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Site Amplification Studies for NPP Sites in Switzerland within the Project Pegasos and PRP

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SITE AMPLIFICATION STUDIES FOR NPP SITES IN SWITZERLAND WITHIN THE PROJECT PEGASOS AND PRP

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ABSTRACT

Based on a request by ENSI (Nuclear Regulatory Authority of Switzerland) to update the existing probabilistic earthquake hazard studies, Swissnuclear, the association of the nuclear power plants in Switzerland, initiated the PEAGASOS Project. The project started in 2001 and finished in 2004. It is for Europe a unique study, which aimed to evaluate uncertainties systematically and comprehensively. It was decided to perform the study on SSHAC-level 4. Level 4, defined by the Senior Seismic Hazard-Committee, is the highest level and was used only once before for the Yucca-Mountain-Project in the USA. In the PEGASOS Project, 21 international experts from Europe and additional supporting experts and companies from US and Europe were involved. The project was divided in 4 sub-projects representing the different steps in a seismic hazard assessment, namely seismic source characterization, attenuation relationships models, site amplification and seismic hazard calculation.

ENSI closely accompanied and reviewed the project. It concluded that PEGASOS project fulfilled the requirements of a level-4-study. The assessment of site-effects and the innovative quality assurance program has set a new benchmark in seismic hazard assessment. The results have been based on the latest state of knowledge and are the best basis to assess the seismic hazard at the four nuclear power plant sites in Switzerland. It also noticed that the derived uncertainties were remarkably large and could probably be reduced by further investigations. The best candidates for reduction of uncertainties were identified in the area of attenuation models and in the site conditions studies. Therefore Swissnuclear initiated the PEGASOS Refinement Project (PRP).

The paper describes in brief the project structure of the PEGASOS and the PRP, the methodology, the sensitivities of the results and the main findings. It discusses the experiences and the lessons learned by one of the site experts. The paper is mainly based on PEGASOS (2004) where more detailed information can be found.

INTRODUCTION

When reviewing a seismic hazard assessment study in different countries, it has been recognized that the results of the studies differ considerably depending not only by methods but also how experts interpret the basic data and the process used in the evaluation. Based on a request of NRC (United Stated National Regulatory Commission) the "Senior Seismic Hazard Analysis Committee" (SSHAC) reviewed the probabilistic seismic hazard analysis in the US since the 1980 and prepared recommendations (SSHAC 1997) to improve the state of art. The main finding was that the differences of the results depend more on the general procedures used than on technical details. The committee prepared recommendations in respect on the process and the task of the experts in such studies. They distinguish 4 possible investigation levels. The individual levels take into account the different knowledge of the so called "informed technical communities", which consist in principle of the known methodologies at the time of the study. The higher the level is the higher the needed time and effort. The following paragraphs briefly describe the scope of each SSHAC-level (SSHAC 1997).

SSHAC-level 1: The project responsible determines and evaluates the data and models based on literature studies and experience. He informally discusses the data and results with colleagues. Uncertainties are estimated based on experience using different methods.

SSHAC-level 2: The project responsible additionally asks for consultation on a formal basis from different experts in interpretation of data as well as the evaluation of methods and uncertainties.

SSHAC-level 3: The project responsible additionally organizes workshops with different experts. Together, they discuss data and methods. Based on the workshop results, the project responsible prepares the interpretation of results as well as the evaluation of uncertainties.

SSHAC-level 4: Formally, a panel of experts is introduced representing the "state of knowledge". This leads to a comprehensive evaluation of the problem at the "state of the art". The experts evaluate each other's results and the individual outcomes are combined by a logic tree. The effort of SSHAC-level 4 is by far greater than the one of the 3 other levels.

The technical work is directed by a Technical Facilitator / Integrator (TFI). He and his team are responsible to guide and supervise the expert's work as well the elicitation of the experts for the PSHA input.

The SSHAC report (SSHAC 1997) defines also the role of experts. The expert's fundamental role in the project has to be the one of an evaluator. He has to review alternative hypothesis and interpretation of data and assign weights for their credibility. Experts also have to assist the TFI in integrating the evaluation of the results of the expert team. The goal is to achieve a representative sample of the so-called "informed technical community."

Most of the studies in practice are performed by individual engineers or groups. This procedure is related to SSHAC Level 1 to 3. Generally, the whole field of knowledge is not covered and in single cases only subjective evaluations and decisions are performed. There are only 2 investigations existing on SSHAC Level 4 up to year 2009, Yucca Mountain Project in US on nuclear waste disposal (CRWMS 1998) and PEGASOS on probabilistic seismic hazard for nuclear power plants in Switzerland (PEGASOS 2004).

EARTHQUAKE HAZARD IN SWITZERLAND

Earthquakes are considered an important natural hazard in Switzerland. Historical earthquakes reached magnitudes larger than M_s 6.0 in the alpine as well in the pre-alpine areas. On a worldwide scale, this level of seismicity is considered as low to medium. In the past, earthquakes originated in practically all areas of Switzerland with varying recurrence rates. In combination with the rather dense distribution of critical infrastructure, the severity of risk has become a matter of major concern of the Swiss government as well as the Swiss private sector.

The first homogeneous countrywide earthquake hazard map was prepared 1977 (ASK 1977) with special emphasis on the requirements of nuclear power plants. 1984, design spectra were developed for different fairly generalized geological ground conditions (HSK 1984).

MOTIVATION FOR THE PEGASOS PROJECT

Probabilistic safety assessment performed for nuclear power plants have shown that earthquakes are a significant contributor the estimated frequency of core damage. ENSI reviewed the older studies and concluded that the seismic hazard assessment were no longer state of the art and required an updating. The new evaluation had to be based on up to date data and had to use the best available methodological approach that would also explicitly consider uncertainties. ENSI issued a set of methodological guidelines to help the power plants operator to plan the new study. The guidelines closely resemble the study level 4 methodology recommendation issued by the Senior Seismic Hazard Analysis Committee (SSHAC).

An unprecedented feature of the present study was the level 4 treatment of site effect. It was decided early to treat site response in the same manner as all other PSHA input components and developed site models based in the existing site specific geotechnical information. The geotechnical data base of the nuclear power plant sites was mainly based on the initial site studies and differed in extend and depth of investigations. Therefore, there was much room for interpretation and large judgment. It was expected that the impact on hazard level is significant and a full level 4 expert elicitation approach is needed.

To use US experience with the methodology, consultants as TFI have been selected who have actively participated in one of the earlier land mark studies to lead the PEGASOS study. Since all required geological seismological and hazard analysis expertise could be found in Switzerland and other European countries, the project director had decided to restrict the selection of individual experts to Europe.

It was assumed expert candidates do not have any experience with expert elicitation and most of them were likely to come from universities and governmental agencies. Training and technical assistance was planned and provided within the project. The experts had to propose and direct data acquisition and process, supervise its execution, than do the interpretation of results, up to and including the development of the final PSHA input model. They were expected to provide concepts and instructions rather than finished products.

It was planned to develop the PSHA input by three groups of experts, each group working under the supervision of a "Technical Facilitator / Integrator" (TFI) in organizational and administrative unit called subproject. Subproject SP1 was responsible for the characterization of seismic sources, SP2 for ground motion, SP3 for site response, SP4 for calculation of the seismic hazard for annual probability of exceedance down to 10^{-7}.

The project organization scheme is shown in Fig. 1. The composition of the 4 subproject tasks teams was different. SP1 experts had to provide the seismic source characterization. It was decided that this task was best assigned to 4 experts teams composed of experts with background in seismology, geology and seismotectonic and that at least one member in the team had to have experience in input preparation for a PSHA. SP2 consisted of 5 experts and SP3 of 4. SP2 and SP3 experts worked individually whereas the SP1 formed 4 expert groups (EG). In each group, the experts were together responsible for the group assessment. SP4 was responsible for the hazard calculation and the sensitivity studies.

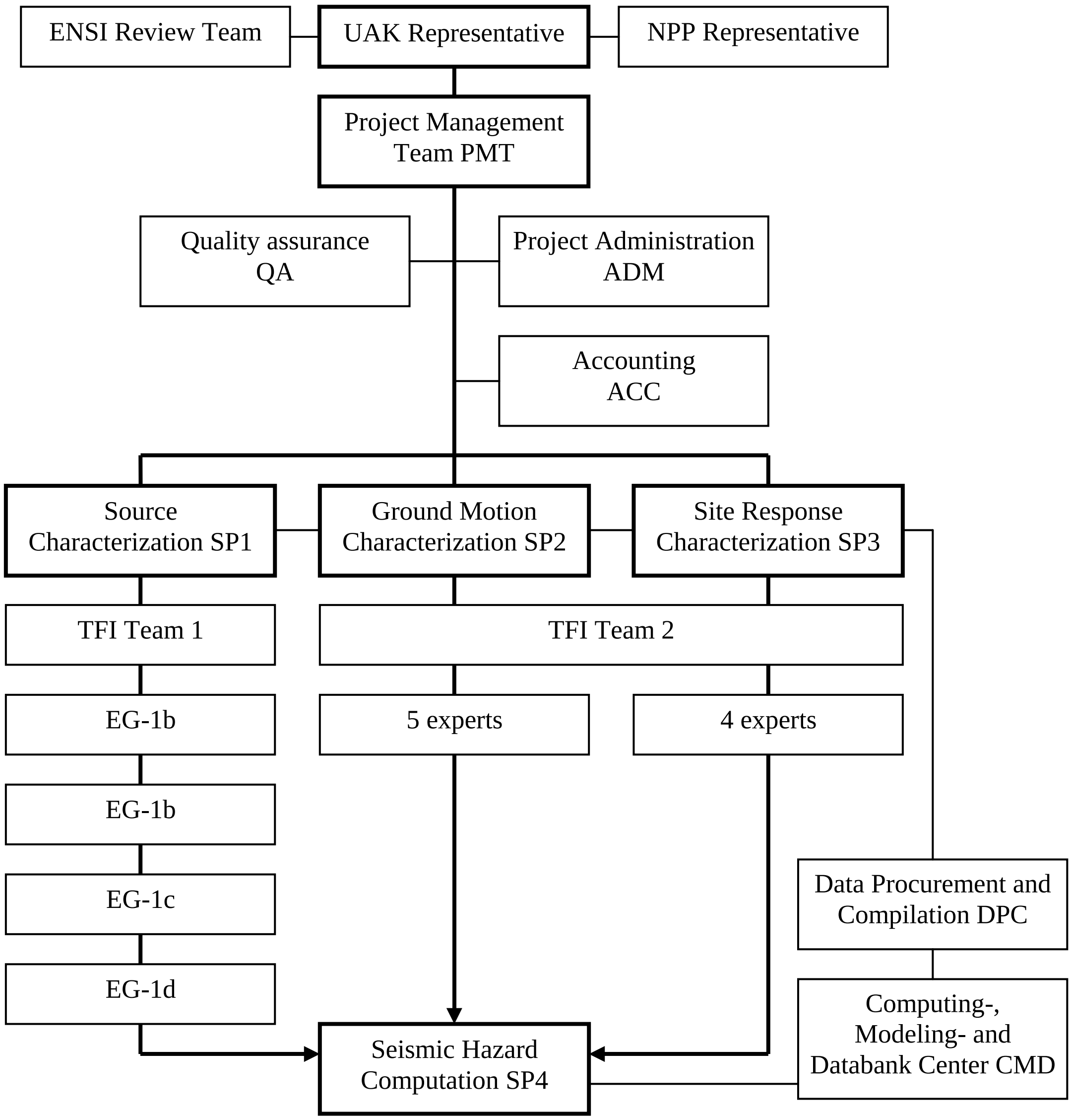

Fig. 1. Project organization scheme (after PEGASOS 2004)

SEISMIC SOURCE CHARACTERIZATION

The task of SP1 was to specify probability models describing the aleatory variability in location, timing and size of future earthquakes within the region. That means to assess the seismic source characteristics, the maximum magnitude and the recurrence. In general 2 seismic source features exist: areal sources and local sources (linear and point sources). The 4 teams discussed and assessed in 3 workshops their models and the individual source characteristics (spatial distribution of seismicity, fault rupture length and orientation, depth distribution, source boundaries, epistemic uncertainties in source definition, M_{max} for areal sources and faults, assessment for earthquake recurrence for areal sources and fault sources, etc.). The work was based on available data which were already developed and experts also made contributions. The teams elaborated quite different models as an interpretation of the basic data set. Figure 2 shows as an example a comparison of the primary seismic tectonic region. Figure 3 displays the most detailed seismic source definition developed by the 4 SP1 expert teams. They show significant differences in the interpretation of the data. Also for the different elements to characterize the source characteristics, the 4 expert groups developed different approaches.

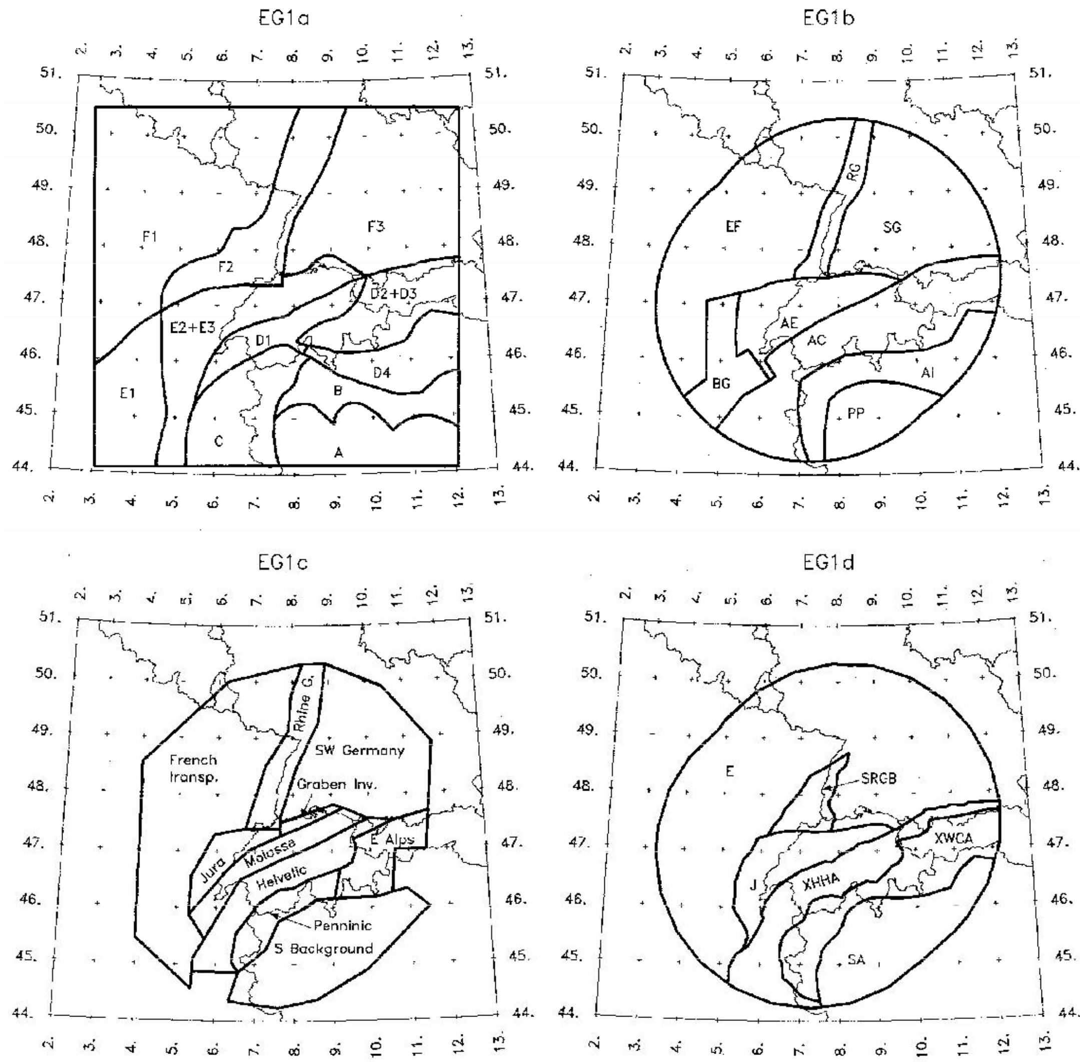

Fig. 2. Comparison of the primary seismotectonic regions developed by the 4 SP1 expert groups (PEGASOS 2004)

GROUNDMOTION CHARACTERIZATION

The task of SP2 experts was to develop ground motion models for horizontal and vertical response spectral values at 5% of critical damping as a function of earthquake magnitude, site to source distant and style of faulting. The models were required to be applicable to a reference rock site condition in Switzerland. The project specified that the expert models be based on moment magnitude and had to be consisted with the seismic source characterization.

The horizontal component models had been developed for median spectral accelerations and the aleatory variability (standard deviation) of $\log_{10}$ acceleration. The horizontal component is defined as the geometric mean of the two horizontal components. For the vertical component, models for H/V ratio and maximum vertical spectral acceleration but not for the aleatory variability had to be developed. To avoid extrapolation of statistical distributions, one also had to set limits to the distribution.

The 5 experts were provided with strong motion data containing European strong motion data and an extensive list of existing attenuation relationships (empirical attenuation relationships, numerical simulation based ground motion prediction equations.). The data base was available to derive new attenuation relationships if desired. The experts decided to use existing models with one exception of a stochastic point source model based on Swiss data. The candidate models used and the selection of the individual experts are shown in Table 1.

In 2 workshops the experts reviewed the potential alternative approaches for ground motion characterization. Based on the discussion in workshop 2, the experts prepared their models to be presented in the individual expert elicitation interviews. In workshop 3, the experts presented their models to the other and the initial models were compared. In the following workshop the following topics were discussed: interaction between subprojects, revised models and hazard sensitivity studies.

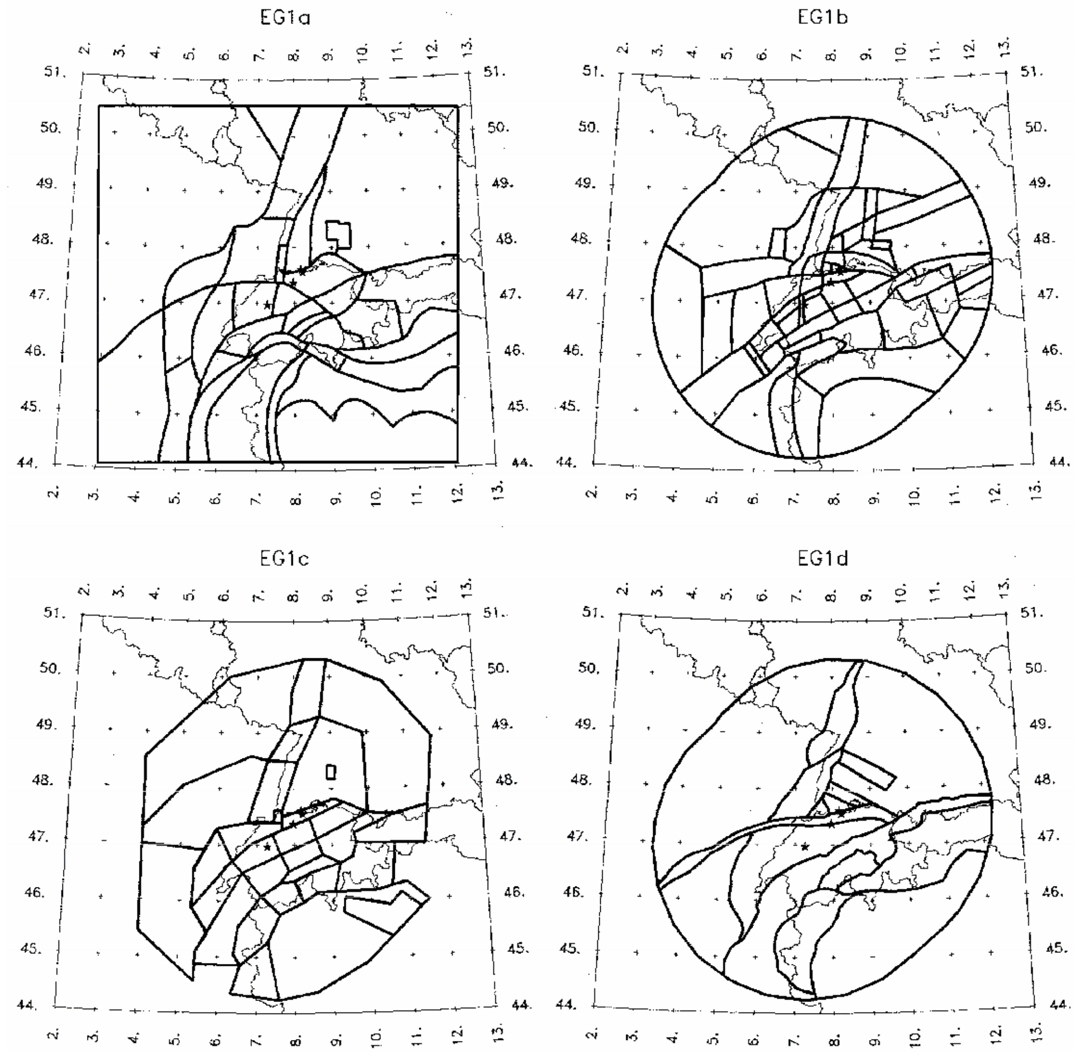

Fig. 3. Comparison of the most detailed seismic source definitions developed by the 4 SP1 expert teams (PEGASOS 2004)

Table 1. Candidate models included in the expert models for the median ground motion (PEGASOS 2004)

Model	Bo	Bu	Co	Sa	Sh
Empirical					
Abrahamson & Silva (1997)	x		x	x	x
Ambraseys et al. (1996)	x	x	x	x	x
Ambraseys & Douglas (2000)	x		x		
Berge-Thierry et al. (2000)	x	x	x	x	x
Boore et al. (1997)	x		x		
Campbell & Bozorgnia (2003)	x	x	x		
Lussou et al. (2001)	x		x	x	x
Sabetta & Pugliese (1996)	x	x	x	x	
Spudich eta al (1999)	x	x	x	x	x
Numerical simulations					
Atkinson & Boore (1997)	x		x		
Sommerville et al (2001)	x	x	x	x	x
Toro eta al. (1997)	x	x	x		
Swiss specific stochastic model					
Bay (2002)			x	x	
Rietbrock (2002)		x	x		

The median spectra for magnitude 6 at a distance of 10 km are compared in Fig. 4. This figure also compares the Boore et al. (1997) for a site with a shear wave velocity $v_{s,30}$ of 2000 m/s. The average of the 5 experts is similar to the Boore model indicating that the median model is similar to California for hard rock. This similarity with the Boore model results because the expert models do not have Swiss specific effects for the source. Swiss specific effects due to wave propagation are stronger but they are only apparent at large distances that do not contribute significantly to the hazard.

Figure 5 shows that the epistemic uncertainty in the median horizontal ground motion is large. This large epistemic uncertainty is an important feature of the ground motion models and has a large impact on the sensitivity to upper fractiles of the ground motion models.

The mean V/H ratios from the 5 expert models for magnitude 6 earthquakes at the distance of 10 km are compared in Fig. 6. The median V/H ratio has greater range in values between the experts than the median horizontal spectra shown in Fig. 4.

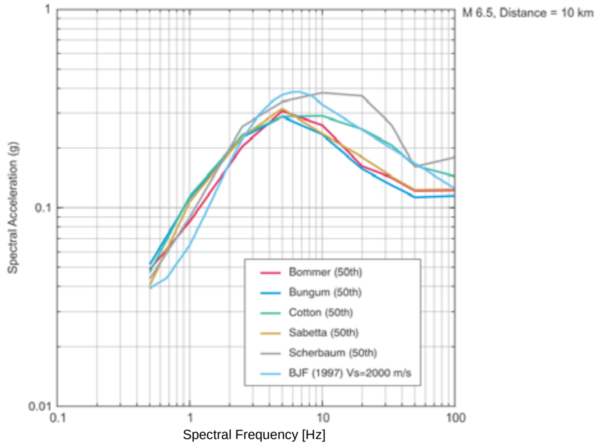

Fig. 4. Comparison of the 50th fractile of the median spectral acceleration for a magnitude 6.5 earthquake at JB distance of 10 km and a strike-slip mechanism, the Bore Joyner Fumal median is also shown for comparison (PEGASOS 2004).

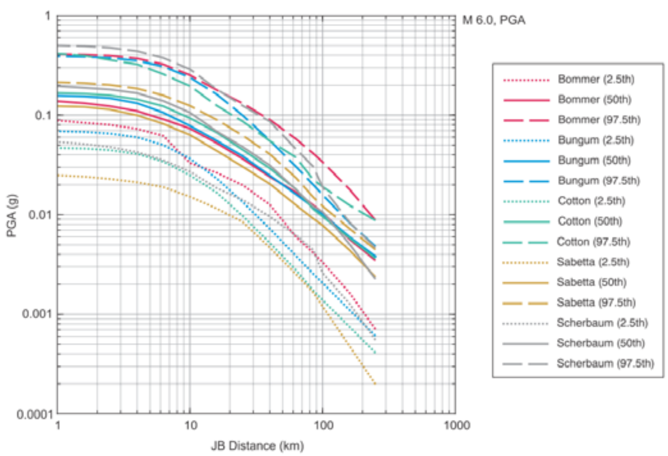

Fig. 5. Comparison of the epistemic uncertainty of the median peak acceleration for magnitude 6.0 earthquake and normal mechanism (PEGASOS 2004).

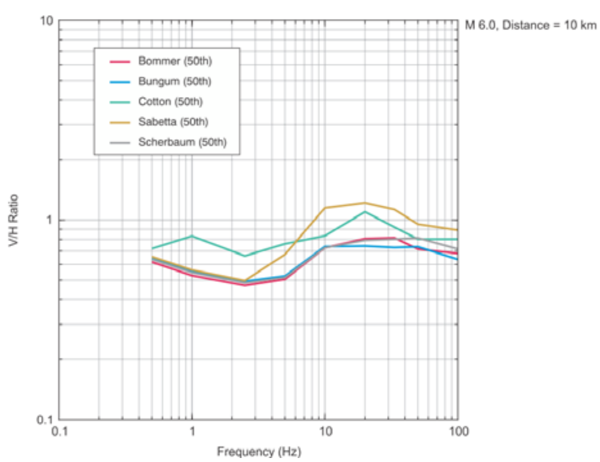

Fig. 6. Comparison of the 50th fractile of the median V/H ratio for magnitude 6.0 earthquake at a distance of 10 km and normal mechanism (PEGASOS 2004).

SITE RESPONSE CHARACTERIZATION

Site response effects were addressed in terms of response spectral amplification models at 5 % of critical damping. Input motion corresponds to a free surface ground motion. Computational models taken into account were 1-D equivalent linear site calculations (SHAKE, RVT), 1-D true non linear site effects calculations, 1-D site effects calculation including effects due to oblique wave incidents and 2 D–site effects computation.

The site studies were primary based on the original geotechnical data of the period of the reactor constructions between late 60’s to the early 80’s. The static test results were considered to be reliable, whereas the dynamic test results were considered for 2 sites acceptable and for the other 2 sites as questionable. Therefore for only one site, a site specific model was used whereas for the other sites G modulus and damping as function of shear strain published data were used. To get v_s profiles and fundamental eigenfrequencies of the overburden layer, ambient vibration measurements were used and SASW measurements were used to check older crosshole data.

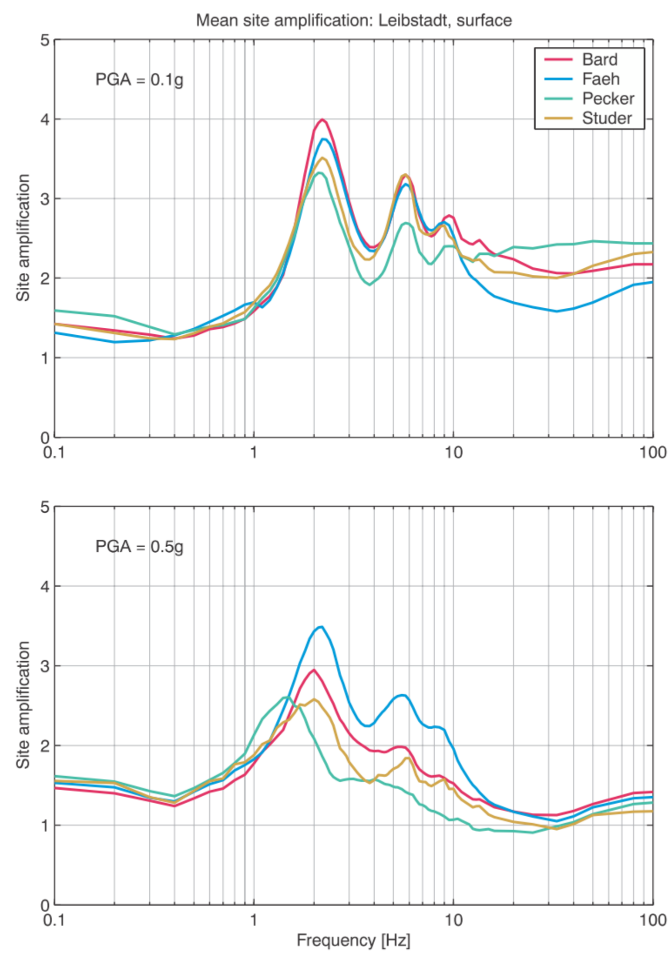

Fig. 7. Mean values of the median amplification function for the surface at the site of Leibstadt for the 4 experts: low and high levels of excitation (PGA of 0.1 and 0.5 g on rock, respectively), magnitude 6 (PEGASOS 2004).

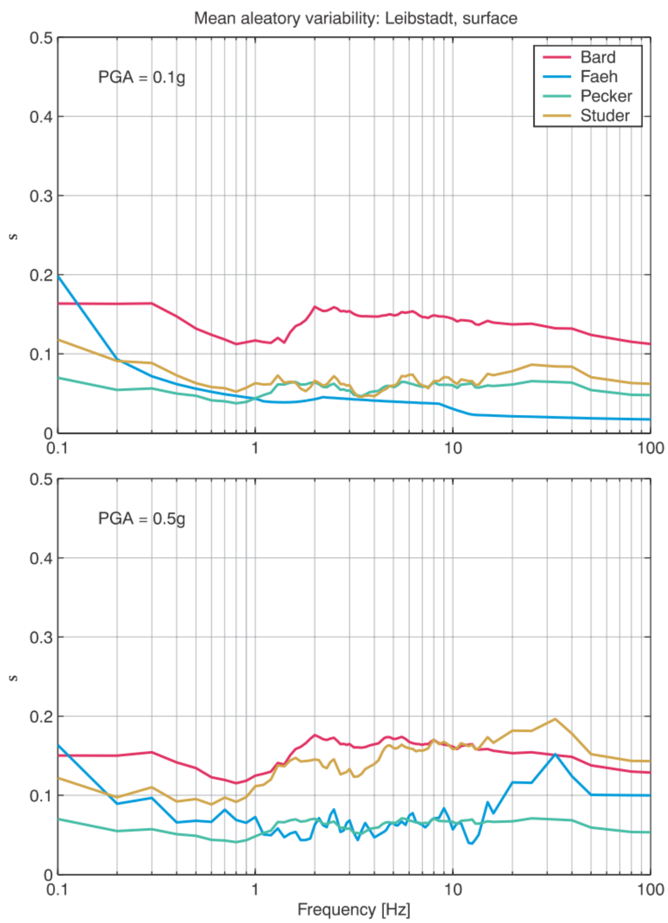

Fig. 8. Mean aleatory variabilities of the amplification function for the surface at the site of Leibstadt for the 4 experts: low and high levels of excitation (PGA of 0.1 and 0.5 g on rock, respectively), magnitude 6 (PEGASOS 2004).

Figure 7 shows the comparison of the results from the 4 experts of the mean amplification function at the surface for one site for low and medium peak ground acceleration. The differences are astonishing small in view of the very different experts models used. The hierarchy of amplification values between experts varies from site to site.

Figure 8 shows the aleatory variability of the amplification function for the surface at one site for the 4 experts for low and high level of excitation. Here the results of the 4 experts differ considerably in contrast to the results of the transfer functions in Fig. 7.

HAZARD CALCULATION

As already mentioned, every expert provided a model for his assessment weighting the individual assessment parameters in a logic tree. These individual logic trees were assembled to subproject logic trees where every expert was given the same weight. In the next step, the subproject tress were combined to the final calculation scheme, see Fig. 9.

A hazard input document (HID) was developed under the responsibility of the TFI. SP4 prepared the rock hazard input files for the rock hazard software FRISK88MP and soil hazard input files for the soil hazard calculation software SOILHAZP.

Under no circumstances, SP4 was allowed to interpret incomplete HID and take a decision on how to fill the gap. Clarification had to be done by the TFIs in cooperation with the individual experts. Several times, the software had to be modified to accommodate unforeseen expert model parameterization.

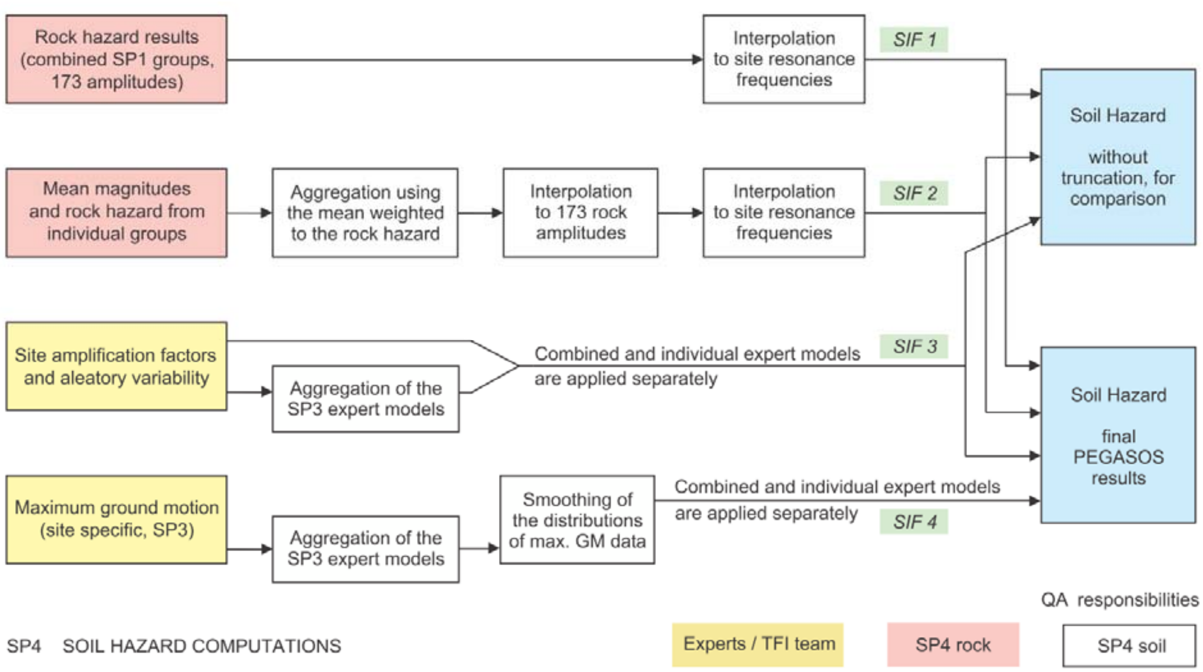

Fig. 9. Soil hazard computation scheme (PEGASOS 2004)

Figure 9 shows the generation of input files from rock hazard results (red) and SP3 soil amplification factors (yellow). The input to soil hazard computation consists of 4 sets soil hazard input files (SIF) (green labels). Soil hazard computations (blue) are performed with and without truncation of large amplitudes (SIF 4).

Computational considerations made it necessary for SP4 to introduce pinch points when computing the total seismic hazard. This reduction of the total number of branches, called algorithmic pinching, is considered to be an algorithmic decision within the technical expertise of SP4 analysts.

HAZARD RESULTS

An example of the final mean hazard curve for one NPP site is shown in Fig. 10 for rock surface and Fig. 11 for soil surface. The epistemic uncertainty is over the whole frequency range very high. It reflects the uncertainty about the parameters associated with the moderate magnitude earthquakes in this part of Europe. The epistemic uncertainty is larger at low frequencies, where the hazard is more sensitive to M_{max} of stronger distance earthquakes.

SENSITIVITY STUDIES

Extensive sensitivity studies have been performed. Their results showed that the ground motion models contribute more to the rock hazard uncertainty than the uncertainty in the source model. The next important contributor to uncertainties is the uncertainty in the site response and the uncertainty in the source characterization.

Due to the significant uncertainties resulted in the project PEGASOS, "swissnuclear" decided in agreement with ENSI to improve the data base in a new project, called "Pegasos Refinement Project - PRP" with the aim to potentially reduces the uncertainties. The project focus on improvement of ground motion models, improvement of site characterization based on new seismic and geological / geotechnical field and laboratory investigations and deepened studies on the interfaces between the subprojects to avoid double counting of uncertainties.

CONCLUSIONS AND LESSONS LEARNED

The following conclusions are the personal opinion of the author.

<u>General</u>

- Modern PSHA state of art requires assessing information on the uncertainties to be encountered. This is, already at least partly, accepted in PSHA for NPPs but still not standard for PSHA in other fields like large dams and hazardous chemical industries.

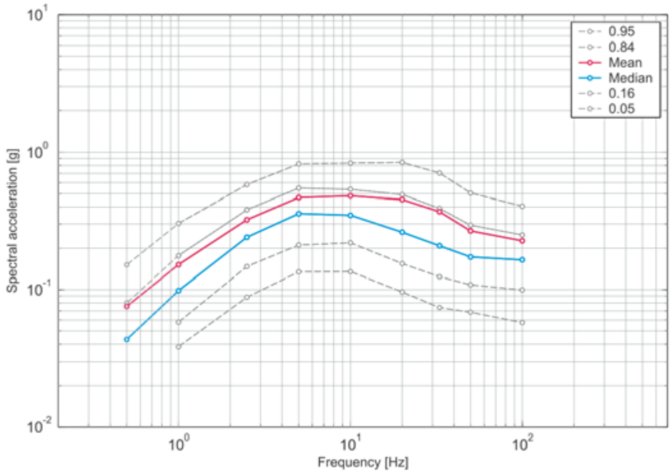

Fig. 10. Gösgen, horizontal component, rock, surface, uniform hazard spectra for an annual probability of exceedance of 10^{-4} and 5% damping (PEGASOS 2004).

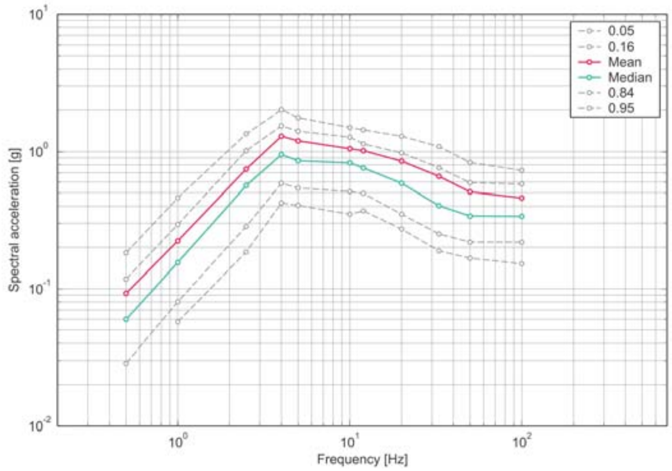

Fig. 11. Gösgen, horizontal component, soil, surface, uniform hazard spectra for an annual probability of exceedance of 10^{-4} and 5% damping (PEGASOS 2004).

- SSHAC-level 4 certainly provides the best representation of the so called "informed technical community and gives therefore the best representation of potential certainties to be encountered. But one must keep in mind that it also involves the biggest efforts in technical and scientific skills as well in time and costs. For very long return periods and high accelerations, data and experience are rare and therefore such a project needs also significant research efforts.

  Even in areas with a relatively good database like in Switzerland, such a study sums up to review an existing site to several millions US Dollar. For a new site, up to 10 Mio USD can result. In Switzerland, the 4 NPP sites were at medium distance to each other thus significant synergies could be used.

- Therefore, for practical reasons the level 4 will only be suitable mainly for assessment of critical infrastructure with an extreme high damage potential in case of an earthquake and projects, which are political controversial, e.g. NPPs and nuclear waste repositories.

- Important for the acceptance of the results of the PSHA by the utilities is to provide an information / training program for utility personnel. Such a program should give information on methods and processes used in the PSHA and the interpretation of the results.

Management

- The success of a level 4 study depends strongly on the ability of guidance of the TFIs. They have to assure that all relevant topics are addressed without influencing experts in their evaluation.
- Due to the fact that the process is expert driven in data procurement, data evaluation and interpretation and methods used it is challenging to keep the budget (even a high budget) and time constraint without restricting to much the work of the experts.
- The careful selection of the experts is crucial. They have to be evaluator and not proponent of their own ideas and have to represent a part of the so called "informed community." Ideally, they should already have experience in PSHA input preparation and process.

Technical

- To get information on uncertainties, long recurrence intervals for earthquakes and high accelerations and magnitudes have to be taken into account. It is therefore important to impose physically realistic boundaries on extreme values to eliminate unrealistic branches in the logic tree.
- Special care has to be given to interfaces between subprojects to avoid double counting of uncertainties.
- Existing data have to be reviewed, if they comply with modern techniques. Some new investigations in general will be needed for reviewing existing sites, particularly, seismic v_s-profiles and geological / geotechnical investigations.

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