PEGASOS Refinement Project

Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites

Volume 6
SP5 - Scenario Earthquakes -

by

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Abstract

Quantifcation of the seismic performance of structures, such as nuclear power plants, is an important step in the design and maintenance process. Response spectral or time history analysis allow an estimation of the structural seismic performance throughout a seismic Probabilistc Safety Analysis (PSA). Before analyses can be performed, acceleration time histories (real records or synthetic accelerograms) consitent with the site-specific hazard must be defined. Thus, the selection of ground motions is a key step in defining the seismic load input for structural analysis.

The report provides a summary of the work performed in the subproject SP5 within the PEGASOS Refinement Project (PRP). The framework of SP5 and its special status within the PRP is explained. The produced results are based on the output specification defined by the needs of the NPPs. At the beginning of SP5 the SP5 experts evaluated and defined the approaches to be used to derive time histories for the project specific needs. The implementation of these approaches is described and discussed with respect to some project specific issues and boundary conditions. Three main approaches have been selected: Development of a) UHS compatible seed time histories, b) Conditional Mean Spectra for risk calculations and associated time histories, and c) Conditional Spectra for risk calculations and associated time histories. All the time histories and control plots are provided in an appendix for each NPP site.

Keywords

Probabilistic Seismic Hazard Assessment (PSHA), Nuclear Power Plant, SSHAC, Seismic Source Characterization, Ground Motion Prediction Equation (GMPE), Site Amplification, Conditional Mean Spectrum, Conditional Spectra, Spectral Matching, Time History Selection, Switzerland

Contents

Chapter 1

Introduction

Seismic design of structures is generally based on a design response spectrum obtained from hazard analysis for a specified return period. The deaggregation of the hazard is used to determine the controlling earthquake scenario in terms of magnitude and distance. For many engineering applications, such as the design of critical facilities or highly irregular buildings, a more complex dynamic analysis is often conducted. Such analysis requires input in the form of design time series with response spectra that are consistent with the target design spectrum. Design time series are usually developed by modifying empirical recordings from past earthquakes representative of the design event. Two approaches exist for modifying time series to make them consistent with the design response spectrum: scaling and spectral matching. Scaling involves multiplying the initial time series by a constant factor such that the spectrum of the scaled time series matches the design response spectrum over a specified period range. Spectral matching involves modifying the frequency content of the initial time series to match design spectrum at all spectral periods or over a specified period range.

Both scaling and spectral matching have different advantages and disadvantages that might make the use of one more desirable than the other depending on the application. Scaling of time series preserves the peaks and troughs of the initial spectra and therefore results in realistic earthquake spectra. However, scaled response spectra usually result in large scatter around the mean structural response and more time series are needed to accurately reproduce the mean structural response. Time series selected for scaling are usually subject to strict selection criteria in terms of magnitude and distance ranges as well as site conditions and possibly other parameters. Spectral matching has the advantage of requiring a smaller number of time series to obtain the mean structural response, however, it suppresses the variability around the mean which may or may not be desirable. More relaxed selection criteria can be used to select the candidate time series. For example, different site conditions can be used because spectral matching corrects for the differences in frequency content resulting from the differences in site conditions. Spectral matching results in relatively smooth spectra that are considered unrealistic when compared to earthquake response spectra with peaks and troughs.

A widely used starting point for time-histories selection is usually provided through the Uniform Hazard Spectra (UHS) and the related hazard deaggregation arising from Probabilistic Seismic Hazard Assessment (PSHA) studies. A principal shortcoming of a UHS curve in the context of seismic PSA studies consists in the fact, that it represents an enveloping spectra from multiple earthquakes at different spectral frequencies. In this report, we review the basics of Uniform Hazard Spectra and Conditional Mean Spectra and present a new approach for developing a suite of realistic scenario earthquake spectra that account for the correlations and variability of the peaks and troughs in the spectra at different spectral periods. These scenario spectra are assigned rates of occurrence that allow reconstituting the hazard curves at different periods.

1.1 SSHAC Process – Center, Body and Range

SP5 is a new subproject that was not part of the former PEGASOS project. SP5 is not directly comparable to SP1, SP2 or SP3 in terms of capturing the center, body and range of the informed technical community. The SP5 Experts acted as a team and thus, ownership of the final scenarios (for the given PRP hazard results) and developed methodologies rest with the team. The interfaces between SP5 and the different subprojects was addressed through dedicated workshops focusing on avoiding inconsistencies in the models between the different subprojects through interaction between the experts in different topics. Transparency and quality assurance is provided following the same procedures as was used in PEGASOS.

The approach selected for SP5 is not full SSHAC Level 4 [Budnitz et al. 1997; Kammerer and Ake 2012] consistent and thus, was not subjected to the same formal strict requirements. In this context, it should also always be mentioned that no single interpretation concerning a complex earth sciences issue is the "correct" one, but also not the "wrong" one. There is a practical difficulty in applying the SSHAC Level 4 approach to the SP5 as this automatically implies the use of multiple methods (and weights) based on each individual expert proposal. In the end, this would lead to different alternative sets of scenario response spectra and time histories for each of the NPPs based on different methods. The results of the different methods might not necessarily be compatible and consistent among each other so that there should not be a mix of results. Furthermore, having multiple alternative result sets again leaves it up to the licensees to apply different interpretations for the selection of the time histories to be finally used in the different (deterministic) frameworks. The SP5 is a post-processing of the hazard results and should lead to a clear and comprehensive set of results to be used by the NPPs. For this reason, the subproject 4 and 5 have not been assigned with a specific SSHAC level. The proposed approach of the project plan for SP5 was to evaluate of all applicable methods of the informed technical community, but make a consensus choice of a single method to be applied for the risk approaches used today. The ownership over the results are within the SP5 expert team through their review and approval of the results resp. method. SSHAC guidelines do not require consensus; however, after interactions, areas of common agreement among expert interpretations are usually reached [Kammerer and Ake 2012]. Independently of this being imposed by the project, the SP5 experts all agreed that the final assessed methods are the most suitable for the purposes of the PRP. Usually, much of the engineering community in the nuclear field relies on codes and standards that have been developed as consensus standards of practice by the larger community. By having results based on the classical UHS based approach, based on the Conditional Mean Spectrum approach and the Conditional Spectra approach the PRP covers a larger range of possible outcomes compared to if multiple approaches would have been used (in a logic tree framework) to develop multiple alternative time histories for the UHS.

1.2 Design Spectra

1.2.1 Uniform Hazard Spectra

Uniform Hazard Spectra (UHS) are a common type of design spectra developed based on the probabilistic seismic hazard approach. A UHS is developed by computing the probabilistic seismic hazard at different spectral periods. For a selected return period or probability of exceedance, the ground motion is measured from the hazard curves for different spectral periods. These ground motions (pseudo-spectral accelerations) are then plotted with respect to their spectral periods to form the UHS. A UHS, therefore, represents ground motion at different frequencies having the same level of exceedance or return period. A deaggregation of the hazard leads to the dominant earthquakes at different frequencies. The use of UHS as a design spectrum allows recovering the hazard at all frequencies and hazard levels. However, the main shortcoming of using the UHS is that it provides an envelope of different earthquakes and not a realistic earthquake scenario. In fact, it is generally observed that the high frequency (greater than 1 Hz) ground motion of a UHS tends to be controlled by nearby moderate magnitude earthquakes while the long period (greater than 1 s) ground motion tends to be controlled by distant large magnitude earthquakes. While using the UHS as a design spectrum usually leads to a reduced number of engineering analyses required, the UHS excites a broad period range in a single evaluation and a greater number of modes of the structure.

1.2.2 Conditional Mean Spectra

Baker and Cornell [2006a] developed the conditional mean spectra (CMS) as alternative design spectra to the UHS. These CMS are anchored at a selected ground motion level and a spectral period of interest (hence the term "conditional") and are constructed using the mean value of the number of standard deviations (ϵ) of the ground motion model at different periods (hence the term "mean"). The CMS is constructed to take into consideration the correlation of the mean ϵ across periods. The use of CMS as design spectra has the advantage that they represent realistic earthquake scenarios; however they represent average spectra and do not capture the peak-to-trough variability of the spectrum. Also, it is difficult to assign rates of occurrence to the CMS and reconstruct the hazard curves at all frequencies and hazard levels. Figure 1.1 shows an example UHS with a 2000 year return period along with the CMS anchored to this UHS at a reference period of 0.75 seconds and the range of the peak-to-trough range around the CMS. The standard deviation (σ) of the CMS anchored at a period T_0 is calculated at any spectral period T as:

$$\sigma_{CMS}(T, T_0) = \sigma(T)\sqrt{1 - \rho^2(T, T_0)}, \tag{1.1}$$

where $\sigma(T)$ is the total standard deviation of the ground motion model at period T, $\rho(T, T_0)$ is the correlation coefficient of the residuals of the ground motion model. Figure 1.1 shows that there is no peak-to-trough variability at the reference period T_0, where the CMS is anchored. For spectral periods close to T_0, a small peak-to-trough variability is observed because the ϵ values are strongly correlated for nearby spectral periods.

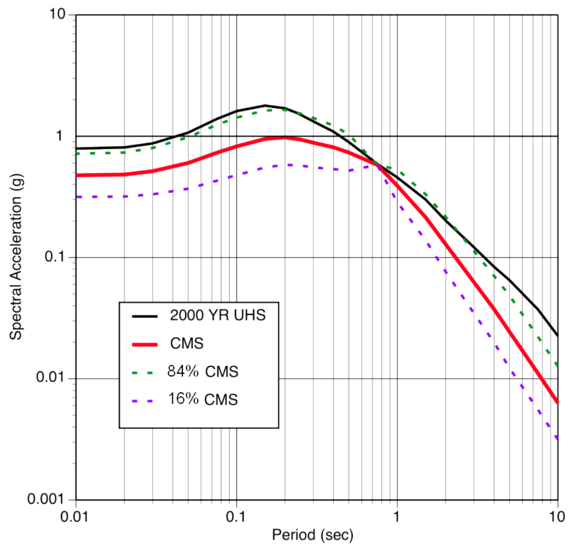


Figure 1.1: Example of the range of peak-to-trough variability around the CMS compared to the 2000 year UHS.

1.2.3 Conditional Spectra

Conditional spectra (CS) or "scenario spectra" are realistic earthquake response spectra that are anchored at a reference period, T_0, and capture the peak-to-trough variability around the CMS anchored at T_0. The use of a relatively large number of CS with assigned rates of occurrence allows recovering the horizontal and vertical hazard curves for a range of frequencies and hazard levels. Using CS as design spectra removes the conservatism from probabilistic risk assessment if systems, structures, and components (SSC) important to safety have different natural frequencies. On the other hand, the use of CS leads to a large suite of design spectra and therefore to an increased number of engineering analyses required. This additional cost may be justified in order to avoid exciting a broad period range in one single evaluation. The number of engineering runs required with the CS can be minimized by using a set of unique scenarios repeatedly with different scaling factors and rates of occurrence.

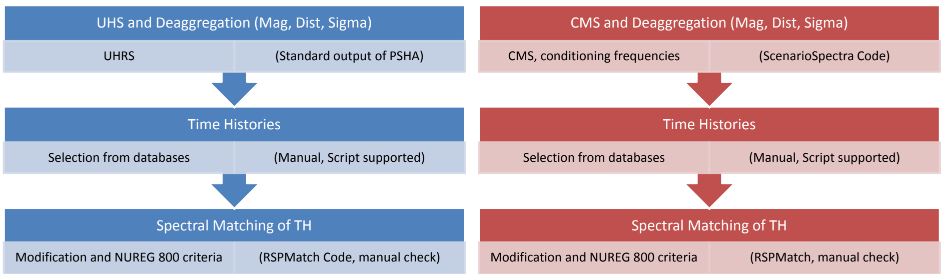
1.3 Seismic PSA Needs and Goal of SP5

A UHS is based on the mean hazard curve, but is not a mean spectrum. The designation "mean" is only due to the fact that it has been derived based on the mean hazard. Fragility analyses are conditional on the mean UHS and not the median UHS. The fragility itself is using the concept of the conditional median, which is not the same as the median hazard.

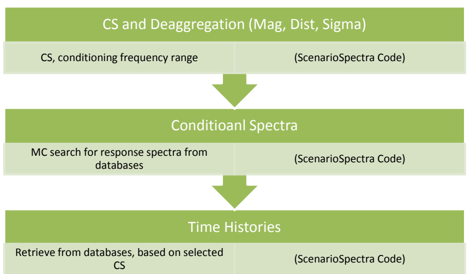
SP5 is developing scenario response spectra and time histories for use by the NPPs as part of their seismic evaluations (e.g. developing fragility curves and conducting SSI analyses). Although there is sometimes significant expert judgment involved in the development of time histories, it is not practical to use multiple sets of alternative time histories in the seismic evaluations. Therefore, SP5 has not developed alternative suites of time histories based on different methods that capture center, body, and range of the alternative methods used by the informed technical community. Instead, the project and SP5 selected a single best approach, based on the consensus among the SP5 team members. SP5 provides outputs based on the classical PSHA results and the proposed Conditional Spectra approach. For the conventional approach which directly uses the UHS for further assessments by the engineers, appropriate seed time histories are provided, which satisfy the requirements explained in more detail in Chapter 2. In case the Conditional Mean Spectrum or Conditional Spectrum approach is used, hazard consistent time histories have been provided for the implementation. Thus, in SP5 there are three cases for which response spectra and consistent time histories have been developed (see also the schematic flowchart comparison in Fig. 1.2):

- UHS (see Chapter 7),
- CMS (see Chapter 8) and
- CS (see Chapter 9).

Note: The CMS and CS approach are not something totally new, but simply a mathematically consistent way on how to define hazard consistent and realistic time histories compared to the manual selection of time histories for the UHS. The CMS and CS approach allow recovering the hazard curves (within a certain range of precision) based on the used time histories.



(a) "Classical" UHS approach (b) CMS approach



(c) Conditional Spectra approach

Figure 1.2: Flowchart comparison for the conditional spectra approach.

As a starting point for the selection of time histories three databases (flatfiles and records) have been used (see Chapter 4):

- NGA-West / NGA-West2 (World-wide database)
- RESORCE (European/Mediterranean database from the SIGMA project; based originally on the SHARE project)
- Swiss specific simulated ground motions (based on the Swiss stochastic model)

The preference is generally to use real recorded (empirical) time histories consistent with the hazard deaggregation of interest and the defined meta data criteria. As the list of criteria includes hard rock conditions (characterized through sites with high shear wave velocities and low kappa (κ) values) the available databases might not contain enough recordings for the intended procedure. In this case, it was planned to add simulated ground motions consistent with the Swiss conditions to the real recordings to provide a large enough pool of data.

1.4 Conceptual Framework

The Uniform Hazard Spectrum represents the spectra from multiple earthquakes at different spectral frequencies. Earthquake scenarios are developed for use in the Seismic PSA to support the selection or development of representative time histories required for the subsequent fragility analysis. Magnitude and distance for the scenarios are based on the modes of the magnitude-distance deaggregation at a selected spectral frequency. A set of corresponding scenario spectra have been developed to support the fragility analysis (selection of spectral shape).

The UHS for four probability levels are used: 10^{-4}/yr, 10^{-5}/yr, 10^{-6}/yr, and 10^{-7}/yr. Through deaggregation of the UHS for the different annual probabilities of exceedance, the contribution for different magnitude and distance bins for all combinations of experts for a single specified spectral frequency are determined. The spectral frequency that is used for the NPP fragility evaluation should be used as the reference frequency f_0 or period T_0 respectively. The full range of the Conditional Spectra for this reference frequency f_0 is defined (median and variability about the median). The median of the Conditional Spectra is given by the CMS [Baker and Cornell 2006b, a]. The development of the median scenario spectrum is based on the computation of the epsilon (ϵ) value required to scale the median spectrum to match exactly the UHS for the given spectral frequency. The mean epsilons at the other spectral frequencies, conditioned on the epsilon at the selected frequency, are then used to develop the conditional mean spectrum.

The variability about the median spectrum is captured by taking a minimum of 30 realizations (named conditional spectra CS) of the epsilon variability about the CMS, accounting for the correlation of the epsilons between different frequencies. This process is repeated for each selected hazard level and for each magnitude-distance bin. A rate of occurrence is determined for each scenario such that the combined rates from the scenarios approximate the hazard. This results in a large number of scenario spectra, but they have the advantage that they reproduce the full hazard at each spectral frequency more accurately than a simplified approach, for example as proposed e.g. in Abrahamson and Yunatci [2010]. At each spectral frequency, the UHS includes the effect of peak-to-trough variability through the standard deviation of the ground motion model. The peak-to-trough variability about the scenario spectra is estimated by means of the correlations of the ground motion variability between different spectral frequencies, as shown by Abrahamson and Al Atik [2010]. This range of peak-to-trough variability can be used for guidance when selecting time histories with the appropriate peak-to-trough variability.

Procedure for the development and selection of scenario time histories

After definition of the scenario earthquakes, scenario time histories can be developed. The SP5 experts provided guidance within the framework of SP5 on how to define and select appropriate time histories to match the UHS and the developed scenario response spectra. A single suite of 30 representative 3-component seed time histories on rock and/or soil surface for each site was developed within the framework of SP5. These are intended to serve as seed for the development of additional time histories by the NPPs. The consistency of the seed time histories developed in the framework of the PRP with the SP2 and SP3 models have been checked by the experts before their final delivery.

Firstly, initial time histories have been selected, which originated from recorded motions but could also have been numerically simulated motions based on seismological models. The selected time histories can be modified to be compatible with the scenario earthquake spectrum either by scaling (multiplying by a constant) or by changing the frequency content while maintaining the non-stationary character of the initial ground motion (spectral matching). A representative set of time histories for each scenario spectrum can then be generated. Afterwards, the time histories can be used to estimate the structural/equipment response and to develop fragility curves for the PSA. The development of the reference scenario time histories have been conducted following the guidelines specified by SP5 in the workshop WS1-SP5 and have also been supervised by the TFI. The resulting sets of selected time histories have been reviewed by the SP5 Experts and documented in this report. The time history report includes the following plots:

- Acceleration, velocity, and displacement seismograms for the initial unmodified and modified time histories
- Fourier amplitude spectra for the initial unmodified and modified time histories
- Comparison of Husid plots (normalized Arias intensity) for the reference and modified time histories
- Comparison of the response spectra of the initial unmodified and modified time histories with the scenario earthquake spectrum.

1.5 SP5 Workshops

A know-how transfer workshop for SP5 was held in July 2011, where all the new experts were introduced to PEGASOS and PRP. Furthermore, the basic concepts of CMS were introduced in order to familiarize them with the possible approaches. The topic of downstream fragility analyses was also presented and discussed in the framework of a specialist meeting. For the latter NPP fragility specialists were invited and the PRP Advisory Committee acted as Resource Experts.

The first SP5 workshop (WS1/SP5) presented the work planned and defined the available alternative procedures for developing the scenarios and reference time histories. Before the workshop all available methods for scenario and time history generation were made available to the SP5 experts for their evaluation. At this workshop, SP5 selected as a team, the best recommended approach to be used for the PRP based on the hazard results feedback.

At the second SP5 workshop (WS2/SP5), the developed initial set of scenario earthquake response spectra and seed time histories were presented to the SP5 Experts for review and feedback. The goal of the workshop was to discuss the scenarios provided and check consistency with the defined approach and the SP2 and SP3 models. For this workshop, only one site could be evaluated within the given time and served as example site for the other ones. Based on the provided information and review of the available suites of scenario time histories, the SP5 experts decided to require some revisions. Furthermore, the workshop served as interface workshop with the other disciplines.

After the WS2/SP5 and the implementation of the proposed approach for SP5 the SP5 experts were provided with results in form of time histories for the UHS and Conditional Spectra approach. The detailed implementation of the approach has been documented in the SP5 summary report and all results were compiled in the appendices of the report. The overview of the final results were presented at the workshop. The third workshop served to review and evaluate the implemented approaches for SP5, as well as to review and evaluate the final results: Seed time histories for UHS, Conditional Spectra consistent time histories (CMS consistent time histories for Gösgen only). The discussion enabled the project to identify and resolve any remaining open items with emphasis on interfaces and subsequent implementation issues by the engineering and risk analysis community

The selected suites of scenarios were revised and provided in 2015 to the SP5 team for their final review. In parallel to the review by the SP5 Experts the scenarios were also checked for consistency with the PRP SP2 and SP3 models (e.g. range of V/H ratios of the scenario spectra versus the soil V/H models).

Table 1.1: SP5 Workshops and Meetings

Date	Workshop/Meeting
31. Aug. & 1.–3. Sept. 2008	PRP Kick-Off Meeting
8.–10. December 2008	Interface Workshop
1.–3. December 2010	SP2-3-4-5 Interface Workshop
6.–8. July 2011	Workshop 6 for SP3 & Know-How Transfer SP5
9.–11. May 2012	Workshop 10 for SP2, Workshop 1 for SP5 & Interface
14.–15. May 2013	Workshop 2 for SP5
1. December 2015	Workshop 3 for SP5

1.6 Role of SP5 Experts in the PRP

In the original project plan (Ver. 3) [swissnuclear 2009] the SP5 experts consisted of the persons listed in Table 1.2. The initial SP5 team was responsible for selecting the time histories reviewed and used by SP3 in the site response studies.

1.6.1 Evaluation Experts

In 2011, the revised and final project plan (Ver. 4.2.1) [swissnuclear 2011] proposed to use new SP5 experts in order to address ENSI's concern that not enough fragility expertise was provided in SP5. Thus, the new subproject 5 was composed of experts from each involved

Table 1.2: Panel of SP5 experts and affiliations at the beginning of the PRP.

Subproj.	Name*	Affiliation
TFI	Prof. Dr. Norman A. Abrahamson	Norman A. Abrahamson Inc. Piedmont, CA, USA
SP2	Prof. Dr. Julian J. Bommer	IC Consultants Ltd., Imperial College, London, UK
SP2	Prof. Dr. Frank Scherbaum	Universität Potsdam, Institut für Geowissenschaften, Potsdam, Germany
SP2 RE+	Dr. P. Martin Mai	Schweizerischer Erdbebendienst, ETHZ, Zürich, Switzerland
SP3	Dr. Jost Studer	Studer Engineering, Zürich, Switzerland

* Without academic titles in the rest of the document
\+ Resource Expert

discipline in order to cover the broad range of the needs of the end users. Also for the SP5 it was decided to make use of four experts listed in Table 1.3 and thus, be consistent with the other sub-projects. The revised SP5 team was responsible for defining approaches and

Table 1.3: Panel of SP5 experts and affiliations for the final implementation.

Subproj.	Name*	Expertise	Affiliation
TFI	Prof. Dr. Norman A. Abrahamson		Norman A. Abrahamson Inc. Piedmont, CA, USA
SP5	Dr. Vincent Andersen	System analyst and interface expertise	ERIN Engineering and Research, Campbell, USA
	Prof. Dr. Jack W. Baker	Civil and earthquake engineering background, with special emphasis on CMS	Stanford University, Stanford, USA
	Prof. Dr. Peter Fajfar	Structural analysis, SSI and fragility expertise	University of Ljubljana, Ljubljana, Slovenia
	Dr. Robert P. Kennedy	Fragility and PSA expertise and member of the Advisory Committee	RPK Structural Mechanics, Escondido, USA

* Without academic titles in the rest of the document

reviewing results required by the output specification such as earthquake scenarios and the associated scenario spectra by post-processing the results obtained by SP4.

1.6.2 Resource Experts

For this subproject mainly two resource experts were involved: L. Al Atik and J.N. Gregor. L. Al Atik developed together with N.A. Abrahamson the original software code for the evaluation and generation of Conditional Spectra [Al Atik and Abrahamson 2013].

J.N. Gregor was tasked with the development of the UHS compatible time histories, which included the selection, spectral matching and compilation of all time histories [Gregor 2014].

Furthermore, S. Godey (EMSC) provided access to the RESORCE database and compiled a flatfile version of the RESOREC database according to the needs of PRP (specification

PMT-AN-1130) [Godey et al. 2013].

B. Edwards (ETHZ) developed on request of the project a simulation based database of ground motions according to the PRP specification PMT-TN-1247.

Chapter 2

Output Specification

The technical note PMT-TN-1146 [Renault 2013] was developed within the PRP as amendment to the project plan output specifications and provides and overview of the NPP requirements for additional SP4/SP5 outputs. The technical note was continuously improved, considering the practical issues and improvements discovered during the implementation of SP5.

2.1 Key Parameters and Boundary Conditions

The frequencies at which the rock hazard are evaluated, are: 0.5 Hz, 1 Hz, 2.5 Hz, 5 Hz, 10 Hz, 20 Hz, 33 Hz, 50 Hz and 100 Hz (as given in the project plan). For soil, the site resonance frequencies are included in addition. For the soil spectrum computation, the rock hazard spectrum has been interpolated in order to match the site specific resonance frequencies.

The UHS for the soil are determined at the depth levels summarized in Table 2.1 and represent geological outcrop motions.

Table 2.1: Elevation levels considered for SP5.

Plant	Elevation 1 (free surface)	Elevation 2 (relative to ground surface)	Elevation 3 (relative to ground surface)
Beznau	0 m	-15 m (reactor building)	/
Gösgen	0 m	-9 m (reactor building)	/
Leibstadt	0 m	-10 m (reactor building)	/
Mühleberg	0 m	-7 m (Turbine and radwaste building)	-14 m (reactor building)

In the PRP, UHS for the annual probabilities of 10^{-2}/yr, $2.1 \cdot 10^{-3}$/yr, 10^{-3}/yr, 10^{-4}/yr, 10^{-5}/yr, 10^{-6}/yr, 10^{-7}/yr have been developed for the rock and all soil levels for all NPP sites (KKB, KKG, KKL, KKM) for the mean, the standard deviation, the geometric mean, the 16% fractile and the 84% fractile (see swissnuclear [2013] Volume 2).

2.2 Seed Time Histories for the Classical Approach

A suite of 30 representative 3-component time histories in acceleration, velocity and displacement on soil (only at 0 m, free surface) for each site for the annual probabilities of 10^{-3}/yr, 10^{-4}/yr, 10^{-5}/yr were developed in the framework of SP5. (For KKB UHS compatible time histories also need to be provided at -15 m.) The seed time histories should have spectral shapes that are reasonably consistent with the target UHS. These are intended to serve as seeds for the development of additional time histories by the NPPs or swissnuclear in the future.

Recommendations:

- The geometrical mean of the two horizontal components of the response spectra of the seed time histories needs to be compatible with the UHS (which represents the geom. mean. component resulting from the hazard analysis). Variability of the two horizontal components about the geom. mean should be included and each horizontal time history component should represent a realistic spectrum and not necessarily match the UHS at each frequency.

- The vertical components of the seed time histories need to match the vertical UHS.

- The suite of seed time histories should preferably be based on recorded ground motions and should be completed by simulations when not covering the required range, but be consistent with the boundary conditions used within the new Swiss stochastic model (Edwards, B. & Fäh, D., 2010, TP2-TB-1052) in order to represent the characteristics of Switzerland.

- The seed time histories should be developed in accordance with NRC NUREG-0800 [NRC 2007] (pages 3.7.1.-7 to 13): The average of the 30 geometrical means of the two horizontal components should fulfill the matching criteria of NUREG-0800.

- The generation of the (3-component) time histories has to satisfy the requirement of the statistical independence of the time histories (focusing on the two horizontal components). If necessary, a baseline correction needs to be applied to the time histories.

- The consistency of the deaggregation at the soil surface with the full hazard background of SP2 (rock) has to be checked.

2.3 Scenario Hazard Curves

For the frequencies of 1, 5 and 100 Hz the total rock hazard was decomposed in scenario hazard curves in terms of magnitude and distance (Fig. 2.1). The requested plant specific bins are provided in Table 2.2. Scenario hazard curves for the soil (surface and sub-surface levels), using the same magnitude and distance bins, have also been developed for all four NPP sites.

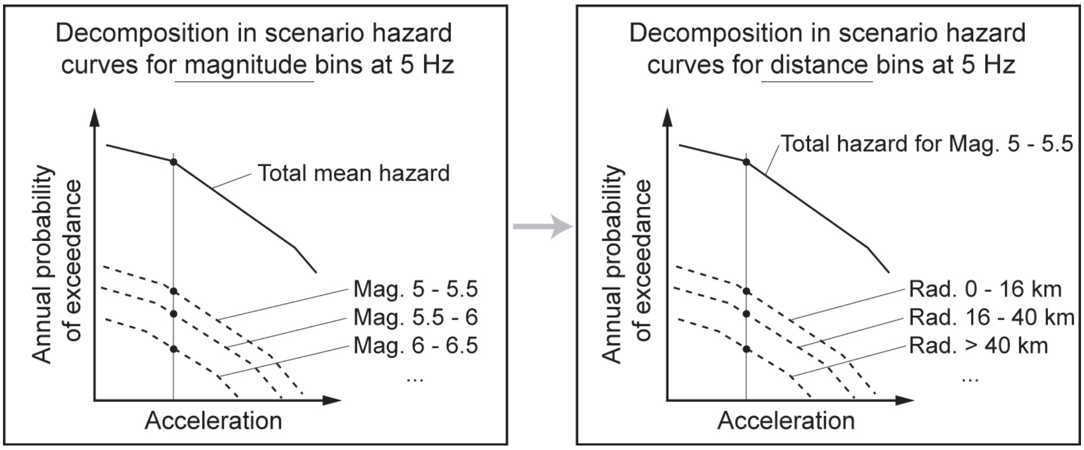


Figure 2.1: Schematic sketch of the decomposition of the mean hazard curves in scenario hazard curves for certain magnitude and distance bins.

Table 2.2: NPP specific scenario hazard curves.

Plant	Magnitude bins [M_W]	Distance bins [km]
Beznau (KKB)	4.5-5	/
	5-6	/
	6-7	/
	>7	/
Gösgen (KKG)	4.5 - 5.5	0-15, 15-40, >40
	5.5 - 6.5	0-15, 15-40, >40
	>6.5	0-15, 15-40, >40
Leibstadt (KKL)	4.5 - 5.5	0-25
	5.5 - 6.5	>25
	>6.5	/
Mühleberg (KKM)	4.5 - 5.5	0-5, 5-25, >25
	5.5 - 6.5	0-5, 5-25, >25
	6.5 - 7.5	0-5, 5-25, >25
	>7.5	0-5, 5-25, >25

2.4 Conditional Spectra (CS)

A table of representative earthquake scenarios in terms of a response spectrum, magnitude, distance and rate of occurrence (see table 5 in the project plan) will only be developed on request for each NPP. A median scenario spectrum (CMS) can be provided or in addition a minimum of 30 realization sample spectra (CS), each being equally distributed among the associated rate. At minimum, the UHS for five probability levels need to be used to develop the spectra: 10^{-3}/yr, 10^{-4}/yr, 10^{-5}/yr, 10^{-6}/yr, and 10^{-7}/yr. The table below summarizes the NPP specific requests. The correlation models for Conditional Spectra are today only available for (soft) rock site conditions and thus, the CS will only be evaluated for rock. The corresponding CS for soil are derived through scaling with the appropriate SP3 amplification function, depending on magnitude, distance and amplitude for the corresponding scenario.

2.5 Scenario Time Histories

In addition to the conditional spectra, also scenario time histories consistent with the CMS have been developed for the site specific output as defined in Table 2.3. As it is not straightforward to develop consistent time histories for different depths, it was decided to develop them based on the rock level and derive compatible time histories for other depth levels.

Table 2.3: Overview of the Conditional Spectra and number of time histories specified in PMT-TN-1146.

	Condit. Freq. or range [Hz]*	Conditional Mean Spectra or Conditional Spectra (Scenarios)			
		Rock	Soil (0m)	Soil (Elev.2)	Soil (Elev.3)
Beznau (KKB)					
Response Spectra:	2.5 - 30	☒ CS	☒ CS	☐ CS	-
Time Histories:**		☒+ Nb:100	☒+ Nb:100	☐+ Nb:100	-
Gösgen (KKG)					
Response Spectra:	5	☒ CMS	☒ CMS	☐ CMS	-
Response Spectra:	16	☒ CMS	☒ CMS	☐ CMS	-
Time Histories:**		☒ + Nb: 30	☒ + Nb: 30	☐ + Nb: 30	-
Leibstadt (KKL)					
Response Spectra:	-	-	-	-	-
Time Histories:**		-	-	-	-
Mühleberg (KKM)					
Response Spectra:	2.5-25	☒ CS	☒ CS	☐ CS	☒ CS
Time Histories:**		☒+ Nb:100	☒+ Nb:100	☐+ Nb:100	☒+ Nb:100

* Range of interest indicated in the table, where the center is represented for a log frequency range by the mean at 8.7 and 8 Hz, respectively.
** The indicated number is the amount of independent time histories which are not scaled.
Nb Number of time histories

The scenario time histories for the CMS should also be developed in accordance with NRC

NUREG-0800 [NRC 2007] (pages 3.7.1.-7 to 13): The average of the 30 geometrical means of the two horizontal components should fulfill the matching criteria of NUREG-0800. Note: The individual time histories of the conditional spectra should have been selected according to the matching criteria.

2.6 Guidance for the Development of Additional Scenarios and Time Histories

The guidance by SP5 is intended to make sure that the subsequent development of scenarios and time histories is consistent with the PRP output. SP5 needs to understand that the developed scenarios and time histories will serve two purposes:

- Defining initiating events and use of occurrence rates for each scenario in the Seismic-PSA for evaluation of the risk contribution.
- The selected or developed time histories are used to estimate the structural / equipment response and to develop fragility curves for the Seismic-PSA.

Structural engineers and PSA specialists will need to be consulted (e.g. at workshops in form of Resource Experts) in order to identify the specific requirements of the scenario spectra and time histories (e.g. duration, frequency content, peak-to-trough variability, scaling, etc.). SP5 needs to define the following properties and meta data for the defined earthquake scenarios:

- Magnitude
- Distance / location of controlling earthquake (long., lat.)
- Source Mechanism
- Dip
- Focal depth
- Site conditions (soil category, V_{S30}, ...)
- Strong motion duration

SP5 also defines the following properties and data for the time histories:

- Time increment
- Total duration (record length)
- Rise time, strong motion duration and decrease time as function of magnitude and distance
- Statistical independence criteria of the time histories
- Requirements for the 3 components of motion (e.g. wave correlation)
- Criteria for filtering and baseline correction

In the end, the SP5 experts did not explicitly recommend specific properties, but pointed to the available literature [Boore and Bommer 2005].

With regard to conditional failure criteria used in Seismic-PSA incoherency models (like e.g. Luco and Wong [1986] or Abrahamson and Bommer [2005]) can be used. This effect is considered to be relevant for large foundation dimensions (e.g. redundant but spatially separated diesel buildings).

The accuracy of synthetic response spectra to match the target response spectra is given by the standard/code used by the NPPs and has not to be defined by SP5.

The soil-structure-interaction analysis requires deterministic inputs like: a) Soil velocity profile, b) Elastic modulus, Poisson ratio, damping, c) Variability of the parameters, which will not be assessed and defined by SP5.

2.7 Constraints and Criteria

Furthermore, the following constraints and criteria were provided by the SP5 experts:

Selection of time histories from databases of real records for (classical) UHS based approach

- Use broader range of magnitudes and distances for the selection consistent with the distribution according to the deaggregation plots: M=5–7.5, R=0–50 km.
- Relaxed constraint on the cross-correlation between components of records for the selection.
- Relaxed constraint on the duration (strong motion and total length) for the selection.
- No constraint on V_{S30} for the selection, as the spectral shape is more relevant.
- No constraint on necessary scale factors.
- If multiple records from a single earthquake are available, then check that the correlation in acceleration and/or velocity is small (<0.1).

Spectral matching of time histories for (classical) UHS based approach

- Fitting range between 0.3 - 100 Hz. Avoid consistent under-prediction.
- Add horizontal component-to-component variability to time histories.
- Standard deviation of geometrical mean from target should be <0.1 (ln units). Otherwise need to compensate in the component-to-component aleatory variability.

Today's, position of the community on the cross-correlation requirements specified in NUREG-0800, is that it only really applies to simulated ground motions and not to the selected real records. Recorded three-component ground motions have a certain cross correlation but this does not need to be below 0.16. The SP5 experts recommended to check if the cross-correlation coefficient falls below 0.30.

Chapter 3

Detailed Hazard Deaggregation

The basis for a refined development of fragility curves is the availability of a seismic hazard binned for certain magnitude-distance pairs. Thus, the Swiss NPPs requested to provide a detailed hazard deaggregation fitting their plant specific needs. Those families of fragility curves can subsequently be used to derive consistently a refined risk evaluation. In the following this hazard decomposition is explained and illustrated.

3.1 Hazard Decomposition in Scenario Hazard Curves

As specified in Section 2.3, the mean rock and soil hazard was decomposed into so-called scenario hazard curves in terms of magnitude and distance bins. This is especially useful for developing refined fragility curves for specific magnitude-distance bins. This chapter includes only one illustrative plot for the Gösgen NPP, a description of the plot and some complementary information. Figures for all frequencies and sites can be found in Appendix C. ASCII files with the tabulated values corresponding to all the figures have been prepared and have the same format as the main hazard result output files. There is one table for each site, frequency, hazard type (rock, soil surface, soil sub-surface) and M–R bin. The file names are self explaining and defined for Gösgen e.g. as:
`Goesgen_<freq>_Hz_Decomposed.<HzdTyp>.MAGbin_<#>.DISTbin_<#>.20140527.asc`, with <freq> adopting one of the nine PRP frequency values, <HzdTyp> beeing RHZ, z1h.SHZ, z2h.SHZ or z3h.SHZ and <#> having number 1 to 4 depending on the amount of magnitude and distance bins, respectively.

Depending on the NPP site three or four magnitude bins have been defined according to Table 2.2. In order to have a common legend across all sites for the figures, the magnitude bins have been named:

- Low Mag. Contribution (red)
- Mid Mag. Contribution (blue)
- High Mag. Contribution (green)
- Very High Mag. Contribution (pink)

The distance bins are labeled with:

- Near-field Contribution (dashed)
- Mid-field Contribution (dotted-dashed)
- Far-field Contribution (dotted)

Figure 3.1 shows the deaggregated rock hazard for the Gösgen site at 5 Hz. The thick black line represents the mean hazard as computed by SP4. The colored solid lines show the hazard decomposed according to magnitude. The dashed, dotted-dashed and dotted line in the same color as the solid line show the distance contribution for the specific magnitude bin. All the thin colored dashed lines in the background show the individual logic tree branch contributions according to the associated M–R bin.

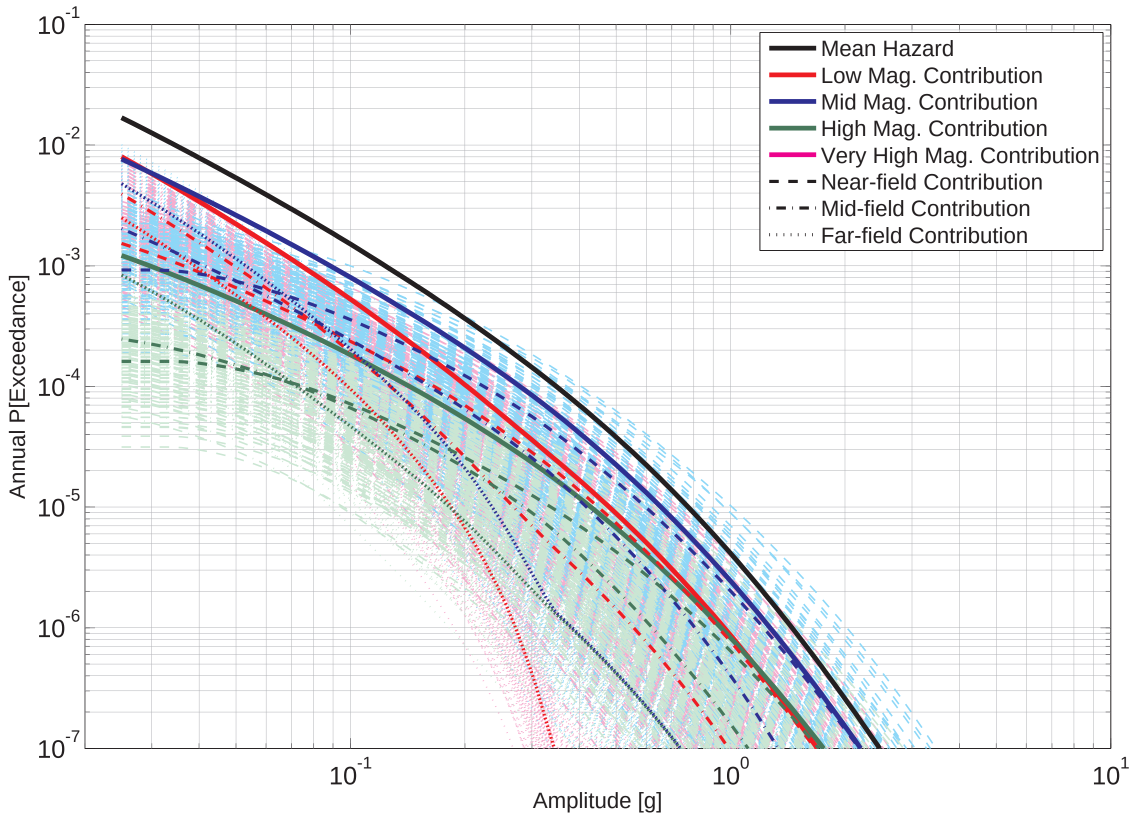


Figure 3.1: Gösgen, decomposed hazard, rock, horizontal component, 5 Hz. Note that the Very High Mag. Contribution is not present for the Gösgen site, as only three magnitude bins are defined for KKG.

In some of the figures in Appendix C, the deaggregated hazard curves for low ground motions at 0.5 and 2.5 Hz are not present. This can be explained with the performed deaggregation interpolation and the matrix shown in Figure 7.3 in the Volume 1. For the soil hazard curves the same truncation limits towards the lower ground motion amplitudes have been applied as for the final hazard results, as shown in Volume 2.

The fractional contribution of M and R change along the hazard curve for each frequency (the contribution is different for each annual probability of exceedance). The distance contributions for the individual magnitude bins have also been plotted and help to understand how the deaggregation plots were built. (For Beznau those plots are not reported, as due to the lack of a distance binning those contributions are 0 or 1.) For all cases the contributions of the M and R bins of the mean rock hazard have been used, as for soil they were not available. Figure 3.2 shows the M–R contribution corresponding to the deggregated hazard shown in Figure 3.1.

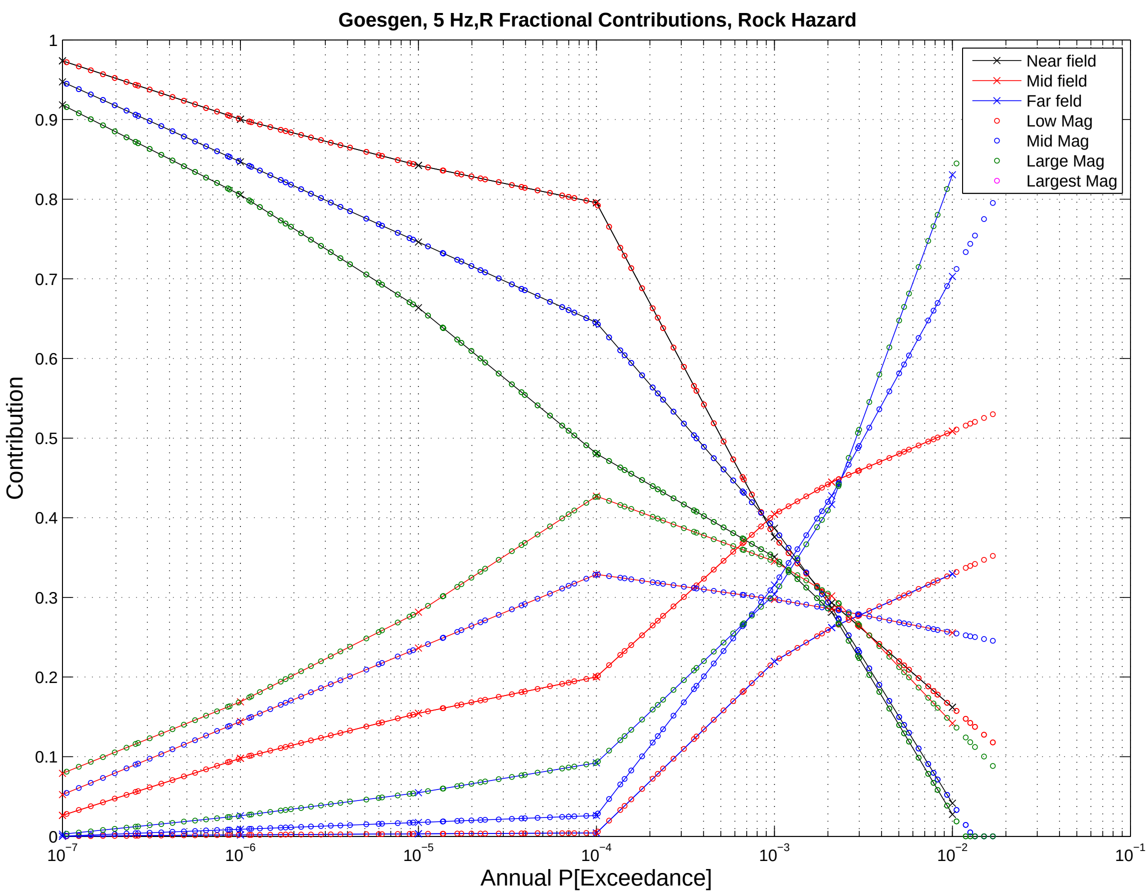


Figure 3.2: Gösgen, hazard contribution, rock, horizontal component, 5 Hz. Note that the Largest Mag. Contribution (green dots) is not present for the Gösgen site, as only three magnitude bins are defined for KKG.

Remark: For Leibstadt there are some scenario hazard curves with non-monotonically increasing slope.

Chapter 4

Ground Motion Databases

Three databases have been used to select and develop the 3-component time history traces for the SP5. A very brief overview is given and some issues and limitations of the available world-wide ground motion records is discussed. Furthermore, the NGA-West1 database has been used as basis for the selection of the time histories for the classical UHS based approach. As the NGA-West2 database also contains the former NGA-West1 records this database is not counted as a separate one.

At the beginning of the task for the selection of records for the Conditional Spectra approach it seemed promising to also be able to make use of the NGA-East database [Goulet et al. 2014], but its completion came too late for the PRP – especially, the vertical component. The records from the NGA-East database were expected to be even more consistent with the expected response spectral shape in Switzerland, as the East US has also very hard rock conditions.

4.1 NGA-West1 and NGA-West2

The NGA-West2 database [Ancheta et al. 2013] (http:/peer.berkeley.edu/ngawest2/databases/) is an improved and extended version of the NGA-West database. Figure 4.1 shows the magnitude-distance distribution of this database. Figure 4.2 shows the distribution of soil conditions, expressed as V_{S30} where available.

4.2 RESORCE

The EMSC has compiled the RESORCE database [Akkar et al. 2014b] (http://www.resorce-portal.eu/) in the framework of the SIGMA project (http://projet-sigma.com/). This database is an improved version of the original SHARE database of ground motions. Upon request, S. Godey has developed a flatfile version of the RESORCE database according to the needs of PRP (specification PMT-AN-1130) in order to be compatible with the input format for the Conditional Spectra approach [Godey et al. 2013]. The PRP specific version of the flatfile and time histories is stored for PRP in the archive EXT-WAF-1022.

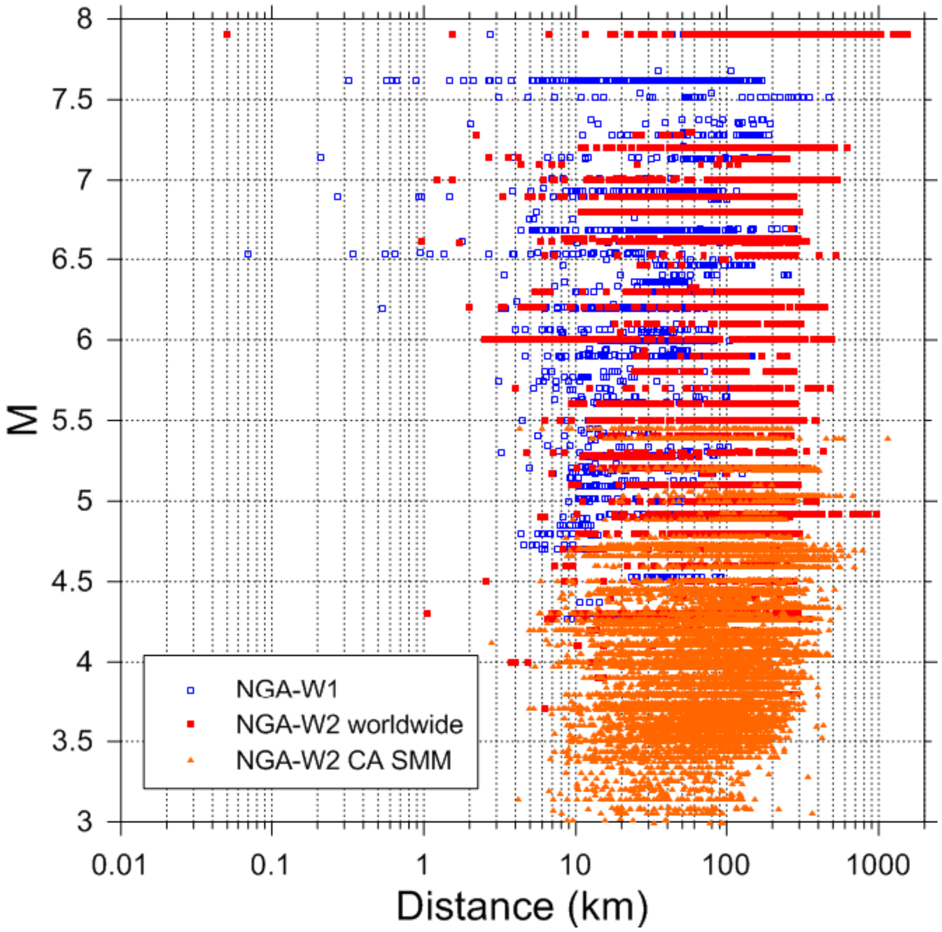


Figure 4.1: Comparison of the magnitude-distance distribution of strong-motion records in the NGA-West2 database (magnitudes 3 to 7.9) and West1 database. Open blue squares are stations included in the NGA-West1. Solid red squares are stations added from worldwide events. Orange triangles are stations added from California only from small to moderate magnitude events (magnitudes 3 to 5.5). The new earthquakes below magnitude 6 are mainly from aftershocks from the 2008 Wenchuan earthquake and Italian earthquakes. [Ancheta et al. 2013]

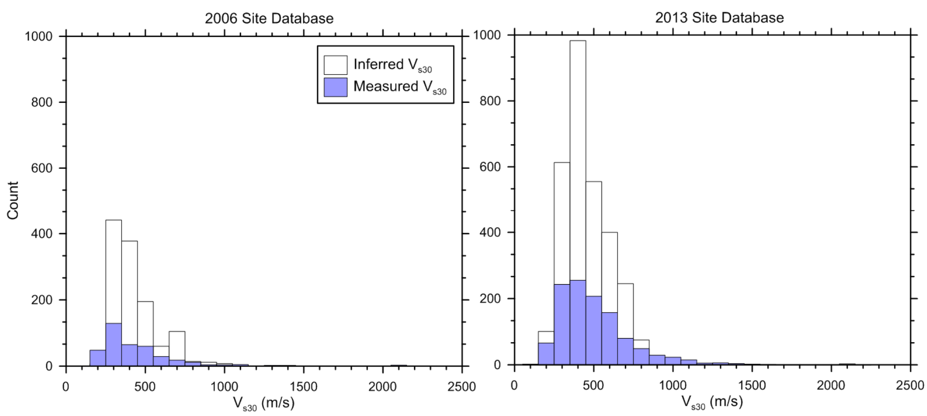


Figure 4.2: Magnitude vs. soil conditions (V_{S30}) for the NGA-West2 database. Histograms of measured and inferred Vs30 at the recording station sites in both the 2006 and 2013 site databases. [Ancheta et al. 2013]

Figure 4.3 shows the magnitude-distance distribution of this database. Figure 4.4 shows the distribution of soil conditions, expressed as V_{S30} where available.

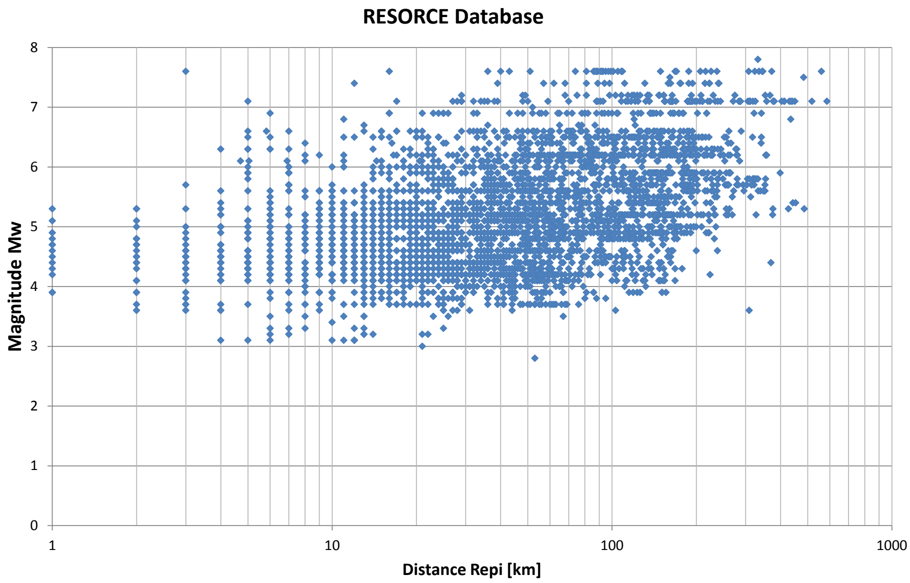


Figure 4.3: Magnitude-distance distribution of strong-motion records in the RESORCE database (magnitudes 2.8 to 7.8).

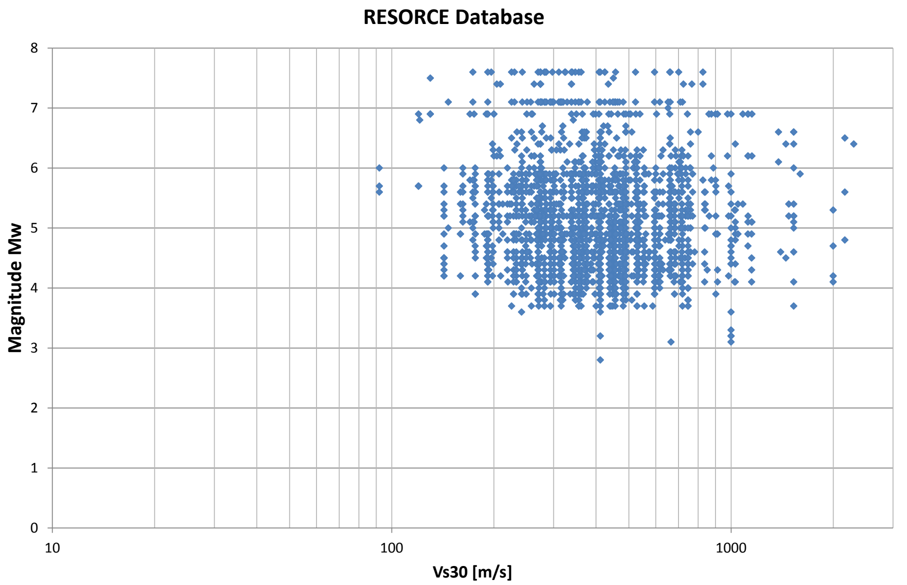


Figure 4.4: Magnitude vs. soil conditions V_{S30}. Note: 1600 out of 3943 events have no assigned V_{S30} value and are thus not represented in the graph.

4.3 Synthetic Ground Motions

In the light of substituting missing records for the specific hard rock conditions in Switzerland, not covered by the NGA-West2 and RESORCE database, the PRP Project Managment Team decided to develop simulation based ground motions. SED was tasked in this context to develop ground motions consistent with the Swiss stochastic model and spanning the range of all possible magnitudes, distances and soil conditions for the PRP hazard. The specification PMT-TN-1247 for the ground motion simulations contains the details of all the scenarios. Here, only the main characteristics are repeated for the sake of overview:

- Distances: R_{JB} = 2, 5, 10, 15, 20, 40, 60, 80, 100 km
- Magnitudes: M_W = 4–8, Steps = 0.5 units
- Stress drop: 30, 60, 90, 120, 240 bar
- Mechanisms: Fault style: Normal with Dip=53°, Strike slip with Dip=79°; Hypocentral depth: 5, 12, 20 km
- Kappa: 0.003–0.031s
- Soil profiles: V_{S30} = 1100, 1800, 2200, 2500 m/s

For this task the software EXSIM was used (http://www.daveboore.com/smsim/exsim_dmb_files_for_distribution.zip), version of 14/03/2013 (code version "last updated on 10 September 2012"). All the resulting scenarios and time histories are stored in the archive EXT-WAF-1023. Figure 4.5 shows the magnitude-distance distribution of this database. Figure 4.6 shows the distribution of soil conditions, expressed as V_{S30}.

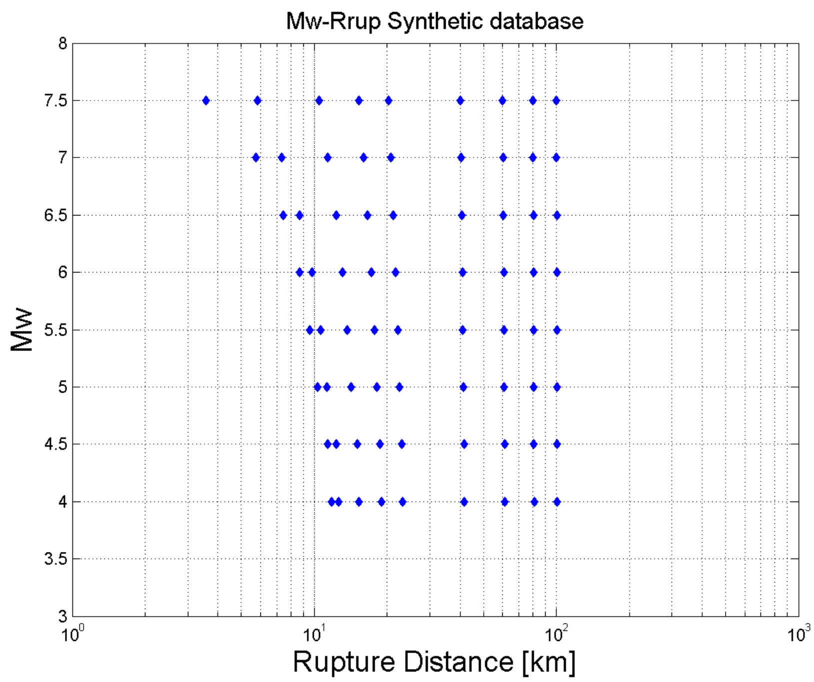


Figure 4.5: Magnitude-distance distribution of strong-motion records in the synthetic database (magnitudes 4 to 7.5). Each symbol in the graph represents hundreds of simulations, which result from a combination of stress drop, fault style, depth and κ.

There are two fundamental issues for the chosen approach for developing synthetic time histories with EXSIM.

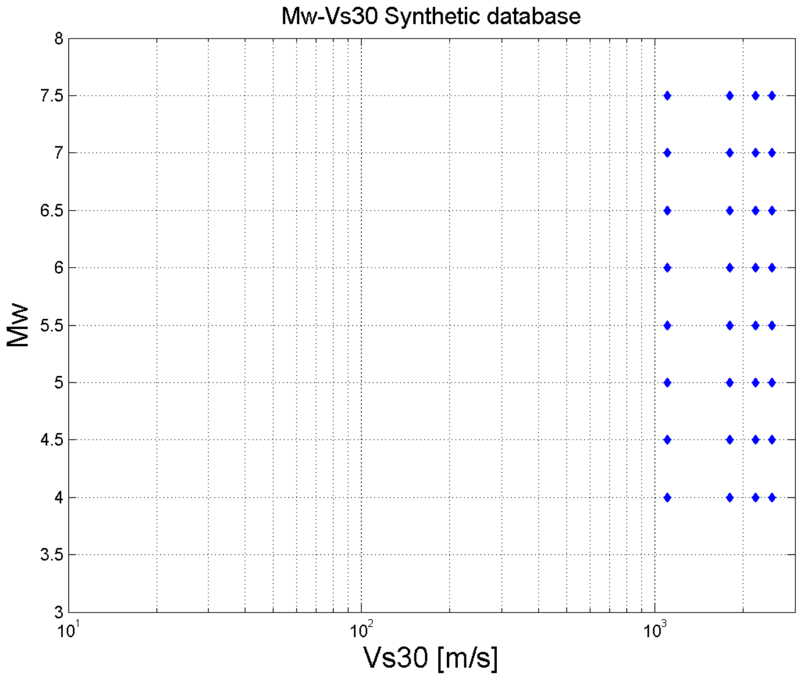


Figure 4.6: Magnitude vs. soil conditions V_{S30}. Each symbol in the graph represents hundreds of simulations, which result from a combination of stress drop, fault style, depth and κ

- The horizontal component of motion is interpreted as geometric mean and the code does not provide the two individual horizontal components of motion necessary for our specific application.
- There is no vertical component of motion as output. It was proposed to use the Edwards et al. (2011) V/H relationship to derive the vertical component in order to be consistent with the Swiss stochastic model. The V/H ratio was applied to the Fourier spectrum and transformed to the time domain in order to provide the vertical time history.

In order to still provide three component time histories and spectra it was decided to follow the approach of Atkinson [2009], where three component time-histories (or equivalently spectra) are produced by randomly assigning two horizontal simulations and one vertical from the same hypocentre (for a given site and event magnitude).

Using Finite-Fault Simulations would have been a solution to those shortcomings, as they provide real three component time histories at each distance of interest. But the necessary resources to run all the required cases and combinations were not available within the framework of the project. Furthermore, in the past it has been observed that the uncertainty stemming from the finite-fault simulations is larger compared to the predictions based on empirical GMPEs and this might be undesired in the context of providing more refined, realistic scenario time histories.

In the end this exhaustive third database was not further used for the development of hazard consistent time histories.

Chapter 5

Prerequisite, Interface with SP4

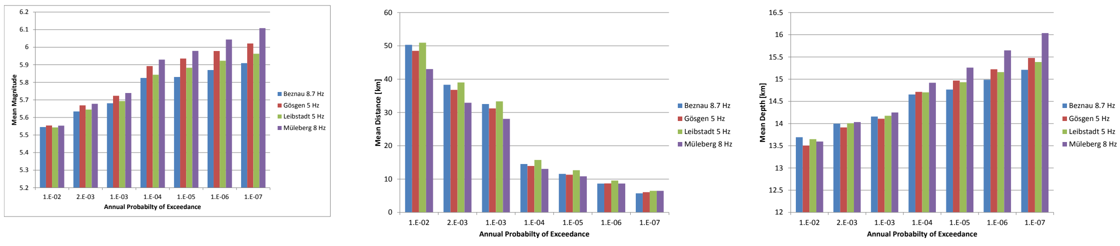
The prerequisite for SP5 consists of three main parts:

- A site-specific table of the controlling distances, magnitudes and depths,
- Spectra for the horizontal and vertical components,
- Contributions by GMPE to the mean rock hazard (in the PRP based on the deaggregation weights).

First, a site-specific table of the controlling distances, magnitudes and depths as a function of the annual probability of exceedance (APE) levels for a given (site-specific) anchoring frequency has to be developed (here i.e. `<site>_<frequency>_meanMRZ.<date>.asc`) (see Fig. 5.1). For the PRP the mean was used to characterize the controlling magnitude, distances and depths. This is obtained by running the MATLAB[*] script `VertRHZ('ALL',9)`. Pre-requisite is the existence of a complete set of rock hazard results, including deaggregation.

The main input to SP5 are the spectra for the horizontal and vertical components, based on the rock hazard results. These files are (partly) created by the MATLAB scripts

[*]MATLAB©is a registered trademark of MathWorks, Inc. in the U.S.A. protected by U.S. and international patents.



(a) Mean Magnitude (b) Mean Distance (c) Mean Depth

Figure 5.1: Mean magnitude, distance and depth distribution as function of APE.

CreateSP5Input_H.m and CreateSP5Input_V.m, respectively. They contain three blocks for the APE levels 1E-08 to 1E-08:

- Uniform hazard spectra (horizontal and vertical, respectively)
- Median horizontal spectral accelerations* and V/H ratios, respectively
- Horizontal σ and vertical σ_{VADD}, respectively (both averaged over all experts)

* The representative median horizontal spectral accelerations are obtained outside MATLAB, with a dedicated Fortran code (SP4toSP5, version 17.02.2014).

The two scripts mentioned above call a series of other scripts for the individual sub-tasks. Pre-requisite for the 'horizontal' script is the existence of the MATLAB variable file PRP_meanMmeanR_4_SP5.<date>.*.mat created by VertRHZ.m. Pre-requisite for the 'vertical' script is the existence of the file PRP_VH.ALL.<date>.mat that contains the V/H ratios and which is obtained by running VertRHZ('ALL',9).

Third, the contributions by GMPE or more precisely the contribution (by APE level) to the mean rock hazard of the individual SP2 Expert–GMPE–V_S-κ logic tree branches have to be evaluated. This has to be provided for the site-specific anchoring frequencies. For that purpose, specific POST88 runs have to be designed at that frequency (if it is a project frequency) or at the two neighboring project frequencies. These POST88 runs use the FRISK88 output of the main computations.

These "sensitivity" POST88 runs are conditional. They are performed without Monte Carlo, to obtain both a constant order of the $V_S - \kappa$ branches and numerically exact weights. We performed them for EG1c only (see e.g. ..\fcomp\EG1c\results\EG1c_go_BUCY_SH_02.in2), thus accepting the small simplification that EG1c is only kind of a sensitivity model, representative of the combination of the four SP1 models. In addition, we need the corresponding mean hazard, thus the four combinations of EG1c and the four SP2 models. This cannot be obtained from the aforementioned conditional runs but has to be obtained separately by running POST88 on the FRISK88 results and aggregating the four hazard parts (see e.g. ..\fcomp\EG1c\results\EG1c_go_4h_BU_02.in2). Two options are possible here: (a) run POST88 without collapse and with Monte Carlo, as has been done for the main runs or (b) use full collapse (justifiable as we are only interested in the mean hazard for that purpose) without Monte Carlo.

Once this data is present the MATLAB script MeanContribPerGMPE.m can be run to obtain the contributions tables that carry the name <site>_Contrib_by_GMPE_<frequency>_<type>_<date>.txt (for <type>, see the PRP specificities below). Since the script is relying on existing (sub-)scripts to load the rock hazard, .frac_t2i files for all nine project frequencies need to exist in the relevant folder. However, only the rock hazard files pertaining to the frequency (or frequencies) to investigate need to be correct: e.g. 'dummy' _4m_ files for the other frequencies can be used for a _4h_ run (see below).

PRP specificities: In PRP and for a later computation for Gösgen (at an anchoring frequency of 1 Hz, see quoted .in2 file) we derived the contributions both for the median and for the 5 point distribution $V_S - \kappa$ corrections. Since there was no FRISK88 results available for the

5-point distribution correction (`*_4h_*`) such runs had to be performed first. The MATLAB script `MeanContribPerGMPE.m` is then run twice (see script-specific help), for the median and for the 5-point distribution $V_S - \kappa$-corrections. Of the two options listed above for the calculation of the EG1c–SP2-models hazard, the first one was used.

5.1 Computational Steps for Extracting the Mean Hazard Contribution

In order to determine the contribution by GMPE to the mean hazard, the mean hazard on rock needs to be decomposed into its site-specific M–R components. The percentual contributions of each individual M–R bin to the mean hazard are extracted from the mean rock hazard deaggregation. However, the hazard deaggregation was re-calculated for this purpose using a smaller M–R increment (than the one used for the main calculations) in order for the site-specific decomposition bin borders to be multiples of this increment. In that way, the contributions in each SP5 M–R bin could be obtained through summation of the subcontributions from the smaller deaggregation bins.

The relative contributions of the individual SP5 M–R bins to the main hazard vary with hazard level and thus, these values change all along the hazard curve. In PRP, typically deaggregation for seven given annual probabilities of exceedance (see Fig. 5.1) was performed. As we need the hazard contributions for our standard vector of (173) spectral amplitude values an interpolation of the percentual contributions is performed. The hazard contribution curve from an individual bin is then obtained through integration from the lowest to the highest APE level.

The percentual contributions obtained from the deaggregation of the mean rock hazard are applied in the same way to both the rock hazard fractiles and to all soil hazard results, irrespective of the fact that for theses curves the percentual contributions from all M–R bins may be different.

As for the main deaggregation, no extrapolation towards hazard levels not sampled during the main computations ($SA < 0.025\,\mathrm{g}$) was performed, the matrix of calculated and interpolated frequency and APE combinations remaining the same as the one documented in Vol. 2 (see e.g. Fig. 2.5.1 to 2.5.5). Since we do not have a deaggregation for APEs > 1E-04 at 0.5 Hz and for APEs > 2.1E-03 at 1 Hz and 2.5 Hz, we do not have M–R contributions either, and therefore, all curves stop when the mean hazard reaches these levels for these frequencies.

5.1.1 Necessary Interpolations

Deaggregation

As already mentioned in Vol. 1, 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 list 28 (4×7) combinations of spectral frequency and PGA or APE at which deaggregation results should be delivered, see Figure 5.2. 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 (Fig. 5.3), nine carefully selected combinations were chosen (green cells in Figure 5.2) for which deaggregation was calculated. For the remaining cells, deaggregation results were interpolated.

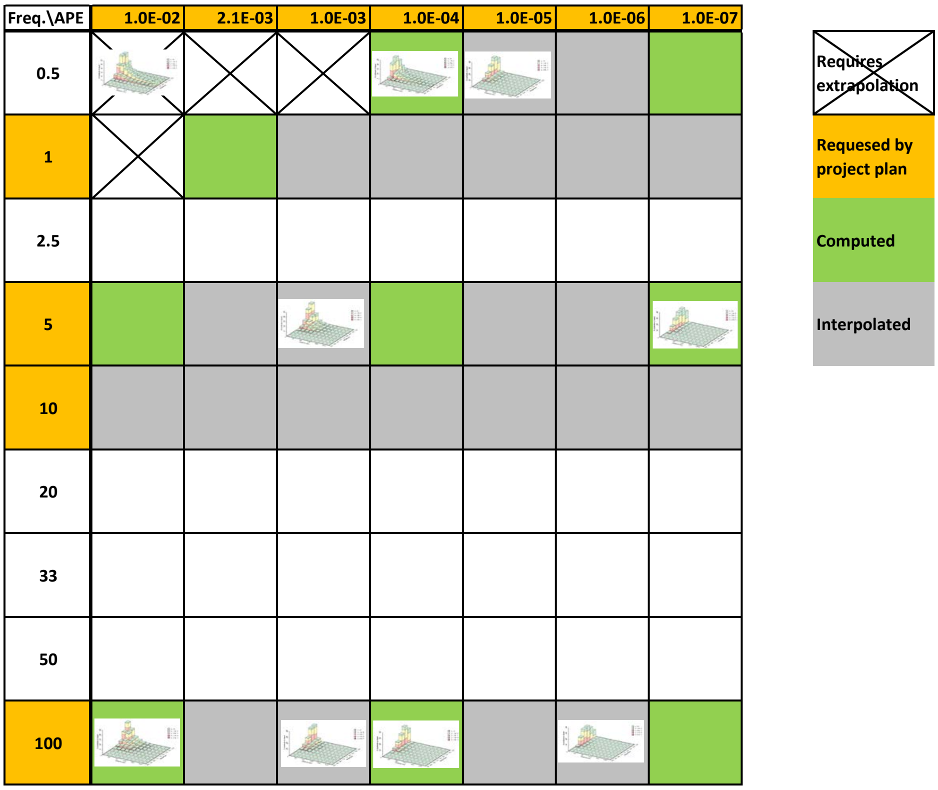


Figure 5.2: Table of the requested, calculated and interpolated combinations of spectral frequencies and annual probabilities of exceedance (APE) for the mean hazard deaggregation. The small deaggreagtion plots superposed on some cells of the matrix indicate approximatively the few corresponding cases evaluated for PEGASOS. Note that for PEGASOS the deaggregation cases were defined in terms of spectral acceleration level and not APE.

Sigma Model

Beside the deaggregation it was also necessary to extract a weighted median aleatory model over all SP2 experts for the rock hazard and interpolate it to be compatible with the required SP5 input format. The calculation is performed using the PRP ground motion logic tree (with its four σ levels) for controlling magnitudes and distance scenarios at seven hazard levels (1E-2 to 1E-8). The controlling magnitude and distance scenarios at the different hazard levels are defined at the conditioning period and based on the deaggregation cases mentioned above. The aleatory model for rock has been defined by the project at nine project specific frequencies and 25 Hz (0.5, 1, 2.5, 5, 10, 20, 25, 33.33, 50, 100 Hz). In order to be compatible with the required SP5 format the available σ values were interpolated (in log-space) to the 57 soil frequencies. The same approach was used for extracting the additional vertical aleatory variability values (σ_{VADD}) to be used for the vertical rock component, based on the provided SP2 expert models.

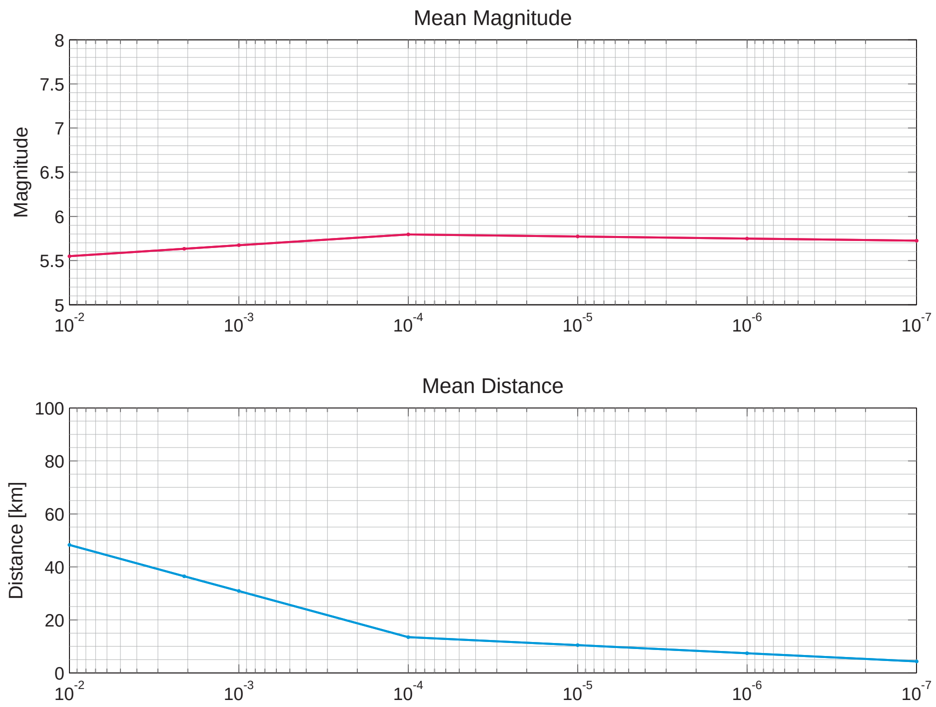


Figure 5.3: Example of the mean magnitude and distance as obtained from the deaggregation, 100 Hz (Beznau, horizontal component, rock).

V/H Ratios

The V/H ratios on rock are dependent on magnitude, distance, frequency and ground motion amplitude. In order to evaluate the necessary V/H ratios for SP5 it was necessary to extract the corresponding deaggregation grid from the available deaggregations. The deaggregations have been computed for this purpose with a δR of 5 km (rather than 20 km) and a δM of 0.1 (rather than 0.5). Subsequently, an interpolation of the deaggregation grid in the frequency-APE(/GM) space was performed.

The purpose is to create a grid of V/H ratios, with the same binning as for the deaggregation, averaging over site dependent style-of-faulting, dip angles, V_{S30} and corresponding weights. For this, the expert-specific weights for the selected V/H rock models are used to compute a weighted median V/H model for rock. In the course of the computation, an interpolation over the vertical rock hazard results, available for the nine project frequencies, is performed, resulting in a vector of 57 frequencies used in SP5.

The mean V/H ratios are used later to multiply the horizontal median response spectra with the vertical rock hazard.

5.2 Workflow for Required Inputs

Step 1: Definition of the conditioning frequency (f_0) range for the site In general the relevant frequency range for the assessment is between 2.5 and 25 Hz (depending on the structure to analyze). The center of this range is represented by its geometrical mean, which is approx. 8 Hz and is then defined as the conditioning frequency f_0. For consistency with the fragility analysis it is recommended to use the spectral frequency which is used for the NPP fragility evaluation as the reference frequency f_0, as everything is conditioned on this frequency.

Step 2: Evaluation of individual GMPE contributions The hazard analysis needs to generate a table for the specified conditioning period which contains the individual GMPE contributions to the mean hazard for each annual probability of exceedance for the site based on the site deaggregation for f_0. (In the following it is implied that the analysis is developed for the conditioning frequency f_0 and thus, f_0 is dropped as index.)

Table 5.1: Schematic overview table for evaluating the GMPE contributions to the total hazard

	Contributions per Annual Probability of Exceedance						
	1E-02	1E-03	1E-04	1E-05	1E-06	1E-07	1E-08
SA_MeanHaz(APE)	*SAvalue*	...					
GMPE_1	*Contrib.*						
GMPE_2	...						
...							

Where $GMPE_i$ represents the mean hazard for the GMPE number i based on each expert and his specific corrections (e.g. host-to-target correction for shear wave velocity and κ). This can result in multiple versions of a GMPE, but where each depends on a different underlying distribution of correction factors. The GMPE name and expert name corresponding to $GMPE_i$ should be stored in order to be able to identify them clearly for the subsequent computation. The mean hazard refers to the total mean over all experts.

$$Contrib(GMPE_i, APE) = w(GMPE_i, APE)\frac{APE(GMPE_i \mid SA(APE)}{APE(meanhazard)} \tag{5.1}$$

with $w(GMPE_i, APE)$ being the logic tree weight defined by each expert for each GMPE. The values at $APE(GMPE_i \mid SA(APE)$ and $APE(meanhazard)$ are defined as depicted by the vertical red line in Figure 5.4 at the crossing of the hazard for the conditioning period T_0 or frequency f_0, respectively.

Step 3: Definition of magnitude and distance pairs and associated source parameters Through deaggregation for the different annual probabilities of exceedance, the contribution for different magnitude and distance bins for all combinations of logic tree branches for a single specified spectral frequency are determined. If the deaggregation is only available for a subset of APE, it is convenient to interpolate the missing ones based on a grid approach. Nevertheless, the change of mean M and R with smaller APE level should be checked in order to verify the accuracy of an interpolation. The source parameters are defined based on the host sources and main contributors, respectively:

- Style of faulting (e.g. strike slip)
- Dip angle

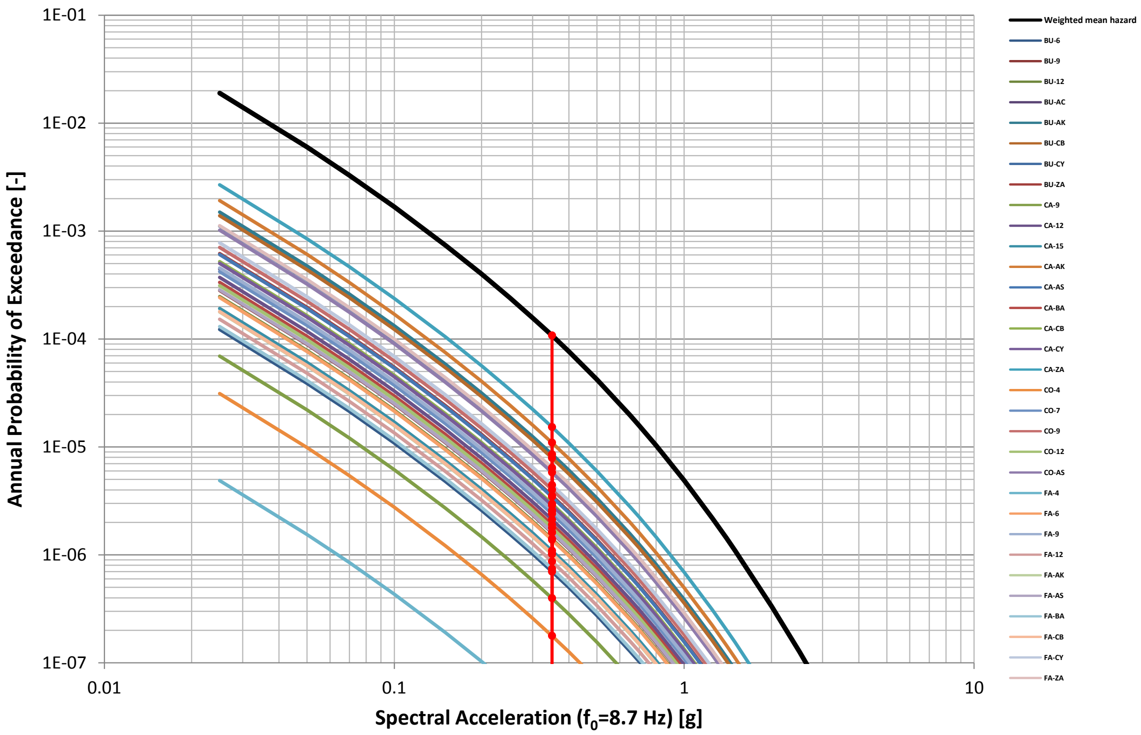


Figure 5.4: Hazard curves for each GMPE and the weighted average hazard from all models combined for the conditioning frequency f_0.

Table 5.2: Template table summarizing the mean magnitude (M), mean distance (R), and depth (H)

	Mean Mag. and Dist. per Annual Probability of Exceedance						
	1E-02	1E-03	1E-04	1E-05	1E-06	1E-07	1E-08
Mean $M(f_0)$	...						
Mean $R(f_0)$	...						
Mean H	...						

Step 4: Evaluate horizontal response spectra and V/H ratio for all parameters and GMPEs Various source parameters with associated weights have been defined and used in the logic tree approach and used in the evaluation for the V/H ratios. Strictly speaking the same could be done also for the response spectra evaluation for each GMPE. For the sake of efficiency and as the representative median response spectra is not used to develop directly time histories, the project has decided to simplify the evaluation by only using the dominant and representative set of source parameters. Thus, the response spectra and V/H ratios are only evaluated for the style of faulting and dip angle defined in step 3 (instead of using all style of faulting and dip angels, for which the resulting spectra would need to be combined according to the source parameter weights). The response spectra and V/H ratios need to be evaluated at the same frequencies in order to be compatible. Note: Alternatively to the V/H ratios for each APE level, a vertical response spectra can also be used directly.

Step 5: Evaluation of the representative median acceleration spectrum The representative median response spectrum (interpreted as geometrical mean of the two horizontal components) is obtained by summing all individual spectral accelerations of the GMPEs multiplied with their contribution of step 2.

$$\ln(MedianSA(f, APE)) = \sum_{GMPE_i=1}^{n} [Contrib(GMPE_i, APE) \cdot \ln(SA(GMPE_i, f))] . \quad (5.2)$$

For the vertical component the representative acceleration response spectrum is derived in our case with V/H ratios as such that

$$VerticalMedianSA(f, APE) = HorizontalMedianSA(f, APE) \times medianV/H(f, APE). \quad (5.3)$$

Step 6: Evaluation of aleatory variability After having calculated the response spectrum to be used for the analysis, also an aleatory variability about the spectrum needs to be defined. Within the project this aleatory variability has been computed based on the various expert models and weights. The values have to be available in dependency of frequency for the required APE levels and need to be interpolated if necessary. As in our case the V/H ratios have been used to come up with a vertical spectrum, only an additional aleatory variability term about the vertical was added. As the horizontal already contains aleatory variability, it is necessary to only add something in case it is present and to avoid double-counting of uncertainties.

Step 7: Computation of Scenario Spectra The scenario spectra for the horizontal and vertical component are computed in the last step by using all products of the previous steps and the horizontal and vertical UHS per APE. Those are:

- Conditioning frequency (which is assumed to be the same for horizontal and vertical)
- Median horizontal response spectra and V/H ratios per APE (step 5)
- Interpolated Sigma values (horizontal and vertical) per APE

The output of the procedure is a list of scenario spectra, rates, scaling factors and some meta data. Furthermore, comparison plots of the computed horizontal and vertical hazard curves, comparisons of the target and computed horizontal and vertical UHS curves, horizontal and vertical calculated CMS curves, and a list of all the time histories defined in a flatfile and based on the identified unique scenario spectra. Conditional Spectra are a means to the end result (time histories), not the result itself. The advantage of this procedure is that it allows considering multiple expert contributions, even if using the same basic GMPEs, and preserves computational efficiency, as it is only necessary to evaluate one resulting representative (median) response spectrum. According to Lin et al. [2013] and Carlton and Abrahamson [2014] this proposed approach is equivalent to the ”exact” solution if the M and R deaggregation is stable (unimodal) over APE and the used GMPEs all have similar spectral shape and epsilons.

5.3 Rock and Soil

Initially, the output specification requests the Conditional Spectra and associated time histories at the rock and soil surface level (see Sec. 2.5). In the course of the project the participating SP2, SP3 and SP5 experts were asked how to develop spectra and time histories consistent at both levels with the UHS. As the development of the soil results is also done in a fully probabilistic framework, there is no direct way how to convert the rock to the soil surface results which would fully reproduce the hazard at both levels. Thus, this attempt was dropped and the project decided together with the NPPs to only develop the Conditonal Spectra for soil surface.

All the steps and computations explained above relate to the rock hazard, as there a deaggregation is available and the GMPEs contributions were determined for producing a rock hazard. It should be noted that all previous known work on this topic was done for GMPEs leading to a rock hazard result. To obtain Conditional Spectra on soil surface a new strategy had to be developed within the project. There are some few alternative ways on how to achieve this, but in the spirit of SP5 the Project Team discussed those with the SP5 experts and all participants agreed to implement only a single and straightforward approach which was consistent with the way how SP3 was developed. This newly developed approach to generate inputs for the Conditional Spectra code is explained in the following.

5.3.1 Approach to get Median Spectral Acceleration on Soil

On rock the following information is available:

- UHS_{rock} for horizontal and vertical component
- Median response spectra for the horizontal rock component (SA_{rock})
- Median aleatory variability for rock (σ_{rock})
- Median V/H ratio on rock (V/H_{rock})
- Median additional aleatory variability for vertical rock component (σ_{VADD_rock})

On the soil level the following information is available from SP3 and the hazard computation:

- UHS_{soil} for horizontal and vertical component
- Median soil amplification functions for the horizontal component (AF_{soil})
- Median aleatory variability for soil (σ_{ADD_soil})
- Median equivalent V/H scaling factors for soil averaged over the four SP3 models (V/H_{soil})
- Median additional aleatory variability for vertical soil component (σ_{VADD_soil}) averaged over the four SP3 experts

In order to be consistent with the development of the SP3 models and the probabilistic hazard computation it was proposed to combine this information to directly produce an input file for the Conditional Spectra computer code at soil surface. The code can be used at any level (rock or soil), as it just relies on getting the right input.

The median soil amplification function is dependent on the spectral frequency and ground motion amplitude (PGA). As simplification the median soil amplification is evaluated based on an average over the three SP3 magnitude bins (M 5, 6, 7). Furthermore, the PGA dependence of the soil amplification function was resolved through linking with the UHS at a given APE and thus, resulting in a function which is only dependent on spectral frequency. The input for the Conditional Spectra approach at surface needs three main blocks for the horizontal and vertical component each:

- Horizontal:
  - UHS_{H_soil}
  - Median response spectra for soil (SA_{soil})
  - Total median aleatory variability at soil surface (σ_{total})
- Vertical:
  - UHS_{V_soil}
  - Median V/H ratio on soil (V/H_{soil})
  - Median total additional aleatory variability (σ_{VADD_total})

In order to obtain the median response spectra for soil, the horizontal median response spectra on rock was combined with the median amplification functions for the horizontal component. Thus,

$$SA_{H\_soil} = SA_{H\_rock} \times AF_{H\_soil} \tag{5.4}$$

The total median aleatory variability at soil surface is obtained by adding the variances:

$$\sigma_{total} = \sqrt{\sigma^2_{rock} + \sigma^2_{ADD\_soil}} \tag{5.5}$$

And finally, the median total additional aleatory variability for the vertical component can be obtained by adding the variances of the σ_{VADD} parts:

$$\sigma_{VADD\_total} = \sqrt{\sigma^2_{VADD\_rock} + \sigma^2_{VADD\_soil}} \tag{5.6}$$

The median equivalent V/H scaling factors for soil (V/H_{soil}) is not derived from the rock V/H ratio, as in the computational evaluation the median vertical response spectra is calculated by multiplication of the median horizontal response spectra with the V/H ratio. As we have a median response spectra on soil surface, this can directly be multiplied with the averaged SP3 V/H ratio for soil (see also Eqn. 5.3).

5.4 Consistency of Correlation (ρ) Models

The Conditional Spectra approach uses a model for correlations of the spectral periods given a conditioning period. The correlation coefficient between ϵ at spectral period T and T_0 is usually defined by $\rho(T_0, T)$. Yet, there are not many published correlations models available, especially when both, horizontal and vertical components of motion are requested. For the PRP only the models of Baker and Jayaram [2008]; Jayaram and Baker [2009]; Abrahamson and Silva [2008] were available, where the latter was updated by the correlation model of Abrahamson et al. [2013]. The SP5 experts considered those to be appropriate and in general applicable to Switzerland.

In the course of the work, the Project Team questioned the robustness of the correlation coefficients, as it relies on the evaluation of residuals with a specific GMPE and selected dataset. This generic issue was investigated by the Project Team to gain more confidence in the application for Swiss conditions. Work done in the USA uses the NGA-West2 database and the results of the different studies is consistent which leads to the conclusion that such correlation coefficients are robust and stable over the world (as a world-wide dataset is used). As an additional check, the Project Team had access to the new European RESORCE database and investigated the consistency of the correlation coefficients of the European dataset with the US dataset. The European correlation coefficients are based on Akkar et al. [2014a] ($4 < M < 8$, $R_{JB} < 200$ km and 150 m/s $\leq V_{S30} \leq$ 1200 m/s). Furthermore, ρ found from the residuals of the BC Hydro Model (N. Abrahamson, N. Gregor, and K. Addo, unpublished report, 2014), which is a GMPE for subduction zone events were overlaid on the ρ from the Abrahamson and Silva (2008) GMPE developed for shallow crustal earthquakes. The correlation coefficients from these different datasets are similar because they have similar average $T_{amp1.5}$ values. The $T_{amp1.5}$ is the lowest spectral period at which the spectral acceleration equals 1.5 times the peak ground acceleration. The comparison of the assessed models is shown in Figure 5.5. As can be seen from the comparison the shapes of the correlation coefficients are very consistent, even though they are based on very different datasets. The Baker and Jayaram [2008] model is calibrated for response spectra with $T_{amp1.5}$=0.1 s. The mean $T_{amp1.5}$ value of the BC Hydro model is 0.08 s, whereas for the shallow crustal dataset it is 0.1 s. As stated in Carlton and Abrahamson [2014], this supports the argument that any variation in correlation coefficients comes from spectral shape rather than tectonic region and that generic correlation models are robust and can be used in determination of CMS regardless of the GMPEs considered.

Another study on European correlation coefficients is Cimellaro [2013]. Cimellaro used the Ambraseys et al. 2005 GMPE with events larger than $M5$ and R_{JB} <100 km. It is very likely superseded by Akkar et al. [2014a]. Sreeram R. Kotha at GFZ also investigated the RESORCE database correlation coefficients and came to the conclusion that the Akkar et al. 2014 correlation structure is very similar to his (with lower event magnitude limit at $M4$) and can be used instead, because the record selection is very similar (Pers. Com., Oct. 2015). However, if only events larger than $M5$ are used, as in Cimellaro, G.P. (2013), the resulting correlations are different from Akkar et al. 2014. Finally, it should be mentioned that the spectral shapes are stable (even though being frequency dependent) and are consistent for $M > 5$ which is the relevant magnitude range for hazard analyses of an NPP.

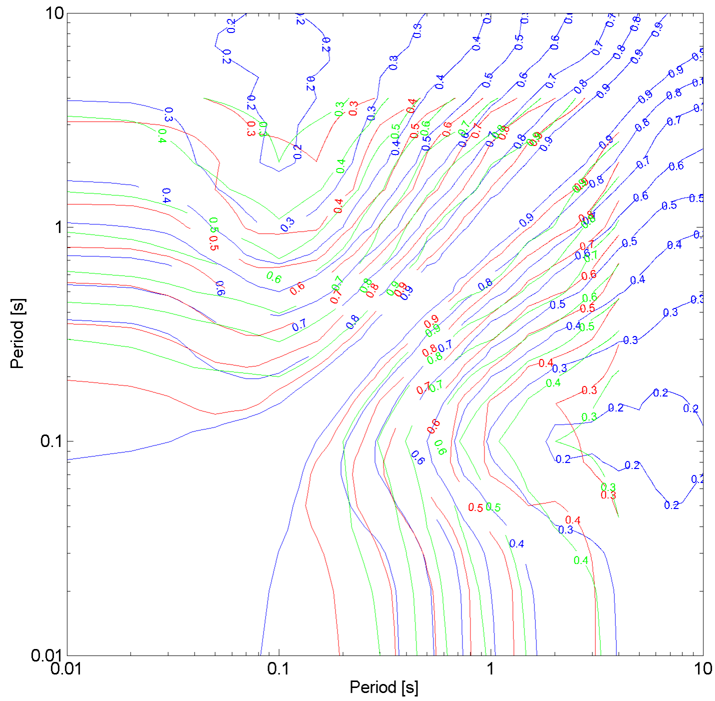


Figure 5.5: Comparison of correlation coefficients (ρ) between the databases for NGA-West2 (blue), BC Hydro subduction (red) and RESORCE based on Akkar (green). Only the horizontal component is shown.

5.4.1 High Frequency Issues

As explained above, the correlation coefficients are dependent on $T_{amp1.5}$, which depends on i.e. κ, V_{S30}, magnitude. For a very hard rock site it is expected that the effect of κ changes the shape of the response spectrum. If the effect of the high-frequency content (i.e., κ) is not taken into account then the correlation coefficients at short periods will be overpredicted for hard-rock sites and underpredicted for soft soil sites (see the lower left corner in Fig. 5.5). These differences in the correlation coefficients are not due to a magnitude dependence (as might be suspected at the first glance), but rather due to the response spectral shape. Therefore, to make applicable the correlation coefficients from one database in model from another database, it is recommended to normalize the periods from the correlation coefficients by the period at $T_{amp1.5}$. Then this normalized periods are multiplied by the $T_{amp1.5}$ from the database of interest. In that way, the effect of high-frequency is intended to be corrected, at least for periods larger than $T_{amp1.5}$. This procedure is used for the PRP SP5, so that the NGA-West2 correlation coefficients are also applicable to Switzerland. In addition, the use of these correlations are also judged to be acceptable and consistent, as the underlying dataset from which the Conditional Spectra were selected originate mainly from the NGA-West2 dataset. If an appropriate very hard rock dataset would have been available (e.g. as NGA-East – nevertheless, only the horizontal component has been processed yet), it would still have been necessary to correct for the effect at high frequencies. When calculating CMS from a controlling scenario spectrum with a $T_{amp1.5}$ value different than the mean value of the dataset (e.g. $T_{amp1.5}$=0.1 s for the NGA-West1 database), the following procedure should be used [Carlton and Abrahamson 2014]. First, multiply $T*$ by $0.1/T_{amp1.5}$ to get $T*'$. Then, use $T*'$ in the Baker and Jayaram (2008) model to estimate $\rho T_i, T*'$. Finally, multiply the periods, not the correlation coefficients, by $T_{amp1.5}/0.1$.

Chapter 6

Implementation Approach

The selection and adjustment of time histories to be used for structural analysis has already been investigated and discussed in the past and is not the focus of this report. Thus, this section will only repeat the key steps and highlight those relevant for the comparison. Beside numerous journal papers, the interested reader is referred to e.g. NUREG-0800, NUREG/CR-6728, ASCE 4 or NEHRP (2011), Haselton (2009) and Baker et al. (2011). The UHS are a standard output of the PSHA and described in terms of mean curve and requested fractiles (e.g. 0.05, 0.16, 0.50, 0.84, 0.95, or much more). Together with the deaggregation results from the PSHA the dominant magnitudes and distances are defined and characterize the relevant scenarios to be modeled as input to dynamic analyses. In the classical approach the analyst selects a suite of preferably recorded seed time histories from the available strong motion databases which fit the basic magnitude and distance requirements defined through the deaggregation information. Furthermore, duration, site conditions, appropriate spectral content, focal mechanism and depth are sometimes used to constrain the selected time histories. The set of selected time histories (e.g. 30 three-component time histories) is then usually fitted to match the mean UHS and the time histories are scaled in amplitude to the corresponding spectral amplitude of the UHS for the other annual probabilities of exceedance. The selected time histories can be modified to be compatible with the earthquake spectrum either by scaling (multiplying by a constant) or by changing the frequency content while maintaining the non-stationary character of the initial ground motion (spectral matching). The constraining reference frequency can e.g. be PGA or a structural relevant frequency (first eigen-frequency) and needs to be consistent with the frequency for which the fragility curves are developed. The geometrical mean of the two selected horizontal components of the response spectra of the seed time histories should be compatible with the UHS (which represents the geom. mean. component resulting from the hazard analysis). Variability of the two horizontal components about the geom. mean should be included and each horizontal time history component should represent a realistic spectrum and not necessarily match closely the UHS at each frequency. Usually, 30 three component records are selected. The average of the 30 geometrical means of the two horizontal components or the ensemble of the 30 vertical components is then used to check the matching criteria with respect to the horizontal and vertical UHS, respectively. Often used matching criteria are e.g. defined in NUREG-0800 or NUREG/CR-6728. The above described procedure implies that the analyst selected and matched the time histories in a consistent and UHS compatible way. The selection is subjective and usually the final check if all used time histories can together accurately reproduce the hazard is not performed.

The so called Conditional Mean Spectrum (CMS) and Conditional Spectra (CS) approach discussed in the following are a more formal way of defining hazard consistent time histories. The median of the conditional spectra is given by the Conditional Mean Spectra [Baker and Cornell 2006a, b]. The development of the median scenario spectrum is based on the computation of the epsilon value required to scale the median spectrum to match exactly the UHS for the given spectral frequency. The mean epsilons at the other spectral frequencies, conditioned on the epsilon at the selected frequency, are then used to develop the conditional mean spectrum. The variability about the median spectrum is captured by taking 30 realizations (named conditional spectra, CS) of the epsilon variability about the CMS, accounting for the correlation of the epsilons between different frequencies. This process is repeated for each selected hazard level and for each magnitude-distance bin. A rate of occurrence is determined for each scenario such that the combined rates from the scenarios approximate the hazard. This results in a large number of scenario spectra, but they have the advantage that they reproduce the full hazard at each spectral frequency more accurately than a simplified approach, for example as proposed e.g. in Abrahamson and Yunatci [2010]. At each spectral frequency, the UHS includes the effect of peak-to-trough variability through the standard deviation of the ground motion model. The peak-to-trough variability about the scenario spectra is estimated by means of the correlations of the ground motion variability between different spectral frequencies, as shown by Abrahamson and Al Atik [2010]. This range of peak-to-trough variability can be used for guidance when selecting time histories with the appropriate peak-to-trough variability.

6.1 Conditional Spectrum Computation Incorporating Multiple Earthquakes and GMPEs

Lin [2012]; Lin et al. [2013] have described the framework on how to accommodate multiple ground motion prediction models (or GMPE) in the CS approach and compared different simplification methods. The following four methods have been discussed there:

Method 1: Approximate CS using mean M/R and a single GMPE

Method 2: Approximate CS using mean M/R and GMPEs with logic-tree weights

Method 3: Approximate CS using GMPE-specific mean M/R and GMPEs with deaggregation weights

Method 4: ”Exact” CS using multiple causal earthquake M/R and GMPEs with deaggregation weights

In real practice the use of multiple GMPEs and experts, as for example in a SSHAC (1997) process, sets clear practical limits to the approach illustrated by Lin et al. (2013). One of the obvious issues being the consideration of multiple experts using the same GMPEs, but with different weights and maybe adjustments. Furthermore, the evaluation of a Nuclear Power

Plant (NPP) implies that there is not a single reference frequency, as multiple structures and components are to be assessed and thus, the conditioning frequency should ideally be a range and not a single value. In the framework of the PEGASOS Refinement Project an approximate, but still fully consistent approach has been developed and is very similar to the method 2 and 3 of Lin et al. [2013]. Carlton and Abrahamson [2014] have demonstrated that the PRP approach (which could be ranked as "Method 2.5" or even "3.5") is indeed very accurate under the given conditions. The PRP approach is described in the following.

The approach approximates the CS using mean M/R and GMPEs combined according to their contribution. The idea is to combine individual GMPEs of each expert according to their contribution (deaggregation) per annual probability of exceedance (APE), but using one mean M and R for all GMPEs per APE. For this, one set of mean source characteristics for all GMPEs is used. Furthermore, a mean hypocentral depth for all GMPEs per APE is defined and used for the V/H ratios, representing an extension compared to Lin et al. (2013). In order to define the CS, UHS for five probability levels have been used: 10^{-3}/yr, 10^{-4}/yr, 10^{-5}/yr, 10^{-6}/yr, and 10^{-7}/yr. This range is considered to be adequate and consistent with the order of values necessary to evaluate core damage frequency for an existing nuclear power plant. For new plants the range might be extended to even lower APE. In order to obtain a better and robust match of the CS over the five required probability levels, two additional bounding APE levels need to be added: 10^{-2}/yr, 10^{-8}/yr and thus, need to be available from the PSHA. The necessary evaluation steps are given below and not specifically illustrated by means of example values in order to keep it short.

6.2 Conditional Spectra

Conditional Scenario Spectra Methodology

The approach for developing Conditional Spectra consists of the following steps:

Select a set of candidate scenario spectra from a ground motion dataset based on magnitude and distance ranges guided by the hazard deaggregation results at a reference period T_0 and a particular hazard level (understood here as rate of exceedance for an UHS). Note that the choice of T_0 does not have a significant impact on the resulting CS. A reference period T_0 chosen around the middle of the frequency range of interest for matching the target UHS curves would be appropriate (e.g. 8 Hz for a range of 2.5 to 25 Hz, which covers the main structures and components of an NPP).

Select a subset of N_j scenario spectra at each hazard level (j) such that when scaled to the UHS at T_0, these spectra fall between ± 2.5 of the standard deviation (calculated using Equation 6.2) around the vertical and horizontal CMS anchored at T_0. This subset of scenario spectra should capture the mean and the variability around the CMS (see schematic Fig. 6.1). Note that at the beginning of the implementation process, the average horizontal and vertical component response spectra of the same scenario were allowed to have different scaling factors to match the horizontal and vertical UHS at T_0, respectively. This was changed subsequently to impose as a constraint the same scaling factor for practical reasons (see Sec. 6.3.1).

For each hazard level (j, starting here with 1 up 7 for APE=1E-2 to 1E-8), scale scenario spectra selected at all hazard levels except for the lowest level (here 1E-2) to match the midpoint between the UHS_j and UHS_{j+1} at period T_0. Assign initial rates of occurrence to

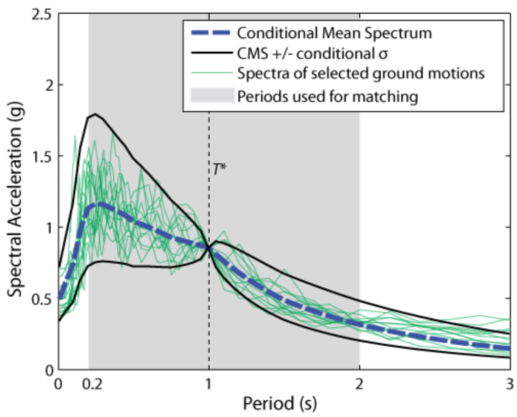


Figure 6.1: Schematic CMS (with T_0=1s); the CMS +/- the conditional standard deviation and the response spectra from ground motions selected previously to match the CMS in a specific imposed period range (modified from Baker [2011]).

the scaled scenario spectra based on the UHS exceedance levels with equal initial rates of occurrence given to scenario spectra at the same hazard level such as:

$$InitialRate_{CSi} = \frac{UHS_j - UHS_{j+1}}{Ntotal} \tag{6.1}$$

where $Ntotal$ corresponds to the total amount of scenario spectra over all hazard levels (here 6 levels are considered, as the N_7 spectra of the last hazard level, here 1E-8, are not considered). The lowest hazard level (here for UHS_1) is only used for setting initial rates of occurrence to the set of scenario spectra scaled to halfway between $UHS(APE = 10^{-2})$ and $UHS(APE = 10^{-3})$ at period T_0.

Then numerically adjust (optimize) the rates of occurrence of the scaled scenario spectra such that their calculated hazard matches the target horizontal and vertical hazard curves for a range of hazard levels and frequencies of interest. This is done by looping over all scenario spectra and adjusting the rate of occurrence of each scenario spectrum (CSi) by certain percentage of the initial rate of occurrence. The misfit between the calculated hazard curves and the target hazard curves is then calculated. If the misfit calculated with the adjusted rate of occurrence is smaller than the initial misfit, then the new rate of occurrence of the scenario spectra (CS_i) is saved. This process is repeated for a number of iterations ($nFit$) until a good match is obtained between the calculated and the target hazard curves.

6.2.1 Conditional Spectra Program (CSProgram)

The program originally developed by N. Abrahamson and L. Al Atik performs the selection of scenario spectra and assigns rates of occurrence to them such that they allow recovering target horizontal and vertical hazard curves for a frequency range of interest. This program is designed to minimize the number of unique scenario spectra needed and reuses the same spectra with different scaling factors and rates of occurrence. The outcome is usually a set of several hundreds of scenario spectra of which a fraction is unique (typically less than 100). The calculated hazard using these spectra along with their rates of occurrence matches the target vertical and horizontal UHS curves at a range of hazard levels and periods. The outline of the program is as follows:

Read a control input file, vertical and horizontal target UHS files, and assigned flatfiles (files that contain empirical ground motion response spectra and their metadata). The input UHS curves are interpolated (log-log interpolation) to the spectral periods in the flatfiles.

Optionally, discard the response spectra that do not satisfy the ranges assigned by the user in terms of magnitude, distance, V_{S30}, strong motion duration, scaled PGV, acceptable instrument location, and usable frequency range.

Calculate the horizontal and vertical CMS curves anchored to the different UHS curves at the user-defined reference period and calculate the variability around each CMS as:

$$\sigma_{CMS_H}(T, T_0, T_{amp1.5}) = \sigma_H(T)\sqrt{1 - \rho^2(T, T_0, T_{amp1.5})}\,, \quad (6.2)$$

$$\sigma_{CMS_V}(T, T_0, T_{amp1.5}) = \sigma_V(T)\sqrt{1 - \rho^2(T, T_0, T_{amp1.5})}\,, \quad (6.3)$$

where the correlation coefficients $\rho(T, T_0, T_{amp1.5})$ (see Figure 6.2) used for the PRP SP5 are from the database corresponding to Abrahamson et al. (2013) (ASK13) (inter- plus intra-event). In order to make applicable these correlations for the PRP, they are corrected by normalizing the periods with the average $T_{amp1.5} = 0.07$ corresponding to the database of Abrahamson et al. (2013) (analog to Fig. 9 in [Carlton and Abrahamson 2014]). Then, the correlations used are as function of $(T/T_{amp1.5})$ where the normalized periods are multiplied by the $T_{amp1.5}$ of the mean response spectra of PRP model. The program then uses $T_{amp1.5}$ computed based on the input median respectively for horizontal and vertical response spectra to calculate the correlation coefficients of the residuals at any period with respect to the reference period defined by the user for Swiss conditions. For the PRP, the standard deviation of the vertical ground motion is estimated as:

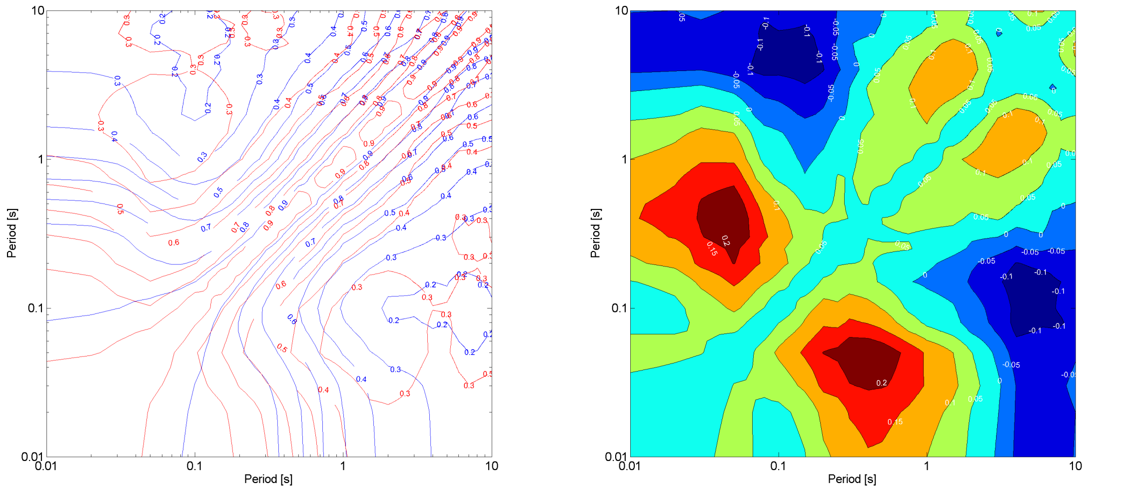
$$\sigma_V(T) = \sqrt{\sigma_H^2(T) + \sigma_{VADD}^2(T)}, \quad (6.4)$$

where $\sigma_{ADD}(T)$ is defined in the input to the program.

Select candidate scenario spectra for each hazard level that fall within $2.5 \cdot \sigma_{CMS}(T, T_0, T_{amp1.5})$ of the vertical and the horizontal CMS curves anchored to the vertical and horizontal UHS, respectively, at the reference period T_0. The residual of the horizontal and vertical spectral accelerations of each candidate spectrum with respect to the horizontal and vertical CMS in natural logarithm units must not be larger than 0.15 at all spectral periods.

From the candidate scenario spectra at each hazard level except for the lowest hazard level, select a subset n (n is assigned by the user) that has the best likelihood of capturing the horizontal and vertical conditional mean spectra and the variability around them. The lowest hazard level is only used for setting rates of occurrence.

Use all the n subsets of scenario spectra and scale them to match the vertical and horizontal spectral accelerations corresponding to halfway between each two consecutive UHS curves at the reference period T_0. This would lead to a total of $n \cdot (nLevels - 1) \cdot (nLevels - 1)$ scenario spectra including some duplicate scenarios that have the same scaling factors. Assign initial equal rates of occurrence to the scenario spectra at each hazard level based on the annual rates of exceedance of the two neighboring UHS curves. These rates of occurrence are changed numerically for each scenario spectrum in multiple iterations such that the misfits of the calculated horizontal and vertical hazard curves with respect to the target hazard curves are



(a) Horiztonal (blue) and vertical (red) model.

(b) Filled contour plot showing the difference between the horizontal and vertical model.

Figure 6.2: Correlation coefficients used by the CS code, build on the ASK13 model (M ≥5, R_{rup} ≤100 km) .

minimized in the frequency range of interest. Remove the scenario spectra that have very low (insignificant) rates of occurrence and consolidate duplicate spectra that have the same scaling factors.

Write output summary file, scenario spectra meta data, vertical and horizontal hazard, UHS, and CMS files.

Based on the practical application of the code in the framework of the PRP, the project team further improved the original code and also added some new features (e.g. utilization of multiple flatfiles, improved simultaneous treatment of horizontal and vertical component, interpolation of correlation coefficients, separate horizontal and vertical correlation coefficients, improved output). The latest version used for the PRP is Ver. 12 [Renault and Dalguer 2015]. For the interested user, a detailed description of the input files for the code is provided in Appendix A.

6.3 Additional Specifications

6.3.1 Scale Factor for Horizontal and Vertical Component

From a practical point of view how the time histories are used by the engineering community to perform SSI and fragility analyses it is better to have the same scaling factor for the horizontal and vertical components of motion. Usually the three component time histories are applied simultaneously within a simulation. As the Conditional Spectra approach makes use of a subset of unique time histories which are scaled to other ground motion levels, it is easier to have the same scaling factor for the horizontal and vertical component, as otherwise all the horizontal and vertical simulations have to be done separately, as different scale factors can apply.

The revised version of the original code imposes equal scaling factors for horizontal and vertical components. Initially scaling factors are calculated independently for each component, then a combination of them is estimated. Several approaches of combinations have been tested, such as arithmetic mean, geometric mean, maximum and minumum between the two compenents, etc.. The geometric mean was found to be the best compromise for defining the same scaling factor, because it provides the minimum misfit of calculated UHS with respect to target UHS.

6.3.2 Correlation Coefficient Models

In the framework of the PRP different versions and alternative correlation coefficient models were evaluated. Two versions of correlation coefficient for horizontal component, respectively named as ASK13 and ASK14, and one version for vertical component (named here GKAS15) have been used. These correlations correspond to the ground motion database used to develop the GMPE from Abrahamson and Silva [2008] and Abrahamson et al. [2014]. Furthermore, the correlation coefficients for the European database RESORCE were investigated, but only the horizontal component was available. Finally, the decision was made to use the correlation coefficient for horizontal component corresponding to the ground motion database used to develop the GMPE from Abrahamson and Silva [2008] and Abrahamson et al. [2014] for all the NPPs and for the two components (horizontal and vertical). These correlations are denoted here as ASK13 (Abrahamson et al.,2013).

Chapter 7

UHS Compatible Seed Time Histories

7.1 Selection and Adjustment of Time Histories

7.1.1 UHS Time History Selection Task

Selection of 30 seed input 3-component (i.e., two horizontal and one vertical) acceleration time history sets for use as input time histories for the spectral matching as specified in Section 4 of PMT-TN-1146 [Renault 2013] is described in the following.

The sets were selected based on the provided controlling earthquakes for the uniform hazard spectrum at the four different plant sites (i.e., Beznau, Gösgen, Leigstadt, and Mühleberg). It was expected that the same 30 sets will be applicable for the four site locations. Time histories were selected from currently available strong ground motion databases (i.e., both European and non-European, see Chp. 4). The selection of the time histories were determined based on the similarity between the spectral shapes of the empirical data and the provided UHS for annual probabilities of 1E-3/yr, 1E-4/yr and 1E-5/yr.

UHS Spectral Matching Task for APE 1E-5

The first step was the development of 30 complete sets of spectrum compatible acceleration time histories for each of the four site locations (i.e., four different UHS) for one annual probability level (e.g., 1E-5/yr). The development of acceptable matches was mainly based on the spectral matching requirements given in NUREG 0800 [NRC 2007] (also see Sections 4 and 8 of PMT-TN-1146).

UHS Spectral Matching Task for 1E-3 and 1E-4

Afterwards, 30 complete sets of spectrum compatible acceleration time histories for the four site locations for the other two annual probability levels (e.g., 1E-3/yr and 1E-4/yr) were developed. These sets were developed based on a scaling of the previously developed spectrum compatible sets in the previous task. The final scaled sets were also required to satisfy the spectral matching requirements given in NUREG 0800 (also see Sections 4 and 8 of PMT-TN-1146).

7.2 Spectral Matching Procedure

The development of the spectrum compatible acceleration time histories employs a time domain approach [Abrahamson 1992; Al Atik and Abrahamson 2009] with the goal of modifying an empirical seed input time history to be spectrum compatible with a given target spectrum without significantly modifying the non-stationary characteristics of the input seed time history. The initial selection of the candidate seed time histories for the spectral matching process was guided by the results (i.e., both design spectra and deaggregation results) of the ground motion development.

Initial candidate seed time histories were selected from both the European database of strong ground motion and the NGA West database. A preference was assigned to the European database by selecting 20 out of the 30 total candidate seed time histories from this database. The remaining 10 sets of time histories were selected from the NGA West database. The selection of a given time history set was governed by expected controlling events in terms of magnitude and distance values and also the similarity between the empirical response spectra and the given design spectrum. Additional considerations were the length of the time history being at least 20 sec or longer, the cross correlation between individual components being less than 0.3 and the overall non-stationary characteristics of the empirical time histories. This last consideration was important when considering the vertical component as some of the older empirical time histories which were not recorded on digital instruments with pre-event memory were considered to be late triggering records that only began recording during the P-wave coda section of the time history.

Based on the expected similarity in the contributing events for the four site locations of Beznau, Gösgen, Leibstadt and Mühleberg, the same 30 selected three component seed time history sets were used in the development of the soil spectrum compatible time histories. For the rock design spectra for the Gösgen site, a separate set of 30 seed candidate time histories was selected based on similar expected controlling events but with a different design spectra used in the selection procedure.

The uniform hazard spectra are defined for both the horizontal and vertical components of motion. For the spectral matching of the two horizontal components, an additional horizontal to horizontal variability was applied to the defined horizontal uniform hazard spectra. This variability is based on a statistical analysis of empirical data and is defined as a function of spectral period.

The spectral matching criteria provided in SRP 3.7.1 [NRC 2008; McGuire et al. 2001] was followed for this analysis. The statistical checks as stated in the criteria were performed based on the linear average of the horizontal and vertical components respectively. These statistical checks were applied for spectral periods of 3.0 and less (i.e., 0.3 Hz and greater). For a given three component set, the zero-lag cross correlation values were computed with the restriction that they be less than 0.3 [McGuire et al. 2001]. Note that this is greater than the value of 0.16 stated in SRP 3.7.1 [NRC 2008] but was deemed acceptable given the large set of 30 three component spectrum compatible sets.

UHS are provide for the horizontal and vertical components based on the mean annual frequency of exceedances (MAFE) of 10^{-3}, 10^{-4}, and 10^{-5} for the spectral period range of 0.01 - 2.0 sec (i.e., 100 Hz - 0.5 Hz). Spectra are provided for soil site conditions for the

Beznau, Gösgen, Leibstadt and Mühlberg site locations. In addition, rock design spectra are provided for the Gösgen site location.

The first step in the spectral matching methodology was to extrapolate the provided design spectra to cover the spectral frequency range of 0.1 - 100 Hz. This extrapolation was needed to provide a target design spectrum over the required frequency range of 0.3 – 100 Hz assisted in the selection of the candidate seed time histories when making the comparison between the empirical response spectra and this extrapolated design spectra. The spectra initially are defined for the spectral period range of 0.01 – 2.0 s (i.e., 100 – 0.5 Hz). To assist in the spectral matching, these spectra were extrapolated to 10 sec (i.e., 0.1 Hz) based on using a $1/T$ spectral decay between the spectral periods of 2 – 5 s (i.e., 0.5 – 0.2 Hz) and a spectral decay of $1/T^2$ between the spectral periods of 5 - 10 sec (i.e., 0.2 – 0.1 Hz), with a transition to constant displacement around 0.2 Hz. As a check on the acceptability of this extrapolation methodology, the PSA and PSV spectra were plotted to confirm their consistency with expected spectral shapes given the controlling earthquakes for the respective target spectra. The extrapolation is used to improve the spectral matching procedure and as well to allow for the statistical checks to be performed out to 3.0 sec in spectral period (i.e., 0.3 Hz in spectral frequency) and allowed for the visual check against any unfavorable low frequency content in the spectrum compatible time histories. The extrapolation is performed for each of the three MAFE levels at all of the site locations. The same extrapolation approach was applied to both the horizontal and vertical design spectra.

Given the suite of horizontal UHS, an additional modification was made to account for the component-to-component variability observed in empirical strong ground motion time histories [Abrahamson and Al Atik 2010]. Residuals were computed between the horizontal component ground motions with respect to the average horizontal component ground motions from the NGA West dataset for all sites with an average shear wave velocity of 400 m/s and greater. Based on this analysis, correlation coefficients were estimated across all spectral frequencies. Following the approach described in Abrahamson and Al Atik [2010], ϵ values (i.e., normalized residuals of the horizontal component with respect to the average horizontal component) were estimated that contain the proper correlation across the spectral frequency range following the principles of generating spatially correlated random fields. See also Section 10.1 for further discussion of the practical implications when the time histories are applied in fragility analyses.

For the application of the spectral matching, a set of correlated ϵ values were randomly generated for a given case (i.e., one of 30 sets of matches) across the full spectral frequency range of 0.1 – 100 Hz. For the first horizontal component the generated ϵ value is applied and for the second component the negative ϵ value is applied. On average, these two horizontal component spectra are equal to the given design spectra and maintain the statistical correlation between horizontal components across the full spectral frequency range. Graphically, an example is shown in Figure 7.1 for one pair of horizontal target spectra and the design spectrum for soil site conditions at the 10^{-4} MAFE level.

7.3 Database and Control Plots

As the NGA-West2 database for time history traces was not available at the time of the completion of spectral matching task of SP5, the NGA-West1 database was used as basis for the selection of the UHS compatible time histories. An overview which summarizes for

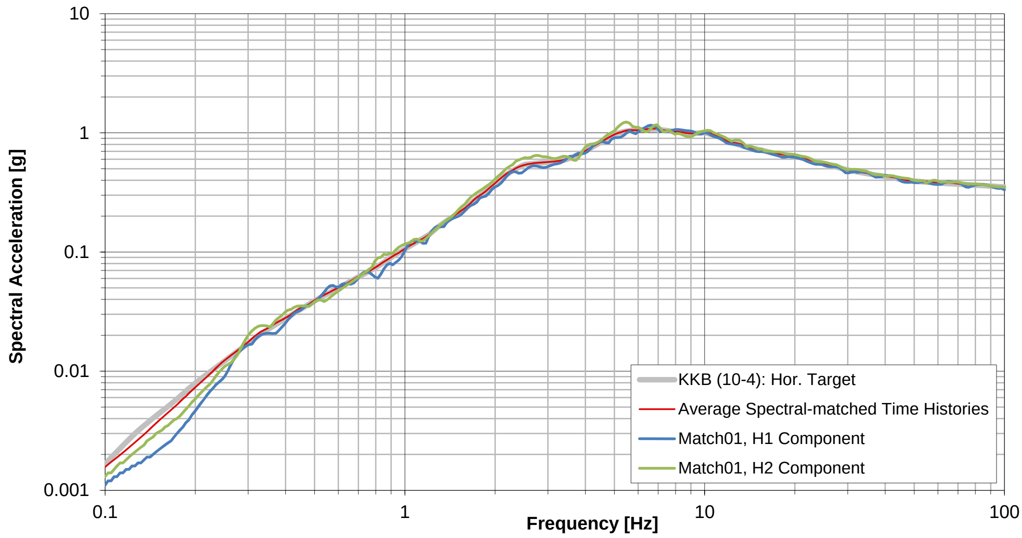


Figure 7.1: Pair of horizontal components of a spectrally matched record compared with the target UHS and the average over all 30 geometrical mean spectra. Note the weaker matching of the components between 0.1 and 0.3 Hz.

the NPPs the earthquake date, station, magnitude (M_W), Distance (R_{epi}), V_{S30} or site class, PGA, PGV, strong motion duration and scale factor (two horizontal and vertical) for selected the time histories is given in Table 7.1. The initial seed time histories were selected from the European database (20 out of the 30) of time histories and the NGA West 1 database (10 out of the 30) of time histories. Note that some of the European time histories are also contained in the NGA West database however, the European RESORCE version of the recordings was selected over the NGA West database time histories. The selection of time histories was based on a broader range of magnitude and distances in line with the controlling events from the deaggregation and the comparison between the empirical response spectral shape and the design spectral shape. It should be noted that the same suite of seed earthquakes were used for all four NPP sites when developing the soil surface response spectra. Only for the case of the rock for Gösgen another set of 30 earthquakes was used due to the different spectral shape at bedrock level (see Table 7.2).

A vast number of control plots were developed based on the recommendations of the SP5 experts. A brief description of those is given below and illustrated here with the help of the Beznau NPP. All other control plots and spectral matched time histories can be found in the appendices for each NPP (App. D to G).

The following control plots were developed for SP5:

- Magnitude vs. distance distribution of selected records (see Fig. 7.2)
- Magnitude vs. V_{S30} distribution (see Fig. 7.3)
- Distribution of horizontal and vertical cross-correlation factors (see Fig. 7.4)
- PGV vs. magnitude and distance
- Distribution of PGA, PGV, PGD of all three components

Table 7.1: Selected 30 candidate seed time histories for use with the soil site condition design spectra at Beznau, Gösgen, Leibstadt and Mülheberg. With NGA as the NGA-West1 database and RES as the European RESORCE database.

Nb	Database	Earthquake	Year	MoDy	Station	Mag	Repi	Vs30
1	RES	Potenza Earthquake	1990	0505	Brienza	5.8	27	506
2	RES	Izmit (Aftershock)	1999	0929	Istanbul Merkez Bayindirlik Ve Iskan Mudurlugu	5.2	45	595.2
3	RES	Lazio Abruzzo	1984	0507	Cassino - Sant'Elia	5.9	16	—
4	RES	Gran Sasso	2009	0406	Aquila Castello	5.1	11	—
5	RES	Patras	1993	0714	Patra-National Bank	5.6	10	364
6	RES	App. Umbro-Marchigiano	1997	1006	Norcia	5.4	33	681.2
7	RES	Umbria Marche	1997	0926	Nocera Umbra	6	11	554.8
8	RES	Aquila	2009	0409	L'Aquila - V. Aterno - Aquil Park In	5.3	18	716.5
9	RES	—	2003	0723	Aydin Kuyucak Kuyucak Saglik Ocagi	5.3	40	300.9
10	RES	Gran Sasso	2009	0406	Celano	5.1	43	—
11	RES	Kyllini	1988	1016	Amaliada-O.T.E.	5.9	36	490
12	RES	Subapp. Dauno	2002	1112	S. Giuliano Di Puglia A	4.6	15	781
13	RES	Kozani	1995	0513	Kozani-Prefecture	6.6	17	510
14	RES	Friuli Earthquake 1St Shock	1976	506	Tolmezzo Centrale - Diga Ambiesta 1	6.4	22	1029.6
15	RES	Aquila	2009	0413	Aquila Castello	5.1	17	—
16	RES	—	2001	0623	Balikesir Merkez Balikesir Huzurevi	4.8	29	662
17	RES	Subapp. Dauno	2003	1230	Casalnuovo Monterotaro (Nuova)	4.5	23	—
18	RES	—	2003	0726	Denizli Merkez Bayindirlik Ve Iskan Mudurlugu	4.9	39	355.9
19	RES	Chenoua	1989	1029	Cherchell	5.9	29	—
20	RES	NE Of Banja Luka	1981	0813	Banja Luka-Borik 9	5.7	7	120
21	NGA	Gilroy	2002	0514	Hollister - Airport Bldg #3	4.9	19.26	345.4
22	NGA	N. Palm Springs	1986	0708	Fun Valley	6.06	22.18	271.4
23	NGA	Chi-Chi, Taiwan-05	1999	0922	HWA043	6.2	48.17	294.2
24	NGA	Chi-Chi, Taiwan-02	1999	0920	TCU122	5.9	43.12	228.6
25	NGA	Chi-Chi, Taiwan-02	1999	0920	HWA056	5.9	57.16	475.5
26	NGA	Whittier Narrows-01	1987	1001	LA - W 70th St	5.99	20.85	511.3
27	NGA	Whittier Narrows-01	1987	1001	El Monte - Fairview Av	5.99	7.5	308.6
28	NGA	Whittier Narrows-01	1987	1001	Bell Gardens - Jaboneria	5.99	11.77	308.6
29	NGA	Mammoth Lakes-03	1980	0525	Long Valley Dam (Downst)	5.91	11.51	345.4
30	NGA	Northridge-01	1994	0117	LA - City Terrace	6.69	39.15	365.2

Table 7.2: Selected 30 candidate seed time histories for use with the rock site condition design spectra at Gösgen. With NGA as the NGA-West1 database and RES as the European RESORCE database.

Nb	Database	Earthquake	Year	MoDy	Station	Mag	Repi	Vs30
1	NGA	Coyote Lake	1979	0806	Gilroy Array #1	5.74	5.96	1428
2	NGA	Morgan Hill	1984	0424	Gilroy - Gavilan Coll.	6.19	54.32	729.7
3	NGA	Morgan Hill	1984	0424	Gilroy Array #1	6.19	31.83	1428
4	NGA	Chi-Chi, Taiwan-04	1999	0920	KAU050	6.2	126.25	680
5	NGA	Chi-Chi, Taiwan-04	1999	0920	TTN051	6.2	95.87	680
6	NGA	Chi-Chi, Taiwan-06	1999	0925	TCU076	6.3	25.09	615
7	NGA	Chi-Chi, Taiwan-06	1999	0925	TCU129	6.3	34.67	664.4
8	NGA	Chi-Chi, Taiwan-04	1999	0920	KAU054	6.2	103.01	577.4
9	NGA	Chi-Chi, Taiwan-05	1999	0922	HWA035	6.2	42.48	500.8
10	NGA	Chi-Chi, Taiwan-06	1999	0925	TCU075	6.3	51.61	573
11	RES	Friuli Earthquake 1St Shock	1976	0506	Tolmezzo Centrale-Diga Ambiesta 1	6.4	22	1029.6
12	RES	Val Nerina	1979	0919	Cascia	5.9	5	659.6
13	RES	Irpinia Italy-02	1980	1123	Bagnoli Irpino	6.2	22	1152.8
14	RES	L Aquila Earthquake	2009	0407	Bazzano	5.6	7	679.2
15	RES	Umbria Marche	1997	0926	Cascia	5.7	35	659.6
16	RES	Umbria Marche	1997	0926	Cascia	6	37	659.6
17	RES	Umbria Marche	1997	0926	Nocera Umbra	6	11	554.8
18	RES	Ano Liosia	1999	0907	Athens-Sygrou-Fix	6	19	519
19	RES	Ano Liosia	1999	0907	Athens-KEDE	6	16	515
20	RES	Ano Liosia	1999	0907	Athens-Geographical Military Service	6	17	887.3
21	RES	Izmit (Aftershock)	1999	1111	Sakarya Akyazi Koyu	5.6	31	616.4
22	RES	Montenegro (Aftershock)	1979	0524	Petrovac-Hotel Rivijera	6.2	17	713
23	RES	Montenegro (Aftershock)	1979	0524	Kotor-Naselje Rakite	6.2	20	688
24	RES	Montenegro(Aftershock)	1979	0524	Hercegnovi Novi-O.S.D. Pavicic School	6.2	30	875
25	RES	Umbria-Marche 3Rd Shock	1997	1014	Cascia	5.6	22	659.6
26	RES	Itea	1997	1105	Aigio-Military Factory (EBO)	5.6	28	664
27	RES	L Aquila Mainshock	2009	0406	L Aquila - V. Aterno - F. Aterno	6.3	5	551.8
28	RES	L Aquila Earthquake	2009	0407	L'Aquila - V. Aterno - Aquil Park In	5.6	9	716.5
29	RES	Kyllini	1988	1016	Amaliada-O.T.E.	5.9	36	490
30	RES	L Aquila Mainshock	2009	0406	Gran Sasso (Lab. Infn Assergi)	6.3	18	488

The magnitude-distance plot is made as a function of epicentral magnitude since some of the European database events are only defined in terms of the epicentral distance and not the rupture or Joyner-Boore distance metrics. Based on some of the large magnitude events with extended fault plane models, the rupture distance is less than the search limit of 50 km, but the corresponding epicentral distance is greater than 100 km.

For comparison purposes the distribution of horizontal and vertical strong motion duration vs. distance of the conditioned records were plotted on top of empirical models applicable for Switzerland (see Fig. 7.5 and 7.6). The comparison was done for the mean magnitude at each annual probability level resulting from the deaggregation (around M6). The dashed line labeled with "sigma" in the plots is an envelope of all standard deviation models for the considered empirical duration models, as given by the authors. The intent was to check if they fall within a reasonable range of the empirical models (mean, $\pm\sigma$) for the strong ground motion duration within 5-75% of Arias Intensity. The following empirical models were used:

- Bommer et al. [2009]
- Kempton and Stewart [2006]
- Abrahamson and Silva [1996] (only model with a vertical duration component)

As mentioned earlier, the SP5 experts requested also a check of the zero cross-correlation but with relaxed criteria. The cross-correlation vs. distance plots were deemed to be reasonably consistent with the distribution of real data when the cross-correlation coefficient for each of the 30 sets falls between -0.3 and 0.3 and 50% of the records $< \pm 0.16$ (see Fig. 7.4).

A basic template for the display of the original and modified time histories was developed and required to fit on one page for the sake of better overview. This template includes all three components for horizontal and vertical original and modified time histories. Furthermore, the normalized displacement time histories and normalized arias Intensity for the original and modified time histories. Fourier amplitude and acceleration response spectra of original and modified time histories are also shown.

7.3.1 Meta Data

Figures 7.2 to 7.4 provide an overview of the magnitude-distance, magnitude-V_{S30} and cross-correlations distribution of the selected time histories. It can be observed that the magnitude-distance coverage of the selected set of time histories is covering well the distribution as found in the hazard deaggregation. On the other hand it is obvious that the available recordings used for the spectral matching at soil surface do not exactly cover the V_{S30} range found at the NPP sites. As the records are spectrally matched to the UHS in the end this is not a problem. Figures 7.5 and 7.6 depict the comparison of the strong motion durations (5-75% Arias intensity) and the empirical duration models for Switzerland as a cross check with the expected SP2-SP3 models.

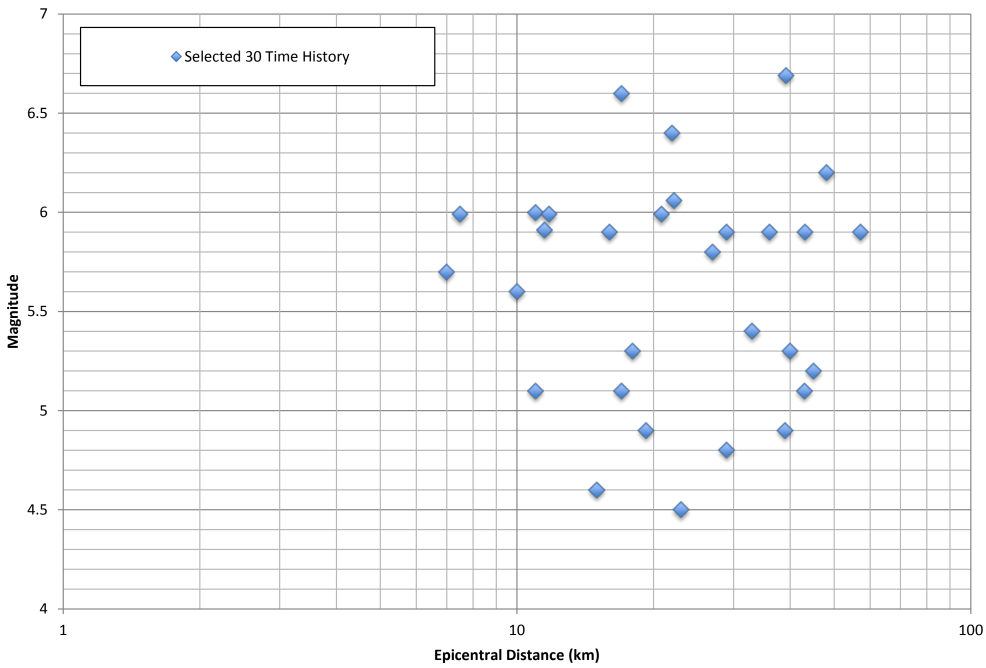


Figure 7.2: Magnitude-distance distribution, all sites, soil surface.

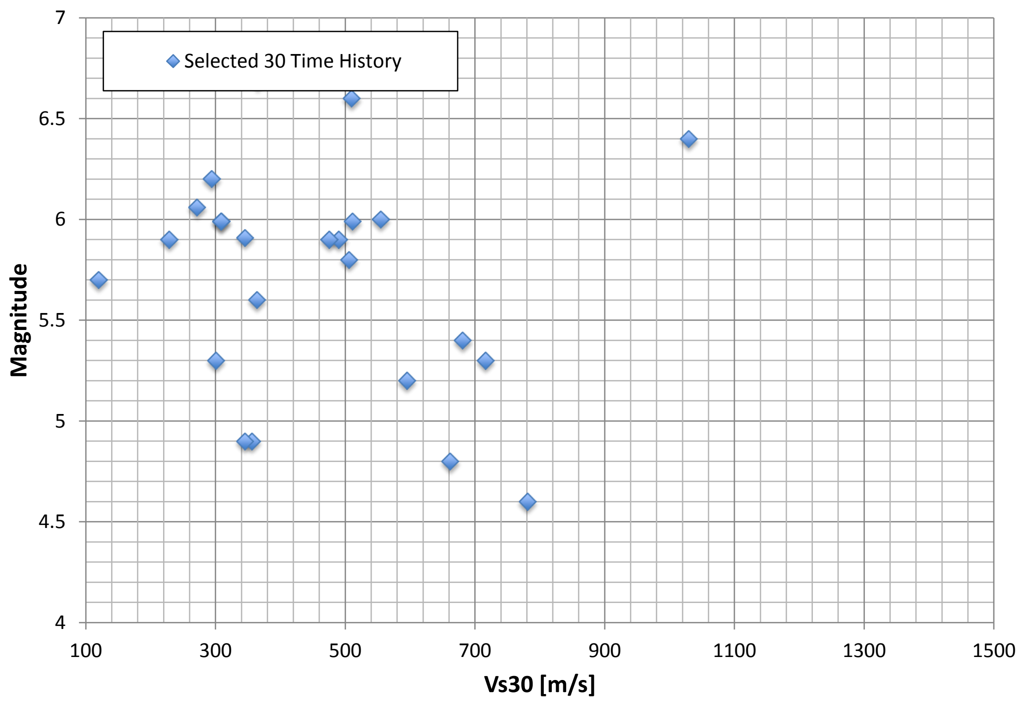


Figure 7.3: Magnitude-V_S30 distribution, all sites, soil surface.

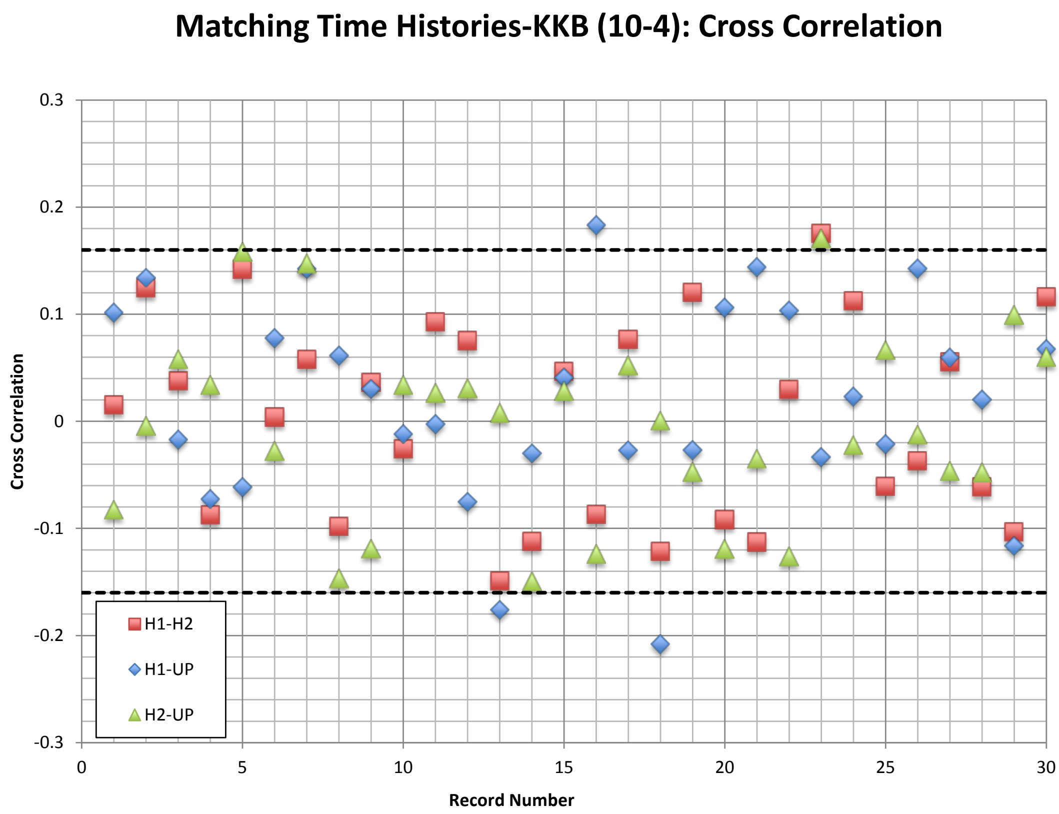


Figure 7.4: Beznau, soil surface, cross-correlation distribution, APE 1E-4.

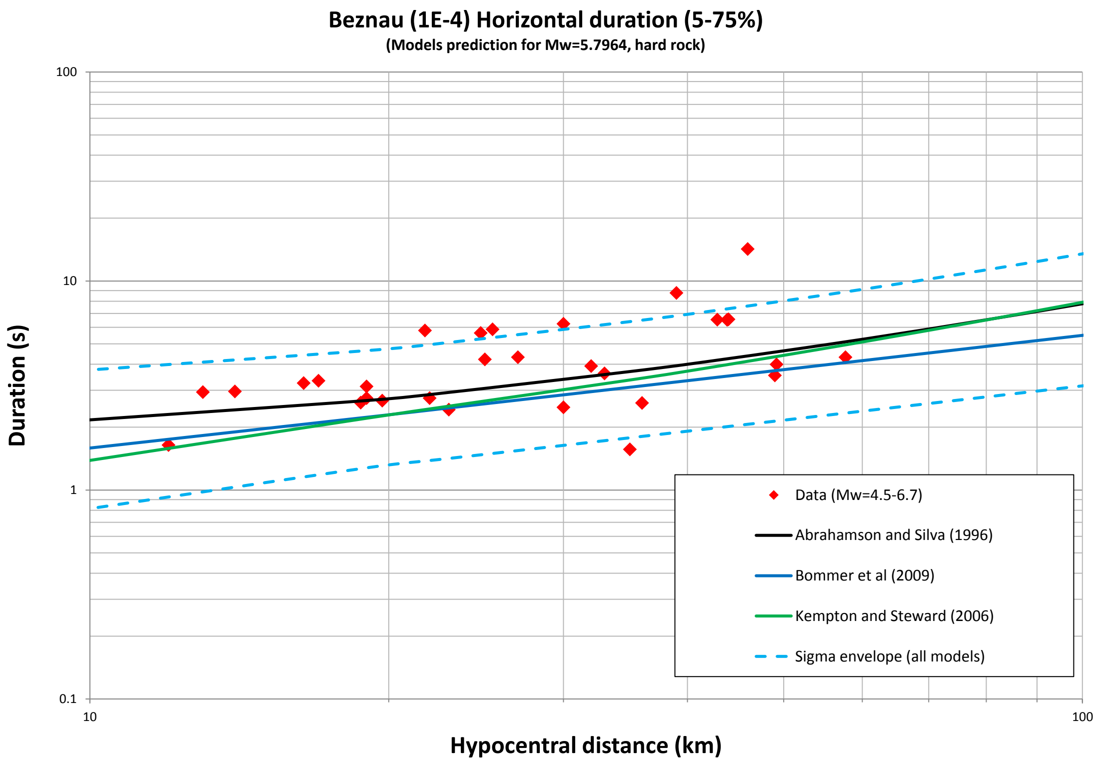


Figure 7.5: Beznau, soil surface, horizontal strong motion duration model (5-75%) comparison, APE 1E-4. Dashed line is the envelope of the standard deviation from all empirical models

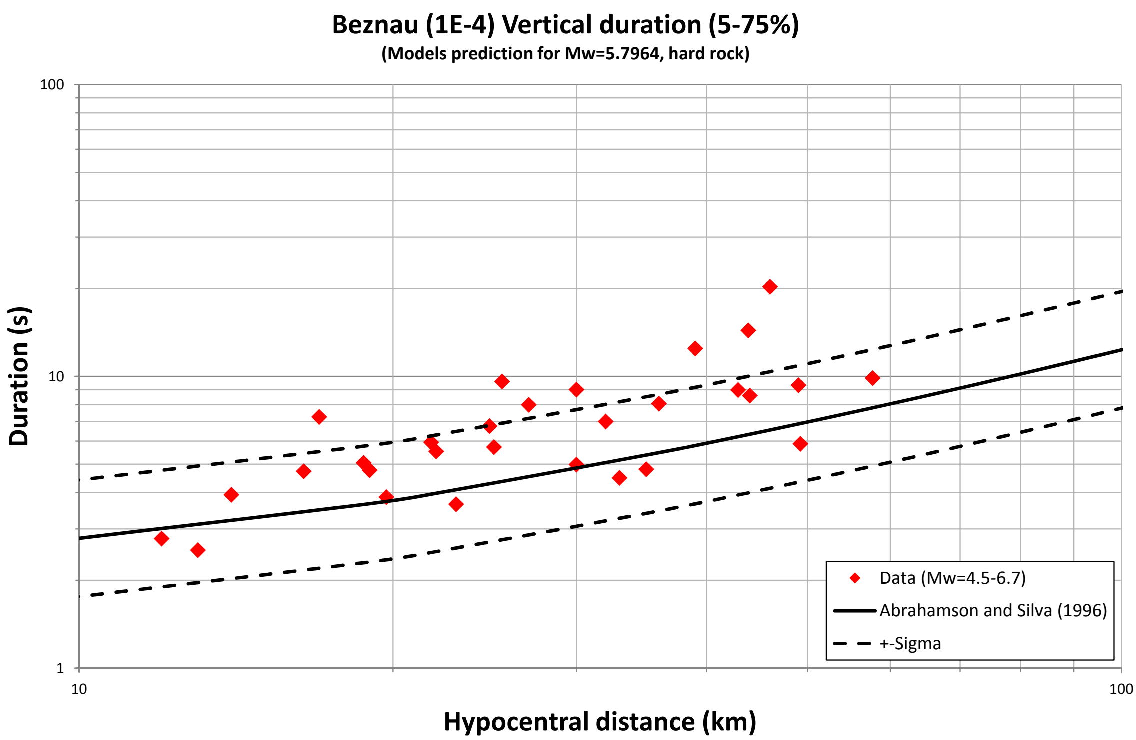


Figure 7.6: Beznau, soil surface, vertical strong motion duration model comparison, APE 1E-4.

7.3.2 UHS Comparison Target vs. Spectral-Matched

A summary plot showing the average response spectra from the 60 horizontal components and the horizontal target is shown in Figure 7.7. The similar vertical plot is shown in Figure 7.8. Both of these spectra satisfy the statistical checks from the spectral matching requirements of SRP 3.7.1 over the frequency range of 0.3 - 100 Hz. Here the lin-log version of the graph was selected to anticipate the engineering preference for the evaluation. The log-log version of the graphs are part of the full set of control plots in the appendices (App. D to G). Figure 7.9 shows the uncertaintiy of the average of the matches. The solid red line shows the average uncertainty for the suite of 30 matches for the horizontal component pairs. This observed sigma variation is a consequence of matching to an H1 and H2 component horizontal target spectra. The development of these H1 and H2 targets was based on the empirical variation model (blue dotted line) that N. Abrahamson and L. Al Atik developed, based on the NGA-West1 database (personal communication, [Abrahamson and Al Atik 2010]). As expected this variation is on average between 0.18 and 0.25. For PRP the difference between the H1 and H2 component was used, while EPRI reports use the difference between a single horizontal component and the average horizontal comment. Thus, the values presented here (and depicted in Fig. 7.9) are twice as large as the EPRI parameter. In the EPRI report 1019200 [Kennedy 2009] this random variability about the horizontal direction is estimated to be between 0.12 and 0.14 (ln units). The geometric mean curve (dashed black line) is the uncertainty between the geometric mean of the two horizontal matches and the target spectra (without the variation for H1 and H2 components). This basically is showing the uncertainty of the average horizontal matches to the target spectra and these results are around 0.05 units or lower. Finally, the solid blue line is the uncertainty between the vertical matches and the vertical target spectrum. Similar to the geometric mean case, the uncertainty is around 0.05 or less. These last two curves are basically showing how well the suite of 30 matches are fitting the target spectra.

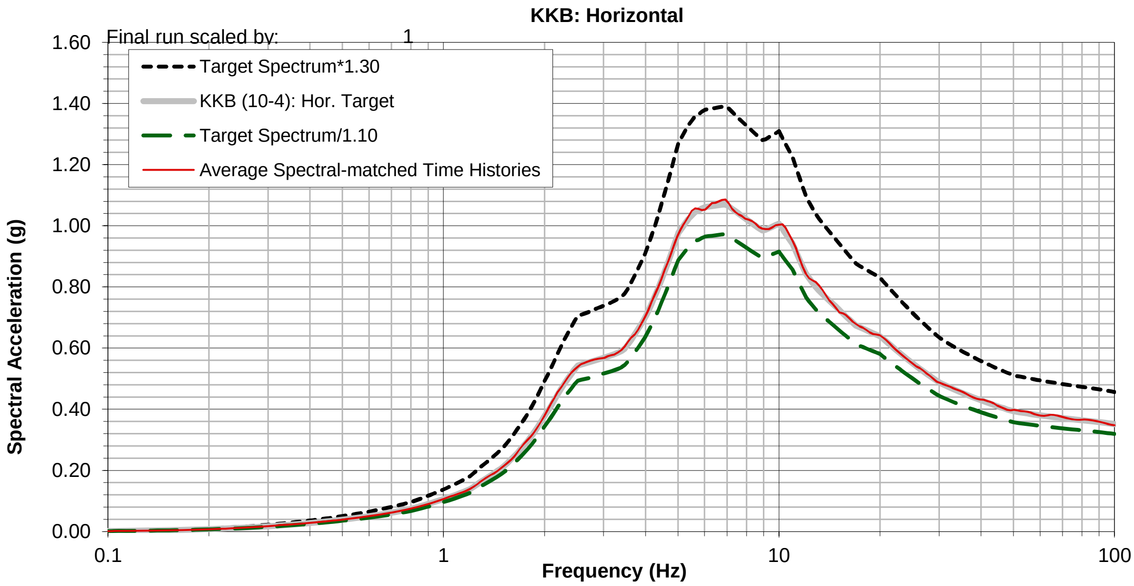


Figure 7.7: Summary comparison plot of the average horizontal response spectrum from the 60 matched horizontal time histories and the target horizontal response spectrum for the Beznau soil site conditions, APE 1E-4.

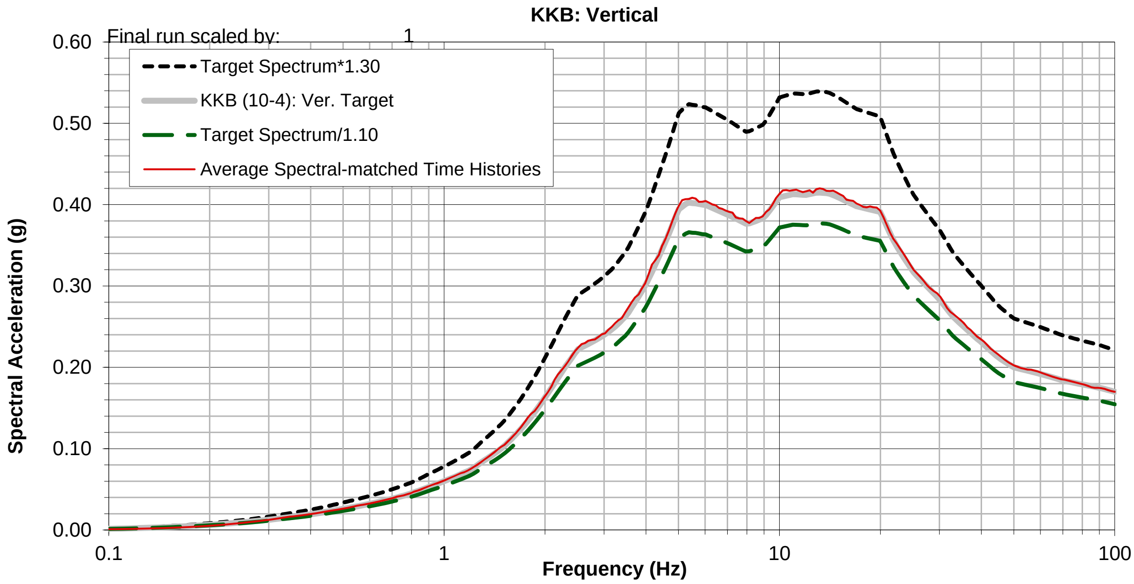


Figure 7.8: Summary comparison plot of the average vertical response spectrum from the 30 matched vertical time histories and the target vertical response spectrum for the Beznau soil site conditions, APE 1E-4.

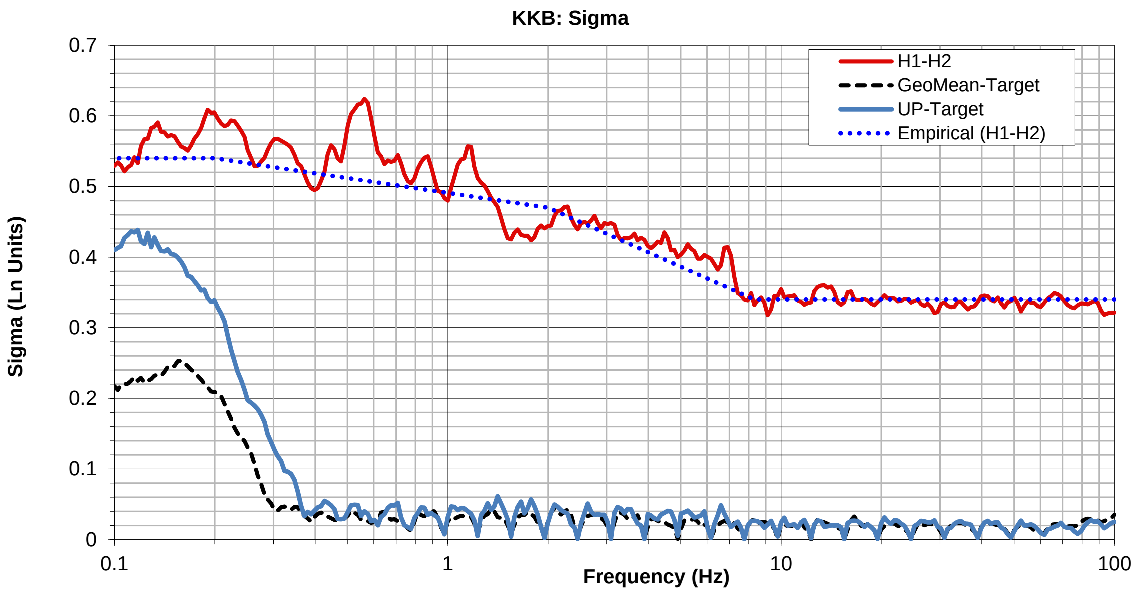


Figure 7.9: Beznau, soil surface, standard deviation control plot, APE 1E-4.

Chapter 8

Conditional Mean Spectra for Risk Calculations

8.1 Selection and Adjustment of Time Histories for Gösgen

8.1.1 CMS Time History Selection Task

Selection of 2 or more sets of 30 seed input 3-component (i.e., two horizontal and one vertical) acceleration time history sets for use as input time histories for the spectral matching as specified in Section 7 of PMT-TN-1146. These time histories were selected based on the provided controlling earthquakes for the CMS for the Gösgen site based on the two specific conditional frequencies of 5 and 16 Hz (see section 7 of PMT-TN-1146). After checking the coverage of the two initial CMS compared to the UHS it was decided to add also a CMS conditioned at 1 Hz to better match the original UHS. Time histories were selected from currently available strong ground motion databases (i.e., both European and non-European, also used in the previous chapter). The selection of the time histories was determined based on the similarity between the spectral shapes of the empirical data and the provided CMS for annual probabilities of 1E-3/yr, 1E-4/yr , 1E-5/yr, 1E-6/yr, and 1E-7/yr.

CMS Spectral Matching Task for 1E-5

The first step was the development of 30 complete sets of spectrum compatible acceleration time histories for the CMS (i.e., 1, 5 and 16 Hz) at the Gösgen site for one annual probability level (e.g., 1E-5/yr). The development of acceptable matches was based on the spectral matching requirements given in NUREG 0800 (also see sections 4 and 8 of PMT-TN-1146).

CMS Spectral Matching Task for 1E-3, 1E-4, 1E-6, and 1E-7 Task

Afterwards, 30 complete sets of spectrum compatible acceleration time histories were developed for the two controlling frequencies (i.e., 1, 5 and 16 Hz) for the Gösgen site location for the other annual probability levels not matched in the previous task (e.g., 1E-3/yr, 1E-4/yr, 1E-6/yr, and 1E-7/yr). These sets were developed based on a scaling of the previously developed spectrum compatible sets. The final scaled sets were also required to satisfy the spectral matching requirements given in NUREG 0800 (also see sections 4 and 8 of PMT-TN-1146).

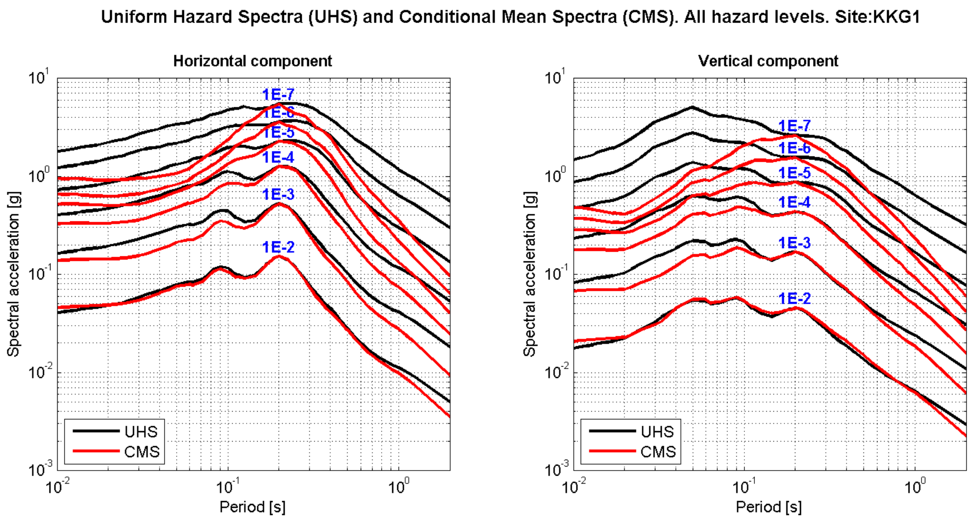
8.2 Database and Control Plots

Conditional Mean Spectra for all NPPs have been developed and are plotted in the appendices for each site. According to the SP5 output specification (Chapter 2) CMS for the site of Gösgen with conditioning frequencies at 5 and 16 Hz had to be developed. All other sites only had one conditioning frequency. Furthermore, in the case of Gösgen 30 three-component time histories had to be developed for the CMS. The selection and matching procedure followed very closely the procedure described for the UHS (Section 8.1). The only real difference was that the tight spectral matching was only done down to the period of 3 s and not 5 s.

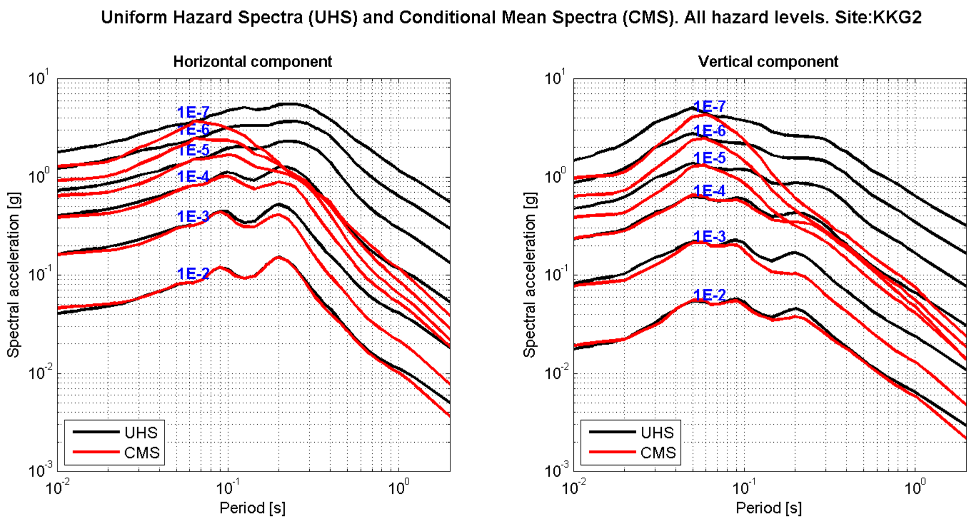
The two developed sets of CMS are shown in Figure 8.1. As can be seen from this figure, the two CMS together do not cover the UHS at long periods (around 1 s), especially at very low annual probabilities of exceedance. At those low probabilities of exceedance the CMS does also not cover the short period range.

Due to this lack of coverage shown in the comparisons the PMT developed a third set of CMS for a conditioning period of 1 s. The red, blue and green dashed lines, respectively for CMS conditioned at 1 Hz, 5 Hz and 16 Hz shown in Figures 8.2 and 8.3, respectively for horizontal and vertical components, are the initial three CMS developed for Gösgen compared to the UHS (black solid line). According to ASCE 7-16 the upper bound envelope of the CMS is not allowed to fall below 75% of the UHS in the frequency range of interest for the analyses. Assuming that those will be used in the framework of the structural and fragility analysis of the NPP this range is usually 2.5 to 25 Hz.

In order to strictly satisfied the ASCE 7-16 recommendations at all periods and hazard levels, the CMS have been (manually) adjusted as follows: The CMS for 1 Hz and 16 Hz, respectively at long and short periods, have been broadened, up to the conditional period, to the UHS level in order to have the correct spectral shape coverage for the time history development. For the intermediate periods, the spectral amplitude at the periods in which the three CMS intersect were moved up and fixed to the -10% UHS level. Another second point at a given period is fixed to the initial CMS. Then the difference in spectral amplitudes between these two periods are calculated by linear interpolation in a logarithmic scale, and then added to the initial CMS. These second points are at the conditioning periods and the limits of the periods covered by the UHS and CMS (e.g. 100 Hz). Special treatment has been applied to the CMS at 1 Hz to facilitate the spectral matching procedure. For this case, the second point was fixed to 3 Hz if the intersection frequency with the CMS at 5 Hz is less than 3 Hz. The red, blue and green solid lines, respectively for the CMS at 1 Hz, 5 Hz and 16 Hz shown in Figures 8.2 and 8.3, respectively for horizontal and vertical components, are the final three broadened CMS, developed for Gösgen and compared to the UHS. As shown in these figures, the broadening is especially obvious for the case at the lower APE levels than 1E-5. The ratio between the upper bound envelope of the CMS and UHS, for the initial and broadened CMS, are also shown in Figures 8.4 and 8.5, respectively for horizontal and vertical components. Important remark: In needs to be noted that those broadened spectra were not used for the development of the conditional spectra approach at Gösgen.



(a) CMS for 5 Hz.



(b) CMS for 16 Hz.

Figure 8.1: Initial CMS for Gösgen.

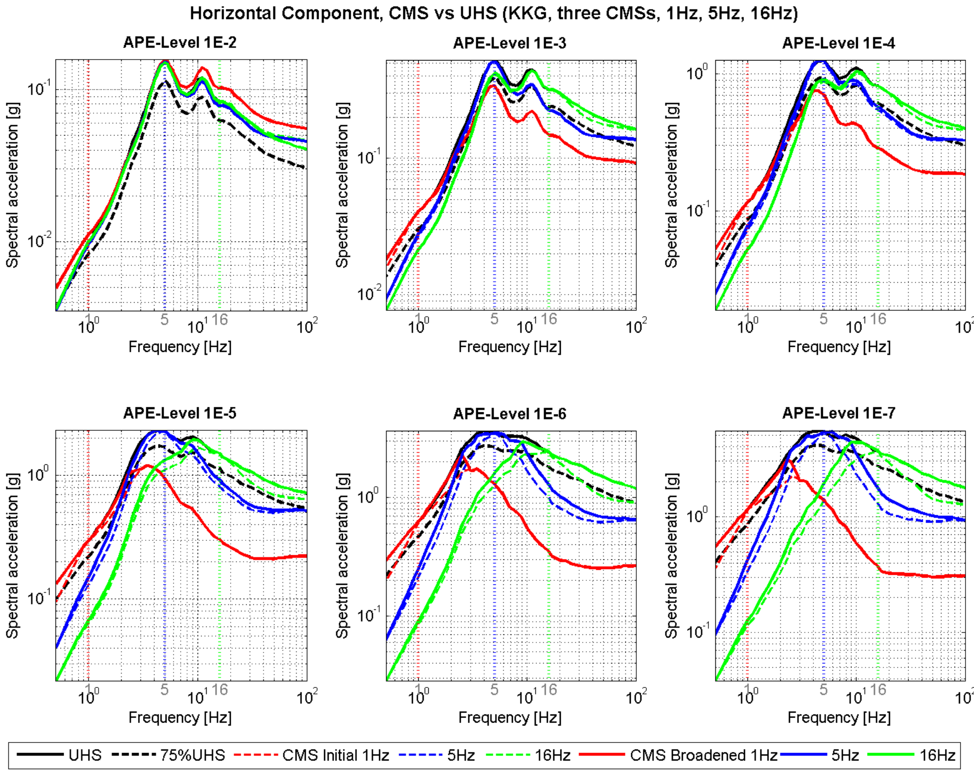


Figure 8.2: All three final horizontal CMS for Gösgen. The dashed black lines show the UHS decreased by 25%.

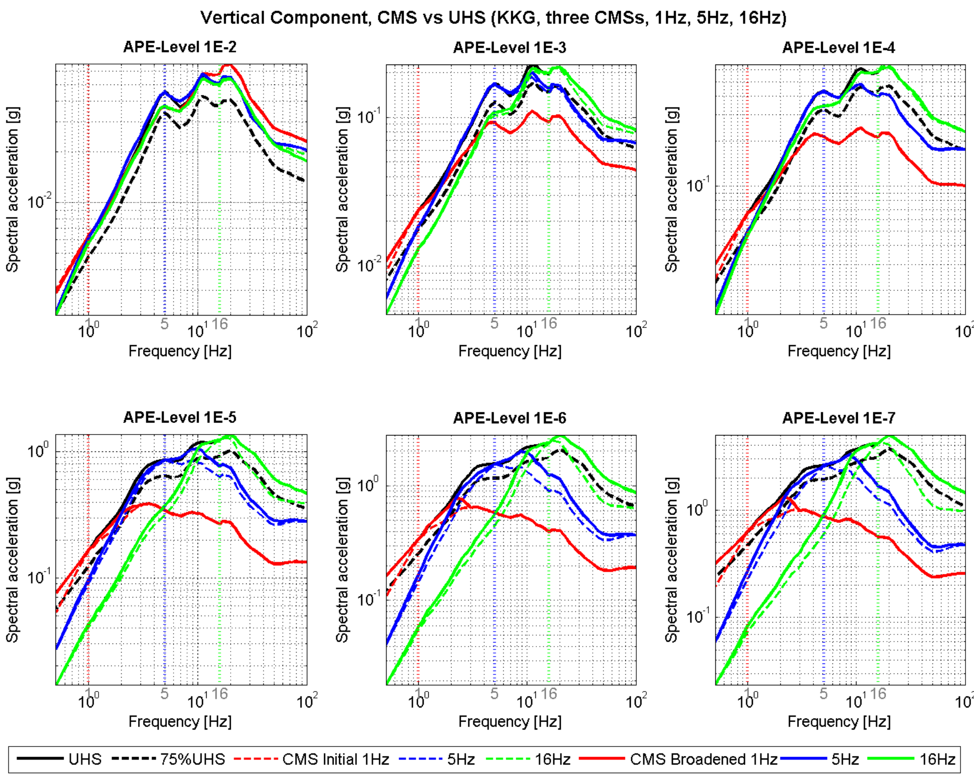


Figure 8.3: All three final vertical CMS for Gösgen. The dashed black lines show the UHS decreased by 25%.

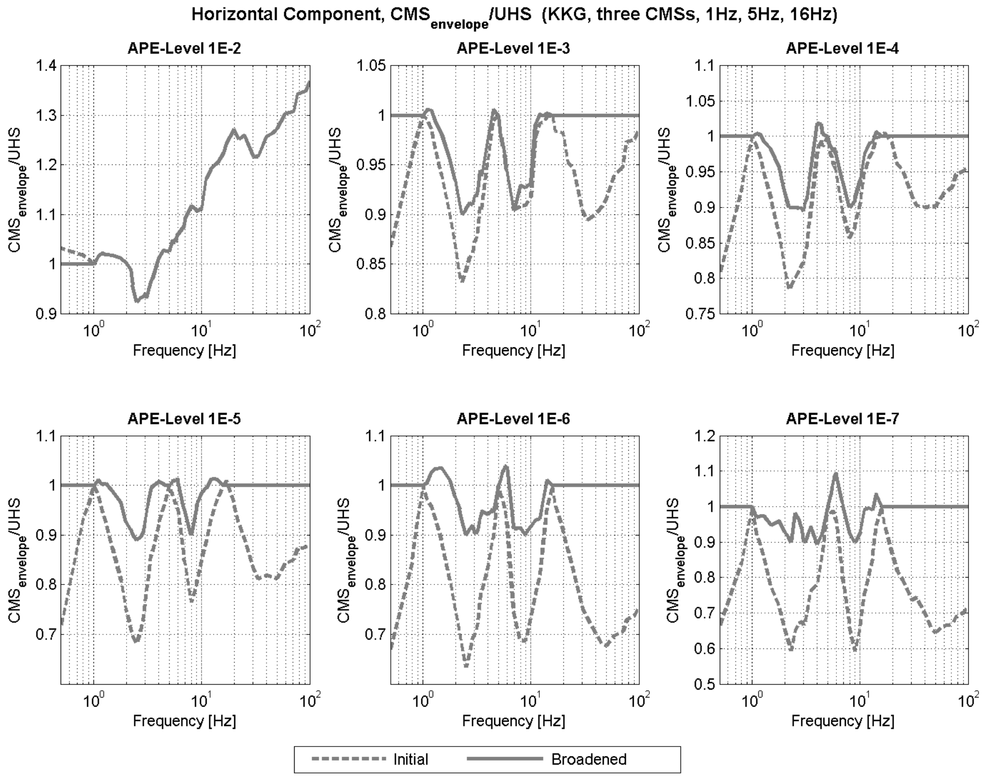


Figure 8.4: Ratio between the upper bound envelope of the CMS and UHS for Gösgen, horizontal component. Dashed lines are for initial CMS, and solid lines for the broadened CMS.

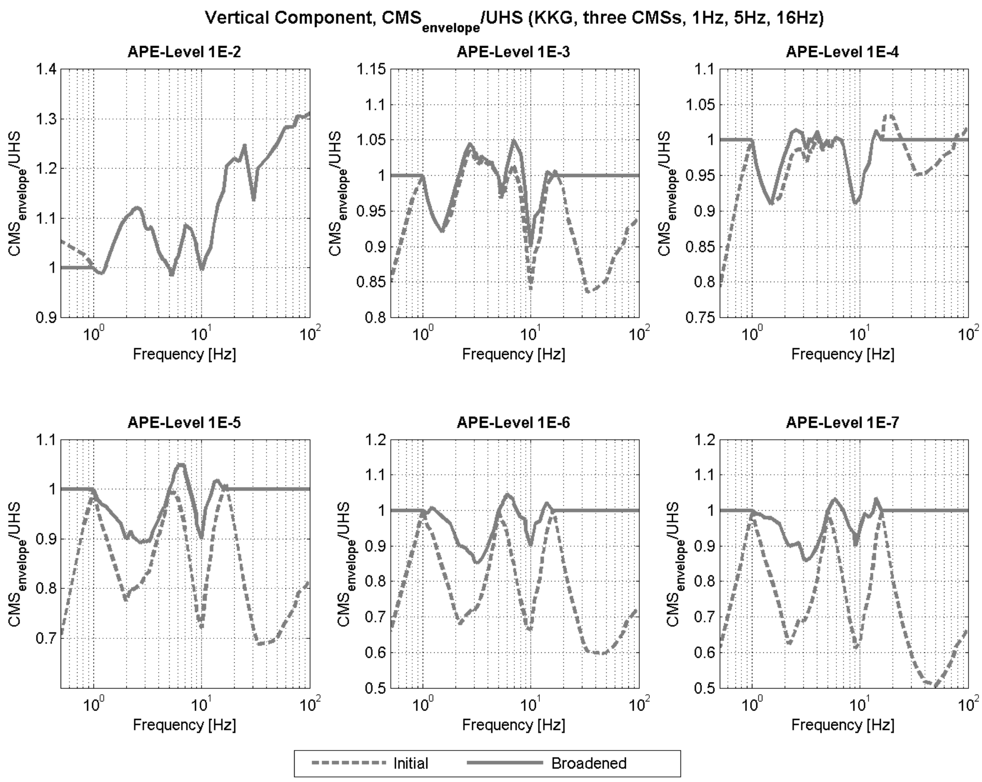


Figure 8.5: Ratio between the upper bound envelope of the CMS and UHS for Gösgen, vertical component. Dashed lines are for initial CMS, and solid lines for the broadened CMS.

Chapter 9

Conditional Spectra for Risk Calculations

This chapter explains all the checks and control plots which were applied to the Conditional Spectra. This includes comparison of horizontal and vertical hazard and UHS curves with the reproduced hazard and all scenario response spectra between the range of interest 10^{-3} and 10^{-7}. As explained above, a broader range of magnitudes and distances was used for developing the Conditional Spectra, but still consistent with the hazard deaggregation. This was necessary in order to have enough records to chose from.

A template similar as the one for the display of the original and modified (spectral matched) time histories was developed and also required to fit on one page to provide a good overview of each of the selected unique time histories. The control plots include a representation of all three components for the time histories, as well as the Arias Intensity, the Fourier amplitude and acceleration response spectra of the time histories. The control plot shows the original, unscaled version of the record.

According to the SP5 output specification (Chp. 2) only CMS for the site of Gösgen with conditioning frequencies at 5 and 16 Hz had to be developed. Conditional Spectra were not part of the requested deliverable for Gösgen. Nevertheless, for the sake of completeness the Conditional Spectra approach was also applied to Gösgen for the conditioning frequency of 5 Hz and its results are presented in the Appendix E in the same way as it is done for the other sites. 5 Hz for Gösgen was selected as the representative conditioning frequency and the results are almost identical to the 16 Hz case.

Table 9.1 provides an overview of the total amount and number of unique scenario time histories per site necessary to reproduce the mean hazard. The unique time histories are the subset of the total amount of time histories which can be used to perform linear structural analyses, as the rest of the time histories correspond to scaled versions of those time histories. The appendix for each NPP contains a table with the details of all scenarios and more importantly each individual rate of occurrence associated with the time histories.

Table 9.1: Amount of unique and total time histories for each NPP.

NPP	Nb. unique TH	Total TH
Beznau	74	406
Gösgen	59	332
Mühleberg	74	366

9.1 Control Plots

In the following only some example control plots for the Beznau site are shown in order to introduce the type of plots which have been created and can all be found for all four NPPs in the appendices D to G. The basic features of the most relevant plots are explained and discussed in the sections below and help to better understand how to interpret the provided figures.

9.1.1 Comparison with UHS and Target Hazard

Figure 9.1 shows the horizontal and vertical CMS derived for the Beznau site (conditioning period is 0.11 s, respectively 8.7 Hz) at all annual probabilities of interest (10^{-2} to 10^{-7}/yr).

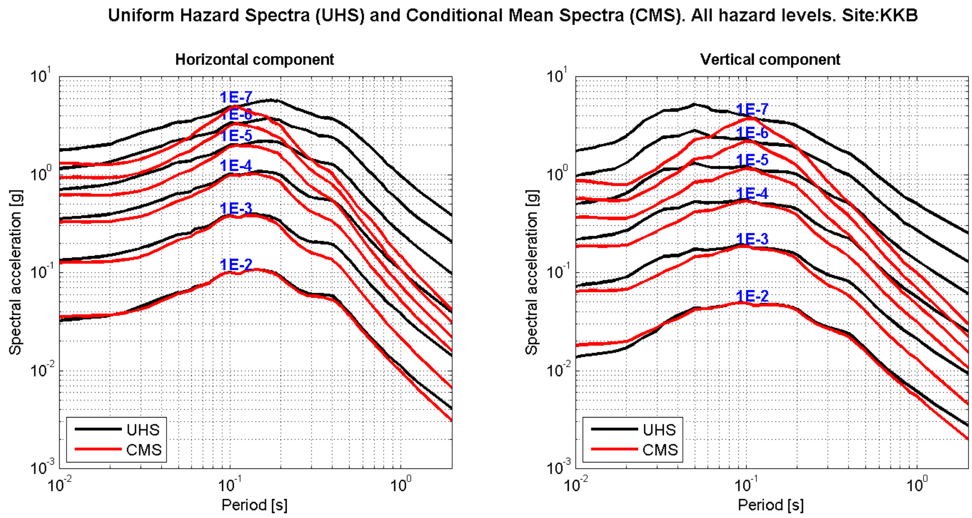


Figure 9.1: CMS for Beznau.

The full set of conditional spectra is displayed in Figure 9.2 and the target UHS are plotted on top (in red).

Hazard curves and UHS for APE of 10^{-2} to 10^{-8} are checked if they match in the range of interest (10^{-3} to 10^{-7}). The matching requirements of the results was set by the SP5 experts as: <0.15 misfit for UHS in strict matching range (e.g. 2.5 to 25 Hz) and <0.20 in the secondary frequency range (below and above main range). Furthermore, the average misfit should be approximatively zero, but not consistently negative. A more detailed table of the hazard misfit for the CS approach for each site is provided in the appendices (e.g. Table D.1). Comparison of target and computed horizontal and vertical hazard curves for all 9 frequencies

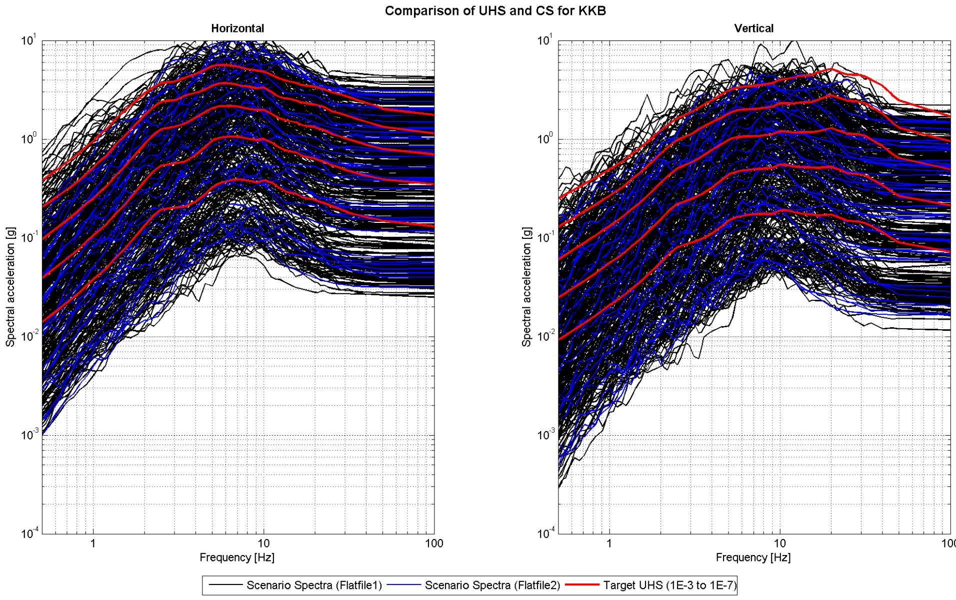


Figure 9.2: Conditional scenario spectra for Beznau compared to the UHS (red). The selected response spectra come from the NGA-West2 database (black) and the blue response spectra originate from the RESORCE database.

down to an APE of 1E-8 in order to check if the misfit in the range of 10^{-3} to 10^{-7} was <20%. Note that the criteria of 20% was checked in terms of ground motion amplitude on the spectra for each APE level. As can be seen from the Figures 9.3 and 9.4 the hazard can be reproduced quite well for the horizontal and vertical components at almost all frequencies. At the high frequencies, where the influence of κ is dominating, the re-computed vertical ground motion is hard to bring to the level of the targeted UHS, especially at very low annual probabilities of exceedance (see also Fig. 9.5).

It was outside of the scope of the subproject SP5 to further improve the fits for the low annual probabilities of exceedance. Based on discussion and feedback from the SP5 experts some ideas on how to improve the vertical fit at the very low APE (e.g. 1E-7) in the future are reported here. First, some very weak spectral matching to create more records with increased high frequency content could be applied. Of course the purpose of the CS approach was to pick unmodified records from available databases in an automatized way and thus, not to apply e.g. spectral matching to some manually selected records. Nevertheless, as discussed earlier in the report, the available databases lack of records for very hard rock which would probably have more high frequency content. The second thought was to re-activate the initial attempt to use stochastic simulations to create an expanded dataset of records - with also high frequency content as necessary. In order to overcome the difficulty to create three-component ground motions from stochastic simulations the experts proposed to use the empirical phase for the three components in place of random phase.

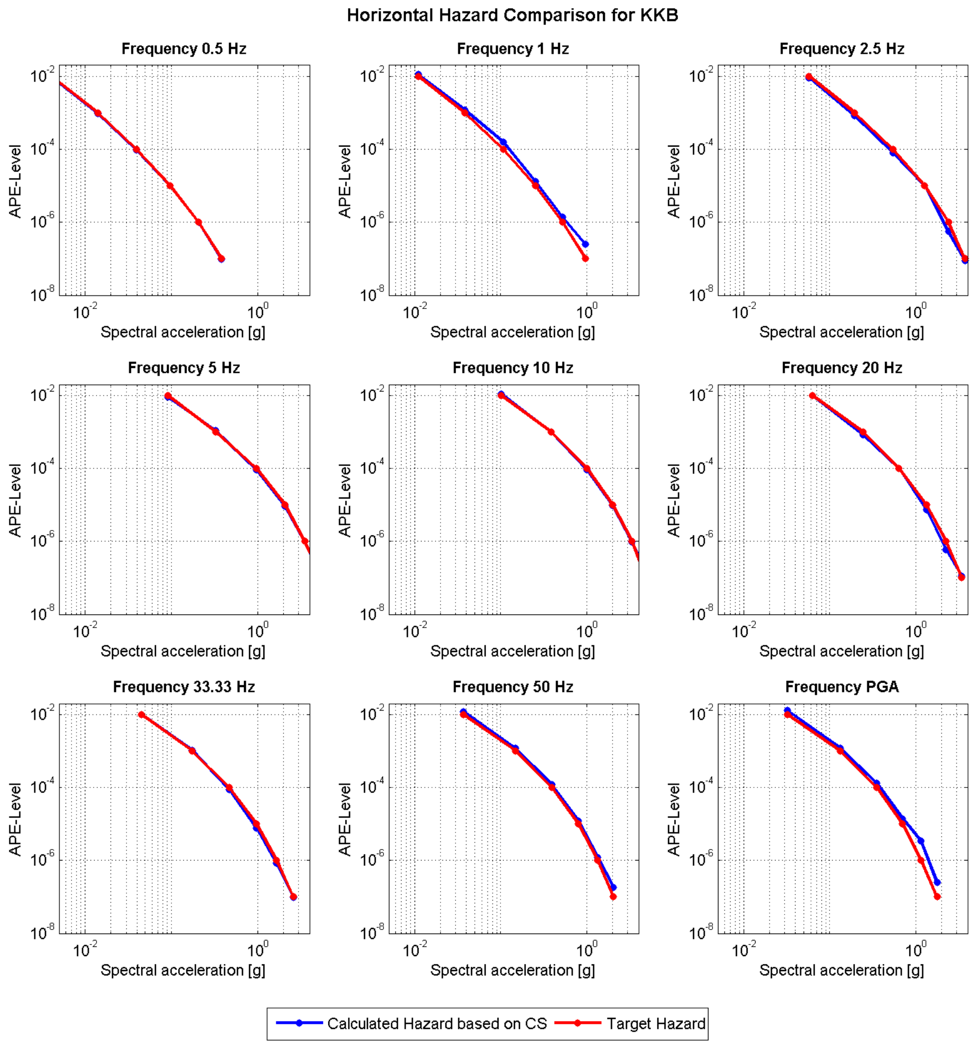


Figure 9.3: Comparison of recomputed horizontal hazard curves and target hazard curves at all nine PRP frequencies for Beznau.

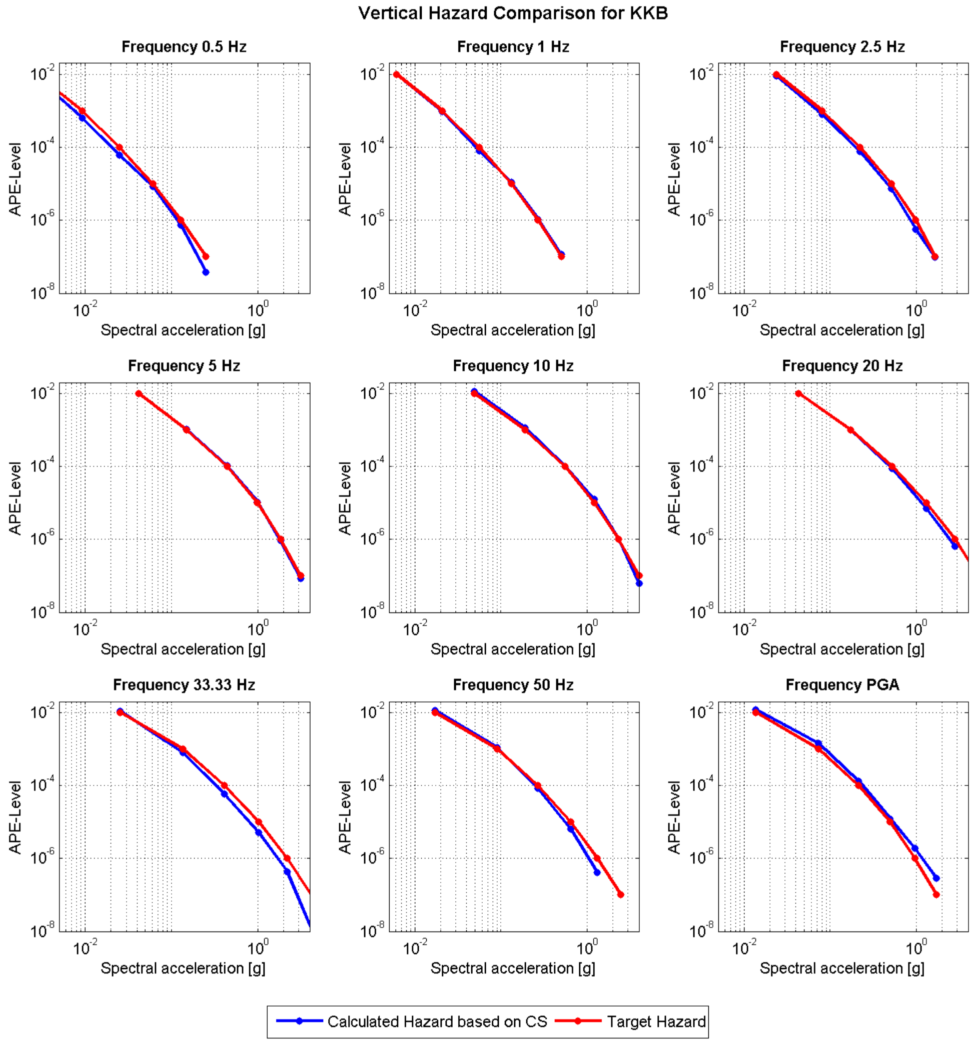


Figure 9.4: Comparison of recomputed vertical hazard curves and target hazard curves at all nine PRP frequencies for Beznau.

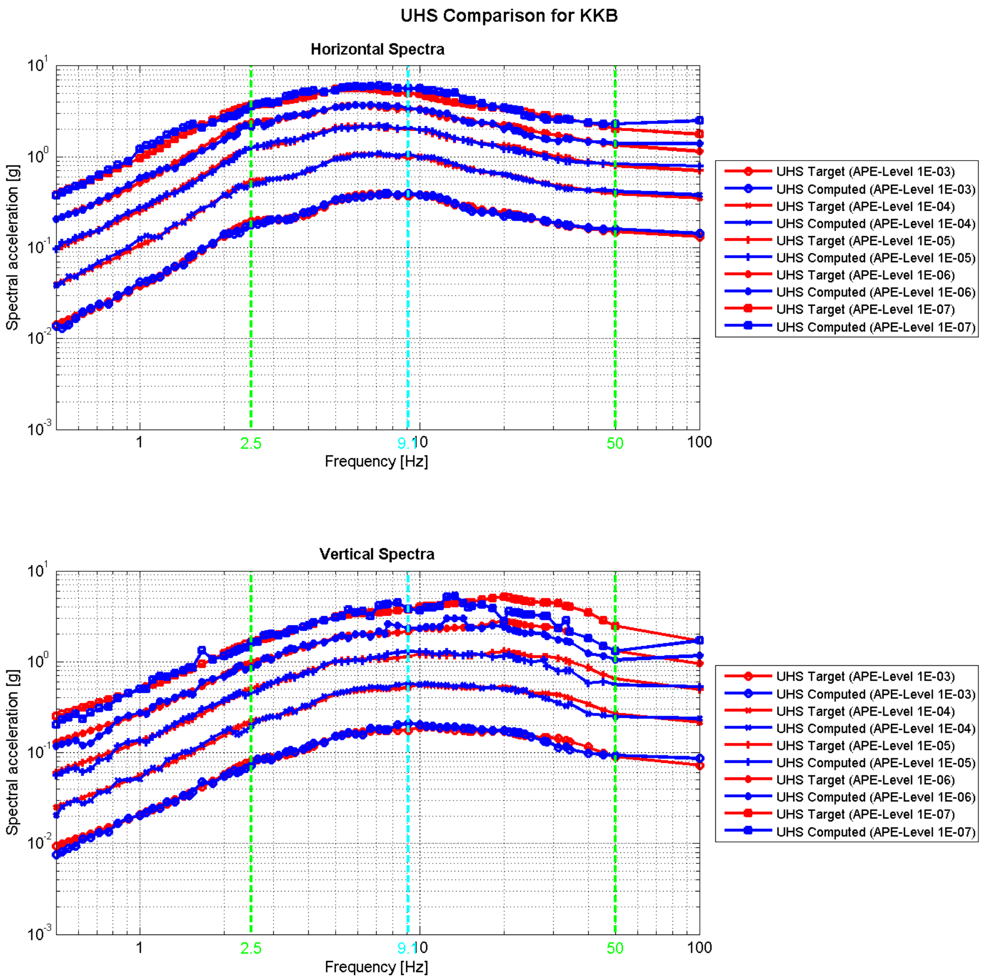


Figure 9.5: Comparison of recomputed UHS and target UHS at 57 soil frequencies for Beznau. The two vertical green lines at the frequencies of 2.5 and 50 Hz represent the range where good matching was required and the ranges outside had a looser matching requirement. The vertical light blue line shows the first eigenfrequency of the soil site.

Average and Maximum Misfit of Calculated UHS

As an overall quality measure the Table 9.2 shows the misfits, for horizontal and vertical components, between the calculated and target UHS for each NPP site. First two columns are the average misfit over all hazard levels and periods, and the last two columns are maximum misfit, usually found in the highest hazard level 1E-7.

Table 9.2: Misfits of calculated UHS with respect to target UHS [%].

NPP site	Average		Maximum	
	Horiz.	Vert.	Horiz.	Vert.
Beznau	-0.87	2.36	-41.23	47.79
Gösgen(f_0=1 Hz)	4.47	2.19	-49.54	35.29
Gösgen(f_0=5 Hz)	-0.27	3.21	-64.03	-58.95
Gösgen(f_0=16 Hz)	0.34	1.39	-63.43	-69.49
Mühleberg	1.14	2.96	-38.45	58.91

9.1.2 Meta Data for the Selected Earthquake Scenarios

As an example, Figure 9.6 gives an overview of various meta information of the selected scenario earthquakes for the Beznau site (here e.g. 406 scenarios). Beside the magnitude-distance and magnitude-V_{S30} distributions, also the rates and scaling factors for the selected earthquake scenarios are displayed.

9.1.3 Scaling of Ground Motions

Scaling of ground motion recordings beyond a factor of two is controversial in the seismological and engineering community. This in most of the cases without any objective reason and is mainly because the natural feature of the observed data is perceived to be artificially altered. Nevertheless, in engineering practice scaling is required to satisfy the requirements of matching a target response spectra, when no observed data satisfy such target. This is specially critical for annual probability levels lower than 10^{-6} where observed ground motions with high amplitude are sparse or not exist at all, thus, lower amplitude level need to be scaled up to ones which have simply not been observed yet. If the frequency content of a selected ground motion is suitable to satisfy the requirements to match the target response spectra (as e.g. defined in design codes) there is no seismological reason why the amplitudes of the selected ground motion can not be scaled. Figure 9.7 shows two scaled ground motions from the selected time histories for Mühleberg. The one in the right column is scaled weakly and the second one (left column) is scaled by a factor of almost 100. Visually both look reasonably good and realistic in amplitude and duration.

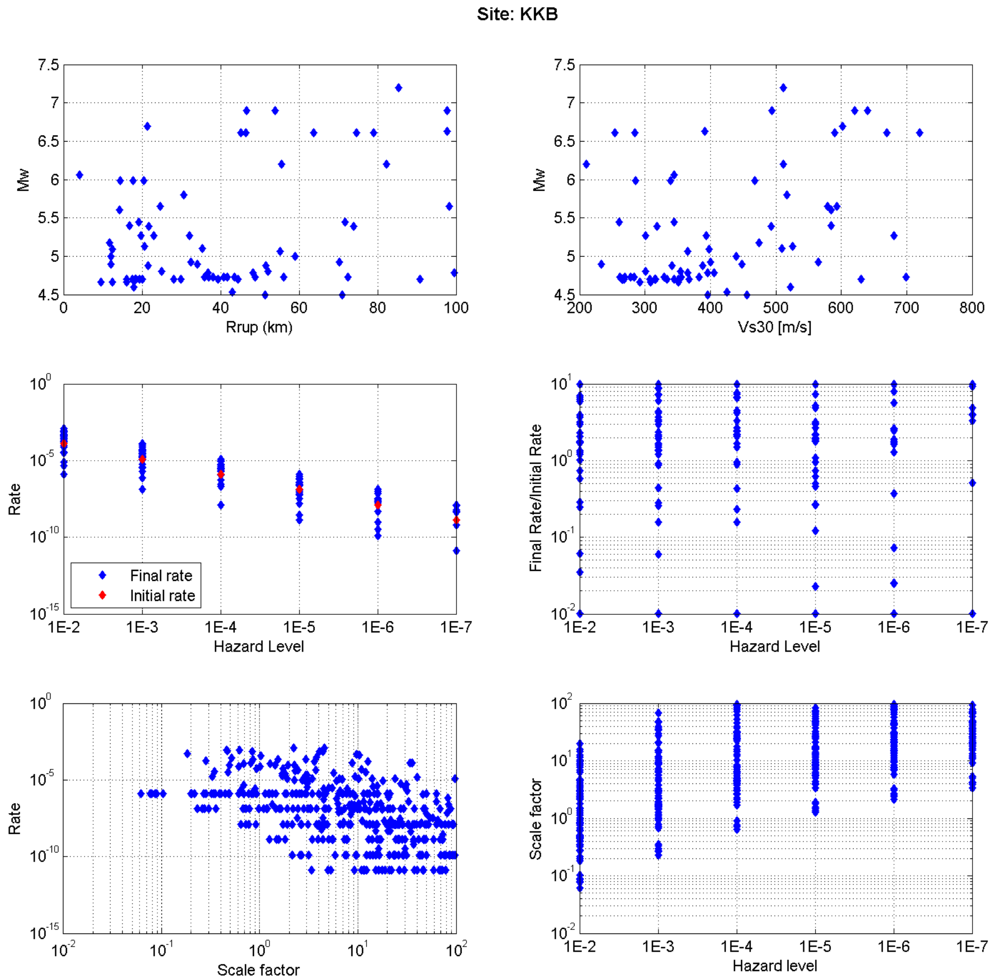


Figure 9.6: Distributions for the unique conditional spectra scenarios. Upper left: Magnitude-distance distribution, upper right: magnitude-V_{S30} distribution, middle left: final and intial rate of occurrence for each hazard level, middle right: ratio of final rate / initial rate for each hazard level, lower left: distribution of scenario rates versus scaling factor, lower right: scaling factor for each hazard level.

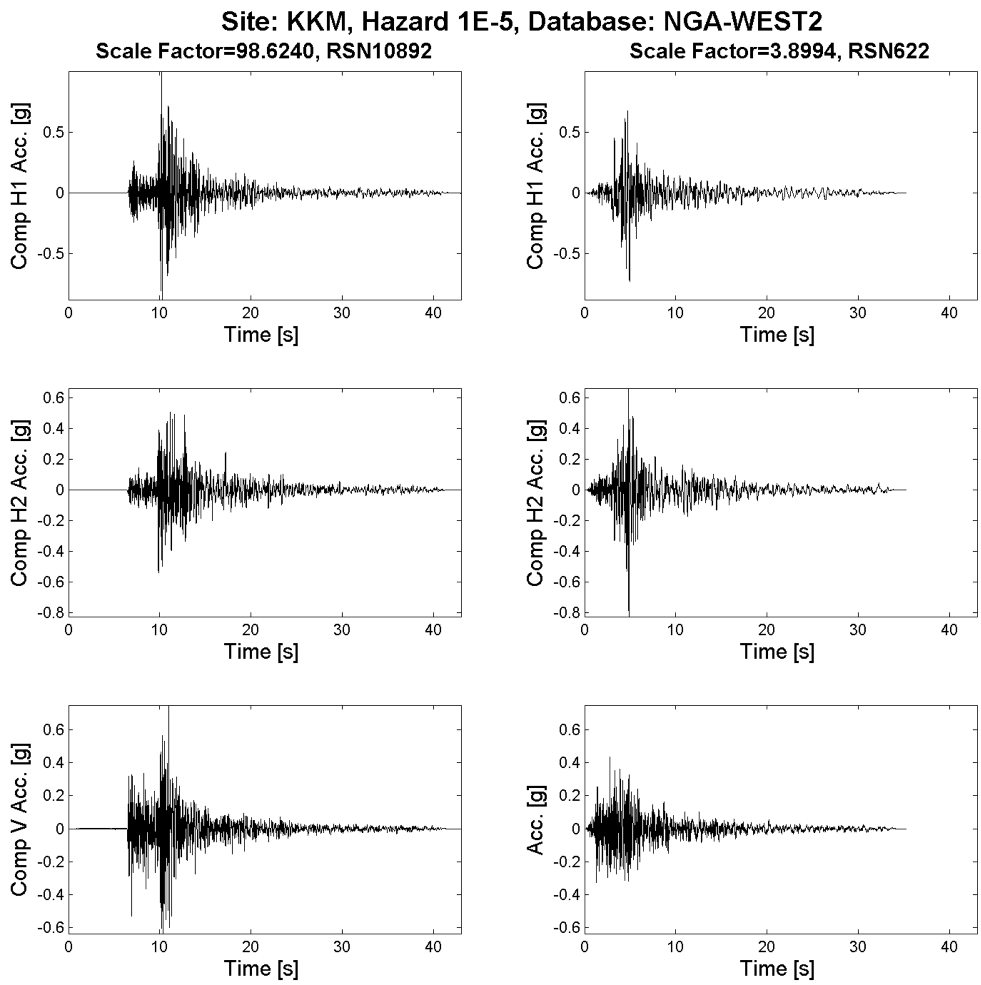


Figure 9.7: Examples of scaled ground motions. Left, with scale factor around 100; right, with scale factor around 4.

9.1.4 Consistency with SP2 and SP3 models

As the response spectra are by definition consistent with the median SP2 and SP3 models and their uncertainty, only two other type of SP2 and SP3 models can be used for comparison:

- SP2 strong motion duration models
- SP3 V/H models (on rock and soil)

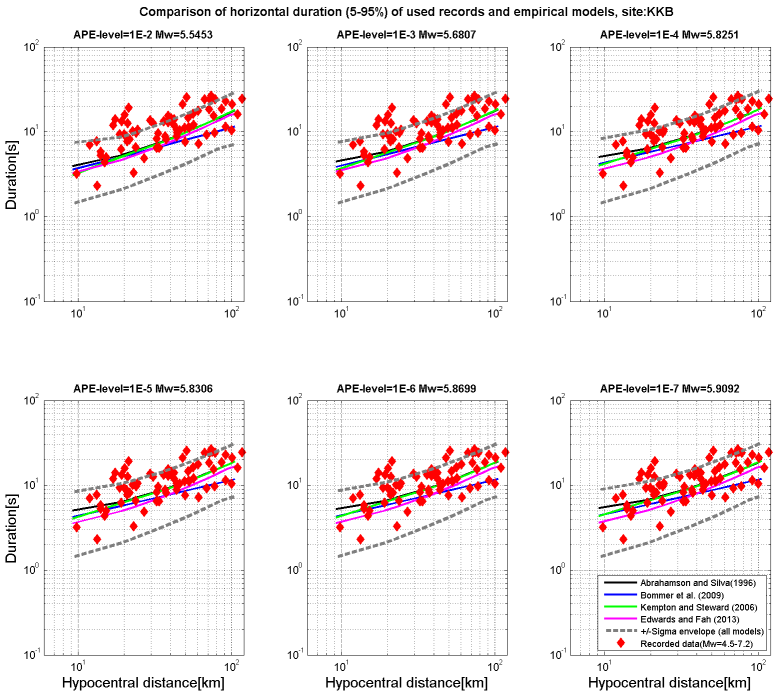
The distribution of strong motion duration of the conditioned records was checked against if they fall within a reasonable range of empirical models (mean, $\pm\sigma$) for 5-75% or 95% Arias Intensity. The following empirical models were used (the same as for the spectral matched time histories in Sec. 7.3):

- Edwards and Fäh [2013]* (only available for 5-95%)
- Bommer et al. [2009]
- Kempton and Stewart [2006]
- Abrahamson and Silva [1996] (only model with a vertical duration component)

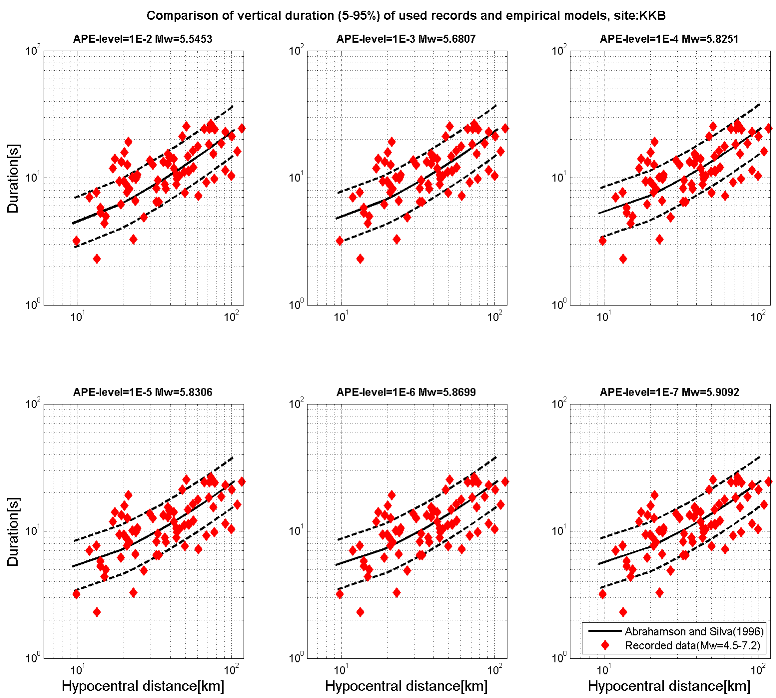
Exemplarily, Figure 9.8 shows how the strong motion durations of the selected time histories compare to the empirical durations models considered adequate for Switzerland. As can be seen, there are some durations higher than the one standard deviation envelope of the empirical models, especially at 1E-2 and 1E-3. This is acceptable, as the duration is not directly relevant to the hazard results and nuclear structures and components are in general not sensitive to duration (like e.g. low frequencies for high rise buildings).

The distribution of the resulting V/H (geom. mean of the two horizontal components) ratio vs. frequency was checked against if they are consistent with the empirical V/H soil models used in PRP. Figure 9.9 compares the V/H ratios of the selected time histories to the average soil V/H model for Beznau and the $\pm\sigma$ range around. The average soil V/H model here represents the average over the four SP3 expert models. As can be seen, the bulk of the selected records for this site are in agreement with the empirical prediction. The comparisons for the other sites can be found in the corresponding site specific appendices.

*The standard deviation model is based a linear regression through the provided sigma values for different distance bins in the Foreland (personal communication by B. Edwards).



(a) Horizontal.



(b) Vertical.

Figure 9.8: Comparison of scenario strong motion durations (5-95%) with empirical duration models: (a) for horizontal component, (b) vertical component. The dashed lines indicate the envelope (upper and bottom bound) of the sigma from all individual models.

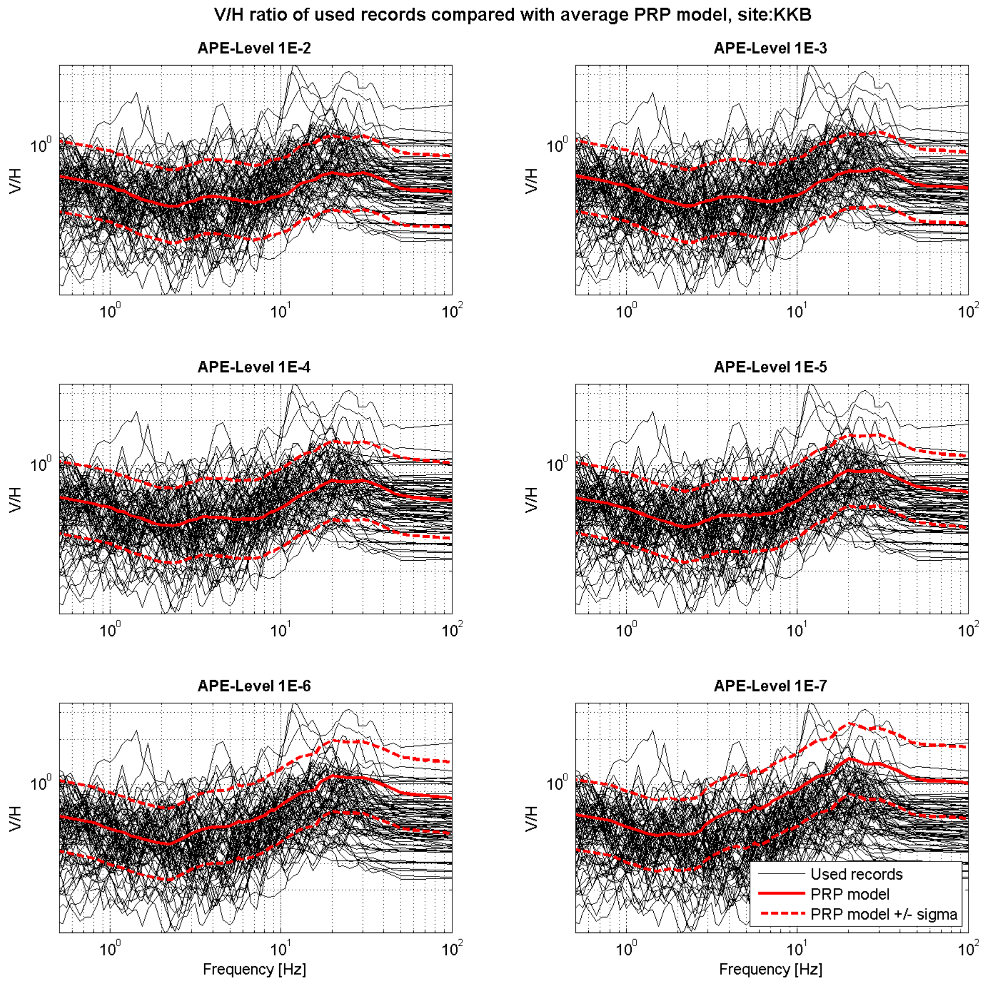


Figure 9.9: Comparison of scenario V/H ratios with averaged V/H soil model for Beznau.

Chapter 10

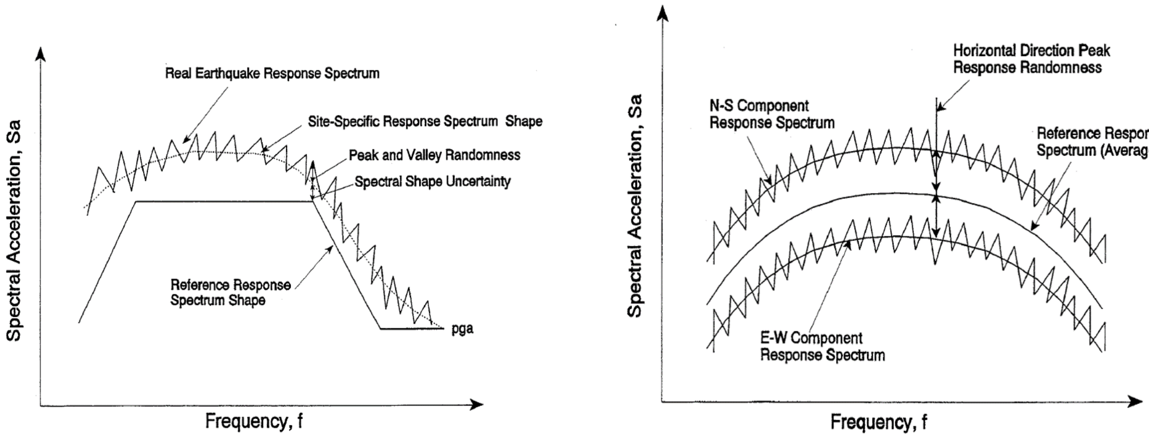
Interface with Engineering

The interface with engineering discussed in this chapter is not thought to cover all aspects of how the PSHA results are subsequently used in the context of structural analyses and the fragility assessment. Here the intent was to address three recurring practical aspects often discussed and encountered when it comes to the practical implementation of PSHA results, as there is not a unique approach to resolve the issues. The scope of this chapter is to explain that PRP probabilistic seismic hazard analysis includes the response spectral peak and valley variability as part of the aleatory variability when developing seismic hazard estimates and thus, should not be included again in the fragility estimate. Furthermore, the consistent evaluation of probabilistic structural response spectra under consideration of the mean and fractiles of the hazard is summarized. At the end a short reminder on the appropriate treatment of the structural results when using the CMS approach concludes this chapter.

10.1 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. 10.1(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. 10.1(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 10.1: 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) 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 10.2). 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.

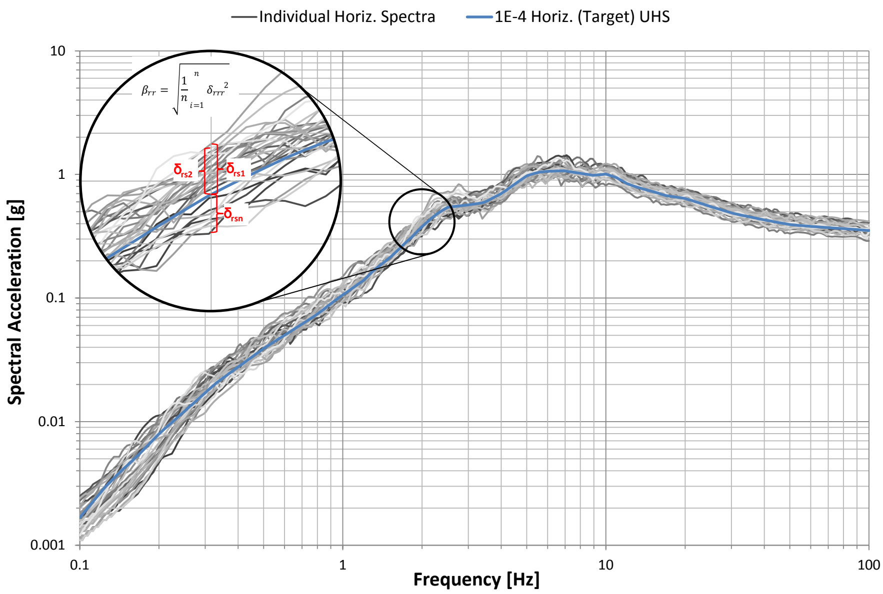


Figure 10.2: Schematic sketch of the evaluation of $\beta_{rs}(\beta_{PV})$ at each natural frequency when using the multiple three-component time-history analysis method with the median response spectra over all selected time histories matched to the UHS.

10.2 Consistent Evaluation of Probabilistic In-structure Response Spectra

The hazard defined by the PRP provides mean and fractiles for response spectra at different annual probabilities of exceedance (APE). The fractiles of the hazard and UHS represent the variability and uncertainty in the ground motion which is to be applied for the structural evaluation as input. In standard practice, often 30 time histories are applied to 30 soil profiles and 30 structural models. In doing this, there is most of the time a potential double counting of the aleatory variability of time histories and the site response analysis.

For the consistent evaluation of probabilistic in-structure response spectra (e.g. floor response spectra) two things have to be considered: a) the variability of the ground motion, and b) the variability of the structural parameters (as e.g. the stiffness, density, damping, etc.). Geometrical variability and modeling uncertainties are not further discussed in this chapter.

Under the assumption that the spectral shape is the same between the different annual probability of exceedance levels between 1E-4 and 1E-7 and the structure responds linearly, a single UHS can be used as the starting point. The response of the structure at the other APE levels can be obtained by simple scaling of the amplitude of the response values. E.g. the ratio between the 1E-5 and 1E-4 UHS at each frequency is used to multiply the stresses, strains and other structural responses to scale them to the 1E-5 APE level and so forth.

For the 1E-4 UHS, 30 3-component time histories are defined, with their geometric mean matching the mean UHS at 1E-4. Each of those response spectra has a variability about the mean UHS in this approach (they include the peak-and-valley variability), but they are all close to the mean UHS in terms of amplitude. Those response spectra or time histories are then used to excite the structure and an average response of the structure for the APE level 1E-4 is obtained. This structural response does not include the full epistemic uncertainty of the ground motion which is defined by the 16% and 84% fractiles around the mean UHS at 1E-4.

If the UHS at the surface is used, the response spectra already include the uncertainty of the SP3 soil profiles and associated material parameters. In this case there is potential double counting in the subsequent structural analysis. If the starting point is the UHS on rock, the epistemic uncertainty of the soil is not present and has to be included in the soil-structure interaction analysis. This is not trivial, as in practice often 30 randomized profiles around one best estimate profile are used. As in PRP up to six "best estimate" soil profiles have been defined for a specific site the epistemic uncertainty of the soil might by underestimated with the standard approach.

The last step consists in scaling the individual structural responses with scale factors derived from the different APE levels (under the assumption everything behaves linearly). In the same way, the structural responses can be scaled to the different fractile levels around each mean UHS for an APE level. In this way, the statistical evaluation of the results reflect all the probabilistic components (ground motion and structural components and also soil if necessary) and map them at the in-structure response spectra.

10.3 Considerations for the CMS approach

When using the CMS approach as alternative to the classical UHS approach it is necessary to remember the overall framework and how the individual time histories consistent with the CMS have to be applied for the structural analyses and the subsequent treatment of the results. Usually, two or more CMS are used to approximate the UHS. Thus, the burden of the engineers is to run a factor of two or more time history analyses, as multiple CMS have to be satisfied. For the (conservative) UHS approach only the defined 30 time histories have to be evaluated. The benefit of using the CMS consistent time histories is of course that the individual spectra do not excite the broad frequency range at once. The envelope of the two or more CMS (in PRP three CMS were defined for Gösgen) is used as quality measure on how well the UHS is reproduced. Thus, when applying the associated time histories in structural analyses, also the results of the structural responses for the two or more CMS need to be enveloped to be consistent with the framework. The structural analyst should be aware of this and not simply average the results of the different CMS based cases.

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Appendices

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