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Approach and challenges for the seismic hazard assessment of nuclear power plants: the Swiss experience

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ABSTRACT The PEGASOS project, a new state-of-the-art probabilistic seismic hazard assessment for the nuclear power plant sites in Switzerland has been carried out from 2000 to 2004. The quantification of the epistemic uncertainty and aleatory variability in seismic hazard at the four Swiss nuclear power plant sites was the key aspect of the PEGASOS project. After the completion of the project, the Swiss utilities decided to perform a refinement of the study by collecting additional data and using new advances in science, especially in the field of ground motion modeling, to further reduce the identified uncertainties. This paper gives an overview of the different components of the project, the used approaches and also identifies some new challenges for the scientific community. An important aspect being: the adjustment of ground motion prediction equations in order to make them applicable to the study region. The importance of those adjustments and their significant impact on PSHA results are also illustrated.

Key words: PEGASOS, PSHA, probabilistic risk assessment, nuclear power plant, Switzerland.

1. Introduction

Critical facilities as e.g., nuclear power plants (NPPs) have been and are built in various countries and regions around the world. Despite the consideration of the static loads, those critical facilities are designed to withstand high dynamic loads as e.g., wind and extreme earthquakes. Conventional seismic hazard maps, as used as basis for the modern seismic design codes of normal buildings, are based on a $2.1 \cdot 10^{-3}$ annual probability of exceedance, which corresponds to 10% exceedance probability in 50 years and thus, can be interpreted as approximately a 475 years return period. Always, the integrity of a NPP during and after an earthquake has been of the highest priority for the designers in order to maintain the public safety and to avoid any major damage to such a critical structure and the environment. According to the actual state-of-the-art, the seismic design of NPPs are expected to fulfil a performance goal of 10^{-5} per year (i.e., the probability of failure of any structure/system/component due to a seismic event must be less than 10^{-5} per year). This requires for the safety analysis of a NPP the definition of acceleration probabilities of exceedance up to at least 10^{-7} per year (10 Mio. year return period) (ENSI, 2009).

The recent accident in Fukushima Dai-ichi, due to the Tokohu earthquake of March 11, 2011, has challenged the nuclear renaissance in many ways, and raised again a lot of questions by the

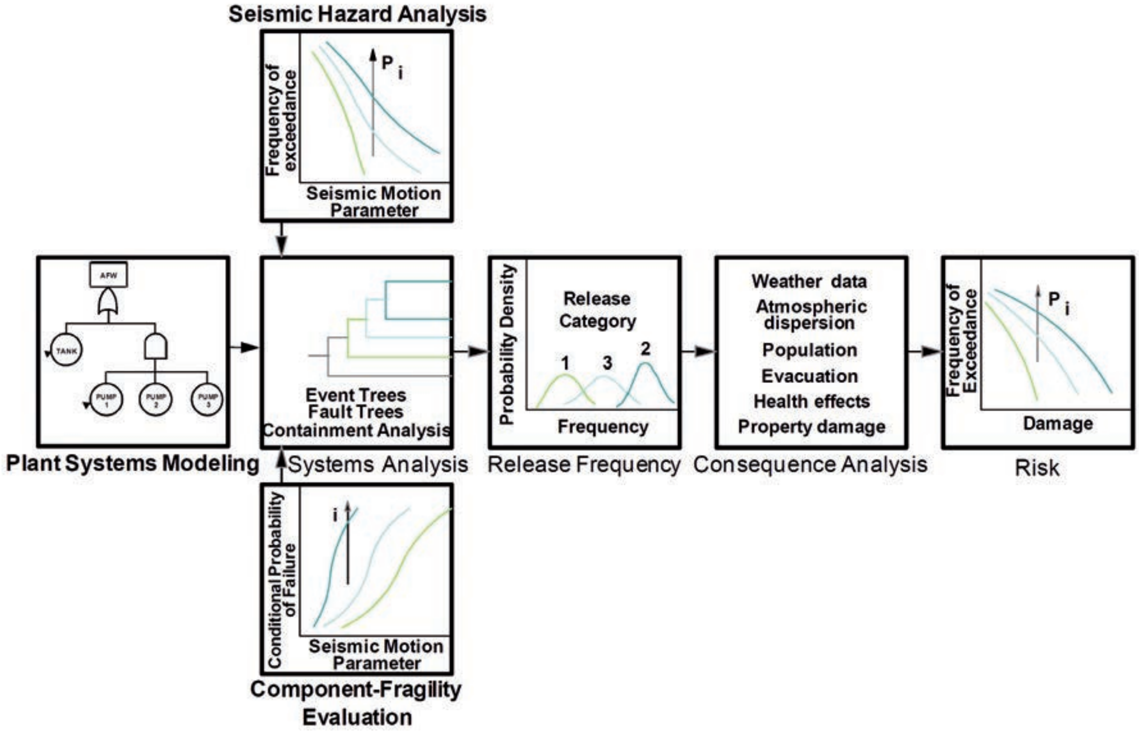

Fig. 1 - Schematic sketch of a seismic PRA for a critical facility (e.g., a NPP).

public and authorities. Nevertheless, the increasing importance of risk-informed approaches in the nuclear oversight process (as established in many countries) has contributed to an increasing use of probabilistic risk assessment (PRA) methods. On the other hand, the new procedures for seismic ground motion assessment, analysis, and design methods represent a significant impact on the relevant NPP design and verification services performed by geologists, seismologists, geotechnical engineers, and structural engineers.

A seismic PRA consists mainly of four parts: i) probabilistic seismic hazard assessment (PSHA), ii) plant systems modeling, iii) seismic fragilities for structures-systems-components and finally the iv) seismic risk convolution (see Fig. 1). The focus of this paper and the Swiss PEGASOS project is on the first part, namely the provision of the necessary seismic hazard input.

The PEGASOS project (German acronym for: Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites), a PSHA for the NPP sites in Switzerland, has been carried out from 2000 to 2004 (see Table 1 for history) and set a new state-of-the-art in the industry (Abrahamson *et al.*, 2002). The PEGASOS project documents the available scientific knowledge related to the occurrence of earthquakes in Switzerland, ground motion models applied in Switzerland, and site response at the four Swiss nuclear power plant sites at that time (NAGRA, 2004; Zuidema, 2006). A key aspect of the PEGASOS project was the quantification of the epistemic uncertainty in the seismic hazard at four Swiss NPP sites. Since the completion of the PEGASOS project, there have been significant advances in the field of ground motion modelling. In addition, there have been several new earthquakes in the small magnitude range recorded in Switzerland.

In the light of the new developments and the newly available data, the PEGASOS Refinement Project (PRP) started in 2008 (Renault *et al.*, 2010). Its first major task, being extensive site investigation studies to satisfy the objective of the reduction of uncertainties for the characterization of a selection of relevant strong-motion recording stations in northern Switzerland and for the site-specific response calculations. The project is subdivided into different Sub-Project (SP) tasks, namely the seismic source characterization, the ground motion characterization, the site response characterization, the approach for the hazard calculation and the resulting scenario earthquakes, based on the main technical topics of a PSHA.

The refinement project is funded and managed by Swissnuclear. Swissnuclear is the nuclear energy section of Swisselectric, which is the association of the Swiss electricity grid companies. The completion of the PRP is expected for 2012.

Table 1 - Short historical background of PEGASOS and the PRP.

1990-1997	Federal Nuclear Safety Inspectorate (HSK) identified the need to update the seismic hazard assessments for Swiss NPPs, as not compliant any more with the state-of-the-art (with regard to progress in the US)
Dec. 1998	Swiss regulator started development of ”PSHA Guidelines” - Based on modern US recommendations - Beyond international state-of-the-art (at that time)
June 1999	Swiss regulator requested Swiss NPP operators to perform a new PSHA that complies with SSHAC Level 4
March 2000	NPP operators submitted first draft project plan: “Probabilistische Erdbebengefährdungsanalyse für die KKW-Standorte in der Schweiz” (PEGASOS)
2001-2004	Project settlement: - Project lead NAGRA (Nat. Cooperative for the Disposal of Radioactive Waste) - 13 Workshops, 17 „Elicitation Meetings“, … - Participatory peer review by HSK
Nov. 2004	PEGASOS review meeting: Specialists meeting, Baden (CH)
2004-2006	Review by the utilities and performance of several additional studies
2007	Organization and planning of a refinement study
2008-2012	Realization PEGASOS Refinement Project

2. Structure and organization of the project

The PEGASOS project consisted of four SPs. For the PRP a new fifth SP was added (Fig. 2):

- Sub-project 1 (SP1): seismic source characterization, with 4 expert groups each with 3 experts;
- Sub-project 2 (SP2): ground motion characterization, with 5 experts;
- Sub-project 3 (SP3): site response characterization, with 4 experts;
- Sub-project 4 (SP4): seismic hazard calculations, with 3 hazard analysts;
- Sub-project 5 (SP5): scenario earthquakes, with 4 experts.

The ultimate challenge in such a large and interdisciplinary project is the communication and understanding between the different disciplines (geology, seismology, geotechnical engineering,

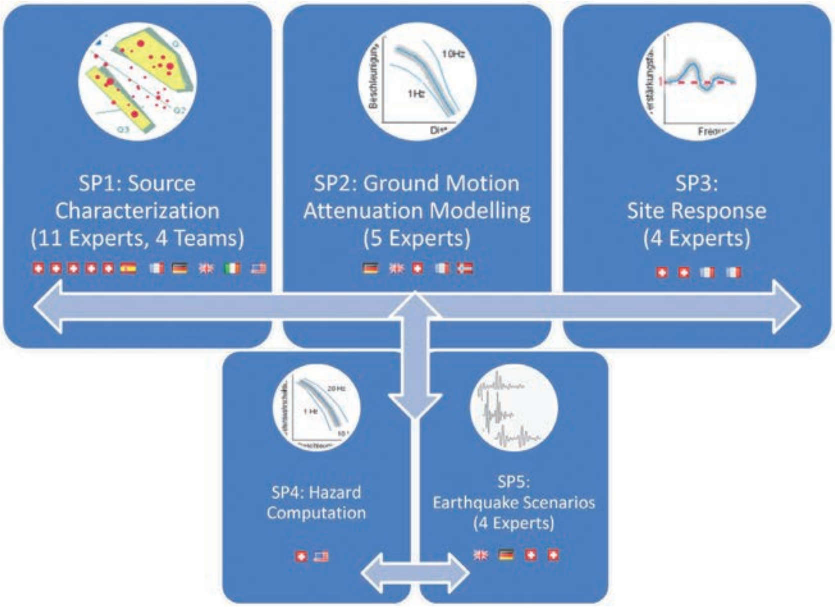

Fig. 2 - Global structure of the PRP with its SPs. The flags indicate the nationalities of the participating experts.

civil and mechanical engineering, probabilistic modeling and software development) and their facilitation. All SPs are interconnected and thus, in the PRP great attention is paid to interface issues in order to ensure a proper and efficient data and knowledge exchange between the different SPs and experts, respectively. During the PEGASOS project, the three sub-projects (SP1, SP2 and SP3) were run in parallel, which made some of the interface issues difficult to handle. In the aftermath of the project this turned out to be an important aspect, as a common understanding of how data and models are used across the expert teams could have avoided some sources of unnecessary uncertainties. Nevertheless, due to time constraints it would have been almost impossible to execute the SPs sequentially.

Compared to the PEGASOS project, there were only small changes to the general approach and structure of SP1 and SP3 in the PRP. This made it easier to address those interface issues in the PRP. Furthermore, a series of dedicated workshops have been held during the PRP to address the interface issues and to avoid any double counting of uncertainties.

In the following, the different SPs and their content will be described in more detail. As within PEGASOS and the PRP the experts have the ownership over the developed models and there is also a full project report available, this paper will not go into the technical details of those models, but rather give an overview from the management point of view and highlight some new challenges.

3. Seismic source characterization (SP1)

The models developed for the PEGASOS project were recently published in a special issue of the Swiss Journal of Geosciences (Burkhard and Grünthal, 2009; Coppersmith *et al.*, 2009;

Musson *et al.*, 2009; Schmid and Slejko, 2009; Wiemer *et al.*, 2009). After the PEGASOS project and a special workshop in 2006 the experts concluded that refinements of the source characterization would not lead to significant reductions in the epistemic uncertainty of the hazard. Thus, within the PRP the SP1 experts used the source characterization developed for the PEGASOS without major modification.

A sensitivity study on the assessment of the maximum magnitude has already been conducted by Swissnuclear to address the regulatory recommendation that the maximum magnitude was one of the candidates for potential refinement. It was found that reducing the uncertainty in the maximum magnitude (*Mmax*) estimates within a reasonable small range, has only a very small impact on the mean hazard. On the other hand, the sensitivity study showed that a truncation of the *Mmax* distributions in the vicinity of the plants could lower the mean hazard slightly, but the effect remains small and developing the technical basis for such a truncation would require a major effort. Based on these sensitivity results, it was decided and concluded that improvements in the approaches to *Mmax* assessments would not be part of the PRP.

As part of their ongoing effort and research, the Swiss Seismological Service (SED) has developed a new earthquake catalogue of Switzerland (ECOS'09) (Fäh *et al.*, 2011) which was made available to the project already before its official publication. Although updates to the earthquake catalogue were not identified as having a high potential to reduce the epistemic uncertainty in the hazard, Swissnuclear decided to include the catalogue updates as part of the PRP to ensure the compatibility of the PRP results with the new generation of seismic hazard assessments for Switzerland which will be based on the new catalogue. A new magnitude conversion/scaling relationship was used for the development of the updated earthquake catalogue of Switzerland. Using the geometries of the current SP1 source zones and following the procedures for computing the source parameters described by each expert team in the PEGASOS elicitation summaries, the new catalogue data have been used to calculate new activity rates (*a*-values), *b*-values, and *Mmax* values. A hazard feedback analysis based on the new ECOS and the new source parameters showed to have a significant effect on the hazard results in reducing the mean ground motions and especially at low annual probabilities of exceedance. Furthermore, extensive sensitivity studies on each SP1 parameter for each expert team model were performed in order to identify the most relevant aspects of the SP1 logic trees and it could be confirmed, that the *Mmax* distributions of the source zones are the most important parameter controlling the hazard results. All other model parameters only play a secondary role with respect to their effect on the hazard results, even if they are scientifically justified to be part of a logic tree. On the other hand, in order to be computationally achievable it turned out that the SP1 logic tree of one expert team needs to be trimmed in order to be implemented. The tree trimming in the PRP is done according to very strict quality assurance criteria in order to accurately maintain the characteristics of the mean, median and relevant fractiles. As a consequence, the Technical Facilitator and Integrator (TFI) project and SP4 group had to build a SP1 "hazard logic tree" entering the hazard computation which was based on the initial "scientific logic tree" defined by the experts. There might be some value in the future to let the experts build and endorse a "hazard logic tree" themselves, even if this requires a longer iterative process and a good focus on only the parts of relevance for the hazard.

4. Ground motion characterization (SP2)

The epistemic uncertainty in the rock ground motion is usually the largest contributor to the uncertainty in the hazard. Since the completion of the PEGASOS project and further assessments (e.g., Bommer *et al.*, 2005; Musson *et al.*, 2005; Sabetta *et al.*, 2005; Scherbaum *et al.*, 2006a), there have been significant advances in the ground motion field with new models being developed that appear to be widely applicable to shallow crustal earthquakes, including central Europe (Campbell and Bozorgnia, 2006; Stafford *et al.*, 2008; Scasserra *et al.*, 2009). In addition, there have been some new earthquakes in the magnitude 4 range recorded in Switzerland. Given these important new data and models and the large impact of the ground motion epistemic uncertainty on the hazard uncertainty, new models and a complete new logic tree for the rock ground motion are developed as part of the PRP. A change from the approach used in PEGASOS is that a single unified ground motion logic tree that captures the approaches considered by all SP2 experts has been developed.

So far, the horizontal ground motion logic tree consists of a mix of Next Generation Attenuation (NGA) models, eastern U.S. models, a Japanese and three recent European equations (whereat it was looked for consistency with the SHARE project - http://www.share-eu.org/). The SED also developed a new Swiss stochastic ground motion model based on the newly collected data which was also added to the logic tree, but can be seen as multiple Swiss models, as several alternative versions can be defined. The stochastic models have a magnitude dependence of stress drop for extrapolating the model to high magnitudes with two parameters: the maximum stress drop and the magnitude at which the stress drop reaches this maximum level.

One of the major tasks in SP2 is the adjustment of the ground motion prediction equations (GMPE) selected for use in the PRP to be applicable in Switzerland. This adjustment includes for all selected GMPEs a correction to a reference rock profile accounting for the differences in the $V_{S\,30}$ and Kappa. Especially the so called “V_S - Kappa adjustment” is not straightforward and still under discussion in the PRP. Furthermore, previous studies have found that empirical GMPEs focused on large magnitudes do not extrapolate well to small magnitudes. Therefore, the GMPEs in the PRP are adjusted in the small magnitude range ($M < 5.5$) to be consistent with small magnitude data observed in Switzerland. The last step is then the testing of the models (i.e., calculation of likelihood values for the seismic intensity observations matching the adjusted and extended models). For this task, seismic intensity observations and Swiss ground motion data are used to test the models.

Besides the definition of the GMPEs for the hazard computations, the SP2 experts have also developed new models for the uncertainties (sigma) of the GMPEs based on a single-station-sigma model (Rodriguez-Marek *et al.*, 2011). This additional aleatory variability logic tree can be used to replace the published sigma values of the original GMPEs. Further details on the theoretical background can be found in Al Atik *et al.* (2010) and Rodriguez-Marek *et al.* (2011). The introduction of the single-station-sigma is very promising in terms of uncertainty reduction and avoiding double counting of uncertainties in SP3. A new revised maximum ground motion logic tree was also developed for the PRP and showed that the earlier limits have already been exceeded by observations since the completion of the PEGASOS project. Nevertheless, sensitivity studies have shown that today’s truncations models would not significantly affect the hazard down to an annual probability of exceedance of 10^{-7}. Furthermore, to evaluate the vertical hazard, V/H models (e.g., Campbell and Bozorgnia, 2003; Akkar and Bommer, 2010; Gülerce and Abrahamson, 2010; Edwards *et al.,* 2011b) have been collected and evaluated to build a new V/H logic tree for rock ground motions.

5. Site response characterization (SP3)

After the PEGASOS project, the SP3 experts and Swiss plants saw potential for a reduction of the epistemic uncertainty of the hazard by also reducing the uncertainty in the site-specific soil properties through measurements at the NPP sites. Thus, the Swiss NPPs have collected new site-specific geotechnical data on soil profiles and the non-linear soil properties. Different measurement techniques (reflexion and refraction seismic, multichannel analysis of surface waves, ambient vibration array and V/H measurements, logging, up-/downhole and crosshole seismics) have been used in the framework of the new campaign, which also enabled an estimation of the range of their applicability and a quantification of the associated uncertainties. The comparison of the results of the different techniques has revealed that for the case of the Swiss NPPs the uncertainty has increased, as the evaluation of the data lead to significantly different models.

Based on the gained insight of the field measurements, site response calculations have been conducted using the new model parameters for the soil profiles and non-linear properties. The same three methods as used in the PEGASOS SP3 logic trees (1D equivalent linear time domain method, 1D equivalent linear Random Vibration Theory (RVT) method, and 1D truly non-linear time domain method) have been evaluated with the new soil data. For each computation method benchmark and cross-check computations have been performed. A positive observation was e.g., that non-linear time domain computations for the same site and input data were performed by two independent contractors with two different constitutive models. Surprisingly, the site amplification results were in very good agreement to each other, which may be due to the vast amount of collected high quality data for this project or the excellent modeling skills of the contractors. The initial benchmark of the RVT contractors revealed something unexpected to the experts. For the same boundary conditions the site amplification functions resulting from computations with different software packages and contractors lead to notable different results. In the framework of the PRP a couple of investigations have been performed to understand these discrepancies, but could not be resolved to the full satisfaction of the project management team. Similar conclusions have also been drawn from other authors (Graizer, 2011). As the RVT approach to site response analysis has become very popular in recent years, because it is much less labor intensive since it does not require choosing and scaling time series, these differences should be further assessed in the future. There are a number of different software codes which have been developed independently and which are based on different approximation formulas, so that their strengths, weaknesses and also limitations should be compared to results with real recorded earthquake data.

The structure and the weights of the site response logic trees developed by the SP3 experts for the PEGASOS project have been revised for the PRP considering the new data. Feedback on the SP3 models has shown that the overall uncertainty of the SP3 models could significantly be reduced, despite the fact that the measurements lead to different interpretations for soil profiles.

This is mainly due to the refined models based on the expert interpretation of the new data and the avoidance of double counting of uncertainties. Furthermore, hazard feedback sensitivities identified the defined site specific shear wave profiles and material properties (shear modulus and damping) as the most important model parameters which control the hazard results. Preliminary hazard computations have shown (depending on the NPP site) some new features which still need to be verified, e.g., a significant shift in the peak (here resonance frequency) of the soil uniform hazard spectrum (UHS) compared to the rock UHS and to the previous spectral shape of PEGASOS.

6. Hazard calculation (SP4)

The generalized form of the mathematical formulation of a PSHA according to Reiter (1990) is:

$$E(a) = \sum_{i=1}^{N} v_i \int_{m_0}^{m_{max}} \int_{r=0}^{\infty} f_i(m) f_i(r) P_i(S_a > a|m,r) dr dm \quad (1)$$

where $E(a)$ represents the expected number of exceedances (mean annual rate) of ground motion levels a during a specified time period t. v_i is the mean rate of occurrence of earthquakes between lower and upper bound magnitudes (m_0 and m_{max}) being considered i the i-th source. $f_i(m)$ is the probability density distribution of magnitude within the source i and $f_i(r)$ is the probability density distribution of epicentral distance between the various locations within source i and the site for which the hazard is being determined. $P_i(S_a > a|m,r)$ describes the probability that a given earthquake of magnitude m and epicentral distance r located in the seismic source i will exceed ground motion level a.

The approach was developed by Cornell (1968) and improved by McGuire (1976) providing the required software support for the numerical hazard evaluation. In the framework of the PRP, the same approach and software for the rock and soil hazard calculations will be used as in the PEGASOS project. Namely, parameterization of all SP models and the use of FRISK88MP (Risk Engineering Inc., 2007).

In a first step, seismic sources (source zones) are defined based on the available earthquake data. Then, magnitude-frequency relationships and spectral attenuation models are derived for the different sources and frequencies, respectively. Hence, rock hazard curves are computed from these three input models. Using site-specific amplification factors, the rock hazard curves are converted into soil hazard curves.

To be consistent with the representation of the UHS, the horizontal rock hazard component is deaggregated in terms of magnitude, distance, and epsilon (number of standard deviations) at the following levels of annual exceedance frequency: 10^{-2}/yr, $2.1 \cdot 10^{-3}$/yr, 10^{-3}/yr, 10^{-4}/yr, 10^{-5}/yr, 10^{-6}/yr and 10^{-7}/yr. The plots are generated for the frequencies 1 Hz, 5 Hz, 10 Hz and 100 Hz (*PGA*). The exact distance bins will be defined after availability of the rock hazard results and hence, the controlling earthquakes for the Swiss NPPs will be determined.

The new step that has been introduced in the PRP is to develop site-specific hazard and scenario spectra from the total hazard curves, and to generate scenario time histories from the defined scenario spectra.

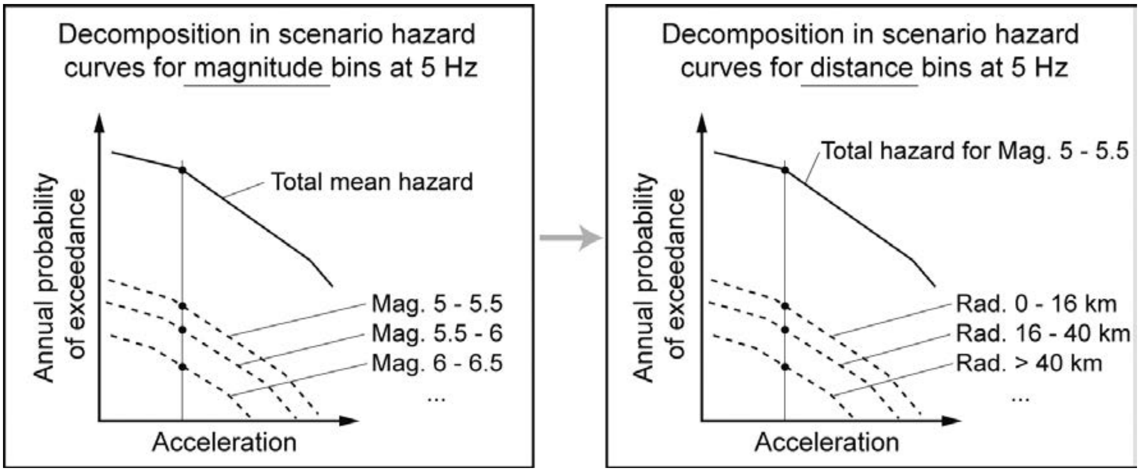

Fig. 3 - Schematic sketch of the procedure of scenario hazard development.

7. Scenario earthquakes (SP5)

Post-processing of the hazard results will be performed in an additional fifth sub-project (SP5) to define seismic hazard outputs that can be directly incorporated in the NPPs' probabilistic safety assessments, based on the development of fragilities for each structure, component and system. This will include the development of scenario earthquake spectra and scenario time histories.

For this, the scenario hazard curves will be developed for the frequencies of 1.5 and 100 Hz (*PGA*). For each of these frequencies, the total hazard will be decomposed in scenario hazard curves in terms of magnitude and distance (Fig. 3).

The UHS represents the spectra from multiple earthquakes at different spectral frequencies. Earthquake scenarios will be developed for use in the probabilistic safety assessment (PSA) to support the selection or development of representative time histories required for the subsequent fragility analysis. Magnitude and distance for the scenarios will be based on the modes of the magnitude-distance deaggregation at a selected spectral frequency. A set of corresponding scenario spectra will be developed to support the fragility analysis (selection of spectral shape).

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' models 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. 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 so called conditional mean spectra (CMS) (Baker and Cornell, 2006a, 2006b; Baker, 2011). 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 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 accurately.

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.

As already mentioned, after the definition of the scenario earthquakes, scenario time histories can be developed. The result is a suite of three-component time history sets for each scenario earthquake developed. First, initial time histories need to be selected, which can originate from recorded motions or numerically simulated motions based on seismological models. Then, the selected time histories need to be modified to be compatible with the scenario earthquake spectrum by either 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 time histories can then be used to estimate more realistic structural responses and to develop fragility curves for the PSA.

8. Identified critical issues

In the course of the project three major issues have been identified, which deserve some special attention and will hopefully be addressed and resolved by the scientific community in the future:

- host-to-target conversions for GMPEs;
- evaluation of the vertical hazard component with empirical V/H models;
- differences in predicted spectral accelerations by the Swiss stochastic model and the empirical international GMPEs.

8.1. Host-to-target corrections of GMPEs

Within the PRP, the SP2 experts decided to apply host-to-target corrections for the GMPE to be applicable for the Swiss reference rock profile (anchored at V_{S30} = 1000 m/s with Kappa = 0.017 s) as well as for the NPP specific site conditions (with V_{S30} between 1100 and 2500 m/s). Where "host" means the region representing the underlying data set of the used GMPE and the "target" region are the NPP sites in Switzerland. In the course of the project a rather complex logic-tree was developed in order to build a clear structure for the different contributing variables and to cover the epistemic uncertainty.

The SP2 experts decided that developing host-to-target region scale factors for the full set of stochastic point source parameters was desired as the stress-drop scaling in Switzerland was not well constrained, but they considered the differences in the shear wave velocity (V_S) profiles

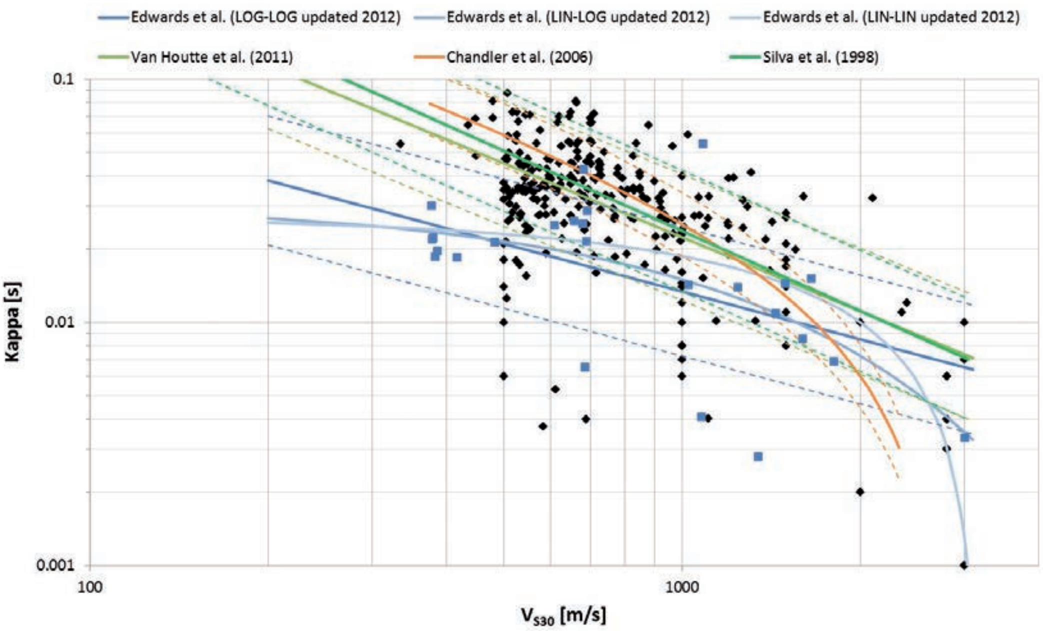

Fig. 4 - Comparison of different available Kappa - V_{S30} models and world-wide data (Renault, 2011). The thick line represents the median model and the thin dashed lines in the same color show the +/-sigma range. The solid back diamonds are world-wide data and the blue squares represent the available Swiss data, on which the Edwards *et al.* (2011) model is based (which was updated in 2012).

and damping in the shallow rock (Kappa) to be important effects that should be considered. Therefore, the objective was to isolate V_S and Kappa correction from the full model correction (Scherbaum *et al.*, 2006b). The target conditions for V_S and Kappa have been determined by the SP3 experts and SED, based on evaluation of the NPP site investigations and the evaluation of recordings at the Swiss network stations, respectively.

Four available empirical V_{S30} - Kappa models have been evaluated in the framework of the PRP: Silva *et al.* (1998), Chandler *et al.* (2006), Edwards *et al.* (2011b) and Van Houtte *et al.* (2011). As can be seen from Fig. 4 the different models have mainly been developed based on data for rock conditions (V_S< 1000 m/s), and only very few data points are available for the very hard rock conditions ($V_S \approx$ 2000 m/s), as being the case for the Swiss NPP sites.

It is obvious that there are different alternative possibilities to define the host and target V_S and Kappa conditions and to combine them in order to determine a correction function. In the framework of PRP hazard sensitivity studies the author and the project TFI have identified those correction functions as being an item of very high relevance in terms of effect on the overall hazard results. Fig. 5 shows an example of V_S and Kappa correction functions for different host and target conditions and the combined correction evaluated for a NGA model. The combined V_S - Kappa correction shown in the bottom graph of Fig. 5 has been obtained with the V_S correction from 800 m/s to 2000 m/s and assuming a host Kappa = 0.04 s combined with different target Kappa values between 0.006 and 0.04 s (the latter value was used to get a V_S correction only). As can be seen from the amplitudes, the effect of the Kappa correction on the high frequency range is quite significant.

Fig. 6 shows the impact of the used correction functions on the seismic hazard. The effect is

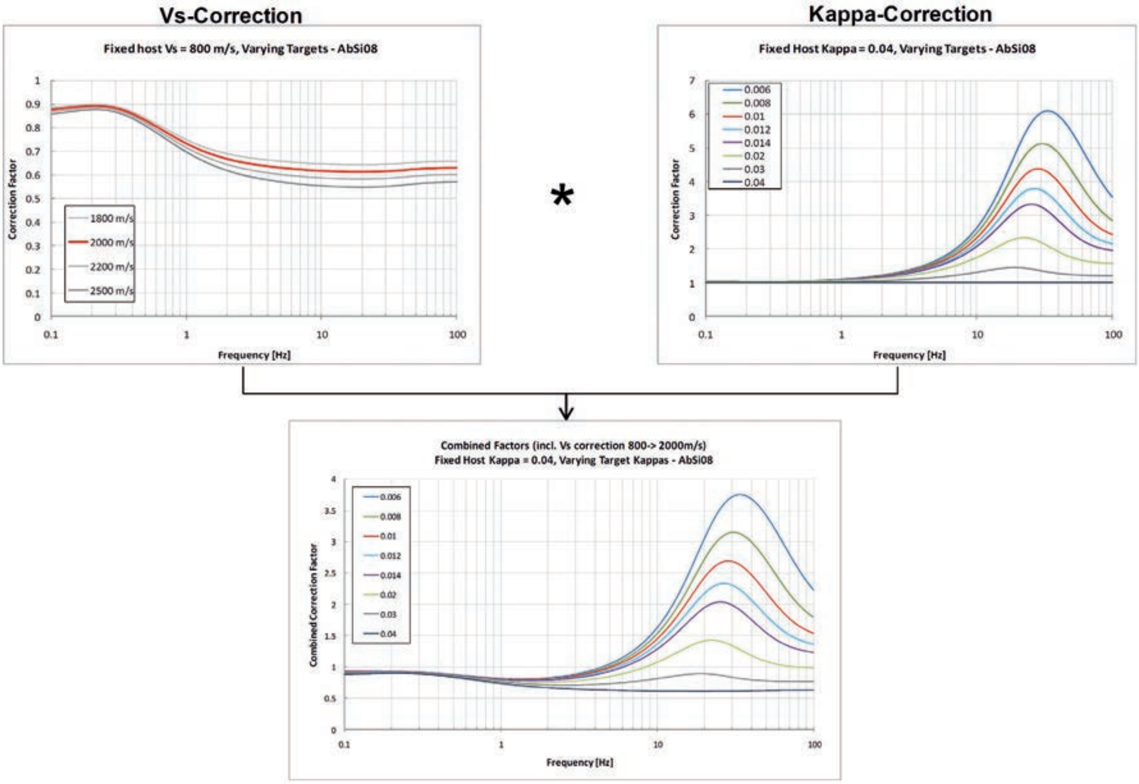

Fig. 5 - Example of V_S and Kappa correction functions for different host and target conditions combined in the bottom to a joint correction function evaluated for the Abrahamson and Silva (2008) GMPE. The top left graph shows the corrections assuming a host V_{S30} = 800 m/s and corrected to 4 different target V_S values in the range of 1800 - 2500 m/s. The top right graph shows the correction functions assuming a host Kappa = 0.04 s and different target values between 0.006 and 0.04 s. The combined V_S - Kappa correction shown here was build with the V_S correction for 2000 m/s (red line) and the different target Kappa values (Biro and Renault, 2012).

quite dominating compared to all other parameters which have been evaluated in the framework of the SP2 refinements. The assumed values for V_S and Kappa in the host and target region are reasonable and credible estimates based on the available information. Depending on the selected host and target V_S and Kappa values and their combination, the correction is smaller or even larger than shown in the example. This high sensitivity to the used values and the hybrid approach (Campbell, 2003) has been brought to the attention of the SP2 experts which have then worked out alternative approaches. There seems to be evidence that the hybrid model approach has some strong limitations in its applicability. At the end, it will be important to verify the V_S - Kappa corrections with some empirical constraints in order to evaluate if the obtained corrections are within a reasonable range.

8.2. Evaluation of the vertical hazard component with empirical V/H models

The previous section has described the Kappa adjustments that have been applied to the horizontal component GMPEs. Within the PRP the approach for the vertical ground motion evaluation is to use empirical V/H ratios to scale the horizontal rock ground motion. The empirical V/H ratios are based on data sets similar to those used for the candidate GMPEs, but

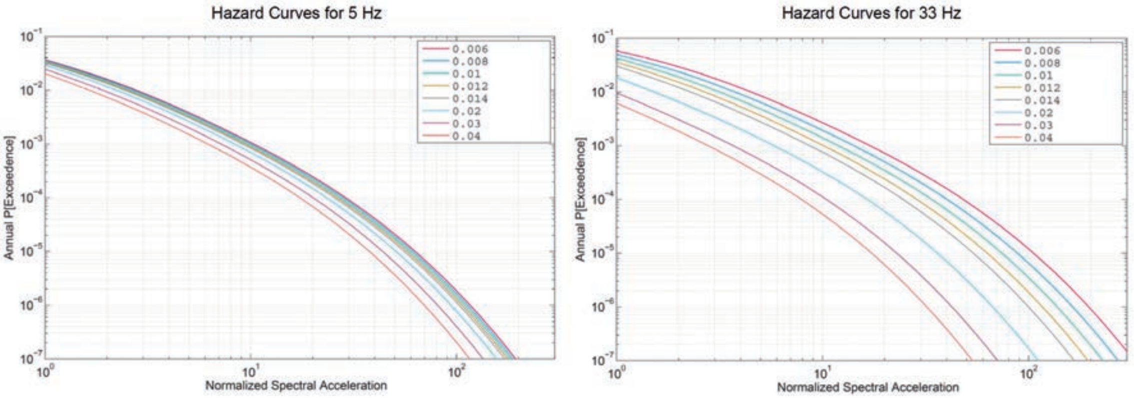

Fig. 6 - Hazard sensitivity to different target Kappa values for 5 Hz (left) and 33 Hz (right) at an example site in Switzerland. The host Kappa is fixed as 0.04 s with V_{S30} = 800 m/s. The target conditions are V_{S30} = 2000 m/s with different Kappa values ranging from 0.006 s to 0.004 s.

the V/H ratios have not been adjusted for Kappa. This raises the question as to the applicability of published V/H ratios to the Kappa adjusted horizontal GMPEs at high frequencies.

At high frequencies, the peak vertical ground motion is generally controlled by P-waves. So the V/H ratio represents the ratio of vertical component P-waves to horizontal component S-waves. The effect of Kappa on the horizontal S-waves is addressed in the Kappa scaling as described above. Thus, the denominator V/H ratio can be adjusted for Kappa, but there is also the issue of the Kappa effects on the P-waves (vertical component). In the past, the Kappa of the vertical component was estimated lower than the horizontal component Kappa, but there is a lack of information and systematic evaluation on this subject. Including effects of Kappa on both components would shift the peak in the V/H ratio to higher frequencies. Nevertheless, there is today no empirical V/H ratio available, which is only based on hard rock or where the ratio has been corrected by the effect of a different vertical Kappa component.

8.3. Differences in predicted spectral accelerations by the Swiss stochastic model and the empirical international GMPEs

Even though, the selected PRP GMPEs have been adjusted to fit the small magnitude data of Switzerland and are V_S - Kappa corrected, the project has identified a significant difference in spectral acceleration amplitude between the "best estimate" Swiss stochastic model and the empirical GMPEs. Of course, the Swiss stochastic model can be scaled to any acceleration level for higher magnitudes with the help of the stress drop parameter. On the other hand, there is also no proof that the predicted spectral accelerations form the GMPEs do not overestimate the ground motions in the Swiss foreland. The author has performed a couple of sensitivity studies in order to address this issue for the experts. The partial conclusion on this item is that the geometrical spreading used for the Alpine foreland within the stochastic model has the largest impact. Nevertheless, it should not be forgotten, that all the parameters within a stochastic model are correlated and cannot individually be responsible. The more fundamental question is what does the stress drop represent when considering the correlation with the geometrical spreading and should the empirical GMPEs be corrected for the regional difference in stress drop? As it seems that there is a relevant difference in geometrical spreading between western North America and Switzerland (and maybe other regions as well), one should consider this in the empirical GMPEs when applied to Switzerland. The SP2 experts have not yet decided what to do about this issue and the project results will significantly depend on the weights between the Swiss stochastic model and the other GMPEs.

9. Summary and conclusions

After completion of the PEGASOS study in 2004, several issues were raised by the regulator, sponsor, and the scientific community, despite the fact that internationally leading experts participated in the project and it represented a new state-of-the-art for PSHA in Europe. In order to address these issues and try to achieve improvements that are capable of realizing reduced uncertainties, Swissnuclear has decided to carry out the PRP between 2008 and 2012. This follow up project made use of all newly available data and especially of the new developments in the field of the new generation of GMPEs.

The hazard feedback evaluation based on the new earthquake catalogue of Switzerland and the new source parameters showed to have a significant effect on the hazard results in reducing the mean ground motions and especially at low annual probabilities of exceedance. This was mainly due to a new magnitude conversion/scaling relationship used for the development of the updated ECOS (SED, 2011). The epistemic uncertainty in the rock ground motion is usually the largest contributor to the uncertainty in the hazard. Thus, new models and a complete new logic tree for the rock ground motion have been developed as part of the PRP. Nevertheless, adjustments have turned out to be not straightforward at all and are still under discussion in the PRP, as they are heavily influencing the hazard results.

In conclusion, it can be said that a few new challenges have been identified in the course of the PRP and still need to be addressed by the scientific community. After completion of the project, Swissnuclear will prepare a final project report covering the PRP results and which will be available for all the PRP participants, reviewers, and the interested scientific community. Further information can be obtained from http://www.pegasos.ch.

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