnitude M_{min}=4.5 and M_{min}=5.0 for 1 Hz. Note: The hazard comparison is based on the expert models as defined in May 2013.

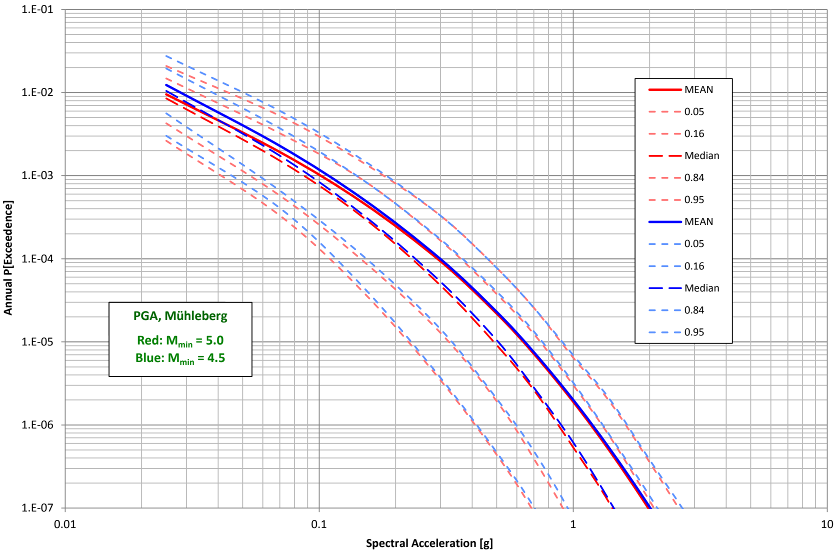


Figure 8.30: Hazard comparison for Mühleberg based on lower bound integration magnitude M_{min}=4.5 and M_{min}=5.0 for 100 Hz. Note: The hazard comparison is based on the expert models as defined in May 2013.

8.2 Hazard Parameter Sensitivity Results

The sensitivity results provide insights into the effect (or lack of effect) of different models and model parameters on the seismic hazard and its uncertainty. Volume 2 of this report contains a complete set of sensitivity plots for each site and each frequency from which a few representative examples are extracted and discussed in this chapter.

8.2.1 SP1: Contributions from Significant Sources

The deaggregation shown in Section 8.1 shows the contribution of different earthquake scenarios (magnitude and distance) to the hazard. A deaggregation can also be made in terms of the contribution of different seismic sources to the hazard. Figures 8.31 and 8.32 show the 100 Hz and 1 Hz hazard separated by source for the Beznau site. As is often the case and as seen in previously in PEGASOS, the hazard at Beznau is dominated by the contribution from the host seismic source (source "E3A" within which the site is located) at probabilities of 10^{-4} or less. This can change if there is a source with a much higher activity rate as is the case for Mühleberg. Figures 8.33 and 8.34 show the hazard by source for the Mühleberg site. The nearby Fribourg fault led to a hazard level that is comparable to the hazard from the host zone.

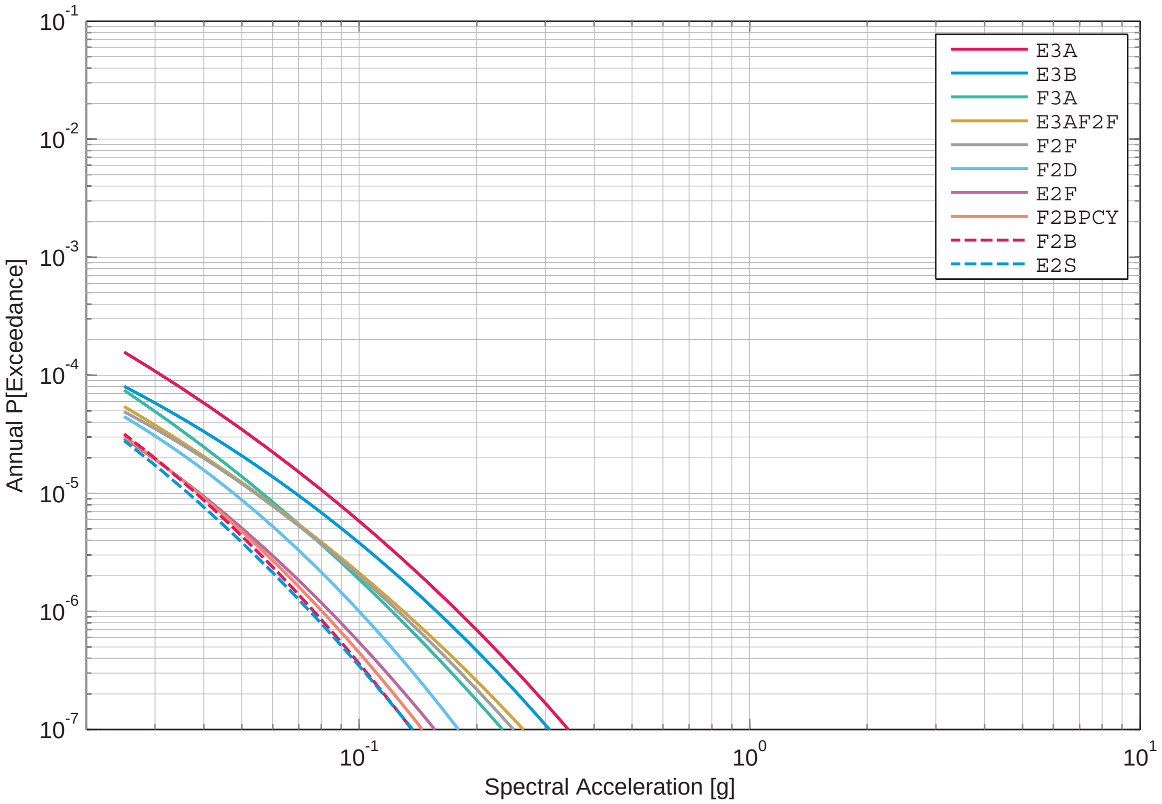


Figure 8.31: Beznau, horizontal component, rock, 10 largest source contributions to mean hazard, EG1a, 100 Hz.

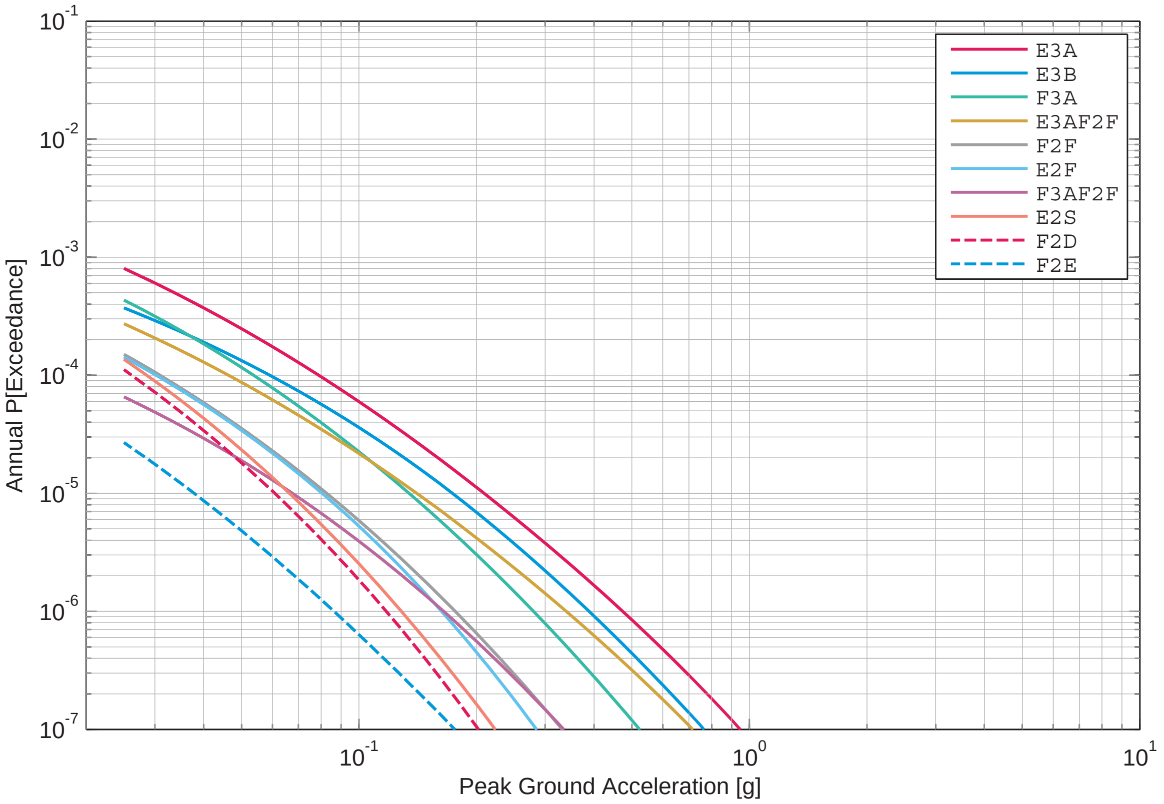


Figure 8.32: Beznau, horizontal component, rock, 10 largest source contributions to mean hazard, EG1a, 1 Hz.

8.2.2 Contributions to Uncertainty

Subproject 1

Figure 8.35 compares the total mean rock hazard obtained using the individual seismic source characterization (SP1) expert teams' models for 100 Hz at Beznau. These results, and the full set of results of Volume 2, show a good degree of consistency among the mean estimates of the expert teams, with usually less than a factor of three in exceedance probability (factor of 1.3 in ground motion) between the lowest and highest expert group's estimate. The results presented in Section 8.1 show that the hazard for 100 Hz is dominated by $M5$ to $M7$ earthquakes at nearby locations (within 20 km).

The results presented in Volume 2 show that the variation in mean hazard between the four SP1 expert teams is larger for spectral accelerations at low frequencies than they are at higher frequencies. This is likely due to differences in the assessments of maximum magnitude as the larger earthquakes are more important contributors to the hazard for low frequency ground motions than for high frequency ground motions.

Gösgen is the site with the highest degree of consistency among the mean estimates of the SP1 expert teams, with a range of factors of 1.5 to 2 in the exceedance probabilities, whereas the other three sites show similar expert-to-expert uncertainty (see Volume 2).

Examples of the hazard sensitivity due to uncertainty in the SP1 models is summarized in the SP1 tornado plots for 1 Hz and 100 Hz for a hazard level of 10^{-4} in Figures 8.36 and 8.37. The top of the tornado plot shows the range of ground motions from the SP1 expert teams.

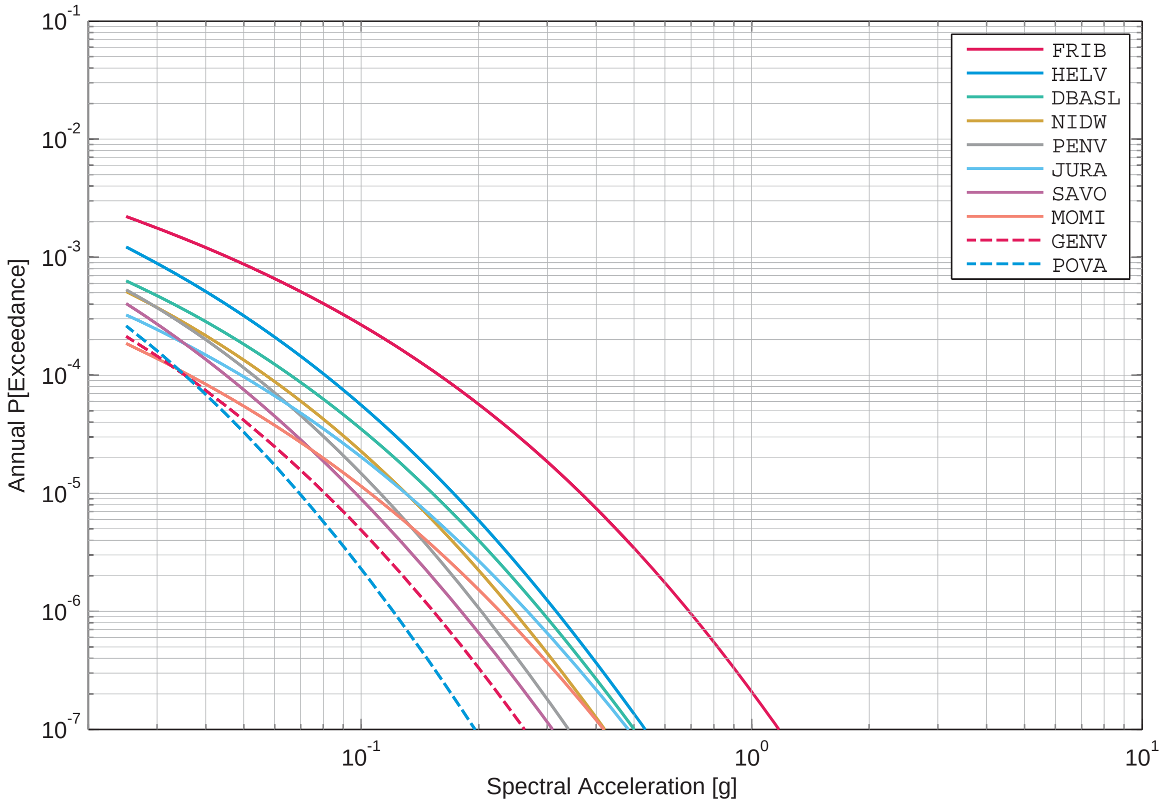


Figure 8.33: Mühleberg, horizontal component, rock, 10 largest source contributions to mean hazard, EG1c, 100 Hz.

The sensitivity of the 100 Hz hazard to the weights on the individual SP1 team logic tree branches is shown in the lower parts of the figures. Individual branches, such as the seismic source zones, spatial smoothing of seismicity, and maximum magnitudes can lead to a ground motion range of factors of 1.5 to 2.0 at the 10^{-4} hazard level.

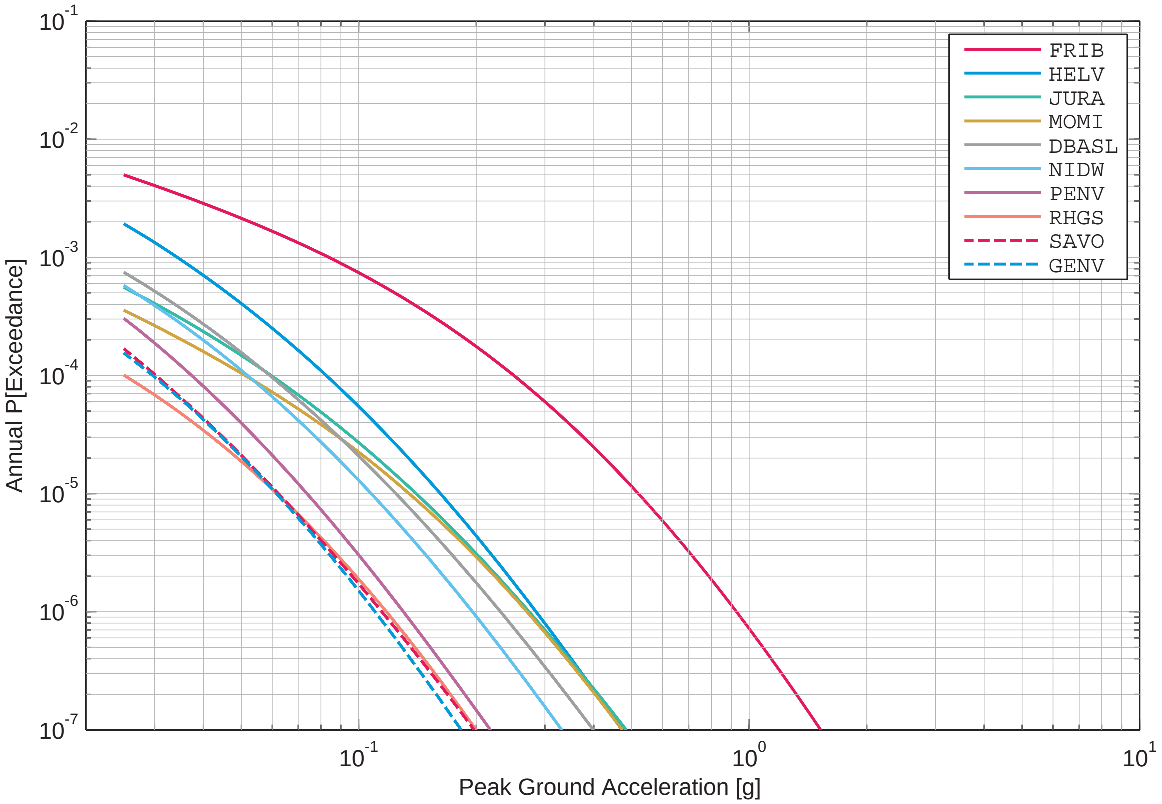


Figure 8.34: Mühleberg, horizontal component, rock, 10 largest source contributions to mean hazard, EG1c, 1 Hz.

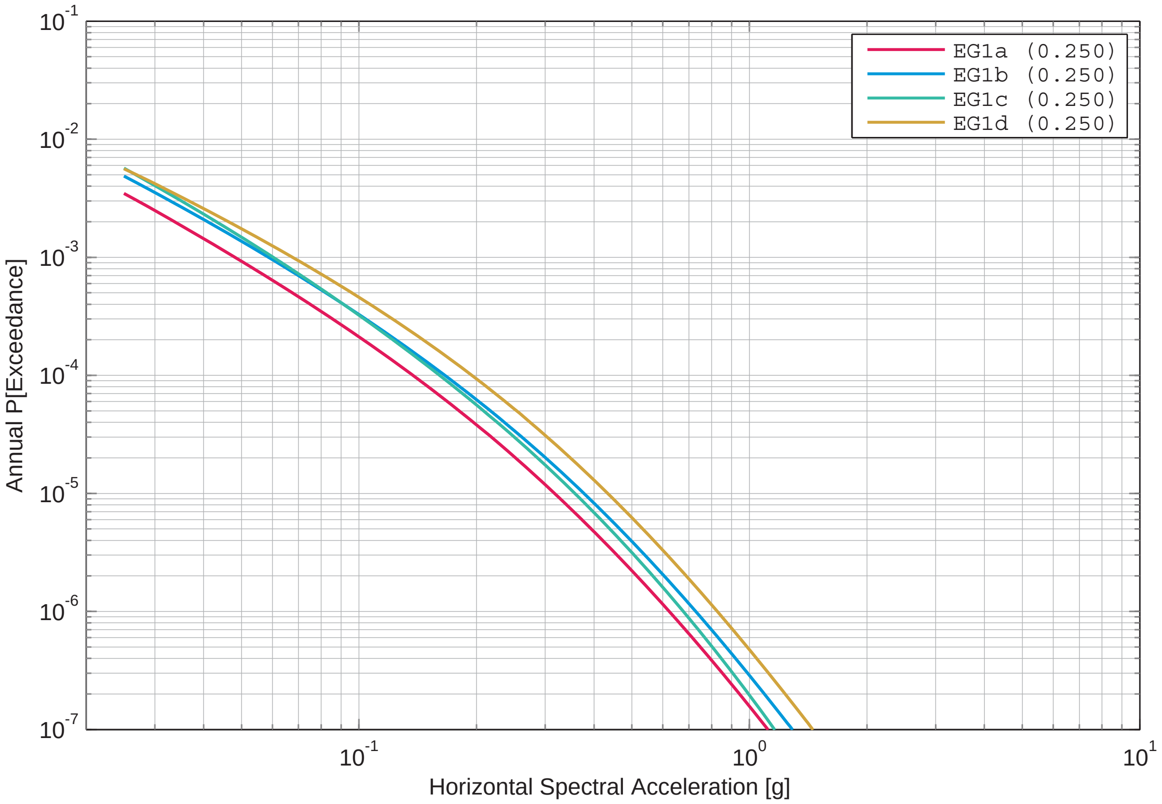


Figure 8.35: Beznau, horizontal component, rock, mean hazard of the four SP1 teams, 100 Hz.

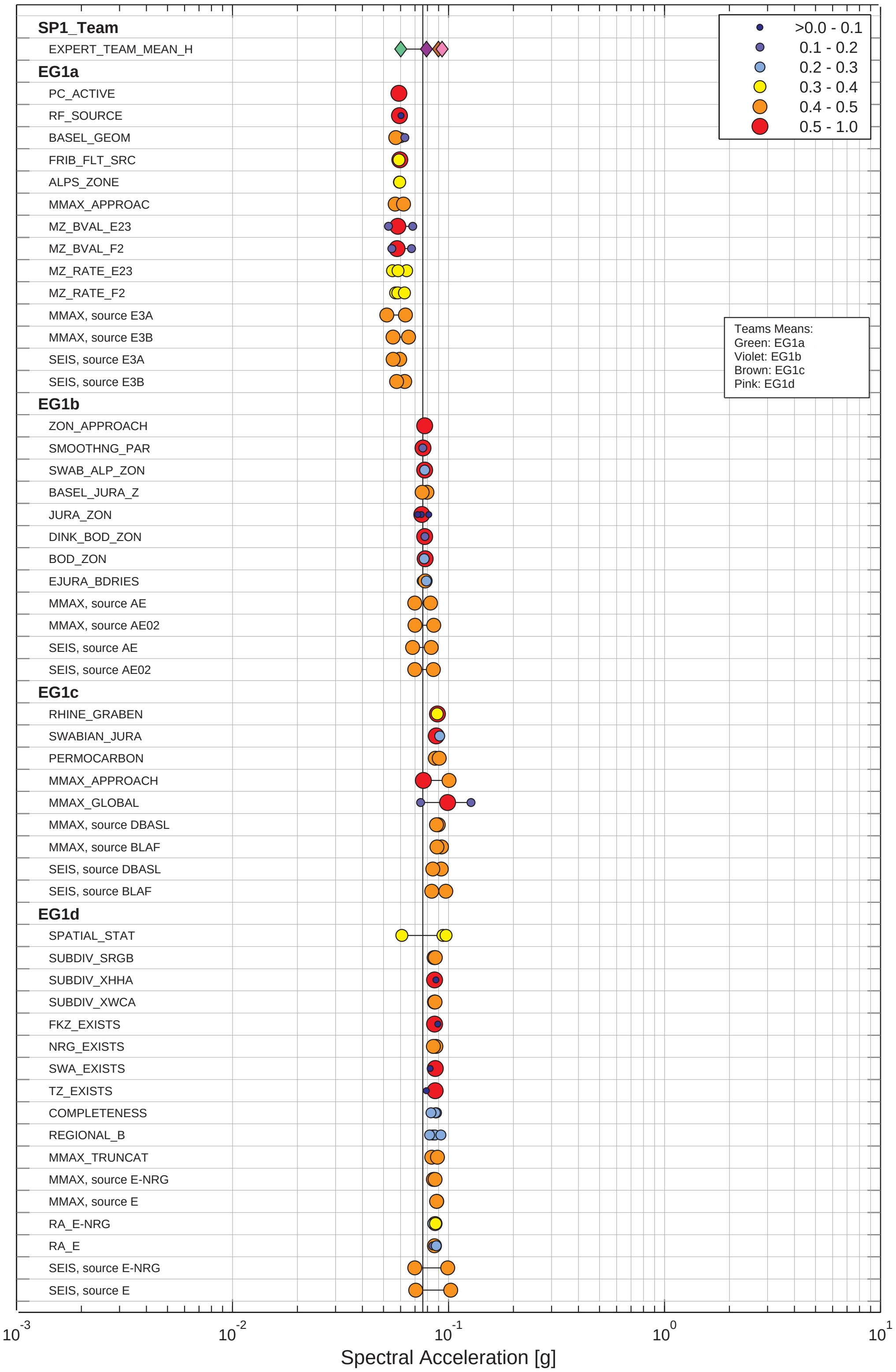


Figure 8.36: SP1 contributions to the uncertainty. Beznau, horizontal component, rock, sensitivity histogram, 1 Hz, annual probability of exceedance of 1E-4. The overall mean hazard shown in this figure as a vertical black line is the horizontal mean hazard obtained by combining the four SP1 expert team's models with a simplified version of Cotton's SP2 model used in these sensitivity calculations. The individual blocks of SP1 expert team's bullets plot on both sides of the overall mean hazard (as defined above). The SP1 expert teams comparison shown in the uppermost line is based on the entire SP2 model.

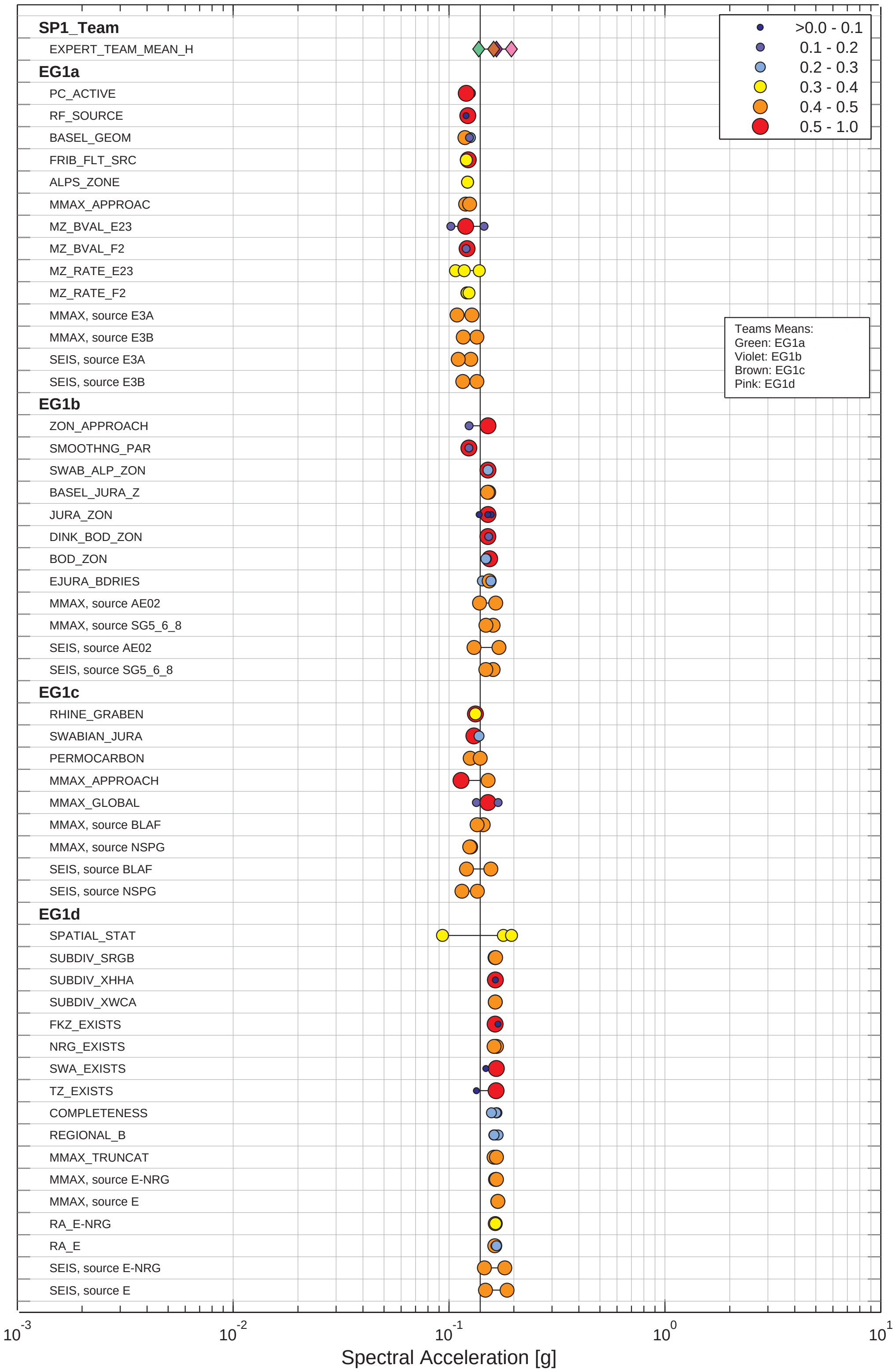


Figure 8.37: SP1 contributions to the uncertainty. Beznau, horizontal component, rock, sensitivity histogram, 100 Hz, annual probability of exceedance of 1E-4. The overall mean hazard shown in this figure as a vertical black line is the horizontal mean hazard obtained by combining the four SP1 expert team's models with a simplified version of Cotton's SP2 model used in these sensitivity calculations. The individual blocks of SP1 expert team's bullets plot on both sides of the overall mean hazard (as defined above). The SP1 expert teams comparison shown in the uppermost line is based on the entire SP2 model.

Subproject 2

Figures 8.38 and 8.39 compare the mean rock hazard curves obtained by the four SP2 experts for 1 Hz and 100 Hz at Beznau (using the seismic source models of the SP1 expert team EG1c). Unlike PEGASOS, the SP2 expert-to-expert uncertainty (about a factor of 1.5 to 2 in exceedance probability) is smaller than in SP1, showing the benefit of the additional studies conducted to help reduce the uncertainties in the rock ground motion models. The within-expert uncertainty for SP2 models leads to about a factor of 10 in hazard (about a factor of 2 in ground motion). The SP2 expert-to-expert uncertainty is much smaller than the SP2 within-expert uncertainty, showing that the SP2 models are not highly sensitive to the selection or weighting of the SP2 experts.

The SP2 tornado plots are shown in Figures 8.40 and 8.41 for the 10^{-4} hazard at 1 Hz and 100 Hz, respectively. The top rows for the tornado plots show the expert-to-expert range for SP1 and SP2. The expert-to-expert range is greater for SP1 than for SP2. This is a change from PEGASOS in which the SP2 expert-to-expert uncertainty was much larger. The tornado plots also show that the SP2 within-expert uncertainty is dominated by the model category (PSSM versus GMPE), individual model within a model category (alternative GMPEs and alternative stress-drops for PSSMs), and the $V_S - \kappa$ correction. In terms of the standard deviation logic tree, the uncertainty in the Phi (ϕ) term leads to the largest uncertainty in hazard.

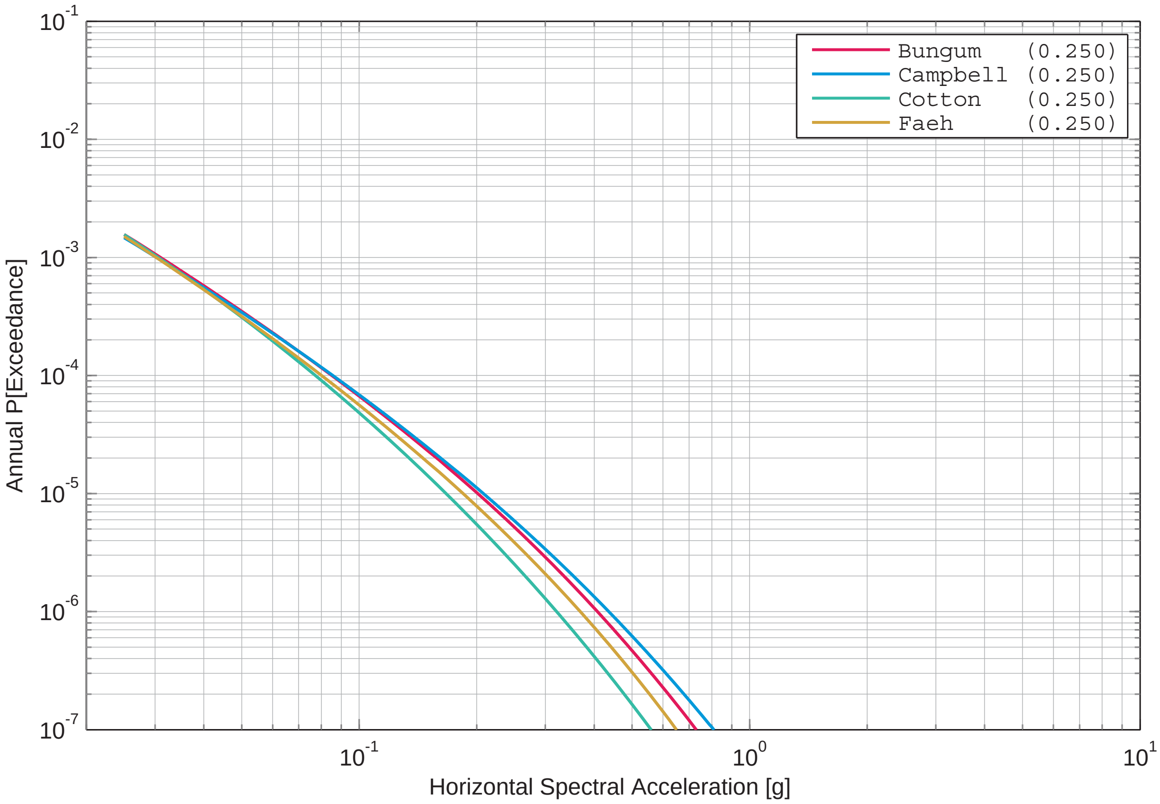


Figure 8.38: Beznau, horizontal component, rock, mean hazard of the four SP2 experts, 1 Hz.

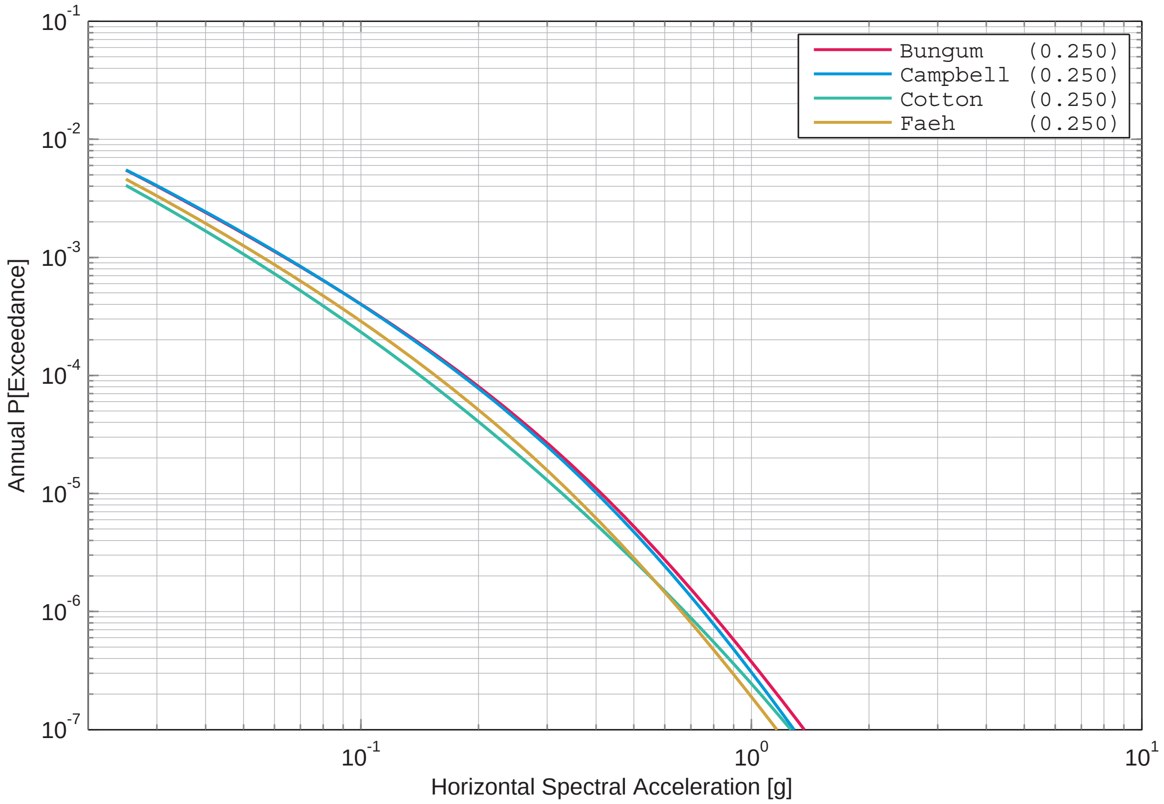


Figure 8.39: Beznau, horizontal component, rock, mean hazard of the four SP2 experts, 100 Hz.

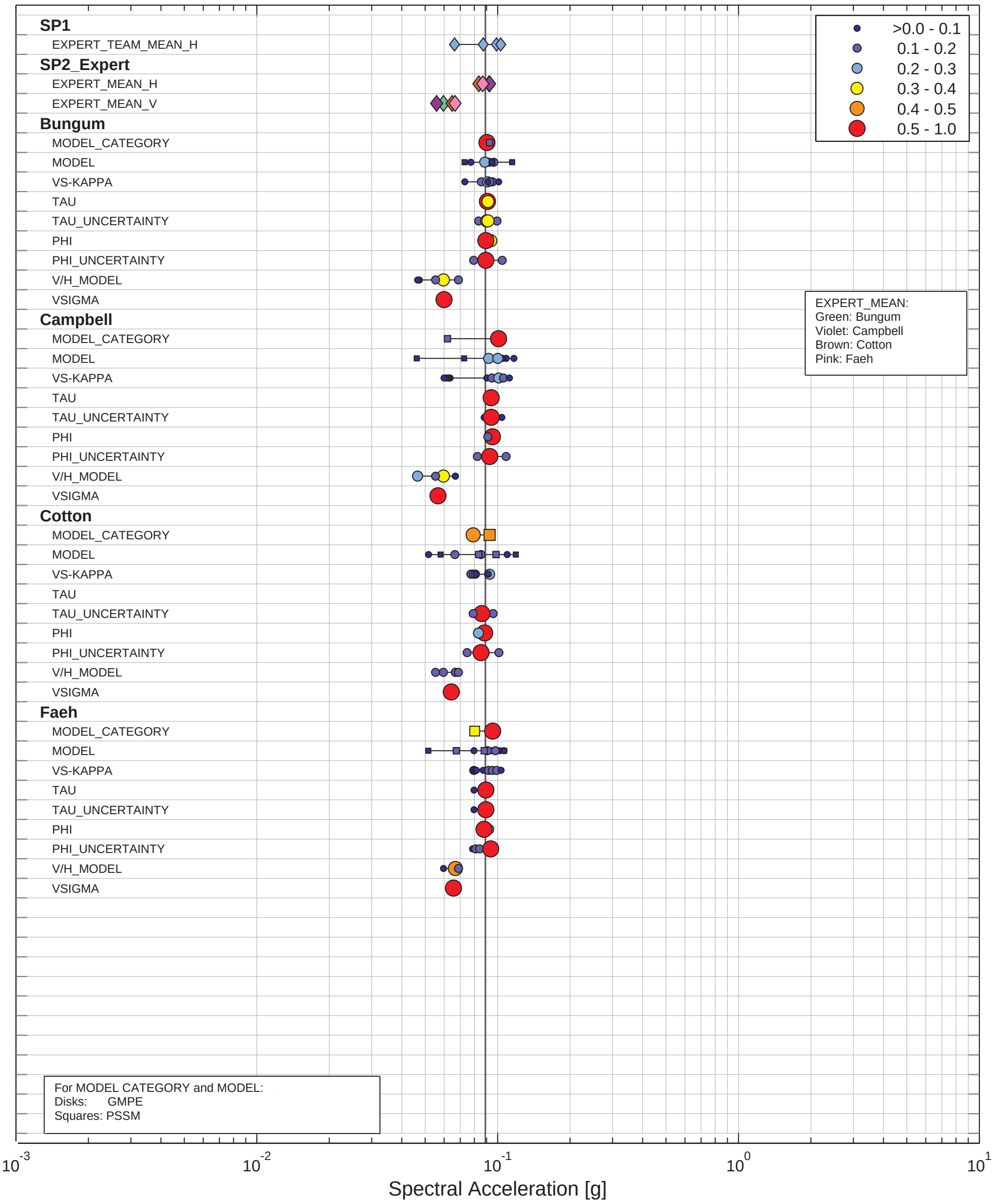


Figure 8.40: SP2 contributions to the uncertainty. Beznau, horizontal component, rock, sensitivity histogram, 1 Hz, annual probability of exceedance of 1E-4. The overall mean hazard shown in this figure as a vertical black line is the horizontal mean hazard obtained by combining EG1c's with the four SP2 models used in these sensitivity calculations. As a reference, the spread of the SP1 teams's mean hazard is shown. The vertical mean hazard for the four SP2 experts is also shown in these figures and the bullets pertaining to global variables of the vertical logic tree ("VH_Model" and "$VSIGMA$") plot below the expert specific mean vertical hazard. The vertical sensitivity results are shown relative to the horizontal mean hazard and thus, plot more to the left of the vertical black line, if the mean V/H ratio is less than unity. In these sensitivity histograms, a distinction is made between GMPE branches,plotted as disks in the relevant levels and the PSSM branches, plotted as squares

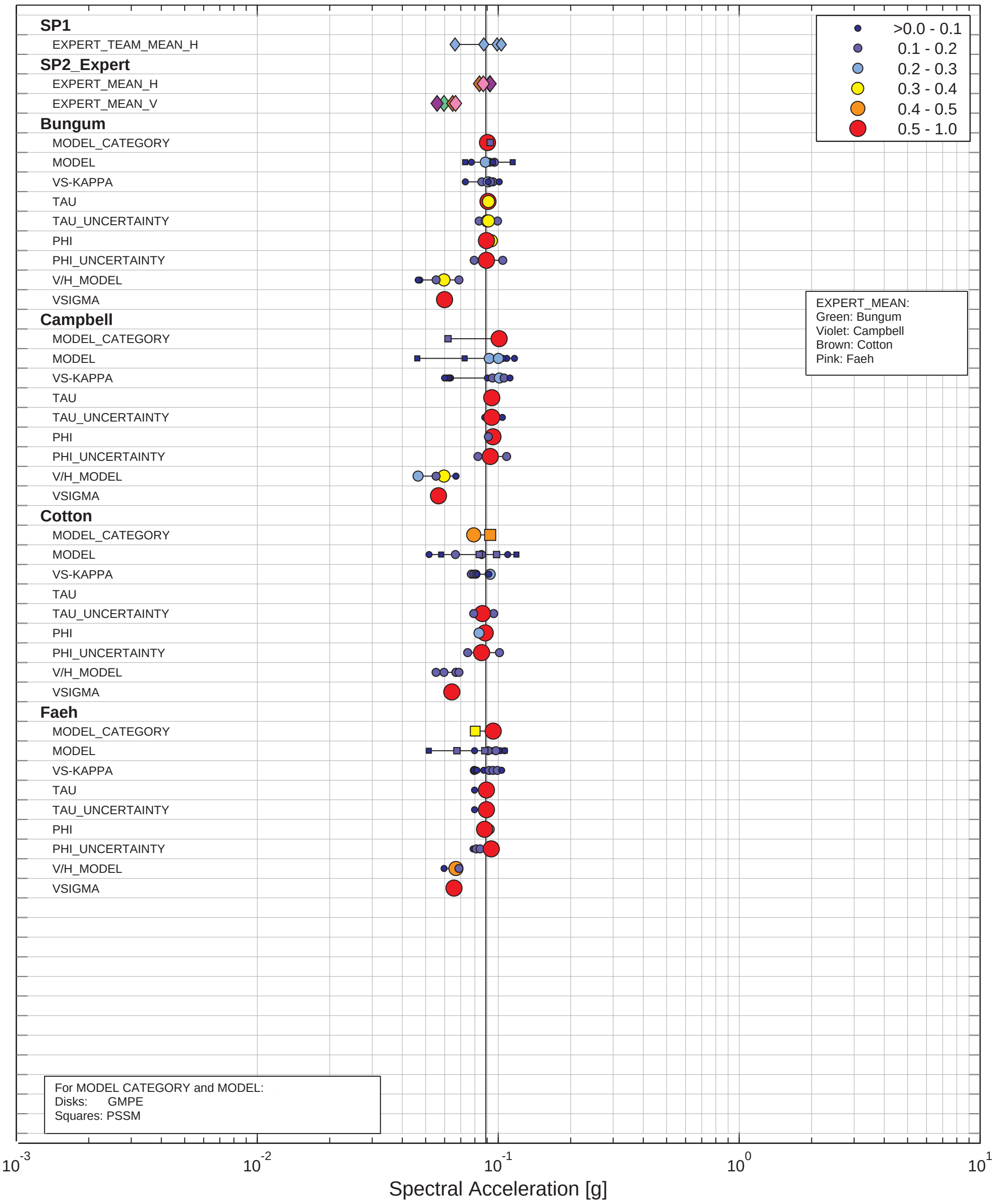


Figure 8.41: SP2 contributions to the uncertainty. Beznau, horizontal component, rock, sensitivity histogram, 100 Hz, annual probability of exceedance of 1E-4. The overall mean hazard shown in this figure as a vertical black line is the horizontal mean hazard obtained by combining EG1c's with the four SP2 models used in these sensitivity calculations. As a reference, the spread of the SP1 teams's mean hazard is shown. The vertical mean hazard for the four SP2 experts is also shown in these figures and the bullets pertaining to global variables of the vertical logic tree ("VH_Model" and "$VSIGMA$") plot below the expert specific mean vertical hazard. The vertical sensitivity results are shown relative to the horizontal mean hazard and thus, plot more to the left of the vertical black line, if the mean V/H ratio is less than unity. In these sensitivity histograms, a distinction is made between GMPE branches,plotted as disks in the relevant levels and the PSSM branches, plotted as squares.

Subproject 3

Figures 8.42 and 8.43 compare the mean soil hazard curves obtained by the four SP3 experts for 1 Hz and 100 Hz at Beznau. The range of the mean hazards for the four SP3 experts is small: at a hazard level of 10^{-4}, the range of spectral accelerations is about a factor of 1.1 for both 1 Hz and 100 Hz. At lower hazard levels, the range remains about the same for 1 Hz, but the range increases for 100 Hz: at a hazard level of 10^{-6}, the expert-to-expert range in the 100 Hz spectral acceleration spans a factor of 1.35. This increased range is mainly due to the increase in the uncertainty of the non-linear behavior of the soils and partly due to differences in the maximum soil ground motion models.

For computational efficiency, the tornado plots for SP3 were produced without taking into account the aleatory variability models of the SP3 experts. Thus, the resulting mean hazard is not equivalent with the full mean hazard. The influence of this simplification is shown in the top part of the sensitivity histogram.

The tornado plots for SP3 are shown in Figures 8.44 and 8.45. For 1 Hz, the expert-to-expert uncertainty range (shown in the top frame) is small, about a factor of 1.2. The within-expert uncertainty for 1 Hz is also small for the horizontal component, but it is larger for the vertical component. For the vertical component, the largest contributor to the uncertainty is the V/H model.

For 100 Hz, the expert-to-expert uncertainty remains at about a factor of 1.2, similar to the range for 1 Hz, but the within-expert uncertainty is larger than at 1 Hz. For the horizontal component, the largest contributors to the within-expert uncertainty are the V_S profile and the material model. For the vertical component, the uncertainty range varies greatly between the SP3 experts: P.-Y. Bard and J. Studer have a range of a factor of 3 due to the inclusion of a very low V/H model [Poggi et al. 2012]; D. Fäh and A. Pecker do not include this V/H model and their uncertainty range is only 1.2 to 1.5.

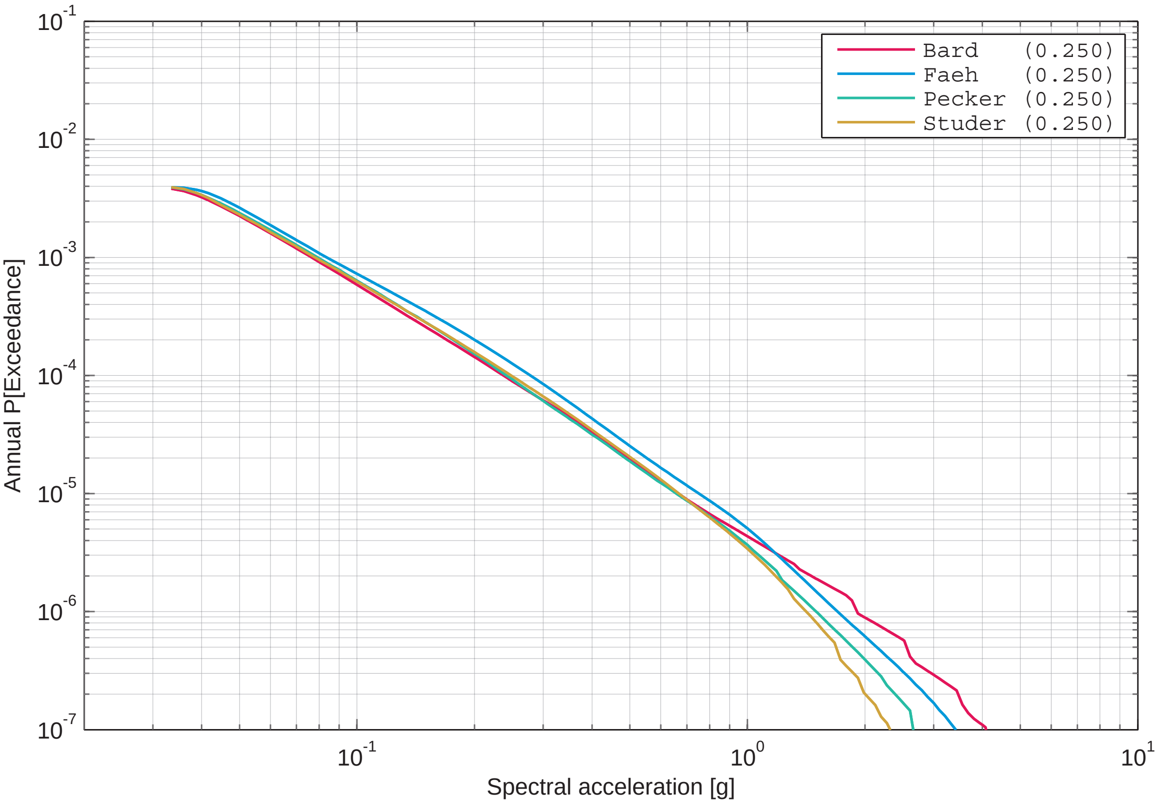


Figure 8.42: Beznau, horizontal component, soil, mean hazard of the four SP3 experts, 1 Hz.

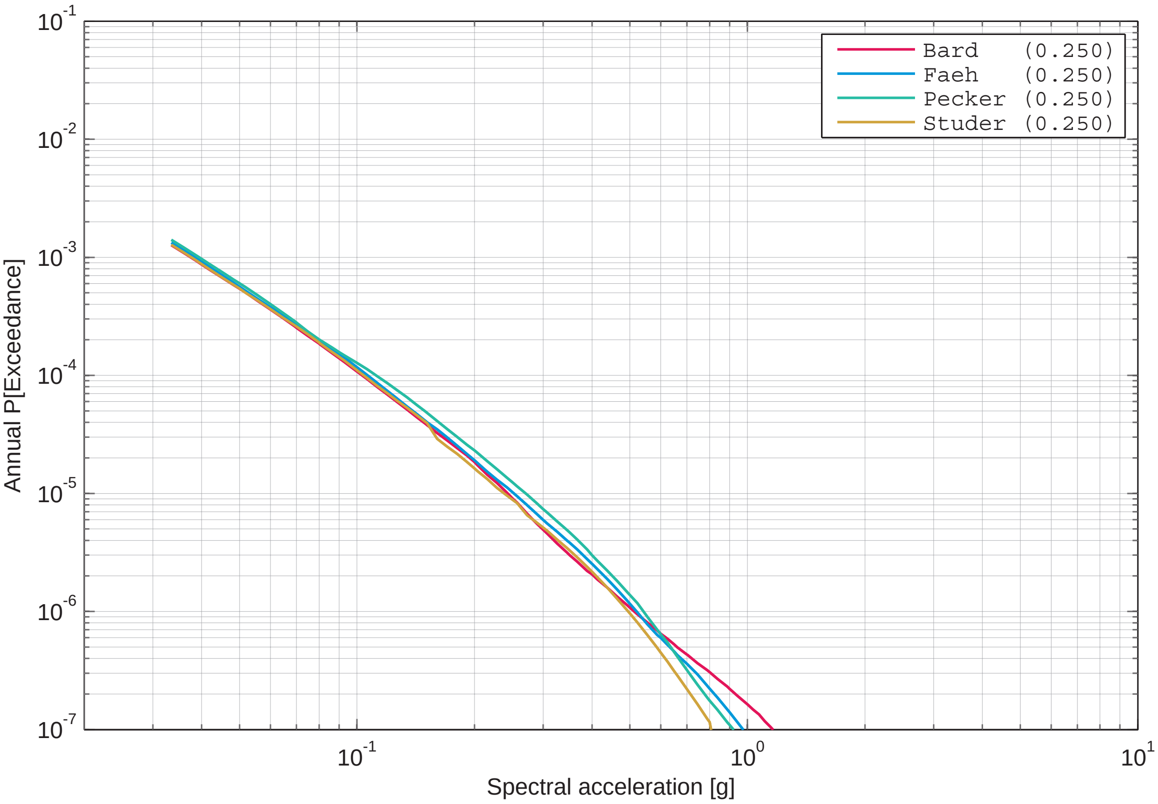


Figure 8.43: Beznau, horizontal component, soil, mean hazard of the four SP3 experts, 100 Hz.

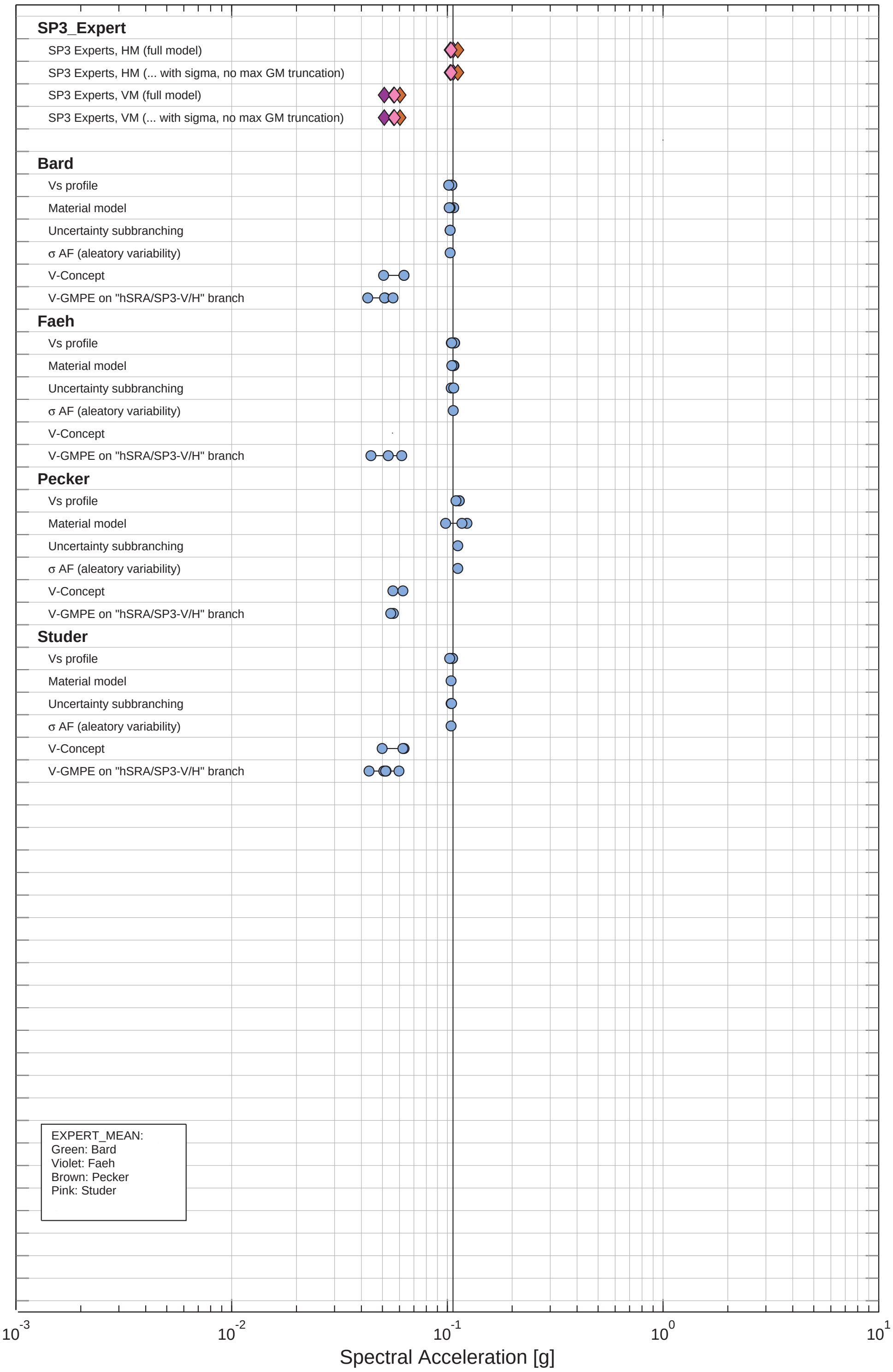


Figure 8.44: SP3 contributions to the uncertainty. Beznau, horizontal component, soil, sensitivity histogram, 1 Hz, annual probability of exceedance of 1E-4. The overall mean hazard shown in this figure as a vertical black line is the mean horizontal soil hazard. The vertical mean hazard for the four SP3 experts is also shown in these figures and plot below the expert specific mean vertical hazard, which is shown relative to the horizontal mean hazard. All bullets are blue in the lower part of the figures because the weights associated with each individual branch are variable as they depend among other on the PGA level. The parameter sensitivity calculations were performed with the aleatory variability set to zero. The influence of this model simplification is shown in the two lines following the relative SP3 expert comparison (for horizontal and vertical component) in the uppermost lines, which are evaluated with the full SP3 models.

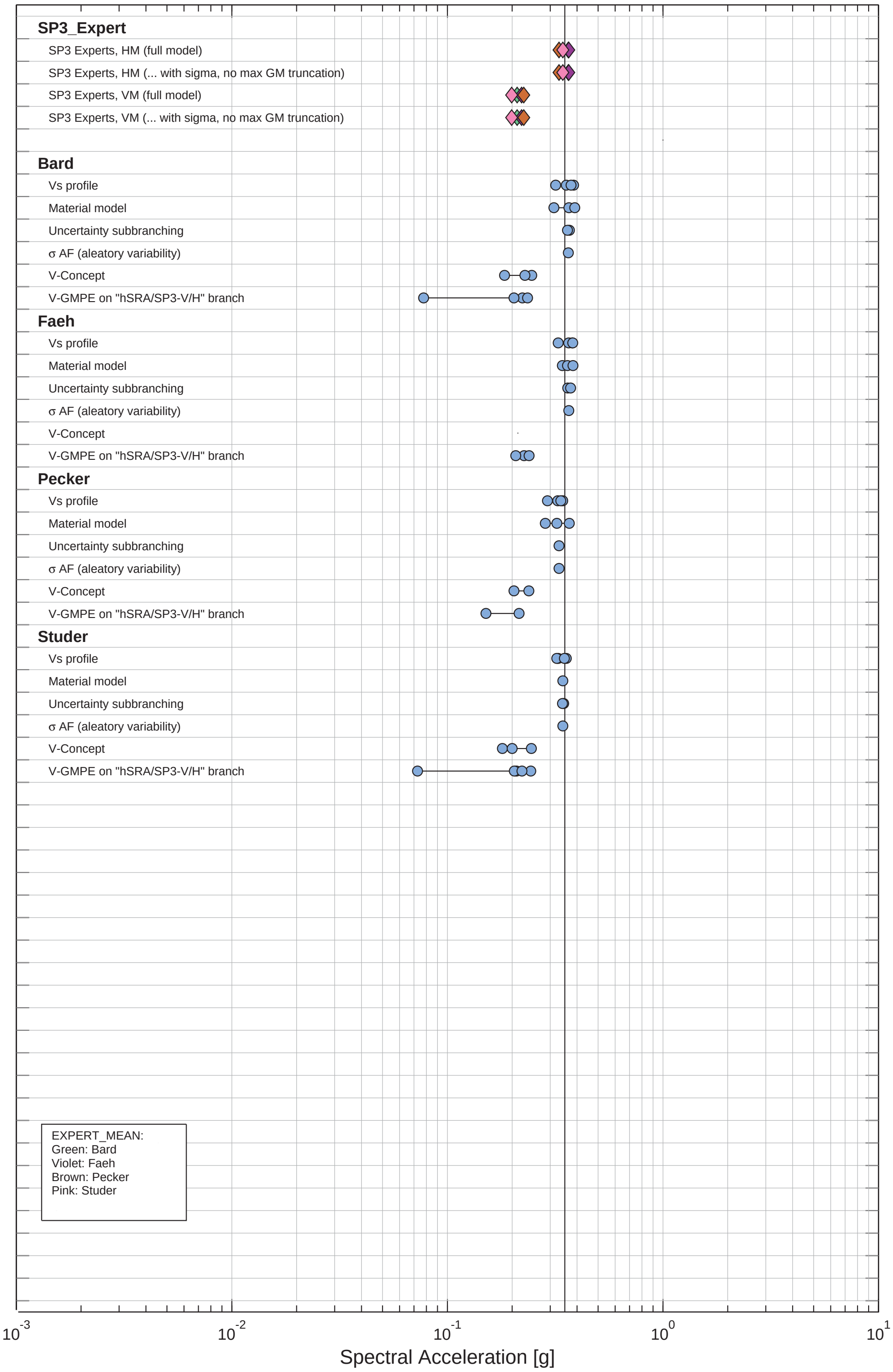


Figure 8.45: SP3 contributions to the uncertainty. Beznau, horizontal component, soil, sensitivity histogram, 100 Hz, annual probability of exceedance of 1E-4. The overall mean hazard shown in this figure as a vertical black line is the mean horizontal soil hazard. The vertical mean hazard for the four SP3 experts is also shown in these figures and plot below the expert specific mean vertical hazard, which is shown relative to the horizontal mean hazard. All bullets are blue in the lower part of the figures because the weights associated with each individual branch are variable as they depend among other on the PGA level. The parameter sensitivity calculations were performed with the aleatory variability set to zero. The influence of this model simplification is shown in the two lines following the relative SP3 expert comparison (for horizontal and vertical component) in the uppermost lines, which are evaluated with the full SP3 models.

Comparison of Contributions to Uncertainty from all Subprojects

The comparison of the tornado plots of all subprojects, as shown in Figure 8.46 for 1 Hz and in Figure 8.47 for 100 Hz, is based on the subsets of the full sensitivity histograms shown above, here for the example of the Beznau site. The subset includes just a single team/expert from SP1, SP2, and SP3 to keep the plot manageable. The uncertainties are compared for the SP1 EG1c team, SP2 expert D. Fäh and SP3 expert P.-Y. Bard.

For 1 Hz, the combined tornado plot shows that the uncertainty for EG1c SP1 model is similar to the uncertainty for D. Fäh SP2 model due to the uncertainty of the maximum magnitude, but the uncertainty from the ground motion model (selection of GMPE) is still the largest contributor. At 1 Hz, the SP3 model of P.-Y. Bard has a relatively small contribution to the uncertainty.

For 100 Hz, the uncertainty in D. Fäh's SP2 model dominates the uncertainty. The SP3 model of P.-Y. Bard has a large contribution for the vertical component, but the uncertainty for the horizontal component is small. The EG1c SP1 model also has a relatively small contribution to the uncertainty.

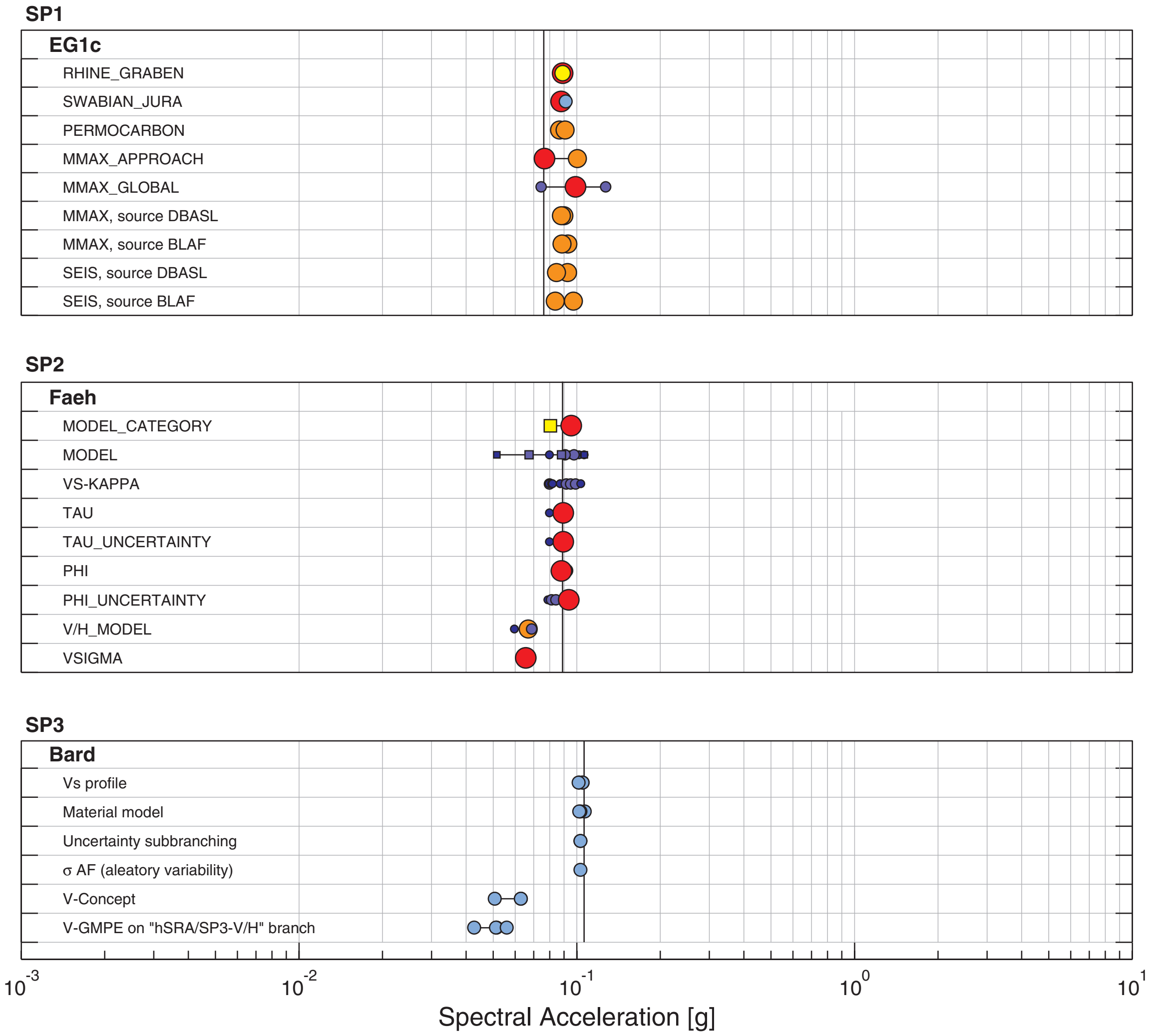


Figure 8.46: Comparison of subproject contributions to the uncertainty. Beznau, horizontal component, sensitivity histogram subset, 1 Hz, annual probability of exceedance of 1E-4.

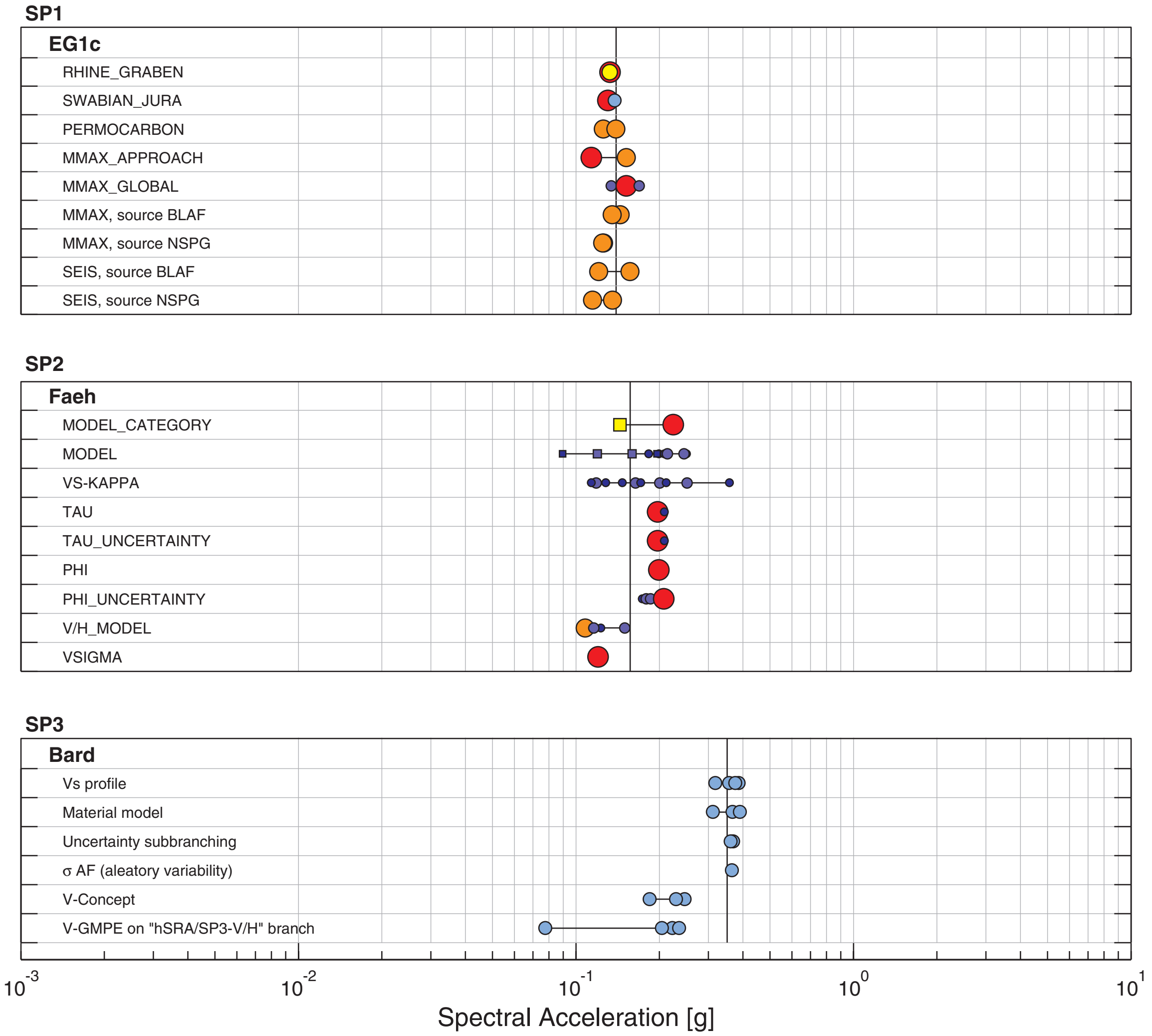


Figure 8.47: Comparison of subproject contributions to the uncertainty. Beznau, horizontal component, sensitivity histogram subset, 100 Hz, annual probability of exceedance of 1E-4.

8.3 Comparison between PEGASOS and PRP

8.3.1 Changes in Mean Rock Hazard

For SP1, the main change was in the updating of the ECOS catalogue. The change in the estimation of the magnitudes lead to a systematic reduction of the hazard. Figure 8.48 compares the mean rock hazard at 100 Hz for Beznau given in the PEGASOS report with the mean rock hazard computed using the updated SP1 models but with the PEGASOS rock ground motion models. In this way, the comparison only shows the effects of the changes for the SP1 model. This figure shows that the new catalog leads to a 22%, 41%, 12% and 12% reduction of the 100 Hz hazard at 10^{-4} for EG1a, EG1b, EG1c, EG1d, respectively.

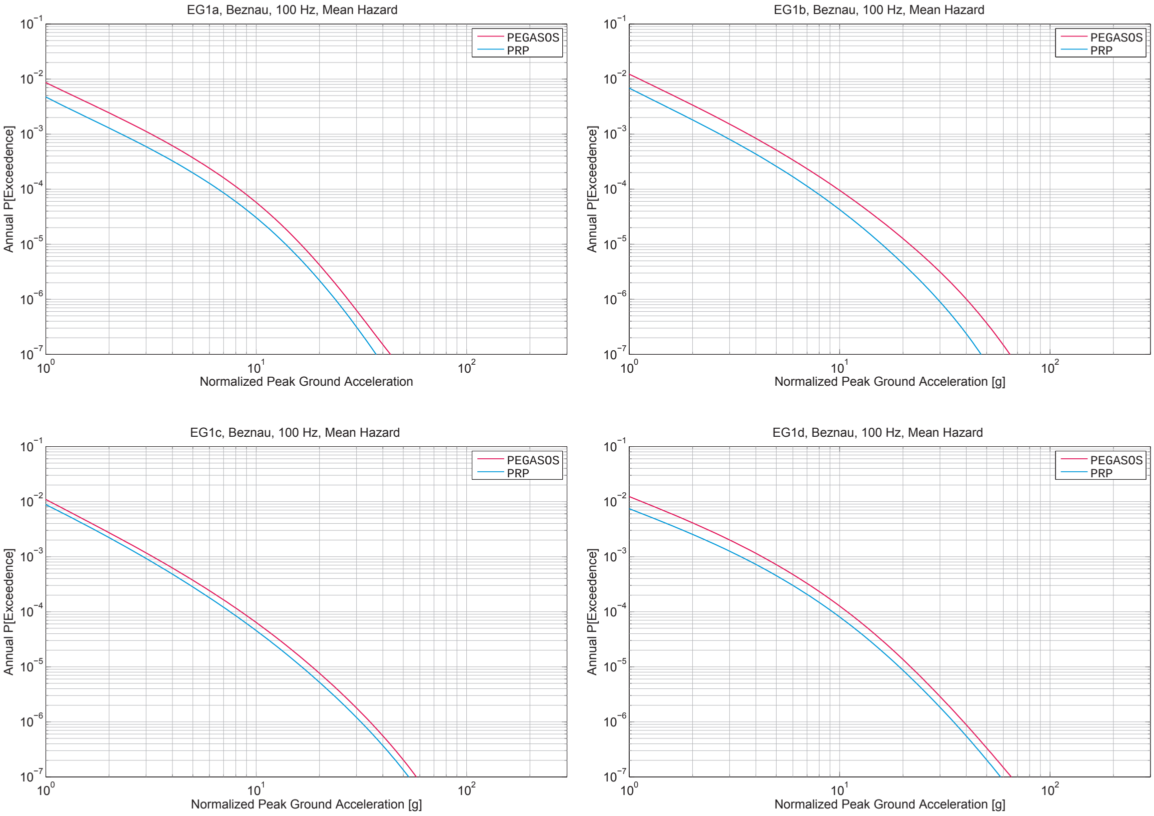
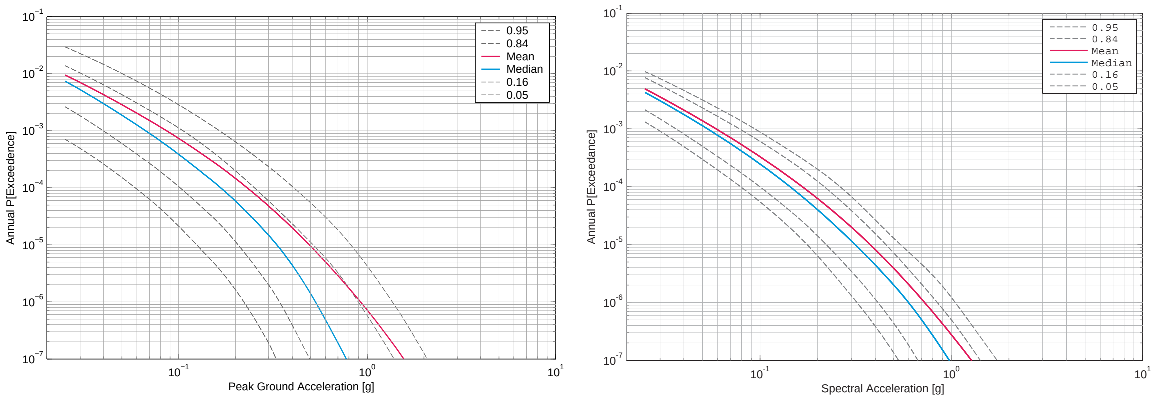


Figure 8.48: Comparison of rock hazard at Beznau between PEGASOS 2004 and PRP 2013, showing the influence of the ECOS catalogue at 100 Hz. This comparison is based on the SP1 hazard feedback TP4-RHZ-1002 to 1005 [TP4-TN-1179].

The rock hazard curves for 100 Hz for the Beznau site from PEGASOS and the PRP are compared in Figure 8.49. In addition to the changes in the SP1 and SP2 models, there are small differences in the reference rock conditions (V_{S30}=2000 m/s for the PEGASOS 2004 rock hazard and V_{S30}=1800 m/s for the PRP 2013 rock hazard at Beznau) and the lower limit of the magnitude integration (M_{min}=5 for PEGASOS and M_{min}=4.5 for PRP), but these differences do not have strong effects on the computed hazard.

Comparing the PEGASOS and PRP hazard curves, shows that there is a significant reduction in the uncertainty of the hazard: at a PGA (100 Hz) value of 0.2 g, the 5–95% fractile range is reduced from a factor of 500 for PEGASOS to a factor of 40 for the PRP. The mean value of the hazard is reduced due to the new SP1 models and the new SP2 models.

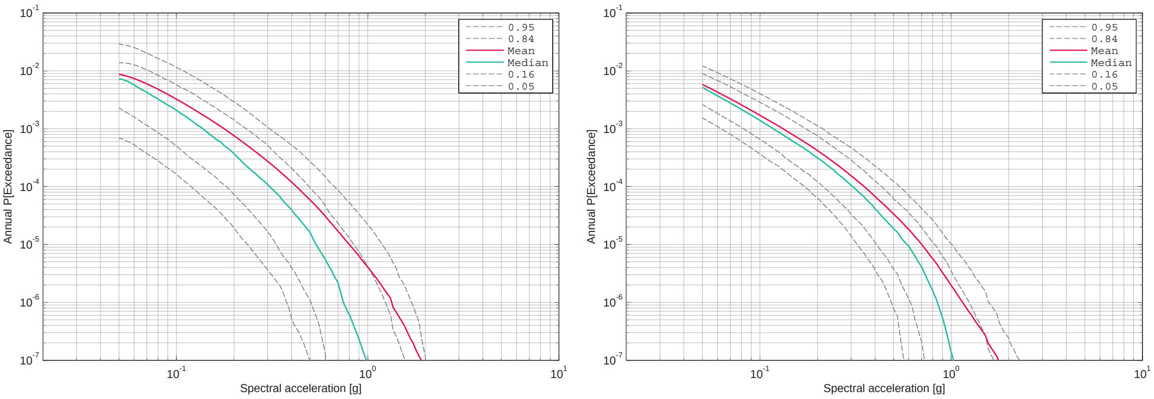


(a) PEGASOS 2004 (b) PRP 2013

Figure 8.49: Comparison of rock hazard at Beznau between PEGASOS 2004 and PRP 2013 for 100 Hz.

8.3.2 Changes in Mean Soil Hazard

The soil hazard curves at 100 Hz for the Beznau site from PEGASOS and the PRP are compared in Figure 8.50. As with the rock hazard, the uncertainty is greatly reduced using the PRP models: at 0.4 g, the 95%/5% range in hazard is a factor of 1000 in PEGASOS, but is reduced to a factor of 100 in the PRP. The uncertainty for the soil hazard for the PRP is similar to the uncertainty the PRP rock hazard.

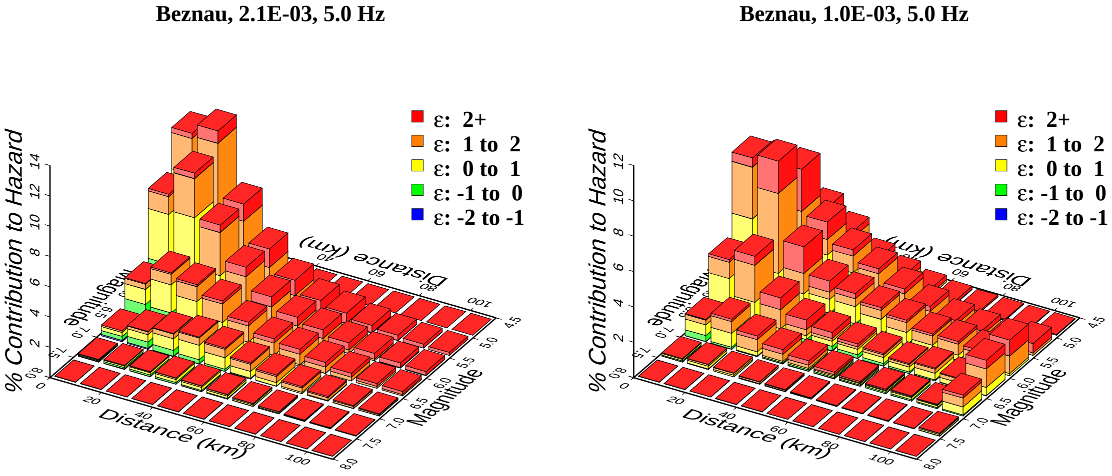


(a) PEGASOS 2004 (b) PRP 2013

Figure 8.50: Comparison of soil surface hazard at Beznau between PEGASOS 2004 and PRP 2013 for 100 Hz. (Remark: The PEGASOS 2004 plot is a non-smoothed reproduction of the original figure.)

8.3.3 Changes in Resulting Deaggregation

As an example, the deaggreagations for 5 Hz and 10^{-3} hazard for PEGASOS and PRP are compared in Figure 8.51. The shape of the deaggregations are similar, showing that this is a stable feature of the hazard.



Beznau, 2.1E-03, 5.0 Hz

Beznau, 1.0E-03, 5.0 Hz

(a) PEGASOS 2004, 0.15 g, 5 Hz.

(b) PRP 2013, 1E-03, 5 hz.

Figure 8.51: Comparison of rock hazard deaggregation between PEGASOS 2004 and PRP 2013. Note: In PEGASOS the deaggregation was performed in terms of spectral acceleration levels, while in PRP it was decided to do it per annual probability of exceedance level.

There is a significant change in the main contribution to hazard which is seen in the comparison of the deaggregation plots between PEGASOS (2004) and PRP (2013). The magnitude and distance deaggregations for PGA (100 Hz, respectively) and 1 Hz for comparable hazard levels for PEGASOS and PRP are shown in Figure 8.52. The distribution has shifted from the main contribution being centered at ≈M6.5 in PEGASOS down to ≈M5.5 in the PRP. The differences are mainly due to the revision of the SP2 models in terms of magnitude scaling for larger events, inclusion of $ZtoR$ scaling, and inclusion of magnitude-dependent standard deviations, but some of the differences are a result of using different distance metrics in PEGASOS and PRP. Changes in the SP1 models were not identified to have contributed to this change in deaggregation.

The reason for the shift in the deaggregation is that the PRP used a newer generation of GMPEs that were based on greately expanded dataset for larger magnitude event. The new GMPEs are mainly based on the distance R_{RUP} (like the NGA-West models and the Zhao et al.), compared to PEGASOS where the GMPEs where mainly based on R_{JB}. Furthermore, the new generation of GMPEs considers a depth term through the depth to the top of the rupture parameter. Previous generations of models were based on datasets which were concentrated on data with $M > 6$ and thus, there was not much data available to identify scaling with depth. The GMPEs using R_{JB} are, by definition, independent of depth.

The steepening of the magnitude scaling below M5.5 in the PRP small magnitude adjusted GMPEs is consistent with the magnitude scaling of the most recent ground motion models (e.g. NGA-West2) that include a greatly expanded dataset below $M5.0$. This feature is now observed at a global level and shows to be very robust. A more detailed investigation and discussion of the change in the deaggregation can be found in Abrahamson [2014] (TFI-TN-1287).

The probability to have an earthquake at very short distance is very low. Small magnitudes are more likely to occur in the short distance range, but as noted above the ground motion

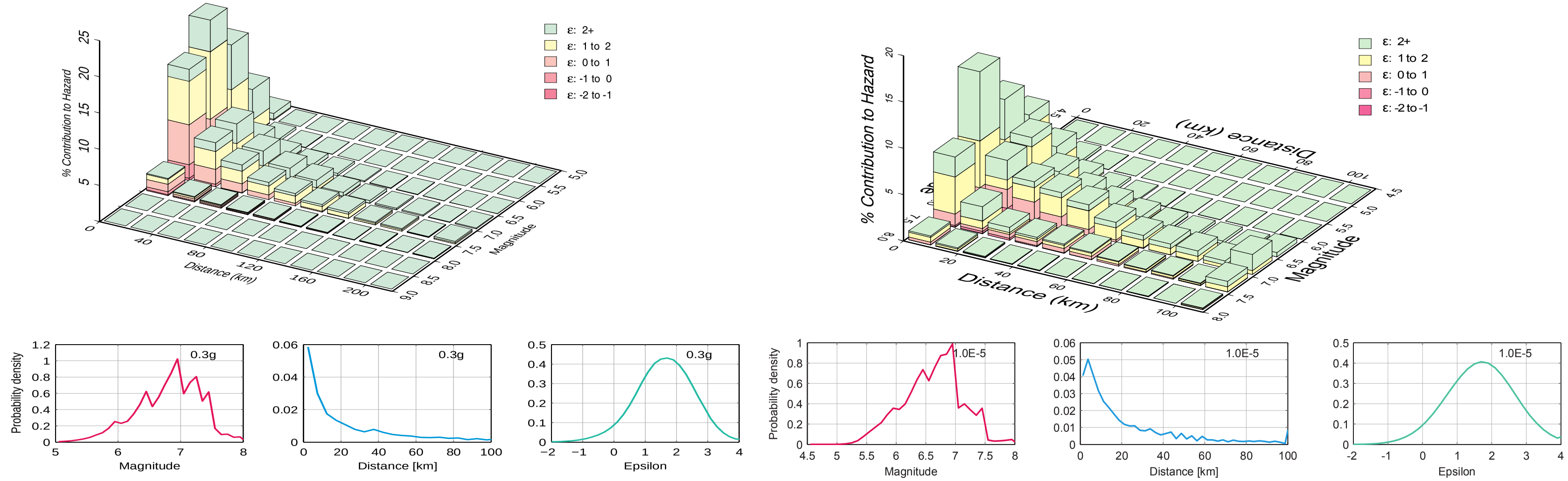


Fig. 2-5.5: Beznau, horizontal component, rock, surface, hazard deaggregation by magnitude, distance and epsilon for ground motion level 0.3 g, 0.5 Hz.

Figure 2.4.17: Beznau, horizontal component, rock, hazard deaggregation by magnitude, distance and epsilon for annual hazard level 1.0E-05, 0.5 Hz.

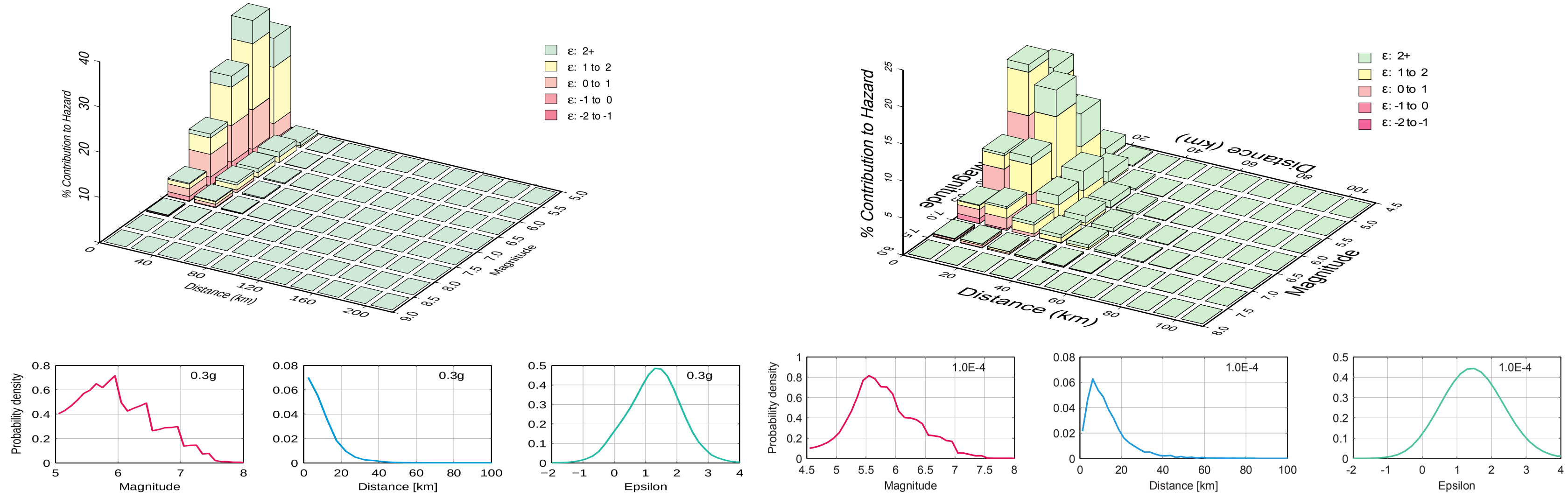


Fig. 2-5.6: Beznau, horizontal component, rock, surface, hazard deaggregation by magnitude, distance and epsilon for ground motion level 0.3 g, PGA.

Figure 2.4.16: Beznau, horizontal component, rock, hazard deaggregation by magnitude, distance and epsilon for annual hazard level 1.0E-04, 100 Hz.

Figure 8.52: Comparison of PEGASOS (left) and PRP (right) deaggregation plots for 0.5 Hz and 100 Hz. Note that in PEGASOS the deaggregation was performed based on a specified ground motion level, whereas in PRP it was done for annual probability of exceedance. The figures extracted from both report are nearly comparable considering this difference. Furthermore, the scale of the two horizontal axes (Mag. and Dist.) are different in this plot for PEGASOS and PRP.

decays rapidly for smaller magnitudes. Furthermore, as the newer GMPEs are dominated by the metric R_{RUP}, this also implies that the distance is increased compared to the equivalent R_{JB} distance. The net effect is a small contribution to hazard at short distances (<10 km).

8.3.4 Change in Uncertainties

Rock Uncertainties

The uncertainties of the PRP and PEGASOS rock hazard studies are compared in Figures 8.53 to 8.56 for the four sites (Beznau, Gösgen, Leibstadt, and Mühleberg). These figures show that the uncertainty for the rock hazard for PEGASOS is much larger than the uncertainty for the rock hazard PRP.

In these uncertainty plots, the uncertainty is shown in terms of the range of the ground motion at a given hazard level, rather than the range of hazard at a given ground motion. For the 5–95% fractile range, the PEGASOS values span factors of 5 to 10 for the four sites covering 1 Hz to 100 Hz. In contrast, the PRP uncertainties for the rock hazard span factors of 3 to 4.

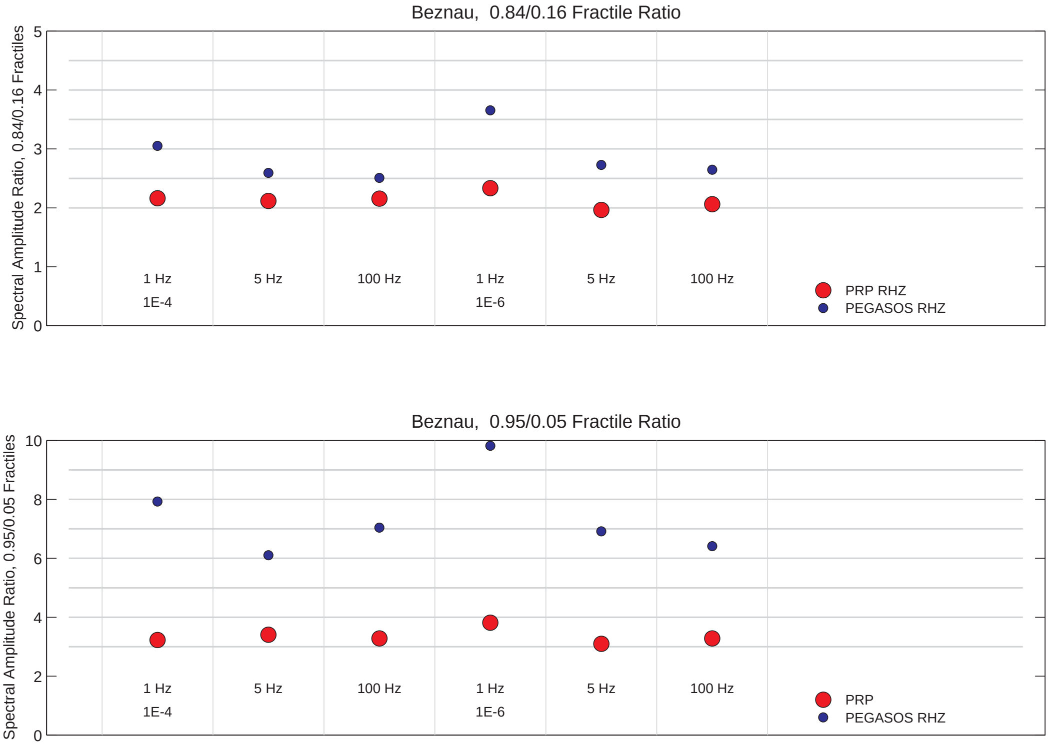


Figure 8.53: Beznau, rock comparison of change of range of results between PEGASOS 2004 and PRP 2013 for 1, 5 and 100 Hz. The upper plot shows the ratio of the 84%/16% fractile and the lower plot of the 95%/5% fractile. The small blue circles represent the PEGASOS 2004 hazard and the bigger red circles PRP 2013.

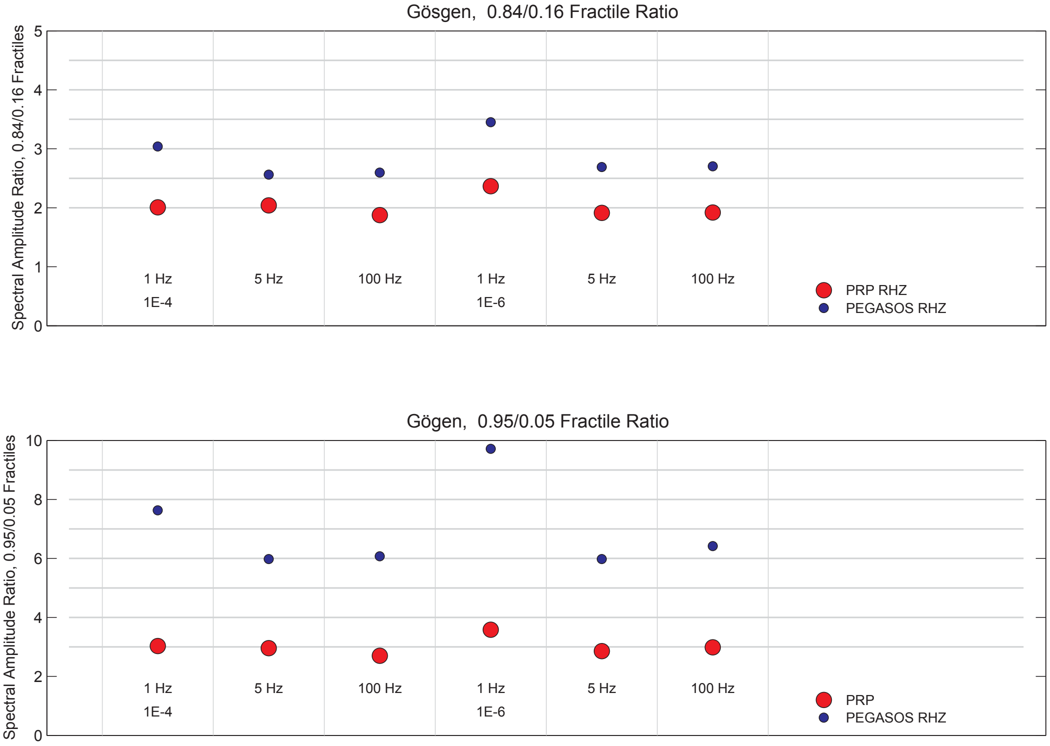


Figure 8.54: Gösgen, rock comparison of change of range of results between PEGASOS 2004 and PRP 2013 for 1, 5 and 100 Hz. The upper plot shows the ratio of the 84%/16% fractile and the lower plot of the 95%/5% fractile. The small blue circles represent the PEGASOS 2004 hazard and the bigger red circles PRP 2013.

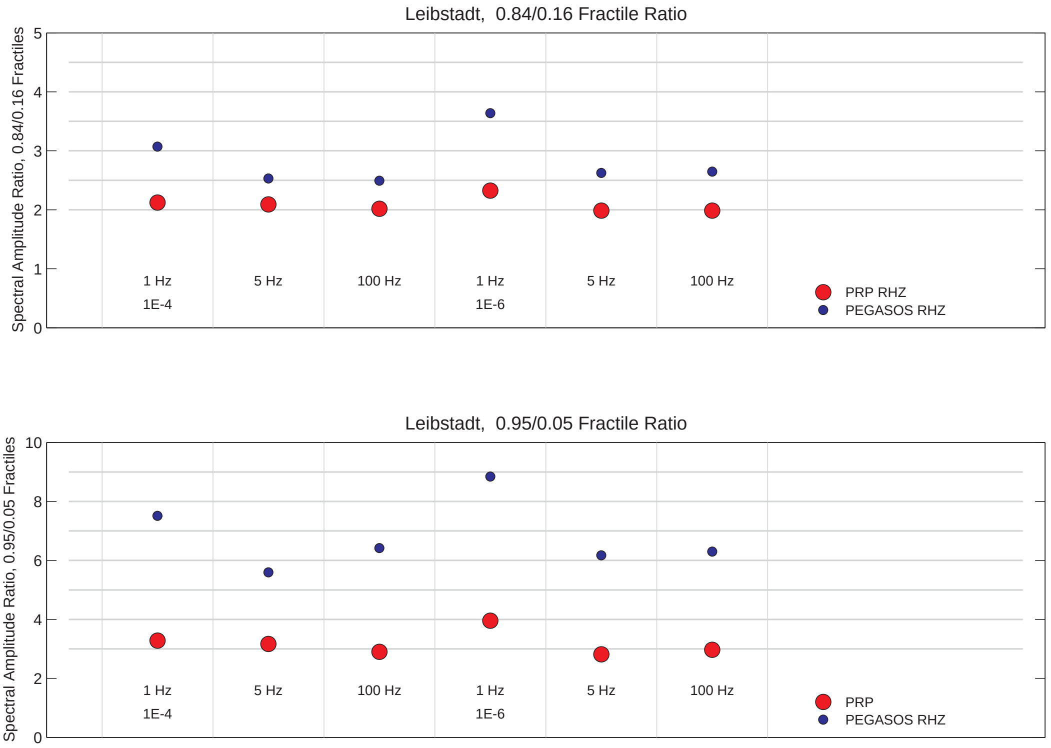


Figure 8.55: Leibstadt, rock comparison of change of range of results between PEGASOS 2004 and PRP 2013 for 1, 5 and 100 Hz. The upper plot shows the ratio of the 84%/16% fractile and the lower plot of the 95%/5% fractile. The small blue circles represent the PEGASOS 2004 hazard and the bigger red circles PRP 2013.

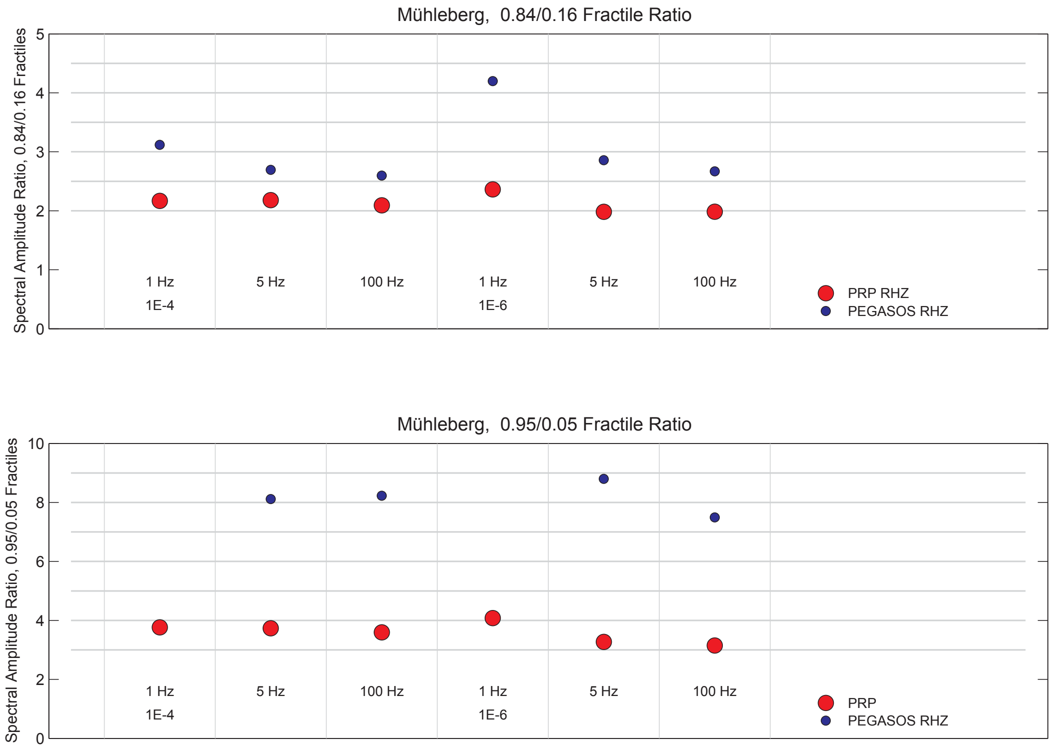
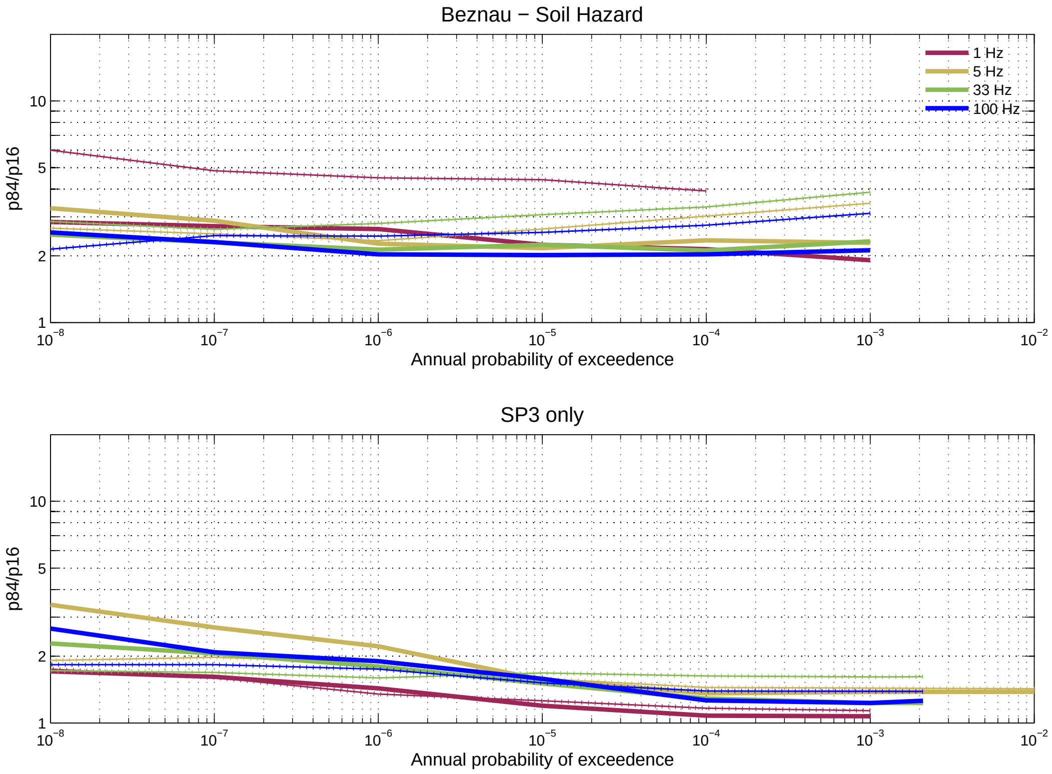


Figure 8.56: Mühleberg, rock comparison of change of range of results between PEGASOS 2004 and PRP 2013 for 1, 5 and 100 Hz. The upper plot shows the ratio of the 84%/16% fractile and the lower plot of the 95%/5% fractile. The small blue circles represent the PEGASOS 2004 hazard and the bigger red circles PRP 2013.

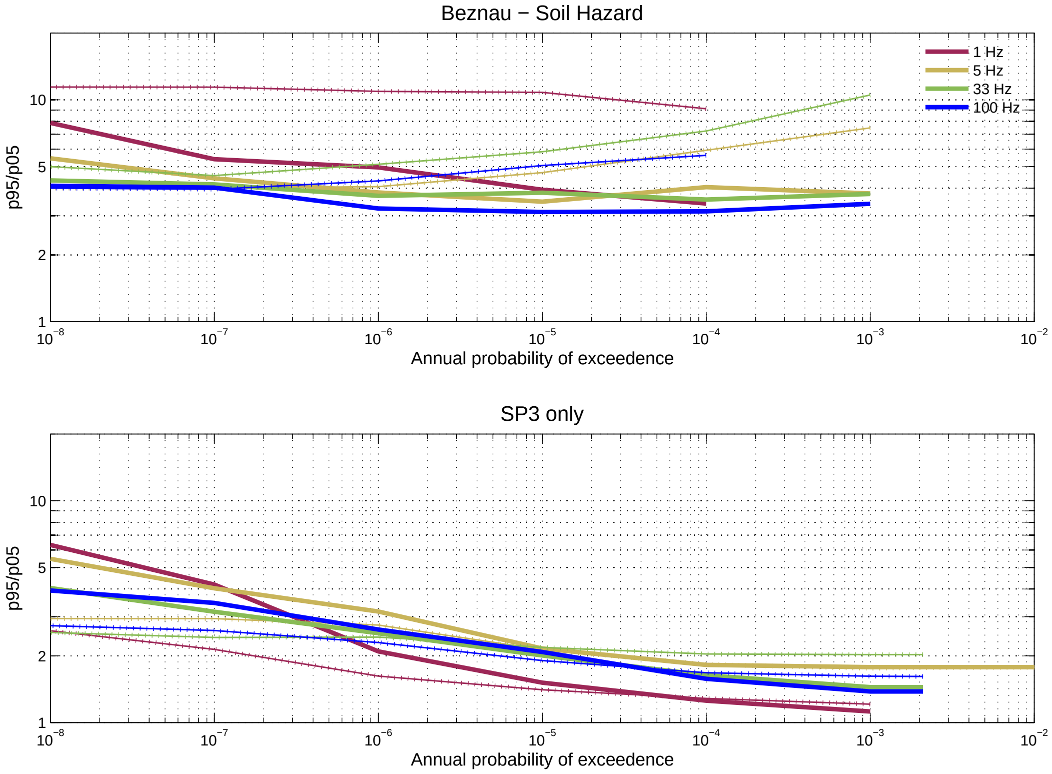
Soil Uncertainties

The uncertainties of the PRP and PEGASOS soil hazard studies are compared in Figures 8.57 to 8.60 for the four sites (Beznau, Gösgen, Leibstadt, and Mühleberg, respectively). These figures show the soil hazard uncertainty as a function of the hazard level and spectral frequency.

At annual soil hazard levels of 10^{-4} to 10^{-5}, the PEGASOS 95%/5% fractile range is larger than the 95%/5% range for the PRP (shown in the upper frame in part (b) of the figures). However, if only the SP3 contribution to the uncertainty is considered (shown in the lower frame) then the 95%/5% range shows much less of a reduction at hazard levels of 10^{-4} to 10^{-5}. At lower hazard levels (10^{-6} to 10^{-7}), the uncertainty due to the SP3 model is increased, reflecting the larger range of soil material properties considered by the SP3 experts during the PRP.

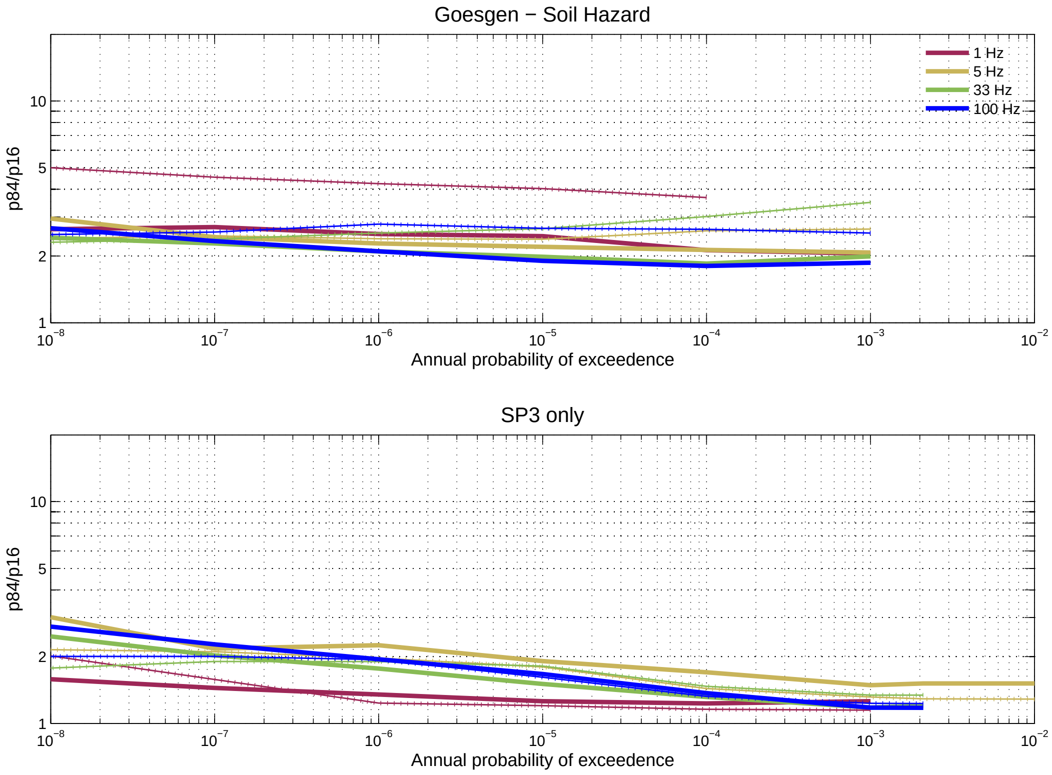


(a) Change in 16% and 84% fractile.

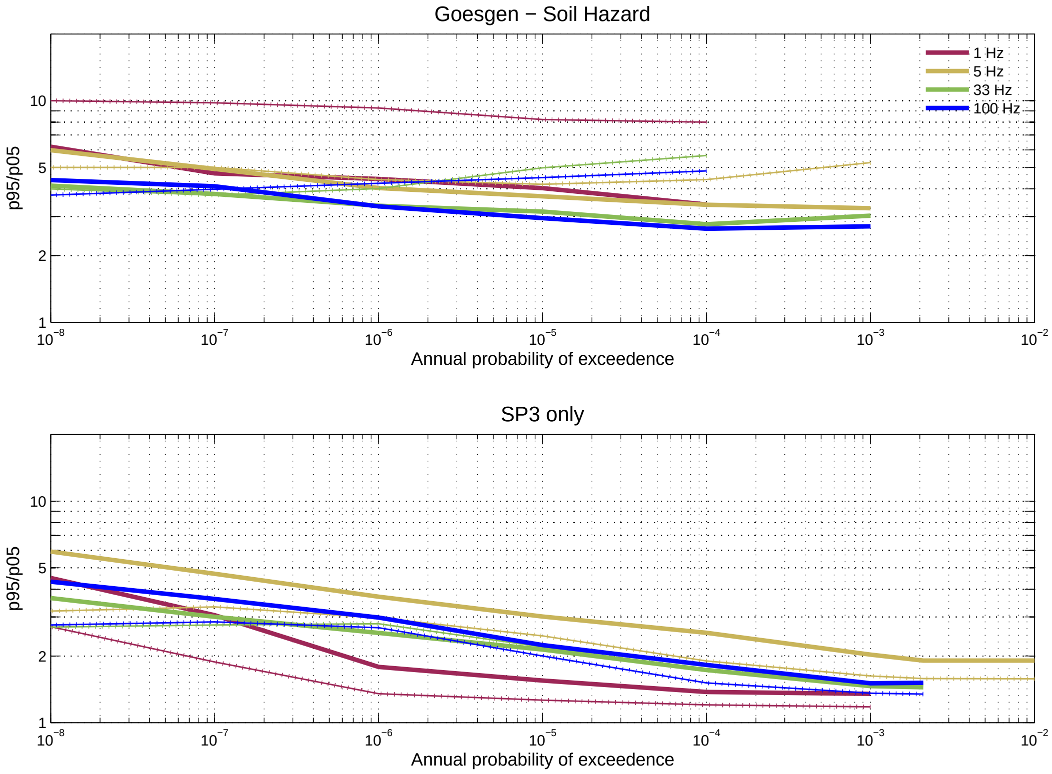


(b) Change in 5% and 95% fractile.

Figure 8.57: Beznau, soil comparison of change of range of results between PEGASOS 2004 and PRP 2013 for 1, 5, 33 and 100 Hz. The upper plot shows the total change and the lower plot the change due to SP3 only. The thin crossed line represents the ratio of the fractiles for PEGASOS 2004 and the thick line for PRP 2013.

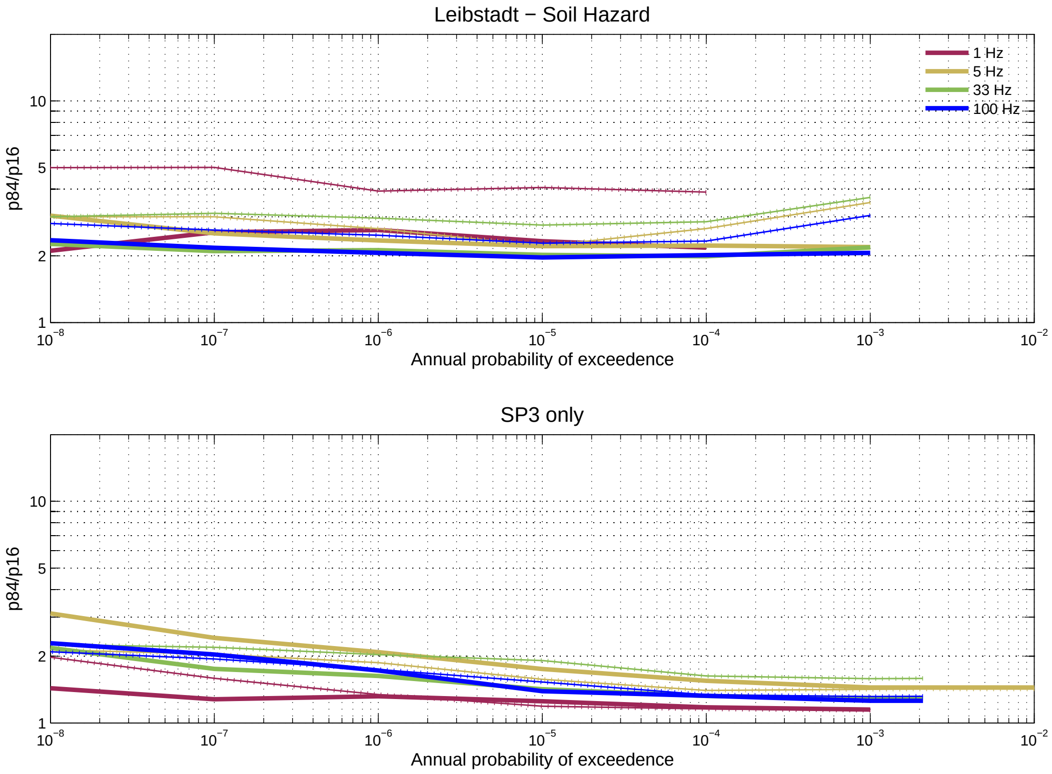


(a) Change in 16% and 84% fractile.



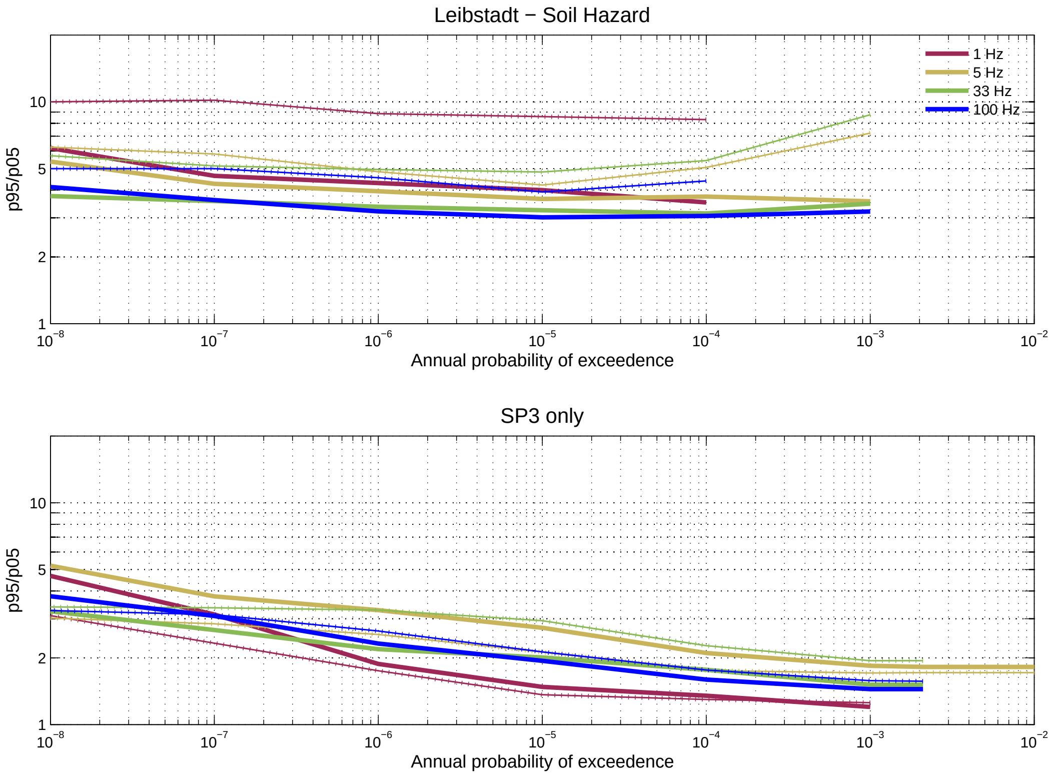
(b) Change in 5% and 95% fractile.

Figure 8.58: Gösgen, soil comparison of change of range of results between PEGASOS 2004 and PRP 2013 for 1, 5, 33 and 100 Hz. The upper plot shows the total change and the lower plot the change due to SP3 only. The thin crossed line represents the ratio of the fractiles for PEGASOS 2004 and the thick line for PRP 2013.


Leibstadt − Soil Hazard

SP3 only

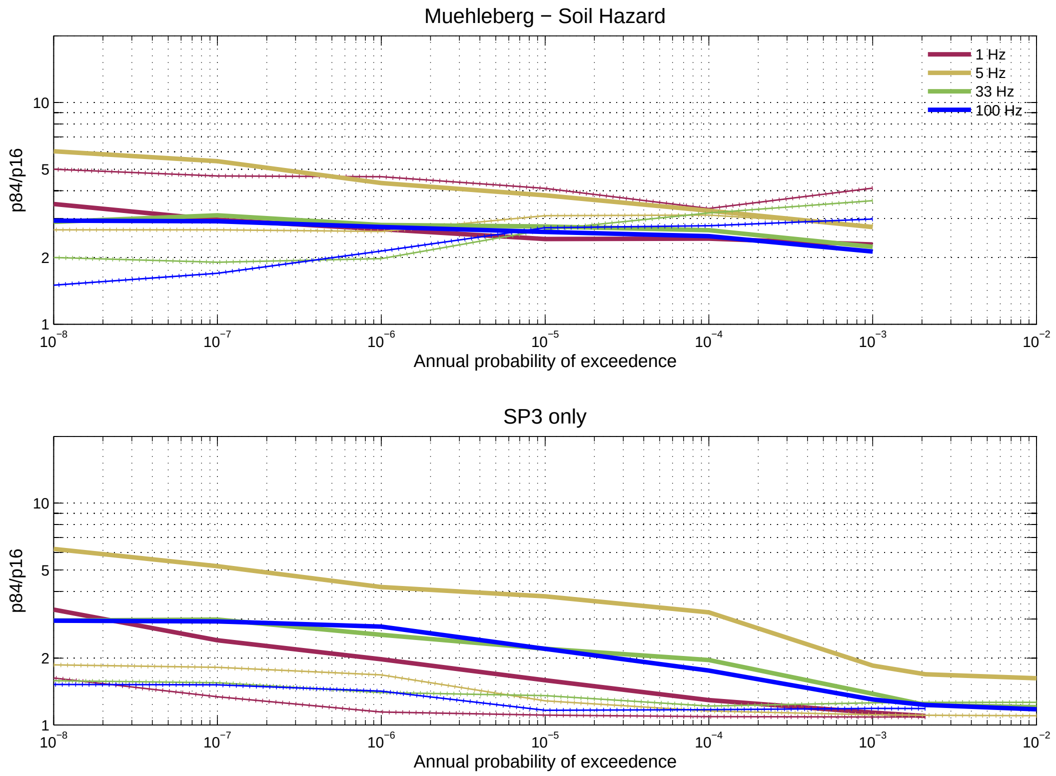
(a) Change in 16% and 84% fractile.


Leibstadt − Soil Hazard

SP3 only

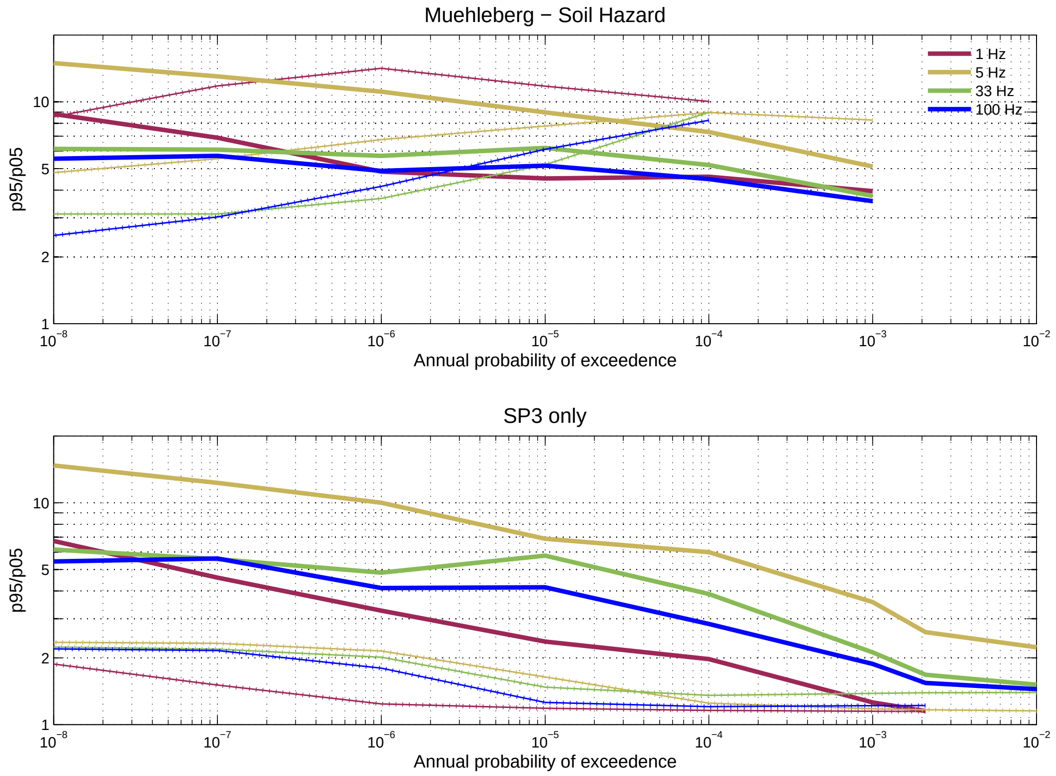
(b) Change in 5% and 95% fractile.

Figure 8.59: Leibstadt, soil comparison of change of range of results between PEGASOS 2004 and PRP 2013 for 1, 5, 33 and 100 Hz. The upper plot shows the total change and the lower plot the change due to SP3 only. The thin crossed line represents the ratio of the fractiles for PEGASOS 2004 and the thick line for PRP 2013.


Muehleberg − Soil Hazard

SP3 only

(a) Change in 16% and 84% fractile.


Muehleberg − Soil Hazard

SP3 only

(b) Change in 5% and 95% fractile.

Figure 8.60: Mühleberg, soil comparison of change of range of results between PEGASOS 2004 and PRP 2013 for 1, 5, 33 and 100 Hz. The upper plot shows the total change and the lower plot the change due to SP3 only. The thin crossed line represents the ratio of the fractiles for PEGASOS 2004 and the thick line for PRP 2013.

8.4 General Hazard Sensitivities and Robustness

The comparisons shown in the following are intended to demonstrate the stability of the results with respect to the different teams and individual experts, respectively. The distribution of the curves allows the robustness of the results to be evaluated. Within SP2 and SP3, each individual expert is supposed to capture the "Center, Body and Range", whereas in SP1 the CBR is represented by a group of experts within each of the four EG1 teams.

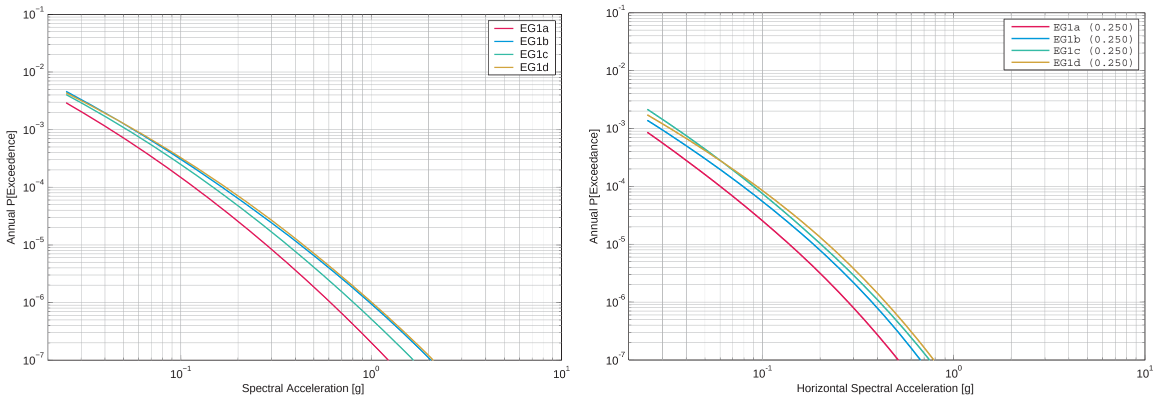
In addition, hazard sensitivity with respect to using a large maximum magnitude everywhere and using simplified site amplification factors based on simple site terms are shown in this section.

8.4.1 Group-to-Group or Expert-to-Expert Sensitivities

The expert-to-expert hazard sensitivities for SP1, SP2, and SP3 are shown for PEGASOS and PRP for the Beznau site for 1 Hz (Fig. 8.61 to 8.63) and 100 Hz (Fig. 8.64 to 8.66). The range of the mean hazard by expert provides an estimate of the stability of the hazard with respect to the selection and weighting of experts. Figures 8.61 and 8.64 compare the range of the mean hazards by SP1 group. Similarly, Figures 8.62 and 8.63 compare the range of the mean hazard by SP2 expert and by SP3 expert for 1 Hz, respectively.

Figure 8.61 shows that the SP1 expert-to-expert range of the mean hazard from PEGASOS is similar to the range from the PRP. Figure 8.62 shows that the SP2 expert-to-expert range is much smaller for the PRP than it was for PEGASOS. Figure 8.63 shows that the SP3 expert-to-expert range on the soil hazard is larger for the PRP than it was for PEGASOS. The same conclusions can be drawn at 100 Hz.

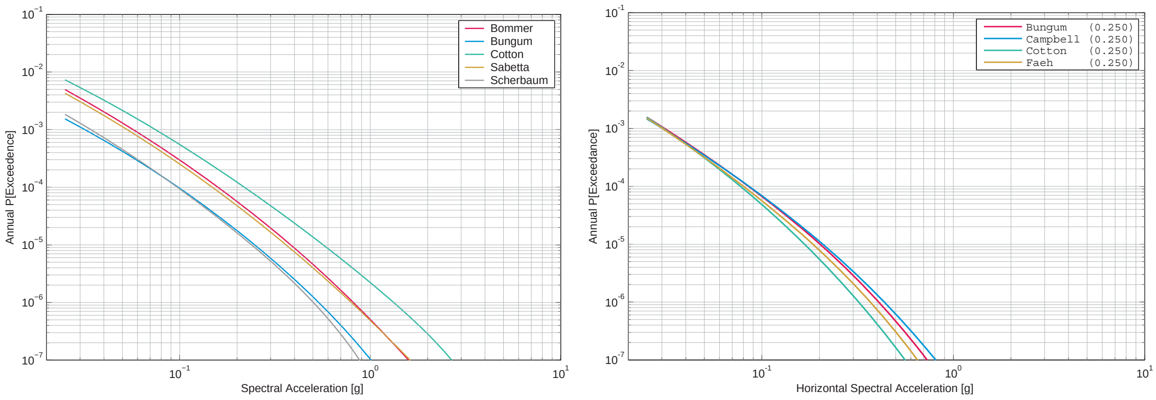
For rock hazard, the 10^{-5} UHS from PEGASOS and PRP are shown by SP2 expert (Fig. 8.67). The expert-to-expert range of the UHS for the PRP is much narrower than for PEGASOS. For soil hazard, the PEGASOS and PRP soil UHS at 10^{-5} are shown by SP3 expert in Figure 8.68. At high frequencies, the expert-to-expert range for PEGASOS is slightly larger than the PRP range.



(a) PEGASOS 2004

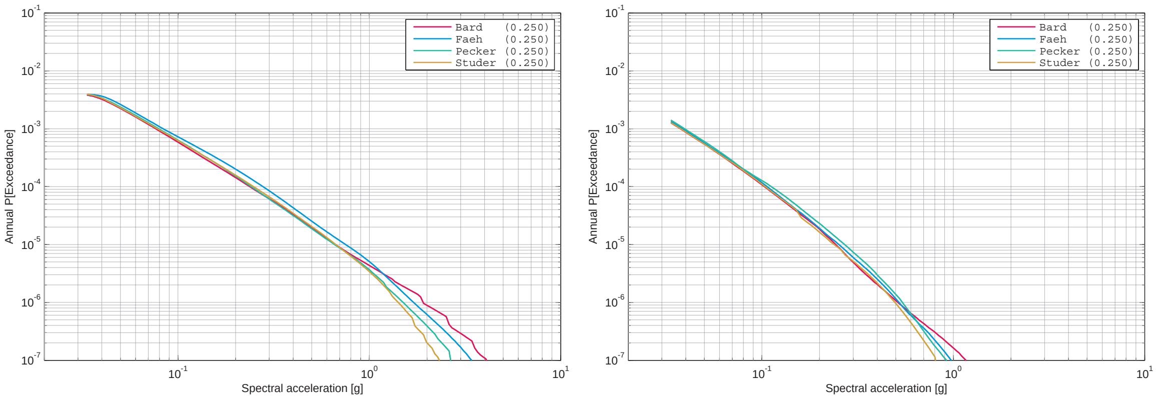
(b) PRP 2013

Figure 8.61: Comparison of the range of mean horizontal rock hazards for the SP1 expert teams between PEGASOS 2004 and PRP 2013. Beznau, 1 Hz.



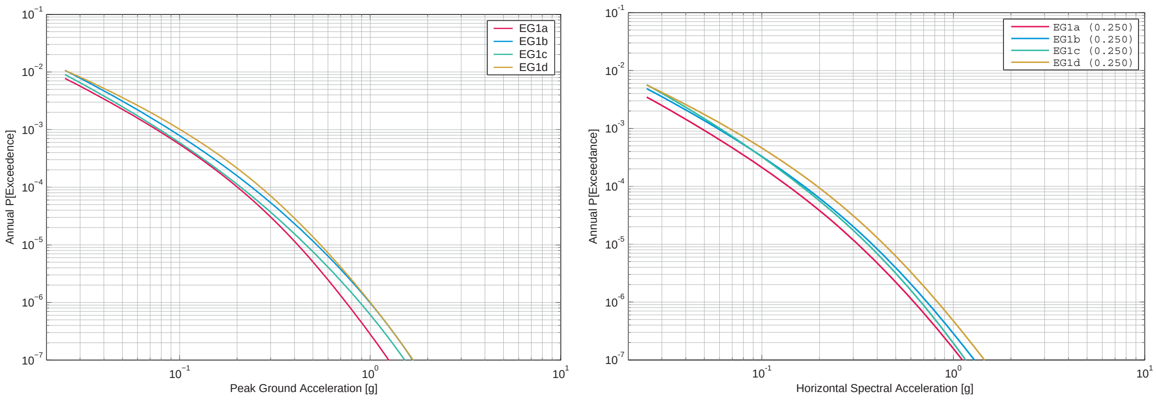
(a) PEGASOS 2004 (b) PRP 2013

Figure 8.62: Comparison of the range of mean horizontal rock hazards for the SP2 experts between PEGASOS 2004 and PRP 2013. Beznau, 1 Hz.



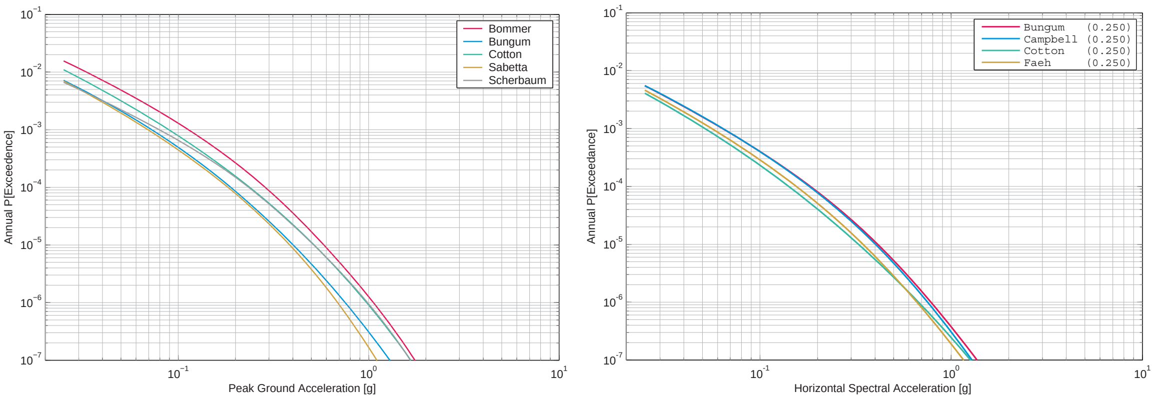
(a) PEGASOS 2004 (b) PRP 2013

Figure 8.63: Comparison of the range of mean horizontal soil hazards for the SP3 experts between PEGASOS 2004 and PRP 2013. Beznau, 1 Hz. (Remark: The PEGASOS 2004 plot is a non-smoothed reproduction of the original figure.)



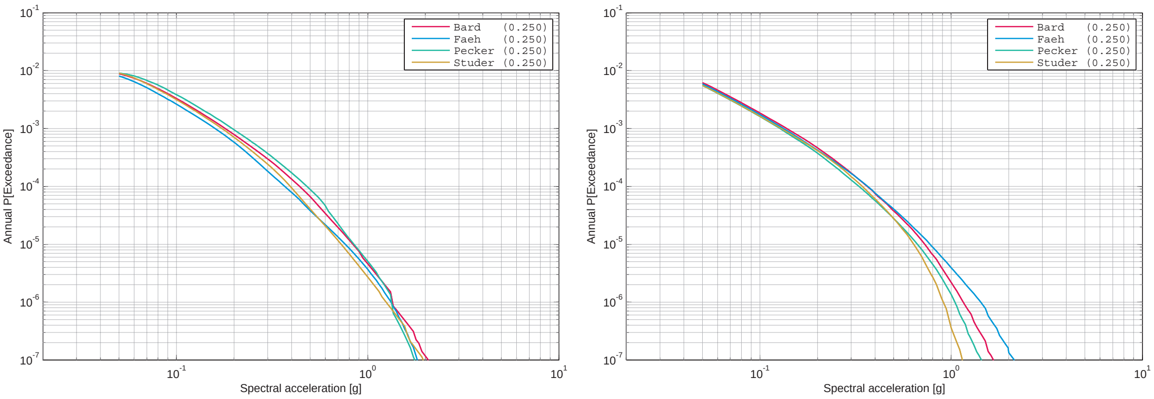
(a) PEGASOS 2004 (b) PRP 2013

Figure 8.64: Comparison of the range of mean horizontal rock hazards for the SP1 expert teams between PEGASOS 2004 and PRP 2013. Beznau, 100 Hz.



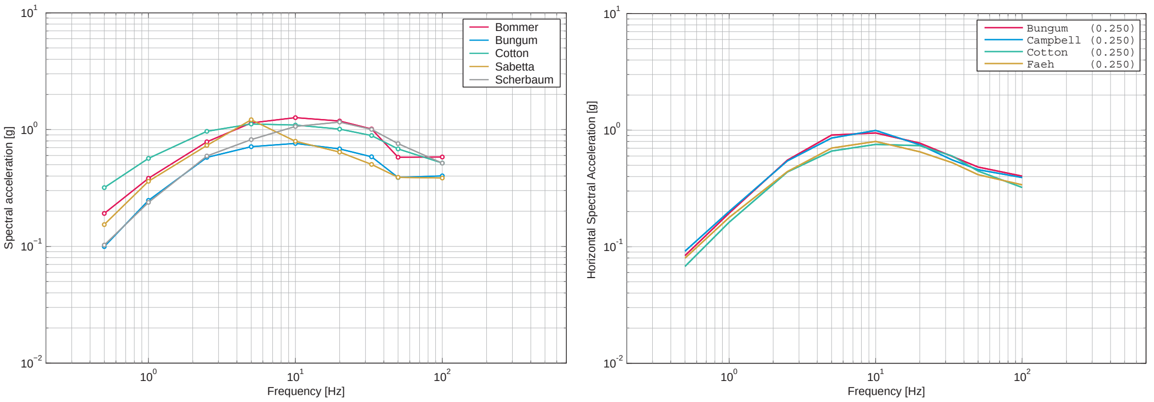
(a) PEGASOS 2004 (b) PRP 2013

Figure 8.65: Comparison of the range of mean horizontal rock hazards for the SP2 experts between PEGASOS 2004 and PRP 2013. Beznau, 100 Hz.



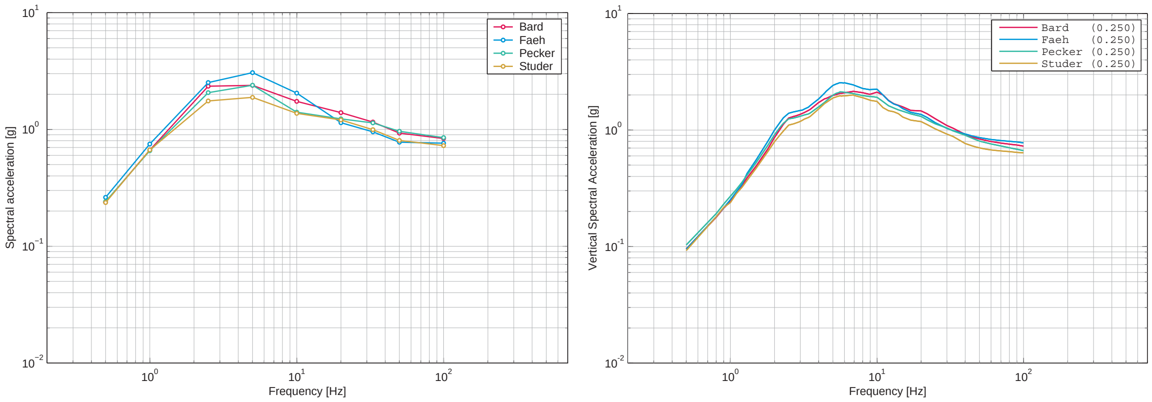
(a) PEGASOS 2004 (b) PRP 2013

Figure 8.66: Comparison of the range of mean horizontal soil hazards for the SP3 experts between PEGASOS 2004 and PRP 2013. Beznau, 100 Hz. (Remark: The PEGASOS 2004 plot is a non-smoothed reproduction of the original figure.)



(a) PEGASOS 2004 (b) PRP 2013

Figure 8.67: Comparison of the range of mean horizontal rock UHS for the SP2 experts between PEGASOS 2004 and PRP 2013. Beznau, annual probability of exceedance of 1E-05 and 5% damping.



(a) PEGASOS 2004

(b) PRP 2013

Figure 8.68: Comparison of the range of mean horizontal soil UHS for the SP3 experts between PEGASOS 2004 and PRP 2013. Beznau, annual probability of exceedance of 1E-05 and 5% damping. Note: The shape of the PRP soil UHS is more detailed as the hazard was evaluated for more frequency points compared to PEGASOS.

The mean, 5%, and 95% fractals for the rock hazard are shown by SP2 expert in Figure 8.69 for 1 Hz and 100 Hz. These figures show that the expert-to-expert uncertainty range is much smaller than the within-expert uncertainty range. The consistency of the center and range of the SP2 expert models demonstrates the stability of the rock hazard in terms of the SP2 expert evaluations.

8.4.2 Maximum Magnitude

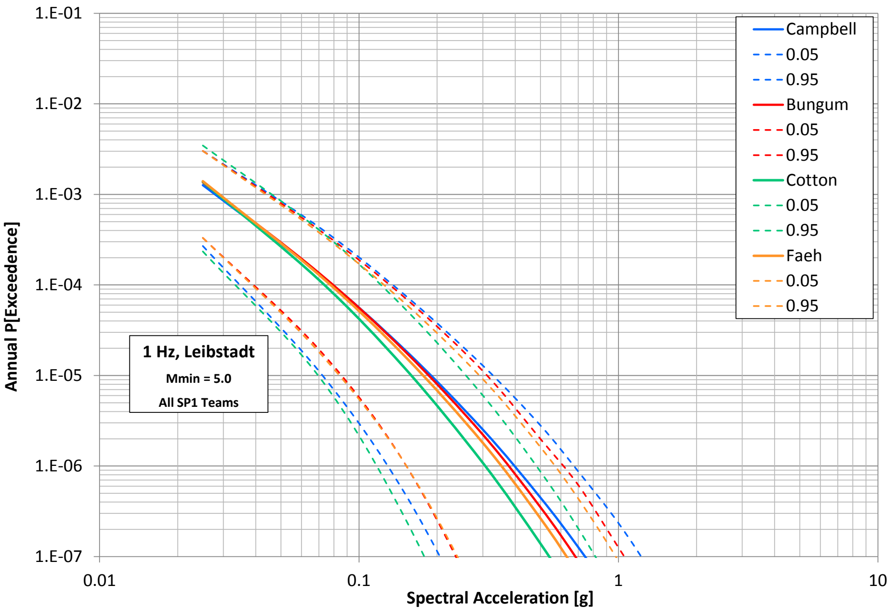
Within the PRP, a sensitivity calculation [Roth 2013] (TP4-TN-1280) was performed in order to assess the effect of assuming higher maximum magnitudes in the source zones considered in the project. For this sensitivity, the original M_{max} distributions defined by the SP1 experts were replaced by a constant value of M_{max}=8. The effect of this assumption is shown for the example of the Beznau site in Figure 8.70.

As can be seen, the difference in hazard, if M_{max}=8 is assumed, is large and thus, the conclusion needs to be that greater attention should be paid to the evaluation of M_{max} within SP1.

8.4.3 Comparison of Combined SP2-SP3 Approach with Evaluation of GMPEs on Soil

The main motivation in the PRP to make use of the approach based on separate rock and soil assessments was to allow for site-specific soil amplification factors to be use. This also allows for a method to reduce uncertainties by investigating/characterizing the site with more detail and effort (for example the collection of data from new site investigations at each NPP). In this sensitivity, the soil hazard is computed using the generic site terms built in the GMPEs rather than the site-specific amplification factors from analytical model calculations.

Figure 8.71 compares the mean soil hazard at the surface for Beznau computed within PRP with the soil hazard obtained when evaluating the GMPEs, with the V_{S30} at the site (see also Table 5.3). For this sensitivity, only the SP1 EG1c source characterization model was used.



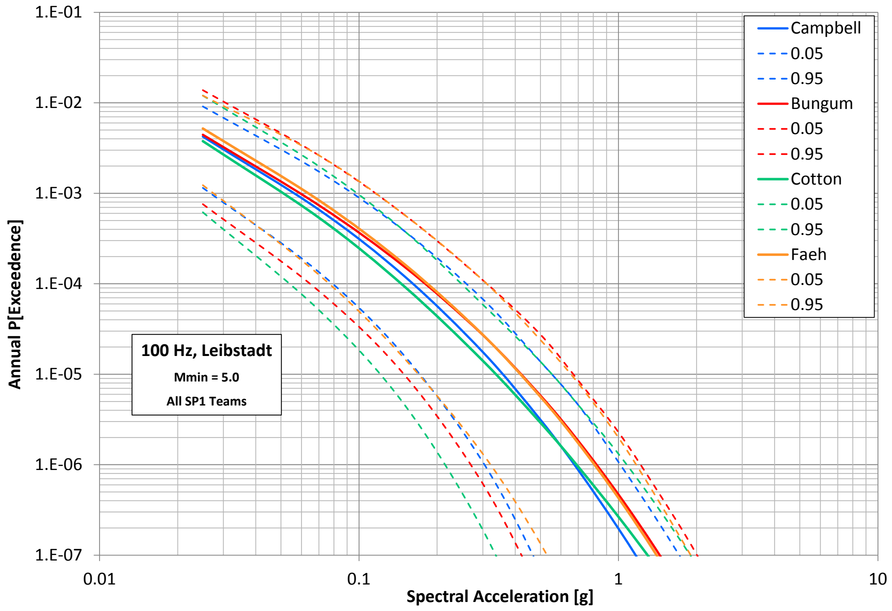


Figure 8.69: Comparison of mean and range of SP2 models. Leibstadt, 1 Hz and 100 Hz.

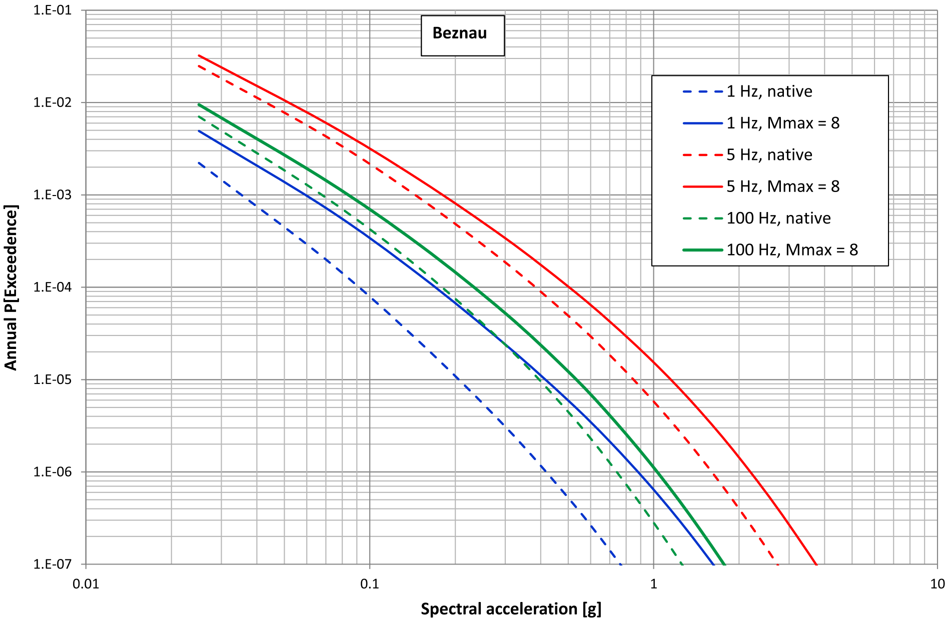


Figure 8.70: Comparison for Beznau between the mean hazard obtained for the original EG1c model (dashed curves) and the results obtained using a modified version of the model with a single value of M_{max}=8.0 in all source zones (solid curves). The entire SP2 model is used for the sensitivity (TP4-TN-1280).

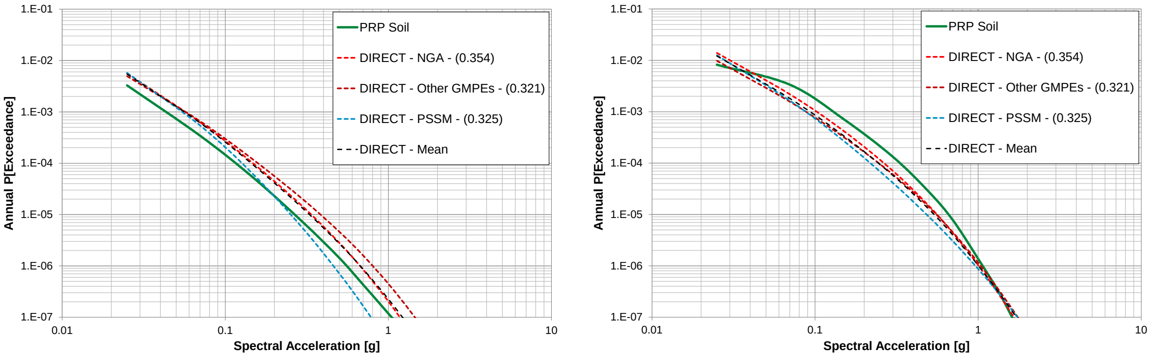
Comparisons for the other sites and other frequencies are documented in the technical note TP4-SUP-1107.

For this comparison, the GMPEs with V_{S30} as a site parameter were used directly used. For the GMPEs which are only based on site categories, the rock category was used. In both cases no $V_S - \kappa$ corrections were applied. The PSSMs allow for a site term by consideration of the V_S-profile using the quarter-wavelength method and κ. The values of V_{S30} and κ_0 used are listed in Table 8.1. The V_{S30} values represent the mean of the candidate SP3 profiles at each site. The target κ_0 values are based on the log-lin $V_{S30} - \kappa$ relationship of Edwards and Fäh [2013] to be consistent with the PSSM approach.

Table 8.1: Surface V_{S30} and target κ_0 used for the comparison analysis (TP4-SUP-1107).

Site	V_{S30} [m/s]	κ_0 [s]
Beznau	516	0.0233
Gösgen	467	0.0240
Leibstadt	526	0.0231
Mühleberg	490	0.0236

As can be seen from Figure 8.71 the two resulting mean hazard curves are different. To show how the different types of models contribute to the differences, the mean hazard (always representing the mean over all four SP2 experts) from the direct evaluation of the GMPEs with surface V_{S30} for soil is split into three categories: GMPEs with V_{S30} as a parameter,



(a) Comparison for 1 Hz. (b) Comparison for 100 Hz.

Figure 8.71: Comparison of the mean soil surface hazard at Beznau (based only on EG1c) for the case of the combined SP2-SP3 approach and the evaluation of the GMPEs with the surface V_{S30} for 1 Hz and 100 Hz (TP4-SUP-1107).

GMPEs based on site category, and the PSSMs. At 1 Hz, the direct method lead to higher hazard because the soil profiles for Switzerland are typically not as deep as the soil profiles for the data used to derive the empirical GMPEs (e.g. California). The 1 Hz hazard curve for the PSSM is similar to the hazard curve for the PRP because the PSSM uses the generic Swiss profile to correct for the site condition. At 100 Hz, the PRP models lead to higher hazard because the GMPEs used in the direct method are not adjusted for κ. The hazard from the PSSM is similar to the hazard from the direct method, but that may reflect the lower stress-drops used for the PSSM.

Chapter 9

Additional Ground Motion Parameters for Structural Evaluations

According to the project plan the PRP output specification addressed some additional parameters to be evaluated if necessary on request of the NPPs. As no logic tree for those parameters and/or models have been developed by the PRP experts, the additional parameters discussed in this chapter are not consistent with a SSHAC Level 4 approach evaluation. However, those topics were discussed at the workshops with the experts and their recommendations were followed. This chapter provides an overview of the suite of alternatives which may be used for further assessments, but does not recommend a specific model.

9.1 Definition of Horizontal Components of Motion and PGA

In the PRP, the hazard is computed for the geometric mean of the two horizontal components ($SA_{geom.mean}(f) = \sqrt{SA_{H1}(f) \cdot SA_{H2}(f)}$) and for the vertical component. The SP2 experts did not directly provide an estimate for the aleatory variability in the geometric mean for directionality for the component-to-component variability. Beyer and Bommer [2006] have evaluated several definitions of horizontal components and their models can be used if the NPPs require that the results be converted to another horizontal component definition.

The spectral values for the individual horizontal components can be developed from the geometric mean. There are two approaches that can be used: estimating the minimum and maximum horizontal component in any direction and estimating the average ratio between the two components for a random orientation. The ratio of the largest component to the median horizontal component has been estimated by several studies. The studies use slightly different definitions of the average horizontal component, but the ratios are not sensitive to these differences. Figure 9.1 compares some of the scale factors obtained [Shahi and Baker 2013]. They range from about 1.2 at short periods to about 1.3 at long periods. The randomly oriented spectral acceleration can be described by the standard deviation of the spectral values over random orientations. The standard deviations from the evaluation of Shahi and Baker [2013] are listed in Table 9.1. As an example, at 5 Hz, the standard deviation is 0.14 natural log units. A random horizontal component can be developed from this distribution with the restriction that it does not exceed the maximum shown in Figure 9.1.

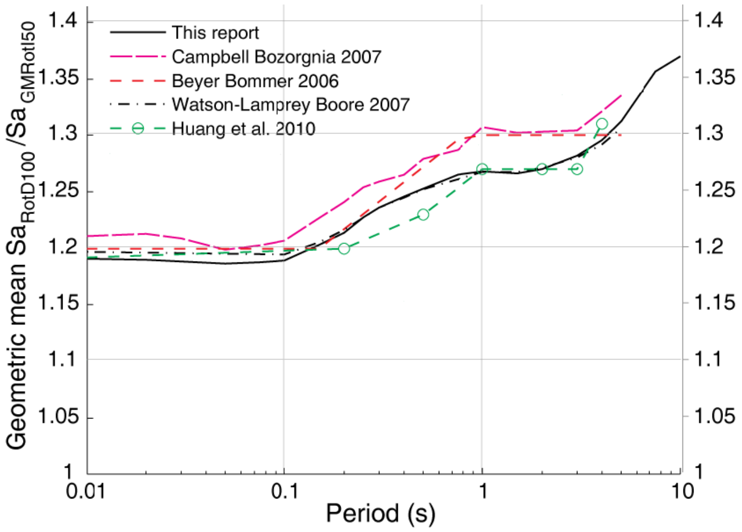


Figure 9.1: Comparison of various geometric mean $Sa_{RotD100}/Sa_{RotD50}$ ratios (modified from Shahi and Baker [2013]).

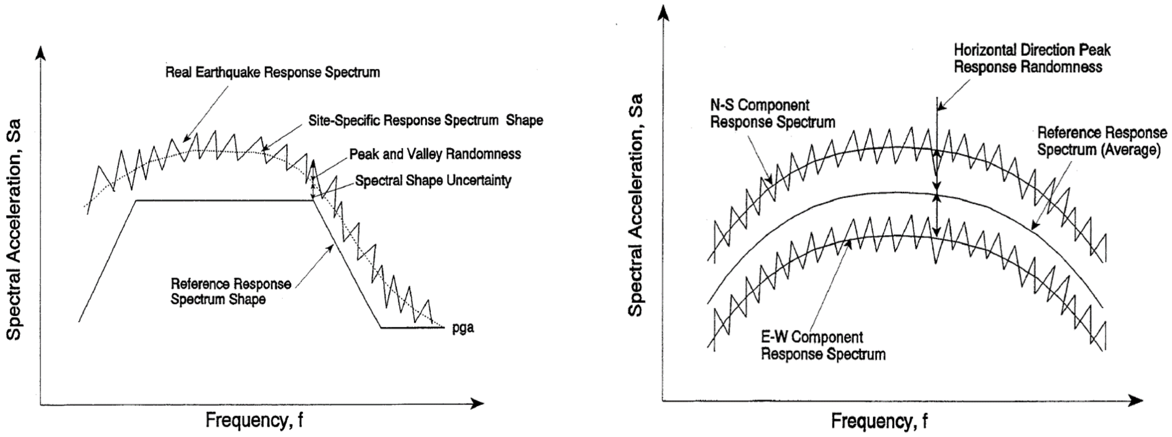
Table 9.1: Standard deviations (in LN units) of randomly oriented spectral accelerations. Based on geometric mean values of Sa_{ϕ}/Sa_{RotD50} at various angles between 0 and 90° [Shahi and Baker 2013].

Period [s]	0.01	0.02	0.03	0.05	0.07	0.1	0.15	0.2	0.25	0.3	0.4	0.5	0.75	1	1.5	2	3	4	5	7.5	10
Std. Dev.	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.14	0.15	0.16	0.17	0.17	0.19	0.19	0.19	0.19	0.20	0.22	0.24	0.29	0.31

9.1.1 Peak-and-Valley Variability

There is uncertainty in the earthquake signature which results in a variability of the response spectrum shape. In order to account for variability between the reference response spectrum shape and real earthquakes which could potentially occur, a spectral shape uncertainty, β_U, has sometimes been specified to be included in the structure fragility. In general, real earthquakes have response spectra different from an idealized smooth reference spectra. Meaning that peaks and valleys in real response spectra for a future earthquake response spectrum, with the same ground motion parameter, would have spectral ordinates which were either higher or lower than the smooth spectrum. This randomness in the peak and valley variability is characterized by β_R and in the past was also specified to be included in the structure fragility. In the following the discussion will only focus on the randomness of the ground motion.

The probabilistic seismic hazard analyses presented here includes the response spectral peak and valley variability as part of the overall aleatory variability. The peak and valley variability of the geometrical mean horizontal component (σ_{PT}, named also β_{PV} in Reed and Kennedy [1994], see Fig. 9.2(a)), which is classically represented by the UHS, is already captured in the standard deviation of the GMPEs used for the hazard assessment. Furthermore, there is also the variability of the two horizontal components about the geometric mean of the two components (the so called "component-to-component" or "horizontal directional component" variability; σ_C, also named β_{dir} in Reed and Kennedy [1994], see Fig. 9.2(b)). This portion of variability is not captured in the GMPEs and thus, is not included in the PSHA results. The latter should be considered to correct the response variability in the framework of structural fragility, as e.g. done in the PRP with the two spectrally matched horizontal components of the time histories. Publications on the subject often use the expression peak and variability for both of these two sources of variability (σ_{PT} and σ_C).



(a) Example horizontal ground response spectra demonstrating peak and valley randomness and spectral shape uncertainty.

(b) Example horizontal ground response spectra demonstrating horizontal component peak response randomness.

Figure 9.2: Fig. 3-1 and 3-2 extracted from EPRI TR-103959 [Reed and Kennedy 1994].

At any annual probability of exceedance, the resulting UHS, which represents the geometrical mean of the two horizontal, on rock and soil (surface and sub-surface levels) already includes the effect of the response spectra peak and valley variability β_{PV} (named β_{rs} in Attachment A of Reed and Kennedy [1994]; logarithmic standard deviation of the geometric mean pseudo-spectral acceleration about the UHS). This statement is true irrespective of whether the UHS is defined at the mean, median, 95%, 84%, 16% or 5% fractiles, because the aleatory variability (including β_{rs}) similarly affects the slope of each of these fractile hazard curves. The difference in amplitude of these various non-exceedance probability curves is due to the epistemic uncertainty. Thus, the current recommendation is to not include peak and valley variability or shape uncertainty in fragility estimates based on the UHS since this would result in double counting of the variability in a PSHA. This understanding has also been assessed and discussed in Kennedy [2009].

When time history based analyses are performed, the component-to-component variability of the two horizontal directions β_{dir} is implicitly captured when real records are used, as the difference in the two horizontal components of the time histories is maintained. In case time histories compatible with the UHS are generated, this component-to-component variability needs to be considered in order to be consistent with the approach. An evaluation of the Shahi and Baker [2013] database has shown that the component-to-component variability (β_{dir}) is on average about 0.15 (ln units) in the frequency range between 0.5 and 100 Hz; Kennedy [2009] in its Table 3-2 estimates this random variability to be between 0.12 and 0.14 (ln units). This horizontal directional component variability represents the random variability of a single horizontal direction component about the horizontal geometric mean. Based on recent work of Watson-Lamprey and Boore [2007] the estimate for the random variability β_{dir}

lies in the range of 0.16 to 0.21 instead of 0.12 to 0.14.

In the update to EPRI TR-103959 the random variability of the vertical component response is provided with β_R=0.22 to 0.28. The vertical component response variability β_{VC} is intended to represent the random variability of the vertical to horizontal geometric mean ratio. This variability is controversial and it has been recommended that it should not be included in the fragility evaluation since it double counts variabilities already included in the vertical hazard estimate. However, most fragility analysts believe that it should be included since the seismic risk is computed in terms of the horizontal geometric mean. Note: The uncertainty β_U portion of the vertical component response variability shown in Table 3-2 of EPRI TR-103959 is no longer included since nobody still arbitrarily sets the vertical component at 2/3 of the horizontal.

In the fragility analysis methodology, the demand analysis is either performed by multiple three-component time-history analyses to estimate both the median and variability of the demand, or by response spectra analysis to estimate the median demand and then estimate the overall demand variability by an SRSS combination of parameter variabilities. In the following the structural uncertainty and variability part of β_U and β_R are not considered, as here we focus on the consistency between the ground motion hazard and the records applied in the structural response evaluation.

The preferred approach should always be to directly put the component-to-component variability in the two horizontal time history components, as it was done in the PRP SP5. Nevertheless, in practice four cases need to be distinguished:

- Response spectra method with the UHS: In the most simplistic case when directly the horizontal and vertical UHS are used as input for the structural analysis the peak and valley variability $\beta_{PV}(\beta_{rs})$ is zero, as the geometric mean of the two horizontal components correspond to the horizontal UHS. The component-to-component variability β_{dir} must be included in this approach to evaluate the composite variability.
- Response spectra method with scenario spectra: In the response spectra method, the response spectral peak and valley variability $\beta_{PV}(\beta_{rs})$ is specifically defined as one of the parameter variabilities. Therefore, it is easy to determine the β_{rs} value to be removed in the fragility evaluation. The response spectra method usually uses the geometrical mean of the two horizontal components, so that the component-to-component variability β_{dir} must be included in this approach to evaluate the composite variability.
- Multiple three-component time-history analysis method with event response spectra matched individually to the UHS: When the multiple three-component time-history analysis method is used to determine the demand median and variability, it is more difficult to separate out the $\beta_{PV}(\beta_{rs})$ included in the analysis. The two horizontal component time-histories used as input are selected and conditioned so as to produce median spectral accelerations at all natural frequencies in the frequency range of interest (generally 2 to 20 Hz) that closely match the target Uniform Hazard Spectrum (UHS). When the geometric mean of the two horizontal components of the individual records are strongly conditioned to closely match the target UHS, so that variability from the UHS shape is small, then β_{rs} is nearly zero and thus, can be ignored. The component-to-component variability β_{dir} must be included in this approach to evaluate the composite

variability. Both of these constraints have been used in the framework of the PRP SP5 for the time histories spectrally matched to the UHS (for the so called "classical approach", see Chpt.7 from Volume 6) and thus, are ready to use for engineering application without any further adjustment.

- Multiple three-comoponent time-history analysis method with the median response spectra over all selected time histories matched to the UHS: In this case, the spectral accelerations at each frequency do not tightly match the target UHS for each individual record. For the suite of individual records, it is then necessary to compute the $\beta_{PV}(\beta_{rs})$ at each natural frequency and average these β_{rs} values over the frequency range of interest in order to remove it when using the composite (mean) variability (see Figure 9.3). As unconditioned, individual real records are used in this approach, β_{dir} is captured, as the difference in the two horizontal components of the time histories is maintained and thus, does not need to be added back in.

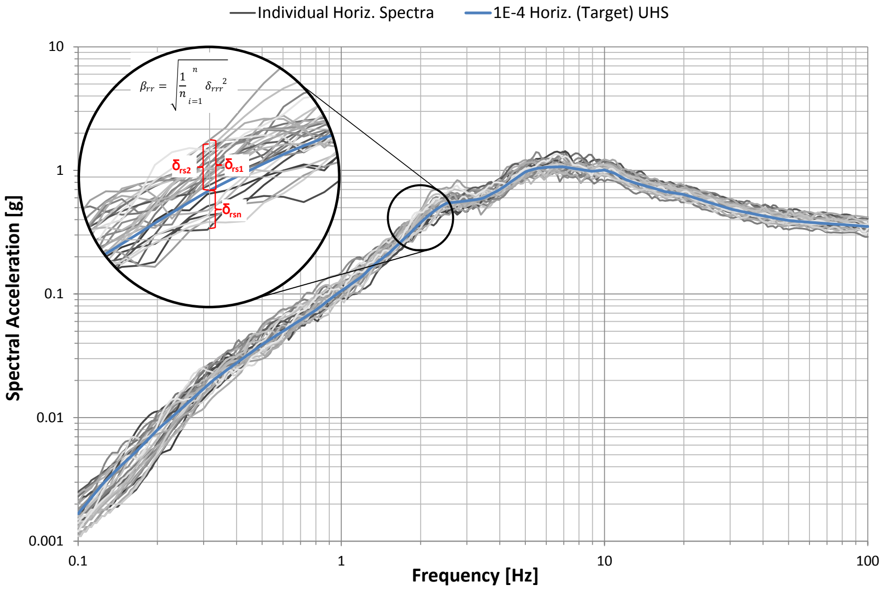


Figure 9.3: Schematic sketch of the evaluation of $\beta_{rs}(\beta_{PV})$ at each natural frequency when using the multiple three-component time-history analysis method with the median response spectra over all selected time histories matched to the UHS.

9.1.2 PGA - Peak Ground Acceleration

Within PEGASOS and the PRP, the spectral acceleration value at 100 Hz is often used as an estimate for the peak ground acceleration (PGA). While this is reasonable for soil sites and soft-rock sites, it may not be appropriate for hard-rock sites. The frequency at which the response spectrum goes flat (equal to the ZPGA) depends on κ (see Figure 4.4(b)). For κ values of 0.02 s or greater, the 100 Hz spectral acceleration is equal to the PGA, but for smaller κ values, the spectrum may not be flat until frequencies of 300 Hz, or more.

Some of the candidate GMPEs used in the PRP did not provide an estimate for the spectral acceleration at 100 Hz. In those cases, the PGA was used as the 100 Hz estimate. This is a reasonable assumption for these GMPEs as they are for κ values greater than 0.02 s.

After the κ correction is applied to the GMPEs, this equivalence of PGA and 100 Hz spectral acceleration may not apply. In the PRP, the SP4 calculations are performed for 100 Hz spectral acceleration, not PGA. For the hard rock conditions, the PGA will be lower than the 100 Hz spectral acceleration as seen in Figure 4.4(b). The average scale factor of the NGA-West2 dataset is 0.988. The site-specific scale factors evaluated within PRP from 100 Hz spectral acceleration to PGA are listed in Table 9.2.

Table 9.2: Approximate reduction factors for converting 100 Hz spectral acceleration to PGA. The three first values correspond to minimum/mean/maximum averaged over all scenarios. As a reference, the last two columns provide reduction factors for APE of 10^{-4}.

Site	Horizontal	Vertical	Horiz. Mean for 10^{-4}	Vert. Mean for 10^{-4}
KKB	0.971 / 0.985 / 0.993	0.976 / 0.984 / 0.992	0.988	0.983
KKG	0.959 / 0.981 / 0.993	0.969 / 0.981 / 0.991	0.987	0.979
KKL	0.969 / 0.985 / 0.993	0.974 / 0.984 / 0.992	0.988	0.983
KKM	0.983 / 0.989 / 0.994	0.979 / 0.986 / 0.992	0.990	0.986

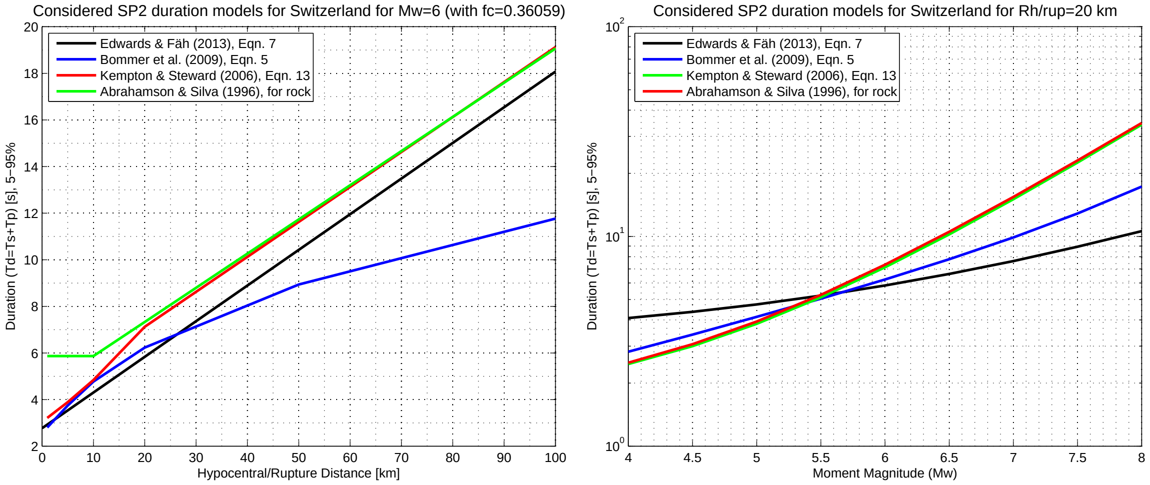
These values were obtained by computation of the site-specific average κ_0 for the horizontal and vertical rock UHS for an annual probability of exceedance of 10^{-4} to 10^{-7}. All the κ_0 were then used to evaluate stochastic models for the site specific conditions up to 1000 Hz and scenarios with M=5, 6, 7 and R_{JB}=5, 10, 20, 40 km. The ratio of the 1000 Hz over the 100 Hz spectral acceleration value was then evaluated in terms of minimum, maximum and mean over all APE levels, while ensuring that the response spectrum flattened out at 1000 Hz.

9.2 Estimation of Additional Ground Motion Parameters

9.2.1 Duration Models for Switzerland

Strong ground motion durations are important to know for the different earthquake scenarios to be defined (as in SP5) based on the deaggregation. The SP2 experts have reviewed and discussed different global duration models for large magnitudes [Abrahamson and Silva 1997; Kempton and Stewart 2006; Bommer et al. 2009], which were judged to be applicable to Switzerland. Also, a duration model developed by SED within the framework of the creation of the Swiss stochastic model and applicable to the stochastic model developed for the small magnitudes in Switzerland was considered. Different versions of the Swiss duration model were proposed in the course of the project, but finally the model published in Edwards and Fäh [2013] was adopted. The SED model was also used as the basis for defining the specification parameters for the SP3 RVT runs (PMT-AN-1132) in order to be fully consistent with the SP2 models at the interface.

These duration models are similar in the near field region (<50km) (see Figure 9.4), which – based on the deaggregation – is the distance range that dominates the hazard for the NPPs. Thus, SP5 reviewed the available duration models consistent with the models defined by SP2 and finally proposed using the SED model to define the range of durations for the scenario earthquakes.



(a) Duration versus distance (b) Duration versus magnitude

Figure 9.4: Comparison of (rock) duration models considered for Switzerland.

9.2.2 Peak Ground Velocity

In the past, there were few ground motion models for PGV, so simplified scaling relations between PGV and spectral acceleration were used to estimate the PGV. Many, but not all, of the new ground motion models include models for PGV. Both the simplified scaling relations developed within PEGASOS and the direct PGV models were considered by SP2, resulting in the advice to consider the recent direct PGV models (e.g. Abrahamson et al. [2013]; Boore et al. [2013]; Campbell and Bozorgnia [2013]; Chiou and Youngs [2013]; Idriss [2013]; Akkar and Bommer [2010]) or Bradley [2013]. Generally, the recommendation is to set a range of the PGV based on the correlation to the $Sa(T = 1)$ and/or $Sa(T = 0.5)$.

In addition to the scale factor between PGV and SA for the median ground motion, the standard deviation of PGV is lower than the standard deviation for spectral accelerations. As an example, the ratio of the standard deviation for PGV to the standard deviation for spectral acceleration at T=1 s is shown in Table 9.3 for a distance of 20 km and a range of magnitudes. For this case, the standard deviation for PGV is about 12% smaller than the standard deviation for spectral acceleration at 1 s. While a change in the median ground motion leads to a simple shift in the hazard curve along the log ground motion axis, a change in the standard deviation will also change the slope of the hazard curve. A reduction in the standard deviation will lead to a steeper slope of the hazard curve. The effect of a change in the standard deviation ($\Delta\sigma$) on the hazard curve at a given ground motion level can be approximated based on the mean ϵ from the deaggregation (scale by $\exp(\epsilon \cdot \Delta\sigma)$). But to fully capture the effect, the hazard would need to be recomputed using the PGV GMPEs with their appropriate standard deviations in the hazard calculation.

9.2.3 Average Spectral Acceleration

A simplified procedure for computing attenuation relations for spectral acceleration averaged over a specified frequency band was developed in the PEGASOS project [Abrahamson et al. 2003] (TP2-TN-0389). This procedure was based on scaling of the attenuation relation for one

Table 9.3: Ratio of the standard deviation for PGV to the standard deviation for $SA(T{=}1\text{ s})$ for a distance of 20 km.

GMPE	$M5$	$M6$	$M7$
Abrahamson & Silva [2008]	1.00	0.94	0.86
Boore & Atkinson [2008]	0.87	0.87	0.87
Campbell & Bozorgnia [2008]	0.84	0.84	0.84
Chiou & Youngs [2008]	0.92	0.86	0.81

of the spectral frequencies. The scaling relation includes scaling of both the median ground motion and the aleatory variability of ground motion. According to the project plan this simplified procedure is only applied at the explicit request of an NPP to estimate hazard curves for average spectral acceleration.

In Baker and Cornell [2006], page 1090, the possibility to predict structural response using averaged spectral acceleration is discussed. The assumption is that the average spectral acceleration can be predicted using means, standard deviations and correlations at individual periods. More recent work on this subject has been conducted by Bianchini et al. [2009].

9.3 Contribution of Soil Profiles and Material Models to Soil Hazard

Soil-structure interaction (SSI) analyses require input ground motions defined at a control point, and soil models (velocity profile and material properties). The PRP soil UHS is based on the mean hazard that includes the weighted set of soil models so it is not clear what would be the appropriate soil model to use. This topic was discussed during SP5 workshop #2 and two approaches were proposed:

- Perform an SSI analysis using the rock UHS as the control motion. The set of soil models from SP3 with the SP3 expert's weights can be used.
- Perform an SSI analysis using the soil UHS as the control motion. The weights for the soil models can be developed using a deaggregation of the soil hazard by V_S-profile and material property model. The weights for the soil models would be based on the deaggreation weights (contribution of each soil model to the hazard).

Both approaches involve approximations because the full logic trees of SP3 include different approaches to different loading levels (e.g. equivalent linear and non-linear), but the SSI will use only a single method. The first method maintains the rock UHS and is an approximation for the soil UHS. The second method maintains the soil UHS and is an approximation for the rock UHS.

In the second method, the soil hazard needs to be deaggregated by soil velocity profile and by material properties. An example of deaggregation of the SP3 hazard for the soil models is shown for all four sites at 10^{-4}. The resulting contributions of the site specific V_S-profiles and material models to the soil hazard are summarized in Table 9.4. The full set of contributions for all APE and frequencies are documented in TP4-SUP-1108. Figures A.53 to A.56 in the appendix show an overview of the contributions for all APE levels and frequencies.

Table 9.4: Contributions of soil profiles and material model to the soil hazard for 100 Hz, at an annual probability of exeedance of 10^{-4} (TP4-SUP-1108).

(a) Beznau

	LB Material	BE Material	UB Material
Profile 1	0.067	**0.147**	0.126
Profile 2	0.049	0.111	0.096
Profile 3	0.029	0.063	0.054
Profile 4	0.050	0.111	0.096

(b) Gösgen

	LB Material	BE Material	UB Material
Profile 1	0.029	0.054	0.042
Profile 2	0.041	0.077	0.061
Profile 3	0.034	0.062	0.050
Profile 4	0.052	**0.093**	0.078
Profile 5	0.041	0.075	0.058
Profile 6	0.036	0.066	0.052

(c) Leibstadt

	LB Material	BE Material	UB Material
Profile 1	0.084	**0.208**	0.119
Profile 2	0.053	0.139	0.081
Profile 3	0.065	0.159	0.091

(d) Mühleberg

	LB Material	BE Material	UB Material
Profile 1	0.057	**0.154**	0.129
Profile 2	0.029	0.088	0.081
Profile 3	0.054	0.139	0.106
Profile 4	0.024	0.074	0.066

9.4 Subproject 5: Scenario Earthquakes

According to the project plan, subproject 5 does not fully conform with the SSHAC Level 4 methodology and it is not a formal part of this report. Nevertheless, subproject 5 represents an important interface in the context of the safety assessments of the NPPs. The interface builds the bridge between two analysis parts with different requirements with respect to quality according to ENSI. The hazard assessment is expected to be performed under the SSHAC Level 4 methodology, while the subsequent engineering assessments of the structures, systems and components need to satisfy different individual quality criteria. In comparison to subproject 4, the output of subproject 5 is expected to change in the near future, as the methods are being further developed. In the future, the assessment of the ground motion response of the structures, systems and components might require inputs which are not covered by the subproject 5 output specification [Renault 2013b] (PMT-TN-1146) and thus can only be specified after the completion of the PRP. The inclusion of subproject 3 (site response characterization) in the SSHAC Level 4 methodology represents a more strict assessment compared to the international practice and, in Europe, PEGASOS/PRP represent the first and only PSHA with such requirements. Based on these circumstances, ENSI accepted that it would be inappropriate to require a SSHAC Level 4 approach for subproject 5 (ENSI letter of 27. March 2013). As the ENSI review process is geared to assessing the conformity of the hazard assessment with the SSHAC Level 4 process, ENSI decided to not comment on subproject 5 within the framework of the formal review process. Thus, swissnuclear decided to document the description of the work performed within subproject 5 in a separate technical report. In the framework of the verification of the safety assessments, it will be necessary, on a case-by-case basis, to evaluate whether the hazard results of subproject 4 have been adequately implemented (e.g. in following the subproject 5 procedure).

Chapter 10

SSHAC Consistency and Level Evaluation

10.1 Introduction

As defined in NUREG/CR-6372 and NUREG-2117 [Budnitz et al. 1997; Kammerer and Ake 2012], the fundamental goal of a SSHAC process is to carry out properly and document completely the activities of evaluation and integration. Evaluation is defined as "The consideration of the complete set of data, models, and methods proposed by the larger technical community that are relevant to the hazard analysis". Integration is defined as "Representing the Center, Body and Range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessment of existing data, models, and methods)".

The general requirements for SSHAC Level 3 and 4 studies are the same: capture the Center, Body and Range (CBR) of the technically defensible interpretations (TDI) through a series of workshops that facilitate interaction and feedback. Figure 10.1 illustrates the key elements of each SSHAC study level and Table 10.1 summarizes the essential steps. The goal of capturing the range of models and methods that would be considered by the broader Informed Technical Community (ITC) is not the same as conducting a survey of judgments of the ITC in terms of what methods, models, and data they would use. Rather, the goal is to capture the CBR that would result if a different set of experts selected from the broader ITC had participated in the complete SSHAC evaluation. That is, if they had been provided with the same technical information and participated in the SSHAC workshops with the interaction and feedback, would they have developed similar models? This distinction is important because the experts' project-specific evaluations and judgments change as a result of their participation in a SSHAC process. As part of the interaction and feedback, the experts learn about the strengths and weaknesses of models and methods for the site-specific application.

The key difference between SSHAC levels 3 and 4 is that a SSHAC Level 3 study uses a single set of experts in a TI team to conduct the evaluations and develop the model (logic tree), whereas a SSHAC Level 4 study uses multiple experts (or expert teams) to conduct the evaluation and develop alternative logic trees that are each complete models. By providing alternative models based on the evaluations from different experts, a SSHAC Level 4 study

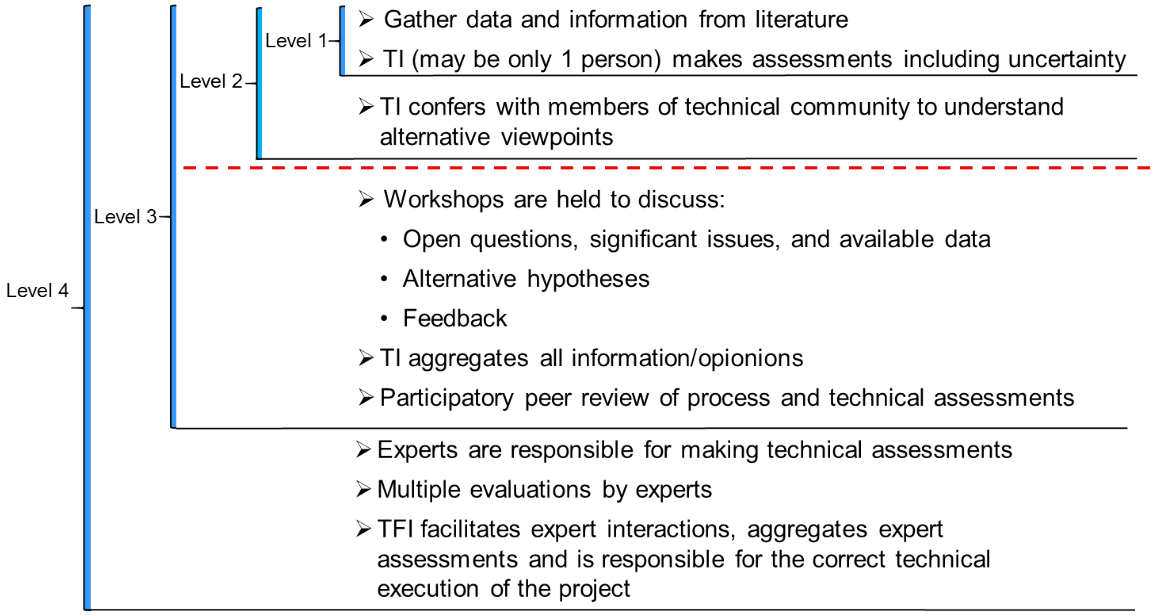


Figure 10.1: Integral key features of a SSHAC study. With TI: technical integrator and TFI: Technical Facilitator/Integrator

allows for an assessment of the robustness of the models through a comparison of the CBR of the alternative models. The SSHAC Level 4 process is intended to address the issue of what would happen if a different expert conducted the evaluation, thereby adding to regulatory assurance in the robustness of the results. The SSHAC Level 4 process also has the advantage that the alternative models can be checked for inconsistent CBRs (significant differences between experts) as part of the feedback process, as well as having the experts critically review each other's models. While the SSHAC process does not require consensus between the experts, if there are significant differences between the models, these differences need to be clearly explained and have defensible technical justifications. Large differences in the CBRs for different experts may also indicate that a larger number of experts groups is needed to obtain a robust estimate of the mean.

The goal of the PRP SSHAC process for the three subprojects (SP1, SP2, and SP3) is to capture the CBR of the seismic source characterization (SSC), ground motion characterization (GMC) and site response characterization (SRC) and, thereby, capture the CBR of the resulting hazard. The focus is on the CBR of the results of the models, not on explicitly including the full range of approaches or models. In many cases, the different models and methods can lead to results that overlap. Therefore, the experts can capture the CBR of the results using different approaches and different subsets of the alternative models and methods. The robustness of the resulting models is evaluated by comparing the CBRs of the results from the individual experts.

The original PEGASOS Project was conducted according to a SSHAC Level 4 process and the successful completion of that process was verified by the issuing of a final closure report by the ENSI-RT [HSK 2004]. A review of the approach used in the PEGASOS Project with the most recent regulatory guidance related to SSHAC Level 3 and 4 projects [Kammerer and Ake 2012] confirms that the approach was consistent with an SSHAC Level 4 process. Motivated primarily by the need for refinements in the ground motions (SP2) and site response

(SP3) components of the project, the PRP was instituted as a means of refining the original PEGASOS models. Whether the evaluations by the SP1, SP2 and SP3 experts as part of the PRP meet the requirements for a SSHAC Level 4 is considered below and evaluated by subproject.

Table 10.1: Summary of essential steps in SSHAC Level 3 and 4 studies

Essential Step	Discussion
1. Select SSHAC Level	Document decision criteria and process
2. Develop Project Plan	Includes all technical and process activities
3. Select project participants	Includes all management, technical and peer review participants
4. Develop project database	Includes compilation of existing available data Can include focused new data collection Data dissemination to all evaluator experts and TI Team members
5. Hold workshops (minimum of three)	Workshop topics: Hazard-significant issues and available data Alternative interpretations Feedback
6. Develop preliminary model(s) and Hazard Input Document (HID)	Preliminary models developed prior to feedback workshop HID provides input to hazard calculations
7. Perform preliminary hazard calculations and sensitivity analyses	Intermediate calculations should display the impact of elements of the expert models Hazard calculations should show the significance of all elements of the models Sensitivity analyses should include the contributions to uncertainties
8. Finalize models in the light of feedback	Feedback provides a basis for prioritizing and focusing the finalization process Implement integration process across all evaluator experts in SSHAC Level 4 process
9. Perform final hazard calculations and sensitivity analyses	Should be conducted to develop the required deliverables for subsequent use of the hazard results
10. Develop draft and final project report	Fundamental documentation of SSHAC process, technical bases and results
11. Participatory peer review of entire process	Periodic written reviews of key products and activities Review of draft report Final written review of technical evaluations and process used

10.2 Interaction at workshops

The SSHAC Level 4 recommendations (NUREG/CR-6372) do not provide any guidance or requirements regarding the degree of interaction or dialog between the experts. To encourage discussion, the TFI assumes the responsibility for challenging and questioning the experts. The purpose of expert interaction is to compare the results from different approaches, identifying the differences, and understand the technical basis for the different approaches. This helps the experts in identifying methods/approaches that they may not have captured in their range of models. The interaction between the PRP SP2 and SP3 experts has achieved this goal as the experts have adjusted their models based on the feedback. Today, the resulting expert models are more robust.

10.3 SP1 SSHAC Level Evaluation

The SP1 component of the PRP was subject to updating and refinement due to potentially new data, models or methods that had become available since the time when the PEGASOS SP1 inputs were finalized. Although all potentially significant new findings from the larger technical community were reviewed by the SP1 teams during the course of the PRP, the only hazard-significant new piece of information was the new earthquake catalogue ECOS09 and the analyses associated with the catalogue.

Consistent with an SSHAC process, the SP1 component of the PRP included both an evaluation phase and an integration phase. During the ”evaluation” phase of the project, new data and information that had become available subsequent to the PEGASOS Project were identified and discussed at SP1 workshops and interface workshops with other subprojects. For example, the SP1 teams evaluated new information related to the depth extent of the Fribourg fault (which is now interpreted to be shallower), published paleoseismic evidence from synchronous subaqueous landslides in Lake Zurich and Lake Lucerne, geomorphic evidence for the possibility of geologically recent activity on the boundary faults to the Permo-Carboniferous troughs and changes in the locations of earthquakes between the ECOS02 and ECOS09 catalogues. This information was evaluated not only for its scientific credibility, but also through hazard sensitivity calculations that tested the significance of the findings in terms of potential changes in the seismic source models and, in turn, in the calculated hazard.

A key piece of new data was the new earthquake catalogue being developed for the project. The SED catalogue development team provided multiple progress reports on the manner in which the catalogue was being compiled and the approaches being taken to convert all earthquake size measures to a constant moment magnitude, M_W. The evaluations of the potential implications of the new catalogue were led by the SP1 teams, with R. Youngs and Ph. Roth providing calculation support and feedback. A wide variety of analyses were conducted to show the differences between the ECOS02 and ECOS09 catalogue in terms of the change in locations and magnitudes for each earthquake in the catalogue, as well as special calculations to show hazard sensitivity (e.g. effects of spatial smoothing, variations in M_{max}).

The PRP SP1 project then moved into the ”integration” phase during which model-building occurs or, in the case of the PRP refinement, the existing SP1 PEGASOS models were reviewed against the new information to determine the need for changes to the models. As discussed in Section 2.2 of this report, workshops and working meetings were held to review new information that might have potential significance for the SP1 models and to review the assessments that the teams were making to evaluate the significance of the new information. Once the ECOS09 catalogue was complete, and as discussed in Section 2.3, each SP1 team requested a range of calculations of M_{max} and recurrence parameters that would provide information to the teams. These calculations were exploratory in nature and were intended to allow each team to probe the implications of the new catalogue for all aspects of their respective models (e.g. seismic source zonations, catalogue completeness, M_{max} distributions, recurrence parameters). The results of these calculations and analyses were duly provided to each team to support their deliberations regarding their SSC models. It should be noted that the questions and analyses by the teams also provided feedback to the catalogue development team at SED and improved the quality of the final catalogue, especially the issues surrounding the M_L-M_W conversion.

In addition to calculations aimed at examining the implications of potential model changes for SSC parameters, the teams were also provided with hazard calculations and sensitivity analyses to test the sensitivity of SP1 model changes to calculated hazard. For example, sensitivity analyses were conducted to examine the implications of including the Permo-Carboniferous troughs as seismic sources. Other calculations were conducted to examine the relative contribution that the M_{max} assessments would have on the calculated hazard.

The completion of the integration phase of an SSHAC process is the finalization of the models, documentation of the technical bases for the assessments and the development and approval of the HID for use in hazard calculations. After receiving all calculations and feedback, each SP1 team finalized their models. The documentation of the technical bases for elements of the models that have been revised from the PEGASOS assessments is given in the Elicitation Summaries (see Volume 3). In turn, each team reviewed the HID that captured their final models and signed the QA certification acceptance form to indicate that the HID accurately represents their final assessments. The HIDs and signed acceptance forms are also given in Volume 3. At the end of the SP1 project, a final set of hazard calculations and sensitivity analyses were conducted to compare the calculated PRP hazard results with the PEGASOS results, and to examine the relative influence of all elements of the SP1 models as well as the relative contribution that each element makes to the total uncertainty in the mean hazard (see Appendix D in Volume 3). With the successful conclusion of both the evaluation and integration activities of an SSHAC Level 4 process, it is concluded that the resulting SP1 models represent the Center, Body and Range of technically defensible interpretations.

10.4 SP2 SSHAC Level Evaluation

Based on the PEGASOS results, the range of the rock ground motion models makes the largest contribution to the uncertainty in the hazard. Given the large increases in the number of available strong motion data as well as the publication of improved ground motion models that required fewer adjustments, it was decided to completely replace the PEGASOS SP2 models with new models. Consistent with an SSHAC process, the SP2 component of the PRP included both an evaluation phase and an integration phase.

10.4.1 Evaluation Process

As part of the evaluation phase, the SP2 experts considered the new sets of available GMPEs, a newly developed Swiss stochastic model and a set of finite-fault simulations. This phase also considered the correction of the global GMPEs to Swiss site conditions for the NPPs and the adjustment of the GMPEs to be consistent with the small magnitude earthquakes in

Switzerland. Two important evaluation phase issues related to the finite-fault simulations and the κ corrections are discussed below.

Finite-Fault Simulations

Although some fine-fault simulation (FFS) results [Dalguer and Mai 2010] were available to the SP2 experts, all of the SP2 experts relied on empirical GMPEs and the point-source stochastic model to define the set of candidate ground motion models. One key reason for not using FFS was that, for high frequencies (of main interest to the PRP), the large number of input parameters needed for the FFS have to be calibrated to match the empirical ground motion data. Instead of FFS methods, the SP2 experts relied on the Swiss point-source stochastic model [Edwards et al. 2010] derived from observed small magnitude data from Switzerland to capture the Swiss-specific effects (source, path, site) in the ground motion. Although the SP2 experts did not use FFS as candidate models on their logic trees, FFS are being used in other ground motion studies around the world: stochastic FFS are used to estimate ground motions in the CEUS [Atkinson and Boore 2006; Atkinson 2008]; the ”Irikura recipe” to compute design ground motions based on kinematic FFS for Japanese NPPs [Irikura et al. 2003; Miyake et al. 2003; Irikura and Miyake 2011]; dynamic rupture models from multiple computer programs can now produce consistent ground motions for a given source input [Harris et al. 2011] and are capable of computing near-fault (<15 km) ground motions for frequencies up to 5 Hz [Harris 2013]. FFS have the advantage that they do not need all of the corrections that have to be applied to the empirical GMPEs, but they still need to have a large number of input parameters defined in order to use them.

It is worth discussing the question whether the PRP is really capturing the full range if the SP2 experts did not include FFS in the set of candidate models. This issue was addressed by considering whether the range of models from the SP2 evaluation capture the ground motions that would be produced by FFS (assuming that the FFS was properly calibrated to the high frequencies). Although the Dalguer and Mai [2010] FFS were not used as candidate models by the SP2 experts, they can still be compared to the range of the models developed by the experts to see if the range in the SP2 models captures the FFS ground motions from large magnitude earthquakes at short distance. Figure 10.2 shows the comparison of the 5-95% range from the final four SP2 experts' models with the median ground motion from the Dalguer and Mai [2010] FFS. Overall, the ground motions from the FFS are within the range of the SP2 models. Because the FFS were not fully validated for the high frequencies, the results of the FFS performed for the PRP were not used to evaluate the centering of the models. The available results of the FFS do not reject the CBR from the SP2 models, which leads to the conclusion that the SP2 models are adequately capturing the CBR of the rock ground motions in Switzerland.

Kappa

In PEGASOS, only two of the five SP2 experts included κ corrections, but with a small weight so it was not identified as a key source of uncertainty for the hazard. As a result, in the initial part of the PRP, it was not clear that a κ correction was needed. Through the SSHAC interaction and feedback process during the evaluation phase, the SP2 experts found that the methods for including κ corrections that were available at the start of the PRP

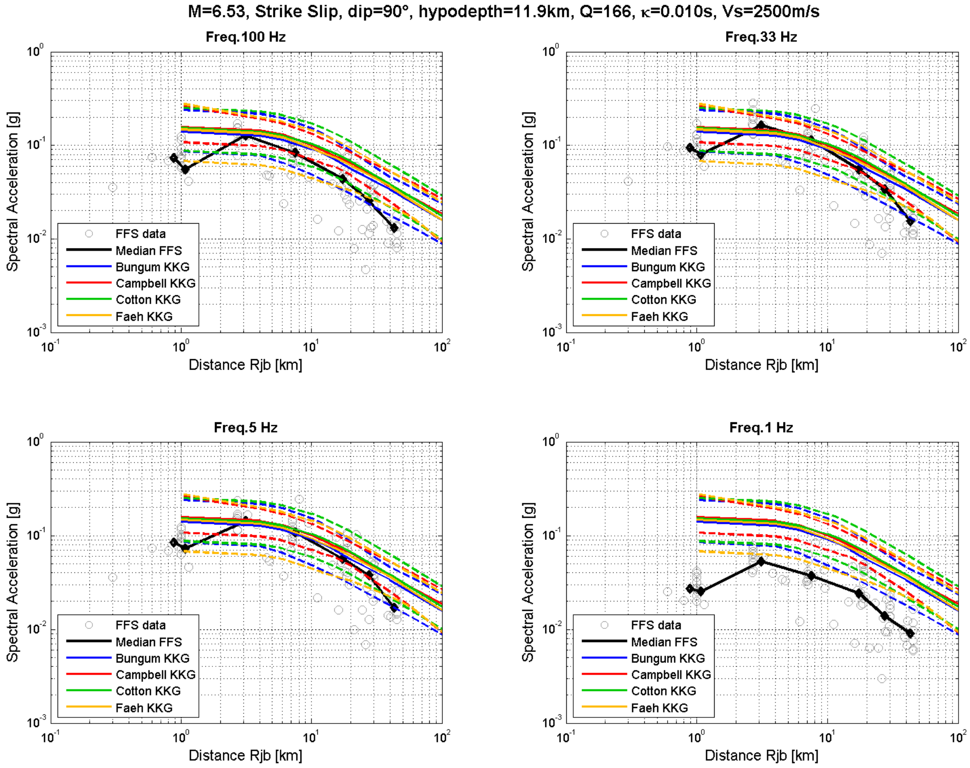


Figure 10.2: Comparison of Finite-Fault Simulations and the range of the SP2 experts' models. The discrete FFS realizations, here for site conditions similar to KKG, are shown as grey circles and the binned median is displayed as a black line compared to the colored median attenuations of each expert. The colored dashed lines represent the range of the expert models.

were not appropriate for the PRP application, or to the application for Switzerland. The κ correction, based on the methods available at the time, was identified as a dominant source of uncertainty. The PMT decided that it was worth delaying the schedule to allow for time to develop improved κ correction methods with reduced uncertainty rather than just using the methods that were available.

As the experts identified the limitations of the available methods, several new methods were developed and evaluated in terms of their applicability to the Swiss NPP sites. The PRP developed a new state-of-the-art for κ corrections. These new methods have not yet been subjected to peer review by the broader ground motion community. This leads to the question: Do these new methods represent the CBR of the TDI that would be developed by the broader ITC if they were part of the SSHAC process? The question here is not what others in the ground motion field would do for κ corrections if they were asked without having the benefit of being part of the SSHAC workshops, but rather, after participating in the workshop discussions, would they also agree that these new methods are appropriate and capture the range?

In the course of the PRP, the methodology for the correction (based on scaling FAS) was significantly improved. Nevertheless, there is still a large uncertainty in the estimation of κ itself (target and host) that could be reduced with further research, but, consistent with the

SSHAC guidelines to represent a snapshot in time, the project decided to capture the current uncertainty and to not conduct additional extensive research for κ. This remains a topic of active research and significant improvements regarding estimation of κ are expected in the next two years.

Roles and Behavior of the SP2 Experts

In the evaluation phase, the SP2 experts initially served multiple roles: acting as proponents and resource experts, as well as evaluators. Serving multiple roles is allowed by the SSHAC guidelines as long as the different roles are clearly identified, but this turned out to be difficult in practice. In the later workshops (from mid 2011), the experts were restricted to evaluator roles in order to allow them sufficient time to properly evaluate the available information and models.

10.4.2 Integration Process

In the PEGASOS study, the logic trees for the SP2 models had a similar structure. The SP2 experts agreed that a common logic tree for SP2 could be used (see Section 4.8.1) and that each of the experts would then conduct their integration using the master logic tree, saving effort on documentation of similar items. To build the master logic tree, the branches proposed by any of the experts were incorporated in the evaluation phase. In the later integration phase, the experts could still make changes by adding their own expert-specific branches to the master logic tree if needed and some experts made use of this opportunity (as described in Section 4.6).

During the integration phase, the use of the master logic tree did not require the experts to include every candidate model in their individual models: as a consequence they put zero weight on some of the branches. The SP2 experts used very different approaches to the integration in terms of how they developed the technical justification for the weights. The primary sources of uncertainty were ground motion method (GMPE versus point source stochastic), GMPE selection and $V_S - \kappa$ correction. The feedback workshop focused on these three topics. The experts checked the centering of their models for both the GMPE and stochastic models and for the κ correction using the available intensity data and small magnitude data. If the experts had acted as proponents rather than evaluators, this would have manifested itself in narrow non-overlapping ranges of the uncertainty for the each model. This check was done by comparing the range of the models.

Change of SP2 Experts in the Course of the Project

The SP2 subproject began with five experts. The extended schedule, due mainly to the need to improve the methods for adjusting the GMPE for κ, led two of the experts (F. Scherbaum and J. Bommer) to withdraw from the project before completing their integration. With the resignations of F. Scherbaum and J. Bommer from their roles as SP2 evaluators in 2011, there were three remaining evaluator experts in SP2. The SSHAC guidelines does not set the number of evaluator experts required for a SSHAC Level 4 study, but the other two subprojects (SP1 and SP2) each have four experts or expert groups. To be consistent with the other subprojects, it was decided by the project to add a fourth SP2 evaluator expert. To allow for an additional expert to be added to SP2 with the least impact on schedule, the new

SP2 expert had to be someone familiar with the SSHAC Level 4 process and with expertise in the most critical technical issues for SP2 ($V_S - \kappa$ adjustment and σ). As a final choice it was decided to add K. Campbell to the SP2 expert evaluator group, which was also endorsed by the TFI and other SP2 experts.

There are two main issues for the SSHAC Level 4 consistency evaluation: (1) does the reduction from five to four SP2 experts still lead to robust results? and (2) does an expert added midway through the project without participating in the earlier workshops have enough feedback? The PMT conducted an evaluation of the stability of the mean hazard based on using different numbers of experts (PMT-TN-1256). They found less than 10% change in the mean hazard if four or more experts were used. Thus, it was concluded that using a minimum of four experts should lead to stable estimates of the mean.

Having an expert start in the middle of the project has the disadvantage that the new expert had not been exposed to all of the previous discussions. To address this, the PRP started over with a new workshop 1 (available data and data needs) and a new workshop 2 (candidate models) to allow the new expert to have input into the discussions and to gain the benefit from interactions with the other experts as part of the evaluation phase. New models and data that were not available during the previous workshop 1 were also considered to bring the evaluation up-to-date.

Although changing the set of experts during the project is not desirable, it provided a unique opportunity to see how similar the resulting models are if a new person is provided with the same information. Initially, the resulting models from K. Campbell were quite different from the other experts, but as he had the opportunity for interaction with the other experts and became more familiar with the Swiss-specific issues, his models became more similar to the others. This demonstrates the important difference between simply asking a member of the ITC for their isolated evaluation and having them go through the SSHAC process.

The consistent results between the four SP2 experts indicates that the mean results are robust with respect to the selection of experts, which meets a goal of an SSHAC Level 4 study. With the successful conclusion of both the evaluation and integration activities of a SSHAC Level 4 process, it is concluded that the resulting SP2 models represent the Center, Body and Range of technically defensible interpretations.

10.5 SP3 SSHAC Level Evaluation

During the PEGASOS Project, the SP3 experts used available site profile data to characterize the sites for input into the site response analysis. For the PRP, new site profile data and lab testing results were collected for each of the four sites. Given this large addition of site-specific data, it was decided to completely replace the PEGASOS SP3 models with new models. Consistent with an SSHAC process, the SP3 component of the PRP included both an evaluation phase and an integration phase.

10.5.1 Evaluation Process

In the evaluation phase, the SP3 experts used the newly collected site characterization data to develop a common set of alternative velocity profiles and non-linear properties for each site. For each site, the range of the consensus profiles captured the range that was allowed by the observations. These sets of profiles were then used in the site response calculations to generate sets of site-specific amplifications.

10.5.2 Integration Process

The four SP3 experts all have expertise in site response but they come from different backgrounds. A. Pecker and J. Studer have backgrounds in geotechnical engineering and P.-Y. Bard and D. Fäh have backgrounds in seismology. In the integration phase, this difference in background was apparent as the SP3 experts tended to rely on approaches consistent with their own backgrounds for the development of the structure and weights on their logic trees to capture the CBR of the site amplification for each site.

The selection of the profiles and non-linear properties were key to defining the range of the site amplification. As this is constrained by data, the results are robust. Similar to the approach in SP2, the SP3 experts decided to develop a common set of soil profiles and material models covering the possible interpretations of all experts. This also avoided duplication of documentation of the basic data and models. The developed set of profiles and material models was used by all SP3 experts in the end and there was no rejection of individual models. It is likely that this occurred because the SP3 is more data-driven and the range of interpretations which are consistent with the data are limited.

As noted for SP2, the SSHAC process is intended to develop models that capture the CBR of the results (here, site amplification). There are many different ways to achieve this goal. The SP3 experts used different approaches to the integration, resulting in very different logic tree and weights; however, the resulting CBR of the site amplification is similar for the four SP3 expert models.

No explicit checking of the centering of the SP3 models was performed, as for SP3, the type of data is very site- specific compared to the data used within SP2. In SP3, the centering is more dominated by the center of the methods used. SP3 used established methods to evaluate the site amplification, which can be judged to result implicitly in centered methods. In the past, these methods were extensively tested and passed benchmarks.

In SP3, the expert J. Studer passed away before signing his HID. He had provided a final model, but could not benefit from the final SP3 hazard feedback. This raised the issue of weighting the SP3 experts by the TFI. As part of the integration, the TFI requested additional sensitivity analyses. The SP3 soil hazard was evaluated with and without consideration of J. Studer's model. The results with and without J. Studer's model lead to similar soil hazard results. Therefore, the TFI judged that it was appropriate to assign equal weights between the four SP3 experts.

With the successful conclusion of both the evaluation and integration activities of an SSHAC Level 4 process, it is concluded that the resulting SP3 models represent the Center, Body and Range of technically defensible interpretations.

Chapter 11

Summary and Discussion of Results

11.1 Main Contributors to Uncertainty in Hazard

One of the objectives of the PRP was to reduce the large uncertainty for the PEGASOS hazard results through the collection of additional data and use of improved models. As uncertainty is reduced, it is not known if the mean will be in the center of the range or near the top or bottom of the original distribution. Reducing the uncertainty in the SP1, SP2, and SP3 models may lead to an increased hazard or a decreased hazard depending on what part of the uncertainty range is reduced.

The hazard computed using the PRP models showed a significant reduction in the epistemic uncertainty of the hazard as compared to the PEGASOS hazard. The largest reduction in uncertainty was at the low frequencies. For example, for Beznau, the 95%/5% fractile uncertainty range of the 1 Hz soil ground motion for a hazard level of 10^{-5} went down from a factor of 10 to a factor of 5. For the moderate frequencies, the 95%/5% uncertainty range of the 5 Hz soil ground motion was reduced from a factor of 5 to a factor of 4.

Although significant reductions in the uncertainty of the SP2 models were made, the epistemic uncertainty in the rock ground motion models remains the dominant contributor to the uncertainty in the hazard for both low and high frequencies. The SP2 uncertainty is dominated by the model category (PSSM or GMPE) and the individual model. At high frequencies, the $V_S - \kappa$ correction is also a large contributor to uncertainty. For the vertical component, the uncertainty in the V/H ratio for hard rock sites dominates the uncertainty.

After SP2, the next largest contributor to the hazard is SP1. In particular, at low frequencies, the uncertainty in the maximum magnitude distribution leads to larger uncertainties in the hazard. At high frequencies the spatial smoothing of the seismicity in the host zone can also have a significant contribution to the uncertainty.

The uncertainty in the SP3 models has the smallest effect on the hazard uncertainty for the Beznau, Gösgen, and Leibstadt NPPs. This is partly a result of having a large amount of site-specific data to constrain the models. The SP3 uncertainty for the Mühleberg site is larger than the other three sites due to difficulties in collecting the new soil data.

11.2 Key parts of refinement compared to PEGASOS

There are some key parts and models which make the difference between the original PEGASOS and the Refinement Project. Those are summarized in the following by subproject and are intended to provide and brief overview of where the PEGASOS models have been superseded by PRP models or data, respectively.

Subproject 1

- Replacement of the ECOS02 by ECOS09: 7 years of additional data, resolution of deficiencies in ECOS02 and improvements in ECOS09, due to reassessment of certain parts of the catalog.

Subproject 2

- Update of older GMPEs by modern GMPEs and a new Swiss stochastic model: Since the time of pre-PEGASOS approximately eight times more data for lager magnitudes at short distances has been collected worldwide, which lead to the development of more modern GMPEs which are better constrained at large magnitudes. Furthermore, in PRP all GMPEs were based on moment magnitude and the native distance metric was used, avoiding two sources of additional uncertainty.
- Correction for an error in the GMPEs: The PEGASOS models overpredicted at small magnitudes the ground motion by a factor of 3. The models used for PRP corrected for the systematic overprediction to be consistent with the Swiss data. The constrained ground motion amplitude for lower magnitudes has been confirmed by the most recently developed GMPEs (e.g. NGA-West2).
- Correction for a deficiency in PEGASOS: In PRP no more double counting of uncertainties between the rock ground motion and site response between SP2 and SP3. An improvement over PEGASOS was the use of the single-station σ concept.
- Host-to-target correction in PRP: Development of new state-of-the-art κ corrections to make the GMPEs applicable to the Swiss hard-rock conditions and reflect the corresponding high frequency content.
- Correction for deficiencies of V/H models: In PEGASOS generic models applicable for soft rock were assumed to be applicable to hard rock. PRP included specific V/H models applicable for hard rock sites.
- In PRP, testing with intensity data for consistency of the predictions with historical data was performed.

Subproject 3

- Replacement of the limited site soil data (shear wave velocity profiles and non-linear material properties) from the '70s with data from the new extensive site specific characterization using up-to-date and multiple methods for the site investigations: Replacement of all site amplification functions.

- Correction for a deficiency of PEGASOS: In PRP no more double counting of uncertainties between rock ground motion and site response between SP2 and SP3: The additional aleatory variability components, already covered by SP2, was removed.
- Update of the maximum ground motion truncation models: the PRP soil truncation models have been raised to a higher ground motion level, based on the observed worldwide data.
- Interface improvement in PRP: PEGASOS used generic rock input motions without consistency to the SP2 models and resulting rock UHS. In PRP this was corrected, using rock input motions consistent with the final SP2 model (including the consideration of $V_S - \kappa$ corrections).

11.3 Lessons Learned

The PRP was conceived as a partial update of the PEGASOS project, however, it is difficult to update only one part of the model. In addition, the field of seismic source characterization and ground motion characterization are changing rapidly with new models and method being developed. Therefore, it is difficult to make a partial update and not address all the new models and approaches. By the end of the PEGASOS Refinement Project, the schedule and budget for the PRP was comparable to the initial PEGASOS Project. When planning updates of hazard studies, sponsors should be aware that full updates will likely be required.

Having in-house expertise in seismic hazard within the project sponsors was a major improvement as it allowed the sponsors to stay informed of the progress during the project and to understand the issues for application of the results.

Testing that the expert models are centered and capture the appropriate range is a key part of the SSHAC procedures. Identification of methods that can be used to test the centering for the models should be considered early in the project. In the PRP, some of these methods were developed too late to be fully exploited.

Conducting significant new research and model development under the SSHAC procedures is not efficient and can lead to large schedule delays. The SSHAC formal structured workshop process does not fit well with a research program. If possible, the main research tasks should be identified and completed outside of the SSHAC process. This would let the SSHAC process focus on the evaluations of available data and models.

One approach to avoiding conducting major research under the SSHAC process is to have ongoing seismic studies that can conduct the needed research over a longer time period and be applied to SSHAC studies when they are ready for application and have been fully tested.

11.4 Outlook for Improvement of Models

The earthquake science models required for PSHA still have large uncertainties. Based on the PRP, models, methods, and data that could be improved and have a significant effect on the computed hazard are listed below.

As seen in the PRP changes in the earthquake catalogue can have a large effect on the hazard. Updates to the catalogue should be monitored and considered for future updates of the PSHA.

Catalogue uncertainty is currently not captured in the SP1 logic trees and a methodology to account for catalogue uncertainty should be developed.

Models for the spatial distribution of sources in the host zone strongly affect the hazard. Larger maximum magnitudes are being considered for many regions. For large maximum magnitudes, the shape of the distribution function should be evaluated and candidate models developed that may deviate from the traditional exponential model.

Kappa has a controlling effect on the high frequency shape of the response spectrum. The methods of estimating κ at a site and correcting GMPEs for κ need to be improved and calibrated. New methods to estimate site specific κ based on data other than earthquake recordings such as microtremor or vibroseis data could be developed. A set of standardized methods for making κ corrections for GMPEs should be developed. Ultimately, the κ correction approach should be replaced with an approach that incorporates κ as a site parameter into the GMPEs; however, this will require a change to a Fourier amplitude spectrum based GMPE.

Most of the existing V/H models are for soil sites and moderate level (linear range) of ground motion. Improved models for the V/H ratio for hard rock sites are needed.

Installation of a sensor at surface and depth in a borehole can help to constrain parts of the PRP model in the future. Continuous recording of small earthquakes and sub-sequent evaluation can allow site-specific parameters/models such as κ to be constrained. These recordings can also be used for developing empirical constraints on the site amplification, V/H ratios at depth and at the surface, site amplification between rock and surface, and single-station σ. In the long term, the small magnitude data will be able to constrain the path effects in addition to site effects.

To address the limitations of applying global ground motion models, the seismic hazard analysis is moving to a greater use of physics-based numerical simulation methods for ground motions. Currently, kinematic simulations are more widely used because they have the advantage that they can be easily be extended to the high frequency range (3 - 20 Hz) that is important for nuclear facilities, but the reliability of the results depends on physically appropriate input source models. In particular, the combinations of key source parameters, such as slip, rise time, and rupture velocity can be controlling aspects of the kinematic simulations. To develop realistic simulations, the correlations of these parameters across the rupture plane needs to be constrained to avoid physically unrealizable parameters combinations. Dynamic rupture models can be used to generate suites of seismic source models for potential future earthquakes that capture the correlation of the key source parameters. As dynamic rupture models are adequately validated against past earthquakes, they can be used to estimate the ground motions directly. This will take several years to accomplish the validations, but these methods are seen as the future of ground motion models for comprehensive seismic hazard studies.

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Appendices

Appendix A

Additional Figures

A.1 Comparison of Forecast Earthquake Recurrence Rates between PEGASOS and PRP

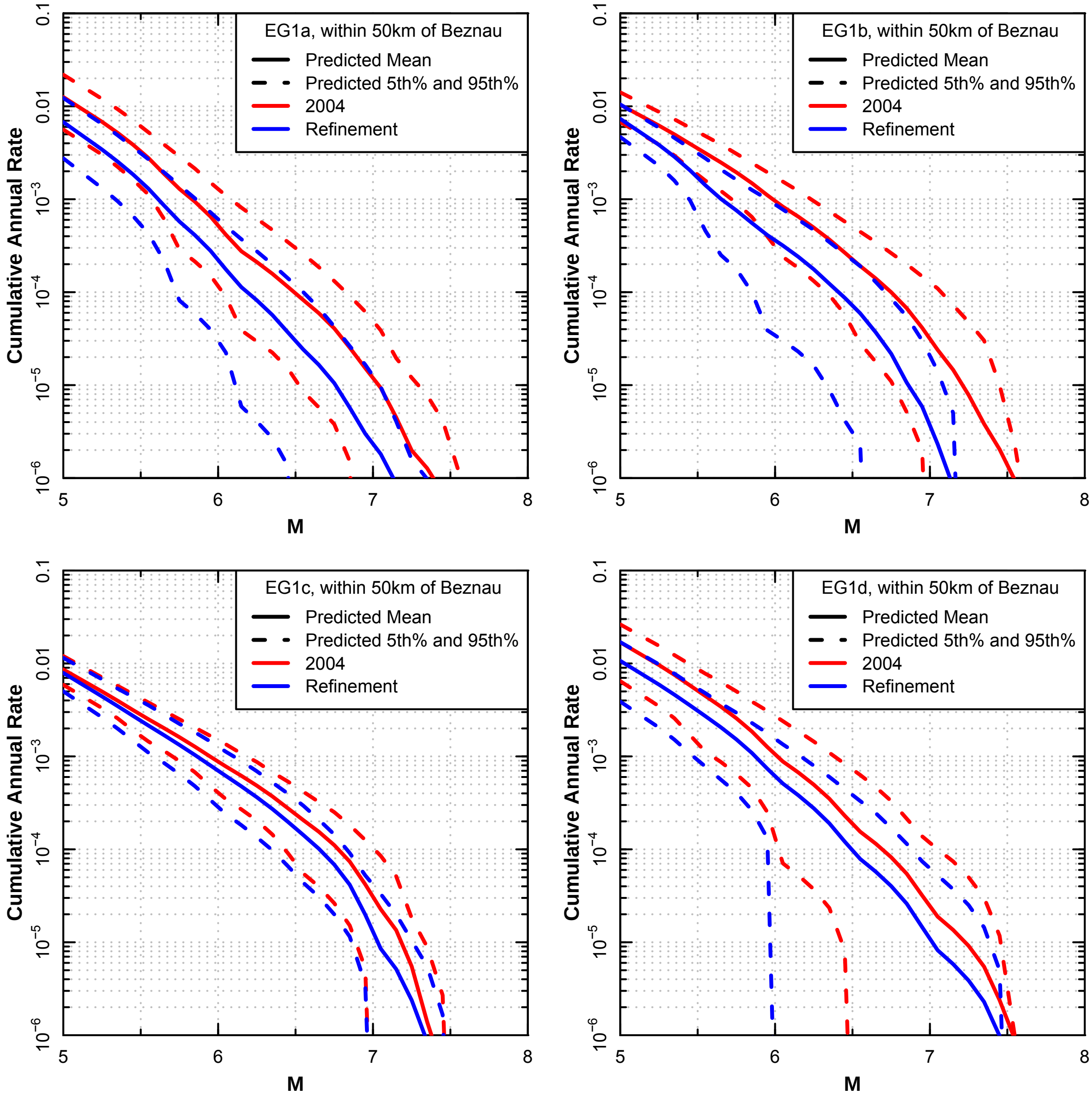


Figure A.1: Comparison of forecast earthquake recurrence rates of PEGASOS and PRP for the four SP1 teams at Beznau. The comparison includes only a zone of 50 km around Beznau.

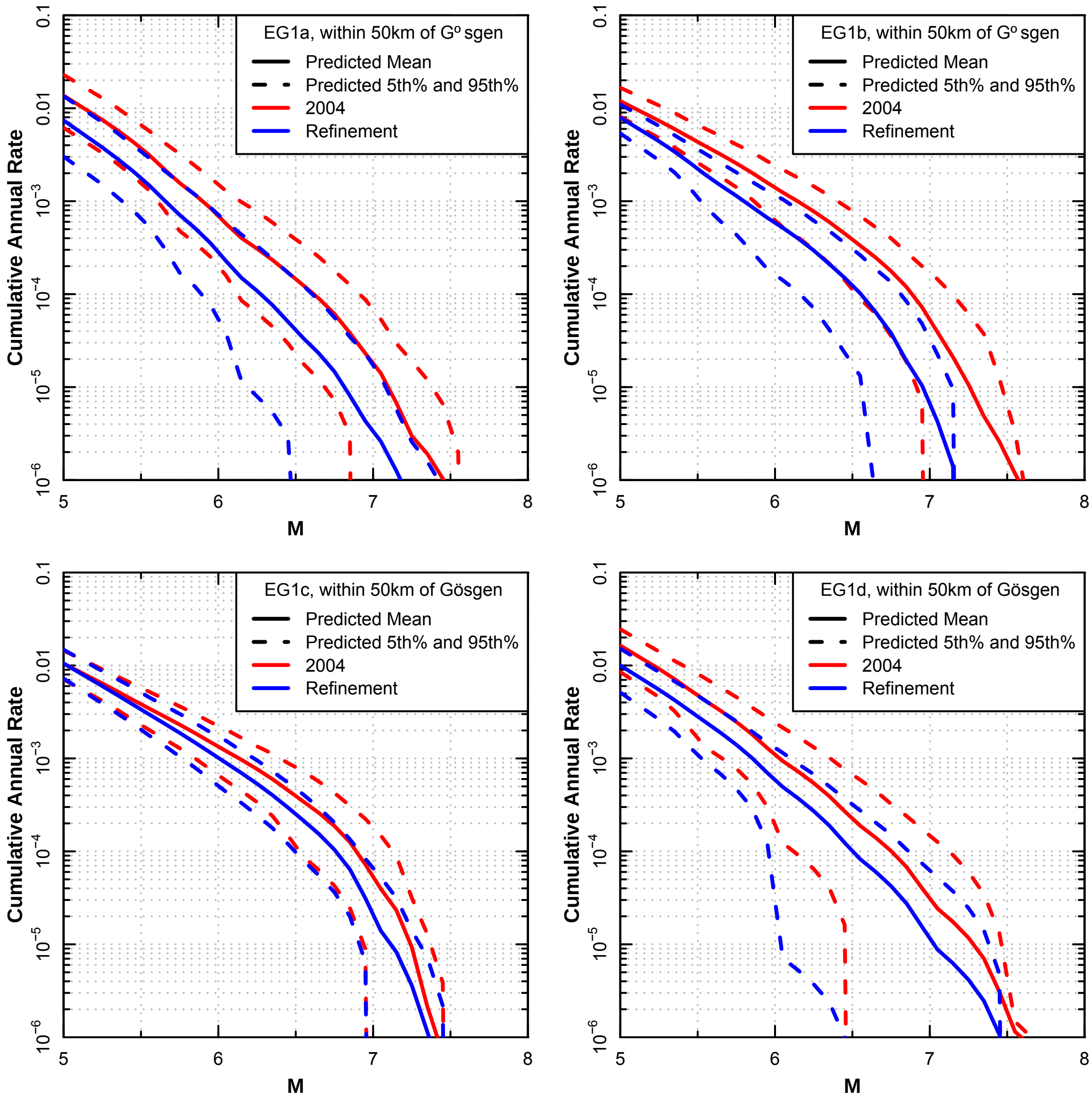


Figure A.2: Comparison of forecast earthquake recurrence rates of PEGASOS and PRP for the four SP1 teams at Gösgen. The comparison includes only a zone of 50 km around Gösgen.

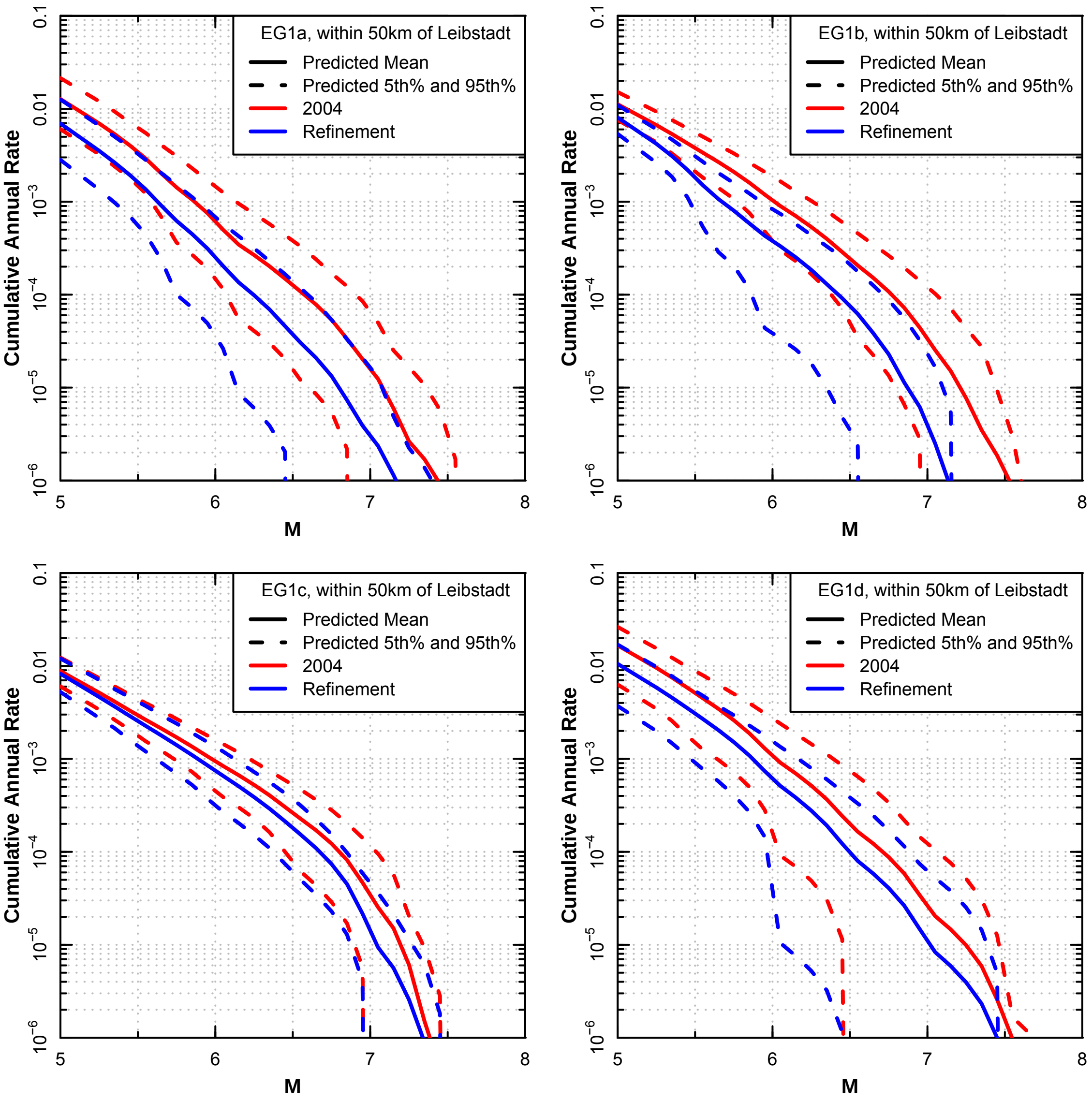


Figure A.3: Comparison of forecast earthquake recurrence rates of PEGASOS and PRP for the four SP1 teams at Leibstadt. The comparison includes only a zone of 50 km around Leibstadt.

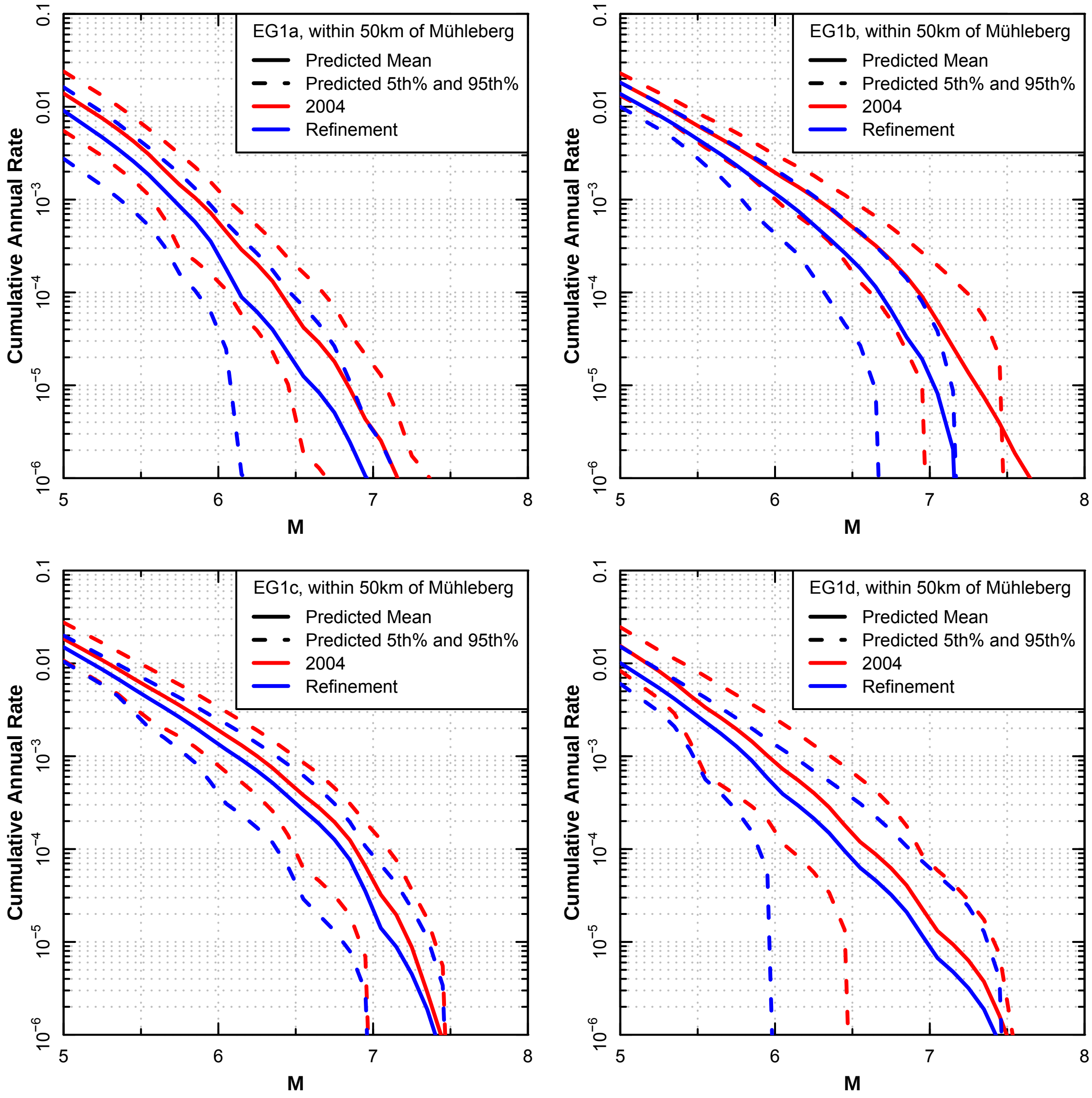


Figure A.4: Comparison of forecast earthquake recurrence rates of PEGASOS and PRP for the four SP1 teams at Mühleberg. The comparison includes only a zone of 50 km around Mühleberg.

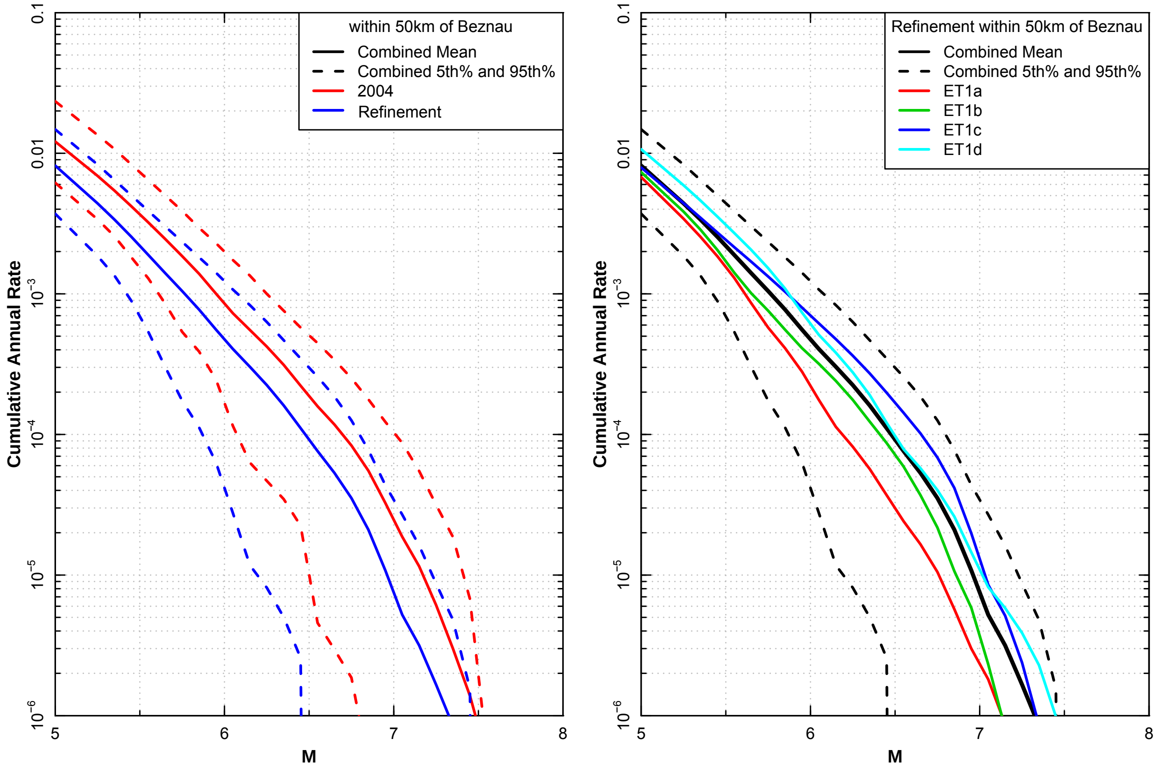


Figure A.5: Comparison of forecast earthquake recurrence rates for the four SP1 teams at Beznau. The comparison includes only a zone of 50 km around Beznau. Left: Combined team comparison between PEGASOS (2004) and PRP (Refinement), right: comparison of the individual team estimates with the combined mean and range.

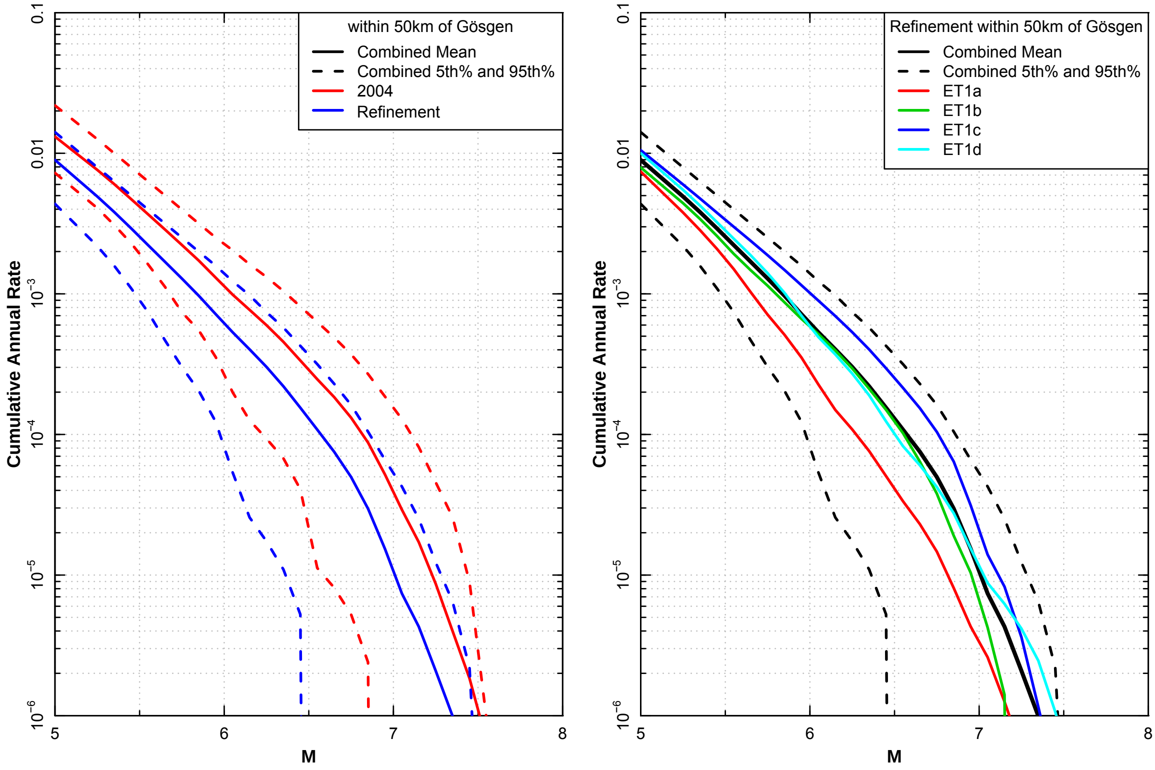


Figure A.6: Comparison of forecast earthquake recurrence rates for the four SP1 teams at Gösgen. The comparison includes only a zone of 50 km around Gösgen. Left: Combined team comparison between PEGASOS (2004) and PRP (Refinement), right: comparison of the individual team estimates with the combined mean and range.

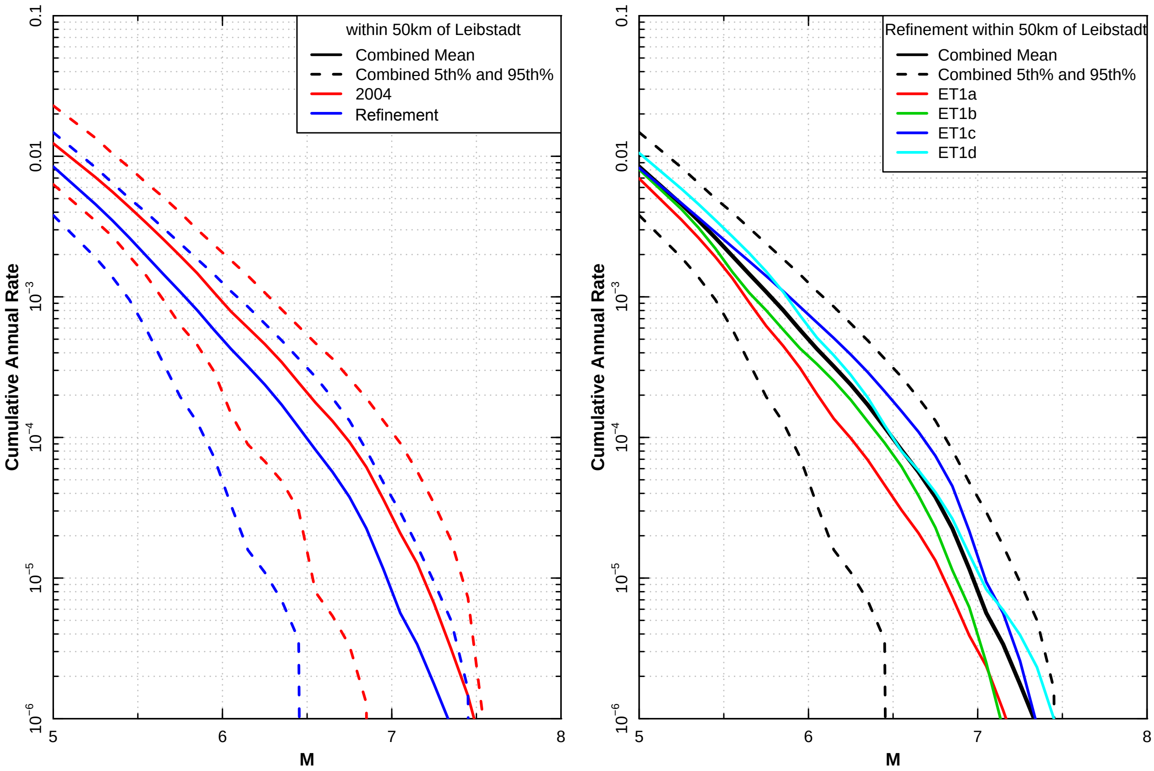


Figure A.7: Comparison of forecast earthquake recurrence rates for the four SP1 teams at Leibstadt. The comparison includes only a zone of 50 km around Leibstadt. Left: Combined team comparison between PEGASOS (2004) and PRP (Refinement), right: comparison of the individual team estimates with the combined mean and range.

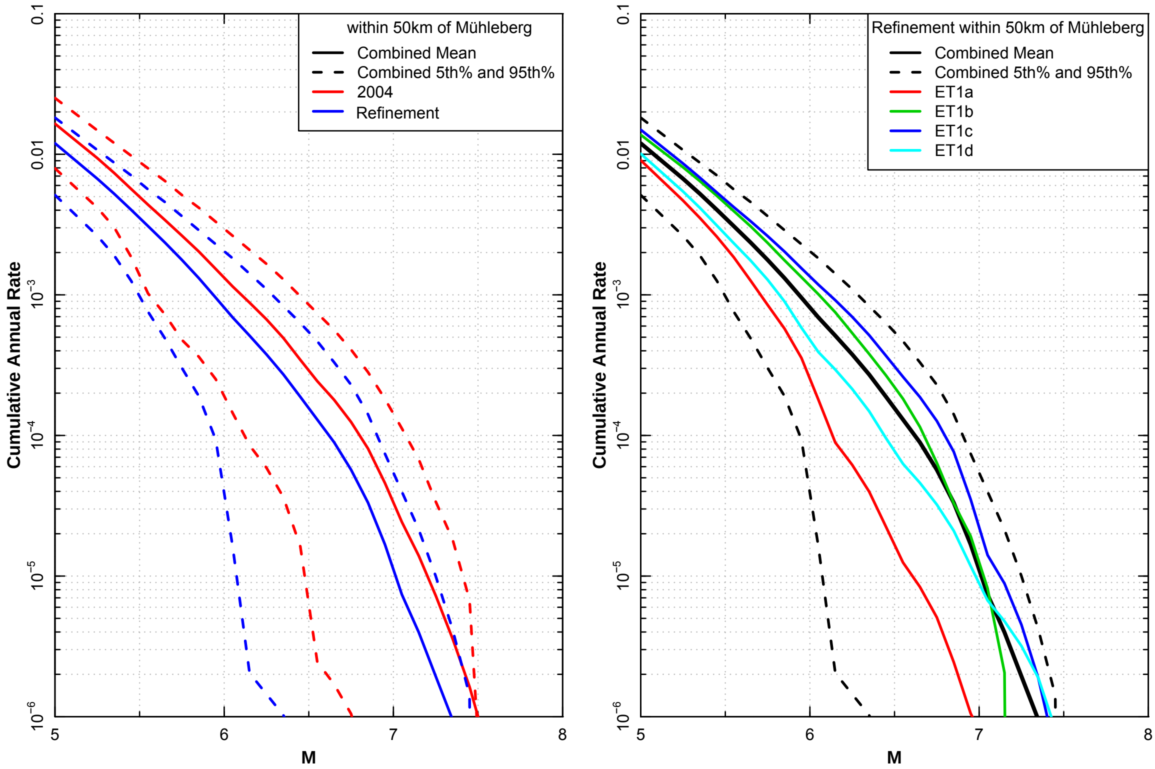
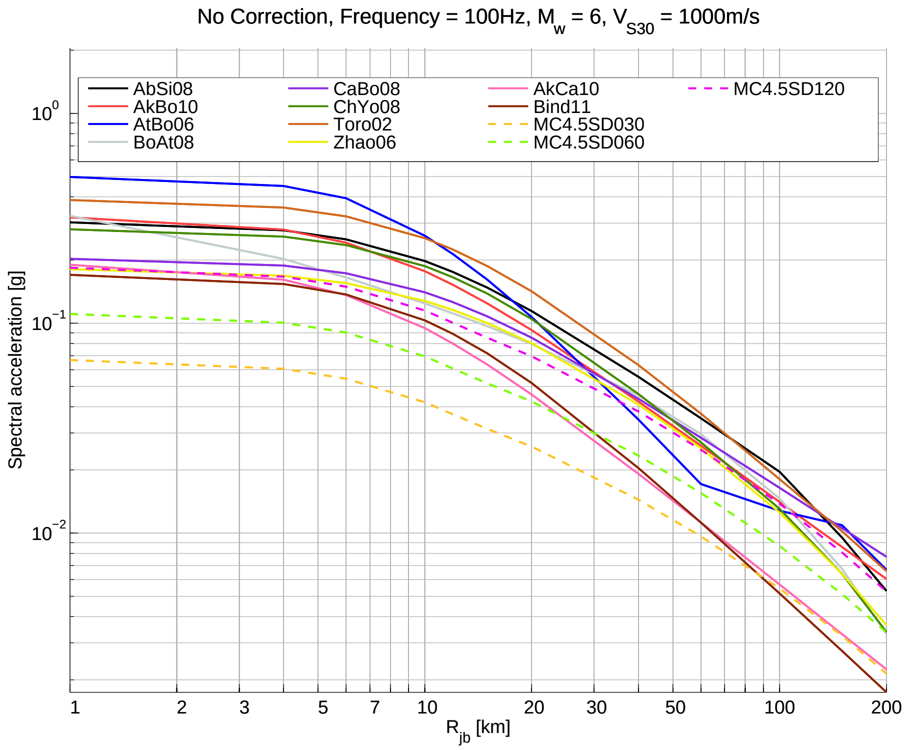
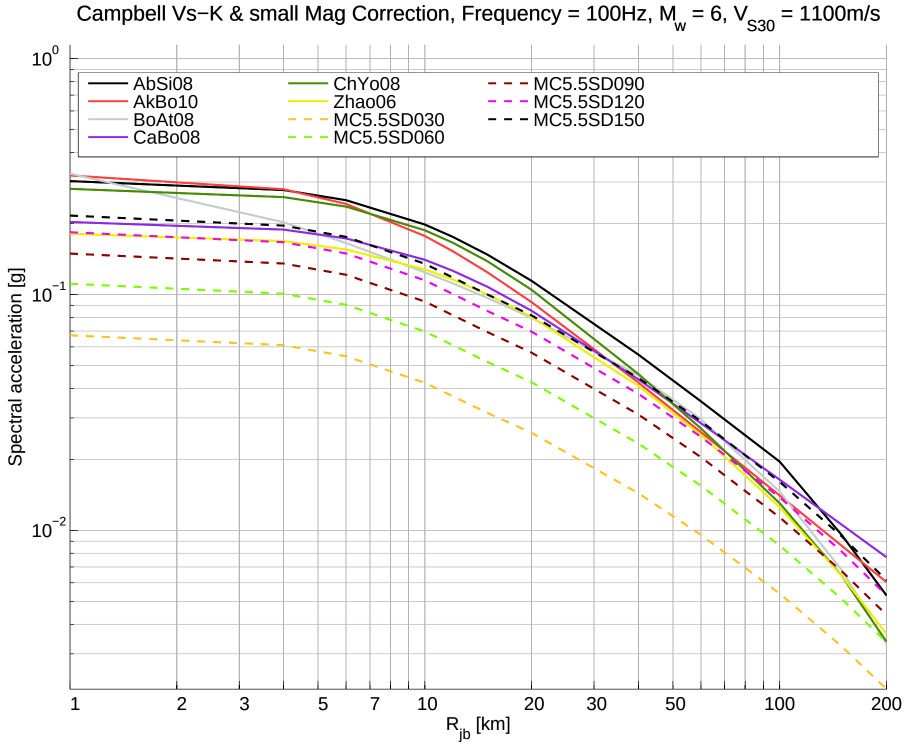


Figure A.8: Comparison of forecast earthquake recurrence rates for the four SP1 teams at Mühleberg. The comparison includes only a zone of 50 km around Mühleberg. Left: Combined team comparison between PEGASOS (2004) and PRP (Refinement), right: comparison of the individual team estimates with the combined mean and range.

A.2 Rock Ground Motion Comparisons

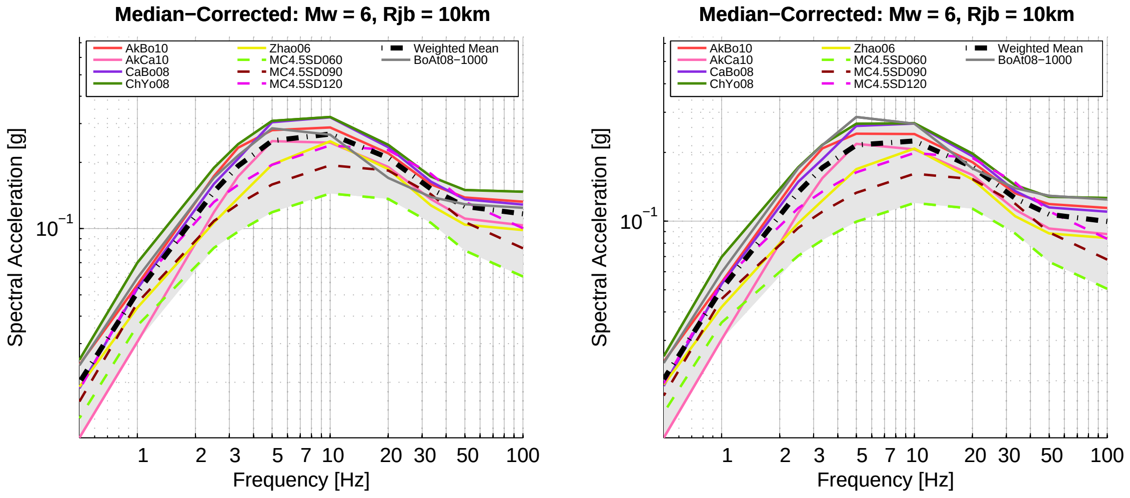


(a) 100 Hz, without corrections



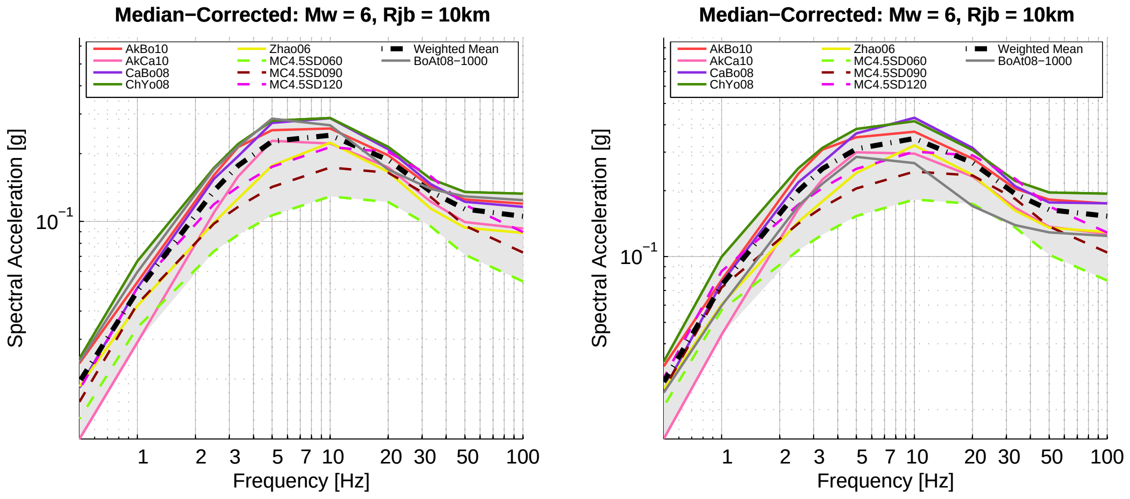
(b) 100 Hz, with corrections

Figure A.9: Comparison of distance scaling for all considered candidate GMPEs and PSSMs for magnitude 6 at 100 Hz. Note: At the end of the project, corrections were not available for all candidate GMPEs, as they were only developed for the NPP-specific conditions based on the individual expert estimates. As an example, for the plot with $V_S - \kappa$ corrections and small magnitude adjustments, the corrections of Campbell at KKM were used (Ver. May 2013).



(a) KKB

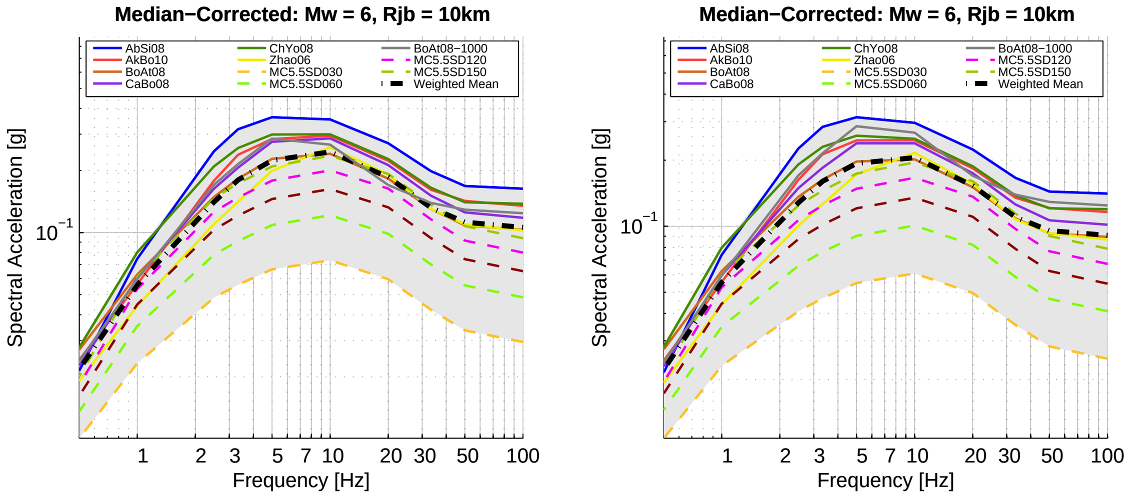
(b) KKG



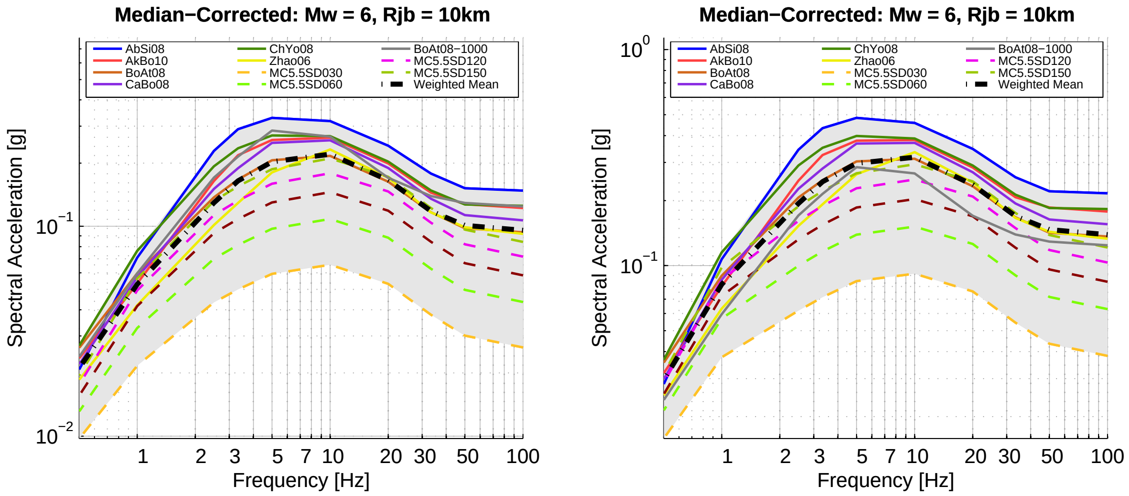
(c) KKL

(d) KKM

Figure A.10: For Bungum, comparison of median horizontal ground motions for M=6 and R=10 km at all four sites, based on $V_S - \kappa$ corrections of May 2013. The expert specific weighted mean of all models is represented by a thick black chain dotted line. Note: The Boore & Atkinson [2008] model with 1000 m/s and without corrections is shown as dark grey curve and designed as ”BoAt08-1000” in the color legend.

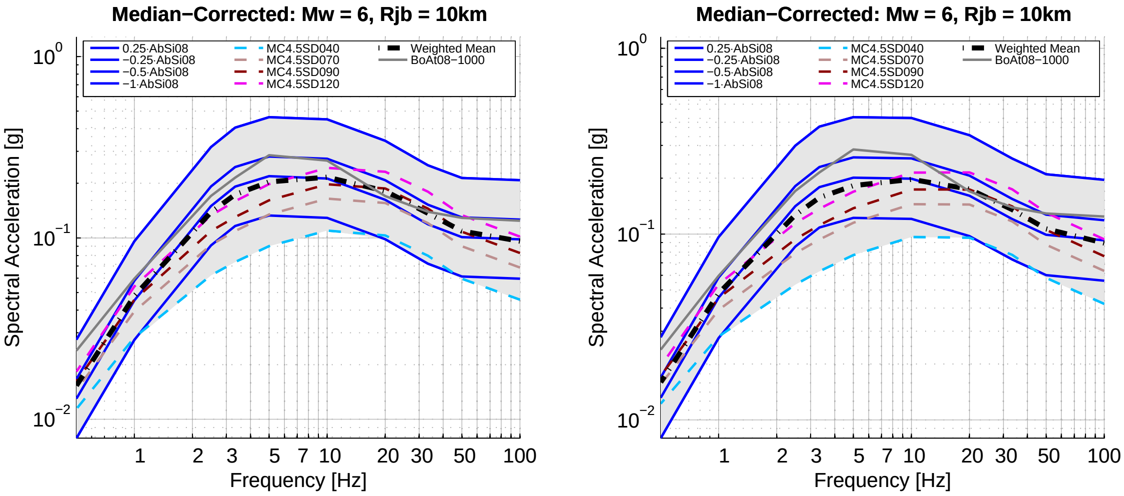


(a) KKB (b) KKG



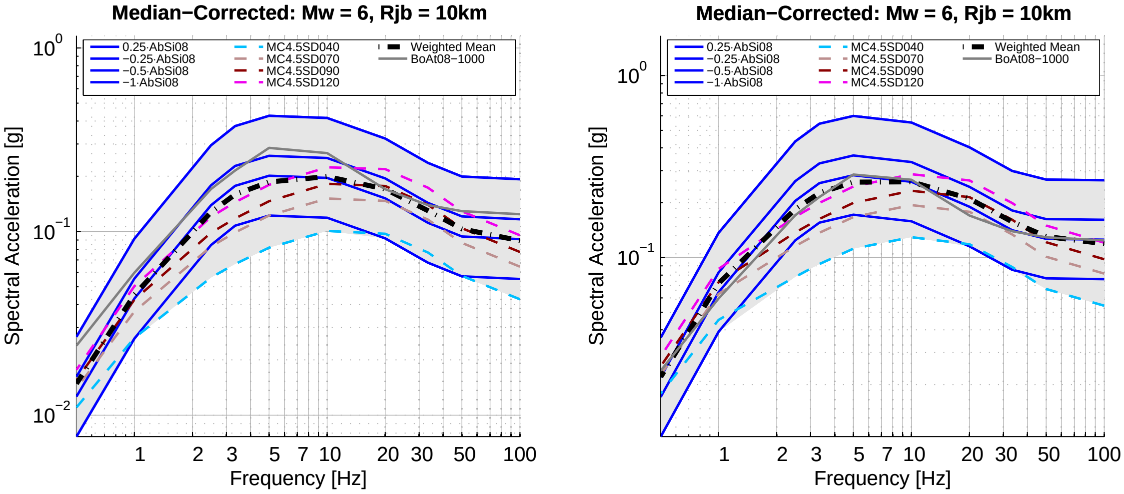
(c) KKL (d) KKM

Figure A.11: For Campbell, comparison of median horizontal ground motions for M=6 and R=10 km at all four sites, based on $V_S - \kappa$ corrections of May 2013. The expert specific weighted mean of all models is represented by a thick black chain dotted line. Note: The Boore & Atkinson [2008] model with 1000 m/s and without corrections is shown as dark grey curve and designed as "BoAt08-1000" in the color legend.



(a) KKB

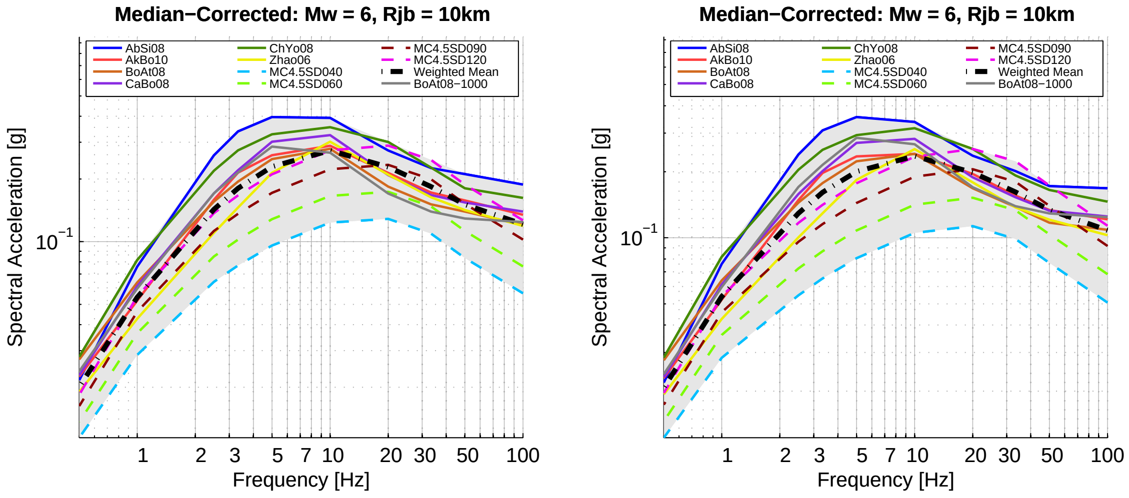
(b) KKG



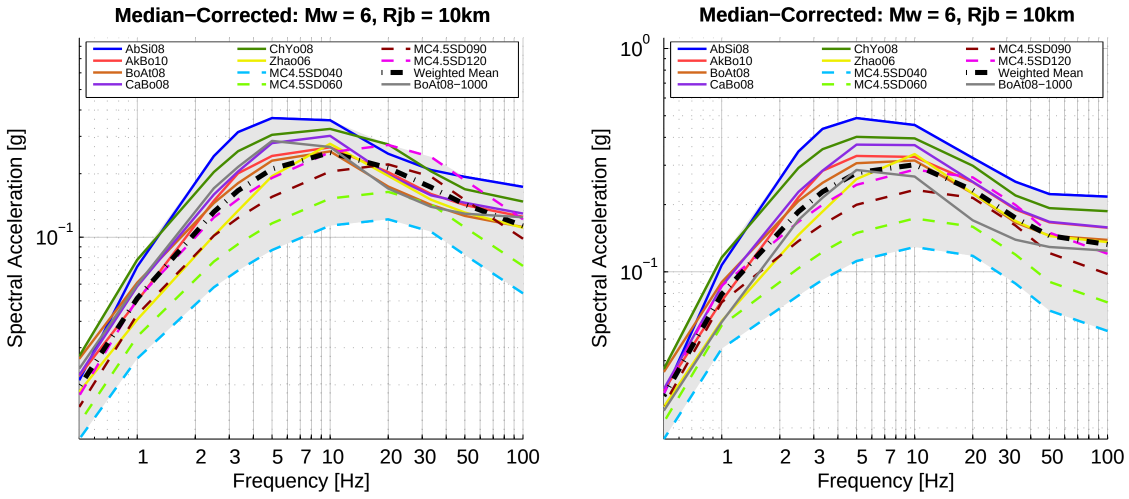
(c) KKL

(d) KKM

Figure A.12: For Cotton, comparison of median horizontal ground motions for M=6 and R=10 km at all four sites, based on $V_S - \kappa$ corrections of May 2013. The expert specific weighted mean of all models is represented by a thick black chain dotted line. Note: The Boore & Atkinson [2008] model with 1000 m/s and without corrections is shown as dark grey curve and designed as "BoAt08-1000" in the color legend.

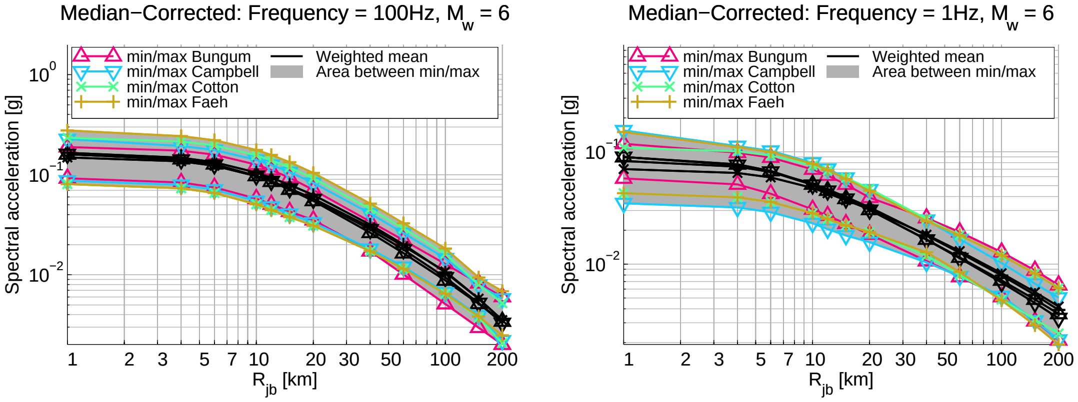


(a) KKB (b) KKG

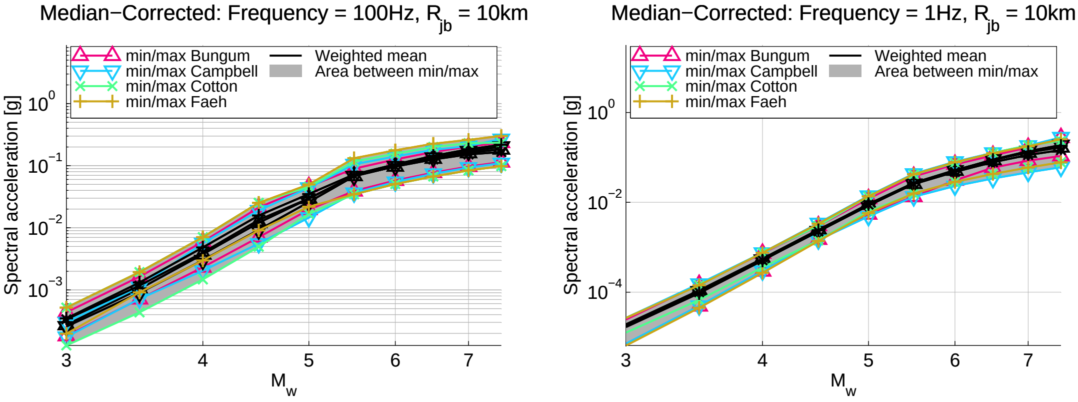


(c) KKL (d) KKM

Figure A.13: For Fäh, comparison of median horizontal ground motions for M=6 and R=10 km at all four sites, based on $V_S - \kappa$ corrections of May 2013. The expert specific weighted mean of all models is represented by a thick black chain dotted line. Note: The Boore & Atkinson [2008] model with 1000 m/s and without corrections is shown as dark grey curve and designed as "BoAt08-1000" in the color legend.

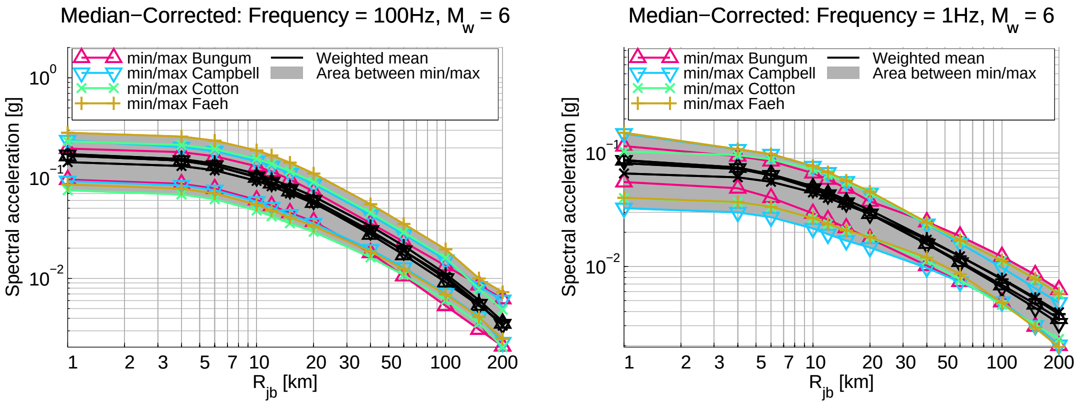


(a) Comparison of Sa vs. R for M_W=6

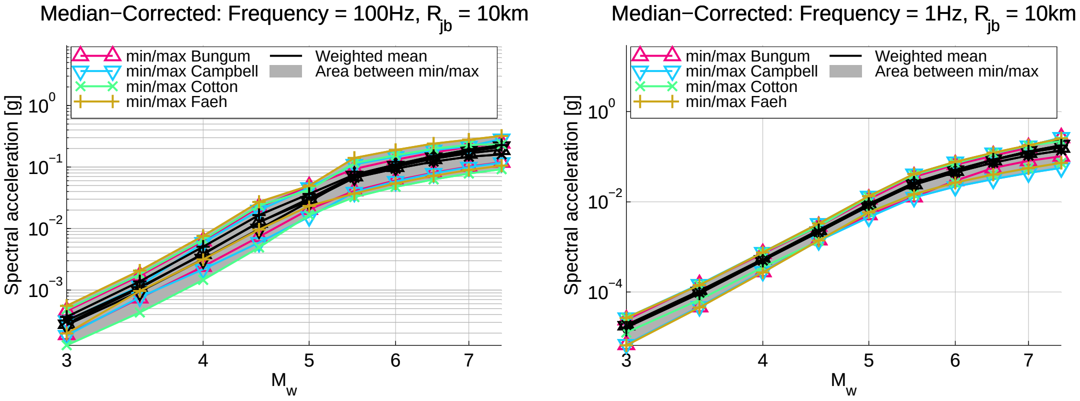


(b) Comparison of Sa vs. M_W at R=10 km.

Figure A.14: Gösgen, Comparison of the expert weighted mean and range of horizontal ground motions for 100 Hz (left) and 1 Hz (right), based on $V_S - \kappa$ corrections of May 2013.

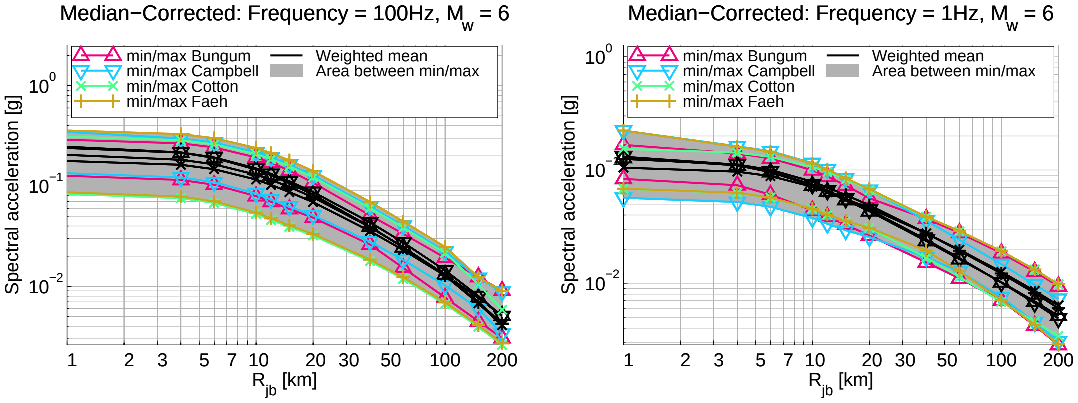


(a) Comparison of Sa vs. R for M_W=6

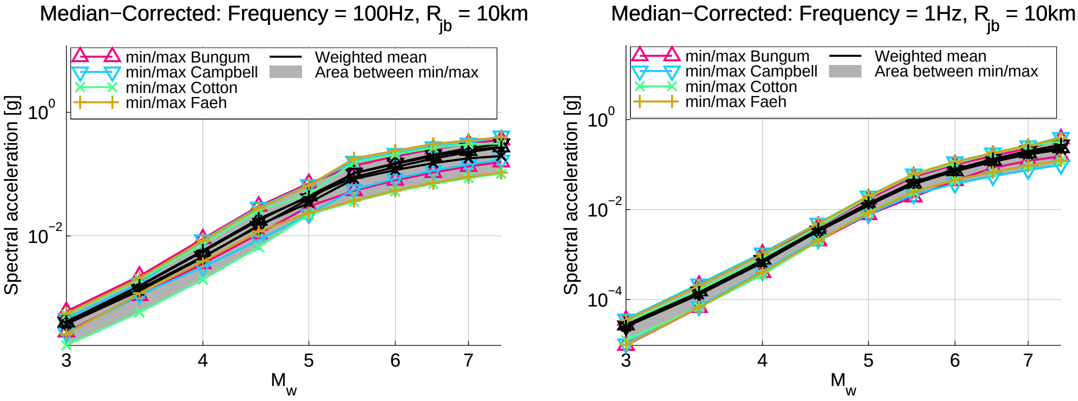


(b) Comparison of Sa vs. M_W at R=10 km.

Figure A.15: LeibstadtComparison of the expert weighted mean and range of horizontal ground motions for 100 Hz (left) and 1 Hz (right), based on $V_S - \kappa$ corrections of May 2013.



(a) Comparison of Sa vs. R for M_W=6



(b) Comparison of Sa vs. M_W at R=10 km.

Figure A.16: Mühleberg, Comparison of the expert weighted mean and range of horizontal ground motions for 100 Hz (left) and 1 Hz (right), based on $V_S - \kappa$ corrections of May 2013.

A.2.1 Rock, V/H Model Comparison

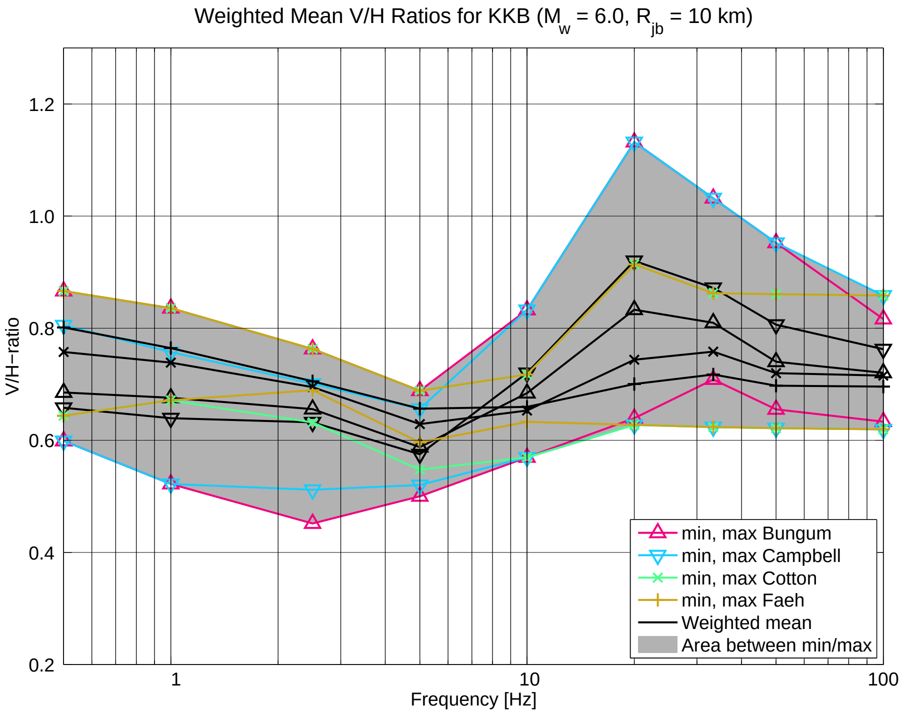


Figure A.17: Beznau, Comparison of the range of V/H models for the four PRP SP2 experts.

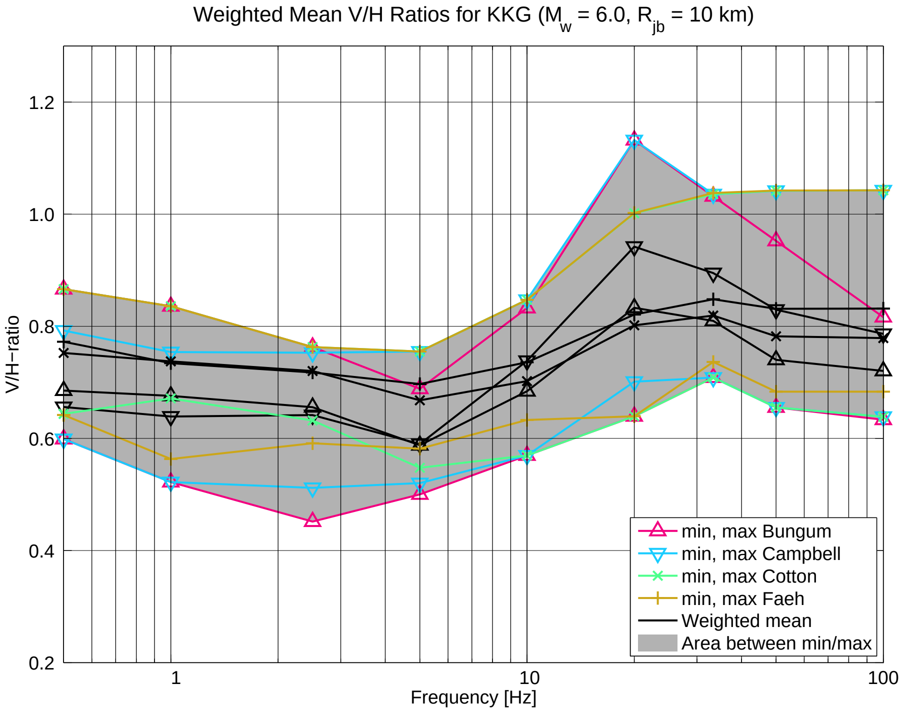


Figure A.18: Gösgen, Comparison of the range of V/H models for the four PRP SP2 experts.

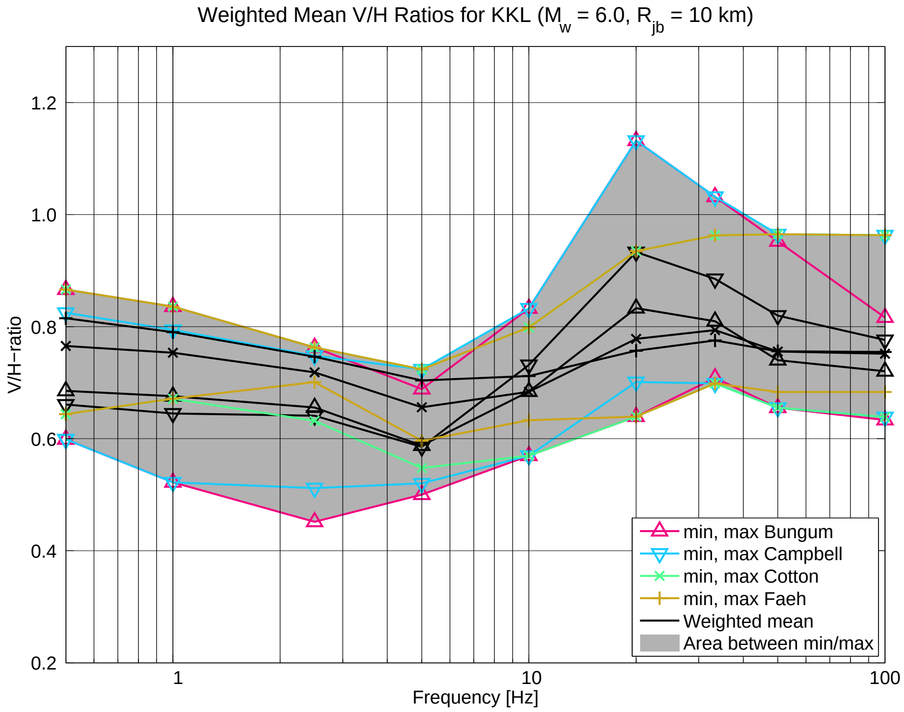


Figure A.19: Leibstadt, Comparison of the range of V/H models for the four PRP SP2 experts.

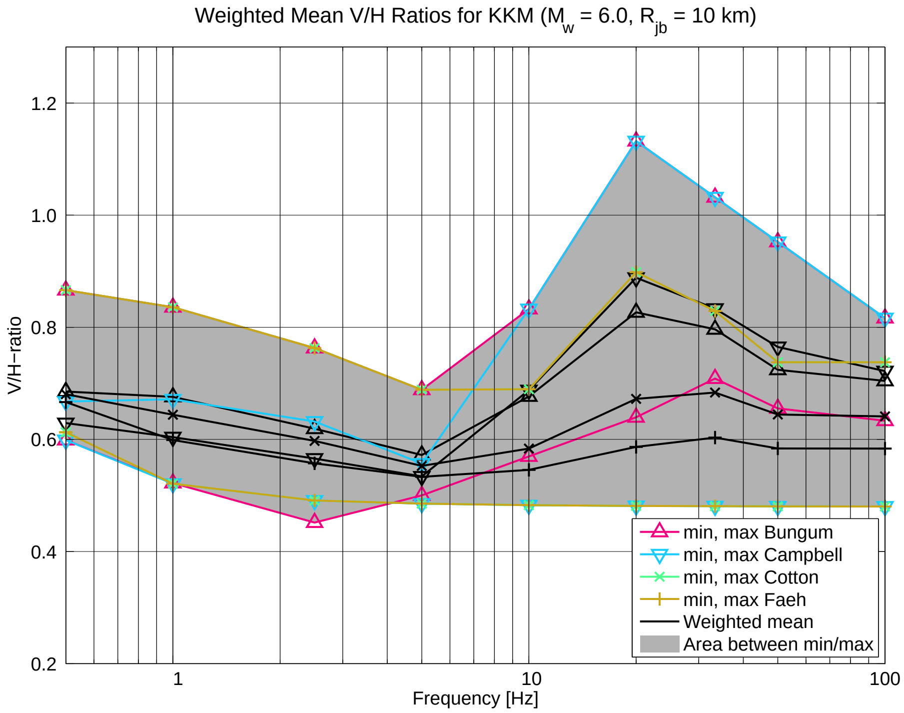


Figure A.20: Mühleberg, Comparison of the range of V/H modelsfor the four PRP SP2 experts.

A.2.2 Rock, Aleatory Variability Model Comparison

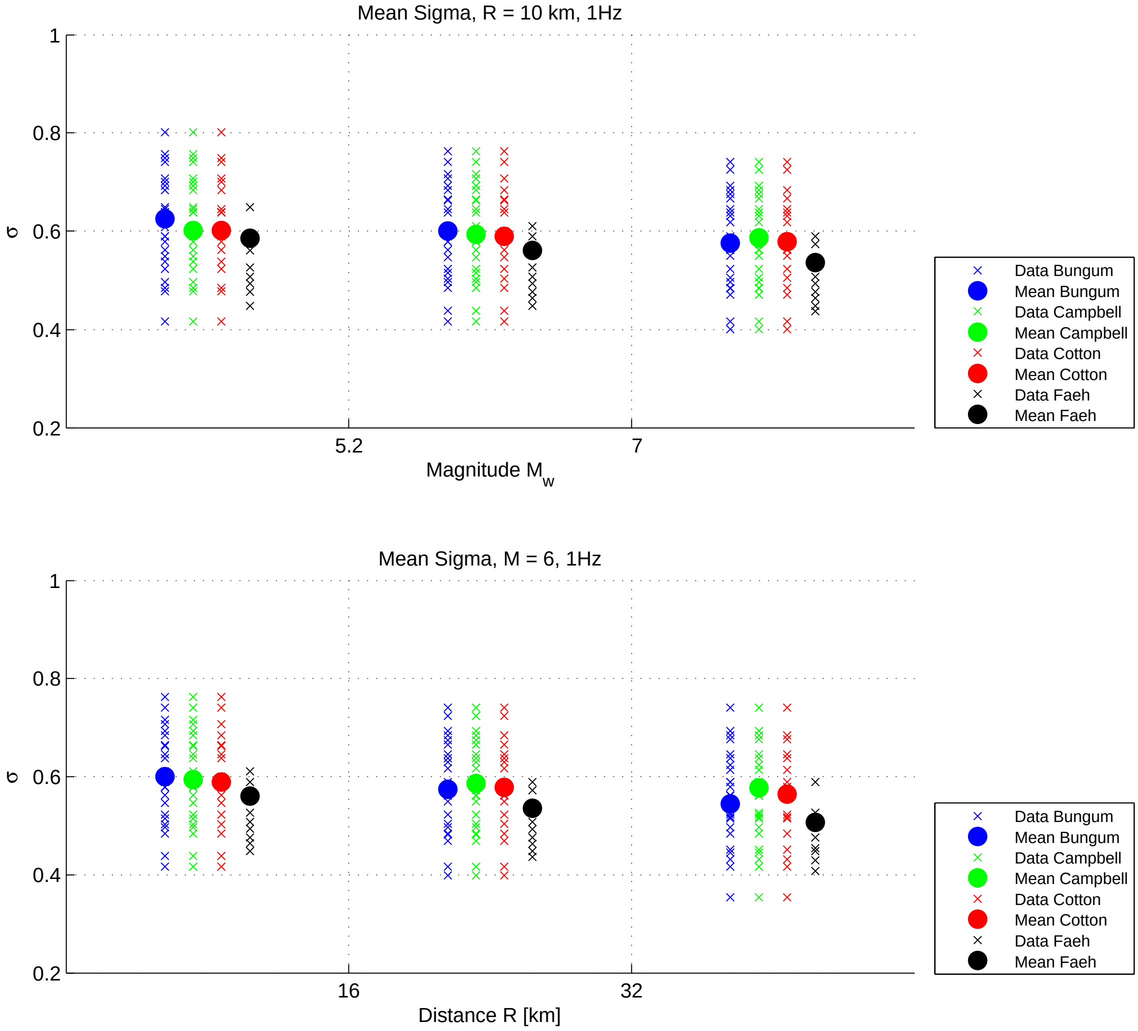


Figure A.21: Comparison of the single-station σ models for 1 Hz by SP2 expert.

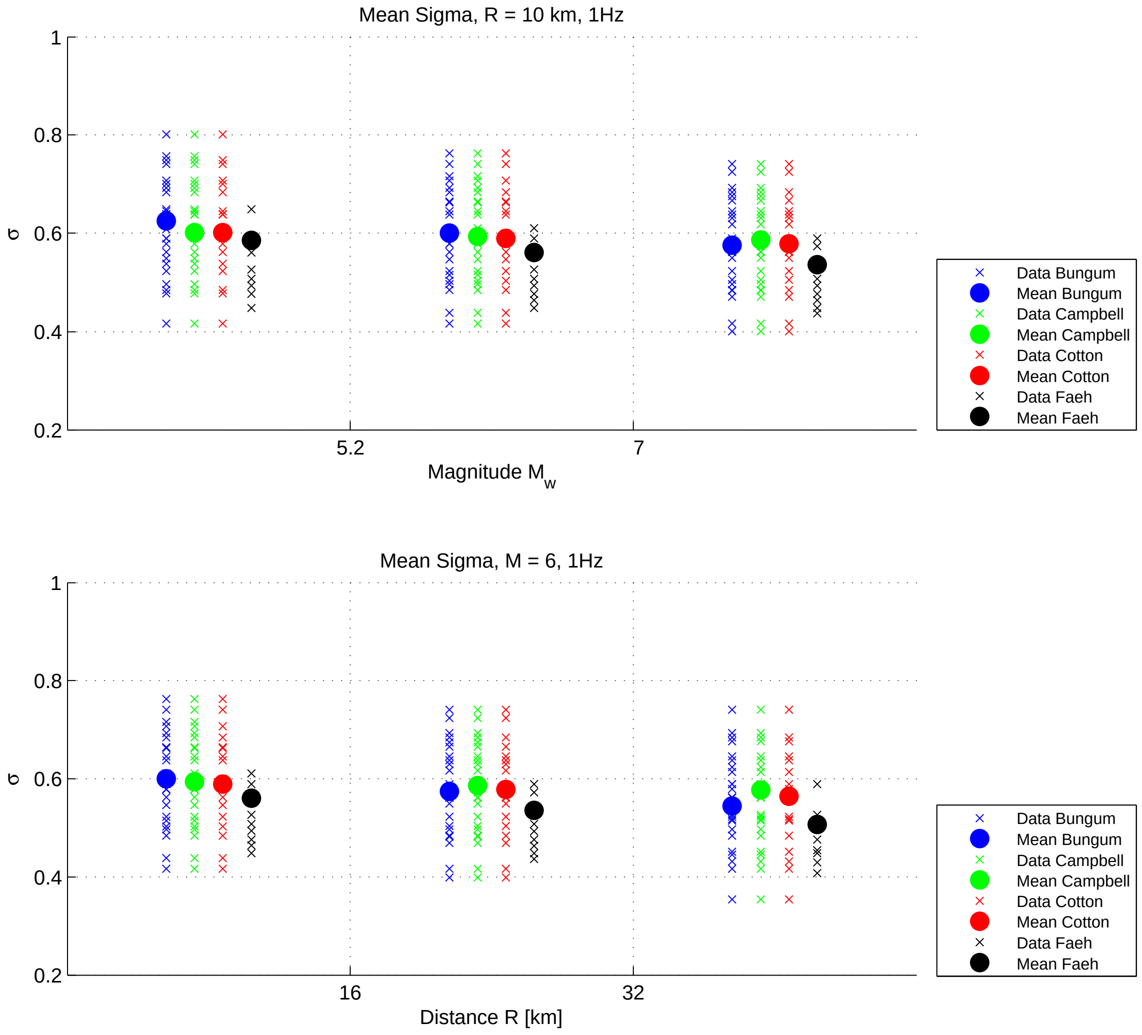


Figure A.22: Comparison of the single-station σ models for 100 Hz by SP2 expert.

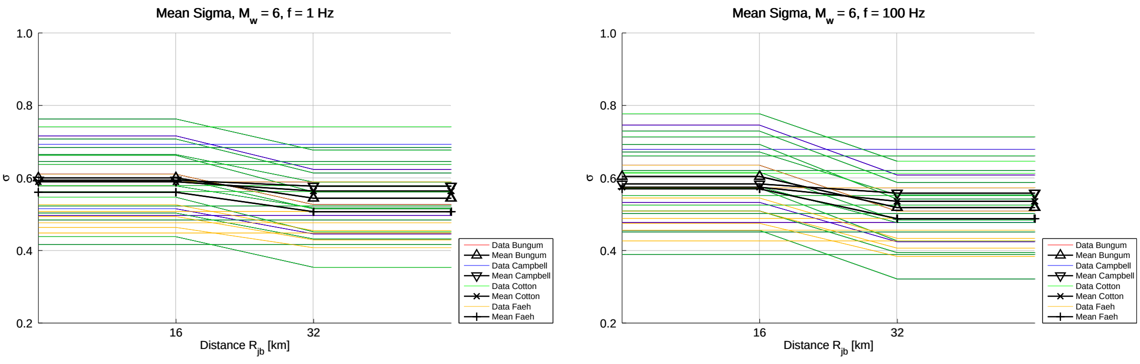


Figure A.23: Comparison of the single-station σ models in dependence of distance for 1 Hz (left) and 100 Hz (right) by SP2 expert.

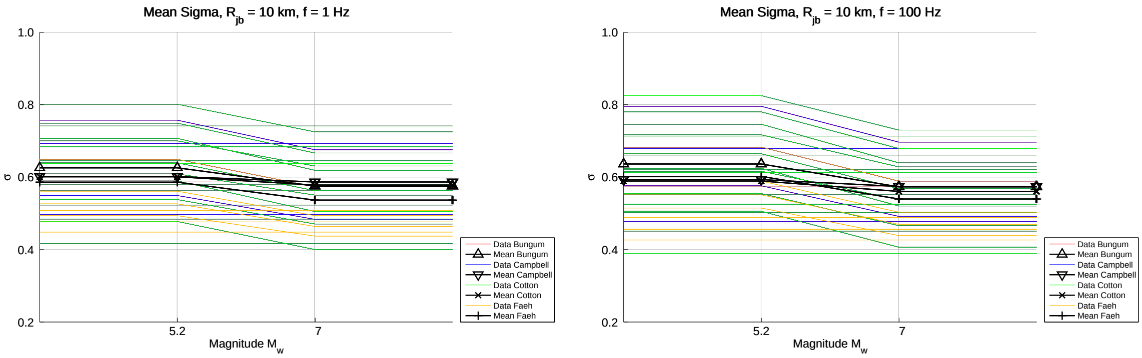
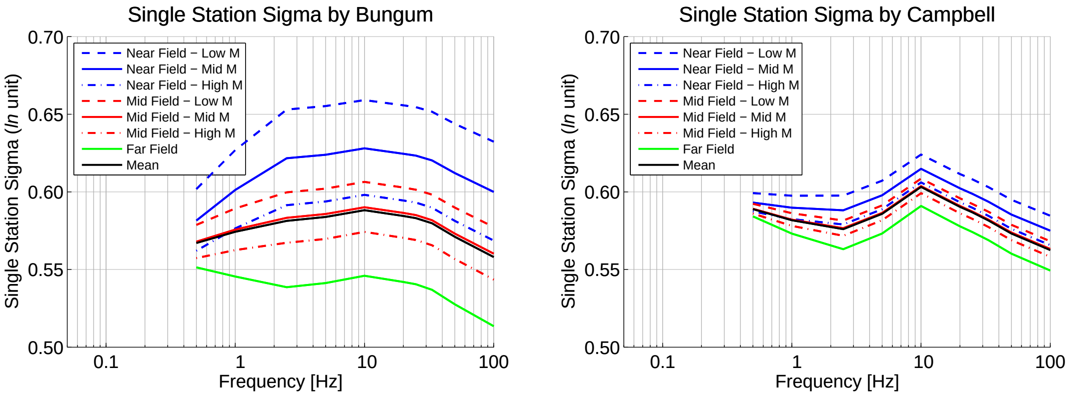
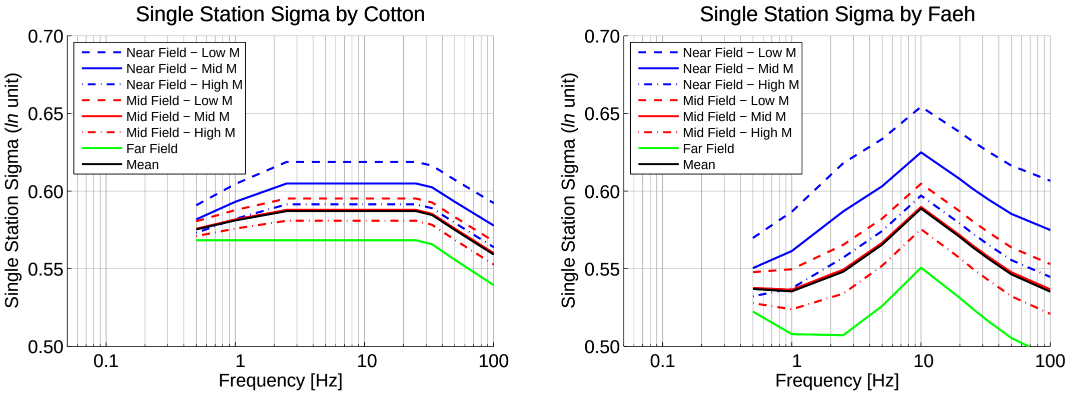


Figure A.24: Comparison of the single-station σ models in dependence of magnitude for 1 Hz (left) and 100 Hz (right) Hz by SP2 expert.

Figure A.25 shows the comparison of the single-station σ models for each expert as a function of frequency for the nine $M - R$ bins. Herein the three distance bins are divided by the three bins around and between 16 km and 36 km. The three magnitude bins are defined by M=5.2 (for periods < 1 s) and M=7 (for 1 s the limit is M=5.3 and for 3 s it is 5.5) [Rodriguez-Marek and Cotton 2011].

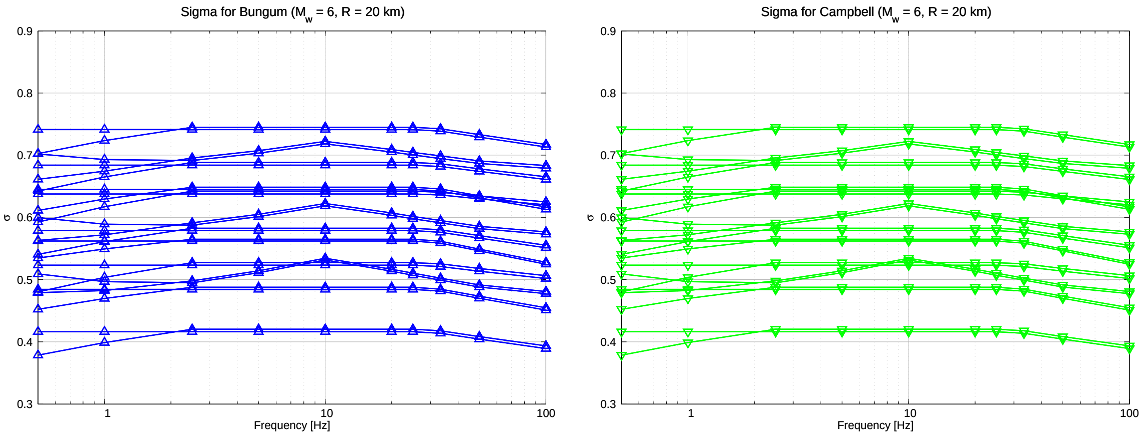


(a) Bungum (b) Campbell

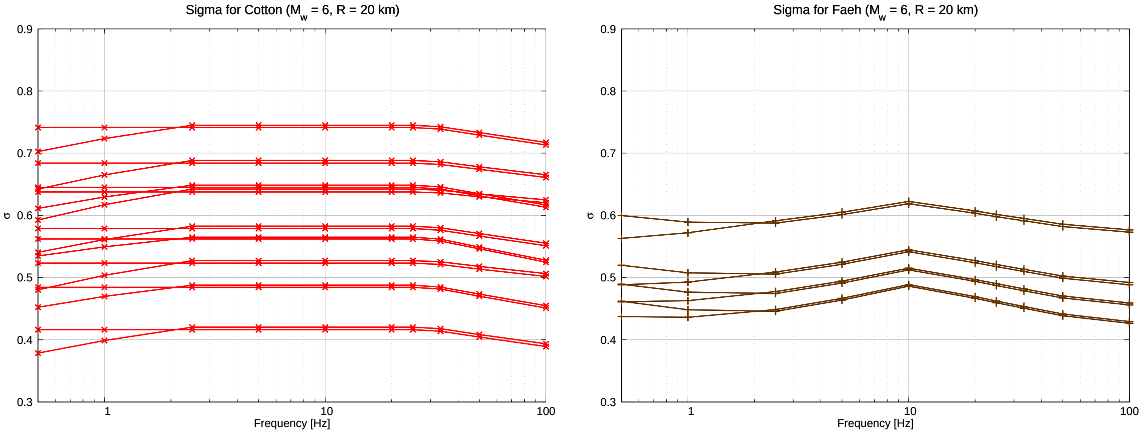


(c) Cotton (d) Fäh

Figure A.25: Comparison of the single-station sigma models in the 9 $M - R$ bins by SP2 expert.



(a) Bungum (b) Campbell



(c) Cotton (d) Fäh

Figure A.26: Comparison of the expert specific σ models for M=6 and R=20 km.

A.2.3 Rock, Maximum Ground Motion

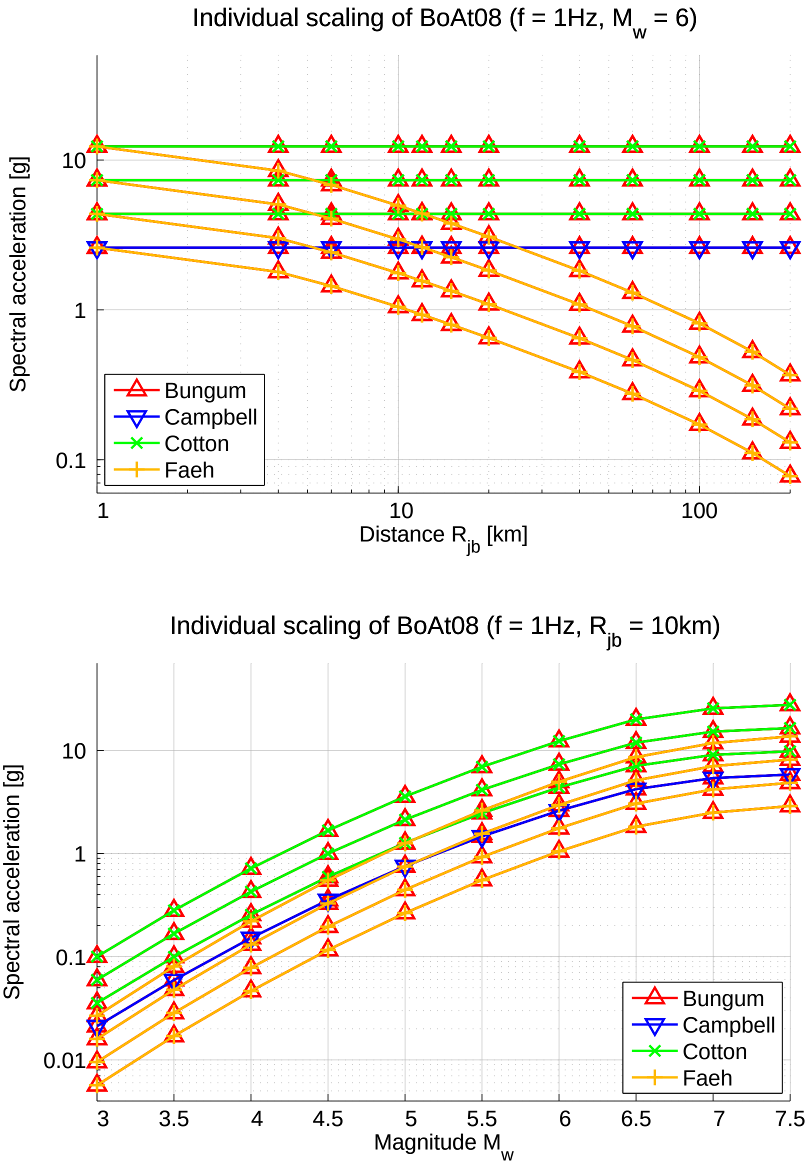


Figure A.27: Comparison of the individual horizontal maximum ground motion truncation models for all four experts for R=10 km and M=6 at 1 Hz.

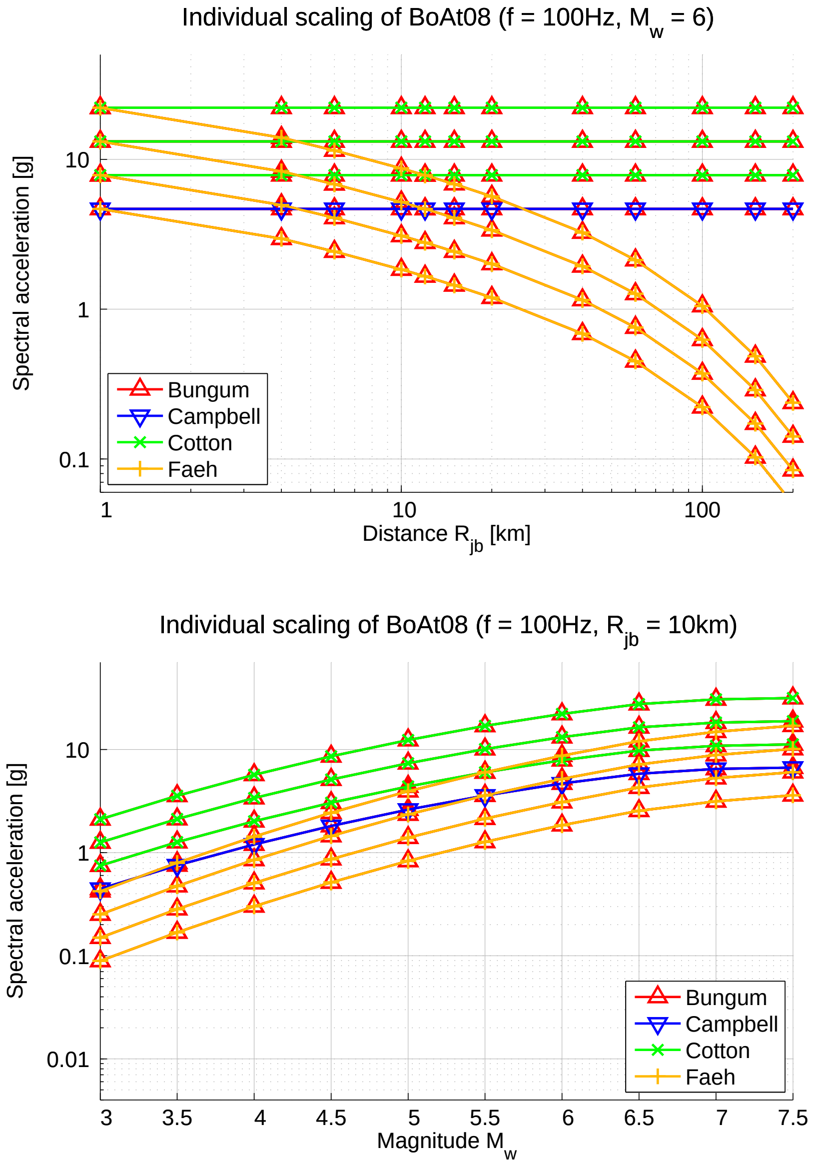
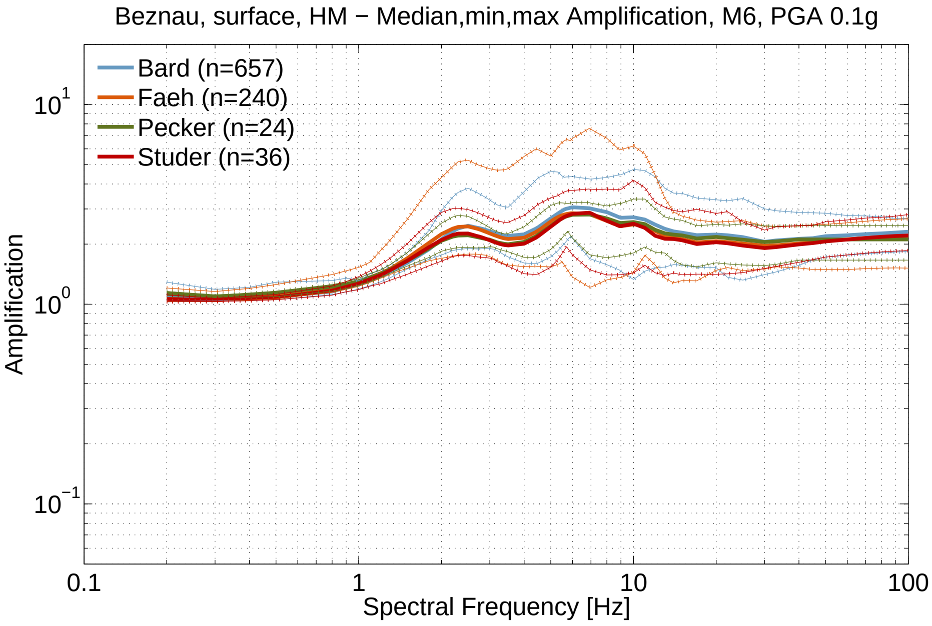


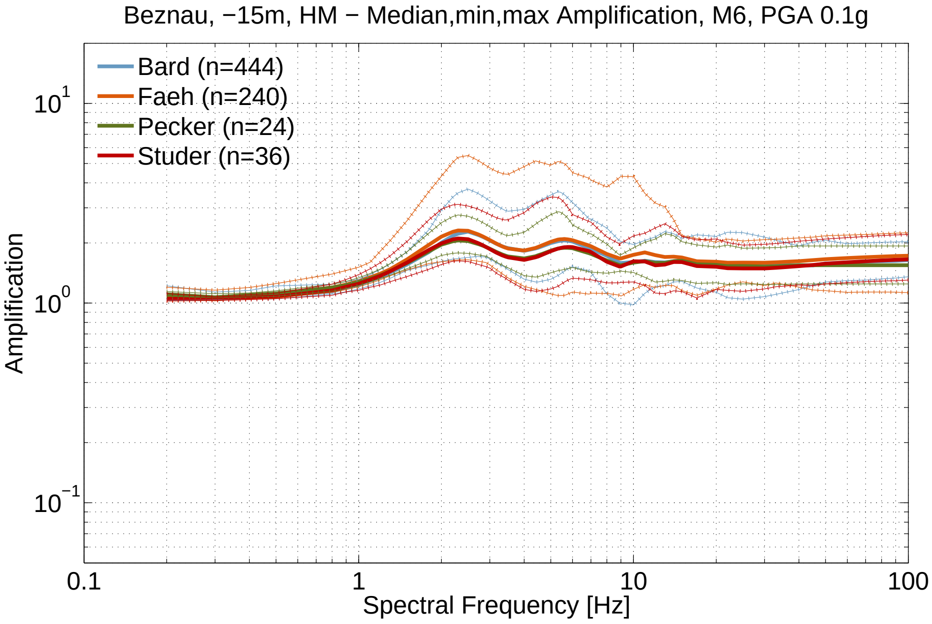
Figure A.28: Comparison of the individual horizontal maximum ground motion truncation models for all four experts for R=10 km and M=6 at 100 Hz.

A.3 Comparisons of Soil Models

A.3.1 Beznau

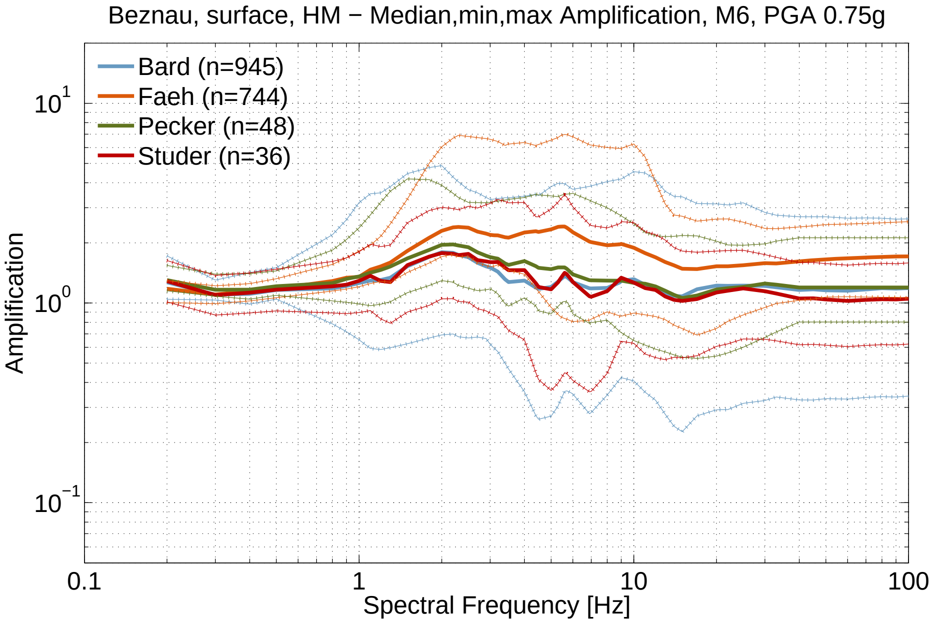


(a)

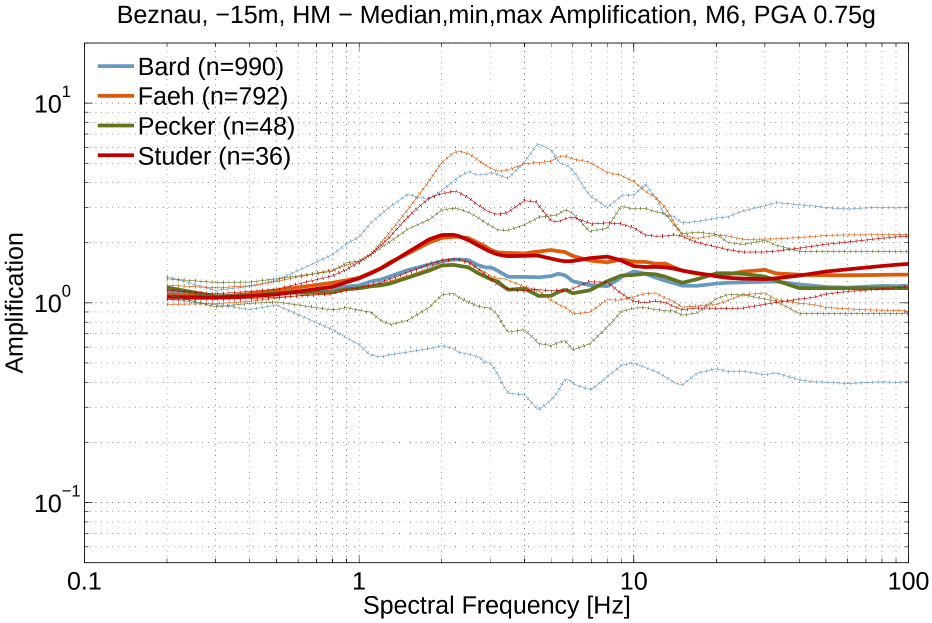


(b)

Figure A.29: Beznau, surface and sub-depth level, horizontal amplification, comparison of expert ranges for 0.1 g.

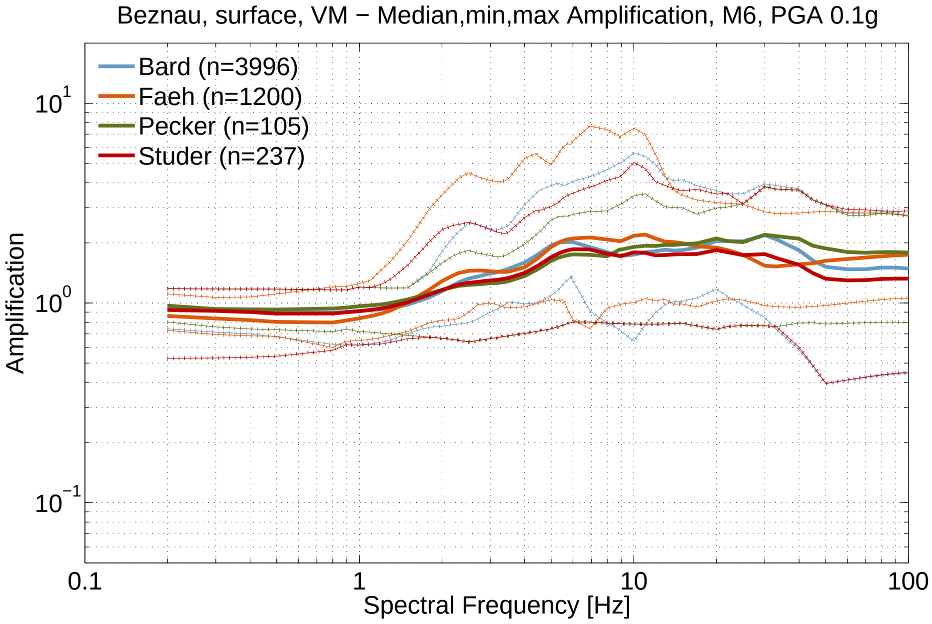


(a)

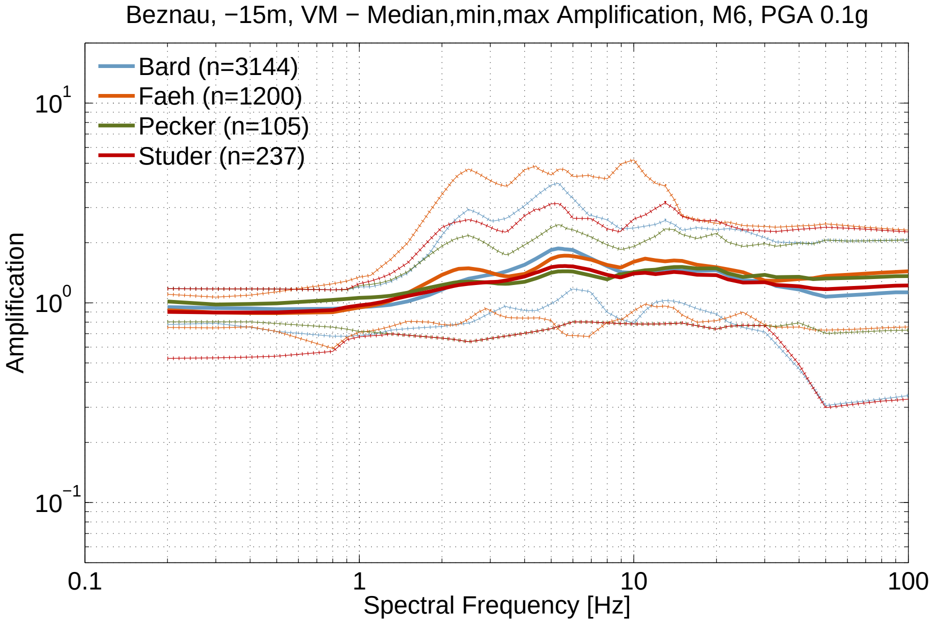


(b)

Figure A.30: Beznau, surface and sub-depth level, horizontal amplification, comparison of expert ranges for 0.75 g.

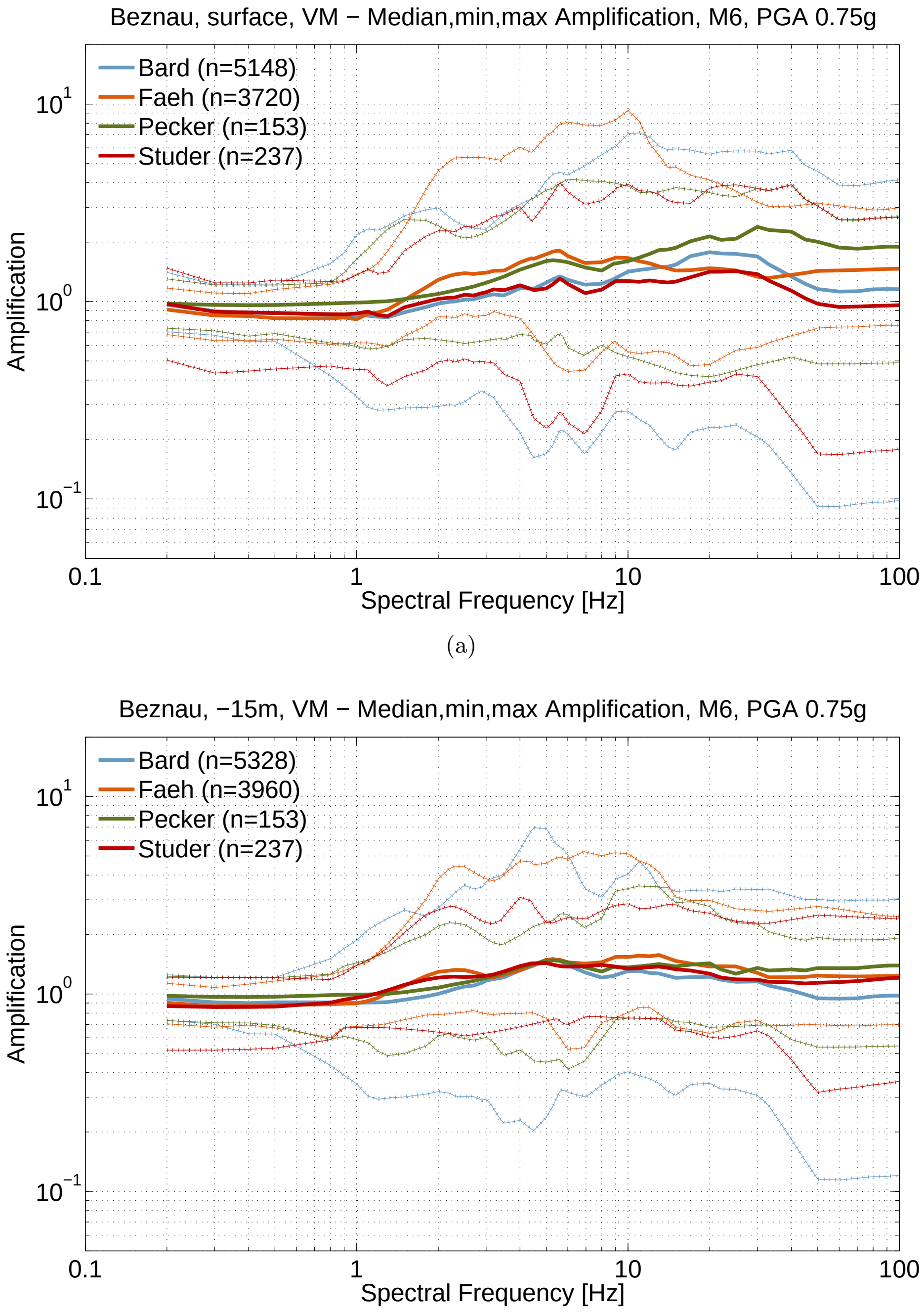


(a)



(b)

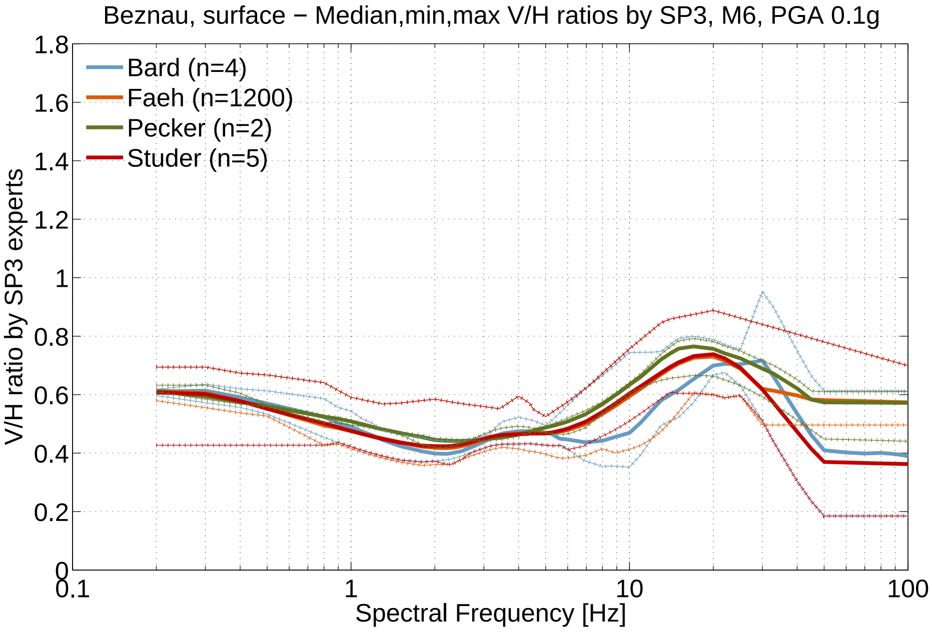
Figure A.31: Beznau, surface and sub-depth level, vertical amplification, comparison of expert ranges for 0.1 g.



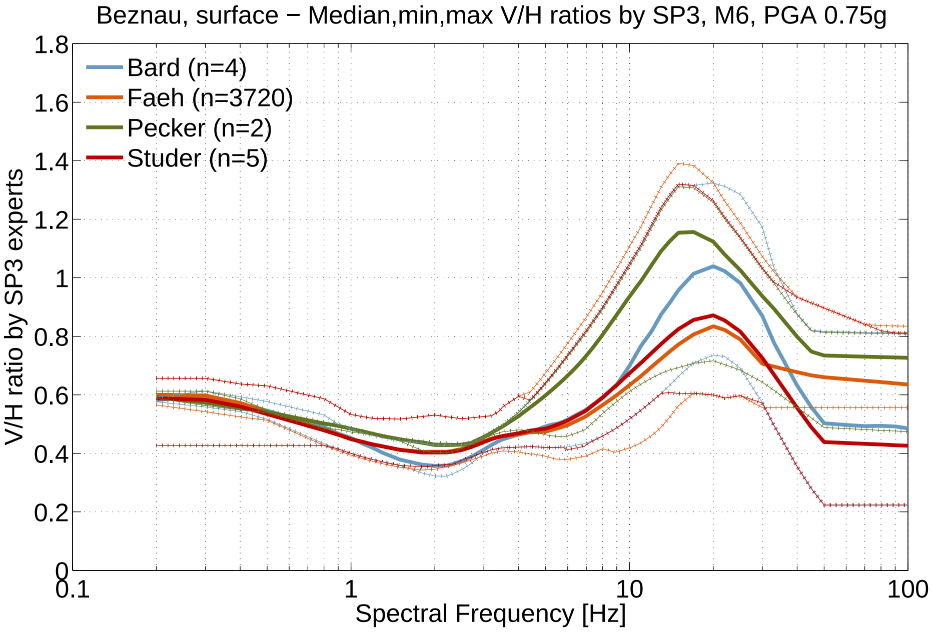
(a)

(b)

Figure A.32: Beznau, surface and sub-depth level, vertical amplification, comparison of expert ranges for 0.75 g.

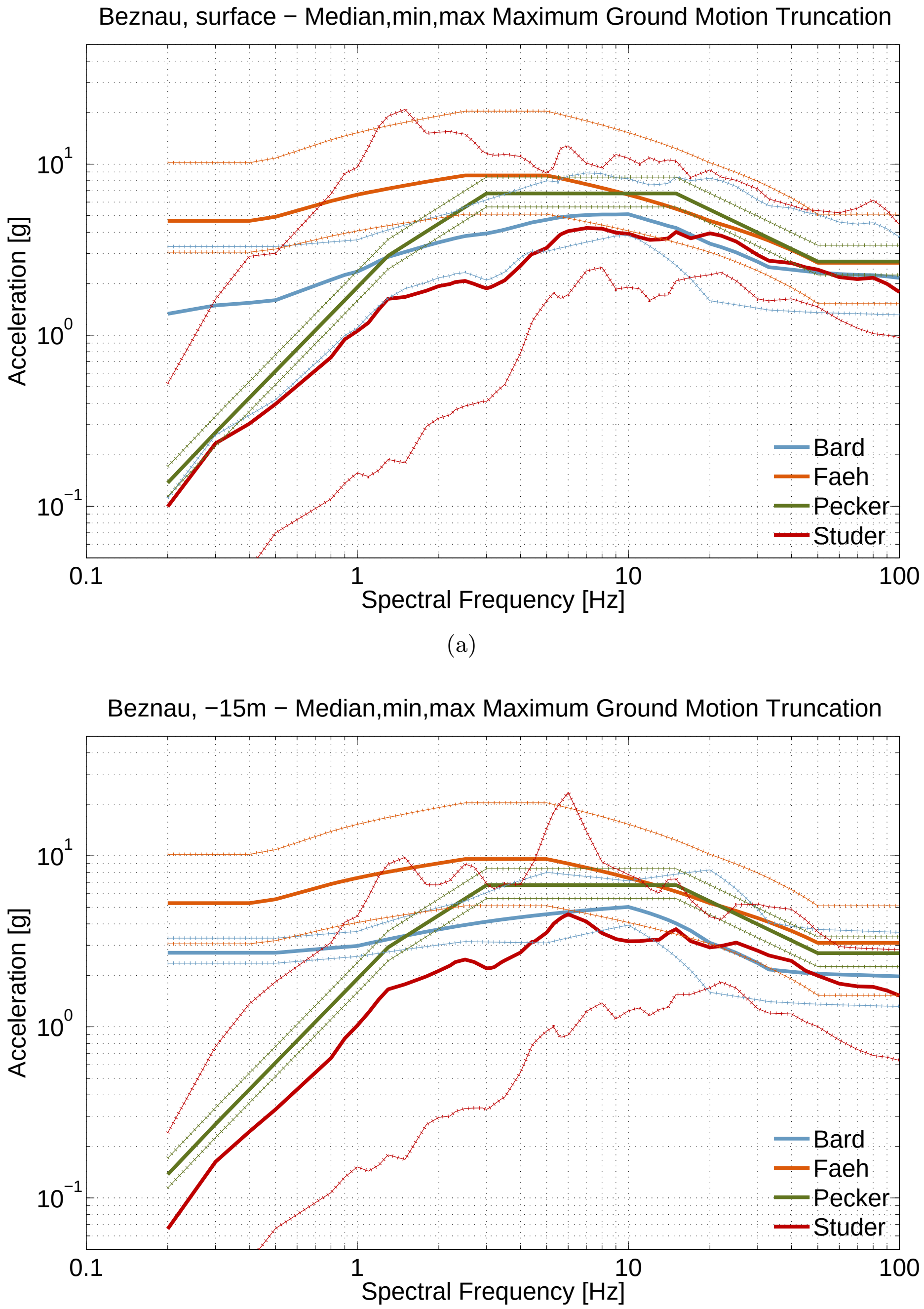


(a)



(b)

Figure A.33: Beznau, surface and sub-depth level, V/H ratios, comparison of expert ranges for 0.1 and 0.75 g.

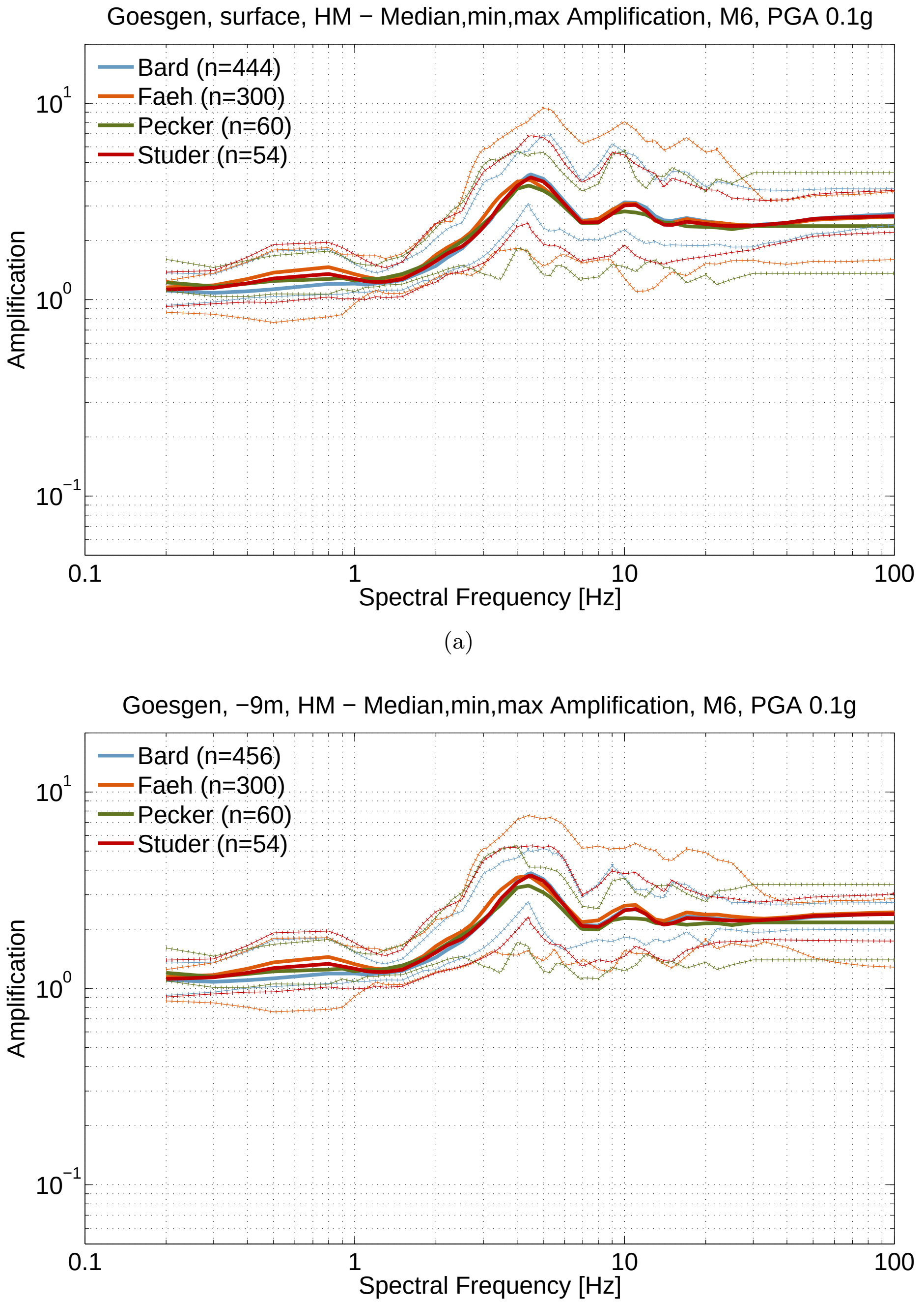


(a)

(b)

Figure A.34: Beznau, surface and sub-depth level, maximum ground motion truncation models, comparison of expert ranges.

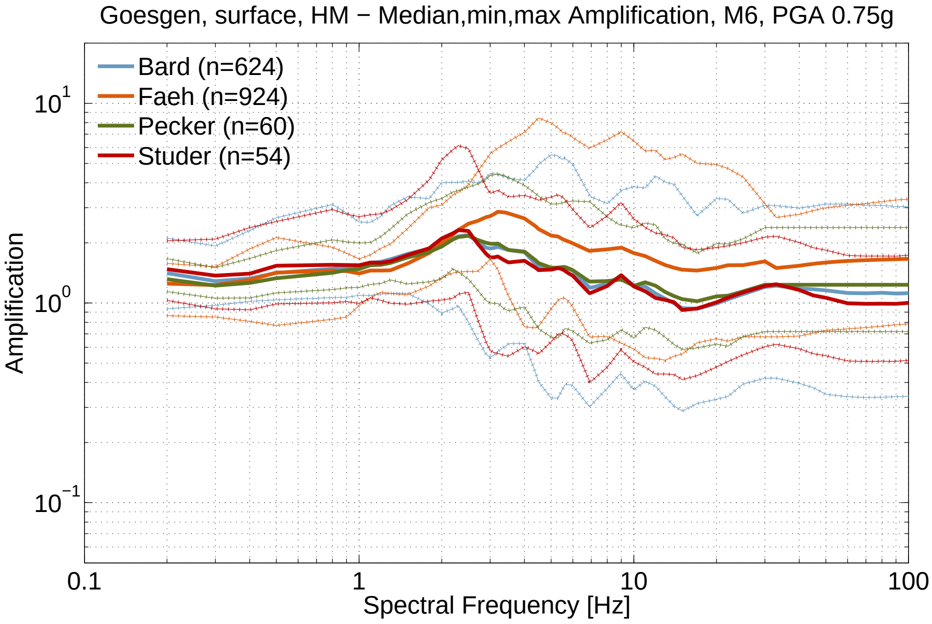
A.3.2 Gösgen



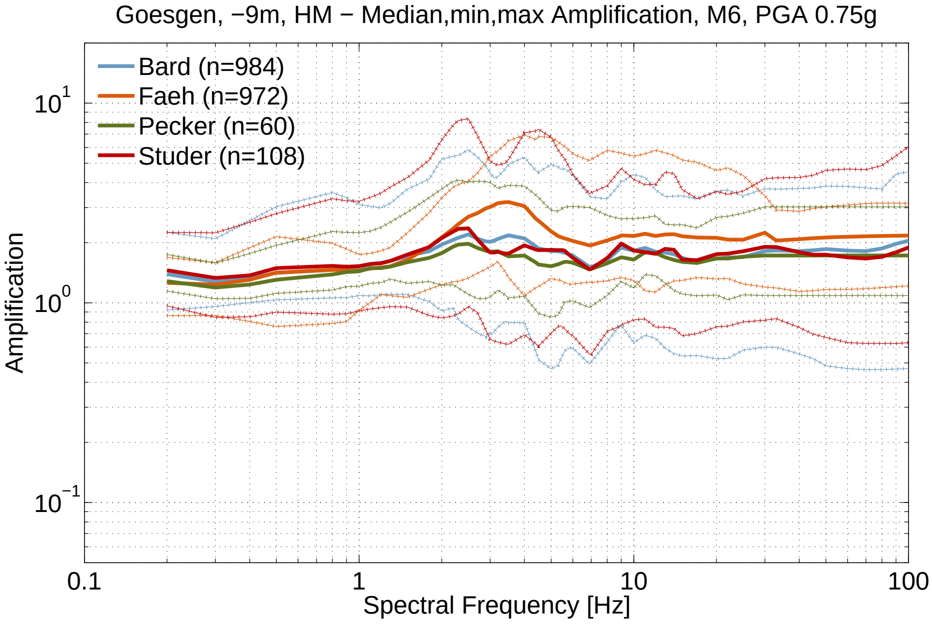
(a)

(b)

Figure A.35: Gösgen, surface and sub-depth level, horizontal amplification, comparison of expert ranges for 0.1 g.

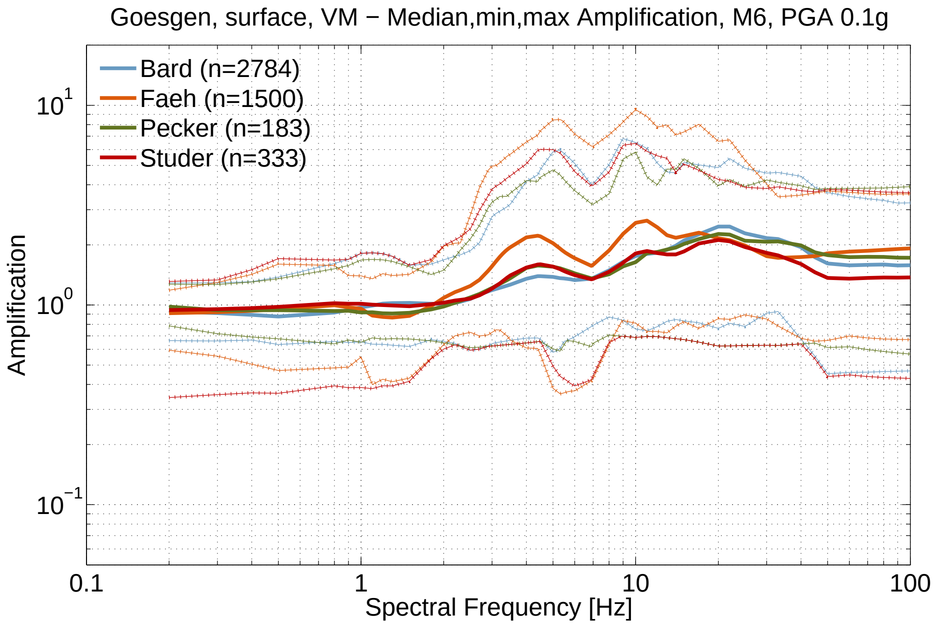


(a)

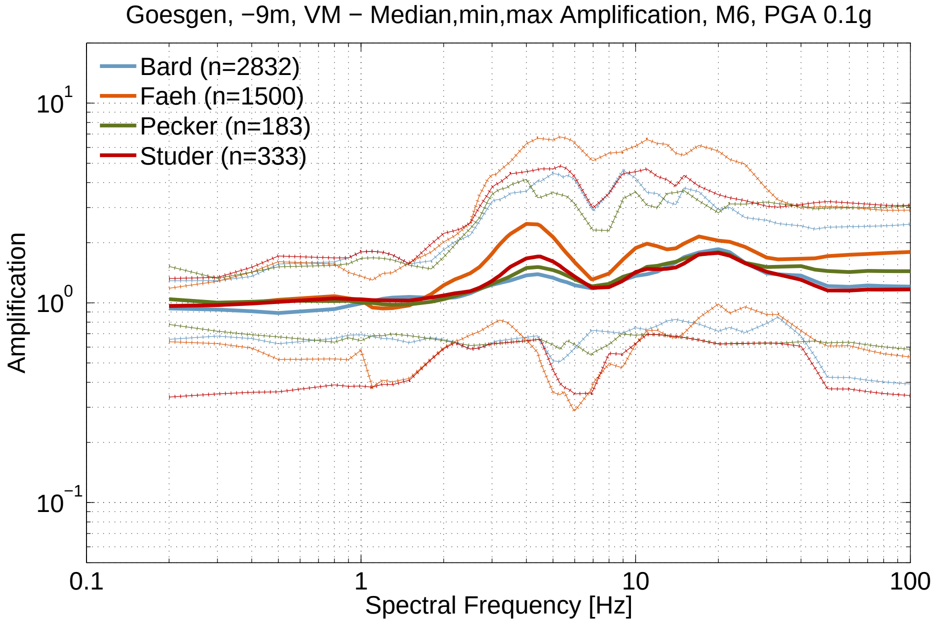


(b)

Figure A.36: Gösgen, surface and sub-depth level, horizontal amplification, comparison of expert ranges for 0.75 g.

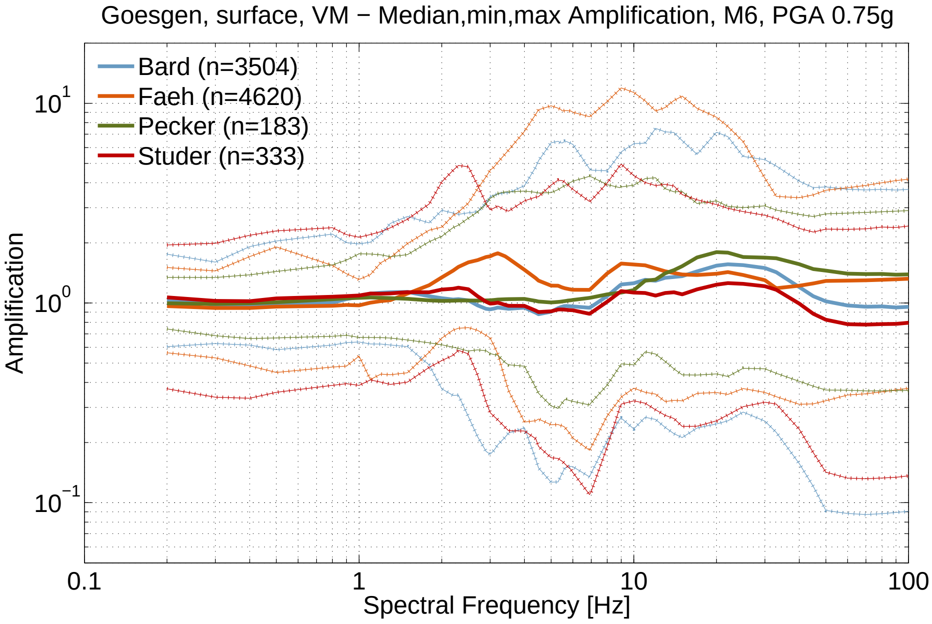


(a)

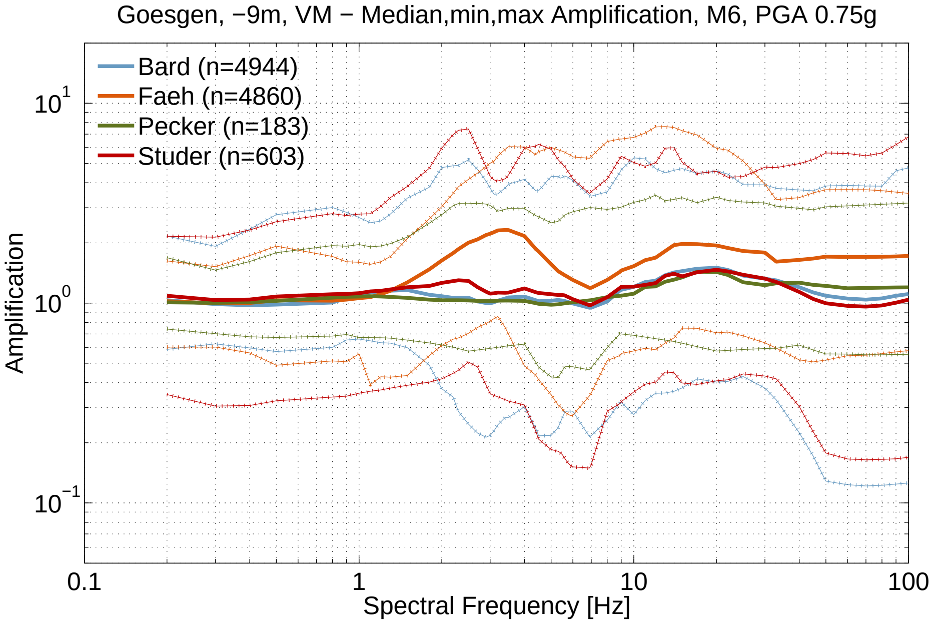


(b)

Figure A.37: Gösgen, surface and sub-depth level, vertical amplification, comparison of expert ranges for 0.1 g.

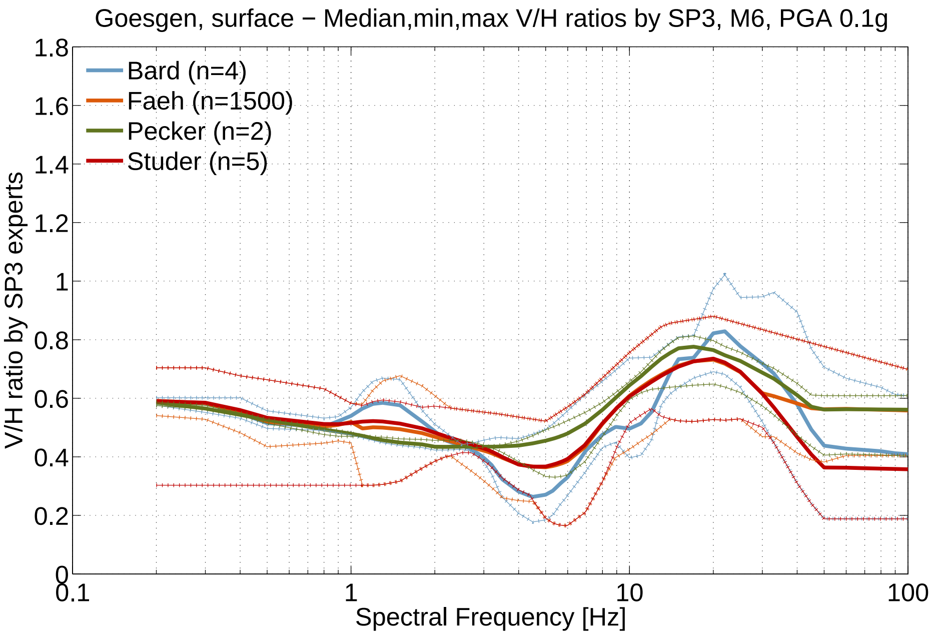


(a)

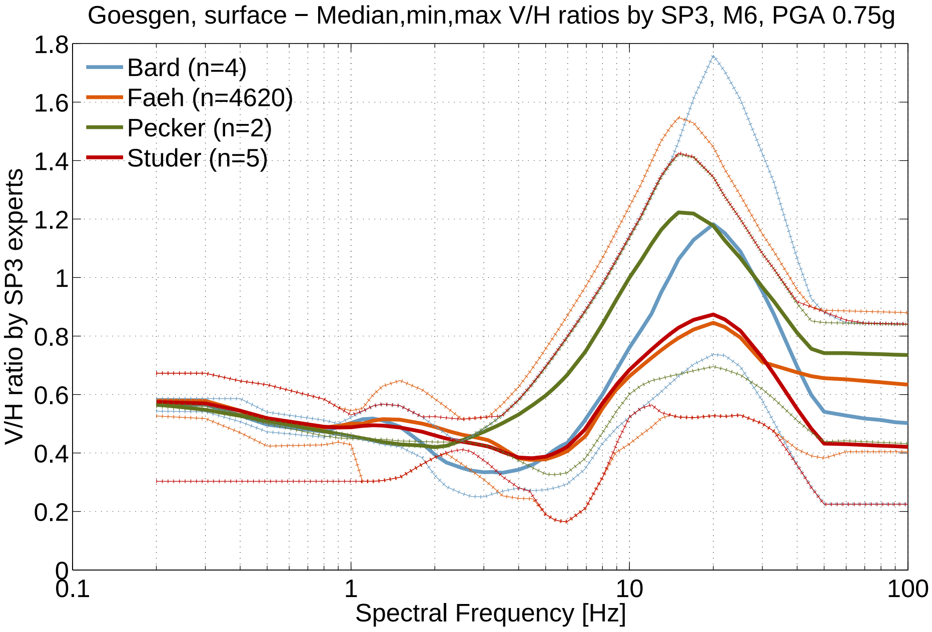


(b)

Figure A.38: Gösgen, surface and sub-depth level, vertical amplification, comparison of expert ranges for 0.75 g.

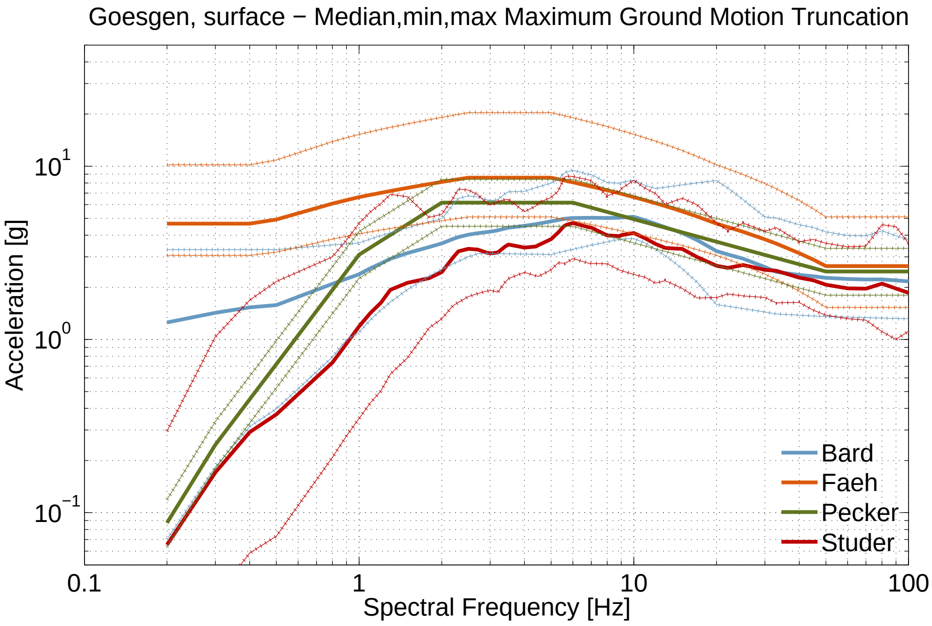


(a)

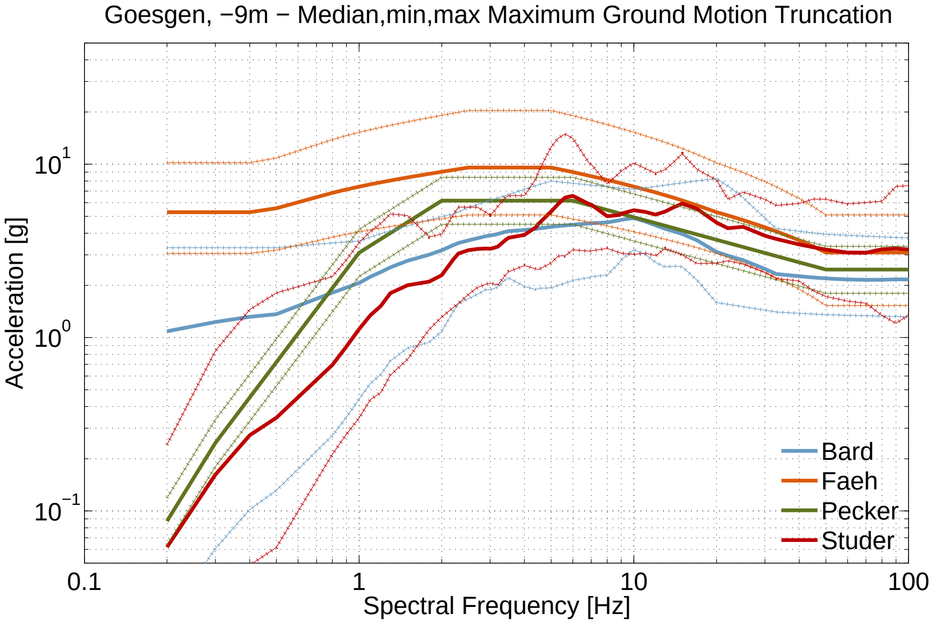


(b)

Figure A.39: Gösgen, surface and sub-depth level,V/H ratios, comparison of expert ranges for 0.1 and 0.75 g.



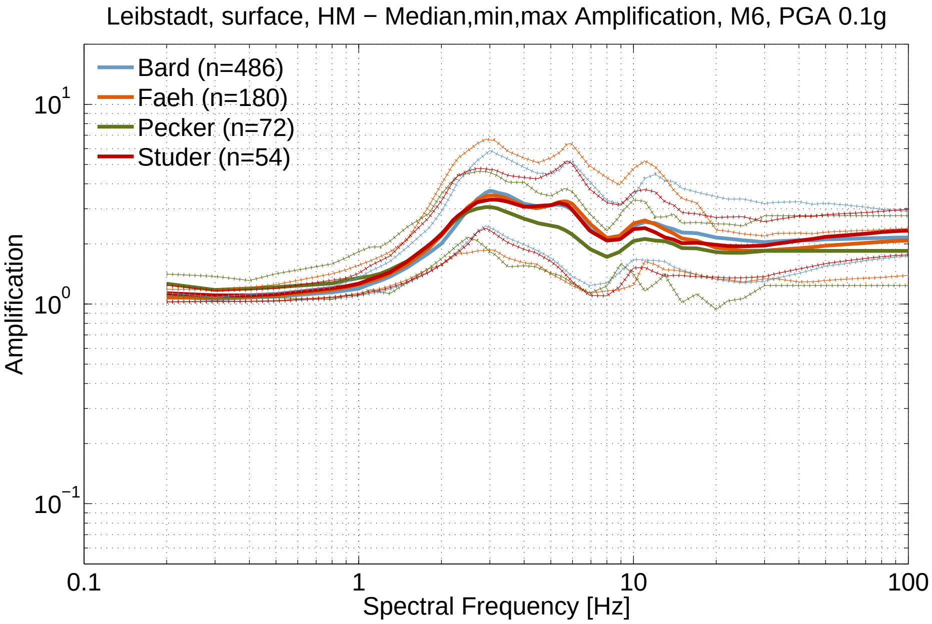
(a)



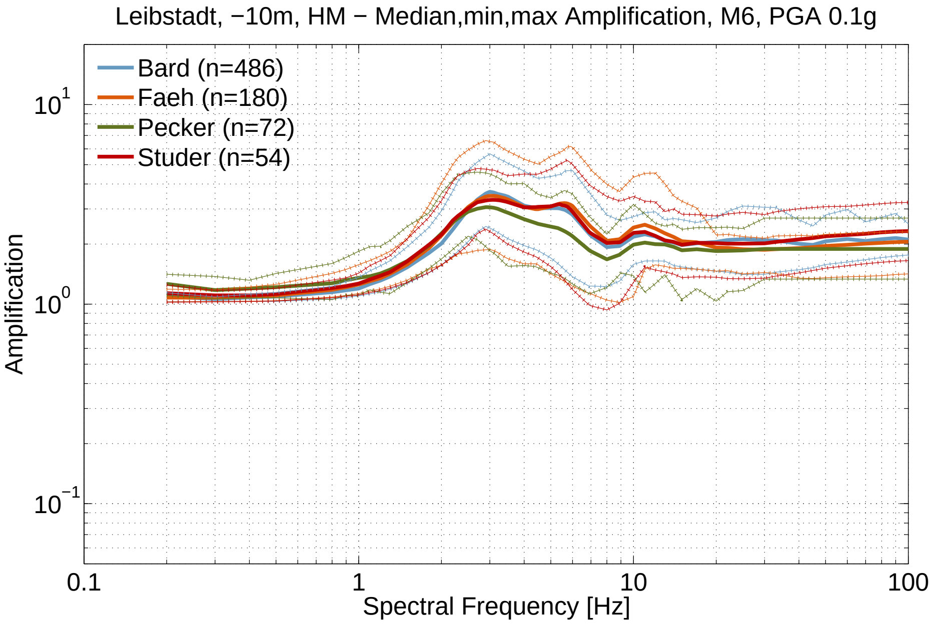
(b)

Figure A.40: Gösgen, surface and sub-depth level, maximum ground motion truncation models, comparison of expert ranges.

A.3.3 Leibstadt

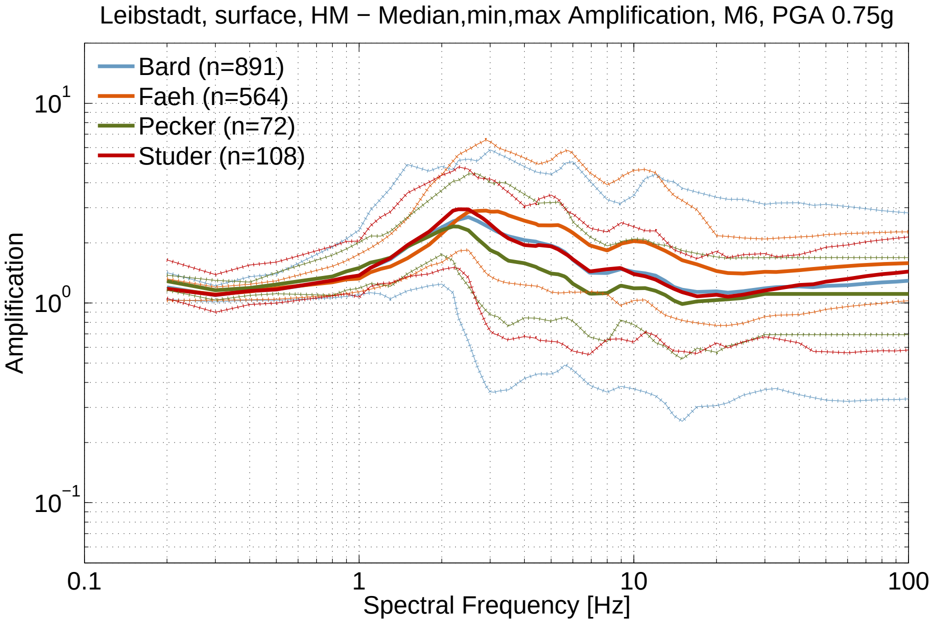


(a)

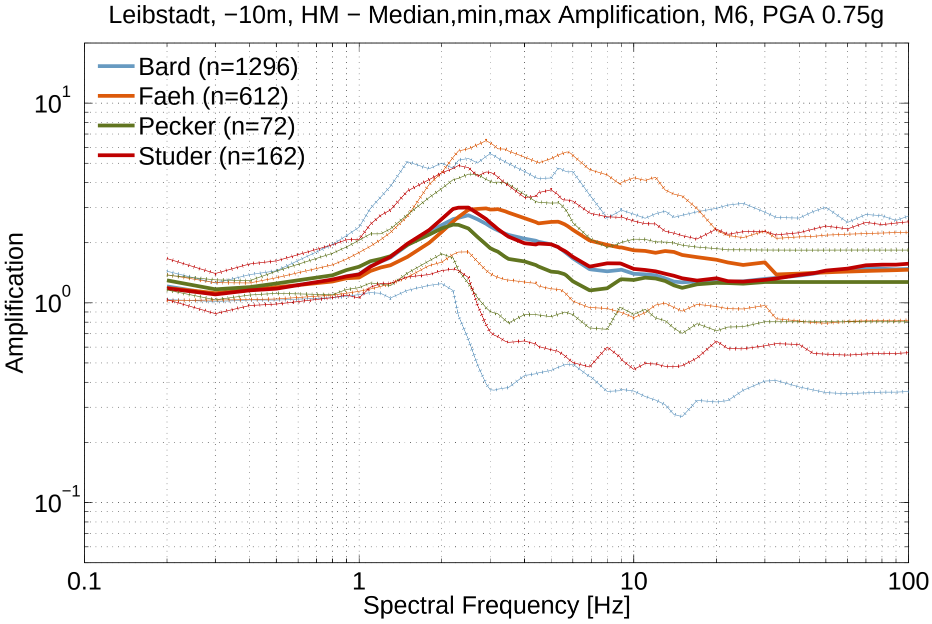


(b)

Figure A.41: Leibstadt, surface and sub-depth level, horizontal amplification, comparison of expert ranges for 0.1 g.

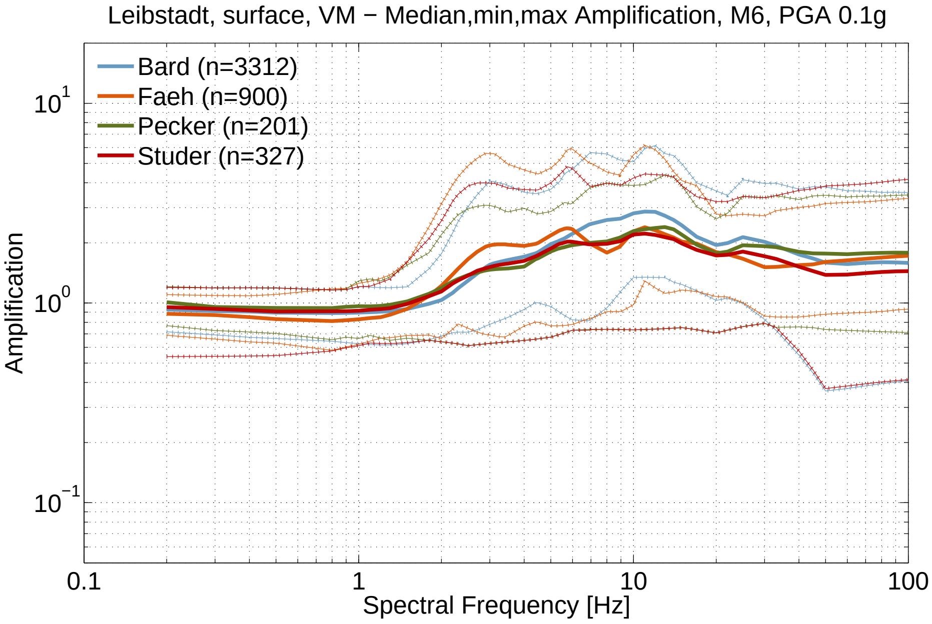


(a)

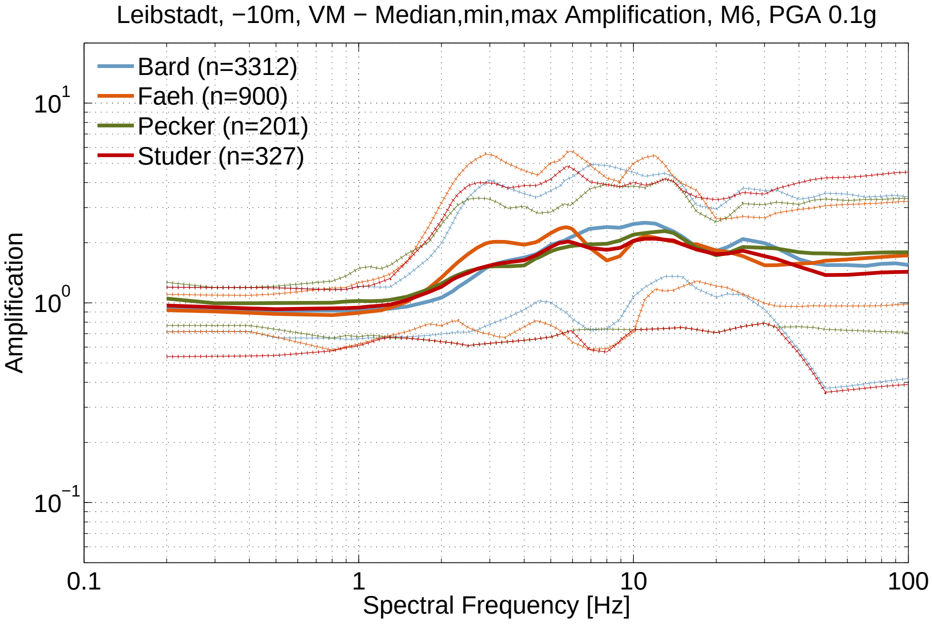


(b)

Figure A.42: Leibstadt, surface and sub-depth level, horizontal amplification, comparison of expert ranges for 0.75 g.

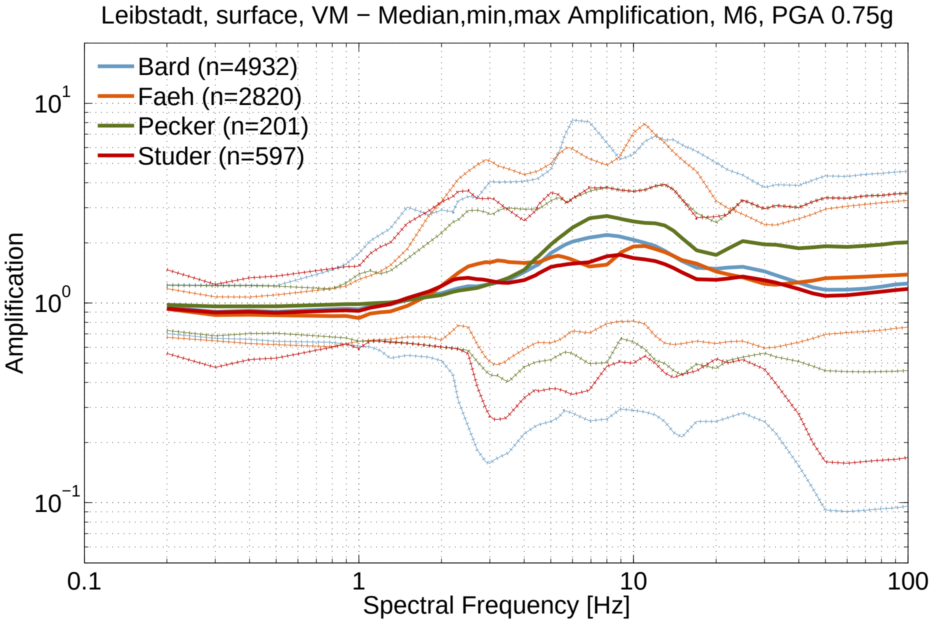


(a)

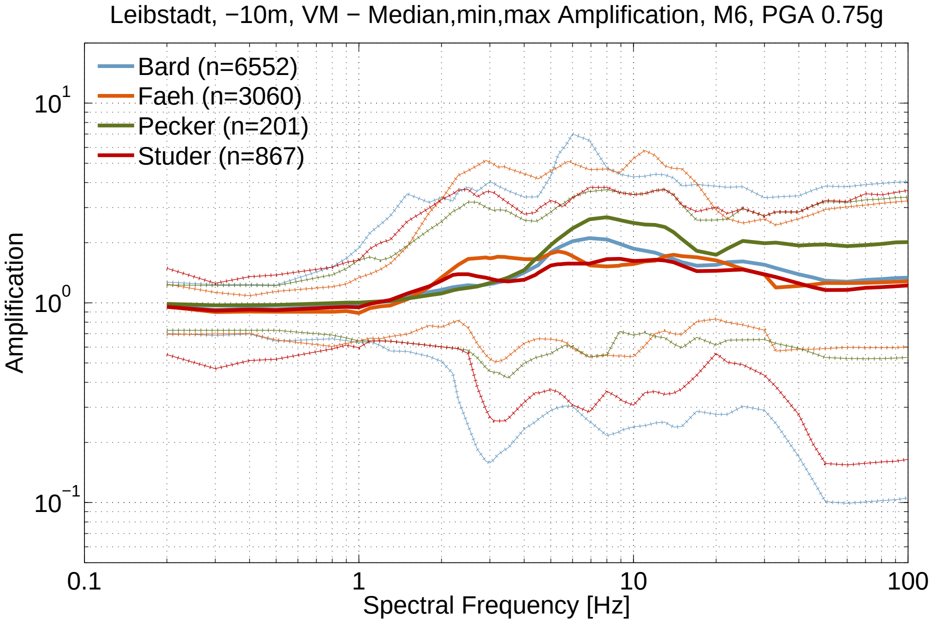


(b)

Figure A.43: Leibstadt, surface and sub-depth level, vertical amplification, comparison of expert ranges for 0.1 g.

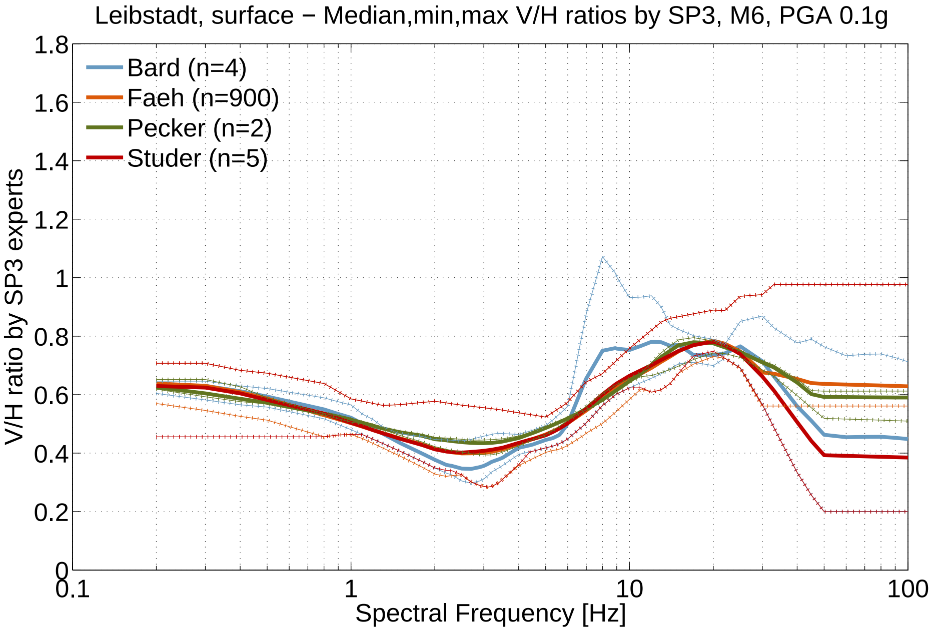


(a)

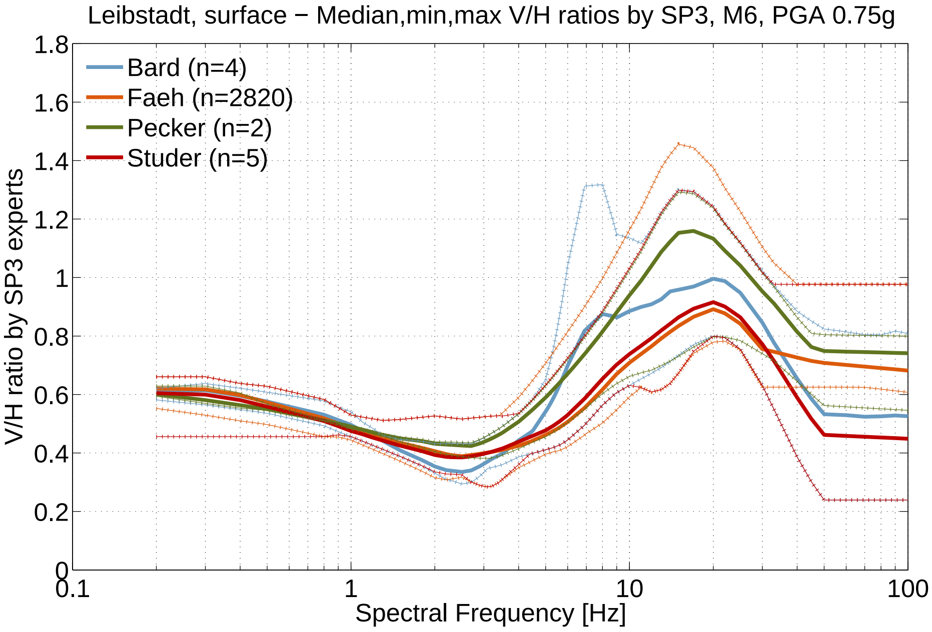


(b)

Figure A.44: Leibstadt, surface and sub-depth level, vertical amplification, comparison of expert ranges for 0.75 g.

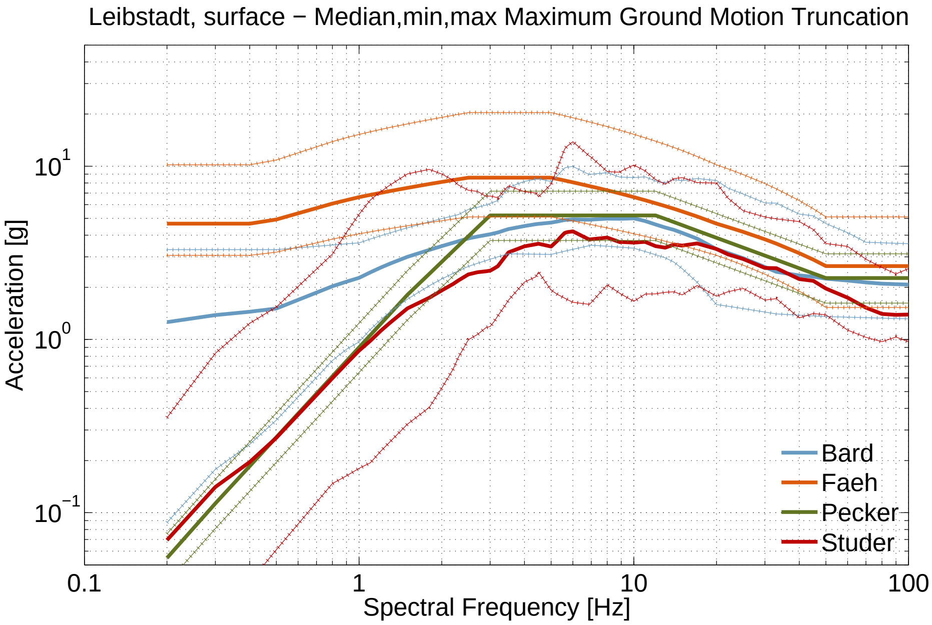


(a)

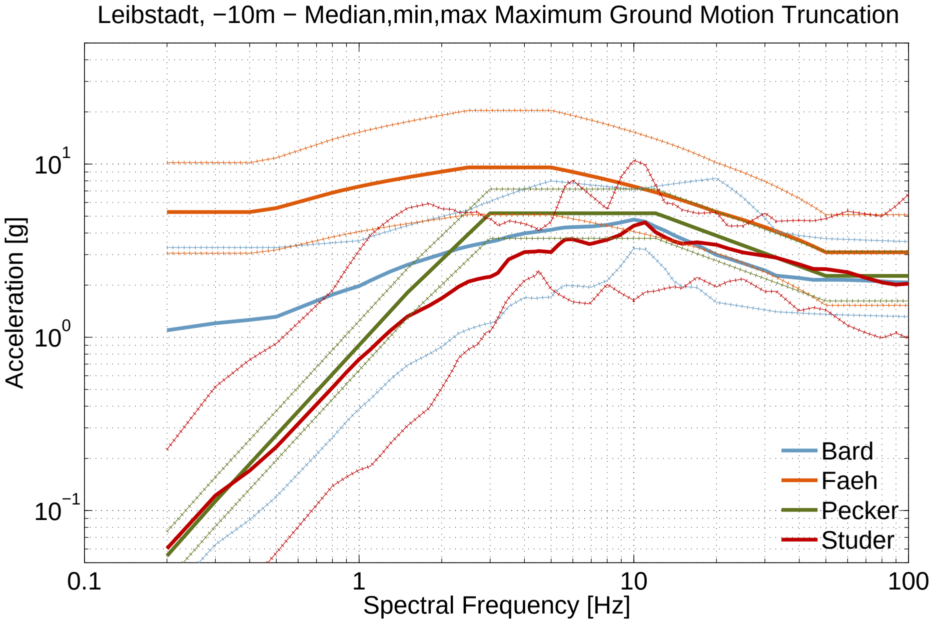


(b)

Figure A.45: Leibstadt, surface and sub-depth level, V/H ratios, comparison of expert ranges for 0.1 and 0.75 g.



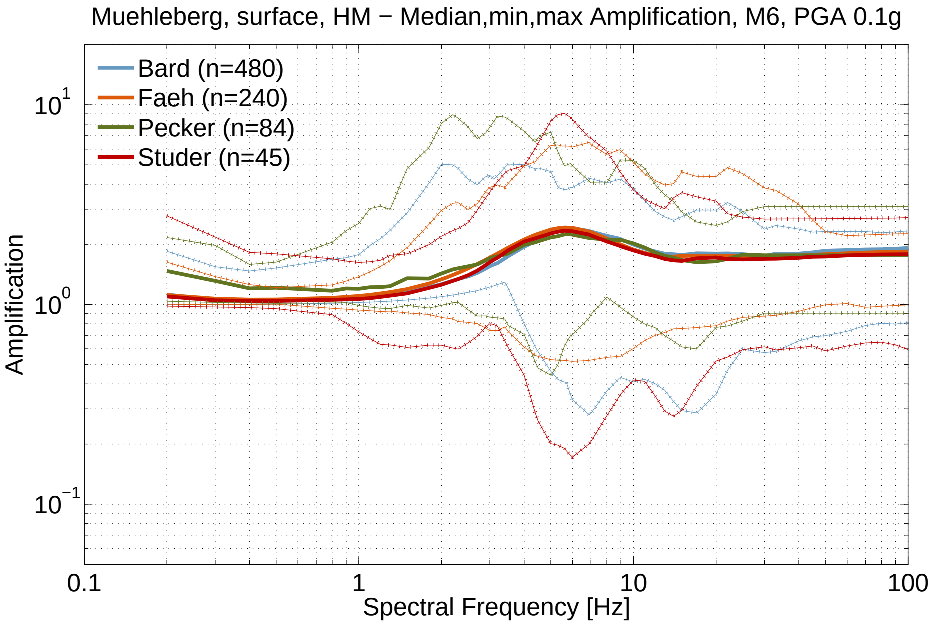
(a)



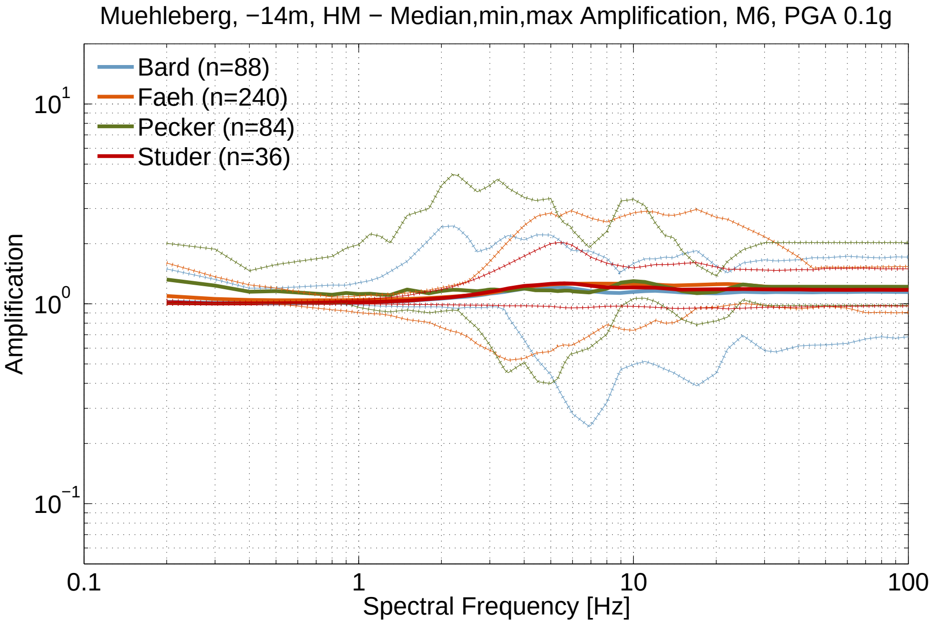
(b)

Figure A.46: Leibstadt, surface and sub-depth level, maximum ground motion truncation models, comparison of expert ranges.

A.3.4 Mühleberg

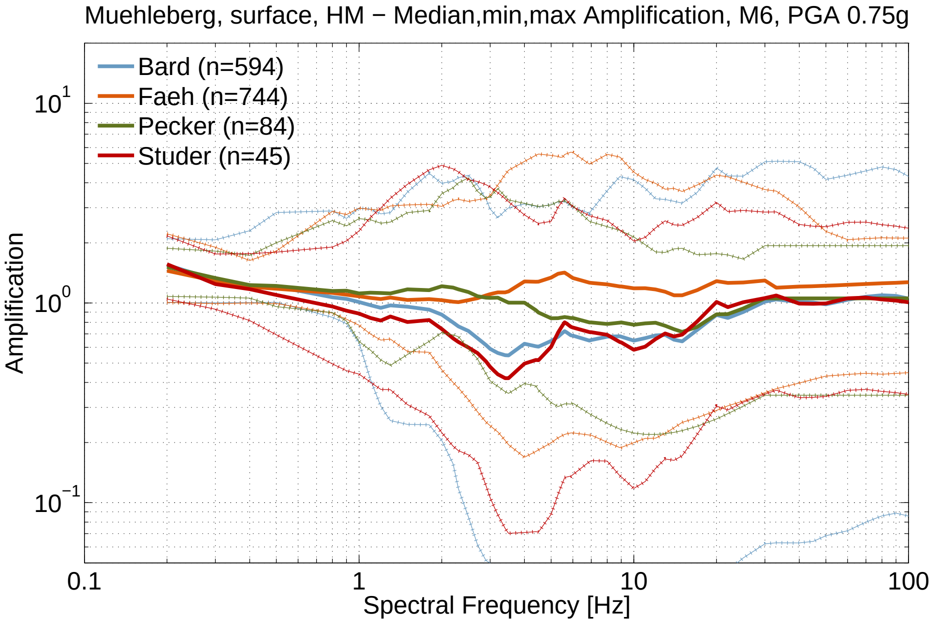


(a)

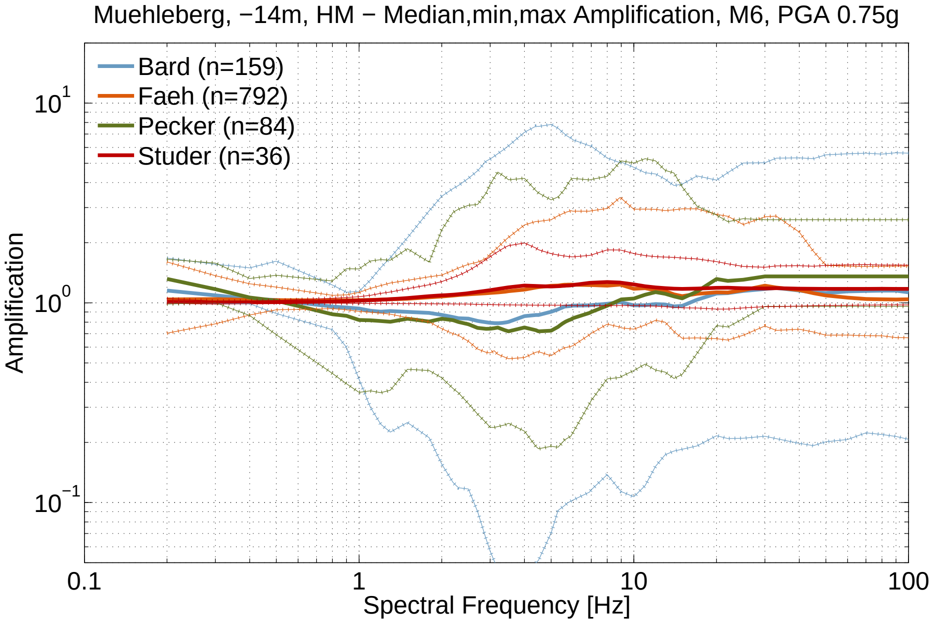


(b)

Figure A.47: Mühleberg, surface and sub-depth level, horizontal amplification, comparison of expert ranges for 0.1 g.

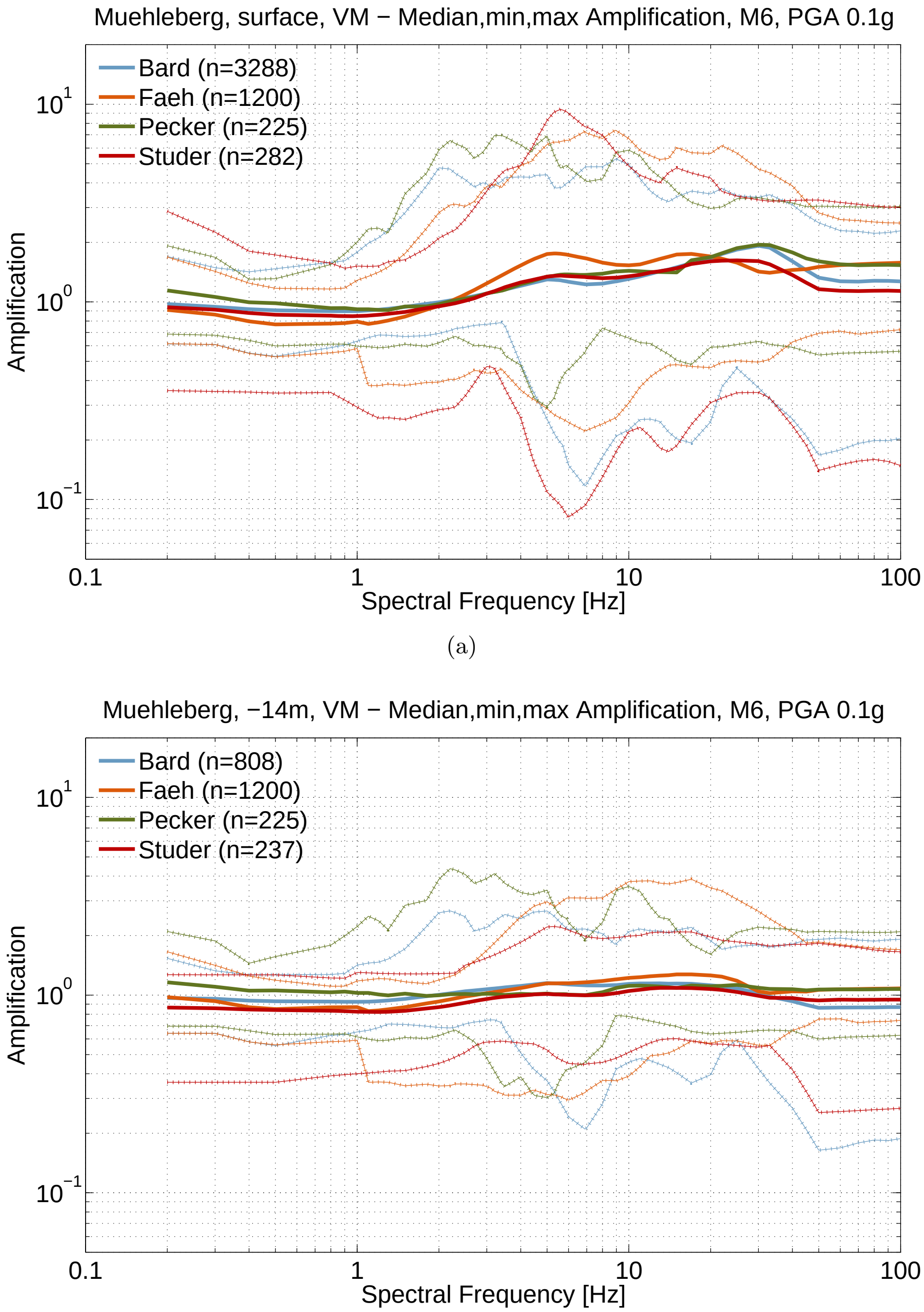


(a)



(b)

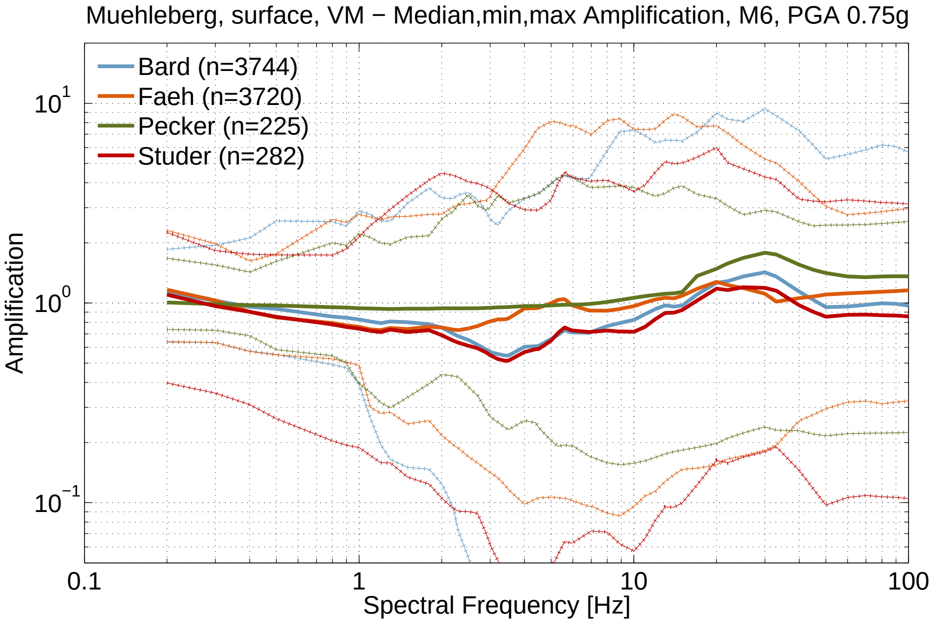
Figure A.48: Mühleberg, surface and sub-depth level, horizontal amplification, comparison of expert ranges for 0.75 g.



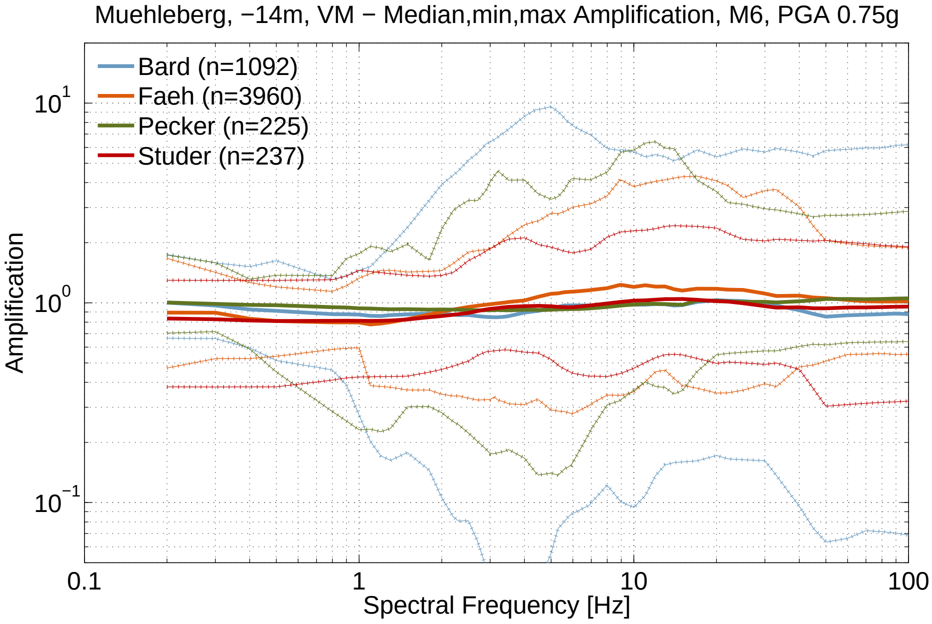
(a)

(b)

Figure A.49: Mühleberg, surface and sub-depth level, vertical amplification, comparison of expert ranges for 0.1 g.

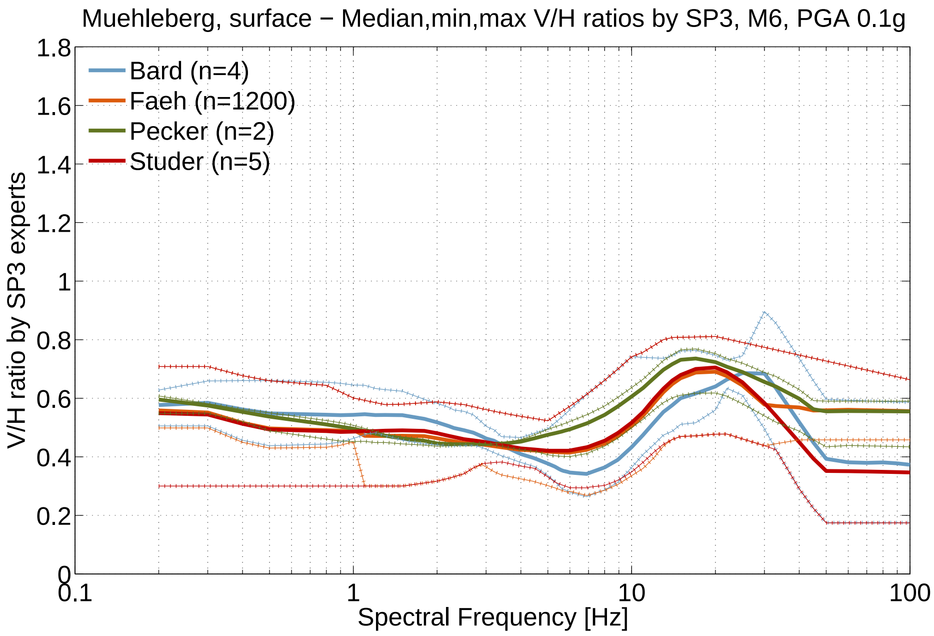


(a)

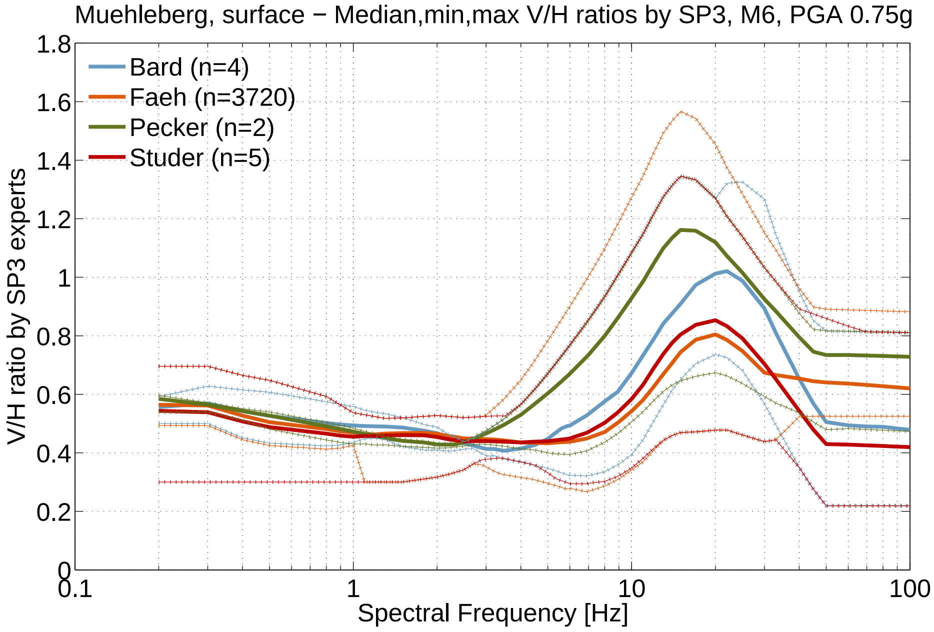


(b)

Figure A.50: Mühleberg, surface and sub-depth level, vertical amplification, comparison of expert ranges for 0.75 g.

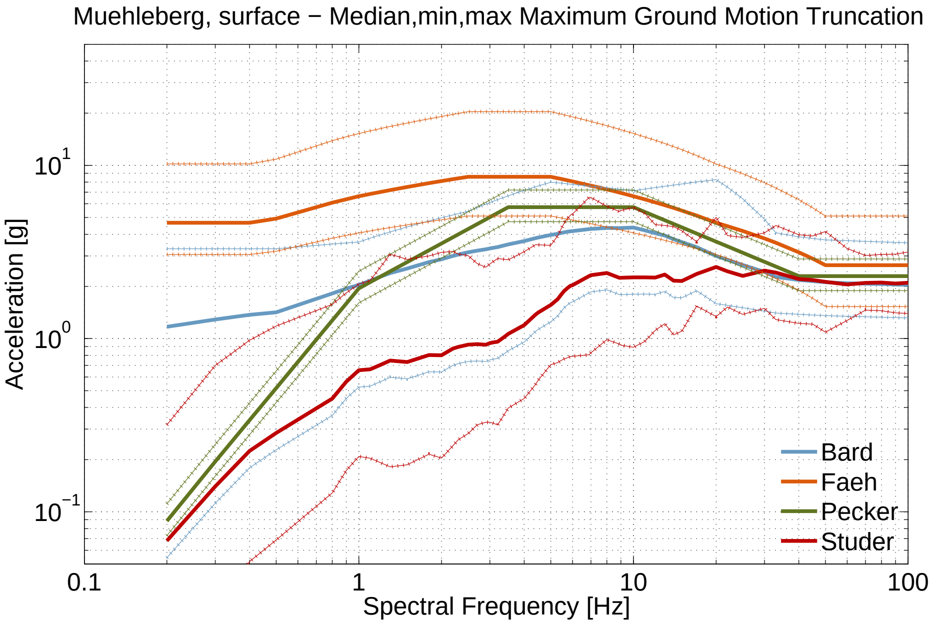


(a)



(b)

Figure A.51: Mühleberg, surface and sub-depth level, V/H ratios, comparison of expert ranges for 0.1 and 0.75g.



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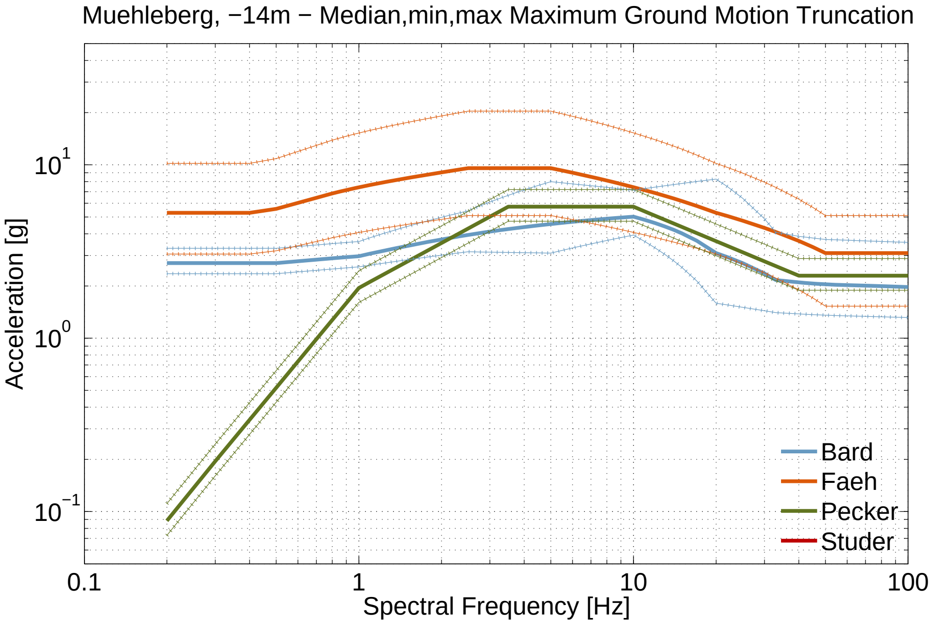

(b)

Figure A.52: Mühleberg, surface and sub-depth level, maximum ground motion truncation models, comparison of expert ranges. Remark: Studer's model is not present in the bottom plot, as for the sub-depth level he doesn't have a truncation and allows all ground motions to come through.

A.4 Overview of Soil Profiles and Material Models Contribution

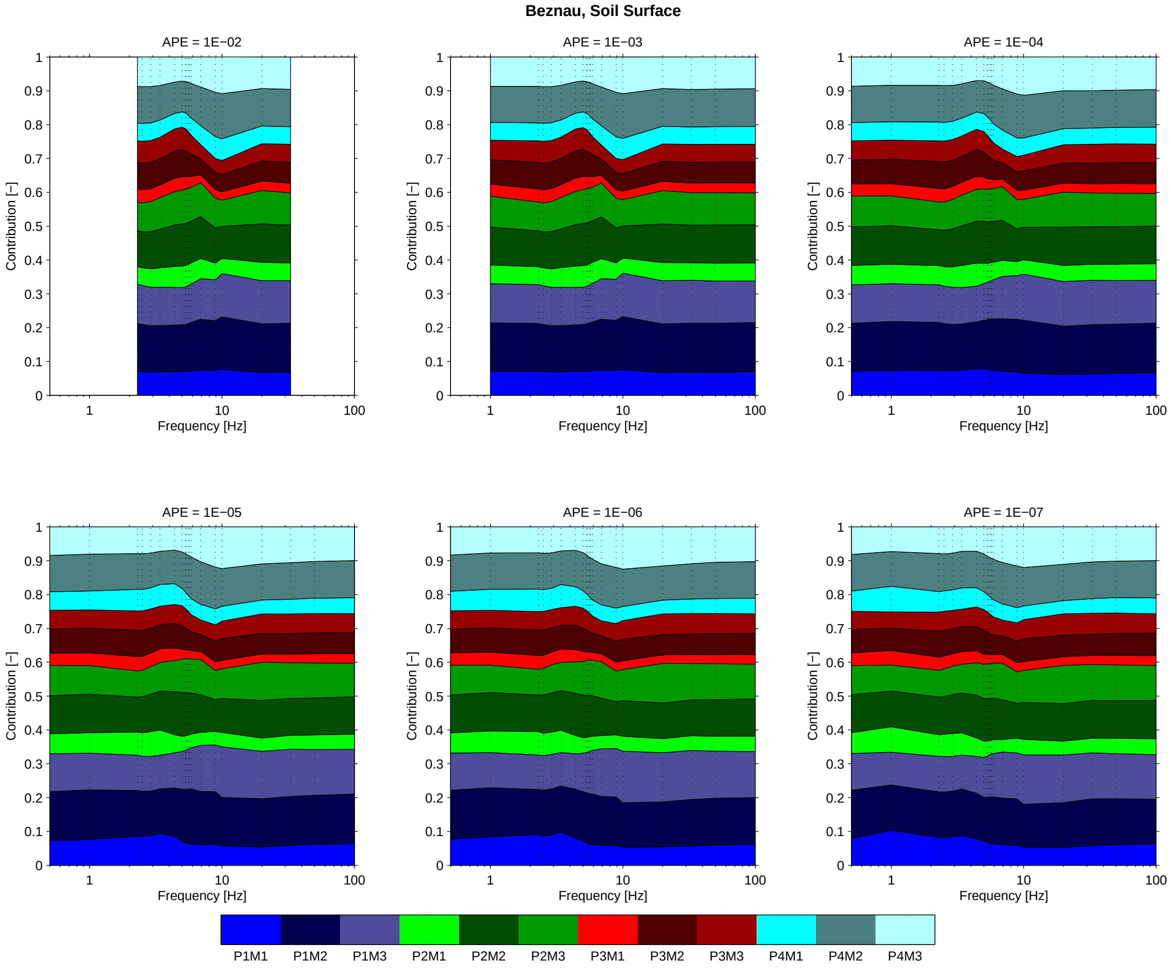

Figure A.53: Beznau, soil surface, contribution of profiles and material models to the mean soil hazard. The dotted lines represent the 20 frequencies for which the contribution was evaluated. The color legend at the bottom describes the profile and material combination. E.g. ”P1M1” stands for V_S-profiles 1 and material model 1, the latter being the lower bound material.

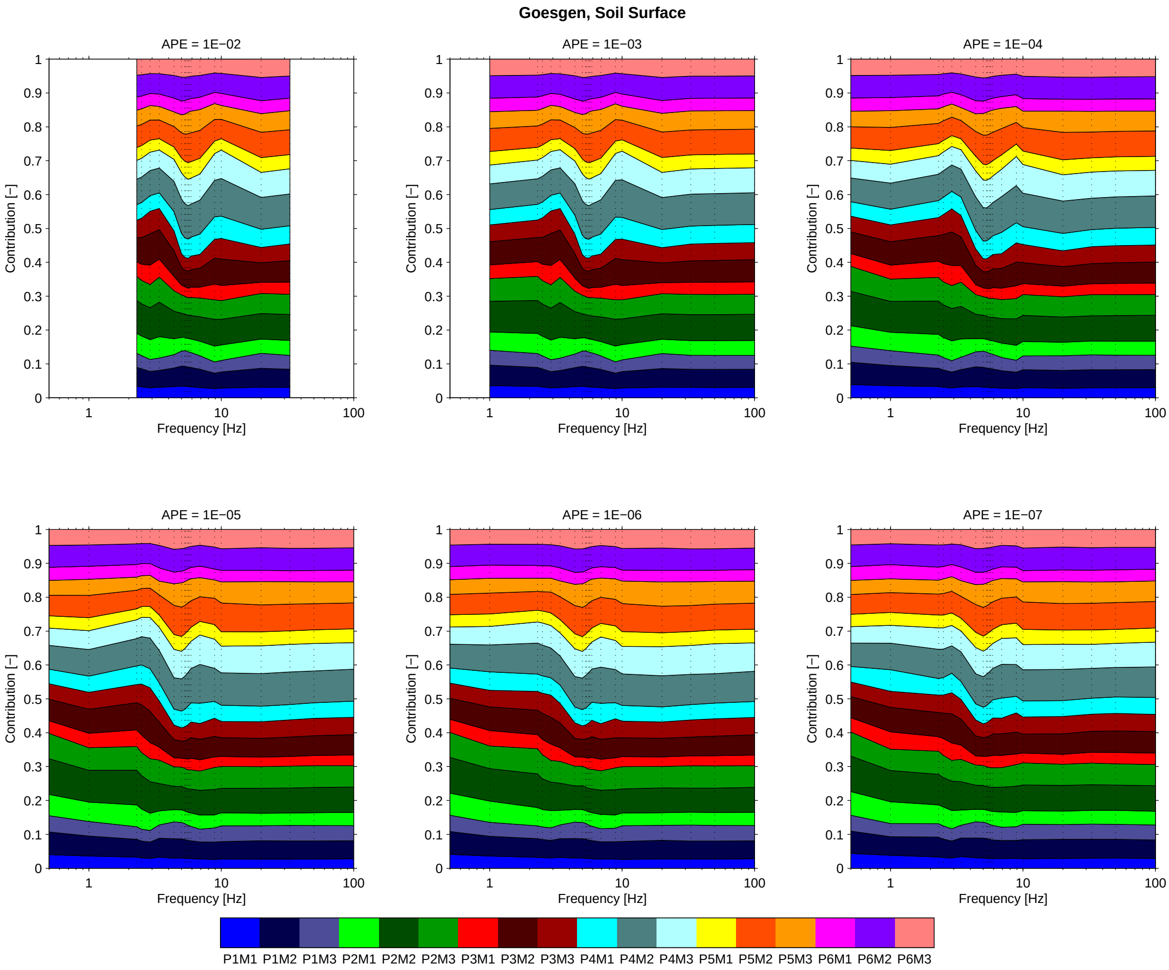

Figure A.54: Gösgen, soil surface, contribution of profiles and material models to the mean soil hazard. The dotted lines represent the 20 frequencies for which the contribution was evaluated. The color legend at the bottom describes the profile and material combination. E.g. "P1M1" stands for V_S-profiles 1 and material model 1, the latter being the lower bound material.

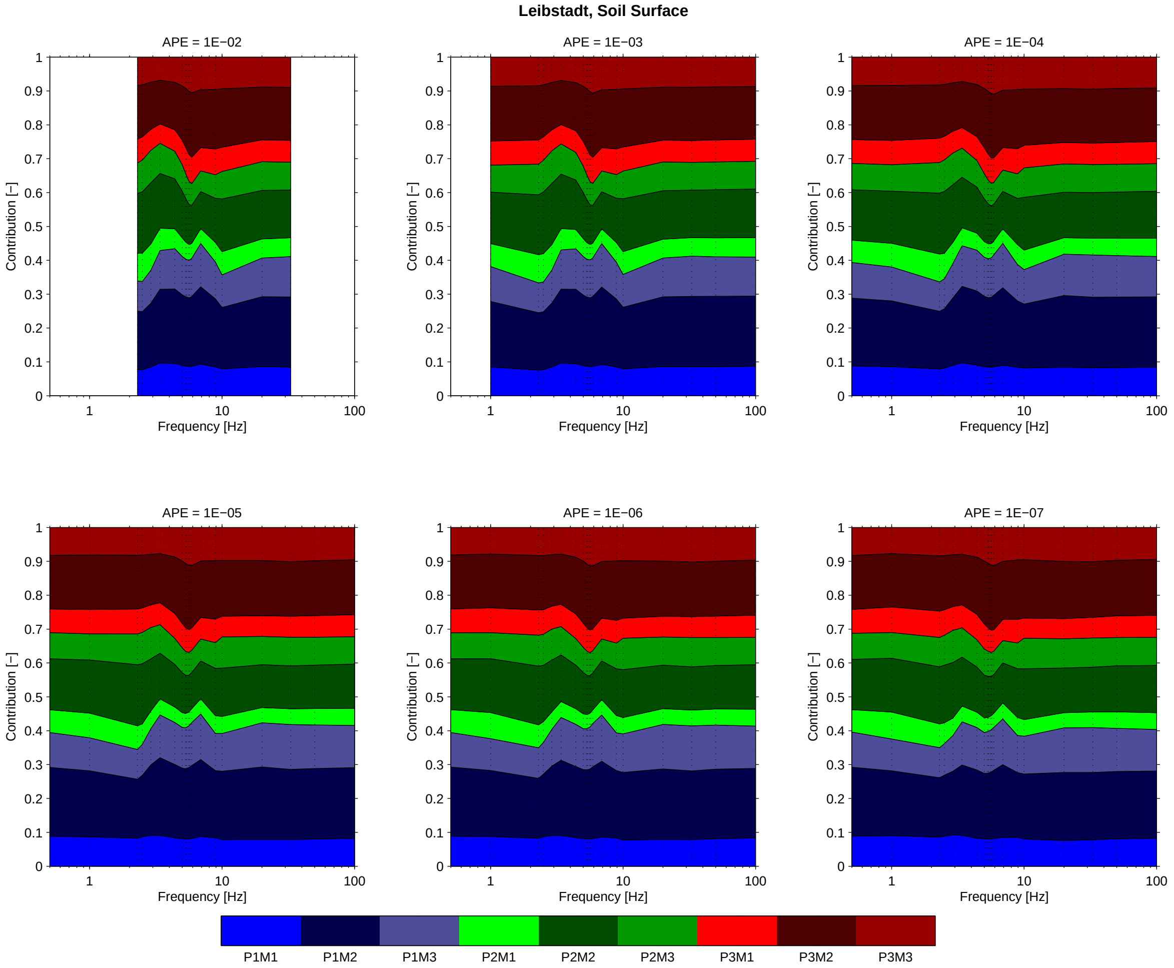

Figure A.55: Leibstadt, soil surface, contribution of profiles and material models to the mean soil hazard. The dotted lines represent the 20 frequencies for which the contribution was evaluated. The color legend at the bottom describes the profile and material combination. E.g. "P1M1" stands for V_S-profiles 1 and material model 1, the latter being the lower bound material.

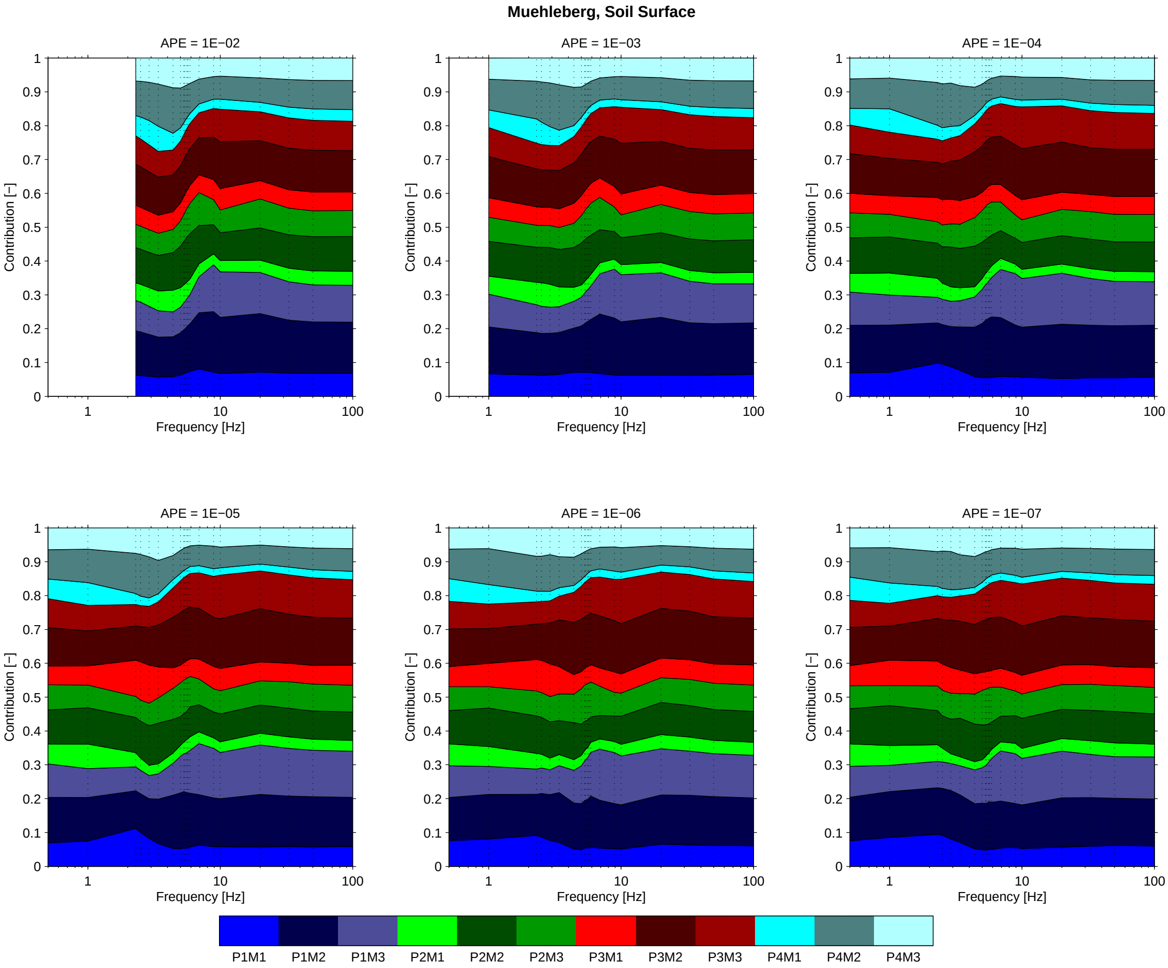

Figure A.56: Mühleberg, soil surface, contribution of profiles and material models to the mean soil hazard. The dotted lines represent the 20 frequencies for which the contribution was evaluated. The color legend at the bottom describes the profile and material combination. E.g. "P1M1" stands for V_S-profiles 1 and material model 1, the latter being the lower bound material.

Abbreviations

AF	Amplification Function
APE	Annual Probability of Exceedance
CEUS	Central and Eastern United States
EGx	Expert Group
ENSI	Swiss Federal Nuclear Safety Inspectorate (Eidgenössisches Nuklearsicherheitsinspektorat), former HSK
ENSI-RT	ENSI Review Team
GMC	Ground Motion Characterization
HID	Hazard Input Document
HSK	Former Swiss Federal Nuclear Safety Inspectorate (Hauptabteilung für die Sicherheit der Kernanlagen), since 1.1.2009: ENSI
HSK-RT	HSK Review Team
ITC	Informed Technical Community
KKx	Kernkraftwerk (German abbreviation for NPP) with: KKB=Beznau, KKG=Gösgen, KKL=Leibstadt and KKM=Mühleberg
Mw	Moment Magnitude
NGA	Next Generation Attenuation
NPP	Nuclear Power Plant
NRC	United States Nuclear Regulatory Commission (U.S. NRC)
PEGASOS	Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites (German: Probabilistische Erdbeben-Gefährdungs-Analyse für die KKW-StandOrte in der Schweiz)
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
PGD	Peak Ground Displacement
PMT	Project Management Team
PRP	PEGASOS Refinement Project
PSA	Probabilistic Safety Assessment
PSHA	Probabilistic Seismic Hazard Assessment
QA	Quality Assurance
RIF	Rock hazard Input Files
RVT	Random Vibration Theory
SED	Swiss Seismological Service (Schweizerischer Erdbebendienst)
SIF	Soil hazard Input Files

SP1	Subproject 1: Seismic source characterization
SP2	Subproject 2: Ground motion characterization
SP3	Subproject 3: Site response characterization
SP4	Subproject 4: Seismic hazard calculations
SP5	Subproject 5: Scenario earthquakes
SRA	Site Response Analysis
SSC	Seismic Source Characterization
SSHAC	Senior Seismic Hazard Analysis Committee
SSI	Soil Structure Interaction
SWUS	Southwestern U.S. (GMC SSHAC Level 3 study)
TDI	Technically Defensible Interpretation
TFI	Technical Facilitator/Integrator
UHS	Uniform Hazard Spectra
USGS	United States Geological Survey
V_S	Shear wave velocity
$V_{S,30,rock}$	Average shear wave velocity in the 30 m below the defined rock surface (rock-soil interface), otherwise 30 m below the soil surface
WUS	Western United States

Glossary of Key Terms

Definitions provided in this Glossary were compiled from multiple reference sources, including the SSHAC guidance in NUREG/CR-6372 (Budnitz et al., 1997), NUREG-2117 (NRC, 2012), and McGuire (2004). The Glossary definitions are consistent with the use of the terms in the PEGASOS Refinement Project report and may not correspond exactly to definitions appearing in regulatory documents of the IAEA, NRC or ENSI. For additional geological terms, the reader is referred to a standard glossary of geology (e.g. Neuendorf, K.K.E., Mehl, J.P., Jr., and Jackson, J.A., 2005, Glossary of Geology, 5th Edition, American Geological Institute, Alexandria, Va., 779 pp.). Throughout this report, designations for formal (capitalized) divisions of time periods followed a Geological Society of America geological time scale (Walker and Geissman, 2009), provided in Figure 11-1.

Active Fault:
A fault that has slipped in geologically recent time, has a clear association with earthquakes and is likely to slip again in the future. Quaternary faults (i.e. those whose most recent slip was in the past 1.6 - 1.7 Myr) are generally considered to be active.

Active Source:
A seismic source that is capable of generating moderate- to large-magnitude ($M \leq 5$) earthquakes.

Aleatory Uncertainty:
The uncertainty that is inherent in a random phenomenon and cannot be reduced by acquiring additional data or information. Examples include future earthquake locations and magnitudes.

Area Source:
A region of the earth's crust that is assumed for PSHA to have relatively uniform seismic source characteristics.

Background Source:
A regional-scale area source.

Bayesian Approach:
An approach to determine a maximum magnitude distribution defined by Johnston et al. [1994] that uses a prior distribution for M_{max} developed from the worldwide Stable Continental Region (SCR) database. It assumes that crust with the same characteristics (extension history, age, stress state, angle of structure relative to stress) has the same prior distribution of M_{max}. The approach updates the prior distribution with a likelihood function that includes local information on the maximum observed magnitude and numbers of observed earthquakes of

various magnitude. The result is a posterior distribution of M_{max} for an individual seismic source.

b-value:
A parameter describing the decrease in the relative frequency of occurrence of earthquakes of increasing sizes. It is the slope of a straight line relating absolute or relative frequency (plotted logarithmically in base 10) to earthquake magnitude. It is referred to as β when using natural logarithms.

Coefficient of Variation (COV):
A statistical term that measures the relative variation of a quantity. It is calculated as the standard deviation of the quantity divided by the mean of the quantity.

Conceptual SSC Framework:
The seismotectonic and seismic hazard-informed context within which data are evaluated and seismic sources are defined and characterized.

Data Evaluation Table:
A table developed for a particular seismic source identified in the SSC Project that provides a summary of the data used for seismic source characterization, including the quality of the data and the reliance placed on it for SSC.

Data Summary Table:
A table developed for a particular seismic source identified in the SSC Project that records the data considered and summarizes the potential relevance that the data may have to seismic source characterization.

Declustering:
A statistical approach that removes foreshocks and aftershocks to produce a catalogue of independent main shocks consistent with the requirements of a PSHA model. Comparison with a variety of declustering approaches used by the USGS and others showed that the results are essentially the same.

Distance, Epicentral:
The distance from the epicenter to a specific location (site). Distance, Fault: The shortest distance from the fault to a specific location (site). Distance, Hypocentral: The distance from the hypocenter to a specific location (site).

Earthquake:
A sudden motion or trembling of the earth caused by the abrupt release of accumulated strain.

Epistemic Uncertainty:
The uncertainty that arises from lack of knowledge about a model or a parameter, which can be reduced by the accumulation of additional information. Epistemic uncertainty is reflected in the different outcomes of viable alternative models, interpretations and/ or assumptions operating on the same data. Examples include geometry of seismotectonic zones and assessed source parameters such as maximum magnitude.

Evaluator Expert:
An expert who is capable of evaluating the relative credibility of multiple alternative hypotheses to explain a set of observations. Requires considering the available data, listening to proponent and other evaluator experts, questioning the technical basis for their conclusions and challenging the proponent's position.

Expert Elicitation:
A formal expert assessment technique of conventional decision analysis in which experts are led through a series of assessment steps to address narrowly defined questions about specific uncertain quantities within their area of expertise.

Expert Assessment:
The use of expert judgment to address technical questions and their uncertainties.

Fault:
A fracture surface or zone in the earth across which there has been relative displacement.

Fault, Dip-Slip:
A fault in which the relative displacement is along the direction of the dip of the fault plane; either downdip (normal fault) or updip (reverse fault).

Fault, Normal:
A dip-slip fault in which the block above the fault has moved downward relative to the block below, representing crustal extension.

Fault, Reverse:
A dip-slip fault in which the block above the fault has moved upward relative to the block below and the fault dip is $> 45°$.

Fault Slip Rate:
The amount of displacement on a fault divided by the time period over which the displacement took place.

Fault, Strike-Slip:
A fault in which the relative displacement is along the strike of the fault plane, either right- or left-lateral.

Fault, Thrust:
A dip-slip fault in which the block above the fault has moved upward relative to the block below and the fault dip is $< 45°$, representing crustal compression.

Fault Zone:
The zone of deformation comprising a fault, which may be hundreds of meters wide.

Focal Mechanism:
A geometrical representation of earthquake faulting expressed in terms of the strike and dip of the fault plane and the rake angle of the slip vector with respect to the fault plane.

Future Earthquake Characteristics:
The expected characteristics of future earthquakes that occur within a particular seismic source. The characteristics identified (e.g. style-of-faulting, orientation of rupture) are those that are potentially important to ground motion prediction equations.

Geon:
A 100-million-year interval of geological time starting with the present and continuing backward through time. Geons are named according to the number representing geological age divided by 100 million. Geological ages less than 100 million years would be in geon 0. For example, an age of 1,650 million years would belong to geon 16.

Hazard Calculation:
The calculation of annual frequencies with which seismic ground-motion amplitudes will be

exceeded as a result of possible earthquakes in the region. The results of this calculation may be represented as mean annual frequencies (”mean hazard curves”) or fractile annual frequencies (”fractile hazard curves”).

Hazard-Informed Approach:
An assessment methodology for characterizing seismic sources that places greatest emphasis and focus on those seismic source elements that are most important to the hazard analysis results.

Hazard Input Document (HID):
A report that provides the documentation necessary for users to implement the input model (e.g. the SSC or GMC model) in PSHA calculations for future applications. The HID includes the logic tree structure (with all branches and weights) for each seismic source, but it does not include the technical basis or justification for the elements of the model.

Hypocenter:
The point in the earth at which an earthquake is initiated. Also referred to as the focus.

Informed Technical (Scientific) Community:
A hypothetical construct of the SSHAC guidelines that embodies the community distribution of uncertainty sought by the SSHAC process at any study level. The goal of a SSHAC process is to ”represent the Center, Body and Range of the views of the informed technical community.” ”Informed” means that the technical community is familiar with the project-specific databases and that the individuals have gone through the interactive SSHAC process. Recent SSHAC implementation guidance [Kammerer and Ake 2012] has replaced the terminology to avoid confusion. In that guidance, the goal of the SSHAC process is said to be twofold:
(1) to consider the data, models and methods of the larger technical community; and
(2) to represent the Center, Body and Range of technically defensible interpretations.

Intensity:
A measure of the effects (e.g. damage) of an earthquake at a particular place. Commonly used scales are Rossi-Forel, Mercalli and modified Mercalli.

Liquefaction/ Paleoliquefaction:
The temporary conversion of water-saturated, unconsolidated soils (sediments) into a medium that behaves like a fluid. It can occur as a secondary hazard related to strong shaking from an earthquake. The age, location and extent of liquefaction can be used to estimate the size and location of prehistoric earthquakes.

Logic Tree:
A series of nodes and branches to sequence the assessments in an analysis by describing alternative models or parameter values or both. At each node, there is a set of branches that represent the range of alternative credible models or parameter values; the branch weights must sum to unity at each node. The weights on the branches of logic trees reflect scientific judgments in the relative confidence in the alternative models.

Longevity, Hazard Studies:
The length of time a hazard study is considered adequate for continued use.

Magnitude (general):
A measure of earthquake size, classically determined by taking the common logarithm (base

10) of the largest ground motion recorded during the arrival of a seismic wave type and applying a standard correction for distance to the epicenter.

Magnitude, Adjusted ($M*$):
Moment magnitude adjusted to correct for a bias that results from the propagation of uncertainty in magnitude estimates through the magnitude conversion process.

Magnitude, Body-Wave (m_b):
Magnitude derived from the largest displacement amplitude of body waves.

Magnitude, Coda-Wave (M_C):
Magnitude derived from the amplitude and duration of the seismic coda (latter part of a seismic wave train).

Magnitude, Duration (M_D):
Magnitude derived from the total duration of the measured seismic wave train.

Magnitude, Lg (m_{bLg}):
Magnitude derived from the displacement amplitude of Lg waves; often used in Eastern North America because it can be accurately measured from typical low-gain seismographs at long distances from the source.

Magnitude, Moment (M, M_w):
Magnitude derived from the scalar seismic moment, M_0. Approximately equal to local magnitude for moderate earthquakes, and to surface-wave magnitude for large earthquakes. As discussed in Hanks and Kanamori (1979), M_w is derived from Kanamori's (1977) magnitude scale based on strain energy drop and is given by the relationship log(M_0 in dyne-cm) = 1.5M_w + 16.1. Hanks and Kanamori (1979) defined the moment magnitude scale M using the relationship M = ⅔log(M_0 in dyne-cm)-10.7. The result is a 0.03-magnitude unit difference between M_w and M for the same value of M_0.

Magnitude, Richter or Local (M_L):
Common logarithm of the trace amplitude (in microns) of a standard Wood-Anderson seismograph located on firm ground 100 km from the epicenter. Correction tables are used to account for other distances and ground conditions.

Magnitude, Surface-Wave (M_S):
Earthquake magnitude determined from the maximum amplitude of 20-second period surface waves.

Maximum Magnitude (M_{max}):
The largest earthquake that a seismic source is assessed to be capable of generating. The maximum magnitude is the upper bound to recurrence curves.

Modeling Uncertainty:
The epistemic uncertainty that results from the use of various models to explain observed data and predict future phenomena. In principle, it can be reduced or eliminated by further testing, data accumulation, or more detailed modeling. It is one source of epistemic uncertainty.

Paleoseismic/Paleoseismicity:
Term referring to the science of evaluating prehistoric earthquakes through the geological analyses of the surficial strata and landforms that have been created, deformed and/or offset by earthquakes.

Participatory Peer Review:
As defined in SSHAC guidance, an ongoing review throughout an entire project that allows reviewers to observe and comment on the process followed and the technical assessments developed. Reviewers must be recognized experts on the subject matter under review (”peers” in the true sense).

Probability of Activity:
The likelihood that a particular tectonic feature is seismogenic and will localize moderate-to-large ($M \geq 5$) earthquakes.

Probabilistic Seismic Hazard Analysis:
An analytical methodology that estimates the likelihood that various levels of earthquake-inducted ground motions will be exceeded at a given location in a given future time period.

Project Manager:
As defined in SSHAC guidance, a dedicated full-time professional who is the point of contact between the project and the project sponsor(s), and who is responsible for ensuring adherence to scope, schedule, budgets and contractual requirements. The PM organizes workshops and keeps the sponsor(s) apprised of progress.

Proponent Expert:
An expert who advocates a particular hypothesis or technical position.

Rate of Seismicity:
Rate of occurrence of earthquakes above some specified magnitude for a specific region.

Recurrence, Recurrence Rate, Recurrence Curve:
The frequency of earthquake occurrence of various magnitudes often expressed by the Gutenberg-Richter relation.

Recurrence Interval:
The mean time period between earthquakes of a given magnitude on a fault or in a region.

Recurrence Model:
A model to express the relative number or frequency of earthquakes having different magnitudes. A common recurrence model is the exponential magnitude distribution.

Recurrence Model (Poisson, Renewal):
A model to express the relative number of earthquakes of different magnitudes that occur within or associated with a particular seismic source. Two models that are commonly used to represent the temporal elements of a recurrence model are Poisson and Renewal. In the Poisson model, the time between consecutive earthquakes follows an exponential distribution and there is no dependence of the timing of the next earthquake on the timing or size of earlier earthquakes. In the Renewal model, the time between consecutive events is assumed to be related to the release and accumulation of strain such that there is a relation between the timing of the most recent event and time to the next event.

Resource Expert:
A technical expert who has either site-specific knowledge or expertise with a particular methodology or procedure useful to the evaluator experts in developing the community distribution.

Seismicity:
The occurrence, intensity and distribution of earthquakes in a region; also refers to the frequency and depths of these earthquakes.

Seismic Moment:
Scalar measurement of the size of an earthquake. It is the product of the area of rupture, the average slip on the fault and the shear modulus of the crustal rocks. It is typically expressed in units of dyne-cm.

Seismic Source:
Traditionally, in a probabilistic seismic hazard analysis, a region or volume of the earth's crust that has uniform earthquake potential or uniform earthquake-generating characteristics. In this project, unique seismic sources (faults, regions) are spatially defined to account for distinct differences in earthquake recurrence rate, maximum earthquake magnitude, expected future earthquake characteristics and probability of generating earthquakes of magnitude 5 or larger.

Seismic Source Characteristics:
The parameters that characterize a seismic source for PSHA, including source geometry, maximum magnitude, earthquake recurrence and future earthquake characteristics.

Seismic Source Zones:
See "Area Source" Volumes within the earth where future earthquakes are expected to occur. The geometry of seismic sources in the SSC Project is defined by differences in earthquake recurrence rate, maximum earthquake magnitudes, future earthquake characteristics and the probability of activity of tectonic features.

Seismic Zone:
A region showing relatively elevated levels of observed seismicity. Seismogenic: Capable of generating tectonically significant earthquakes ($M \geq 5$).

Seismotectonic Province:
A region of the earth's crust having similar seismicity and tectonic characteristics.

Sensitivity Analysis:
The calculation of the effect that a particular input parameter or model has on the output of a seismic hazard analysis. This may be represented as multiple hazard curves for these alternative input assumptions.

Single-station standard deviation (σ):
Estimates of single-station standard deviation can be used as a lower bound to probabilistic seismic hazard analyses that remove the ergodic assumption on site response (see Al Atik et al. [2010]; Rodriguez-Marek et al. [2011, 2013]). Within this concept the aleatory variability is divided in to two parts: Tau (τ), being the between-event part and Phi (ϕ), describing the within-event part.

Smoothing:
The spatial variation in the rate of activity (a-value of the earthquake recurrence relationship) and the b-value (slope of the recurrence curve).

Source Zone:
See Area Source.

Spatial Clustering:
Observed or inferred proximity of earthquake occurrences.

Spatial Stationarity:
A model in which the locations of future earthquakes are assessed to follow the spatial distribution of past earthquakes.

SSC Model:
A seismic source characterization model to represent the parameters that characterize a seismic source for PSHA, including source geometry, probability of activity, maximum magnitude and earthquake recurrence.

SSHAC (Senior Seismic Hazard Analysis Committee):
A committee sponsored by the NRC, DOE and EPRI to review the state-of-the-art in PSHA and to develop methodologies for using expert judgment and treating uncertainties in seismic hazard analyses. The report of the SSHAC is given in Budnitz et al. [1997], which is also termed the SSHAC guidelines.

SSHAC Methodology:
The recommended methodology for conducting a PSHA given in Budnitz et al. [1997].

SSHAC Assessment Level:
See SSHAC Study Level

SSHAC Study Level:
One of four ”Study Levels” (also called SSHAC Levels) identified in the SSHAC guidelines, ranging from Level 1 projects, which involve very few participants, to Level 4 projects, which involve multiple participants and workshops.

Stability:
Characteristic of a hazard input model such as the SSC model that properly quantifies current knowledge and uncertainties such that the identification of new data, models and methods will not lead to the need to significantly revise the model.

Stable Continental Region:
A region of the earth's crust that is defined by Johnston et al. (1994) as having particular characteristics relative to the age and style of most recent tectonism.

Technical Facilitator/Integrator (TFI):
A SSHAC term for an individual or team responsible for considering the data, models and methods of the larger technical (scientific) community and for assessing and representing the Center, Body and Range of technically defensible interpretations in a seismic hazard model. In this project, this was done using a SSHAC Level 4 assessment process.

Tectonic Province:
See Seismotectonic Province.

Temporal Clustering:
Occurrences of multiple closely timed earthquakes separated by longer periods of quiescence. Events that tend to cluster represent a deviation from a stationary Poisson process.

Upper-Bound Magnitude:
See Maximum Magnitude.

Uncertainty:
A general term. See Epistemic Uncertainty and Aleatory Uncertainty.

Variance:
The expected value, taken with respect to its probability distribution, of the squared deviation of an aleatory variable from its expected value.

V/H:
Ratio of the vertical and (geom. mean) horizontal component of ground motion, used e.g. to derive vertical estimates of the ground motion by applying the V/H ratio models to the horizontal component of a GMPE.

Weight:
A numerical value ($\leq$1.0 or 100%) assigned to alternative credible models or parameter values. Weights reflect scientific judgments that any particular model or parameter value is the correct model or parameter.

Zonation:
The process of developing seismic source maps (or a set of seismic zones).

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