PEGASOS REFINEMENT PROJECT: NEW FINDINGS AND CHALLENGES FROM A PSHA FOR SWISS NUCLEAR POWER PLANTS

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ABSTRACT

The PEGASOS project, a state-of-the-art probabilistic seismic hazard assessment for the nuclear power plant sites in Switzerland has been carried out from 2000 to 2004. Since the completion of the PEGASOS project, 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. 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 started in 2008. 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. This paper provides an overview of the project and the contents of the different project 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. Some new findings and challenges of the recent study will be discussed with regard to the applicability and implementation in the NPPs in Switzerland.

INTRODUCTION

Nuclear power plants (NPPs) have been and are built in various countries and regions around the world. Despite the consideration of the static loads NPPs are designed to withstand high dynamic loads as e.g. wind and earthquakes. 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 lifeline structure. 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 public and authorities. 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. 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. The focus of this paper and the PEGASOS project is on the first part, namely the provision of the necessary seismic hazard input.

The PEGASOS study (German acronym for: Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites) was carried out from 2000 to 2004 and evaluated the seismic hazard considering the broad knowledge of the international expert community in earthquake science and geotechnical engineering [1]. 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 [19][32]. A key aspect of the PEGASOS project was the quantification of the epistemic uncertainty in the seismic hazard at these four sites. The epistemic uncertainties are usually due to the very limited data on (i) strong earthquakes, (ii) ground motion attenuation, and (iii) soil properties at the NPP sites.

An overview of the activities since the completion of the PEGASOS project and a general outline of the PEGASOS Refinement Project (PRP), with its aim to reduce the uncertainties in the hazard at the four nuclear power plant sites in Switzerland can be found in [21]. This paper is intended to summarize the status and progress of the Refinement Project. Furthermore, new findings and challenges resulting from the PRP will be discussed. The project itself is sub divided into five subprojects (SP) based on the main technical topics of a PSHA. The 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 PEGASOS Refinement Project is expected for 2012.

SSHAC Methodology

The PEGASOS project was conducted according to the “Senior Seismic Hazard Analysis Committee” level 4 [25][28]. Like its predecessor, the PRP is essentially equivalent to a SSHAC level 4 study. The PRP is carried out according to the SSHAC guidelines and the recent implementation of the SSHAC Guidelines for PSHAs [15]. The latter reflects the experiences gained from SSHAC level 3 and 4 PSHAs around the world and updates the 1997 SSHAC guidelines. It should be noted that a draft NUREG with the title "Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies" is under preparation addressing most of the practical issues encountered when running a SSHAC study and will certainly help to improve the acceptance and understanding of such complex projects.

STRUCTURE AND ORGANIZATION OF THE PROJECT

The PEGASOS project consisted of four subprojects. For the PEGASOS Refinement Project a new fifth subproject was added (Fig. 1):

- Subproject 1 (SP1): Seismic source characterization, with 4 expert groups each with 3 experts
- Subproject 2 (SP2): Ground motion characterization, with 5 experts
- Subproject 3 (SP3): Site response characterization, with 4 experts
- Subproject 4 (SP4): Seismic hazard calculations
- Subproject 5 (SP5): Scenario earthquakes, with 4 experts

All subprojects 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 subprojects. During the PEGASOS project, the three subprojects were run in parallel, which made some of the interface issues difficult. Compared to the PEGASOS project, there are only small changes to the general approach of SP1 and SP3 in the PRP, including their overall structure of the logic trees. This makes 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.

After the start of the PEGASOS Refinement Project, swissnuclear decided to incorporate the planned new Swiss NPP projects in the PRP as it was the intention to also use the PRP results for other purposes than just the Probabilistic Safety Assessment of the existing plants, as for example for safety analyses for new site permits or retrofitting actions. After the accident in the NPP of Fukushima Dai-ichi, Switzerland has decided to suspend the plans for the three replacement NPPs. Nevertheless, all additional site investigations have been incorporated in the evaluations for the PRP and will be beneficial for the completion of the project.

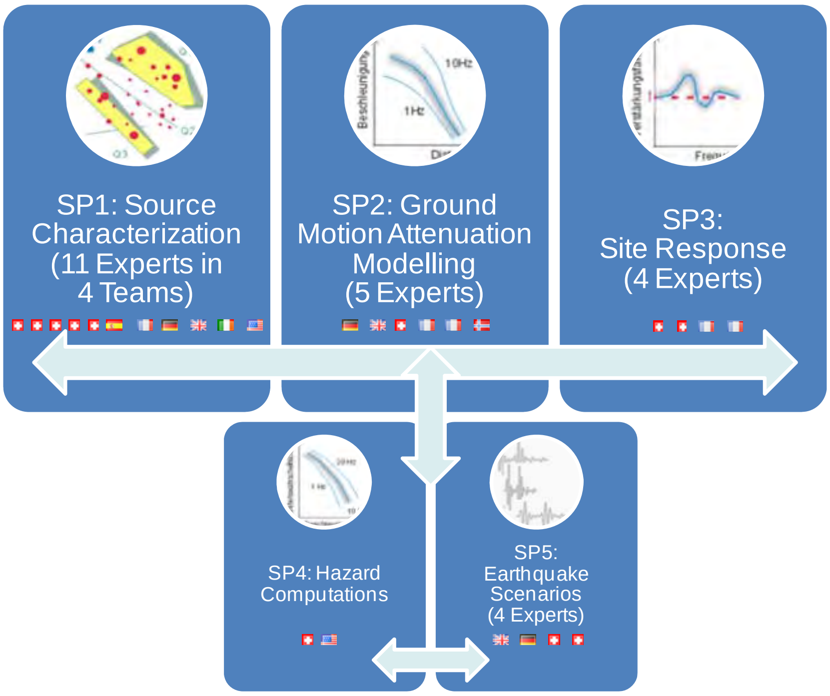

Fig.1: Structure of the PRP with its subprojects

SEISMIC SOURCE CHARACTERIZATION (SP1)

The models developed for the PEGASOS project were recently published in a special issue of the Swiss Journal of Geosciences [6][9][18][31]. 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 regulator 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) has only a 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 research, the Swiss Seismological Service (SED) has developed a new Earthquake Catalogue of Switzerland (ECOS'09) which was made available to the project [11] and will be published officially soon. Although updates to the earthquake catalog were not identified as a having a high potential to reduce the epistemic uncertainty in the hazard, swissnuclear decided to include the catalog 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 team 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. As consequence the project TFI (Technical Facilitator and Integrator) and SP4 group had to build a (trimmed) SP1 "hazard logic tree" entering the hazard computation which was based on the "scientific logic tree" defined by the experts. There might be some value in the future to let the experts build 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.

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, 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 [7][29][24]. 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 NGA models, Eastern US models, a Japanese and a new European equation. 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 major task in SP2 is the adjustment of the ground motion prediction equations (GMPE) selected for use in the PRP to be applicable in Switzerland. The steps in this procedure have been defined as follows: An inversion of selected GMPEs to find the point source stochastic parameters for each GMPE. Then, adjustment of all selected GMPEs to a reference rock profile accounting for the differences in the $V_{S,30}$ and Kappa. Especially this so called “Vs-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 from Switzerland. The last step is then the testing of the models (i.e., calculation of likelihood values for the intensity observations matching the adjusted and extended models). For this task, intensity observations and Swiss ground motion data are used to test the models.

Beside 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. 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 [2][23]. 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. Furthermore, to evaluate the vertical hazard, V/H models have been collected and evaluated to build a new V/H logic tree for rock ground motions.

Vs-Kappa corrections of GMPEs

As already mentioned above, the SP2 experts are applying a frequency dependent correction function to the selected GMPEs in order to account for the differences in the soil profile (Vs) and damping in shallow rock (Kappa) between the host (region representing the underlying dataset of the used GMPE) and target region (NPP sites in Switzerland). The process to determine the host Kappa and Vs-profiles for each GMPE is based on finding the best equivalent stochastic model parameters after inversion of a stochastic model for each virtual host region of empirical equations. Then, a correction function resulting from the ratio of the host and target response spectra is determined according to the hybrid model approach [7] (which was already applied in PEGASOS [25]). The target conditions for Vs 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.

There are a couple of choices which need to be made in order to apply the hybrid model approach evaluation. First, the host Vs profiles (shape and the associated $V_{S,30}$ value) and Kappa need to be determined which are usually unknown for a GMPE. Both are implicit information already part of the dataset with which the model was derived or are based on assumptions of the authors. The same applies to the target region (here the Swiss NPP sites), but one can perform measurements in order to define those at the sites of interest, if Vs and Kappa are interpreted as site specific parameters. For example, the SED determined average conditions for northern Switzerland as being $V_{S,30}$=1000m/s and Kappa=0.017s [10].

In the framework of a comparison of available empirical $V_{S,30}$-kappa models four models have been evaluated [10][26][12][30]. In order to take care of the uncertainty in the NPP specific Kappa value estimation, the SP2 experts have requested to also evaluate alternative models to define the NPP specific kappa. Most of the evaluated models didn’t specify a model for the uncertainty about the median model. Thus, those uncertainties have been evaluate by the author based the underlying data in order to provide guidance for the distribution about each model. The recent paper of [30] shows a very similar model as [26] and the co-author S. Drouet was so kind as to provide the collected V_{S30}-Kappa dataset used for the development of the new model. Based on the provided data which includes Japan, NGA USA, NGA Taiwan, California, France, Switzerland and other world wide data (see Figure 10 in [30]), the missing standard deviations have been derived. The derived standard deviations of the evaluated models are listed below:

- Edwards et al. (2011) $\sigma(\mathrm{LOG}(\kappa)) = 0.229$
- Silva et al. (1998) $\sigma(\mathrm{LOG}(\kappa)) = 0.249$ (Initially model had no σ model)
- Van Houtte et al. (2011) $\sigma(\mathrm{LN}(\kappa)) = 0.580$, which corresponds to $\sigma(\mathrm{LOG}(\kappa)) = 0.252$
- Chandler et al. (2006) $\sigma(\kappa) = 0.35$, which corresponds to $\sigma(\mathrm{LOG}(\kappa)) = 0.13$

As can be seen from Fig. 2 the different models have mainly been developed based on data for rock conditions and only very few data points are available for the very hard rock conditions (Vs≈2000m/s), as being the case for the Swiss NPP sites. The blue points in Fig. 2 represent the Swiss data which was used to derive the Swiss model in [10].

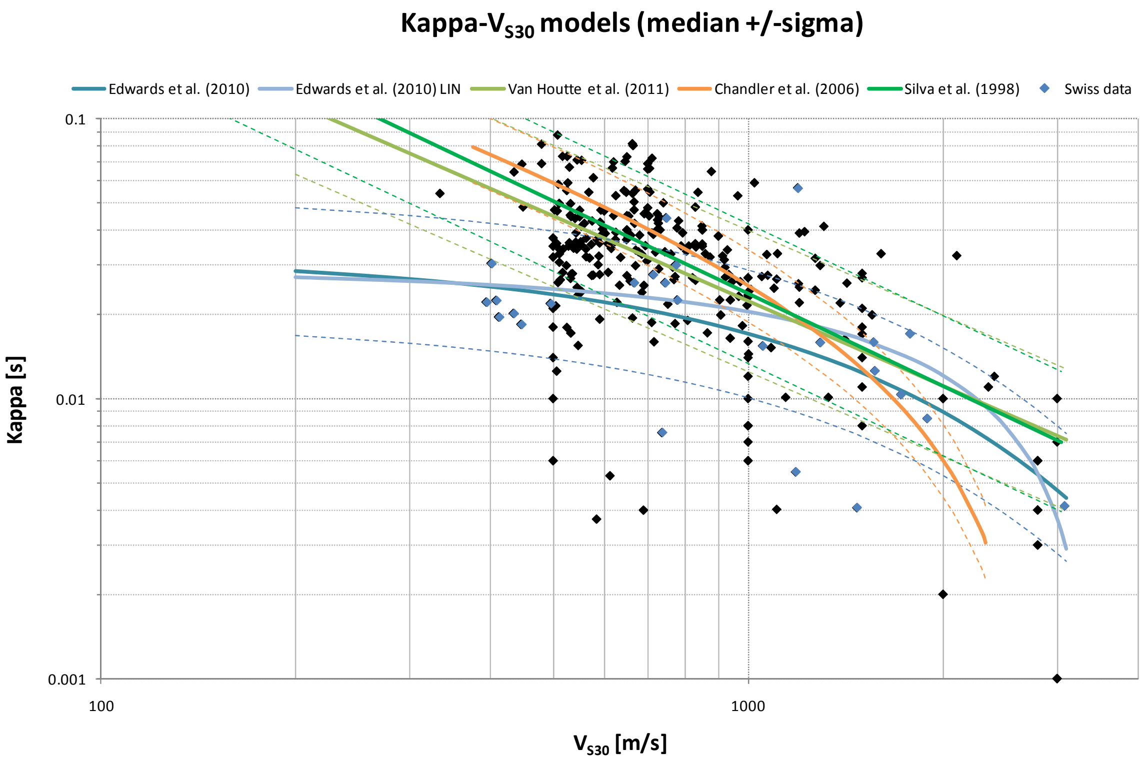

Fig. 2: Comparison of different available Kappa-VS30 models and world-wide data. The thick line represents the median model and the thin lines in the same color show the +/-Sigma range.

It is obvious that there are different alternative possibilities to define the host and target Vs 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 N. Abrahamson have identified those correction functions as being an item of very high relevance in terms of effect on the overall hazard results. Fig. 3 shows an example of Vs- and Kappa-correction functions for different host and target conditions and the combined correction evaluated for the Abrahamson & Silva (2008) GMPE. The combined Vs-Kappa correction shown in the bottom graph of Fig. 3 has been obtained with the Vs-correction from 800m/s to 2000m/s and assuming a host Kappa=0.04s combined with different target Kappa values between 0.006 and 0.04s (the latter value was used to get a Vs correction only). As can be seen from the amplitudes, the effect of the Kappa correction on the high frequency range is quite significant.

Fig. 4 shows the impact of the correction functions displayed in Fig. 3 on the seismic hazard. The effect is not negligible and dominating compared to all other parameters which have been evaluated in the framework of the SP2 refinements. The assumed values for Vs 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 Vs 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 has been brought to the attention of the SP2 experts which are investigating the problem and trying to work out an alternative solution. 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 Vs-Kappa corrections with some empirical constraints in order to evaluate if the obtained corrections are within a reasonable range.

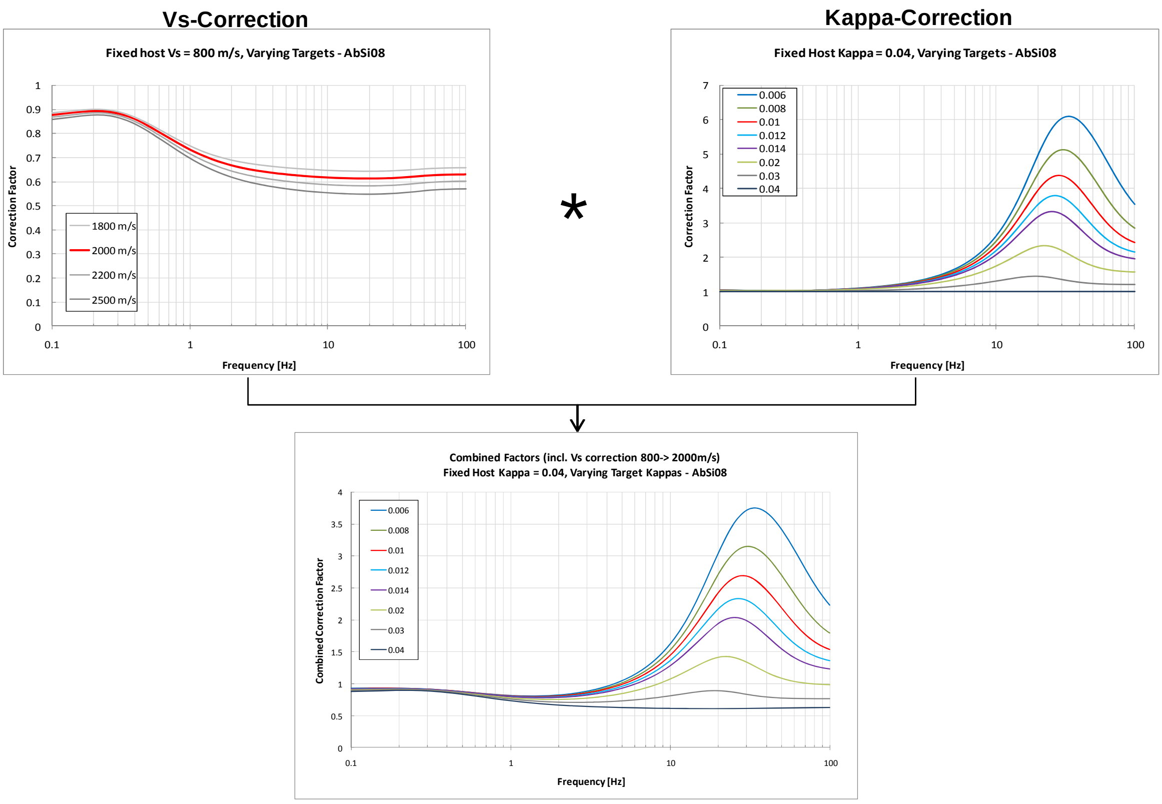

Fig. 3: Example of Vs- and Kappa-correction functions for different host and target conditions combined in the bottom to a joint correction function evaluated for the Abrahamson & Silva (2008) GMPE. The top left graph shows the corrections assuming a host $V_{S,30}$=800m/s and corrected to 4 different target Vs values in the range of 1800-2500m/s. The top right graph shows the corrections functions assuming a host Kappa=0.04s and different target values between 0.006 and 0.04s. The combined Vs-Kappa correction shown here was build with the Vs-correction for 2000m/s (red line) and the different target Kappa values.

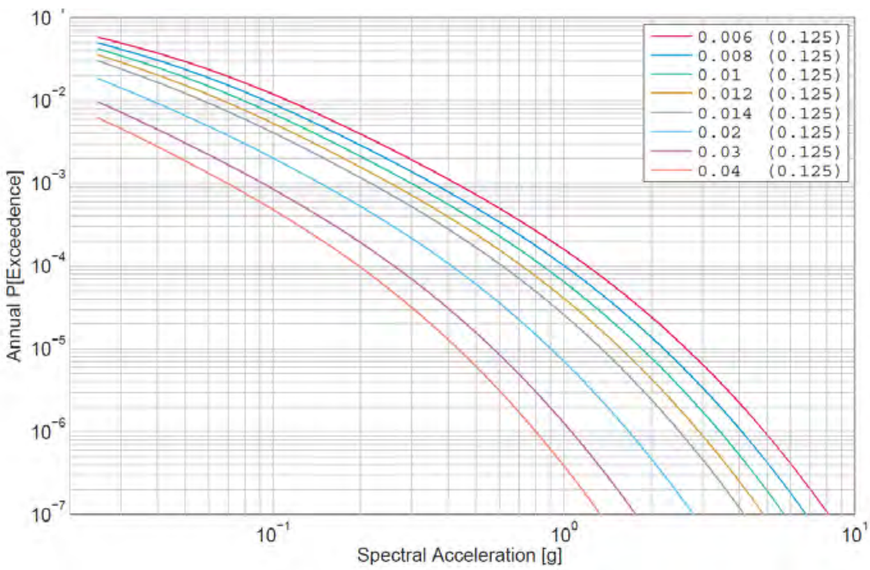

Fig. 4: Hazard sensitivity to different target Kappa values for 33 Hz at an example site in Switzerland. The host Kappa is fix 0.04s with $V_{S,30}$=800m/s. The target conditions are $V_{S,30}$=2000m/s with different Kappa values from 0.006s to 0.04s.

SITE RESPONSE CHARACTERIZATION (SP3)

Normally, there is the potential for a significant reduction of the epistemic uncertainty of the hazard by reducing the uncertainty in the site-specific soil properties through measurements at an NPP sites. Thus, the Swiss NPPs have collected new site-specific geotechnical data on soil profiles and the non-linear soil properties [16]. Different measurement techniques 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. A preliminary conclusion of the comparison of the results of the different techniques is that for the case of the Swiss NPPs the uncertainty has increased, as the evaluation of the data lead to significantly different models.

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 (1-D equivalent linear time domain method, 1-D equivalent linear Random Vibration Theory method, and 1-D 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 Random Vibration Theory contractors revealed something unexpected to the TFI and SP3 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 couldn't be resolved to the full satisfaction of the project management team. Similar conclusions have also been drawn from other authors [14]. As the RVT approach to site response analysis has became 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 and 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. The evaluation of the final models will show how much the site amplification changed compared to the PEGASOS project. 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 of the soil UHS compared to the rock UHS and to the previous shape of PEGASOS.

HAZARD CALCULATION (SP4)

The generalized form of the mathematical formulation of a PSHA according to [20] 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. vi 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 A. Cornell [13] and improved by R. McGuire providing the required software support for the numerical hazard evaluation [17]. 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 subproject models and the use of FRISK88 [22].

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 Uniform Hazard Spectrum (UHS), the horizontal rock hazard component will be 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•10^{-3}/yr, 10^{-3}/yr, 10-4/yr, 10^{-5}/yr, 10^{-6}/yr and 10^{-7}/yr. The plots will be generated for the frequencies 1 Hz, 5 Hz, 10 Hz and 100 Hz (PGA). The deaggregation in terms of distances for all expert combinations will also be performed. The exact distance bins will be defined after availability of the rock hazard results and hence, the controlling earthquakes 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.

SCENARIO EARTHQUAKES (SP5)

Post-processing of the hazard results will be performed in an additional fifth subproject (SP5) to define seismic hazard outputs that can be directly incorporated in the nuclear power plants' probabilistic safety assessments. 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. 5).

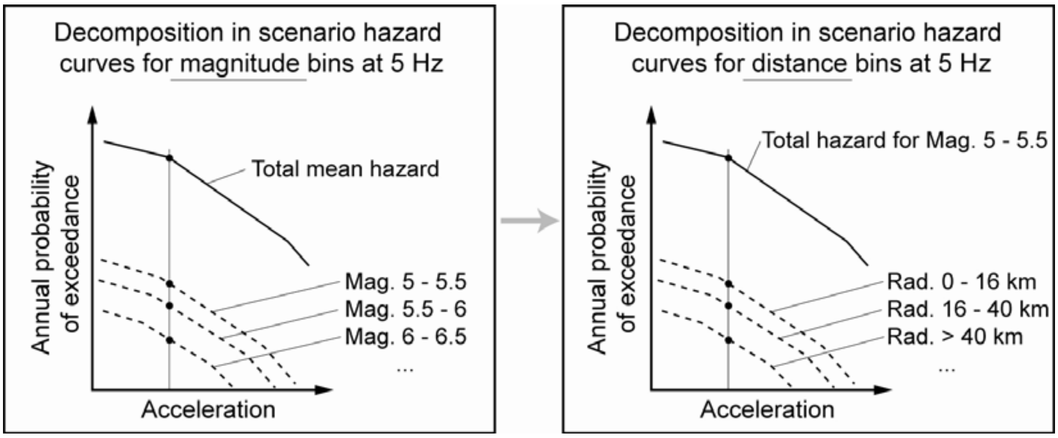

Fig. 5: Schematic sketch of the procedure of scenario hazard development

The Uniform Hazard Spectrum represents an envelope of the spectra from multiple earthquakes. Scenario spectra for individual earthquakes will be developed for use in the PSA. Magnitude and distance for the scenarios will be based on the modes of the magnitude-distance deaggregation. The scenario spectra (also called the conditional mean spectra [3][4][5]) account for the correlation of the ground motion variability between different spectral periods. The UHS for four probability levels will be used: 10^{-4}/yr, 10^{-5}/yr, 10^{-6}/yr, and 10^{-7}/yr. For each probability level, a minimum of two scenario spectra should be defined to cover the range of frequencies in the UHS. A rate will be determined for each scenario such that the combined rates from the scenarios approximate the hazard at each spectral period.

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 the structural response and to develop fragility curves for the PSA.

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 launch the PEGASOS Refinement Project in 2008. This follow up project will make use of all newly available data and especially of the new developments in the field of the new generation of ground motion prediction equations. Nevertheless, there are still a few challenges ahead which need to be resolved. The PRP is expected to be completed by 2012 and swissnuclear will prepare a final project report covering the PRP results and which will be available for all the PRP participants, reviewers, and on request for the interested scientific community. Further information can be obtained from http://www.pegasos.ch.

STATEMENT

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