Earthquake engineering needs and seismic hazard assessment

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Abstract

We present a detailed discussion on the needs of hazard assessment for different applications of earthquake engineering and risk assessment. This discussion includes design and risk assessment issues. We define the requested information from seismic hazard analysis as an input to a meaningful and economical engineering analysis. This provides the basis for a detailed review of the main methods of contemporary seismic hazard analysis: (1) traditional Probabilistic Seismic Hazard Analysis (PSHA) as used in building codes of many countries, (2) scenario-based seismic hazard analysis or neo-deterministic seismic hazard analysis (NDSHA) as the principal alternative, and (3) the state of the art physics-based deterministic method.

We demonstrate that only the physics- and scenario-based seismic hazard analysis method that combines (a) contemporary seismic waveform modelling, (b) an in-depth geological and seismo-tectonic analysis of the region of interest, and (c) empirical information is able to provide the complete set of input information for economical earthquake engineering analysis that allows to combine improved seismic performance of both the structures and components with reasonable design costs. We show that the scenario-based seismic hazard method can easily be adapted/extended for risk assessment as required in assurance applications by developing state of the art probabilistic data models that are in compliance with observational data assembled in earthquake catalogues.

The paper includes a practical example of the scenario-based approach for the development of the design basis of a critical infrastructure and the risk assessment for a seismically induced production loss of a nuclear power plant located in Switzerland.

We recommend that DSHA and NDSHA must be used for engineering design. When/if PSHA is required based on national regulations, it is highly

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recommended to compare the results/output of PSHA results with that of physics- and scenario-based analysis or NDSHA maps.

Keywords: seismic hazard analysis, seismic design, seismic risk analysis, earthquake engineering.

1 Introduction

The discussion among seismologists about the “pros” and “cons” of deterministic and probabilistic seismic hazard analysis has a long history and caused many sharp controversies in the past. While the seismic design of critical infrastructures such as nuclear power plants and dams was and to a large extent is still based on deterministic design procedures, the probabilistic method that was formulated as a risk-based approach [1] has been gradually introduced over the years for national building codes of many countries. Risk-based approach also found a wide range of applications in the insurance industry [2] to support the calculation of risk insurances premiums exposed to seismic hazard. Both applications are mostly based on the use of probabilistic seismic hazard maps which portray a spatial distribution of peak ground acceleration (pga) for a specific probability of exceedance appropriate for the intended purpose. Applying a Poissonian assumption for earthquake recurrence [1], this probability of exceedance is usually converted into a return period. The latter is frequently incorrectly interpreted as a temporal characteristic of the recurrence of earthquake ground motion accelerations although there is no basis for this interpretation and the above assumption [3].

Following the completion of a number of comprehensive probabilistic seismic hazard studies in the USA [4] has leaded to (a) the development of the SSHAC procedures [5], (b) an extended use of probabilistic risk assessment by the US NRC [6], and (c) incorporating risk-based methods into design procedures of critical infrastructures. The first risk-based design approach was related to the licensing of the US nuclear power plant Diablo Canyon located close to the Hosgri fault in Central California coast, and not far from the San Andreas fault. The application of the SSHAC procedures outside the USA was facing practical problems both for risk applications as well as for the evaluation of the design of existing nuclear power plants [7, 8].

The damaging large earthquakes of Sichuan, China (May 12, 2008), L’Aquila, Italy (April 6, 2009), Haiti (January 12, 2010) as well as the Tohoku earthquake in Japan (March 11, 2011) have provided very valuable experiences and lessons for any responsible seismologist or earthquake engineer for a thorough review of the currently adopted methods for seismic design. Observed data from these events have amply demonstrated that published probabilistic seismic hazard maps underestimate the seismic risk for the affected areas [9] and for other seismically active regions as well. It was demonstrated that sophisticated site-specific probabilistic risk analyses based on the logic-tree method applied to the Tohoku earthquake source may support incorrect conclusions to specify (an underestimated) seismic load for the design of critical infrastructures [10]. It follows that such errors will result in improper design of structures, both for residential areas and critical infrastructures; and certainly have contributed to huge losses of human life and a spectacular catastrophe of the Fukushima nuclear reactors.

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Therefore, it is necessary and worthy to evaluate the strengths and vulnerabilities of seismic hazard analysis methods based on more objective criteria which are based on the intended practical engineering applications. Such evaluation has also to examine critically any major substantial improvements in the methodology of physics- and scenario-based seismic hazard and risk analysis. These methods are based on incorporating advanced and realistic seismic waveform modelling. Frequently they are summarized under the name of neo-deterministic seismic hazard analysis method (NDSHA) [11] or in case of site evaluations for critical infrastructures as scenario-based method [12]. They provide a meaningful alternative or complementary method to the currently used seismic design procedures.

In section 2, we analyse the needs of seismic hazard analysis, expectations of the output for different engineering applications, and perform an evaluation of the capability of different methods in meeting the requirements.

In section 3, we outline the procedure for the development of seismic design basis for a critical infrastructure based on the neo-deterministic method, including an approach for risk analysis.

In section 4, we provide an example analysis for the proposed site of a new nuclear power plant in Switzerland (generic study).

Section 5 is dedicated to conclusions.

2 Needs and expectations of seismic hazard analysis for engineering and risk management applications

Klügel provided in [2] a comprehensive overview on the areas of application of seismic hazard analysis. Summarizing this discussion of different areas of applications results in the following classification:

1. Design applications to develop earthquake-resistant infrastructures
    a. Earthquake-resistant design of dwellings (residential area) and lifelines
    b. Earthquake-resistant design of critical infrastructures like
        i. Nuclear power plants and research reactors
        ii. Radioactive waste repositories
        iii. Chemical plants
        iv. Bridges
        v. Military plants
        vi. Liquefied gas pipelines and pressurized gas storage tanks and
        vii. Dams.
2. Risk assessment and risk management applications
    a. Financial risk analysis for estimating capital and life losses caused by earthquakes (risk insurance problem, production loss risk)
    b. Technical risk analysis evaluating the risk associated with the operation of a critical infrastructure with respect to a critical infrastructure and to possible environmental impact.

The goals of engineering analysis supporting these different applications are very different. Consequently, methods to be used for the analysis also shall be different. For example, for a lifeline that has to operate without repair during or after an earthquake (e.g., a pump with the associated support system); or a hospital building that shall be available after a strong earthquake, it is frequently sufficient to perform a linear-elastic structural analysis. The reason is that significant non-linear deformations associated with the onset of damage are not permitted. Essentially, this means that the behaviour of such lifeline structures during an earthquake has to remain within it linear-elastic design limits. A completely different picture may arise for residential dwellings. Here some limited damage and therefore a nonlinear response with residual nonlinear deformations of structural and non-structural elements may be acceptable as long as it is possible to evacuate people out of their homes. For insurance risk evaluations, it may be of interest to assess the grade of damage to assess the potential financial consequences due to repair costs. Similarly, for storage facilities (e.g., tanks), or piping systems, it may be sufficient to demonstrate that the integrity of system boundaries are maintained, therefore a non-linear response during an earthquake and limited residual deformations or even partial failures of supporting structures may be acceptable. Of course, in all cases the decision maker may also request a full scale linear elastic behaviour of the structure during an earthquake. The problem is that such an approach is not cost-effective and therefore the resulting design may not be economical.

Therefore, in current engineering practice different goals of engineering analysis for complex infrastructures are formulated in terms of required performance levels for the different systems, structures and components depending on their technological functions. The required performance levels may reach from linear-elastic design limits till the acceptance of significant nonlinear response with residual deformations, as long as this behaviour is commensurate to the function of the system or component.

From this discussion, it can be concluded that the most challenging case with respect to engineering analysis is to perform a comprehensive nonlinear analysis leading to realistic results (of the structural analysis).

This is a significant change in comparison to the time when both traditional deterministic [4] and traditional seismic risk assessment methods [1] were developed. At that time methods of structural analysis were limited to linear-elastic methods with some minor extensions to the analysis of the most simple non-linear vibration systems (limited models with just a few degrees of freedom). Therefore, it was sufficient for any type of seismic hazard analysis to provide just the information requested for a linear-elastic structural analysis. This information was typically provided in the format of design earthquake response spectra developed from linear-elastic structural response analysis. To cope with the manifold different types of earthquakes leading to different responses of structures both the deterministic as well as the probabilistic method attempted to develop design spectra in the format of broad-band spectra. In case of the probabilistic method these spectra took the format of a uniform seismic hazard spectrum. Corrections to these spectra with respect to tolerable nonlinear deviations were introduced by engineers developing structural response factors using for example different types of ductility definitions. The incorporation of structural response factors allowed reducing design loads in comparison to a full linear-elastic response in accordance to the design ductility and the structural redundancy considered by the designer. The basic analysis methods remained to be linear-elastic.

In the changed situation today, it required that a seismic hazard analysis provides significantly more information to the earthquake engineer and risk analyst. This can easily be demonstrated by remembering elementary physics. To cause damage to a structure or component (residual nonlinear deformations) it is necessary that an earthquake causes destructive work. For performing work according to energy conservation principles only the following energy sources are available:

- The seismic input energy of the earthquake imparted to a structure.
- The potential energy of the structure (and subsequently, the potential energy of components fixed to structural floors).

The part of the seismic input energy of the earthquake, that can be imparted to a structure and can be converted into structural vibration, depends both on characteristics of the earthquake (defined in seismic hazard analysis) as well as on characteristics of the structure.

The relevant earthquake characteristics are:

- the amplitude of ground excitations,
- the spectral shape of ground excitations , and
- the duration of shaking.

These characteristics can be defined (within some epistemic uncertainty bounds due to limited knowledge and some aleatory variability due to simplifications of the models used in comparison to real world systems [13] with the help of models using information like magnitude of the earthquake; distance between earthquake location (asperity) and site; faulting style; internal earthquake source characteristics; direction of seismic wave radiation with respect to fault rupture propagation; attenuation characteristics of the wave path; site characteristics; etc as input parameters.

The key structural characteristics limiting the seismic input energy to a structure are:

- the natural frequencies for different vibration modes (the lower frequencies being the most important),
- mass and material distribution of the structure, and
- material and structural damping characteristics.

For mobilizing the potential energy of a structure to perform destructive work, it is necessary to convert the potential energy into kinetic energy. For this transformation, a minimal amount of seismic input energy of the arriving waves at a site is necessary. It is understandable that this minimal level is specific for the individual structure.

Therefore, for correctly characterizing the non-linear response of a structure (component) during an earthquake, very detailed information has to be provided by seismic hazard analysis. The minimal information is:

- ground motion duration, and
- the temporal-spatial distribution of ground motion excitations at the site.

It is understandable that due to the complexity of the task to define these characteristics, some simplifications have to be made in practice. Nevertheless, it should be clear that the only way to respond to the requirements of modern engineering applications consists in improved modelling of multi-dimensional seismic wave propagation in whatever analysis context (neo-deterministic or probabilistic) these models may have to be applied.

The extensive use of seismic waveform modelling in different scales is the key characteristic of the neo-deterministic or scenario-based method. Traditional PSHA, on the contrary, is based on the use of empirical ground motion characteristics based on data collected from different seismo-tectonic regions that are not validated for the sources or even just for the region where they are applied. The highest level of “ignorance” of the true earthquake engineering applications was reached by the development of the SSHAC-procedures [5]. These procedures require/expect the involved experts that (their) hazard estimates do reflect the centre, body, and range of uncertainty of knowledge that would have been expressed/acknowledged by the technical informed community willing to accept the SSHAC procedures. In practice, this leads to the situation that empirical ground motion prediction models from other regions are imported to regions even where sound regional models are available, and so the models are completely unacceptable (e. g., models developed for crustal earthquakes are applied in subduction areas [14]). Instead of focussing on the development of reliable regional models, a complex weighting procedure based on logic trees is applied as its rule “I don’t know what the correct model is but by mixing them somehow I may get a better guess “. The gaps left by the traditional PSHA

Table 1: Fulfilment of engineering and risk analysis needs by different seismic hazard analysis methods.

Seismic Hazard Analysis Method	**Hazard Output Information**	**Additional Compensating Engineering Methods**	**Known Strengths and Vulnerabilities**	**Level of Fulfilment of Engineering and Risk Analysis Needs**
Deterministic Seismic Hazard Analysis	Site Intensity	Assignment of engineering parameters to site intensity; synthetic time-histories for dynamic analysis derived from response spectra	Macroseismic intensity is a very good hazard estimator; Assignment of engineering parameters is associated with significant uncertainties; Uncertainty can be reduced using waveform modelling techniques	Medium, not applicable for risk analysis
Deterministic Seismic Hazard Analysis	Site specific design response spectrum for maximum credible earthquakes – either for far field and near field earthquakes separately or in form of a broad-band spectrum	Synthetic time-histories for dynamic analysis	Based on the use of empirical ground motion prediction equations; in case of lack of regional data imported information is frequently used, inherent conservatism due to the focus on rare strong events	Medium to high (conservative design), not applicable for risk analysis
PSHA [1]	Hazard Curve in terms of site intensity	Assignment of engineering parameters to site intensity; synthetic time-histories for dynamic analysis derived from response spectra	The design hazard level in terms of probability of exceedance has to be defined by the decision maker, optimistic results in high active seismic regions, weak link to engineering geology of the region, lack of data problem	Low-to medium, applicable for risk analysis

Table 1: Continued.

Seismic Hazard Analysis Method	**Hazard Output Information**	**Additional Compensating Engineering Methods**	**Known Strengths and Vulnerabilities**	**Level of Fulfilment of Engineering and Risk Analysis Needs**
PSHA [5]	Hazard Curves in terms of spectral accelerations, Uniform Hazard Spectra for different probabilities of exceedance	Hazard deaggregation to understand hazard background without link to geology; synthetic/artificial time-histories from response spectra	Large complexity, artificial and physically unsound separation of seismic wave propagation into source, path and site effects, insufficient treatment of physical dependencies in probabilistic models, weak link to geology, large uncertainties of the output, optimistic results for high seismic areas (can be proven by converting results to site intensities)	Low (for design), low for risk analysis (due to inappropriate uncertainty propagation models)
Neo-deterministic (scenario-based) seismic hazard analysis (NDSA)	Hazard background in physically traceable scenarios, assessment of the temporal-spatial distribution of ground excitations is possible	Information can be used directly, some simplification based on conservative assumptions may be needed to reduce the computational effort	Strong link to the geological and seismo-tectonic specifics of the region, traceable hazard sources large computational effort for multidimensional analysis	High, not applicable for risk analysis
Probabilistic scenario-based seismic hazard analysis (extension of NDSA)	Information as from the neodeterministic method, frequency of occurrence for critical scenarios [12]	Information can be used directly, some simplification based on conservative assumptions may be needed to reduce the computational effort	Strong link to the geological and seismo-tectonic specifics of the region, traceable hazard sources large computational effort for multidimensional analysis, lack of data for rare events as for PSHA	High (design) – best available method for risk analysis

method have to be filled up by earthquake engineers with what appears to sound as reasonable but unfortunately not related to correct assumptions for quantifying seismic hazard (*e.g., "high acceleration – that means high magnitude earthquake = long strong motion duration"*) [15, 16] .

Seismic waveform modelling can also be applied in a probabilistic context (outside the standard PSHA model in [1, 5]). Such new methods are in discussion or under development [17] which needs broader support for practical applications.

Table 1 summarizes the assessment of the capability of seismic hazard analysis methods with regard to meeting earthquake engineering and risk analysis applications. The overview considers different seismic hazard analysis methods including differences in the output hazard parameters. The evaluation is focussed on the usability of the method with respect to the design and risk analysis of critical infrastructures.

3 Scenario-based approach for the development of the seismic design basis for critical infrastructures

Figure 1 shows in the form of a mind map the key elements of the seismic design procedure as they are embedded into the decision making process for selecting a site and deciding on the seismic design basis for a critical infrastructure. The procedure is based on a combination of deterministic and probabilistic assessment elements. While the design is developed based on a scenario-based procedure combining traditional DSHA with waveform modelling as it is characteristic for NDSHA, an additional risk analysis is performed to check the credibility of the design from a risk perspective. The procedure outlined here follows in general the approach suggested first in [18].

In Figure 1, steps in the management decision process are highlighted in red (e.g. site selection and the decision on the seismic design basis), while the key steps of the seismic design procedure are highlighted in green. Supporting steps (required information) are shown in light blue colour.

According to the procedure, the first step consists in the development of a noninformative (generic) seismic hazard for candidate sites suitable for the construction of the planned critical infrastructure. This more generic (or regional) seismic hazard analysis is based on

- a preliminary earthquake catalog,
- a regional seismo-tectonic model including e. g., fault maps on a larger regional scale,
- a global geological model of the region, and
- readily available or generic regional ground motion models and magnitude-fault length scaling relationships.

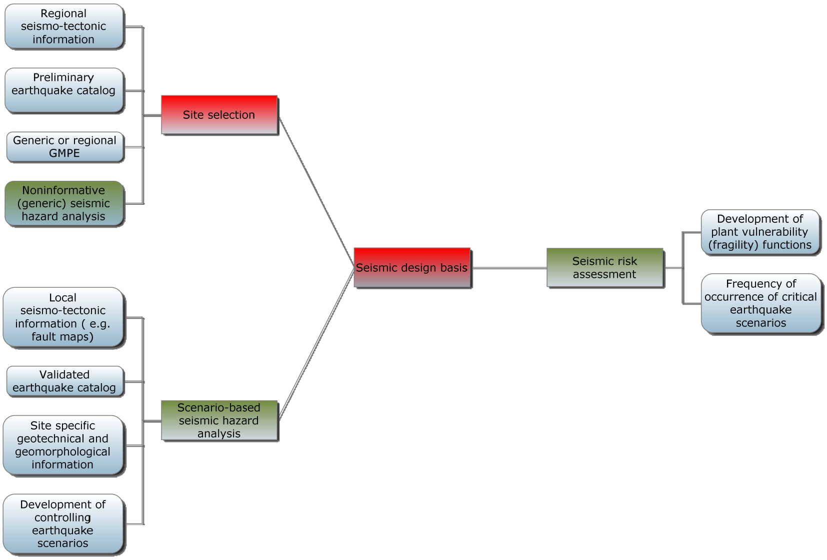

Figure 1: Mind map illustrating the key elements of the scenario-based seismic design procedure.

Performing a generic seismic hazard analysis for several candidate sites includes:

- selecting the target parameter of the analysis to characterize ground motion intensity, and
- developing an enveloping response spectrum for the target parameter.

As target parameters may serve different seismological or engineering characteristics or combinations thereof, the use of combinations of parameters is preferable because a single parameter barely can express the engineering effects of seismically induced ground motions. The only exception is the site-specific intensity that can be used as a criterion for the selection of the most suitable site for the construction.

For a generic seismic hazard analysis, it is sufficient to develop an enveloping (pseudo) spectral acceleration response spectrum and to provide an assessment of the maximum strong motion duration of the underlying controlling earthquakes (for elastic design of structures and components, this is not even required). This is sufficient for robust decision making. Figure 2 shows a flow chart with the key working steps for the development of a preliminary seismic design basis by the help of a preliminary non-informative seismic hazard analysis. The methodology follows essentially the traditional approach of deterministic seismic hazard analysis (DSHA).

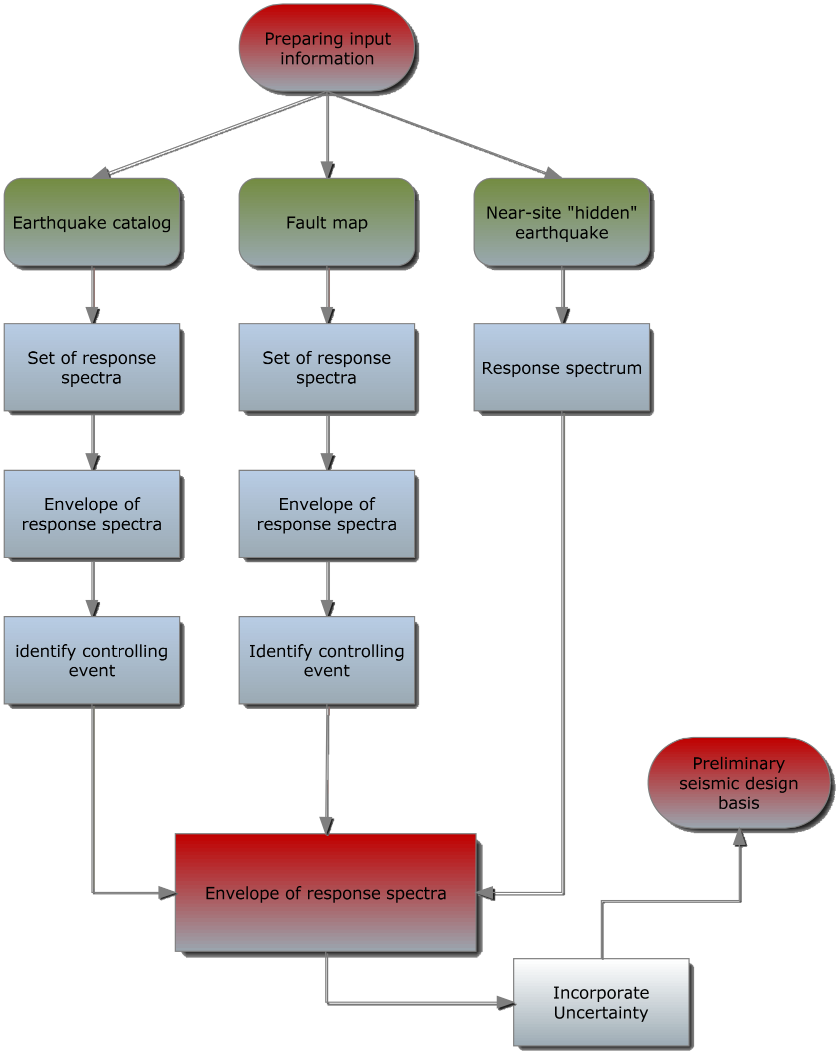

Figure 2: Flow chart illustrating the working steps of the generic seismic hazard analysis (DSHA method).

To derive a preliminary design spectrum, three hazard input components have to be processed and evaluated:

- Historical and instrumentally recorded earthquakes (from the preliminary catalog) have to be processed into response spectra by the help of a generic or a regional ground motion prediction equation; an envelope of all obtained response spectra has to be derived.

- The available fault maps have to be processed into fault characteristic response spectra by defining for each fault a single controlling earthquake characterized by maximum credible magnitude and the shortest distance from fault to site; an envelope of all obtained response spectra has to be derived.
- For the near-site surroundings the existence of a hidden undetectable active fault has to be assumed. A controlling event for this fault has to be defined based on the resolution limits of the site investigation program and the quality of historical information available. In case of high quality long term historical information (and presuming that the site of interest is not directly located in the area of largest historical earthquake event) it is sufficient to assume a controlling event with a magnitude corresponding to the maximum magnitude observed in the same seismo-tectonic province reduced by the error of magnitude estimates ($1.5\sigma = 0.5$ magnitude units). A minimum value of magnitude 5.5 is suggested in case of in-sufficient historical information and insufficient information from site specific investigations. The distance to site has to be assumed as half of the corresponding fault length projected to the surface.
- The final step consists in the development of an envelope of all obtained response spectra and the incorporation of uncertainty. For this purpose it is suggested to perform a parametric sensitivity study on the effect of using alternate empirical ground motion prediction equations suitable for the region to define possible epistemic uncertainty. The final preliminary design basis spectrum is then defined as the envelope of the response spectra multiplied by the factor $F = \exp\left(\sigma_c^2 / 2 \right)$ where σ_c is calculated as the Gaussian error law combination of epistemic uncertainty and aleatory variability:

$$\sigma_c = \sqrt{\sigma^2_{epi} + \sigma^2_{aleatory}} \qquad (1)$$

The resulting factor F should be in the range of 1.3–1.4 as long as a set of suitable for the region empirical ground motion prediction equations is used.

The maximum strong motion duration has to be assessed based on the controlling events derived from each component of seismic hazard input information using the maximum strong motion duration from each of the single controlling events.

After site selection and the development of the key design features of the critical infrastructure to be built (e.g., for a nuclear power plant) a scenario-based seismic hazard analysis based on the site-specific information and considering the specifics of the preliminary design of the plant to be built is to be performed.

A key topic is the gathering of local information of faults in the surroundings of the site and the assessment of their seismogenic potential. Typically, it is expected that the near-site hazard contribution can be reduced in comparison to the preliminary seismic hazard analysis by obtaining a more detailed fault mapping from geologists. A characteristic feature of the refined scenario-based seismic hazard analysis consists in the replacement of empirical ground motion prediction equations by waveform modelling techniques. These techniques are applied to obtain a set of source and site compatible ground motion time histories as required for non-linear structural dynamics to support the final design of the critical infrastructure.

The results of the more specific scenario-based seismic hazard analysis (based on NDSHA procedures) are used to check and to validate or modify the design features of the plant with respect to earthquake resistance.

To complement the deterministic seismic design analysis, an additional risk assessment will be performed as the concluding step of the design development procedures. In general it can be expected that this risk assessment will confirm the robust design of the plant. If necessary, design modifications can still be performed to address specific insights from the risk assessment.

4 Example for design procedure

The procedure has been applied in a generic study for the development of the seismic design basis of a new nuclear power plant near the existing Goesgen nuclear power plant in Switzerland.

4.1 Sources of geological and seismo-tectonic information

Several past seismic hazard studies performed in Switzerland have provided a large amount of information from the beginning of the site evaluation process.
Several past seismic hazard studies performed in Switzerland have provided a large amount of information from the beginning of the site evaluation process.
The main source of input for the first component of the generic seismic hazard analysis is based on (a) the site specific earthquake catalogue of Goesgen developed by comparing several published earthquake catalogues of Switzerland and the neighbouring countries [18], (b) a regional geological fault map of Switzerland from Swisstopo and (c) a detailed local fault map for the surrounding area from NAGRA. The detailed local fault map allows a direct estimate of seismic hazard from near-site sources without the need for refinement for a later detailed analysis.

4.2 Development of preliminary seismic design basis

The empirical ground motion prediction equations of Ambraseys *et al.* [19] were considered as the generic empirical ground motion prediction model appropriate for Switzerland because it was based on a broad European database. The equations for stiff-soil were applied because the average shear wave velocity at the plant site lies between 420 and 520 m/s. This selection was justified by a detailed comparison with other empirical ground motion equations leading to similar or lower hazard results.

The evaluation of historical events resulted in a list of earthquakes with magnitudes larger than 5, as given in Table 2. Earthquakes with magnitudes smaller than 5 (EMS 98 intensity <=VII) do not present a problem to engineered structures like a NPP, and therefore can be ignored.

Figures 3 and 4 compare the response spectra of the largest historical events: the Kaiseraugst earthquake reported from the Roman times and the Basel earthquake. Because the source mechanisms were not known, all different faulting styles considered by Ambraseys *et al.* [19] are applied. Not unexpectedly, thrust faulting produced the highest response spectrum. Based on the analysis, the Basel earthquake can be regarded as the controlling earthquake for the reference site by considering all recorded or reported earthquakes in the catalogue. At the same time, the spectrum of the Basel earthquake represents the enveloping response spectrum for historical events. For a magnitude 6.6 event, a strong motion (uniform) duration of 14s is considered as a reasonable estimate. The (best estimate) PGA at the reference site for the Basel event is 0.112 g. The associated site intensity in EMS98 scale is VII-VIII. The evaluation of local fault map information was performed using the generic Wells and Coppersmith [20] equations.

Table 2: Historical earthquakes with magnitude exceeding 5.

Year	Location	Mw_Catalog, Goesgen	Distance, km
250	Kaiseraugst (Augusta Raurica)	6	25.05
1721	Aesch	5	30.01
1356	Basel	6.6	30.01
1356	Basel	5.4	34.42
1650	Basel	5.3	38.79
1777	Sarnen	5.1	57.87
1601	Unterwalden	5.9	57.89
1964	Sarnen	5.3	61.55
1774	Altdorf	5.7	78.40
1729	Frutigen	5.2	85.78

Independently from the age of the faults it was assumed that all faults might be reactivated during the lifetime of the planned new nuclear power plant. To incorporate possible epistemic uncertainty into the analysis the maximum credible earthquakes were assigned using the median plus 1 sigma estimate from the Wells and Coppersmith [20] equations.

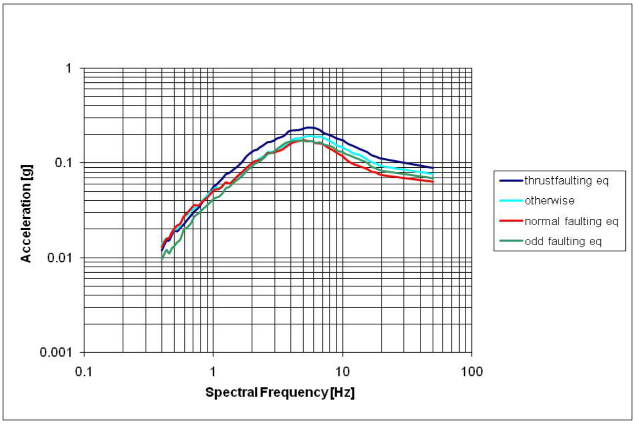

Figure 3: Site specific response spectra of the Kaiseraugst (250) earthquake at the plant site.

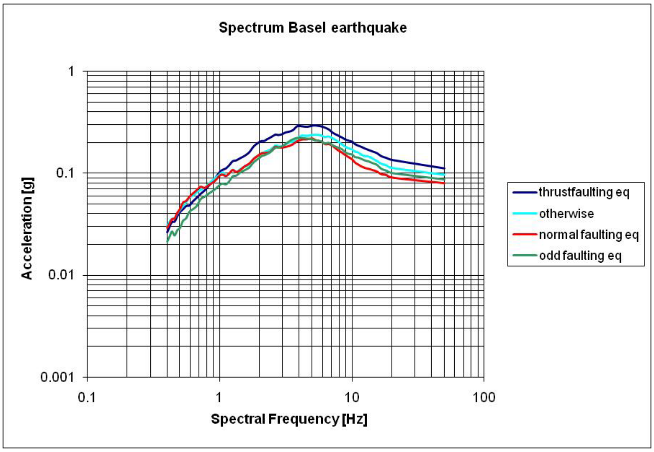

Figure 4: Site specific response spectra for the Basel earthquake (1356).

Figure 5 shows the magnitude distribution obtained by the described method from the information of local fault maps.

Detailed analysis of the local fault map identified a possible critical near-site scenario: the “Engelberg scenario” under the assumption of re-activation of the corresponding fault system. The scenario is characterized by a magnitude of 5.2 (median + 1 sigma) and a shortest distance to the site of 3.5 to 4.5 km. The most likely fault mechanism is normal, but in the generic study a more general approach was applied. Therefore, all fault styles considered in the Ambraseys [19] equations, except for blind thrust (the fault is not blind) faulting, were included in the analysis. The strong motion duration of the Engelberg scenario event is approximately 5s. The associated site intensity in EMS 98 scale is VII. Figure 6 shows the response spectrum obtained for this earthquake scenario.

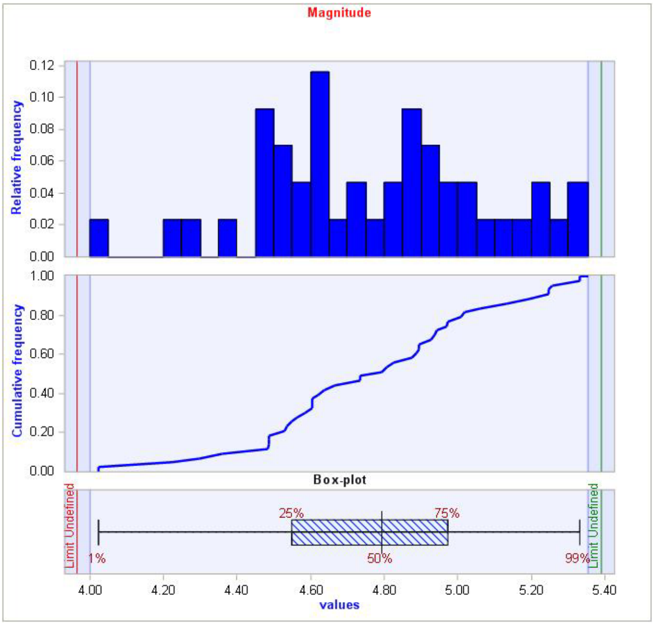

Figure 5: Estimated magnitude distribution from the local fault map.

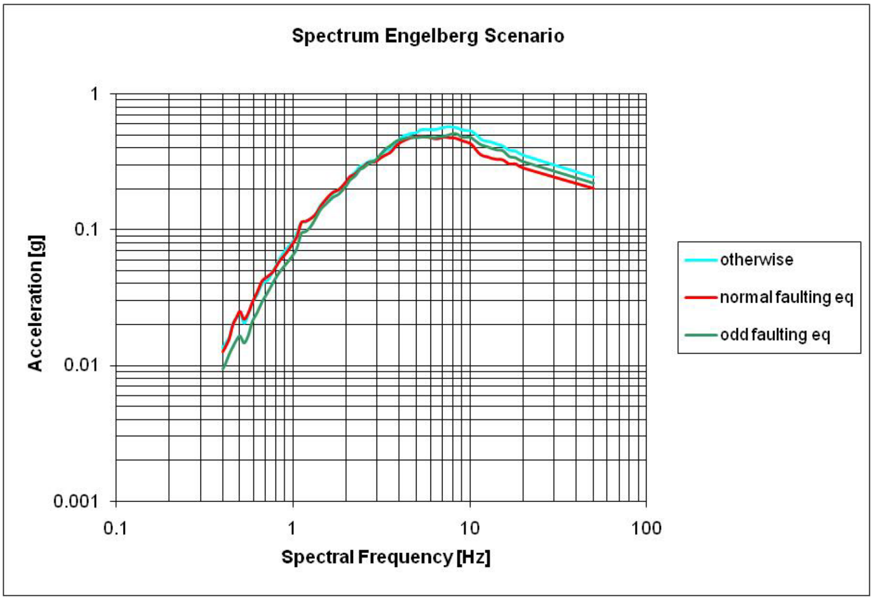

Figure 6: Site specific response spectra of the Engelberg earthquake scenario at the Reference site.

The total uncertainty (composite uncertainty) of the ground motion predictions was estimated to be $\sigma_c = 0.78$. Therefore the safety factor to be considered in the design basis was estimated as $F = 1.36$.

Figure 7 shows the resulting preliminary design spectrum constructed as the envelope of all seismic information processed according to the procedure.

The computed "mean" response spectrum is anchored at a PGA value of 0.33g, while the best estimate spectrum is anchored at 0.243g. These PGAs refer to the maximum horizontal acceleration. The preliminary seismic design basis is very conservative and robust, because it considers all seismic sources of Switzerland (historical events, active and not active sources) of engineering importance. The resulting spectrum has a spectral shape which envelops the response spectral shapes for all underlying seismic sources. The strong motion duration is set to the value corresponding to the strongest historical event, despite the fact that this event will lead to a significantly lower response spectrum.

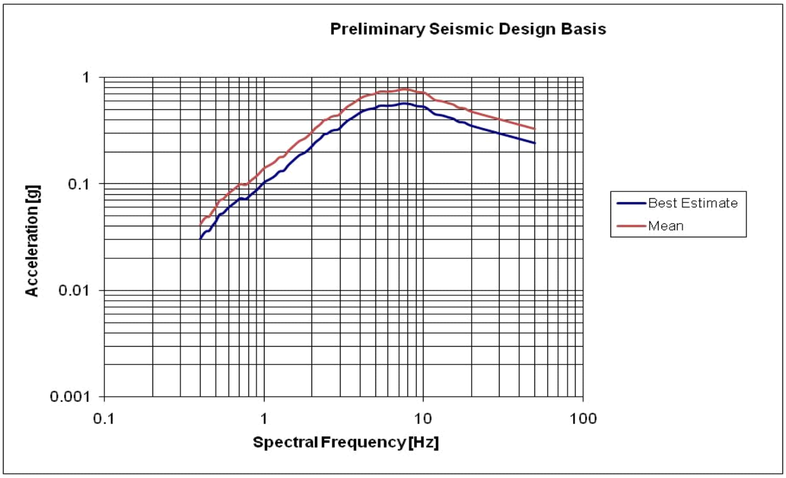

Figure 7: Preliminary seismic design basis (best estimate, mean).

4.3 Refined seismic hazard analysis – final seismic design basis

Because very detailed information already was available during the preliminary phase of the development of the design basis, the refinement phase focussed on the modelling of critical scenarios. The Basel earthquake scenario and the Engelberg earthquake scenario were selected for the analysis.

The Basel earthquake scenario was investigated using a hybrid technique based on a combination of modal summation and finite difference methods to simulate the ground motion at the reference site [21]. A large set of sensitivity analyses was performed to estimate the range of ground motion parameters expected. These analyses included a variation in (1) bedrock model, (2) source radiation pattern, and (3) earthquake magnitude. A total of 14 analyses were performed. In most cases, the calculated PGAs fell below the reference PGA value of the preliminary design basis. Only when the upper bound PGA value for the historical Basel earthquake magnitude (Mw=6.9) was estimated for the maximal radiation pattern configuration, the reference PGA value was exceeded.

The Engelberg scenario was investigated with a kinematic model [22]. The theoretical maximum magnitude value of Mw=5.2 was postulated for all simulations. A large set (totalling 44 cases) was used for performing sensitivity analyses, including variations in source, path (with epicentral distance) and site parameters. The mean value for PGAs of all simulations fell below the preliminary design basis reference PGA value. The short duration of strong motion was confirmed and so also a site intensity of VII (EMS 98) confirmed. An earthquake of this magnitude does not concern the safety of a modern nuclear power plant due to its insufficient energy contents imparted to the structures.

Therefore, the preliminary seismic design basis was confirmed as a sound basis for engineering design.

4.4 Risk analysis: loss of production

The scenario-based approach allows for a flexible approach to risk analysis. The basic concept is that the available data shall drive the selection of the probabilistic model used in the analysis. Because the seismic activity is not stationary – the Poisson assumption is in general not applicable to seismic activity (see discussion in [8] and [17]), a time-dependent model has to be applied for the assessment of instantaneous risk. Different time-dependent models have been suggested in the past for site-specific analysis [12] or for the development of time-dependent seismic hazard maps and an intermediate-term earthquake prediction [23].

In this example, risk assessment was limited to the evaluation of a possible earthquake-induced production loss during the planned lifetime of the new nuclear power plant (about 60 years). As a criterion for a possible production loss, the exceedance of a site intensity of VI was applied in the analysis. The conditional probability that such an event will lead to a production loss was estimated based on a calculated plant fragility function and was found to be about 5% (mean). Because the risk assessment is limited to a short period of time, it is feasible to perform the analysis on the basis of historical information only. The data presented in Table 2 was used and the associated site intensities were calculated based on the equations used for the development of the Swiss national earthquake catalogue [24]. The general renewal process model (GRP) as described in detail [25] and as implemented in the reliability software tool WEIBULL++7© [26] was applied for the analysis. The type I GRP model was found to provide the best prediction of past earthquake observations. The GRP is characterized by three parameters, the rebuild effectiveness factor q, the event rate λ and the power coefficient β of the renewal process. The best estimate calculated parameters are:

$$\beta = 0.4573, \lambda = 0.0759, q = 2.3842E-8$$

The small value of q is a clear indication that the Poisson assumption for the recurrence of site intensities greater or equal VI is not justified for the reference site. The prediction of events exceeding intensity VI over the lifetime of 60 years resulted in the following two-sided confidence interval (90% confidence):

$$n = \left(0.0396, 0.554, 2.0152\right)$$

Therefore, the chance that the new plant will be subjected to earthquake intensity larger than VI during the planned lifetime of 60 years cannot be completely excluded. The probability that at least a single event leading to site intensity greater VI will occur is approximately 40% (mean value). Hence, the total probability of a seismically induced production loss over the lifetime of the structure is about 2%.

5 Conclusions

1. The dramatic limitations of traditional PSHA methods [1, 5] have been amply observed in recent damaging earthquakes, proving that the methods are not able to provide reliable seismic hazard estimates especially in areas of high and low seismicity. This raises the need to develop alternative methods to meet the needs for modern earthquake engineering.
2. Modern seismic hazard analysis methods based on the extended use of waveform modelling techniques (NDSHA) or scenario-based SHA can provide a meaningful alternative to PSHA for engineering needs in developing a robust seismic design basis for critical infrastructures [11].
3. A comprehensive procedure has been developed for developing the design basis of critical infrastructures like a nuclear power plant and its application has been demonstrated for a generic planning study.

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