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Consistent Reliability between Siting & Design: Requirements on Hazard Accuracy

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ABSTRACT: The lecture presents the requirements on hazard accuracy required for siting of new nuclear facilities taking into account design as well as risk-informed considerations. The requirements are derived from the perspective of a potential licensee of a new nuclear facility and of a current operator of a nuclear power plant. Based on these requirements a critical review of the currently in use methodologies of seismic hazard analysis is performed covering both probabilistic methods (PSHA – Probabilistic Seismic Hazard Analysis) as well as deterministic (DSHA- Deterministic Seismic Hazard Analysis) methods based on examples at their most elaborate state (the Swiss Project PEGASOS based on SSHAC – level 4 procedures as example for PSHA) and MCE (maximum credible earthquake) approach as example for DSHA. A formal procedure is described to develop a site-specific seismic hazard for design purposes. A computational case study is presented for an existing site of a critical infrastructure in a low to moderate seismic area, demonstrating the advantages of the proposed methodology.

1 INTRODUCTION

After a long period of stagnation the construction of nuclear power plants became feasible again both in the USA as well as in Europe. In many IAEA member states the question of a final repository for high-active radioactive waste is still unresolved or currently under consideration. Both the construction of new nuclear power plants as well as of storage facilities require a detailed seismic hazard analysis to assure a proper design of the new constructions. Additionally an increasing quest for a realistic seismic hazard analysis is caused by risk-informed applications requiring the development of a seismic PRA for existing nuclear power plants. Seismic hazard re-evaluations have also been performed for nuclear power plants in the new member states of the European union, many of them not being designed against large seismic loads originally.

A variety of different methods for performing seismic hazard analysis is available. The large quake in Sumatra from 26th December 2004 is stressing the importance of a robust basis for the seismic design of critical infrastructures, competing with the requirement of a cost-effective design of new structures. This lecture presents the requirements on hazard accuracy required for siting of new nuclear facilities taking into account design as well as risk-informed considerations. The requirements are derived from the perspective of a potential licensee of a new nuclear facility and of a current operator of a nuclear power plant. Based on these requirements a critical review of the currently in use methodologies of seismic hazard analysis is performed covering both probabilistic methods (PSHA – Probabilistic Seismic Hazard Analysis) as well as deterministic seismic hazard (DSHA) methods based on examples at their most elaborate state. As an example of a sophisticated PSHA the recently performed Swiss research project PEGASOS (PEGASOS, 2004) based on SSHAC – level 4 procedures (SSHAC, 1997) will be used. As an example for a modern DSHA approach the MCE (maximum credible earthquake) methodology will be used also in its most elaborate way as f. e. outlined by Mualchin (Mualchin, 2004) and Krinitzsky (Krinitzsky, 2004).

Based on this review a formal procedure is described to develop a site-specific seismic hazard for design purposes. A computational case study is performed for a potential site of a critical infrastructure in a low to moderate seismic area demonstrating the advantages of the proposed methodology, taking the site conditions of the Goesgen plant as an example.

2 REQUIREMENTS TO A RELIABLE SEISMIC HAZARD ANALYSIS AND REVIEW OF PSHA AND DSHA METHODOLOGIES

2.1 *Overview on requirements*

From the perspective of a user of the results of a seismic hazard analysis the following general requirements to the analysis can be formulated:

1 Requirement of conservative realism

The results of a seismic hazard analysis shall be realistic and reflect the specific site conditions both with respect to seismic activity as well as to site ground conditions. An overly conservatism shall be avoided taking into account the whole chain of design calculations. Safety margins will be introduced in the design be using appropriate computational methods and safety factors (importance factors) if appropriate.

2 Requirement of validation of results

The results of a seismic hazard analysis shall be validated as far as possible. This may require the development of a special validation procedure including benchmark tests, which can be judged by engineering common sense.

3 Requirement of robustness or time-invariance

The results of a seismic hazard analysis shall be robust, meaning that they shall not be due to change during the design life of the infrastructure of concern. A consequence of this requirement is, that different methodologies for seismic hazard analysis may have to be used for infrastructures with different lifetime.

4 Requirement of the minimization of interface issues between seismic hazard analysis and the intended use of the results

The results of a seismic hazard analysis shall be presented in a format which is directly applicable for the intended use – design analysis or seismic PRA. Typically this means that the output of a seismic hazard analysis shall be presented in the format of the required input parameters of the later design or PRA analysis.

5 Requirement of tracebility and logical consistency

The assumptions used at different steps of the seismic hazard analysis shall be traceable for the final user and logically consistent. This requirement includes also the requirement of mathematically consistency in the meaning that the mathematical models used shall correspond to the observed behavior of earthquake occurrences in nature. The used mathematical assumptions themselves shall be interconsistent. The mathematical methodology as a whole shall possess the property of mathematical convergence in the sense of assuring stable results.

In addition to these requirements the principle of simplicity of analysis shall be applied as far as possible. Practical experience has shown that simplicity and error proneness of the analysis are closely tight properties.

2.2 *Requirement of conservative realism*

To assure compliance with this requirement the context with the intended application of the results shall be observed. The design of new critical infrastructures is the most important application and will be looked at in more detail.

2.2.1 *Current design practice for nuclear facilities*

Up to now in most countries safety critical nuclear facilities (f. e. buildings housing equipment required for the safe shutdown of a nuclear power plant, reactor containments, critical storage facilities etc.) have been designed using linear-elastic dynamic models with some limited damping and using guaranteed minimal material parameters. The time-histories required for the dynamic analysis were developed artificially from normalized seismic design spectra using an enveloping spectral shape anchored a defined level of pga by using spectral matching methods. The generic spectral shape was derived from engineering experience reflected in recordings of historical earthquakes. Usually a rather broad-banded spectrum for pseudo-spectral accelerations for a specified damping was applied, derived by methods like proposed by Newmark & Hall (1982) and/or as included into the corresponding standards f. e. in NRC RG.1.60. At that time most of the instrumental seismic recordings came from a few areas of the world characterized by rather frequent strong-motion events (California, Japan, Turkey, Balkan area in Europe). Rather few recordings for near-site conditions were available at that time, which was compensated by broadening the spectrum towards higher frequencies.

At that time the instrumental pga from earthquake recordings was interpreted by engineers as the relevant anchor (scaling) point of their design spectra. That means that instrumental pga was interpreted as a kind of effective pga (EGA) directly useable for civil engineering design purposes. This approach actually remained unchanged till now. It is challenged today because more and more near-site recordings accompanied by large improvements in seismometry appeared, leading to an incredible increase of measured pga values due to the improved ability to measure single spikes.

Analyzing this design approach the following elements of conservatism can be identified:

1 The use of a broad-banded spectrum.

No single earthquake will challenge the whole spectrum used for the design. It would rather show maximal amplitudes in a smaller range of characteristic frequencies. Therefore in a real earthquake only a part of the plant equipment will be challenged by the maximal accelerations derived from the broad-banded spectrum.

2 The use of linear-elastic models with (limited) damping

This modeling approach typically leads to the use of rather stiff constructions, because it is intended to assure an elastic behavior of the civil works up to rather higher ground accelerations. Yielding is not credited in the design of critical facilities required for safe shutdown of the plant.

This design approach has led to some not very favorable design solutions for anchorage and component fixing points, because ductility demands were not considered in the early designs. Meanwhile many plants have performed modifications to improve the anchorage of components allowing for some ductile behavior of the construction.

The degree of conservatism introduced by this design approach of course depends on the true ductility μ of the construction. For existing designs the ductility is limited by limiting tolerable displacements, which shall not be exceeded to assure the functionality of the equipment, housed by the construction. Nevertheless some structural damage in terms of yielding is tolerable. The safety margin introduced by the use of linear-elastic models can roughly be estimated based on the proposal of Newmark & Hall (1982):

$$R_\mu = \sqrt{(2\mu - 1)} \qquad (1)$$

Here R_μ can be interpreted as an safety factor. Using a typical value for the ductility of a reinforced concrete structure of $\mu = 2.2$, we obtain a safety factor of 1.8 implicitly introduced by the design methodology. Design specific values may deviate and even be higher in dependence on the displacement restrictions applicable.

A similar safety margin is introduced by limiting the damping credited in the design analysis (typically 2% for operational earthquakes and a maximum value of 7% for safe-shutdown earthquakes).

3 The use of minimal material parameters

In design analysis material parameters are used typically which reflect the minimal guaranteed strength of the materials employed. Realistically material parameters deviate into the range of higher strength if proper quality assurance measures were taken during the manufacturing process. During the design stage this safety margin cannot be quantified. Corrections in the calculations are not made at a later stage normally to avoid to much interference with the licensing process (to avoid iterations) even if later available material test results (described in quality assured certificates) show much higher strength parameters. The total safety margin introduced in the current design practice of nuclear facilities can be expressed in a format suggested by Bertero (1989):

$$R = R_\mu R_S R_\xi \qquad (2)$$

where R is the total safety margin expressed as a total load reduction factor, R_μ is the ductility based load reduction factor, R_ξ is the damping related load reduction factor.

The total safety margin introduced by the contemporary design methodology for nuclear facilities can be judged approximately by a comparison to standard civil building codes currently in use in different countries. Such a comparison was provided in Kappos (2002) and is repeated here in table 1.

Table 1 Seismic force reduction factors for high ductility R/C structures (Kappos, 2002).

Code	Symbol	Frame	Structural wall	Frame wall
EUROCODE 8	q	5	4-5	4.5-5
UBC (1997)	R	8.5	4.5-5.5	8.5
NZS 4203	μ	≤ 6	≤ 5	$\leq 5-6$
Japan	$1/D_s$	2.2-3.3	1.8-2.5	2.0-2.9

In addition to these large safety margins the European Utility Requirements for new nuclear power plants require the use of a safety importance factor of 1.4 as a multiplier to the design basis pga derived from a seismic hazard analysis. This approach leads to a minimal safety margin of about a factor of 3 (based on the Japanese practice, assuming minimal ductility) up to maximum values of more than 10 (US-practice) in comparison to the design practice of conventional buildings. It is worth to note, that many design codes are using elastic design spectra derived from seismologic hazard spectra by multiplying them by a factor of 2/3 (for periods of 0.2 and 1 sec, as typical anchor points) (Krawinkler & Miranda, 2004). This can be looked at as a conversion from instrumental spectral accelerations into effective ground accelerations.

With perspective to seismic hazard analysis the large conservatism already introduced by the design methodology means, that the analysis shall be performed as realistically as possible, avoiding the introduction of additional margins for "believed to be real" or "subjectively sensed" uncertainties. The critical questions with respect to the conservatism of any type of seismic hazard analysis are:

- The geometrical characterization of seismic sources especially with respect to the travel path between source and the site of interest
- The characterization of seismic sources with respect to their capability to produce strong earthquakes in terms of the maximum feasible magnitude
- The development of a realistic regionally validated attenuation model or even better of different specific models for each identified seismic source taking into account its specifics. A realistic attenuation model means, that it shall be physically bounded. This can be achieved by comparison of calculated ground motion levels to the strength of natural ("Precarious Rocks", Reiter, 2004, Anderson et al, 2000) or historical landmarks.

A realistic-conservative seismic hazard analysis is characterized by avoiding maximizing the conservatism in all areas of the analysis. Uncertainties shall be considered in the analysis as far as they are supported by empirical data from the area of interest, either by appropriate statistical methods or by robust analysis assumptions (safety factors) but not by both of them at the same time.

2.3 *Requirement of validation of results of seismic hazard analysis*

The validation of the results of a seismic hazard analysis is a mandatory prerequisite before practical application in decision making. The need for the validation of results is even acknowledged by seismologists (Musson, 2004) due to the increasing complexity of the methods and the seemingly increasing amount of uncertainties involved in the analysis. A validation is especially required for probabilistic seismic hazard analysis due to their tremendous complexity and the large amount of subjective assumptions made at each step of the analysis.

On the first glance a validation of the results of a seismic hazard analysis seems to be a very difficult task especially in low seismic areas due to the lack of data. But it shall not be forgotten, that low seismic areas are low seismic areas by human experience and this human experience can be used to validate or to refute the results of a seismic hazard analysis. Klügel (2004) provided a first systematic attempt to validate the results of a complex probabilistic safety analysis (PSHA) based on the SSHAC procedures using a set of benchmark tests. The benchmark tests suggested generally can be classified into the following categories:

1 Tests on seismic activity
2 Tests based on a comparison with historical observed seismic activity
3 Tests on attenuation models
4 Tests based on a comparison with previous seismic hazard analyses for the same area or with an alternative methodology (f.e. DSHA using the MCE approach).
5 Independent analysis of uncertainty propagation and sensitivity studies

All test categories require the availability of at least a simplified seismic hazard code. In many cases the analysis model can be reduced to a Two-source-model modeling the background source surrounding the site of interest and the strongest near-site source known from earlier studies or from the study to be reviewed. For deterministic seismic hazard analysis it is sufficient to perform tests in the categories 2 and 3. A general application of the validation tests methodology can be found in Klügel (2004) and in Klügel & Groen (2004).

Below some general examples for validation tests are given.

2.3.1 *Tests on seismic activity*

Most areas in the world show lower seismic activity than is observed in California or in Japan. On the other side the seismic activity in the later countries is very well documented by instrumental recordings. A typical test consists in performing a simplified probabilistic seismic hazard analysis with a two-source model as mentioned above using the parameters of seismic activity for the South-Californian background source for the near-site source and of the San Andreas fault for the next closest to the site of interest source in conjunction with a well-known (available before the study to be reviewed was performed) empirical attenuation law. A comparison for pga would be sufficient, but care shall be taken, that the site specific conditions (soil class) are matched by the used correlation. Such an analysis can be performed easily with any seismic hazard code available. For European conditions the classical correlation of Ambraseys & Bommer (1991) can be used, which can be assigned to a representative shear wave velocity of 820 m/s. For other soil conditions scaling laws can be used, f. e. using the following correlation which is derived from an proposal of Boore et al (1997):

$$SA_{ref} / SA_{site} = \left(V_{s,30\_ref} / V_{s,30\_site} \right)^{-BV} \quad (3)$$

where $V_{s,30\_ref}$ is the reference shear wave velocity associated with the attenuation law available (here for Ambraseys & Bommer (1991)) and $V_{s,30\_site}$ the reference shear wave velocity of the site of interest. The values for the coefficient BV are given in table 2.

For stiff soil conditions (shear wave velocity between 360 and 760m/s), which are typical for many European sites a synthetic correlation proposed by Klügel (Klügel, 2004) can be used, which is proven to be on the conservative side.

Table 2. Values of BV from Boore et al (1997).

Frequency [Hz]	0.5	1.0	2.5	3.3	5.0	6.7	10.0	pga
BV	0.655	0.698	0.487	0.401	0.292	0.238	0.212	0.371

The parameters for the seismic activity for the San Andreas fault and the South-Californian background source are given in table 3.

Table 3. Parameters of the seismic activity of California

	San Andreas Fault	South California Background Source
Type of equation	Gutenberg-Richter (a, b)	$N = \exp(-M / b)$
Coefficients	a=3.3, b=0.88	b=0.48

If a new (simplified) code is developed, it is recommended to calibrate the code to Californian conditions by performing a calibration analysis using a Californian attenuation law, f. e. Campbell & Bozorgnia (2002). The results of the calibration analysis for a return period of 10000 years should be similar to the design safe shutdown earthquake (SSE) of Californian nuclear power plants like Diablo Canyon. An adjustment can be performed by adjusting the uncertainty in the distance between source and site of interest to achieve the requested mean hazard.

As a result of the test the mean pga for a return period of 10000 years (for a test performed in terms of a PSHA) shall be compared with the comparable results of the study to be reviewed. If the results of the benchmark test fell below the results of the study it has to be concluded, that the study did not pass the test (for a site in a low to moderate seismic area).

A similar test can be constructed by using directly the rates of earthquakes presented in the de-clustered earthquake catalogues typically used as an input for a PSHA to characterize the seismic sources. These data can be fitted into a general magnitude-frequency relationship of an appropriate shape (even Gutenberg-Richter, if the shape is appropriate and seismic activity is judged to be stable) and shall be used for both sources in the simplified seismic hazard model. This artificially doubles the seismic activity in the area of interest because all reported macro-seismic events are accounted twice. A similar analysis than can be performed and the results once again compared with the results of the study. If the test results fell below the study results, the study once again has to be assessed as not passing the test.

2.3.2 *Tests based on a comparison with historical observed seismic activity*

The idea of such tests is based on a comparison of the results of a PSHA or a DSHA for a given sit with macro-seismic events in the national earthquake catalogue. This comparison shall be performed on an intensity basis (Modified Mercalli) because intensity as a measure of damage contains the information needed for the later use in civil engineering.

In case of a PSHA a return period is to be selected, which is decently well covered by the completeness of the seismic catalogue. For European conditions (Mediterranean or Central European conditions) this return period can be selected to be 1000 years referring to a statistical confidence (for a Poisson process) of about 89% of observing the related seismic event. The pga from the study to be reviewed can be converted into the intensity scale by using the correlation of Murphy & O'Brian (1977):

$$\log(pga) = 0.25 I_s + 0.25 \quad (4)$$

where the pga is given in cm^2/s. If the resulting site intensity I_s (some limited attenuation shall be credited from the epicentre to the site surface) was never observed, it shall be concluded, that the study did not pass the validation test. Attention shall be paid, that correlation (4) has to be related to a pga frequency of 33 Hz as it corresponded to the measurement limitations of the early seventies in the last century.

The comparison with historically observed macro-seismic events can be extended by the use of maps showing isoseismals derived from historical events. This information can be used to assess the historically observed peak ground accelerations directly, using once again correlation (4). By using boot strap techniques (Castillo et al, 2005, Noubary, 2000) it is possible to evaluate the limiting distribution of observed intensities (therefore they have to be split off to obtain decimal numbers) and subsequently the limiting distribution for the maximal peak ground accelerations leading to structural damage based on historical data. If these pga values are much lower than the evaluated mean values in the analysis, the study to be reviewed has not passed the benchmark test.

2.3.3 *Tests on attenuation models*

The use of reasonably validated attenuation models is a key question for both PSHA as well as deterministic seismic hazard analysis. Analysis performed by different authors with respect to empirical attenuation laws showed large differences between the different correlations. An interesting observation is, that American correlations (mostly from California) show much higher peak ground accelerations starting from a distance of about 10 km than most of the available European correlations like Ambraseys & Bommer (1991, 1995) or Schwarz & Ende (2004). This can be illustrated by figures 1 to 2.

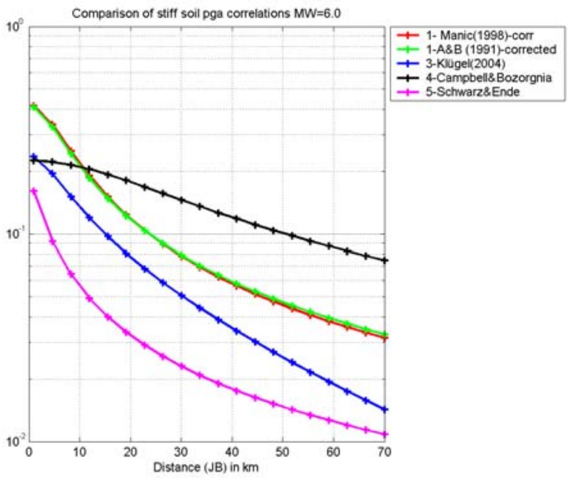

Figure 1. Comparison of attenuation laws, M_w=6.0

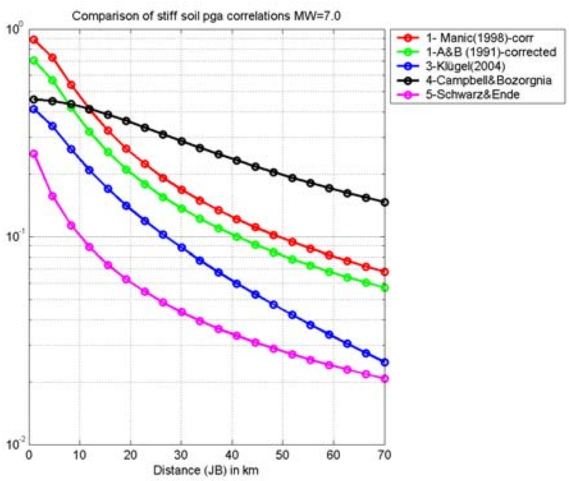

Figure 2. Comparison of attenuation laws, M_w=7.0

A similar picture will occur if we compare the spectra.

It shall be noted, that in the PEGASOS-project (PEGASOS, 2004) the correlation of Campbell-Bozorgnia got a very high rating by most of the experts for the distance range below 10 km and up to 60 km.

The correlation of Klügel (Klügel 2004) is a synthetic weighted model, which was developed to study uncertainty propagation and the information loss observed by statistically weighting earthquake recordings from different area. It also included the Campbell & Bozorgnia (2002) equation in the data sampling process to build a meaningful replica model for the attenuation models used in PEGASOS.

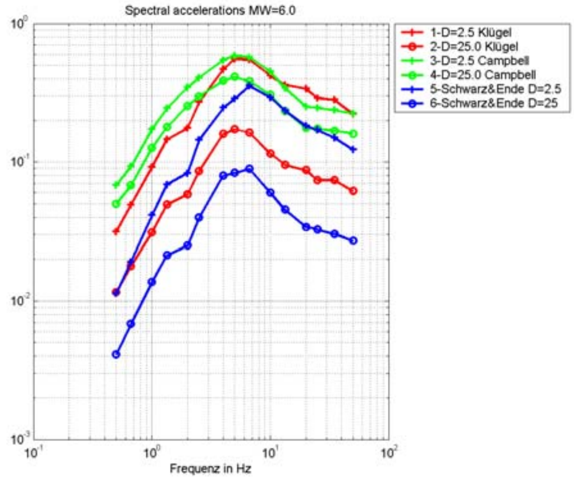

Figure 3. Comparison of attenuation laws, M_w=6.0. Spectra for Joyner-Boore-Distances of 2.5 and 25 km.

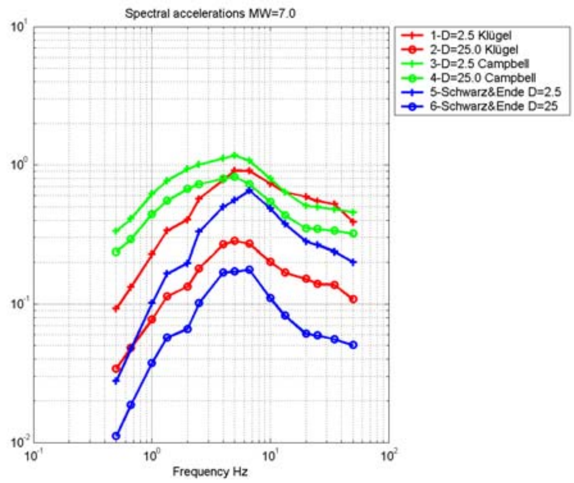

Figure 4. Comparison of attenuation laws, Mw=7.0. Spectra for Joyner-Boore-Distances of 2.5 and 25 km.

The correlation of Schwarz & Ende (2004) is a new correlation, which has the advantage of being developed purely on regional grounds.

The question for the reasons of the observed behavior arises. One of the possible explanations is the large amount of data from different areas, different measurement conditions and different wave travel path and site conditions used for the development of these correlations, which was interpreted as inherent random variability of earthquake occurrence. In fact the empirical correlations derived statistically represented the mean of a large amount of attenuation characteristics from different areas. The standard deviation associated with these empirical laws mainly reflects the variability of measurement conditions and cannot be used as a direct measure of the "inherent" randomness of earthquake occurrences or "aleatory uncertainty" as some seismologists want to make believe the final user of their analyses. The situation will get even worse, if in the framework of a PSHA following the SSHAC procedures (PEGASOS, 2004) the attempt is made to develop a weighted attenuation model by combining different attenuation models assigning weighting factors based on a purely subjective judgment. The result will be a weighted mean of a "mean of medians" (under some circumstances even of means, care shall be taken in which format the regression was performed) leading to an unjustified increase of the uncertainties in the final hazard results, which more correctly shall be called a systematic bias rather than uncertainty. Such approaches only succeeded in practical applications, as long as no measure for the correctness of the used attenuation laws was available. Meanwhile different approaches have been developed to test attenuation laws against physical data. One approach consists in the comparison of the developed attenuation laws with the strength of natural landmarks which survived without damage in areas of high seismic activity. An example of this approach is the theory of "precarious rocks" which is based on a comparison of the toppling ground motion of rocks in the Mojave desert near the San Andreas fault with the results of existing attenuation laws (Brune, 1999, Anderson et al, 2001, Reiter, 2004). This approach effectively leads to some "peak damping" of the results, because it is very reasonable to assume (and rather easy to show computationally) that single "spike" instrument values at high frequencies recorded by strong motion devices, will not topple a massive standing rock. Meanwhile even some authors of attenuation laws which have been in use for a long time in the USA, admitted, that the currently ongoing work on the recalibration of attenuation laws may lead to a reduction of the peak ground accelerations of a factor of 2 in the high magnitude area (>7.0) and of a factor of about 1.5 in the moderate magnitude area for buried earthquakes (Abrahamson, 2004).

A similar approach is based on a comparison of attenuation laws with historical landmarks which survived a long time period including some historically observed strong earthquakes. This can be a very promising approach in seismic active countries with a long history of civilization like for the Mediterranean region (Stucchi, 2004). Nevertheless attention shall be paid to the question of the regional validation of the attenuation laws used for a site-specific seismic hazard analysis. A method for the regional validation of empirical attenuation laws will be given below as a part of the methodology to develop a site specific seismic hazard for design purpose.

Simple validation tests can be performed on the basis of a comparison of the used attenuation law with seismic recordings at the site of interest even using information from weaker earthquakes preferable from the near field. The near field is especially important for existing critical infrastructures in low seismic areas because the seismic hazard for these structures is often dominated by near site earthquakes because they were frequently not considered in the original design.

Schwarz & Ende (2004) have shown that adding strong motion data from the same region to the regression result of recorded data from weak earthquakes does not largely affect the calculated (and magnitude dependent) mean (median in a lognormal interpretation of the regression results) in comparison to a situation where the original data were extrapolated to larger magnitudes. This supports the idea of tests even by using empirical correlations derived from recordings of weaker earthquakes.

A successful test would result in a similar spectral shape resulting from the used attenuation model as from recorded earthquakes. The calculated median values of the spectral ordinates of the used attenuation law shall fall in the range of $\mu + 0.5\sigma$ of the recorded spectra to pass the test.

2.3.4 *Tests based on a comparison with earlier seismic hazard analysis for the same area or a comparison with an alternate methodology*

Such tests are meaningful in case of the re-evaluation of the seismic hazard for an existing critical infrastructure. Sometimes they can also be useful for siting of a new nuclear facility if an independent source of information is available. This can be the case if the siting analysis is performed by an engineering company or by a group of experts (in case of a PSHA following the SSHAC-procedures) and independent information f. e. provided by the national seismological service is available. Sometimes reasonably high developed seismic hazard maps (scenario based or probabilistic ones up to a return period of 10'000 years) are available for comparison.

Such a comparison has been performed for Swiss conditions after the release of the preliminary results of the PEGASOS project (PEGASOS, 2004), although the maps developed by the Swiss seismological service are not completely independent from the PEGASOS-project due to the heavy involvement of experts from the Swiss seismological service into the PEGASOS project.

Figure 5 shows a comparison between the 5Hz seismic hazard curves developed by the Swiss seismological service in 2003 and in 2004 (as a trial to adjust the hazard maps to the PEGASOS results) for rock related to the site of the nuclear power plant Beznau with the preliminary PEGASOS results. Figure 6 is a reproduction of the actual Swiss seismic hazard map published at the internet site of the Swiss seismological service illustrating that the sites of Swiss nuclear power plants are located in the low seismic parts of Switzerland.

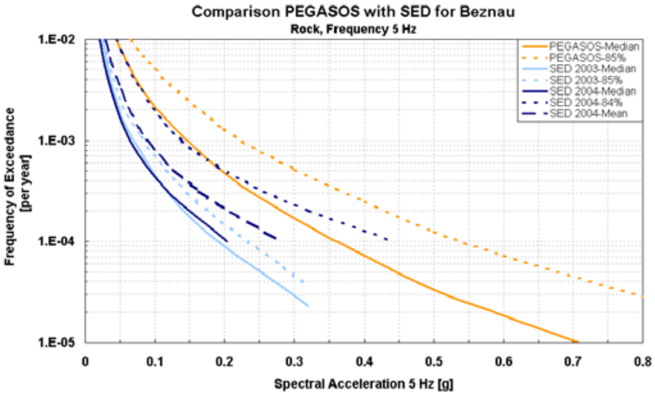

Figure 5. Comparison of preliminary PEGASOS results with hazard maps of the Swiss Seismological Service (SED).

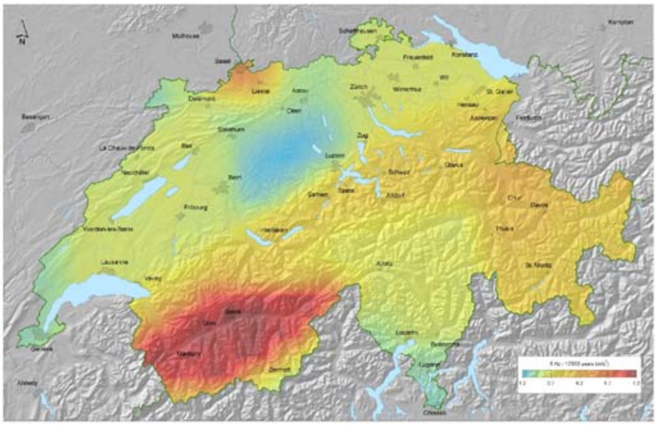

Figure 6. Swiss Seismic Hazard Map (Swiss Seismological Service (SED), 2004), rock, 5Hz, 5%-damping.

Similarly a comparison with an scenario-based seismic hazard map or an earlier deterministic analysis can be performed. If the differences between earlier analysis and the study under review are small or can be explained by new technical information the test can be considered as passed.

2.3.5 *Independent analysis of uncertainty propagation and sensitivity studies*

This task is especially important for a review of a PSHA involving expert judgment. The available experience of the review of a large scale PSHA following the SSHAC procedures (PEGASOS, 2004) has shown that there is a large danger of misinterpreting sources of uncertainties by the involved scientists, as long as the final results are not calibrated against real physical data (Klügel, 2004). The consequence of this misinterpretation is the accumulation of errors during the process of the study. For a modern PSHA based on logic (or event) trees this problem has a sound mathematical background, which shall be explained taking the PEGASOS project as an example.

This PSHA was performed as a research project sponsored by the Swiss NPP utilities to improve the assessment of seismic risk in support of the plant-specific seismic PRAs. The experience of seismic PRAs in Switzerland had shown the importance of a realistic seismic hazard definition for the final results of such a study (Klügel et al, 2004). This can be illustrated using the results of the Goesgen seismic PRA obtained before the start of the PEGASOS project. Figure 7 shows the hazard curves used for the study, which are according to the understanding of contemporary proponents of the SSHAC-procedures not diffuse enough, thus not uncertain enough and figure 8 shows the obtained results in terms of the distribution of the core damage frequency. The empirical error factor (95% fractile / median) of the resulting distribution is almost 100 and mostly driven by the uncertainty in the hazard.

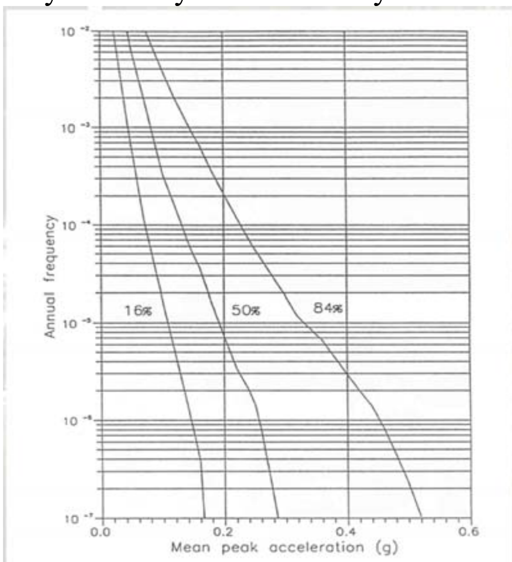

Figure 7. Hazard curves used for the Goesgen seismic PRA study 2001.

It is obvious that a practical, risk informed decision making is not possible with this amount of uncertainties.

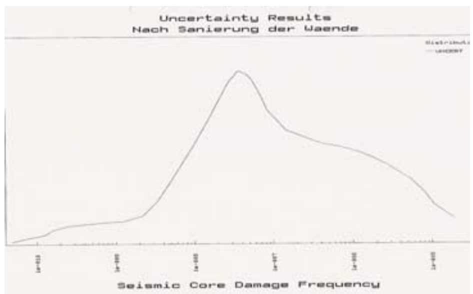

Figure 8. Distribution of the seismic core damage frequency of the Goesgen seismic PRA 2001.

It was also strange to draw the conclusion that the risk of a modern nuclear power plant designed with a high degree of redundancy and diversity of safety systems, possessing f. e. a bunkered safety system, located in a historically known as low to moderate seismic area, shall be driven entirely by the seismic risk contribution (it currently makes up about 75% of the overall risk of the plant) although there is no evidence of an increased seismic activity or new technical information in comparison to the time of the design of the plant. The intention of the Swiss nuclear power plant utilities driving the start of the PEGASOS project was to improve knowledge on seismic risk contributors and to get an improved re-evaluation of the seismic hazard curves.

The PEGASOS project followed the methodology of the SSHAC (1997) procedures for the treatment of uncertainties including the extensive use of experts at its most elaborate way – level 4 – in conjunction with a logic tree methodology for the seismic hazard quantification. A total of 21 well-known seismology experts were nominated as participants in the project from a selection of 101 originally proposed experts. Two other experts, one of them a co-author of the SSHAC procedures, participated in the project as team facilitators for the expert elicitation process. A very strict quality assurance program was established for the project.

For the quantification of the seismic hazard the code FRISK88M® was used, which is qualified by US NRC. Before approval and practical implementation of the results by the final user a detailed review was performed including validation tests similarly as described above (Klügel, 2004). The validation tests performed showed that the preliminary results of the PEGASOS project cannot be explained by the empirical observation of earthquakes in Switzerland with respect to earthquake recurrence frequency and shape of the derived uniform hazard spectrum. A detailed analysis of uncertainty propagation was requested to explain the unexpected, and erroneous outcome of the study.

From an organizational perspective the PEGASOS-project was subdivided into 3 subprojects for source (SP1), ground motion (SP2) and site effect (SP3) characterization, with their respective expert groups and the team facilitators (TFI) and a seismic hazard computation group (subproject 4-SP4). Within the framework of each subproject a group of experts developed their own assessments concerning the identification and the scope of epistemic and aleatory uncertainties directed by the responsible TFI. Following SSHAC-level 4 guidelines the treatment of aleatory and epistemic uncertainties was performed independently assuming that both sources of uncertainties are completely uncoupled. Although the experts were free to include or exclude uncertainties as well as to define the size of uncertainties, some standard set-up was developed, including the typical sources of uncertainties to be considered within each subproject. The general mathematical approach for the overall integration of the results was mainly defined by the software tool (FRISK88M®, assumption of a stationary homogenous Poisson process for earthquake recurrence, use of the truncated Gutenberg-Richter-correlation for magnitude recurrence). Aleatory and epistemic uncertainties were generally treated as parametric uncertainties. Logic trees were used to assign weights to different parametric descriptions of the topics under discussion. The uncertainty distributions for the different parameters (one for epistemic, one for aleatory for each parameter) were treated as discrete probability distributions. To represent the intended distribution a low number of points was used typically, which under certain restrictions for the distribution of the residuals retained the information on the moments of the distribution. In PEGASOS any of the mathematically possible combinations of logic tree branches across the different subprojects was regarded as a physically possible combination. This means that the uncertainty propagation across the project for epistemic and aleatory uncertainties was based on the assumption of a complete uncoupled behavior of the different types of uncertainties associated with the process of seismic motion propagation. This assumption is unfortunately not generally justified by the physical nature of the processes. For instance, it is known that recorded site ground motions at soil sites can be lower than at rock sites for the same distance between site and source (McGuire et al, 2001). The propagation of the uncertainties through the PEGASOS-logic trees used in the analysis can be represented in the following general form:

$$H(f) = \sum_{i=1}^{k^{n-1}} \prod_{j=1}^{n} w_{ij} F(f, w_{ij}) \qquad (5)$$

where $H(f)$ is the hazard level (on-site spectral acceleration) for a given frequency of exceedance and a random variable, k is the maximum number of possible states at a single branch in the logic tree (multistate branches), w_{ij} is the weighting factor used at branch j - a random parameter derived from the expert evaluations for branch j , $F(f,w_{ii})$ is the assignment law - assigning an on-site ground motion level (spectral acceleration) to the fixed frequency of exceedance f depending on the values of the random weighting factor w_j which is given implicitly by the seismic hazard model, mainly driven by the attenuation law, n is the number of branches of the combined logic tree. The function $F(f,_{wij})$ can be thought of as an assignment law assuring that the input required in the logic tree for branch j+1 is provided at branch j. Running through the whole tree assures that the requested spectral acceleration corresponding to the fixed frequency of exceedance f and to the set of weighting factors w_{ij} is calculated. Equation (5) shows, that the distribution of the hazard level for a fixed frequency of exceedance depends on the number of branches in the logic tree. It is important to note, that the number of branches is not restricted by the SSHAC-method. Simplifying equation (5) by replacing the non-linear function by its Mac Laurin series representation and neglecting the Lagrange residual of the series approximation we obtain the following equation:

$$H(f) \approx \sum_{i=1}^{k^{n-1}} \prod_{j=1}^{n} \left(w_{ij} \sum_{\nu=0}^{k} w_{ij}^{\nu} \frac{F^{(\nu)}(f, w_{ij})}{\nu!} \right) \qquad (6)$$

From equations (5,6) it can be seen, that the distribution for the spectral acceleration for a fixed frequency of exceedance can be approximated by a sum of products containing the random weighting factor w_{ii}. It can also be observed that the order of the products containing the weighting factors w_{ji} is higher than the order of the sums, if sufficient terms of the Mac Laurin series are used to replace the assignment law F. Such functions tend to have a limit distribution close to a lognormal rather than a normal distribution as would have been suggested by the central limit theorem (Swain & Guttmann,1983). The shape of the distribution of ground motion parameters derived from a probabilistic seismic hazard analysis for a fixed frequency of exceedance was a topic of a special analysis, which is presented in Klügel & Groen (2004). This analysis confirmed the assumption of a lognormal distribution as reasonably supported based on a performed Andersen Darling test. Equation (5) also shows that with an increasing number of independent uncertain (random) parameters introduced at the branches of the logic tree, the final distribution for the seismic hazard – the distribution of the spectral acceleration for a fixed frequency of exceedance – is getting more and more diffuse. With other words, we obtain the effect, that the larger the number of logic tree branches, the more diffuse the final distribution will be.

This problem is still enlarged by using expert opinion for the quantification of the weighting factors and even worse by using equal weights. The introduction of experts leads systematically to an increase of the number of branches in the associated logic trees, where the total number of artificially added branches is equal the number of independent subprojects into the whole project was subdivided

$$N_{add\_branch} = N_{subproject} \, .$$

In case of PEGASOS there were three different subprojects, so at least 3 additionally branches were added at the starting point of the logic trees of each subproject. The consequence was a large blow-up of the size of the integrated logic tree accompanied by a huge increase of the diffusity of the final results.

Equation (5) is very educative in the sense, that it demonstrates that without setting constraining boundary conditions for the final results of the analysis, a formal mathematical convergence in the sense of a stable distribution is not possible. With other words, we obtain the effect, that the larger the number of logic tree branches, the more diffuse the final distribution will be. To reduce the effects of this poorly constrained behavior on the results it is necessary to reduce the number of random parameters used in the model to the absolutely unavoidable minimum. Unfortunately this leads to some problems associated to the tasks of a TFI (Team Facilitator & Integrator). On one hand he shall elicitate the expert opinion to discover all sources of uncertainties, on the other hand he shall be aware, that uncertainties shall be described by a minimal set of parameters. This conclusion can also be formulated differently – the better the experts tried to discover and to quantify uncertainties following the SSHAC-procedures – the more diffuse the resulting distribution will be.

The review of the preliminary PEGASOS results revealed (Klügel, 2004) that the rule of minimizing the number of random parameters to describe the hazard model was not followed in the PEGASOS project, probably because no attention was paid to this issue in the SSHAC procedures (SSHAC, 1997) themselves (there was one exception, Mr. Bungum in subproject 2, who recognized that earthquake recurrence is not an ergodic stochastic process and therefore the models prescribed in the PEGASOS project themselves are unrealistic leading to large uncertainties. So he found that there wasn't any need to add more sources of uncertainties).

Many sources of reducible uncertainties were discovered in the review of the PEGASOS project and the most important were preliminary quantified. The results of the validation tests and of the analysis of uncertainty propagation indicated, that the preliminary PEGASOS results over estimate the seismic hazard at the sites of Swiss nuclear power plants by a factor between 2 and 3. There is also some concern that the spectral shape of the resulting uniform hazard spectra does not correspond to the deaggregation results of the study themselves. The later is showing controlling earthquakes (actually not associated to known faults, the sources are regarded as undetectable, but of rather high magnitudes up to 6.5, in one case up to 7.1) very close to the site, but the obtained spectral shape corresponded rather to far-field spectra from more distant seismic sources.

It shall be made clear here, that the experts involved in the PEGASOS-project are not to be blamed for this unfortunate outcome of the study. They were "forced" into a project framework, which was following the SSHAC procedures very closely, as was even acknowledged by the regulatory participatory review team in a formal letter.

Problems with the preliminary results of sophisticated PSHA involving expert judgment according the TFI model of SSHAC are not new. The large differences between the EPRI and the Lawrence Livermore studies in the USA have been published in the 80-ies and in the early nineties (Krinitzsky, 1993) and have led to a correction of the Lawrence Livermore study. Nevertheless the US NRC made the decision to use the median curves instead of the mean curves as a basis for both seismic PRA studies as well as for the IPEEE program. Similar problems are now reported in conjunction with the study for the Yucca Mountain project, there also a corrective action program is required (Reiter, 2004).

2.4 *Requirement of robustness and time-invariance*

This requirement is to some extent related to the requirement of realistic conservatism. Some additional aspects will be discussed in the next paragraph in connection with the need to take into account the design lifetime of the structure to be constructed. Practical experience has shown, that the use of PSHA – methods has not led to time-invariant or robust analysis results. A permanent increase of the seismic hazard has been observed combined with an increase of the complexity of the analysis. From a perspective of decision-making, such a tendency is very dangerous, because large variations in the seismic hazard assessment may lead to the complete loss of the investment due to a possible loss of the operational license or to the closure of the plant because larger upgrades are not feasible for economic reasons.

A DSHA in the form of the MCE (maximum credible earthquake)-methodology is in principle time-invariant and open for the implementation of new technical information. It is also far less vulnerable to subjective mathematical speculations and primarily based on data, even if it has to be acknowledged, that expert knowledge is required for the interpretation of the available empirical data.

Some concern may arise that a DSHA-methodology leads to too conservative results. This is not the experience of the author. Just on contrary, it was observed that PSHA-methodology far more resembles a worst case analysis methodology. The question, whether a PSHA at its present state has something in common with a risk-informed seismic hazard analysis will be discussed in chapter 4.

2.5 *Requirement of the minimization of interface issues between seismic hazard analysis and the intended use of the results*

This requirement seems to be very natural in the sense of quality assurance and nobody would expect that it would be violated by any study. Unfortunately the case is not as obvious as it appears at the first glance.

With respect to nuclear installations the following different applications shall be distinguished.

1 Application for the design of new nuclear installations
2 Application for the re-evaluation of the seismic hazard for an existing design due to new technical information
3 Application for a seismic PRA

Within each type of application the following criteria shall be taken into account:

1 Lifetime of the installation

It is a huge difference whether the design lifetime of the installation is 60 to 80 years as for a nuclear power plant or 1’000’000 years as for a final repository of high radioactive waste. For design applications this issue can be resolved by using a time invariant methodology for the seismic hazard analysis.

For a PRA application interested in a realistic risk assessment over the lifetime of the structure this factor is of crucial importance.

2 Engineering parameters used in the structural analysis by engineers

Different engineering parameters are used by engineers to evaluate structural damage. For design purposes they often depend on national regulations. Most standards are still force based. As described above for nuclear installations in most countries dynamic linear-elastic models with limited damping are in use, which differs from standard industrial applications allowing for the use of inelastic design spectra and load reduction factors. The required time-histories (typical a set of different time-histories is used) are developed for the elastic design spectra. It shall be stated here, that there is no need to match historical earthquakes by these time-histories while developing them– anyway the next earthquake will for sure create a different time history when considered in the analysis and the elastic design spectrum used is already an enveloping one. The anchor point (in terms of pseudo-spectral acceleration) used for the rescaling of a generic design spectrum (typically normalized to 1g at a certain frequency – typically 33 Hz) to derive the final design spectrum is still frequently called by engineers peak ground acceleration – pga. The meaning of this term is although completely different from the understanding of a seismologist. In seismology the pga is just a single recorded “spike” instrumental value independent from the related frequency. Such a parameter is completely meaningless for a design analysis. Unfortunately in the current practice seismologists tend to present the results of their studies in terms of instrumental pga due to the lack of communication with the final user of their results.

This problem can be resolved easily by developing results in terms of effective ground accelerations (EGA) as it is suggested now in some standards. EGA is defined as the average spectral acceleration of an elastic uniform hazard spectrum for 5 % damping between 2 and 10 Hz, divided by 2.5 and assigned to a frequency of 33 Hz (period of 0.03 s).

For a finer differentiation of the results (less conservatism) it might be worth to develop two different hazard spectra – one for large distant earthquakes and one for near-site earthquake if they cannot be excluded by site investigations. Such an approach is possible both in terms of a probabilistic seismic hazard analysis as in terms of the more robust deterministic seismic hazard analysis based on the methodology of the maximum credible earthquake.

The use of the EGA instead of pga is also possible if the seismic hazard analysis is performed in terms of epicentral intensities (modified Mercalli). As can be seen from equations (5) and (6) this approach would be the preferable one for a PSHA, because it automatically reduces the amount of random parameters required for the analysis leading to more stable results. Instead of using a set of independent random parameters of

$$\{M, T(f), S_a\} \tag{7}$$

a two-step procedure is used, based **on one independent random parameter the intensity I**, which directly can be converted into EGA f. e. by using equation (4) or by developing a new correlation from the waste amount of historical data available. Using the EGA value, a design spectrum which for example is compatible with the elastic EUROCODE 8 spectrum can be constructed easily (the pga computed from intensities is used as EGA in replacement of the peak ground acceleration for a return period of 475 years a suggested in the code for non-nuclear facilities). Such design spectra for different site intensities I_s are shown in figure 9 for stiff soil conditions and 5% damping.

In dependence of the safety importance of the building of interest an additional safety importance factor can be assigned as required by the European Utilities requirements for new nuclear power plants (a factor of 1.4).

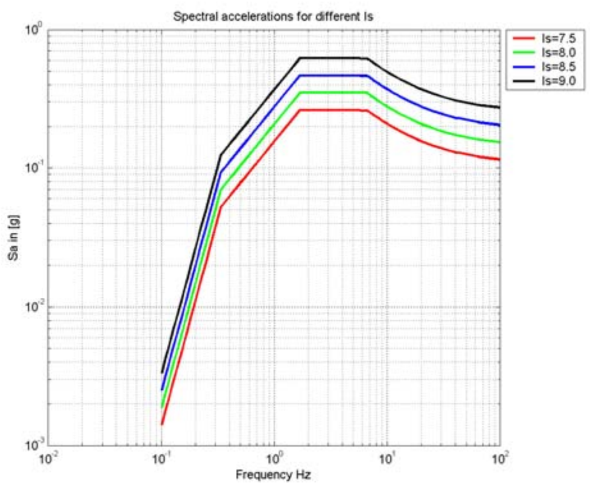

Figure 9. Site-Intensity based Eurocode 8 compatible elastic design spectra for Nuclear Power Plants for 5% damping.

Vertical loads can be derived additionally using available standardized average ratios between the vertical and the horizontal components of an earthquake (usually a factor of 2/3 is appropriate).

In terms of a seismic PRA the question is even much simpler. In most seismic risk studies, which have been performed up to now, the pga is used in a similar sense as described above like an EGA. That means it has been used in the sense of a damage index to calculate fragilities based on a rather crude safety factor approach and a comparison of a median-centered site-specific hazard spectrum to the design spectrum. This methodology is certainly appropriate for rock sites and intentionally conservative for areas with low to moderate seismic activity. For soil sites it would be more appropriate to use spectral averaged fragilities developed for the frequency range between 2 and 10 Hz (instead of 3 to 8 Hz as was used I the US) to achieve compliance with engineering standards. Therefore the results of a risk-informed seismic hazard analysis (this is something different from a PSHA as will be shown below) shall be presented in terms of spectral averaged accelerations although the use of EGA would also be acceptable. The main difference to a design application is that hazard spectra have to be developed for each fault recognized as active or for each seismic source independently. Each seismic source then will be associated with its own set of seismic initiators and fragilities derived on the basis of the site specific spectrum. For a seismic PRA it does not make any sense to use a uniform hazard spectrum as basis for the development of seismic initiating events, because the nuclear installation will for certain be challenged by only one earthquake from one specific site at one point of time. So the development of uniform hazard spectra would be an unnecessary step of the analysis, if the later shall be used for a seismic PRA. The direct use of intensities for a seismic PRA has not been considered seriously and is somewhat complicated due to the interface between hazard analysis and structural engineering calculations, which are force or displacement based. Directly intensity based fragilities are although feasible, at least for buildings.

For an EGA-based PRA it is on the other side important to check the lower level truncation limits of the used fragility curves against information from intensities. So it is rather well known, that an intensity of I=V will not cause any damage to compact industrial buildings, while in some existing PRA studies the corresponding pga of 0.03g is already considered as causing damage with some probability.

2.6 *Requirement of tracebility and logical consistency*

This requirement also seems to be a very natural one. Unfortunately once again the practical fulfillment of this requirement is not so obvious (the author happened to be a certified quality manager). The easier part of this request seems to be the question of tracebility of assumptions and results, because this is mainly a question of documentation. Nevertheless the experience from the PEGASOS-project has shown, that this goal cannot be achieved easily in practice. The problem consists in the response to the question, what information is required to be presented as the study results from the perspective of an external reviewer not involved into the project directly and what information is required for a decision maker and external stakeholders. Here a PSHA is in the very unfortunate situation, that uncertainties and probabilities are very difficult to communicate to decision makers and external stakeholders, while extreme values like the maximum possible earthquakes or fuzzy numbers like credible (attenuation) distances can be communicated easily. After the Sumatra earthquake from December 26th the people are not very interested to learn that such a tsunami occurs once in 700 years, but are much more interested in the question, why it was not considered to develop efficient protection measures, once such event is feasible.

Also from the point of view to hand over information to an independent external reviewer the experience from the latest PSHA can't be characterized as positive. In case of the PEGASOS-project (PEGASOS, 2004) the summary documentation consists of 6 volumes, the total documentation of about 60 Gbyte data files. It is easy to understand that a complete review of this information takes several years. Such a time period is completely inappropriate for any practical decision making with respect to capital investment into nuclear installations (this is actually the idea of selecting a site for a new nuclear installation) which should be based on the review of results of such a study

Concerning the logical consistency of used mathematical and physical assumptions the question with respect to a deterministic seismic hazard analysis methodology (MCE) is rather simple to answer. The methodology starts from a detailed analysis of the area of interest and the associated fault systems. For each observed fault the maximum possible earthquake magnitude is defined based on the fault geometry (length and width) – see figure 10. Attenuation laws are assigned in correspondence to the fault characteristics or established in an intentionally conservative way, preferably based on earthquake recordings from the region. As the characteristic attenuation distance, the distance between the central segment of the fault system to the site is used. Once for all identified faults the maximal feasible magnitude, the attenuation law and the attenuation distance are defined, the resulting spectra for each of the faults and a design basis envelope can be constructed. To assure some conservatism the design ground motion level is anchored at the median plus one standard deviation level ($\mu+\sigma$), where the values are obtained from the corresponding attenuation equations. The use of the $\mu+\sigma$ value is justified by the empirical observation, that most regional attenuation laws describe the free field accelerations of each single earthquake reasonably well within an accuracy of $\pm\sigma$. The use of the $\mu+\sigma$ value shall provide some intended conservatism. In dependence of the safety importance of the structure a safety factor of 1.4 will be used to increase the required design accelerations (Krinitzsky, 2004).

It is obvious, that such a methodology in principle is time invariant besides some new technical information which may be obtained during the future lifetime of the structure.

It is easy to understand that the MCE methodology is very transparent, especially for engineers and decision makers and less complicated to implement then a PSHA following the SSHAC-guidelines. The only point of critics, which in principle is debatable, too, is the possibility of some overly conservatism due to the use of the $\mu+\sigma$ acceleration level, which for a lognormal distribution of the ground motion accelerations corresponds to the 84% fractile and not to the mean. But looking at the whole line of calculations as discussed in paragraph 2.1 and remembering, that this methodology was developed and used in the USA, where the seismic building codes allow for load reduction factors as high as 8.5 it gets understandable, that some additional conservatism at least for critical long-lived infrastructures may be appropriate. So the whole methodology of the maximum credible earthquake, which is extensively used outside the nuclear field for critical infrastructures like bridges and dams is overall logically consistent. The result of a study based on the MCE approach mainly depends on the accuracy of the attenuation laws, which have to be regionally validated.

Looking at contemporary PSHA - methodology with the SSHAC-procedures as reference in mind, we get a different picture. The methodology as currently practiced is entirely based on the so-called ergodic assumption stating that earthquake recurrence can be assumed to be an ergodic stochastic process, typically. Because ergodic stochastic processes converge to be stationary this assumption justifies:

- the use of an homogenous Poisson process (this is a stationary process) to calculate probabilities of exceedance for ground motion levels
- the use of a stationary magnitude-frequency –relation mostly in the shape of an exponentially truncated Gutenberg-Richter-correlation, which reflects the most "chaotic" state of knowledge on seismic activity of a given area, because it corresponds to the maximum of Shannon (information) entropy of the system (Berrill & Davies, 1980)

The ergodic assumption in the form of de Finettis theorem as its Bayesian interpretation has also be used to justify the separation between epistemic uncertainties and aleatory uncertainties in the SSHAC –procedures (SSHAC, 2004).
Even if the ergodic assumption was correct (it is of course not and seismic activity is not stationary just due to the underlying physical mechanisms "creating earthquakes" which are time-dependent!!!, as will be discussed in chapter 3) there would have been some logical inconsistencies in the method. For example it makes no sense to assign parametric uncertainties to the coefficients a and b in the truncated Gutenberg-Richter-Correlation once this equation was selected for magnitude-frequency – recurrence and the coefficients were evaluated based on maximum likelihood estimators. Due to the fact that this equation reflects the maximum entropy or the maximum uncertainty in information about our system – seismic activity – the resulting equation actually has the meaning of **our best estimate of complete lack of knowledge** or of the maximum of uncertainty of our system. It obviously does not make sense to add artificially some parametric uncertainty to a state which already is the best estimate of the maximum of uncertainty.

Unfortunately earthquake recurrence is not an ergodic stochastic process as will be discussed below. This means that the currently practiced PSHA-methodology does not base on a logically consistent and correct mathematical basis.

3 DISCUSSION OF THE ERGODIC ASSUMPTION

The question of ergodicity of the stochastic process of earthquake recurrence is similar important both with respect to formal mathematical convergence as to the question of the separation of epistemic and aleatory uncertainties. The authors of SSHAC (1997) used the de Finetti theorem, which is just a Bayesian interpretation of Kolmogoroffs theorem of the ergodicity of a stochastic process to justify this separation. As already pointed out, the so-called ergodic assumption is also used to justify the transfer of seismic recordings from other areas to the site of interest in case of lack of data (by some assumed similarity of tectonic regimes). The property of ergodicity of a stochastic process is on the other hand a necessary requirement to assure its convergence to a stationary homogenous process as it is used by current PSHA methodology in the form of a stationary homogenous Poisson process. If this property is not fulfilled, the use of a stationary stochastic process for the description of earthquake recurrence is by no means justified. It may be worth to remember some essential terms from the theory of stochastic processes following the excellent presentation of the Bayesian interpretation of the topic given by Gill (Gill, 2002) starting with some general terms. A stochastic process is a consecutive set of random quantities defined on some known state space, Θ, , indexed so that the order is known:

$$\left\{\theta^{[t]} : t \in T\right\} \tag{8}$$

A Markov chain is a stochastic process with the property that any specified state in the series, $\theta^{[t]}$, is dependent only from the previous value of the chain, $\theta^{[t-1]}$. This can be stated more formally:

$$P\left(\theta^{[t]} \in A \middle| \theta^{[0]}, \theta^{[1]}, \ldots, \theta^{[t-2]}, \theta^{[t-1]}\right) = P\left(\theta^{[t]} \in A \middle| \theta^{[t-1]}\right)$$

(9)

So a Markov chain wanders around the state space (here f. e. the space of possible earthquake magnitudes) remembering only where it has been in the last period. A fundamental concern is the transition process that defines the probabilities of moving to other points in the state space, given the current location of the chain. The most convenient way to think about this structure is to define the transition kernel, K, as a general mechanism for describing the probability of moving to some other specified state based on the current chain status. It is required that $K(\theta, A)$ be a defined probability measure for all θ points in the state space to the set. $A \in \Theta$ When the state space is discrete, then K is a matrix mapping, $k \times k$, for k discrete elements in A, where each cell defines the probability of a state transition from the first term to all possible states:

$$P_A(\theta) = \begin{pmatrix} p(\theta_1, \theta_1) & \ldots & p(\theta_k, \theta_1) \\ \vdots & \ddots & \vdots \\ p(\theta_k, \theta_1) & \cdots & p(\theta_k, \theta_k) \end{pmatrix} \tag{10}$$

where the row indicates where the chain is at this period and the column indicates where the chain is going in the next period. When the state space is continuous, then K is a conditional probability density function, $PDF : f\left(\theta \middle| \theta_i\right)$, meaning a properly defined probability statement for all $\theta \in A$, given some current state, θ_i.

An important feature of the transition kernel is that transition probabilities between two selected states for arbitrary numbers of steps m can be calculated multiplicatively. For instance the probability of transitioning from the state, $\theta_i = x$ at time 0 to the state $\theta_j = y$ in exactly m steps is given by the multiplicative series:

$$p^m\left(\theta_i^{[0]}=x,\left|\theta_j^{[m]}=y\right.\right)=\sum_{\theta_1}\sum_{\theta_2}...\sum_{\theta_{m-1}}p\left(\theta_i,\theta_1\right)p\left(\theta_1,\theta_2\right)...p\left(\theta_{m-1},\theta_j\right)$$

(11)

With respect of the application of the theory of stochastic process to seismology the following features are of interest:

- · Homogeneity
- · Irreducibilty
- · Stationarity
- · Recurrence

A Markov chain is said to be homogeneous at step m if the transition probabilities at this step do not depend on the value of m. With other word this means that the transition probability to get from state i to state j for a homogenous Markov chain does not depend on the order how state j was achieved starting from state i:

$$P\left(\theta^{[t]}\in A\left|\theta^{[0]},\theta^{[1]},...,\theta^{[t-2]},\theta^{[t-1]}\right.\right)=P\left(\theta^{[t]}\in A\left|\theta^{[t-1]}\right.\right)=P\left(\theta^{[t]}\right)=P_A\left(\theta\right)$$

(12)

This just corresponds to de Finettis concept of exchangeability; an infinite sequence of random variables is said to be exchangeable, if the joint distribution of any finite subset of the variables is invariant under permutation of their order.

There are also properties directly associated with states. A state is absorbing if once the chain enters this state it cannot leave: $p\left(A,A^c\right)=0$. A typical example of an absorbing (at least temporarily absorbing) state in seismology is the occurrence of characteristic earthquakes with a limited range of possible magnitudes – a feature caused by controlling tectonic properties of the area as long as these controlling mechanisms exist. The obverse of absorbing is transient. A state is transient if, given that a chain currently occupies state A, the probability of not returning to A is non-zero. A more general case of absorbing is the situation where a state, A, is closed with regard to some other state, $B: p\left(A,B\right)=0$.

A Markov chain is irreducible if every point or collection of points (a subspace, required in the continuous case), A, can be reached from every other point or collection of points. So irreducibility implies the existence of a path between any two points in the subspace. With other words – with any reduction of the set of interest – we would lose information because some paths to get to some points in the subspace from other points are getting lost.

In seismology this is the case if truncation is used on lower and upper magnitudes in magnitude – recurrence correlations.

If a subspace is closed, finite, and irreducible, then all states within this subspace are recurrent. A more stricter requirement is the so-called Harris recurrence that guarantees, that the probability of visiting A infinitely often in the limit is one. This is a special case of positive recurrence. Another important term with respect to the use of the theory of stochastic processes is the term of a stationary stochastic process. For a stationary Markov chain (discrete case) is valid:

$$\sum_{\theta_i}\pi^t\left(\theta_i\right)p\left(\theta_i,\theta_j\right)=\pi^{t+1}\left(\theta_j\right)=\pi\left(\theta\right) \quad (13)$$

Here π^t is the marginal distribution in a Bayesian sense.

It is also necessary to discuss about periodicity. It is possible to define the period of a Markov chain. This is simply the length of time to repeat an identical cycle of chain values. For an aperiodic chain the length of time is the trivial case with cycle length equals 1. It is desirable to have the property of aperiodicity, because the recurrence property alone is not sufficient to assure that the chain reaches a state where the marginal distribution remains fixed and identical to the posterior of interest (other words reaches the stationary state). To assure the convergence to a stationary stochastic process it is required that a Markov chain is ergodic.

If a chain is irreducible, positive Harris recurrent, and aperiodic, then we call it ergodic. Ergodic Markov chains have the property:

$$\lim_{n\to\infty}p^n\left(\theta_i,\theta_j\right)=\pi\left(\theta_j\right) \quad (14)$$

for all θ_i and θ_j in the subspace. Therefore, in the limit the marginal distribution at one step is identical to the marginal distribution at all other steps. Better yet, because of the recurrence requirement, this limiting distribution is now closed and irreducible meaning, that the chain will never leave it and is guaranteed to visit every point in the subspace. Once a specified chain is determined to have reached its ergodic state, sample values behave as if they were produced by the posterior of interest (in seismology sample earthquake recurrence recordings behave like the final limiting distribution of earthquake recurrence).

There are different velocities for a Markov chain to achieve its ergodic state – usually depending on speed of convergence – ergodic, geometrically ergodic and uniformly ergodic – chains are distinguished.

The PSHA methodology based on Cornell (1968) uses an stationary homogenous Poisson process to describe earthquake recurrence, therefore requires the ergodic assumption as the basis to justify the selected mathematical concept. On the other hand it is also easily understandable that ergodicity and mathematical convergence of a PSHA are closely tight terms. Only the property of ergodicity assures the convergence of the time dependent stochastic process of earthquake recurrence to a limiting stationary distribution and allows to perform judgments on this distribution based on a limited set of information – earthquake recurrence recordings usually assembled into earthquake catalogues.

As pointed out, a Markov chain is recurrent if every point or collection of points (a subspace, required in the continuous case), A, can be reached from every other point or collection of points. For earthquake recurrence this means that any possible magnitude value can be reached from any other possible magnitude value without dependency on the previous state. The observation of large earthquakes after foreshocks and of aftershocks after large earthquakes as well as of earthquake swarms is an obvious violation of this requirement, because they show a clear dependence on previous states of the chain. Similarly the requirement for aperiodicity is violated by the observation of "characteristic earthquakes" which are characterised by a specific range of possible magnitudes depending on fault characteristics (thus violating again the requirement of recurrence).

Fault mechanics even use the term "seismic loading cycle" to express the periodicity (although not perfect) of the generation of large earthquakes at specific faults. So earthquake occurrences observed in nature are not in compliance with the mathematical property of recurrence required for ergodicity. The need to perform complicated de-clustering procedures to separate earthquake events itself is simply an implicit acknowledgement of seismology that earthquake recurrence is not ergodic. A similar acknowledgement is the trial to predict the return of certain characteristic earthquakes in time.

There is no justification for the use of the so-called ergodic assumption in seismology. Unfortunately this means that the currently in use mathematical methodology for a PSHA is not justified. Many so-called "uncertainties" can be explained, just by the attempt to compare the behaviour of nature with an inadequate mathematical model.

4 SUMMARY OF THE REVIEW OF SEISMIC HAZARD ANALYSIS METHODS

Based on the requirements for a reliable seismic hazard analysis and the above discussion on the principle alternatives – a PSHA and a DSHA some summary conclusions can be drawn, which methodology is more appropriate to develop a reliable seismic hazard assessment suitable for practical decision making with respect to siting of a nuclear installation. This summary is presented in table 4. The main conclusion is that a deterministic seismic hazard analysis is clearly superior to the currently in use PSHA-methods. The later even have to be regarded as mathematically ill-posed if they are based on the ergodic assumption.

Table 4. Summary of the review of seismic hazard analysis methods

Requirement	PSHA	DSHA (MCE)
Conservative Realism	Current practice of PSHA has shown a tendency to overly conservative and sometimes completely unrealistic results at least in low seismic areas. Large methodological improvements would have been required to obtain a realistic-conservative methodology.	Achievable, the whole line of calculations from the seismic hazard definition to the structural design and the design and qualification of components shall be supervised to assure a reasonable and not too conservative safety margin.
Validation of results	First attempts for validation have been undertaken leading to the correction of intermediate results of large PSHA-studies. The effort for validation is tremendous.	Achievable with reasonable effort, the main focus on the selection of appropriate attenuation laws and the geometrical characteristics.
Robustness and time-invariance	The contrary is demonstrated in the available practical applications with a certain tendency to a worst-case analysis if applied for low seismic areas.	Achievable. Uncertainty is limited to the accuracy of data collection. New information can be easily implemented.
Requirements of interface minimization	Achievable, if the project management of a PSHA study is performed by safety analysts with a broader technical background.	Achievable, if the project management of the study is performed by safety analysts with a broader technical background.
Requirement of tracebility and logical consistency	For PSHA-methods which are based on the ergodic assumption this is not achievable. Large improvements in the layout of the study' documentation are required moving from quantity towards quality.	Achievable. The results are easy to communicate to the public.

One of the arguments in favour of the use of PSHA is the need to provide the required input for a seismic PRA. So the additional question to be answered is, whether contemporary PSHA-methodology is suitable to provide the appropriate input for a seismic PRA. Once again the PSHA-methodology based on the SSHAC-procedures and using the ergodic assumption is used as a reference.

Unfortunately people often believe in names instead of looking into the core of a problem – so once a methodology is called "probabilistic" people start to believe that this has something to do with risk-informed applications or with probabilistic risk assessments for nuclear power plants. In fact there are many differences between a PSHA and modern PRA-methodology. The most important are listed below.

1 Modern PRA-methodology is based on data (failure and maintenance data, event data to develop initiating event frequencies etc.), which is updated regularly. For this purpose Bayesian approaches as the most advanced methodology are used. This also allows some trending. Extrapolations from the past into the future are not made. A PRA is based entirely on past and preferably plant-specific experience. PSHA is extrapolating from past experience into the future, f. e. using stationary magnitude-relationships to derive maximum magnitudes, which have never occurred in reality and cannot be proven to happen by any available scientific method.

2 PSHA is a worst-case methodology. A typical example is the assumption of a floating, undetectable earthquake source, just below the site of interest, typically creating the largest contribution to the seismic hazard, except, the plant had been erected directly on a large active fault which would cause larger quakes, than the assumed hidden one. This assumption is maintained, even in case of complete lack of evidence of the existence of such an earthquake source. In a PRA such a problem would be treated in a Bayesian sense using a non-informative prior for the probability distribution of the existence of such an earthquake source.

$$P_{M|M>M_{science}} = P_M P_{M>M_{science}} \tag{15}$$

$P_{M|M>M_{science}}$, means the probability of occurrence of an earthquake with a magnitude which is larger, than can be predicted by scientific site investigations of any kind.

P_M is the probability of occurrence of an earthquake of any magnitude near the site of interest.

$P_{M>M_{science}}$, is the conditional probability, that once an earthquake occurred, its magnitude would be larger than it would have been established by the available scientific methods. It is understandable that this probability shall be assumed as far below 1, because modern geology and empirical seismology including historical seismology have found the root causes and the associated faults for most of the large earthquakes which occurred in modern times. There are only very few incidents, if any, where large intraplate earthquakes occurred and the associated fault systems or hot spots were not found (Krinitzsky, 1993). So the conclusion is, that a PSHA biases the results of a seismic hazard analysis systematically towards an increase of the risk contribution of near-site earthquakes.

A similar situation like described for the case of a PSHA with respect to the hidden earthquake would occur for a PRA if unproven speculations would have been included into the study. As such an example anomalies of the gravitational field of earth can serve. People do not know very much about the material nature of gravitational fields, so who can exclude, that a reactor building will be destroyed by such all of a sudden occurring anomaly, not yet known?

3 The treatment of uncertainties in a PSHA and a PRA is completely different. Modern PRA-methodology also considers state-of knowledge uncertainties. They are treated either by bounding conservative assumptions, f. e. in case of thermo-hydraulic success criteria or by sensitivity studies using different modeling assumptions. The most reliable modeling assumption is typically selected as the base case. The sensitivity cases provide additional information which shall be credited in practical decision making to avoid cliff-edge effects. A correct PRA would never include mutually exclusive physical assumptions into one logical model, because the only consequence of doing this is, that the result of the study will deviate from reality for sure. Only one of the mutually exclusive assumptions can be true by definition. PSHA methodology does include mutually exclusive assumptions into their logic models due to the attempt to predict the future behavior of fault systems. So it is possible, that a fault is active with a 50% probability. The results of the study would of course be completely different if the fault is assumed as either not active or as active, so a study which assumes a 50% probability for a fault being active, is wrong in any case.

The question remains whether there are alternatives to the described methodology of probabilistic seismic hazard analysis. Among the tested and better known alternatives the theory of characteristic magnitudes combined with models which are using directly the recurrence period of an earthquake at a specific fault as a random parameter shall be mentioned. These models essentially started from Kostrovs equation (Kostrov,1974) showing that the accumulation of seismic moment is proportional to the average strain of the area of interest. Under conditions where there wasn't observed aseismic slip (creep) (or the later could have been quantified) it was possible to show for some interplate areas (Scholz, 2002), by a comparison with historical earthquakes, that the moment releases tend to occur in the shape of single events containing about 95% of the accumulated moment. This gave basis to the assumption, that strong characteristic earthquakes on faults occur nearly periodic and their recurrence can be described by using the recurrence period directly as an random parameter. This approach shows some progress to the assumptions based on the use of an homogenous stationary Poisson process (Cornell, 1968):

- Earthquake occurrence is periodic or nearly periodic and therefore not ergodic
- It better reflects the known mechanisms of occurrence of stronger earthquakes by strain accumulation

For the recurrence period different statistical models have been tried, the most used assumption was based on the use of a lognormal distribution.

In practice the theory of characteristic earthquakes was incorporated into "hybrid" models combining a Poisson model for small earthquakes (notably with a Gutenberg-Richter correlation for the magnitude – frequency relationship) and a model for the upper tail of magnitudes based on characteristic magnitudes for known fault structures (WGECP, 1995, Wu & et al, 1995). The following problems remained unsolved:

- Due to the rare occurrence of strong earthquakes in intraplate conditions it was not possible to verify the theory of characteristic earthquakes by historical observations under these conditions
- The model fails under conditions, where variable aseismic slide (creep) occurs
- The interaction of fault segments in forming larger events as well as the occurrence of smaller earthquakes on known and well studies fault segments are not explainable by characteristic earthquakes.

It can be summarized that characteristic events only occur if some controlling barriers preventing the aggregation of fault populations exist and remain intact. Unfortunately the duration of such a temporarily possible state is not predictable. This is the reason why the key mathematical assumption of the theory of characteristic magnitudes– the assumption of independence between the recurrence periods of characteristic earthquakes is not justified. The quantification of the characteristic magnitudes therefore is valid only under very specific conditions.

Another principal alternative consists in the use of Markov or semi-Markov models (Patwardhan & et al, 1980). In a theoretical sense this is a promising approach, because it allows to describe the seismic loading cycle of earthquakes like it is inherent in fault mechanics by temporarily absorbing states (seismic gaps in time and space, or characteristic magnitudes as long as stable barriers preventing fault aggregation during an earthquake exist) and transitions in the magnitude state space. It is also possible to include the dependence between different earthquake events related to different loading cycles. A challenge would be the incorporation of very strong and rare earthquakes which are not caused by a controlled sliding mechanisms but by thermo- and hydrodynamic effects (latent hot spots). Such strong earthquakes have the potential to change the geological environment strongly leading to the problem, that no data will be available to make predictions for the next cycle, because the previously known fault systems may not exist any more. For Markov models generally a large data problem exists even if the very strong earthquakes which would change the geological environment drastically are excluded (this is justified, because they would like a super volcano cause much more direct damage to human kind, then the failure of any critical infrastructure).

So finally it has to be summarized, that still a large effort is needed, to develop a mature risk-informed seismic hazard analysis methodology. The current PSHA methodology does not provide the required basis for a reliable decision making with respect to siting of a nuclear installation.

To provide an input for plant specific seismic PRAs it is therefore recommended to return to Bayesian approaches both for the development of magnitude-frequency relations as well as for the assessment of source-specific upper magnitude characteristics. This is feasible but it shall be stated clearly that the knowledge of the underlying mechanisms creating earthquakes are not yet sufficiently understood to allow for risk-informed applications for the seismic design of nuclear installations. The contribution of seismic risk to the operation of nuclear power plants therefore shall be expressed either as an integrated measure – integrated core damage frequency over the lifetime of the structure(to take into account the partial periodicity of earthquake occurrence) – or in a conditional sense, like for events of malevolent origin expressing the (conditional) degree of protection of a nuclear installation against the maximum earthquake. The later parameter in principle can be standardized to assure a comparable protection of nuclear power plants world wide.

5 METHODOLOGICAL FUNDAMENTALS FOR A RELIABLE SEISMIC HAZARD ANALYSIS SUITABLE FOR PRACTICAL DECISION MAKING

Based on the above discussions about the pros and cons of the different seismic hazard analysis methods the basics of a methodology suitable for practical decision making on siting of a nuclear installation will be sketched in this chapter. Special emphasis will be given to low to moderate seismic areas, because in all other cases sufficient data for a reasonable hazard assessment is available

The first point to make is, that including uncertainties in decision making is very important, but much more important is, to base decision making on facts and data. So the starting point of any seismic hazard analysis methodology is the gathering of technical relevant information and data. The IAEA safety guide "Evaluation of Seismic Hazards for Nuclear Power Plants" (IAEA, NS-G-3.3, 2002) gives an excellent guidance on this issue. Here the procedures will be commented from past experience of the review of a large scale PSHA and as an introduction to the recommended hazard evaluation methodology, recommending the systematic development of a geological, geophysical and geotechnical database. According the IAEA safety guide the investigations shall be performed at four different scales:

- Regional (presented on maps with scale of 1:500000)
- Near regional (presented on maps with scale of 1:50000)
- Site vicinity (1:5000)
- Site area (1:500)

The investigations required in the safety guide allow for developing a very complete picture of the geophysical situation of the considered site.

A rather new methodology to perform site vicinity and site area analysis consists in the use of modern methods of 3D- reflex-seismometry, a tool which was developed in conjunction with geologic exploration and which f. e was successfully implemented for the investigation of the site conditions of a possible site of a final waste repository in Switzerland (Lambert, 2001).

This information shall be complemented by seismological data (the safety guide calls this a seismological database), which shall be explained and interpreted in the context of the assembled geological database. Typical information required are:

- Historical earthquake data (from written history)
- Paleoseismological data
- Available instrumental recordings
- Site-specific instrumental data (if available).

The site-specific instrumental data is of special importance, because it can also be used to calibrate available attenuation models to the site specific conditions.

Based on an integration of the information available the IAEA-safety guide recommends the development of a regional seismotectonic model.

To assure a reasonable assessment of maximum possible earthquake magnitudes in low seismic areas it is highly recommended to use analogies between the seismotectonics of the region of interest and other regions in the world following the extraregional seismotectonic method (Reisner & Ioganson, 1996). This methodology gives a reasonable, data or facts constrained, estimate of the upper level of possible magnitudes reducing the dependence on formal statistical extrapolations. For Central Europe the data from Reisner & Ioganson (1996) can be recommended to be used directly. The seismotectonic model of the region shall include a not to fine zonation of the historically and seismotectonically differentiable provinces and a detailed map of known fault structures with their main characteristics as for example:

- Length
- Width
- Slip rates/Uplift data
- Segmentation
- Related earthquake observations and instrumental data

The next and actually the first step of the hazard assessment is the development of maximal possible magnitudes to be associated with the different seismic provinces and faults.

For this purpose it is necessary to distinguish between identified fault sources and areas with diffuse seismic activity, where faults can not be identified. The reason for this can be manifold. Sources can be buried and therefore are not detectable or the site is an intraplate one, with very low seismic activity and therefore with little or even complete lack of meaningful seismic recordings.

For known faults reasonable good estimates for the maximum possible magnitudes are available based on the assumption that the fault would rupture at its full length (figure 10, Mualchin, 2004). Similarly empirical correlations can be used, like the following proposal for the Mediterranean area (Gülkan & Erdik, 1986):

$$\log(L) = -3.9 + 0.8 * M_s \qquad (16)$$

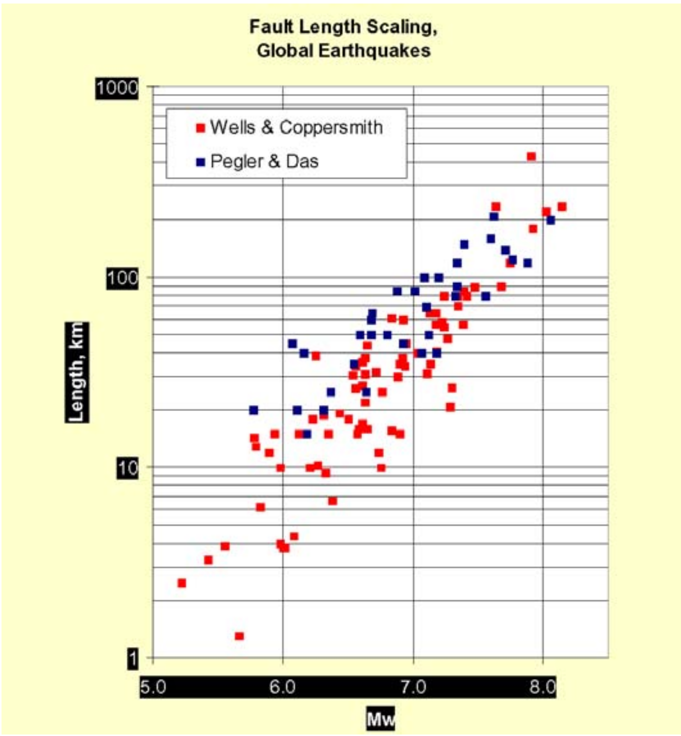

Figure 10: Fault Length Scaling – Maximum Magnitudes (figure taken from Mualchin, 2004)

Care shall be taken to the larger variability of earthquake source parameters under intraplate conditions (Scholz, 2002). The typical mean slip rates for large crustal earthquakes for a fixed fault rupture length under intraplate conditions are approximately by a factor of 3 higher (scaling regime 2, according to Scholz, 2002) than for interplate conditions, leading to higher stress drops (mean values) and thus to higher (mean) seismic moments than for interplate conditions. Using the simplified model of a point seismic source this means that the size of potentially strong earthquake sources is smaller in comparison to interplate conditions (assuming the same seismic moment of the earthquake). This has some consequences:

- Potential fault sources are more difficult to detect under intraplate conditions (smaller fault size)
- The directly affected (by fault rupture) damage area for intraplate earthquakes is expected to be smaller than for interplate earthquakes
- The attenuation of seismic waves is to be expected weaker than for interplate conditions, because the rupture process is stopped earlier (for the same amount of energy, or the same seismic moment) and the amount of energy spent for fault rupture is smaller.
- For the same reasons the duration of intraplate earthquakes is to be expected shorter than for interplate earthquakes.

This supports the conclusion drawn from the review of the PEGASOS-project, that attenuation laws from other regions shall not be transferred to the region of interest (Klügel, 2004) without validation.

Therefore for practical applications it is recommended to derive a lower bound for the dependence between rupture length and magnitude under intraplate conditions. This will provide some conservatism in the assessment of the maximum possible earthquake. For moment magnitudes $M_w>6.0$ the following correlation is suggested for intraplate conditions:

$$\log(L) = -4.71 + 0.84 M_w \qquad (17)$$

Equation (17) approximately describes the lower data range of figure 10. The potentially smaller rupture lengths for intraplate conditions underline the importance of careful near-site investigations to avoid or at least to map near-site fault systems.

Based on the collected historical, paleoseismological, and seismotectonic information the maximal possible magnitudes have to be developed:

- For known fault systems the maximal magnitude is derived from the seismotectonic characteristics of the fault
- For areas with diffusely distributed seismic activity in first order the information from the extraregional seismotectonic model (Reisner & Ioganson) shall be used and compared with the regional historical and paleoseismological information. In the case that historic macro-seismic or paleoseismological events are reported with higher magnitudes than according the estimates from the extraregional seismotecconic model (and these differences can be explained) it is suggested to perform some statistical extrapolation of the available data using bootstrap techniques (Noubary, 2000). For this purpose the estimated magnitude from the extraregional seismotectonic model shall be included into the sample of the magnitudes of the historic (or discovered from paleoseismology) events. As the maximum possible magnitude it is recommended to use the value of the upper limit magnitude distribution corresponding to the 95% confidence level. For the estimate (the bootstrap) it is reasonable to assume that the maximum magnitude is a magnitude value which exceeds the largest value in the sample by an amount equal to the difference between the largest and the second largest earthquake in the sample. By performing a sufficiently large sampling using a pseudorandom number generator the required confidence level can be achieved. This approach integrates in a very natural way all available information with respect to the maximum magnitude without leaving the available technical data basis.

Once the maximum earthquake is defined for each of the known fault systems and for the relevant area sources the site specific ground motions in terms of source-specific spectra can be developed. A source-specific approach has the advantage, that a later deaggregation of the results (like for a PSHA) can be avoided, because the information from each identified seismic source will be kept just from the start of the analysis and the obtained results are related to identified seismic sources.

To obtain site-specific ground motions it is necessary to define the attenuation distances and the attenuation correlations.

For identified fault systems the attenuation distance can be defined as the horizontal distance on surface from the center of the (active) fault to the site of interest.

For source areas with diffuse seismic activity according the MCE-methodology it is recommended to use half of the theoretical rupture length as the attenuation distance. This expresses the term "credible" in the concept of the Maximum **Credible** Earthquake (MCE). Indeed it is not likely to assume that just the site of interest is located very closely to the epicenter of the next earthquake, which will occur with the largest possible magnitude. This approach simplifies the analysis and makes the development of seismic hazard maps for areas with diffuse seismic activity very easy. In Klügel (2004) it was shown, that this approach leads to similar results like the results from a PSHA for a frequency of exceedance of 0.0001 if the mean of a lognormal distribution is used for spectral accelerations (instead of $\mu+\sigma$, which would be more conservative, but this may be justified for critical infrastructures if the national design rules allow for large load reduction factors due to the use of inelastic spectra) without the need to explain the meaning of the exceedance frequency, which at the best is some statistical average over a long time period. Additional safety margins can be applied by using a safety importance factor for critical infrastructures.

In case of a study for a nuclear installation with the large amount of data available as required in the IAEA safety guide (IAEA, 2002) a maximum use of this information shall be taken. Therefore for areas with diffusely distributed seismic activity (or diffusely not clearly defined fault populations) it is reasonable to assume that the maximum earthquake would take its origin in the geometrical center of the area. This is equivalent to the assumption that seismic activity is distributed uniformly over the whole seismic zone. This is a reasonable assumption. Otherwise a more detailed map of the fault population would have been available for more specific analysis after the site investigation stage. Additionally it is recommended to consider a background seismic source near the site in a distance which corresponds to the accuracy of the near-site investigations required according the IAEA safety guide, in case that the near-site investigations have not shown any active fault near the site of interest. This accuracy is approximately 250 m in distance, but potentially limited in depth (buried earthquake). Nevertheless the existence of larger capable earthquakes (of earthquakes which potentially rupture the surface) can be excluded after the required detailed investigations (or the site would have been moved). The upper magnitude is therefore not higher than 5.0, which corresponds to the upper limit of the stick-slip sliding mode of earthquake generation, which probably can be explained by dynamic changes in the normal stress field (Krinitzsky, 1993). This is also a size of a seismic source which would be difficult to detect. As the corresponding attenuation distance once again the assumption of a uniform distribution of the fault population (or of seismic activity) over the region of the investigation can be used, which corresponds to an attenuation distance of 2.5 km (Joyner-Boore distance).

The next step is the selection of the attenuation law. As stated above it is required to have a regionally validated attenuation law, because the transfer of correlations from other areas or the use of a statistical mixture of correlations would lead to some additional not intended conservatism. In low seismic areas it might be difficult to collect sufficient data to develop an own attenuation law. Here the lessons learned from the development of regional attenuation laws after the Kocaeli (Izmit) earthquake can be used for validation (Schwarz & Ende, 2004). There it had been shown, that the shape of the attenuation law (if provided in the standard logarithmic form, Ambroseys & Bommer, 1991) did not change very much if to a dataset from rather weak aftershock earthquakes strong motion data from the same region were added. This information can be used to calibrate available regional attenuation models (they shall be pure in the sense, that they shall not contain any information from other regions) to the regional conditions using a rather crude but "good" engineering practice technique – called "fitting factor"-approach.

For this purpose separate fitting factors for each spectral acceleration have to be developed based on local recordings. The measurement site conditions preferably shall be known, although even a lack of knowledge in this area can be compensated by the method. The spectral "fitting factor" $F_f(M,D)$ is just the ratio between measured spectral accelerations at site and the calculated spectral accelerations from the baseline attenuation model in logarithmic scale.

$$F_f\left(M,D\right)=\log\left(S_{a,measured}\right)\Big/\log\left(S_{a,calculated}\right) \quad (18)$$

If sufficient data is available it is recommended to use different "fitting factors" for near-site and far field recordings, to address the differences in the spectral shape. For the baseline attenuation model it is recommended to use a correlation, which was derived for similar seismotectonic conditions.

With a regionally validated attenuation model developed, it is now possible to perform the seismic hazard analysis required for siting.

As an example case study such an analysis has been performed for the site of the Goesgen Nuclear Power Plant, with the exception that the calibration of the attenuation law for the Goesgen conditions is still preliminary due to the lack of seismic recordings.

Two cases have been considered based on one geometrical zonation developed during the PEGASOS-project, which consisted of 30 zones described as area sources. Different maximum magnitudes were used for the two cases. For the first case the maximum magnitudes developed by the experts in the PEGASOS-project were used. These values were typically higher than from the extraregional seismotectonic model by half a magnitude unit. The extraregional seismotectonic model was used as the principal alternative. For this purpose the maximum magnitudes were developed from the data provided by Reisner & Ioganson for the region of Switzerland. Additionally a background source with maximum magnitude M_w=5.0 was added to the zonation, to include the uncertainty with respect to the location of small earthquake sources at a distance of 2.5

km to the site in both cases. The resulting hazard spectra are shown in figures 11 and 12 (median, mean, and μ+σ-values, abbreviated as seismologist mean). For the distant sources (geometrically defined as area sources) enveloping spectra were constructed. They are shown separately from the spectra of the near-site background source (abbreviated as back), which governs the seismic risk in both cases for structures and components with a period smaller than 0.25-0.3 s. It is worth to mention that the results of the first case of the analysis are very close to the results of the historically first site specific hazard study (the finally used design basis is based on pga values which are about a factor 2 higher). The original study was performed before the "discovery of epistemic and aleatory uncertainties".

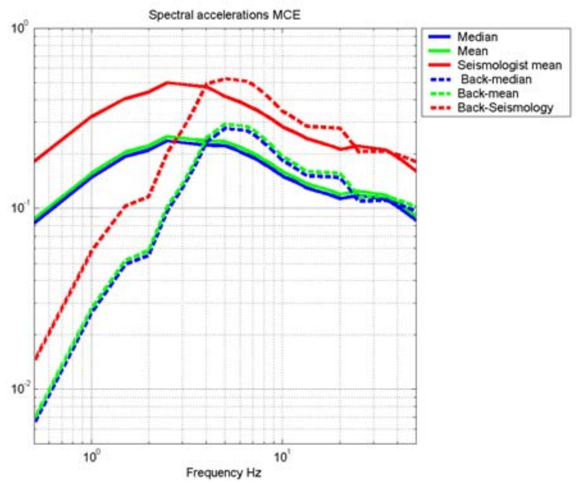

Figure 11. Site Specific Design Seismic Hazard Spectra using the MCE approach – Case 1, Maximum earthquake magnitudes used from the PEGASOS project.

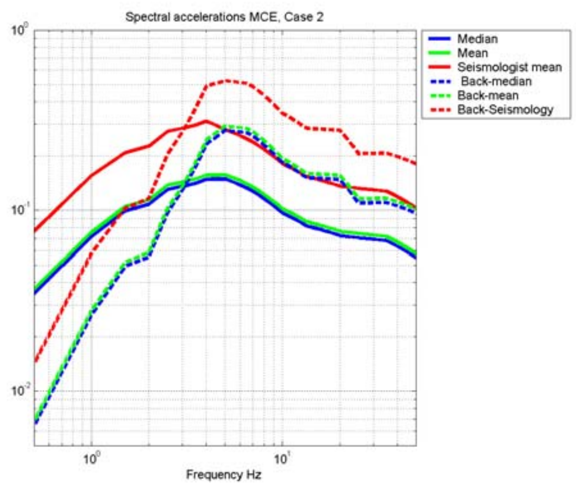

Figure 12. Site Specific Design Seismic Hazard Spectra using the MCE approach – Case 2. Maximum earthquake magnitudes derived from the extraregional seismotectonic model (Reisner & Ioganson, 1996)

For the analysis presented here the epistemic uncertainties were assumed to be systematically excluded by engineering investigations according to the IAEA safety guide (IAEA, 2002). So the results presented here show effectively how a reduction of uncertainties can be achieved by effective site-specific and near-site investigations.

Based on the case study the conclusion can be drawn, that in low seismic areas under predominantly intraplate conditions the design basis seismic hazard is largely affected by the conservative assumption of the possibility of a moderate near-site earthquake caused by variations in the normal stress field (stick-slip sliding mode). It is interesting to observe, that the mean and the median values of ground accelerations are very close, due to the exclusion of "epistemic uncertainties" related to the attenuation correlation by using a regionally validated attenuation model.

It can also be concluded, that the current minimal requirements of IAEA for seismic design of nuclear power plants (instrumental pga of at least 0.1g) can be judged as reasonable for central European conditions.

The obtained results are time-invariant and robust with respect to variations in the assumptions of the seismic features of available more distant seismic sources due to the use of the maximal magnitudes for these sources and of a regionally validated attenuation model.

In combination with the custom procedure of using linear-elastic design methods while observing ductility requirements as far as reasonable in the construction of the plant, it can be concluded, that the recommended seismic hazard analysis procedure will assure a reliable and robust basis for decision making. It is suitable to assure a high level of safety of the nuclear facility including some reasonable safety margin.

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IAEA/ICTP Workshop on Earthquake Engineering for Nuclear Facilities - Uncertainties in Seismic Hazard Assessment

"Consistent reliability between Situng and Design: Requirements on Hazard Accuracy"

Trieste, Italy, 14 – 25 February 2005

(Unit 34) - (Dr. Jens-Uwe Klügel)

Contents

- Introduction
- Requirements to a Dependable Seismic Hazard Analysis
  - Basic requirements
  - Practical implementation
- Review of existing approaches (PSHA, MCE)
- Methodology for the development of a dependable seismic hazard specification for Nuclear Installations
- Conclusions

Introduction - I

- Construction of new Nuclear Power Plants feasible (even in Europe)
- Construction of other Nuclear Facilities
  - Final repositeries
  - Intermediate storage facilities
- Highly compatible energy market
  - Need for an efficient dependable design
  - Safety margin to respond to “unexpected” events (Sumatra quake +Tsunami was assessed a rare event based on probabilistic assessments)

Introduction - II

- Development of new seismic hazard analysis methods
  - PSHA with heavy involvement of expert elicitation
  - Modernized deterministic approaches MCE
  - Need for risk-informed seismic hazard analysis to be used as an input for seismic PRAs
- Development of new design methods and codes
  - Performance based earthquake design
    - Two or more functionality states
    - Limited failure allowed (assure survival of inhabitants)
- How these new methodologies can and shall be applied for nuclear installations.

Introduction III

- Lecture will present
  - General requirements to seismic hazard analysis leading to a consistent reliability between hazard specification and design = Concept of realistic conservatism
  - Review of existing methods
  - Proposal of a dependable seismic hazard analysis methodology which meets this requirement
  - Discussion of requirements to a risk-informed seismic design methodology
- Inspired by lessons from seismic PRA applications and the reveiw of the PEGASOS-project

Requirements to a Dependable Seismic Hazard Analysis, Overview

1. Requirement of conservative realism
2. Requirement of validation of results
3. Requirement of robustness or time-invariance
4. Requirement of the Minimization of interface between seismic hazard anaylsis and the use of the results
5. Requirement of tracebility and logical consistency

Requirement of Conservative Realism -I

- Results shall be realistic
  - Reflect site conditions
  - Regional attenuation characteristics
  - Regional seismic activity
  - Overly conservatism shall be avoided
    - Conservatism is introduced by robust design methods incorporating safety afctors
    - Use of safety importance factors (1.4 – EUR-requirements) for critical structures

Requirement of Conservative Realism –II, Conservative elements in current design practice

- Use of broad - banded design spectra (enverloping f.e. according Newmark&Hall, regulatory design spectra RG 1.60)= conservative
  - No single earthquake will challenge the whole spectrum (peaks limited to a few characteristic frequencies f.e. two-peak spectra)
  - Only a part of plant equipment (in comparison to the total design spectrum) will be submitted to maximal accelerations in the range of their natural frequencies

Requirement of Conservative Realism –III, Conservative elements in current design practice

- Use of elastic design spectra and linear-elastic structural models with (limited) damping
  - In the past – stiff constructions, less attention to the use of ductile constructions
  - Improvements due to plant modifications (modern anchorage concepts for components)
  - Large potential for load reduction which is not credited in the current design

$$R = R_{\mu} R_{S} R_{\xi} \qquad R_{\mu} = \sqrt{(2\mu - 1)}$$

Load reduction factor R including margin for ductility, overstrength and damping

Requirement of Conservative Realism –IV, Design margins for R/C Structures, Kappos (2002)

Code	Symbol	Frame	Structural Wall	Frame Wall
EUROCODE 8	q	5	4-5	4.5-5
UBC (1997)	R	8.5	4.5-5.5	8.5
NZS 4203	M	<=6	<=5	<=5-6
JAPAN	$1/D_s$	2.2-3.3	1.8-2.5	2.0-2.9

Requirement of Conservative Realism –V, Design margins for R/C Structures

- Simplified Conclusion

A nuclear installation which is designed for an SSE corresponding to a pga of 0.1g possesses an equivalent fragility of a civil structure designed to a pga of up to 0.85 g

Frequently instrumentation values from hazard analysis are multiplied by a factor of 2/3 before use in building codes

Requirement of Conservative Realism –VI, Design margins for R/C Structures

- Other Conclusion

- Seismic design of civil structures cannot be judged by their design „pga“ –value
- The whole line of design calculations shall be reviewed
- Good reason for American seismologists to be a bit more conservative

Requirement of Validation of Results

- Validation of results is mandatory for any safety application
- Especially true for seismic hazard analysis
  - High complexity of the studies
  - Many subjective assumptions up to the formalized use of expert knowledge
  - Increasing amount of diffcult to interpret results observed in conjunction with increasing popularity of PSHA methods

Requirement of Validation of Results-II

- Seems to be a difficult task especially in a low seismic area (lack of data)
- Klügel (2004) developed an engineering approach to validation
  - Use of a set of benchmark tests
  - Detailed independent uncertainty analysis (Klügel& Groen, 2004)
- Alternative methods for expert elicitation (principle of empirical control, calibration, performance –based methods)

Requirement of Validation of Results-III

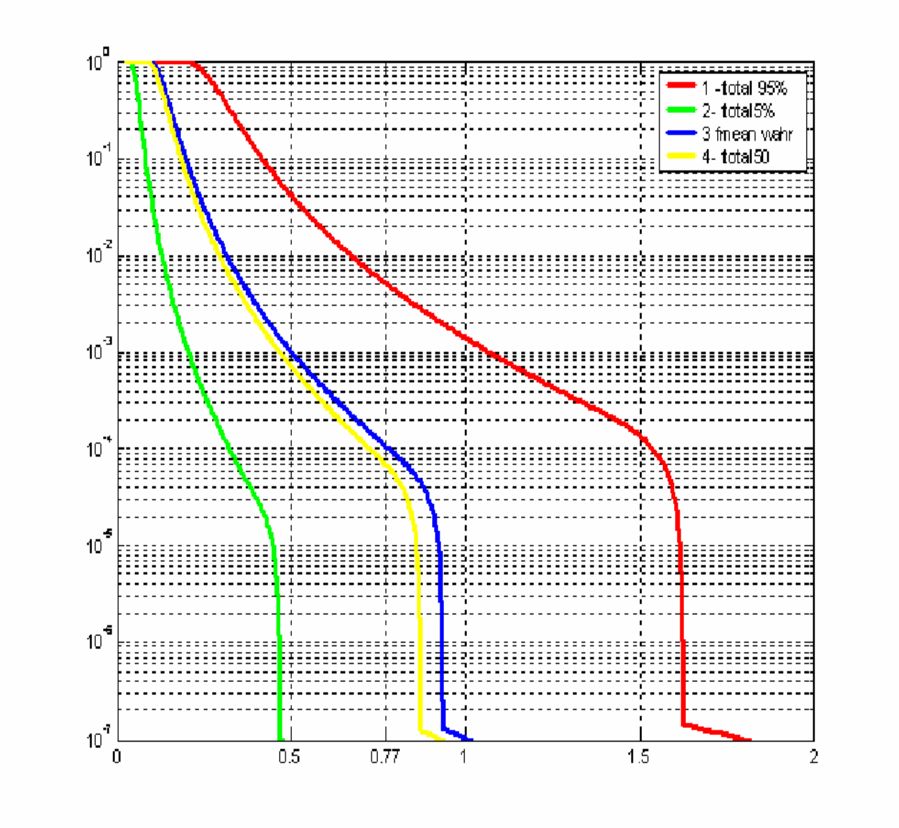
- Benchmark tests
  - Tests on seismic activity
  - Tests based on comparison of historical seismic activity
  - Test on attenuation models
  - Tests based on a comparison with earlier or similar studies or using alternative methods
- Effort for validation depends on the complexity of the study

Tests on Seismic Activity

- Most countries in the world show lower seismic activity than California or Japan
- In most cases national/regional attenuation models are available from earlier studies
- Results of a new PSHA-study can be tested against the bounding assumption of having seismic activity of California while maintaining the known attenuation laws for the region
- Shows whether the results of a new study (shall be lower than the test result) are constrained by the historical observed seismic activity

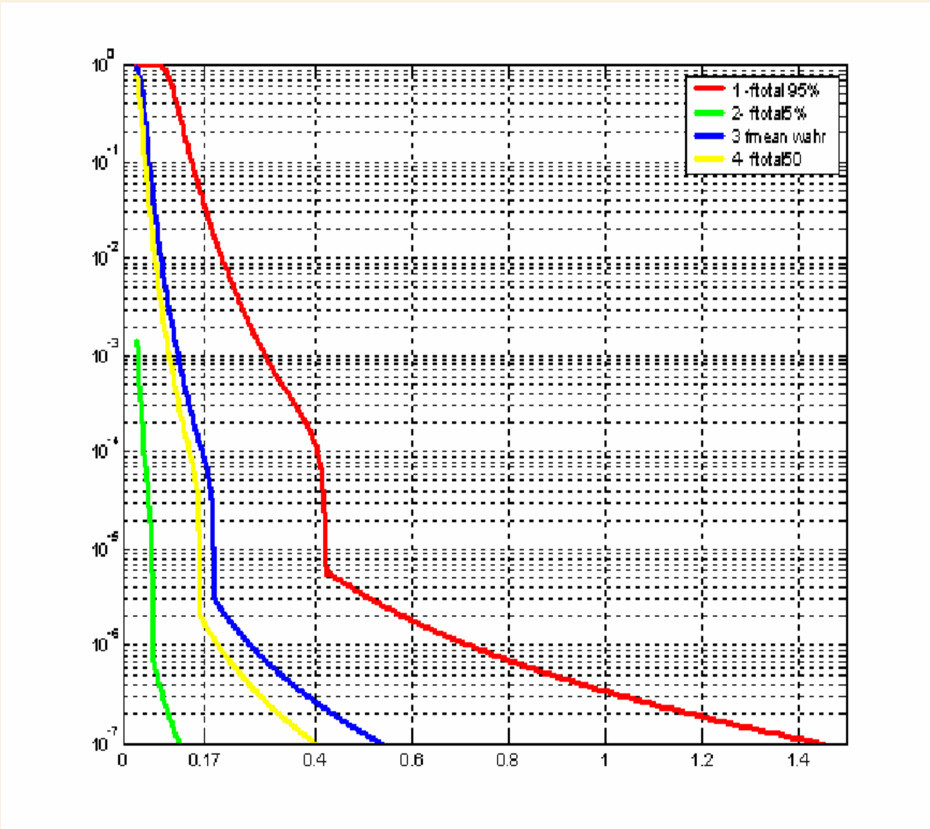
Example for a benchmark test against Californian seismic activity (San Andreas+Background source)

Part I –Calibration of simplified Two-source model



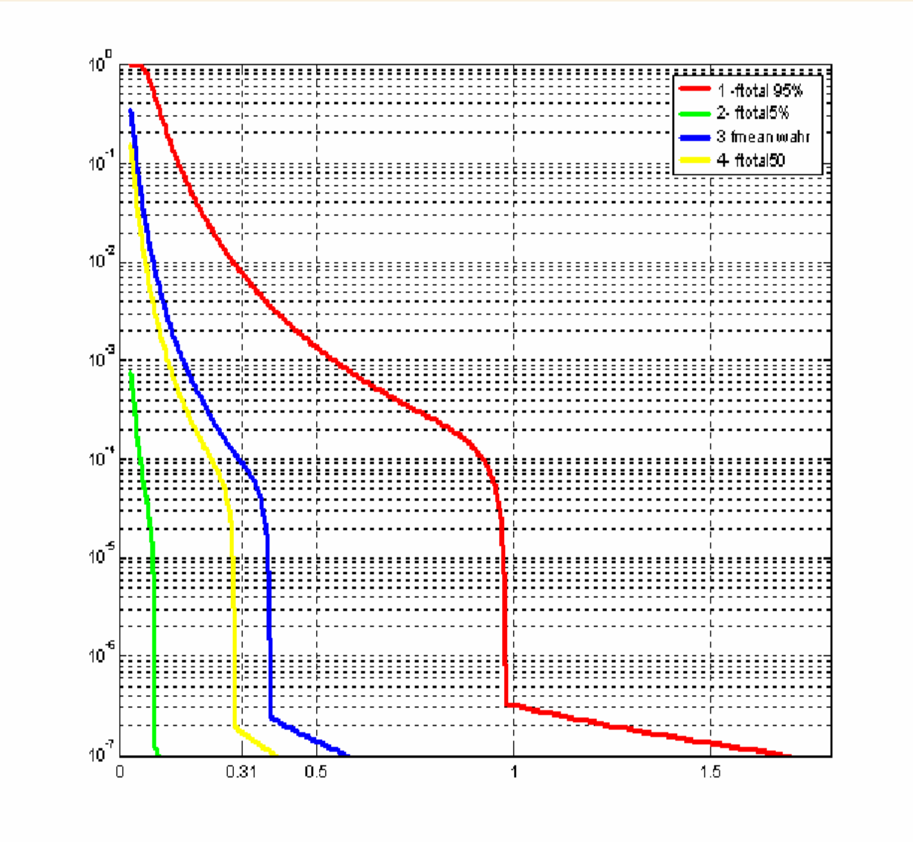
- Combined use of a Californian model for magnitude-recurrence and Californian attenuation law led to a SSE pga value of 0.77g
- Good compliance with NPP design basis for SSE

Test A – Use of an European Attenuation Law



- Californian Seismicity combined with the attenuation law of Ambraseys & Bommer (1991) *1.17
- SSE pga value is 0.17g

Test A –Modern Attenuation Law for near-site and medium distant earthquakes

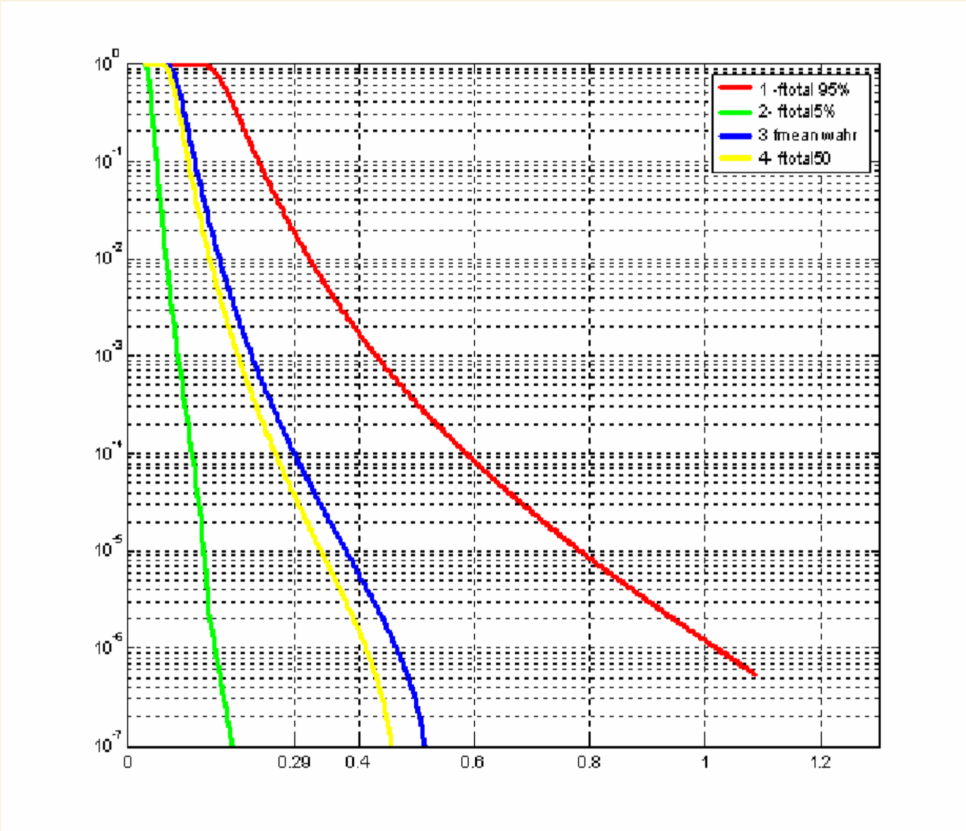


- Attenuation Law of Schwarz & Ende (2004)
- SSE pga value is 0.31 g
- Preliminary PEGASOS results for the site of interest showed 0.45 g
- Preliminary results didn‘t pass the test
- Indication for underestimation of attenuation in the PEGASOS-study

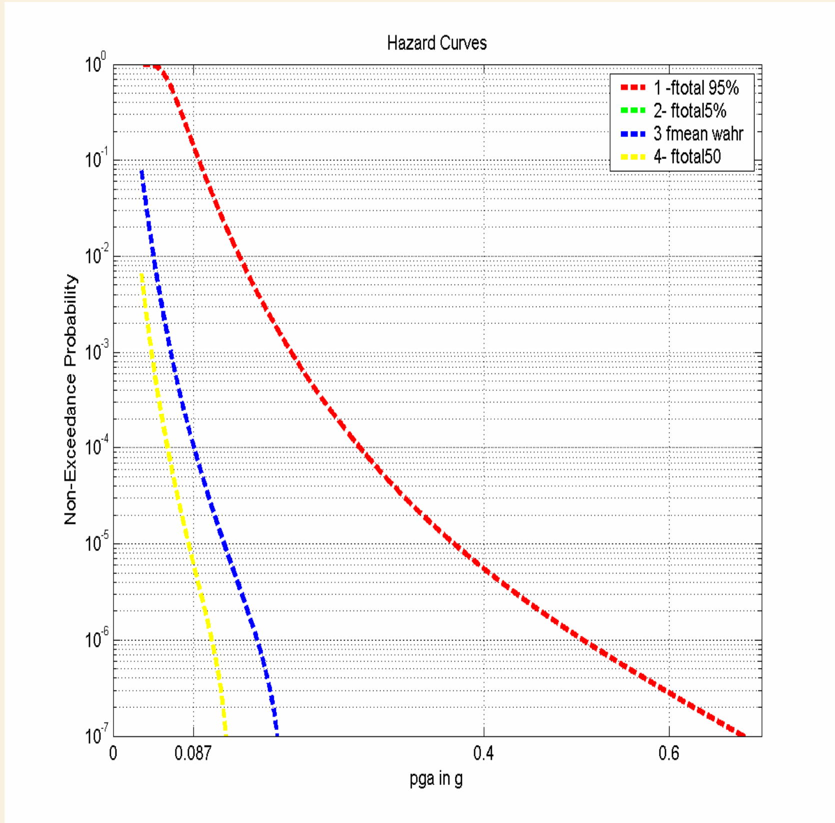
Similar tests on seismic activity with a two-source model

- Similar tests were performed with other assumptions on the seismicity model
  - Test B) – recurrence parameters derived from the first swiss PSHA (Zwicky et al)
    - Seismic activity of distant sources added to the Basel seismic source
      - Conservative overestimation
  - Test C) recurrence parameters from the de-clustered PEGASOS catalogue, assigned to both sources (double counting),
    - additional 6 strong earthquakes during the last 12000 years suspected by Paleo-seismologists added to the Basel source

Results of Test b) – Attenuation Campbell&Bozorgnia – Schwarz&Ende



Campbell&Bozorgnia



Schwarz & Ende

Overview on the Benchmark Test Results a) to c) for SSE pga

Benchmark Test	Attenuation Law		
PEGASOS (Preliminary) = 0.45g	Campbell & Bozorgnia	Ambraseys & Bommer (1991)	Schwarz & Ende
a) Californian seismicity	0.77g	0.17g	0.31g
b) B&H with increased seismicity	0.29g	0.14	0.09g
c) Doubled PEGASOS seismicity	0.22g	0.15	0.08g

Tests on historically observed seismic events

- Historical seismic activity is expressed in an intensity scale (modified Mercalli)
- Often isoseismals are available
- Murphy & O'Brian (or other relation)

$$\log\left(pga\right)=0.25I_s+0.25$$

Study results for a certain return period, where reasonable catalogue completeness can be assumed, can be converted to site intensities and compared with historical events

Tests on attenuation laws

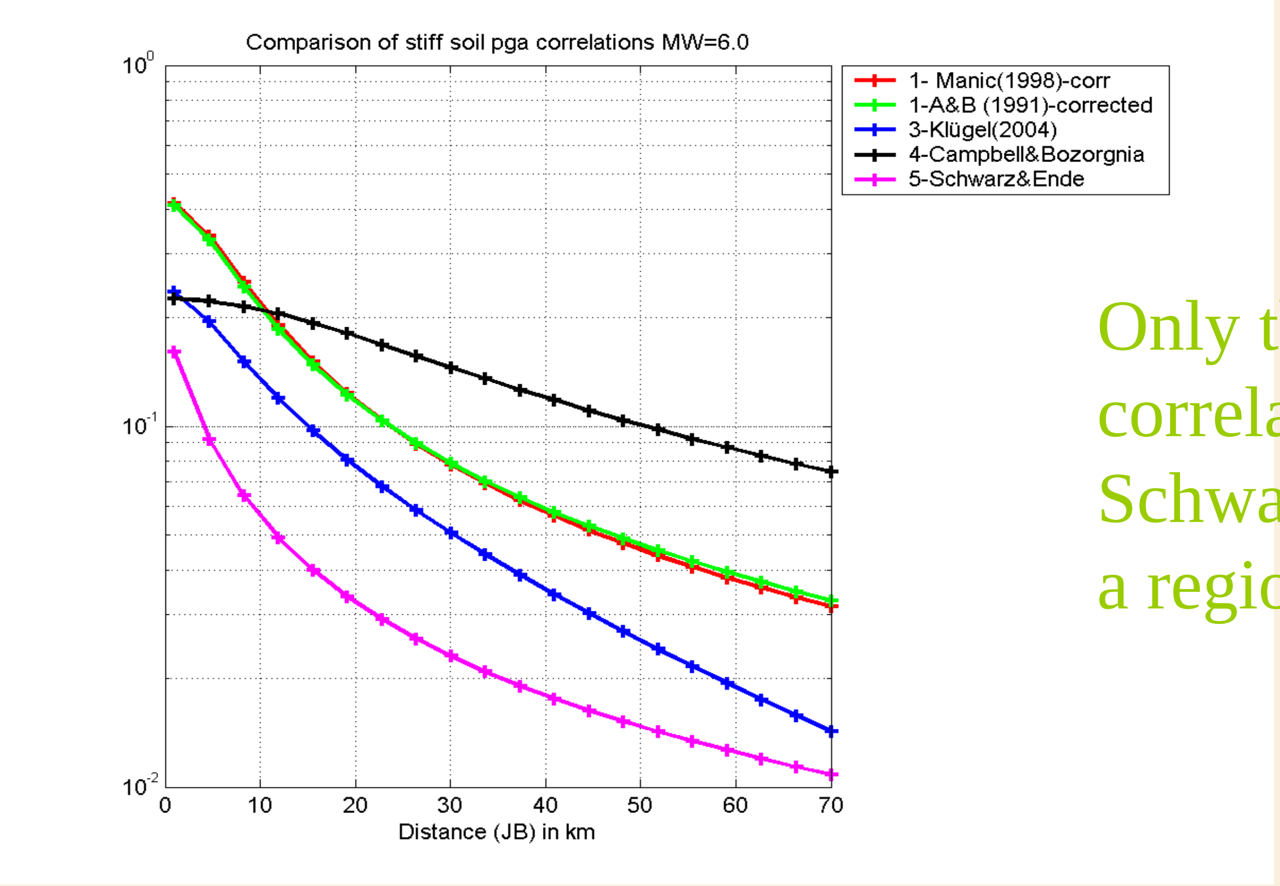
- It is a common belief among seismologists that attenuation laws shall be developed based on seismic recordings from many earthquakes from different regions
- Statistically these data are processed to develop a correlation as a regression mean
  - Due to the use of log –fitting functions this regression mean is treated as the median value for ground acceleration in seismic hazard models
  - The used correlation is actually a „mean of medians or means“ containing variability of earthquake occurences resulting from regional and site specific characteristics and from variability in measurememt conditions
- Such correlations are not suitable for performing a site-specific hazard analysis like for a nuclear power plant without removing the regional variability

Tests on attenuation laws

- What happens if such attenuation laws are used in a PSHA following the SSHAC-procedures?
  - Additional epistemic uncertainty is added to the model
    - Without removing the region to region and site to site variability from the equation!!

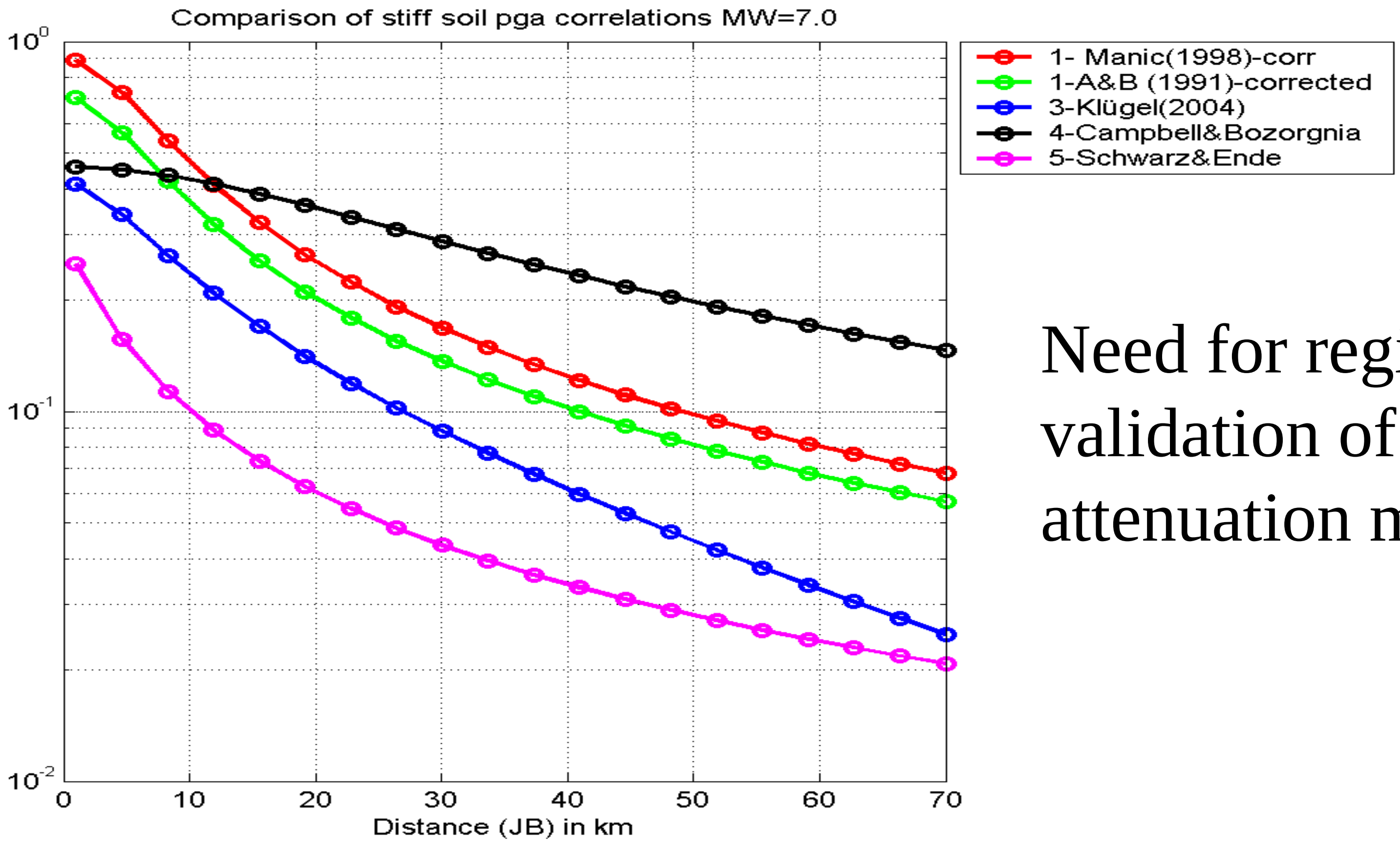
Double-Counting of „Uncertainties“ = systematic methodological bias

Comparison of attenuation laws from different regions-I



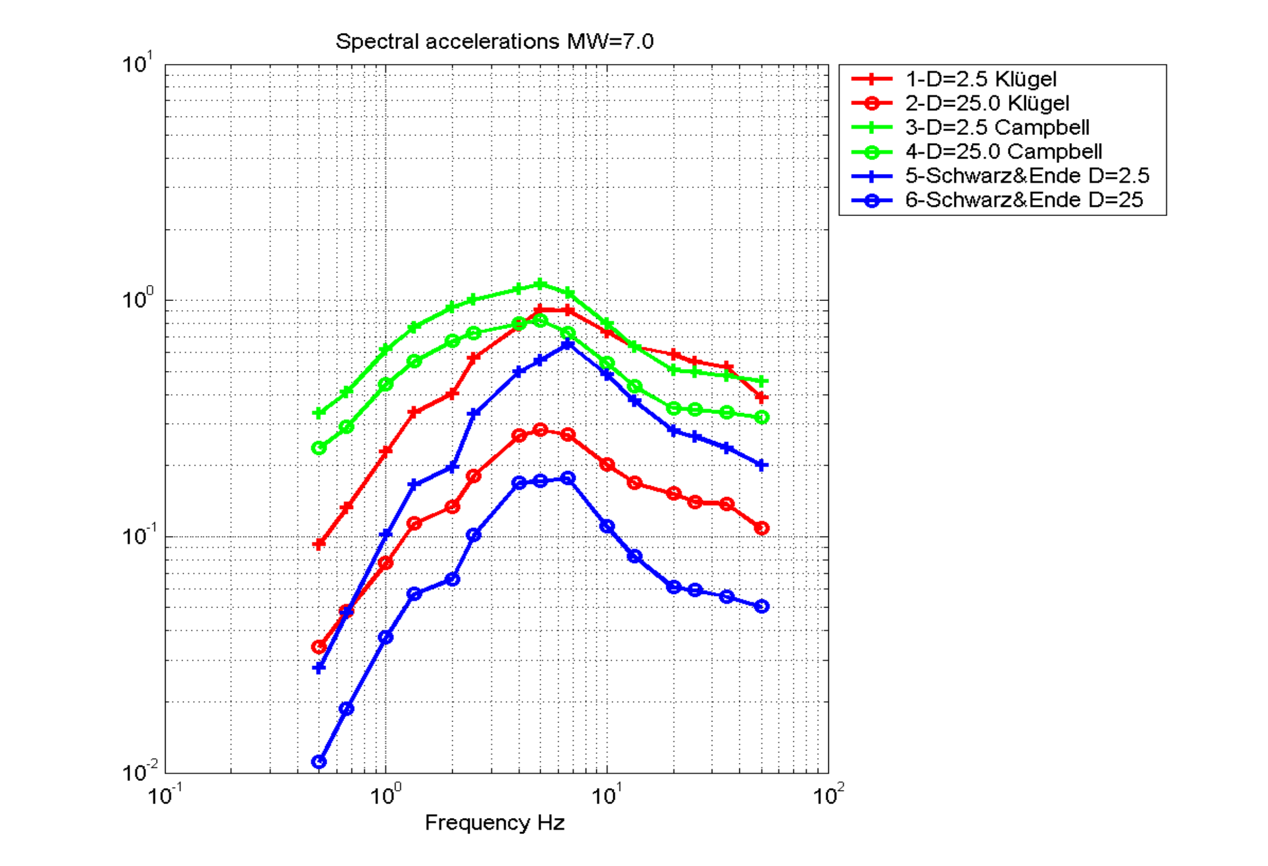
Only the correlation of Schwarz&Ende is a regional model

Comparison of attenuation laws from different regions-II



Need for regional validation of attenuation models

Comparison of different attenuation laws - III



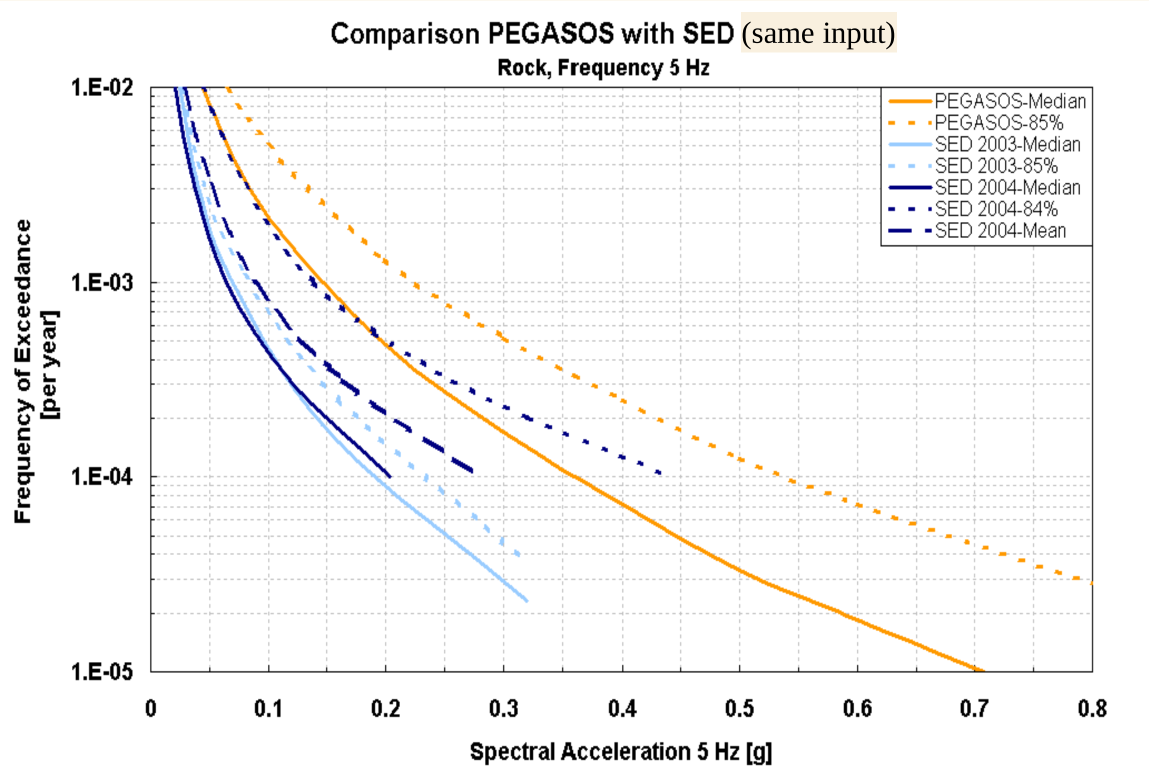
Test on attenuation laws - II

- Tests can be performed by comparing calculated ground accelerations (spectral accelerations) with accelerations required to destroy natural or historical landmarks
  - „Theory of precarious rocks“ – J. Brune (1999)
    - Clear indication that american attenuation laws have to be corrected to get into compliance with these observations
  - Comparison with historical macro-seismic events
    - Scenario-based approach with reconstruction of spectra in the range between 1 and 5 Hz (natural frequencies of historical structures)

Tests based on a comparison with earlier studies or alternate methodologies

- In developed countries many hazard studies are available using different approaches
- Can be utilized for a comparison to new studies
- Differences shall be explained
  - New technical information (based on facts)
  - Recognized errors in earlier studies (should be quantifiable)

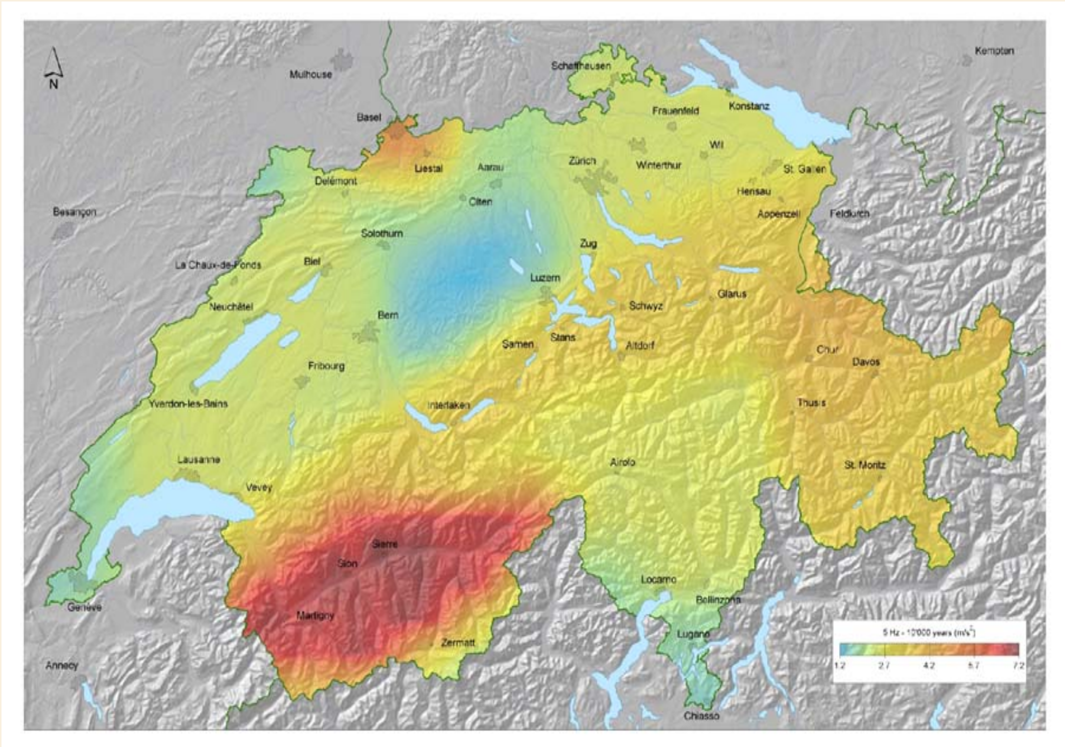
Example: Comparison of Preliminary PEGASOS-Results to other studies



Comparison with a PSHA of the Swiss Seismological Service (SED, 2003, 2004)

Difference more than by a factor of 2

Example: Comparison of Preliminary PEGASOS-Results to other studies-II



Swiss Probabilistic Seismic Hazard Map, return period 10000 years, available on the web

Swiss NPPs located in low seismic areas

Independent Analysis of Uncertainties

- Important for PSHA based on logic trees (Klügel & Groen, 2004, Klügel 2004)
- Seismic hazard for a fixed frequency of occurence

Mac Laurin Series development results in

$$H(f) = \sum_{i=1}^{k^{n-1}} \prod_{j=1}^{n} w_{i,j} F\left(f, w_{i,j}\right)$$

Result depends on the number of branches of the logic tree

$$H(f) \approx \sum_{i=1}^{k^{n-1}} \prod_{j=1}^{n} \left(w_{i,j} \sum_{\nu=0}^{k} w_{i,j}^{\nu} \frac{F^{(\nu)}\left(f, w_{i,j}\right)}{\nu!} \right)$$

Independent Analysis of Uncertainties-II

Number of uncertain (random) parameters shall be minimized

Detailed analysis/search for reducible uncertainties

Separation of aleatory and epistemic uncertainties leads to diffuse results

Requirement of robustness and time-invariance

- Important issue for practical decison making (protection of investment)
- To some extend related to the requirement if conservative realism
  - A „worst case analysis“ is more likely to be time-invariant, but economically inefficient
- Practical experience has shown that PSHA studies do not lead to time-invariant results
  - Steady increase of the seismic hazard levels without new techncial information (facts) in low seismic areas
- DSHA are in principle time-invariant

Requirement of Minimization of Interface Issues

- Avoid unneccessary complexity and potential error sources
  - Often communication errors
- Different application areas:
  - Design of a new nuclear installation
  - Re-evaluation of the seismic hazard of an existing installation
  - Application for a seismic PRA

Requirement of Minimization of Interface Issues-II

- Criteria to be considered
  - Lifetime of the structure
    - Big difference between a final repository (1 million years) or a nuclear power plant (60-80 years) if a time-dependent hazard assessment methodology is used
  - Engineering parameters used in the later application
    - Typical alternatives are effective ground accelerations (EGA) called by engineeers pga
    - Elastic spectra (spectral accelerations for certain values of damping)
    - Arias intensity et al.

Requirement of Minimization of Interface Issues-III

- Frequent communication problem
  - „Spike“ instrumental peak ground accelerations measured by seismologists are equaled to engineering pga (EGA)
  - Engineers understand as a a pga the anchor point of a design spectrum
  - Different understanding leads to additional work or even to wrong applications
  - Seismic PRAs at the current state are using either pga (in the sense of a EGA) or spectral averaged accelerations

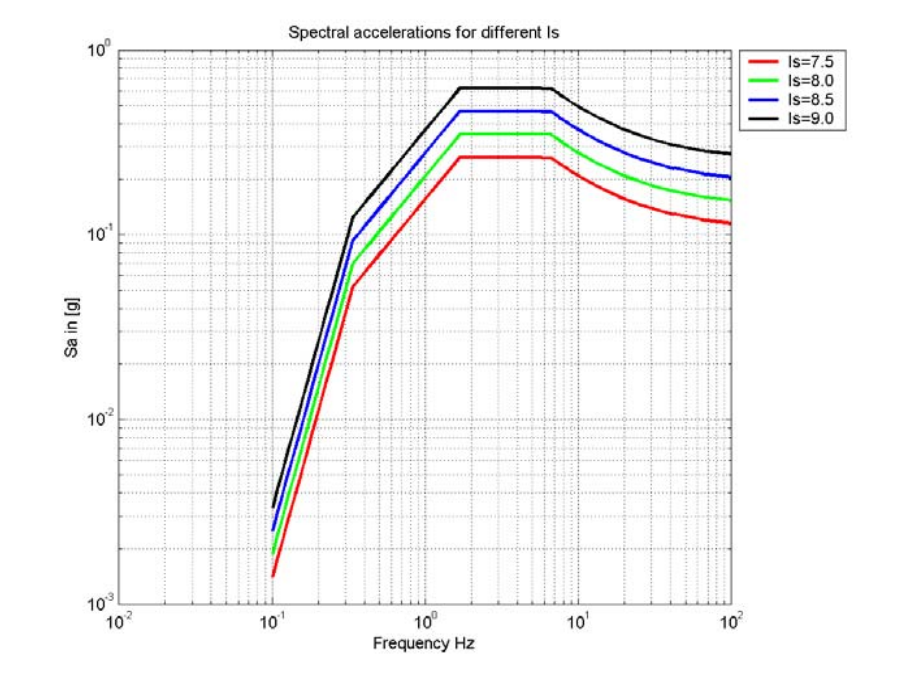
Requirement of Minimization of Interface Issues IV

- Sometimes seismic hazard analysis delivers results which are not needed in the later application (especially true for a PSHA)
- Results of a seismic hazard analysis shall be presented in a directly useable format
  - Use of EGA instead of instrumental pga – requires development of attenuation laws in terms of EGA
  - Alternative – use of intensity (maybe in future Arias intensity) instead of spectral accelerations
  - Large advantage with respect to a PSHA

Reduction of the number of random physical parameters

Advantages of the use of Intensities

EUROCODE 8 compatible design spectra for I_s



- Reduction of random parameters

$$\left\{M, T\left(f\right), S_a\right\}$$

Replaced by one physical parameter I,

Easy to develop elastic design spectra

Requirement of tracebility and logical consistency

- Natural QA requirement
- Logical consistency shall also include consistency of used mathematical assumptions
- In practice more complicated
  - Example PEGASOS documentation – 6 volumes based on a total of 60 Gbyte documentation
  - Tracebility is completely lost

Requirement of tracebility and logical consistency - II

- Mathematical consistency
  - Problematic for PSHA
  - Model of a Poisson process requires that earthquake recurrence is an ergodic stochastic process (process shall be stationary)
  - Use of truncated Gutenberg-Richter correlation for magnitude recurrence also requires stationarity
  - Separation of epistemic and aleatory uncertainties is based on De Finettis theorem of exchangeability – another formulation of the ergodic assumption
  - Model of characteristic magnitudes is not an ergodic model (model of a periodic process) but allowed to be used in a PSHA

Requirement of tracebility and logical consistency - III

- Truncated Gutenberg-Richter –Correlation corresponds (Berrill & Davies, 1980) to the maximum entropy of the magnitude distribution = State of most complete lack of knowledge of seismic activity in an area
- Max Likelihood Estimate represents the Best –estimate for this state
- What sense does it make to add aditional uncertainties to a complete lack of knowledge state?

Requirement of tracebility and logical consistency - IV

- DSHA in the format of MCE is easier to be performed in compliance with this requirement
- Simple, easy to communicate, time invariant
- Corresponds to the „theory of accumulation of strain energy“ – most strain energy is released in large events = necessary to design against the maximum magnitude
- Distance to the seismic source shall be credible
  - After site investigations strong near site sources can be excluded or taken into account realistically
  - Easy to calculate required design spectra

Discussion of the „ergodic assumption“

- Ergodicity of a stochastic process is a well defined mathematical property requiring
  - Irreducibility
  - Aperiodicity
  - Positive Harris recurrence
- Simplified – any magnitude value can be reached by paths from any other previous state (magnitude), there is no periodicity (return of characteristic events)
- Sample values behave as they were produced by the posterior of interest (exchangeability of time and space)

Discussion of the „ergodic assumption“ -II

- Earthquake recurrence is not ergodic and not stationary
- Swarms, foreshocks and aftershocks (not all paths in the magnitude state space possible)
- Model of „strain energy“ – seismic cycle with temporarily periodicity (temporarily absorbing states = characteristic magnitudes)
- Declustering required to get earthquake recurrecne it fitted into the „mind set“ of a Poisson process (Gardner & Knopoff, 1974)
- Poisson models or models of characteristic magnitudes only suitable to describe a long-term average behavior of earthquake recurrence – seismic risk is dominated just by the deviations from the average

Other „Probabilistic approaches“ - I

- Stochastic models related to the model of „characteristic magnitudes“ using the recurrence period as a random parameter (WGECP)
  - Improved methodology in comparison to the assumption of a Poisson process (at least for plate boundary regions with defined fault areas)
  - Removes the „ergodic assumption“ (implicitly)
  - To some extend in compliance with fault mechanics

Other „Probabilistic approaches“ - II

- Theory of characteristic magnitudes not verified for intraplate conditions
- Model fails, where large aseismic sleep exists
- Interaction of fault segments as well as occurrence of smaller events at known fault segments not explained
- Large events may change local tectonic conditions

→ Key modelling assumption of independence of the recurrence periods between different characteristic earthquakes is not justified

Other „Probabilistic approaches“ - III

- „Markov models“
  - Theoretically a very promising approach because it allows to model dependence between recurrence periods of earthquakes as well as transitions to a completely different seismic cycle
  - Data problem is not resolvable
    - Transition probabilities in case of a change of tectonic conditions after a large event

On the Relation of PSHA and SEISMIC PRA

- People tend to believe in names instead into the true character of methods
- The acronym „Probabilistic“ does not mean that a PSHA is risk-informed or provides the required input for a seismic PRA
- Many differences in methodology and approaches
- Clear indication that a PSHA has more a charcter of a „worst case“ analysis

On the Relation of PSHA and SEISMIC PRA-II

- Example for the worst case character,
  - PSHA in low/moderate seismic areas shows a dominate risk impact of „hidden“ undetectable near-site earthquakes
  - No evidence for such seismic sources or only as very weak diffuse sources (observed periodic earthquakes with M>= 4.0-4.4)
  - PSHA assumes a conditional probability of 1 for the existence of such undetectable, speculative quakes
  - PRA treatment would be different, risk impact would be very low

$$P_{M|M>M_{science}} = P_M P_{M>M_{science}}$$

On the Relation of PSHA and SEISMIC PRA-III

- For the assessment of seismic risk it seems to be more reasonable
  - To use average risk measures calculated over the lifetime of a structure
    - Using Bayesian techniques to take into account of changes in seismic activity
  - Or to use conditional risk measures to define a required defense grade of a Nuclear Power Plant against seismic hazards as it is a typical approach for external events of malevolent origin

Review Summary on Methods

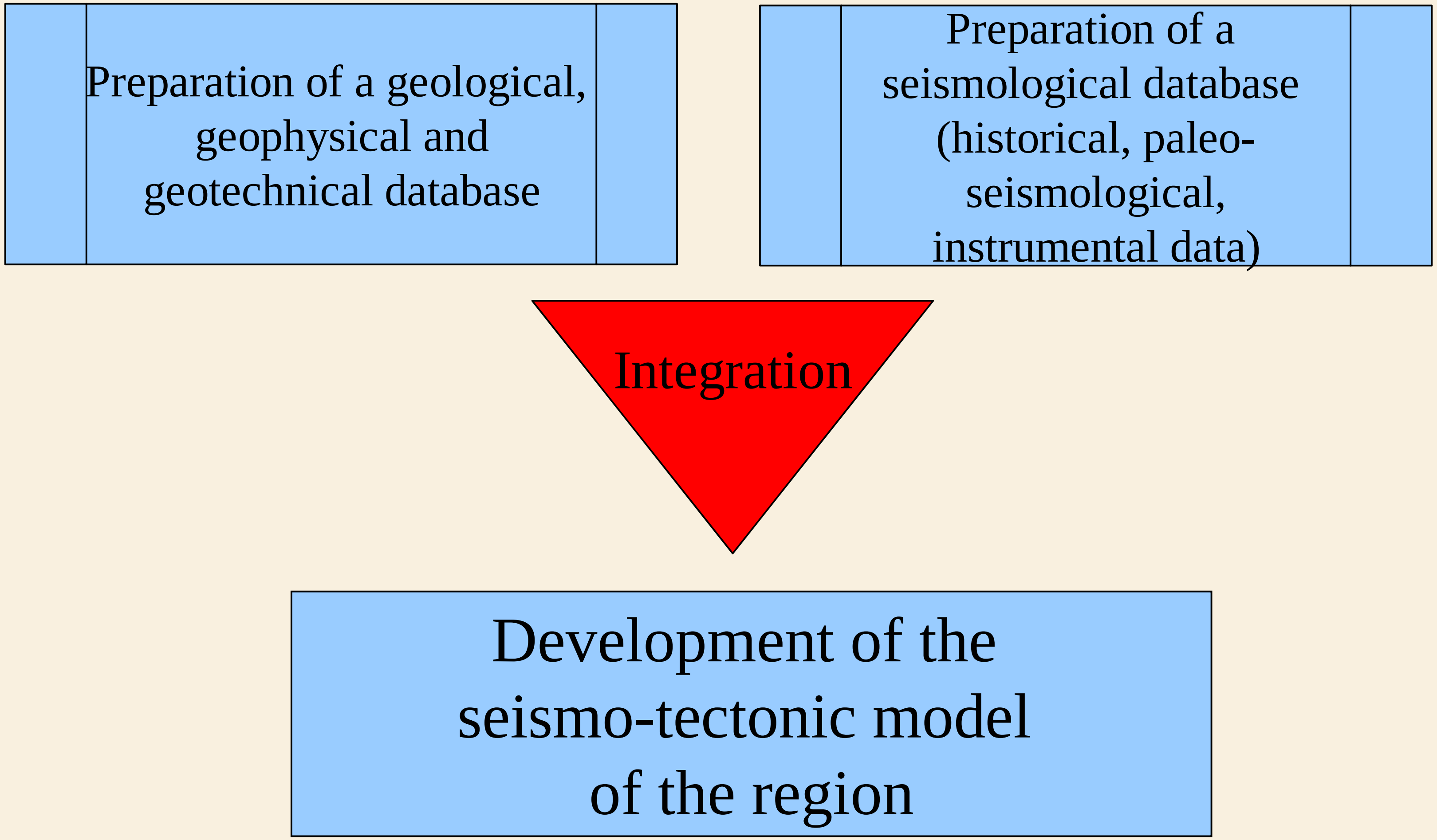
Requirement	PSHA (at ist present state)	DSHA (MCE)
Conservative Realism	Tendency to overly conservative and sometimes unrealistic results (low seismic areas)	Achievable, necessary to avoid overly conservative assumptions in hazard analysis by supervision of the whole design calculational process
Validation of results	First attempts. Effort tremendous	Achievable with reasonable effort. Based on data and facts.
Robustness and Time-Invariance.	Current practice contradicts this requirement	Achievable. Uncertainty limited to the accuracy of data collection.
Interface Minimization.	Achievable with im-proved project management.	Achievable.
Traceibility and logical consistency	For PSHA based on the ergodic assumption not achievable	Achievable

Fundamentals of a Dependable Seismic Design of Nuclear Installations

- Shall be based on gained knowledge and experience in seismic hazard anaylsis and site specific data
  - Data collection in compliance with IAEA-safety guide NS-G-3.3, 2002
- Incorporate possible critical scenarios as far as feasible by using reasonable safety margin (enveloping uncertainties)

Informative MCE approach in combination with linear-elastic design methods

Fundamentals of a Dependable Seismic Hazard Analysis - I



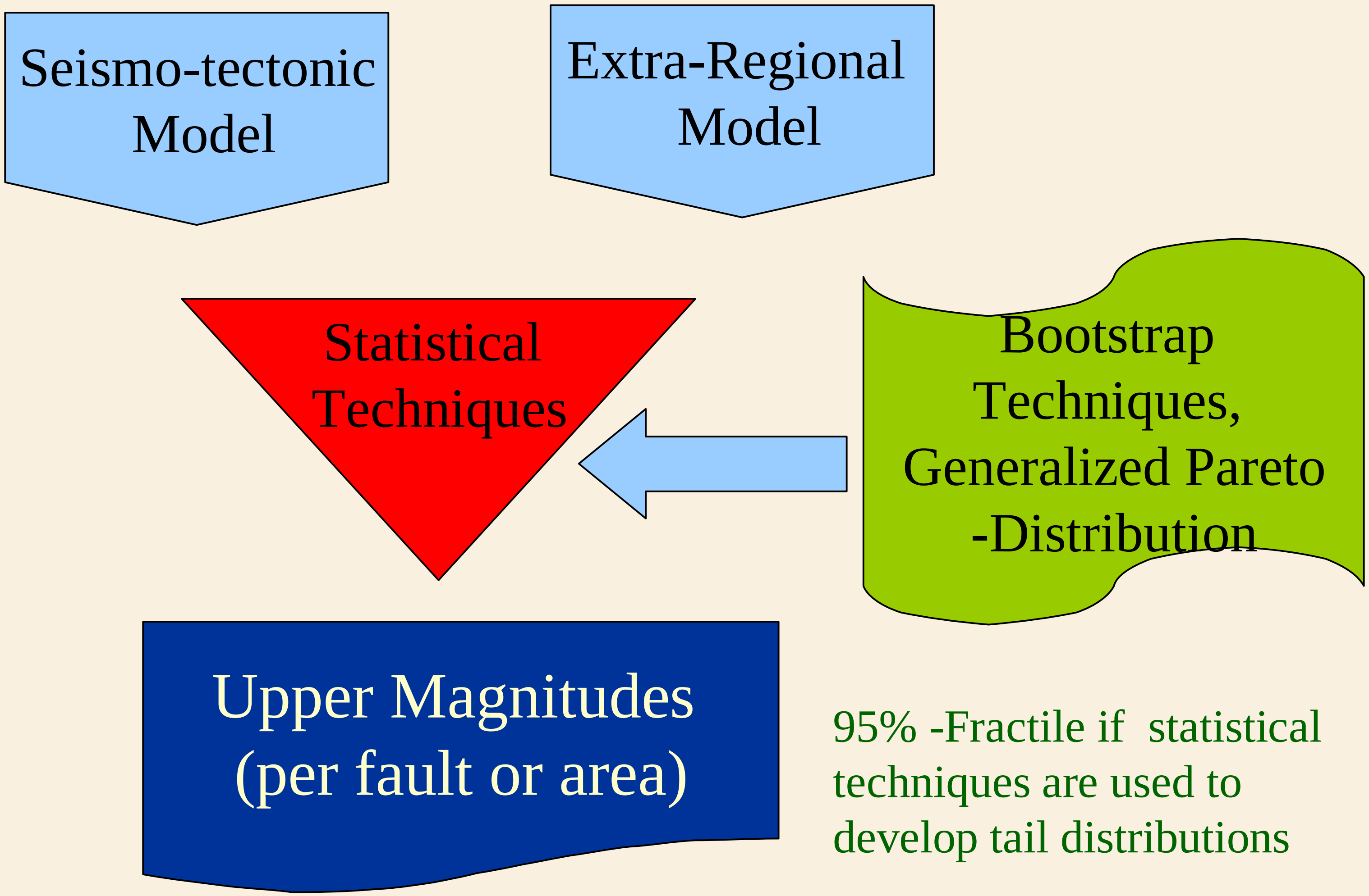
Fundamentals of a Dependable Seismic Hazard Analysis - II

- Seismo-tectonic Model
  - Reasonable fine zonation of the historically and seismotectonically differentiable provinces
  - Detailed map of known fault structures with main characteristics
    - Length/Width
    - Slip rates/uplift data
    - Segmentation
    - Earthquake observations (including historical) and related instrumental data

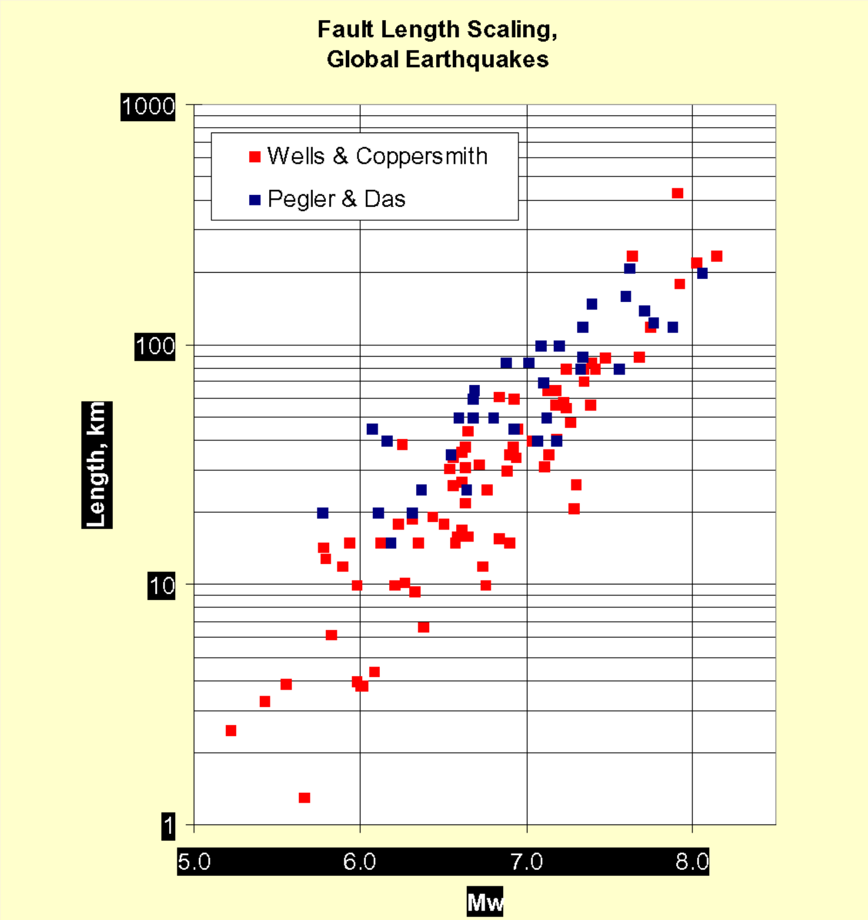
Fundamentals of a Dependable Seismic Hazard Analysis - III

- Important steps for low seismic areas
  - Comparison with the results of the extraregional seismotectonic method (f.e. Reisner & Ioganson, 1996) with respect to upper magnitude limits
    - Detailed information f.e. for Central Europe available
  - Definition of plate-conditions
    - Interplate (boundary)
    - Intraplate

Fundamentals of a Dependable Seismic Hazard Analysis - IV



Fundamentals of a Dependable Seismic Hazard Analysis – V- Maximum Magnitude



- Sufficient data available for boundary plate conditions

$$\log(L) = -3.9 + 0.8M_s$$

Gülkan & Erdik,1986

- Difficult for intraplate conditions (smaller fault size for same magnitude)

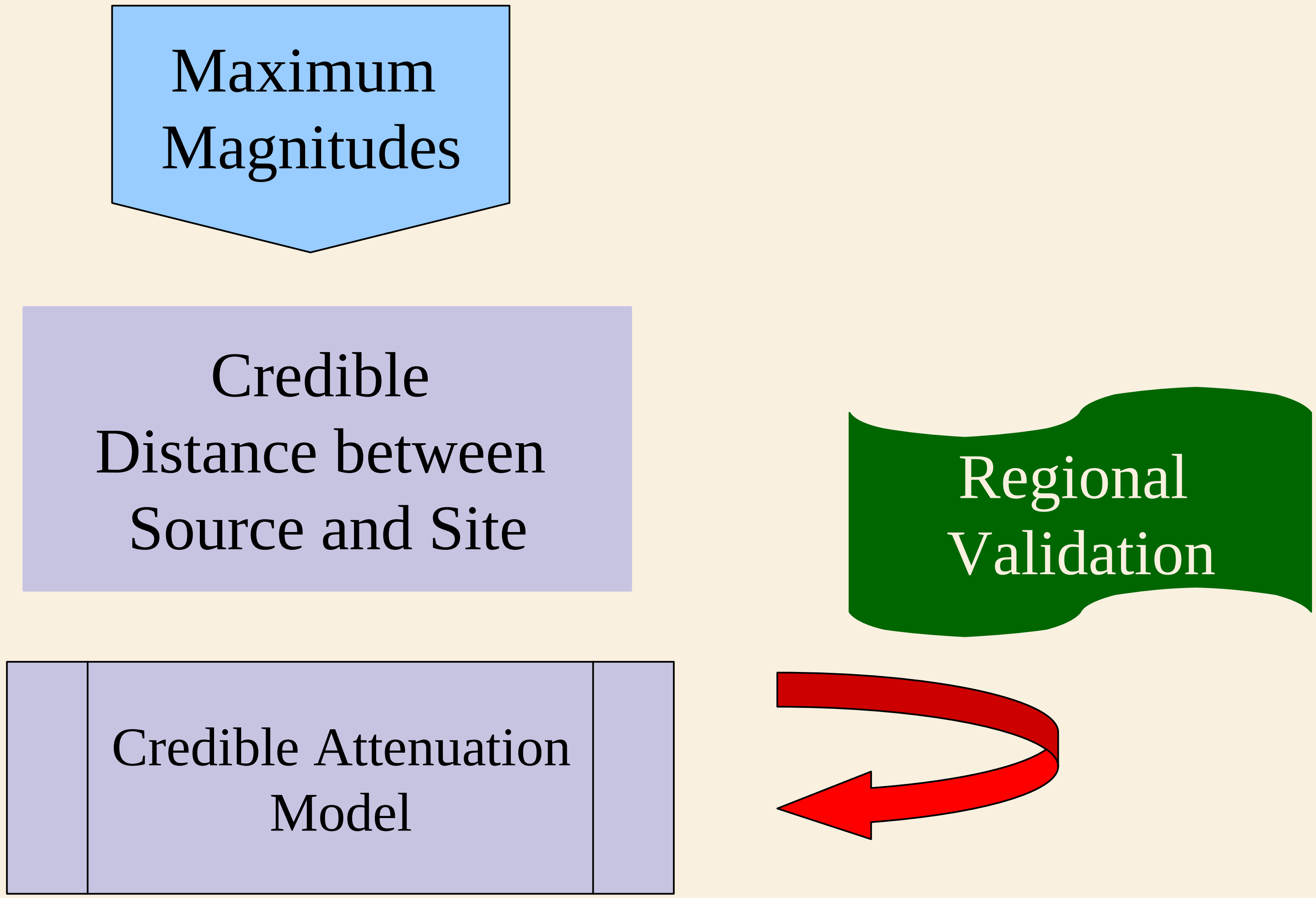
$$\log(L) = -4.71 + 0.84M_W$$

Fundamentals of a Dependable Seismic Hazard Analysis – VI- Maximum Magnitude

- If historical (including paleoseismological) or the extraregional method indicate the possibility of larger magnitudes, these values have to included into the analysis (in the analysis sample)
- Appropriate and easy to perform technique – Bootstrap
  - Resampling of the observed ordered maximum values
  - Simple basic assumption that the theoretical maximum magnitude is larger than the largest in the initial sample by the difference between the largest and the second largest observed value δ
  - 95% –fractile of the resampled upper magnitude limit distribution is used
  - Simple rule of thumb -

$$M_{upper,95\%} \leq M_{upper,observed} + 2\delta$$

Fundamentals of a Dependable Seismic Hazard Analysis – VII- Ground Motion

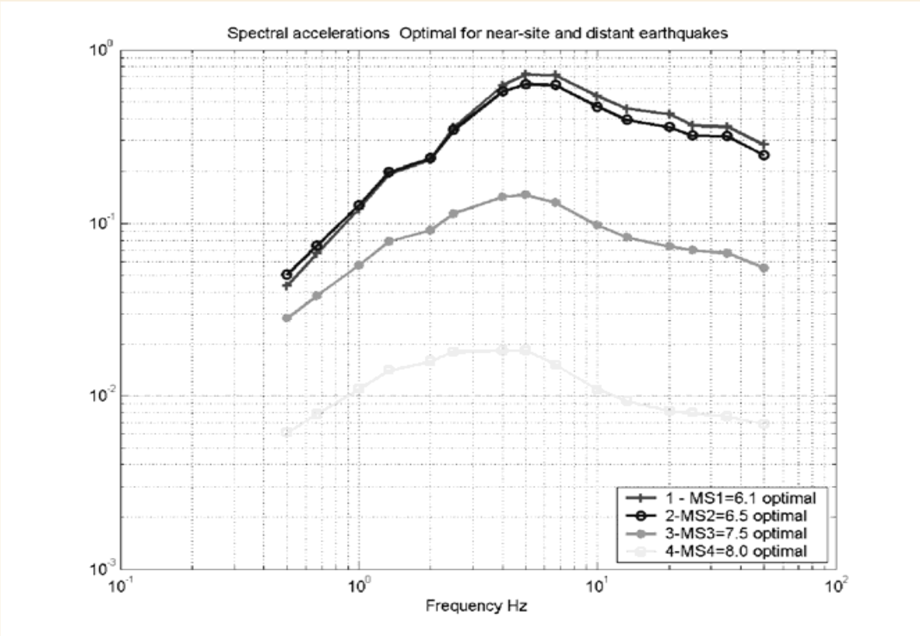


Fundamentals of a Dependable Seismic Hazard Analysis – VIII- Ground Motion

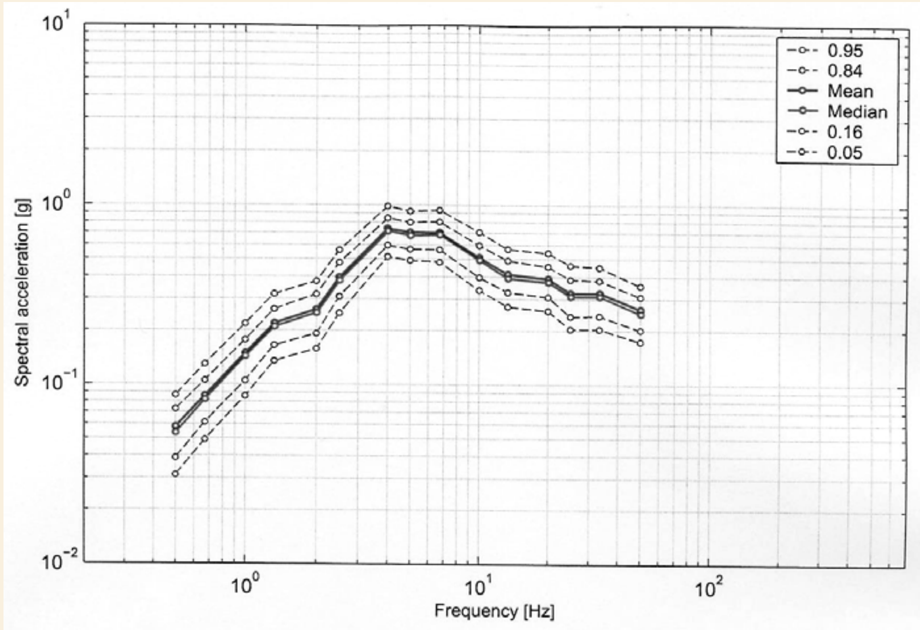
- Credible Distance
  - Realistic information on the distribution of seismic activity on faults is often not available
    - Instationary
    - Normally shortest distance between fault and site
  - Realistic information on the distribution of seismic activity for area sources typically not available
- Two possibilities
  - use half of the theoretical rupture length (can easily be calculated) – less informative
  - Distance from central fault segment to site
  - Use seismic zonation and assume a uniform distribution for seismic activity over the area (maximum entropy) – use mean distance

Fundamentals of a Dependable Seismic Hazard Analysis – IX- Ground Motion

MCE – distance half of rupture length



PSHA – return period 10000 y.



Same maximum magnitudes and attenuation model used, Mean values very close (Klügel 2004)

Fundamentals of a Dependable Seismic Hazard Analysis – X- Ground Motion

- Assumption of an uniform distribution of seismic activity is more common
  - Makes use of the site investigations, performed according the IAEA safety guide (no near site or known near-site sources)
    - Detailed at site areas (1:500)
    - Site vicinity (1:5000)
    - Near regional (1:50000)
    - Regional (1:500000)
- Weak earthquakes (stick-slip sliding mode) cannot be localized
  - Consider a background source of Mw=5.0 (in low/moderate seismic areas) at 2.5 km distance (uniform distribution for the site vicinity research area)

Fundamentals of a Dependable Seismic Hazard Analysis – XI- Ground Motion

- Regionally validated attenuation model
- Validation difficult in low seismic areas
    - Physical models are also limited due to the lack of data
  - Experience from data analysis after the Izmit earthquake (Schwarz & Ende)
    - Shape of an attenuation equation developed on weak aftershock data does not change largely, if strong motion data from the same region is added

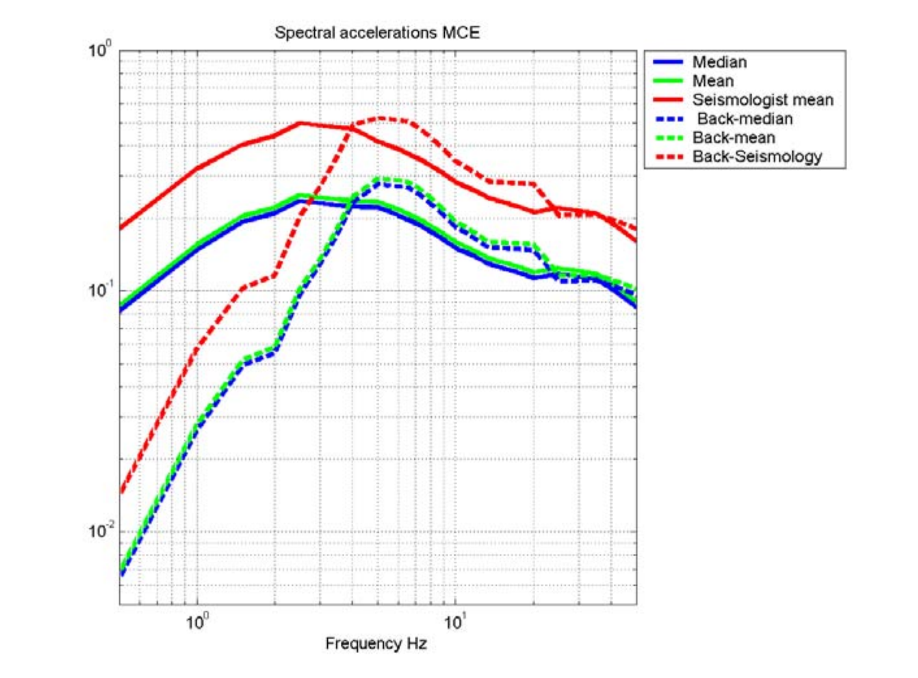
→ Simple engineering calibration technique

Fundamentals of a Dependable Seismic Hazard Analysis – XII- Ground Motion

- Calibration – „Fitting Factor“ Approach
  - Select a basis attenuation model developed for a region (no regional variability) preferably with seismotectonic similarity and similar ground conditions
  - Develop response spectra (5%-damping) for the site of interest using existing recordings (even for weak quakes)
  - Develop and apply fitting factors

$$F_f(M,D) = \log(Sa,measured) \,/\, \log(Sa,calculated)$$

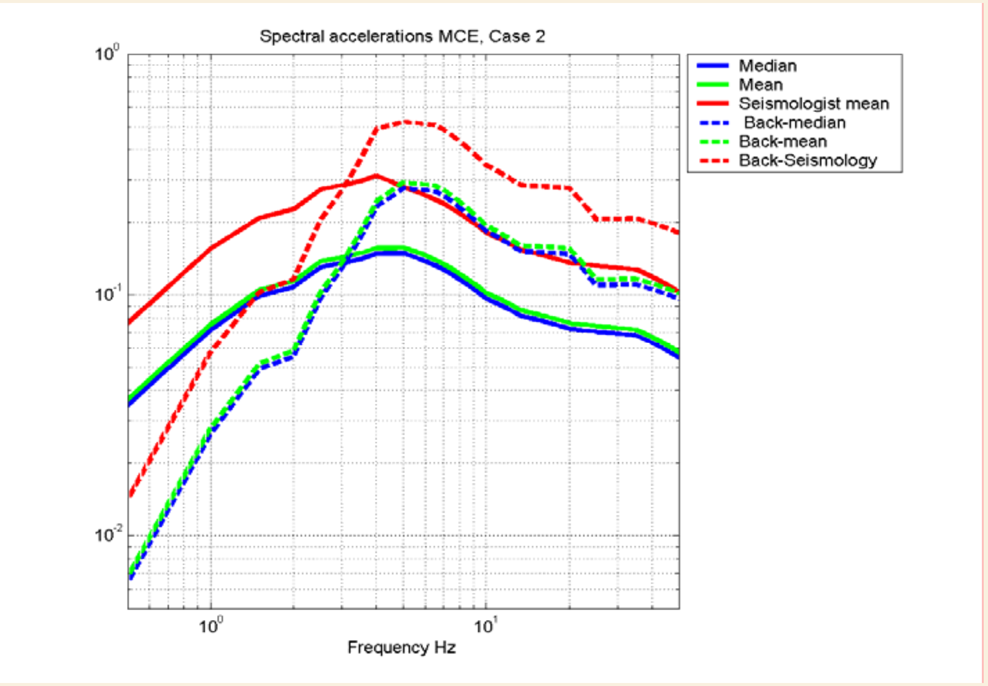
Practical application – Case 1



- Case 1 – maximum magnitude values from PEGASOS-experts + background source at 2.5 km
- Information from each source maintained – no need for de-aggregation
- 0.1 g EGA is a reasonable anchor point for design spectra in low seismic areas (stiff soil conditions)

Background sources govern the design of buildings with a fundamental period below 0.25 - 0.3s in low seismic areas

Practical application – Case 2



- Maximum magnitudes derived from the extraregional model for central Europe (Reisner& Iogonson, 1996) – lower by 0.5 magnitude units
- Additional Background source

Conclusions

- Proposed methodology is robust and time-invariant
  - In conjunction with the current practice of linear-elastic design methods leads to robust design including a reasonable safety margin
- Proposed methodology allows to make direct use of the results of site investigations
- Final result in a direct and realistic de-aggregated format (related to real sources)

Conclusions

- Proposed methodology is simple, it also allows for developing an input to a seismic PRA if conditional risk measures are used
  - Conditional risk of core damage for all NPPS in case of occurrence of the maximum possible magnitude can be calculated
  - This parameter can be used to develop risk-informed design criteria for nuclear installations
    - Example 0.1 % conditional CDF in case of occurence of the maximum magnitude