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A scenario-based procedure for seismic risk analysis

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Abstract

A new methodology for seismic risk analysis based on probabilistic interpretation of deterministic or scenario-based hazard analysis, in full compliance with the likelihood principle and therefore meeting the requirements of modern risk analysis, has been developed. The proposed methodology can easily be adjusted to deliver its output in a format required for safety analysts and civil engineers. The scenario-based approach allows the incorporation of all available information collected in a geological, seismotectonic and geotechnical database of the site of interest as well as advanced physical modelling techniques to provide a reliable and robust deterministic design basis for civil infrastructures. The robustness of this approach is of special importance for critical infrastructures. At the same time a scenario-based seismic hazard analysis allows the development of the required input for probabilistic risk assessment (PRA) as required by safety analysts and insurance companies. The scenario-based approach removes the ambiguity in the results of probabilistic seismic hazard analysis (PSHA) which relies on the projections of Gutenberg–Richter (G–R) equation. The problems in the validity of G–R projections, because of incomplete to total absence of data for making the projections, are still unresolved. Consequently, the information from G–R must not be used in decisions for design of critical structures or critical elements in a structure. The scenario-based methodology is strictly based on observable facts and data and complemented by physical modelling techniques, which can be submitted to a formalised validation process. By means of sensitivity analysis, knowledge gaps related to lack of data can be dealt with easily, due to the limited amount of scenarios to be investigated. The proposed seismic risk analysis can be used with confidence for planning, insurance and engineering applications.

Keywords: Scenario-based seismic hazard analysis; Siesmic risk analysis

1. Introduction

Earthquakes, as many other natural disasters, have both immediate and long-term economic and social effects. Seismic hazard analysis based on the traditional methodology of probabilistic seismic hazard analysis as developed by Cornell (1968), McGuire (1976, 1995) and expanded for the treatment of uncertainties by using expert opinion (SSHAC, 1997) cannot fill the gap of knowledge in the physical process of an earthquake. As discussed by Klügel (2005a,b,c,f), these methods lead to ambiguous results due to their incapability to correctly model the dependencies between large numbers of uncertain random parameters. Wang (2005) argued that a probabilistic seismic hazard analysis, as practiced today, leads to the loss of physical meaning in the results and provides the decision maker with an infinite choice for the

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selection of a design basis earthquake. Klügel (2005e) demonstrated that the results of a probabilistic seismic hazard analysis, presented as a uniform seismic hazard spectrum, do not provide the required input for a seismic probabilistic risk assessment (PRA), as required for risk informed regulation in nuclear technology. Furthermore, the multiscale seismicity model (Molchan et al., 1997) supplies a formal framework that describes the intrinsic difficulty of the probabilistic evaluation of the occurrence of earthquakes by using a simple probabilistic model like the (truncated) Gutenberg–Richter equation without considering dependence on the scale of the problem. According to this model, only the ensemble of events that are geometrically small, compared with the elements of the seismotectonic regionalisation, can be described by a log-linear magnitude frequency (FM) relation. This condition, largely fulfilled in the early global investigation by Gutenberg and Richter (e.g., see Figure 49 of Bath, 1973), has been subsequently violated in many investigations. This violation has given rise to the Characteristic Earthquake (CE) concept (Schwartz and Coppersmith, 1984), in disagreement with the Self-Organised Criticality (SOC) paradigm (Bak and Tang, 1989). The main problem is proper choice of the size of the region for analysis, so that it is large enough to guarantee the applicability of the Gutenberg–Richer (G–R) law and related concepts. Additionally, G–R equation has no objective time-series analysis for obtaining realistic earthquake magnitude recurrent times and therefore results using G–R projections have a profound uncertainty.

Therefore, meaningful alternatives are essential for users and decision makers in selecting a robust design basis for civil infrastructures. Results from a deterministic scenario-based seismic hazard analysis methodology (e.g., Field, 2000; Panza et al., 2001) provide a meaningful alternative both for design applications, as well as for modern risk analysis.

2. Methodology of deterministic scenario-based seismic hazard analysis

The methodology of deterministic scenario-based seismic hazard analysis in this paper represents an extension of the methods, which have been used for deterministic seismic hazard analysis in high seismic areas like California for more than 30 years (Mualchin, 1996). The extension specialises in the treatment of problems specific to seismic hazard analysis for low to moderate seismic areas, incorporates physical modelling approaches and introduces a sound methodology for risk assessment.

2.1. Concept of scenario-based seismic hazard analysis

The selection of one or a limited set of scenario earthquakes is the central concept of the methodology. The selection of scenario earthquake(s) includes the following steps:

- Characterisation of seismic sources for capacity/potential and location.
- Selection of hazard parameter(s) to characterise the impact of an earthquake on the infrastructure.
- Development of an attenuation model for the parameter to derive the values of the parameter(s) at the site.
- Incorporation of site effects, and near-field and potential directivity/focusing factors.
- Definition of the scenario earthquake(s).

2.2. Characterisation of seismic sources

The selection of scenario earthquake(s) requires a detailed analysis of all regional seismogenic or active seismic sources surrounding the site of interest and assessment of their capability and potential to produce earthquakes of a significant size. For this step, all available information shall be explored. Fig. 1 shows the concept in a schematic way.

In the understanding of Fig. 1, a “capable fault” is a fault that has a significant potential for relative displacement at or near the ground surface.

The selection of the scenario earthquake(s) focused on the largest (magnitude) earthquakes expected from each source. These earthquakes traditionally are called maximum credible earthquakes (MCEs). The use of the MCE ensures that effects from all other magnitudes are explicitly considered. In other words, by virtue of designing a structure to withstand the MCE, it will automatically withstand all other (smaller) earthquakes. The focus on large magnitudes is justified, because the destructive potential of earthquakes primarily depends on its energy content (proportional to the magnitude) and the transfer of this energy into a structure. For

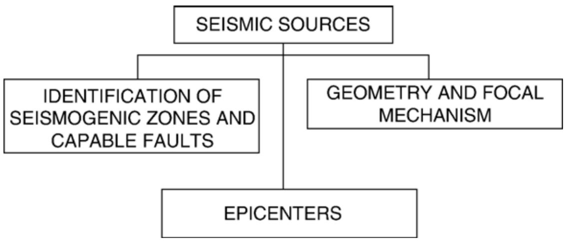

Fig. 1. Information to characterise seismic sources.

specific source – propagating media – site configuration, it is obvious that larger magnitude earthquakes will produce more impact on a given structure at the site, all other factors being fixed. The selection of the maximum credible earthquake or the maximum possible magnitude (PSHA using the truncated Gutenberg–Richter equation) under the given seismotectonic environment is a challenging task and requires the use of all available information (geological, geophysical, geotechnical and seismological) especially for the design of critical infrastructures (IAEA, 2002a, b). The acquisition and interpretation of the required information is an interdisciplinary task involving experts in different fields of geophysics, geology, and seismology, geotechnicians as well as civil engineers and safety analysts, specifying the requested information. Destructive potential of earthquakes does not depend on secondary properties such as spike in the instrumental time-histories (e. g., Uang and Bertero, 1990), which provide the basis for the uniform hazard spectra— the common outputs of traditional PSHA. That the results of traditional PSHA are based on statistical outliers can be demonstrated by the mathematical formulation of the hazard integral used in PSHA (EPRI, 2005; Abrahamson, 2006):

$$v(S_a>z) = \sum_{i=1}^{n_{\text{source}}} N_i(M_{\min}) \int_M \int_R \int_\varepsilon f_{mi}(M) f_{Ri}(r,M) f_\varepsilon P \times (S_a>z|M,R,\varepsilon)\, d\varepsilon\, dR\, dM \tag{1}$$

Eq. (1) represents the usual annual frequency of events, leading to a spectral acceleration S_a, exceeding a hazard value z. It is evaluated by summing up the contributions of all relevant sources and by performing source specific integration over magnitude, distance and the error term (named aleatory uncertainty) of the attenuation equation, multiplying the source specific frequency density distributions with the conditional probability of exceedance of the specified hazard level z. The conditional probability of exceedance is calculated based on the corresponding attenuation equation. The attenuation equation can have the following format:

$$\log(S_a) = g(M,R,X_i) + \varepsilon \tag{2}$$

with the error term expressed as the multiple of the standard deviation $\varepsilon = a\sigma_{\log}$ of the attenuation model. The standard deviation $\sigma_{\log}$ reflects the variability of measurement conditions under which the data points (including the data points used for the measurement of magnitude and location) used for the regression were obtained. X_i represent additional explanatory variables (or classification properties for the specific travel path from the seismic source to the site) of the attenuation model, which may or may not be considered in the model. Examples for these additional explanatory variables are:

- site conditions (e.g. shear wave velocity, depth of surface layer),
- topographical and directivity effects,
- hanging wall and footwall effects,
- fault style,
- aspect ratio of the seismic source,
- material properties of the travel path of seismic waves.

The result of PSHA using Eq. (1) is clearly driven by the number of standard deviations considered as the boundary condition for the integral over ε. The number of standard deviations considered is in principle unlimited, although physical boundaries (e. g. maximal ground motion) can be provided. Therefore, the conclusion is that the hazard integral (1) can converge to infinity (this means that it does not converge at all) or to a maximum ground motion level set by the analyst in advance. From Chebyshev's inequality

$$\Pr(|X-E)(X)| \geq a\sigma) \leq \frac{1}{a^2} \tag{3}$$

in conjunction with Eq. (1) it follows directly that the results of a PSHA are driven by the recordings of statistically rare time-histories, which (due to the second ergodic assumption (Klügel, 2005c)) frequently were recorded under measurement conditions completely different from the site of interest. It is obvious that the traditional PSHA (SSHAC, 1997) represents a worst-case model, leading systematically to ambiguous results. Klügel (2005c) discussed that the mathematical formulation of the hazard integral (Eq. (1)) or as formulated in the SSHAC-report (SSHAC, 1997) is incorrect. Its derivation is based on a separation of random variables approach treating the error term and the random explanatory variables of the attenuation equation (e. g. magnitude, distance and the other explanatory variables (site conditions, hanging wall and foot wall effects, topographical and directivity characteristics, if the later are considered at all)) as statistically independent. Obviously, this assumption is not true.

The development of Eq. (1) was based on a heuristic bias. Originally PSHA assumed that the uncertainty of the problem is completely concentrated in the error term ε of the attenuation equation, regarding all other modelling parameters as exactly known. This assumption was the result of the division of labour between different groups of geophysicists. One group was responsible for the evaluation of earthquake magnitude (or intensity) and earthquake epicentre location, while another group used this information to develop attenuation models assuming earthquake magnitude and location as exactly known. Later on, the uncertainty of other modelling parameters were included in the analysis (e. g. of *a* and *b* parameters of the Gutenberg–Richter equation, and of the epicentre location). Unfortunately, people forgot that the evaluation of magnitude and earthquake location is based on measurements. Therefore, the obtained values are not known exactly and (in a probabilistic approach) have to be treated as random parameters. This means that the error term ε in the attenuation equation does include the measurement uncertainties associated with the evaluation of magnitude and epicentre location (and the effects of other explanatory variables not explicitly considered in the attenuation equation). Therefore, an attenuation equation represents a multivariate distribution of the considered ground motion parameter expressing its dependence on a set of random model parameters. For replacing this multivariate distribution by the simplified model of a lognormal distribution (or normal distribution in log-scale) for use in a PSHA logic tree (here magnitude and distance are "exactly known" for each single path through the tree) it would have been required to consider the dependency between the model parameters and the error term ε or to adjust the residual error.

In seismic highly active regions like California, the selection of seismic sources can be reduced to the identification and assessment of seismogenic faults, which can produce earthquakes of significant damaging potential. In less active regions and where instrumentally recorded earthquakes are not available, as is the case for several European areas, historical intensity data should be used to obtain an overall picture of the spatial distribution of the shaking intensity during written historical time. Although the epicentral locations and estimated magnitudes of historical earthquakes may not be as accurate as those of instrumentally recorded earthquakes, they can provide valuable, although incomplete, information on (1) the seismicity over long periods, (2) a rough delineation of seismic source zones and (3) reasonable estimates of future earthquake magnitudes, by assuming stable seismotectonic conditions for the region. It may even be possible to derive information on the frequency of large earthquakes, which are of interest for a scenario-based methodology, by time-series analysis. What particularly distinguishes the results obtained by a scenario-based methodology and the traditional PSHA is the way in which the methods are applied to different seismogenic zones. Both the identification and delineation of the potential seismogenic sources (areas or lines) constitute one of the fundamental problems in seismic hazard analysis. The assumption of traditional PSHA that earthquakes can occur everywhere, is no replacement for the resolution of this problem, because PSHA considers these "hidden" earthquakes in the output (Uniform Hazard Spectrum — UHS) only weighted by their (subjectively assessed) frequency of occurrence. If indeed a "hidden" earthquake occurs, the resulting response spectrum will differ systematically from (and it may not be enveloped by) the calculated UHS. As discussed in detail by Panza et al. (2003a) and Klügel (2005d), the assumption of spatially uniform activity within areal sources in traditional PSHA methodology is physically unrealistic and mathematically questionable. Alternative procedures for source modelling that elude source zones have been proposed. For example, one can make use of seismic parametric catalogues (historical and instrumental records) to define the possible locales of seismic events (Molchan et al., 2002). This approach, called historical, has been widely applied in the past.

Other proposals based on the seismic catalogues are due to Veneziano et al. (1984), and Kijko and Graham (1998). In this context, Frankel (1995) also proposed a procedure using spatially-smoothed historical seismicity for the analysis of seismic hazard in Central and Eastern USA.

Woo (1996) suggested another procedure for area sources statistically based on kernel estimation of the activity rate density inferred from regional seismic catalogue. Such approach considers that the form of kernel is governed by the concept of self-organised criticality and fractal geometry, with the bandwidth scaled according to magnitude. In general, the epicentre distribution of historical earthquakes gives a better indication of seismic zonation and generally leads to a non-uniform distribution of seismicity within the zone. Obviously, the most appropriate method suitable for the region of interest shall be selected based on the available data. Because the damaging effect of earthquakes also depends on the "distance" between the assumed earthquake location and the site of interest, a decision for defining the distance has to be made. For a mapped capable fault, the shortest distance between fault and site is usually considered. In an area with low and diffused seismicity, characterised by an areal source, the distance defined can be either between the site and central area of the earthquake epicentres or between the site and the nearest approach to the epicentral zone. The former assumes a more likely location of earthquakes in the zone interior, whereas the latter assumes the possibility of earthquakes at the zone boundary. The use of the shortest distance corresponds statistically to the assumption of a beta-distribution for the spatial distribution of seismicity in the areal source with shape parameters below 1. In a Bayesian approach, this corresponds to a specific class of non-informative priors within an interval, which means area in this case (Atwood, 1996), which is more appropriate than the frequent assumption of a uniform distribution. Bayesian techniques based on new information (epicentre location) can be used to refine the spatial distribution.

2.3. Selection of a parameter to characterise the impact of an earthquake

Different parameters are used by engineers to evaluate structural damage. For design purposes they often depend on national regulations and standards. Most standards are force-based. The design basis forces are derived typically from linear-elastic response spectra, taking into account some damping of the structure. These are adjusted by load correction factors for the required application. The anchor point (of a response spectrum for pseudo-spectral accelerations) for scaling a generic design spectrum (often normalised to 1 g) is at a certain high frequency (typically around 33 Hz) and the final design spectrum commonly used by engineers is scaled by peak ground acceleration (PGA). In the past, following the original idea of Cancani (1904), PGA values were derived from intensity attenuation equations and therefore closely related to observed damage. At that time (before the mid 70s), measurements of ground motions were few, being limited by available instrumentation and seismic networks. The measured values were actually "peak-damped" without high frequency contents, because the latter were not measurable (high frequency peaks were filtered). Therefore, the physical meaning of the measured PGA values was quite close to the modern understanding of an effective ground acceleration (EGA) as used nowadays in engineering (with some minor difference in the values of the spectral amplification factors). This led to an implicit correlation of the observed intensities with the spectral acceleration reflecting the range of natural frequencies of civil structures. Indirectly, this correlation incorporates both the energy content of an earthquake, as well as the energy (defined by spectral shape and level) transfer into a structure. This picture has changed due to the development of modern seismic networks and instrumentations capable of recording high frequency contents of earthquake vibrations. Such high frequency vibrations, except for very brittle failure modes, generally do not cause damage to reasonably designed industrial structures and even to those not especially designed against earthquakes. Indeed, it is known that intensities (as a damage characteristic) correlate much better with peak ground velocity (PGV) or with the spectral acceleration corresponding to the first natural frequency of structures. Furthermore, ground motion measurements at a free surface (e. g. free standing soil column) are hardly representative for the interactions of seismic waves with massive buildings, which are considered by engineers. That the results of traditional PSHA are driven by extreme earthquake recordings (statistical outliers) as discussed in Section 2.2 leads to a critical issue with respect to the development of design basis earthquakes. The PSHA-approach of developing uniform hazard spectra in terms of spectral accelerations and then disaggregating (based on spectral accelerations) to find controlling scenario earthquakes (in terms of magnitude and distance bins) without consideration of the energy content of the causative event results in the fact that low magnitude, near-site events are selected with preference. This has been shown in a few case studies (e. g. Chapman, 1999) and this is also observed with respect to the PEGASOS-results for the NPP Goesgen. Furthermore, the selection of controlling events is not unique. The obtained low magnitude, near-site events can be judged frequently by structural engineers as not damaging. They can be eliminated from further consideration (e. g. EPRI, 2005). The potential consequence is that the final design of the structure using PSHA may be inadequate with respect to the impact of higher energy (larger magnitude) earthquakes from distant sources. This danger is reduced substantially by the deterministic scenario-based approach, because it focuses on large earthquakes from the beginning of the analysis.

Nevertheless, the selection of appropriate physical parameter(s) to describe the damaging impact of an earthquake on structures more reliable is an important question for any methods The selected parameter is important for later analysis steps, because the attenuation models to estimate the site hazard uses the same parameter. Generally, the parameter characteristics can be classified as structure-dependent or structure-independent.

2.4. Structure-independent parameters for impact characterisation

Due to the traditional division of labour between geophysicists and engineers, structure-independent impact parameters have some advantages due to their possible general-purpose applications. Spectral or peak ground accelerations are traditional structure-independent parameters for characterisation of the impact of earthquakes. As discussed in Section 2.3, the sole use of spectral accelerations or spike peak ground accelerations may be misleading. Meaningful alternatives, which have found practical application, are the *Arias-Intensity* and the *Cumulative Absolute Velocity* (CAV).

The *Arias Intensity* (Arias, 1970) is defined as:

$$I_A = \frac{\pi}{2g}\int_0^{\tau} a^2(t)\mathrm{d}t \tag{4}$$

where τ is the duration of the strong motion (eliminating the contribution of Coda waves) and $a(t)$ is the acceleration time-history. Because *Arias-Intensity* represents a measure of the elastic energy content of an earthquake ground motion, it can be used to select design earthquakes in cases where inelastic behaviour of structures or components is not permitted (e.g., for brittle failure modes).

The *Cumulative Absolute Velocity* (EPRI, 1991) is calculated as:

$$\mathrm{CAV} = \sum_{I=1}^{N} H(\mathrm{pga}{-}0.025)\int_{t_i}^{t_{i+1}} |a(t)|\mathrm{d}t \tag{5}$$

where N is the number of 1-second time windows in the time series, pga is the peak ground acceleration in the i-th time window and $H(x)$ is the Heaviside function. CAV can be used to define the ductile (low cycle fatigue) failure mode condition of structures and components.

2.5. Structure-dependent parameters for impact characterisation

Structure-dependent parameters can provide valuable information for the characterisation of the destructive potential of earthquakes. Most of them are based on an assessment of the energy transfer into a structure. The disadvantage is that the need to consider the physical characteristics of the structure may be too elaborate for general purpose applications. The analysis requires the use of appropriate time-histories, which can be synthetic seismograms and/or recorded data. More effort is needed here than for cases using structure-independent parameters. Therefore, the use of a structure-dependent parameter is recommended for specific structural analysis, for which deterministic scenario-based earthquakes approach is most appropriate.

Such an energy-based approach, more advanced than structures design by balancing energy demands and inputs, allows (1) proper characterisation of different types of time-histories (impulsive, periodic with long-duration pulses, etc.) which may correspond to fairly realistic earthquake strong ground motions, and (2) simultaneous consideration of the dynamic response of a structure from elastic to ductile failure conditions.

The absolute energy input per unit of mass, can be expressed by:

$$E_I = \int_0^{\tau} \ddot{u}_t\,\dot{u}_g\mathrm{d}t \tag{6}$$

where $u_t = u + u_g$ is the absolute displacement of the mass, and u_g is the earthquake ground displacement. Another energy-based parameter, denoted as seismic hazard energy factor (AE_I), was introduced by Decanini et al. (1994), to take into account the global energy structural response amount. AE_I represents the area enclosed by the elastic energy input spectrum corresponding to different intervals of time, T (from T_1 to T_2) and is expressed by:

$$\mathrm{AE}_I = \int_{T_1}^{T_2} E_I(\xi = 5\%, T)\mathrm{d}T \tag{7}$$

Other structure-dependent parameters for impact characterisation of earthquakes can be considered, too.

2.6. Attenuation relationships

For the selection of appropriate scenario earthquakes, as well as for the assessment of the impact on structures at a site, attenuation relationships are required. They should be developed for the selected parameter characterising the impact of earthquakes on structures. In principle, the relationships show the parameter values as a function of distances for earthquake magnitudes. In a deterministic scenario-based seismic hazard analysis, an iterative approach is feasible for the first (screening) stage in which simple empirical relations, based on traditional parameters like spectral accelerations or peak ground velocities or accelerations may be used. This is possible because the analysis focused on large earthquakes and on well-identified or characterised seismic sources. For general purpose applications (e.g., the development of a general seismic hazard map for a region), the analysis can be limited to the first screening step. For site and project specific analysis, a second step refining the analysis results is done.

The scope of the refinement analysis shall be defined according to the importance of the construction project or the infrastructure. The refinement also considers the costs associated with the seismic design in comparison to the costs for additional analysis required to reduce the investments in protecting hardware (cost benefit considerations). A general rule of thumb from the perspective of risk analysis practitioners is that the costs of additional analysis should not exceed 10% to 15% of the costs of additional hardware required to solve the problem in a conservative way.

The refinement of the analysis can be based on (1) the use of more sophisticated empirical attenuation models considering an in-depth characterisation of the physical effects important for the site, or (2) the incorporation of physical models for the selected scenarios considering the possible variability of source parameters as well as the specific topography of wave propagating media from source to site (e.g. the use of synthetic seismograms, Panza et al., 2000; Panza et al., 2003b). The use of synthetic seismograms has the advantage that any deconvolution of seismic wave propagation from source to site into separate modeling components like source effects, attenuation and site effects can be avoided. It also allows to consider multi-dimensional effects. The practical disadvantage is that such an approach is labour intensive. For screening or general purpose applications, it is sufficient to define approximate source geometry from the geological and seismological evidences to assign source to site distance. The upper envelope or arithmetic mean of the mean (regression) curves can be selected as a more or less conservative screening model. In selecting candidate attenuation relationships, it is important to ensure that they are applicable for the region (e.g., Parvez et al., 2001).

Such an assessment can be performed easily by comparing the candidate attenuation equations with available instrumental earthquake records or with the historical intensity attenuation characteristics obtained from a seismic catalogue of the region. Such a comparison can help to develop realistic relationships even with few available records. This pragmatic approach constrains the inflating statistical effects introduced by the ergodic assumption (Anderson et al., 2000; Klügel, 2005b) made by researchers to compensate for lack of data. The approach also constrains the uncertainties of the attenuation relationships to a manageable size as supported by data.

Empirical attenuation correlations for spectral accelerations (even developed specifically for a region) have limitations for near-fault conditions (e.g. Bolt and Abrahamson, 2002; Mollaioli et al., 2003). These correlations are typically based on a model of simple amplitude decay with distance using a far-field approximation to a point (seismic) source characterisation (Aki and Richards, 2002). This approximation is not valid for near-fault conditions because it neglects multi-dimensional wave interference effects (Richwalski et al., 2004). Near-fault earthquake hazards can best be assessed by applying advanced dynamic source modelling. In general purpose applications (e.g., seismic hazard maps), the effect of such earthquakes can be approximated by a reasonably large value of hazard parameter for seismic design for any infrastructure in the near-field region.

2.7. Incorporation of site effects

In general, site effects cannot be treated separately from the overall seismic waves propagation from causative seismic sources under consideration to the site through the propagating media (e.g., Field, 2000; Panza et al., 2001). For site effects, the scenario-based methodology again allows for an iterative procedure. For the selection of scenario earthquakes, a first screening step can be based on traditional site classification based on soil properties (e.g., shear wave velocity, depth of soil surface layer, etc.). For general purpose applications such as the development of regional hazard maps, it is possible to limit the analysis to its first step. For site-specific applications, the analysis shall be refined for the selected scenario earthquakes. The most appropriate way of doing this is the use of physical modelling based on synthetic broadband seismograms. This approach allows incorporating the solution of the attenuation problem with site effects in a physically correct manner. It is important to note that the models should conform to the principle of empirical control. Accordingly they have to be checked against earthquake recordings from the region when available.

2.8. Definition of deterministic scenario earthquakes — Maximum Credible Earthquakes (MCEs)

After completion of the procedural steps for attenuation correlations and site effects on the screening level, the final set of scenario earthquakes can be developed by geologically-based earthquakes which would cause maximum impact at the site. For this final selection, directivity, fling and topographic factors shall be considered because of their potential impact. The selected scenario earthquakes will be the basis for detailed site-specific analysis as well as for risk analysis applications. It is important to note that the number of scenario earthquakes to be considered for detailed analysis is rather limited. Even for a complicated seismotectonic region with considerations of directivity and topographic effects, the final set will not likely exceed five scenarios for site-specific applications and will frequently be constrained to a single scenario as in California. The use of limited scenario earthquakes substantially reduces the effort for additional analysis beyond the screening level. Fig. 2 illustrates the work-flow for the definition of scenario earthquakes.

3. Specific issues

Specific important issues with respect to the application of the deterministic scenario-based methodology,

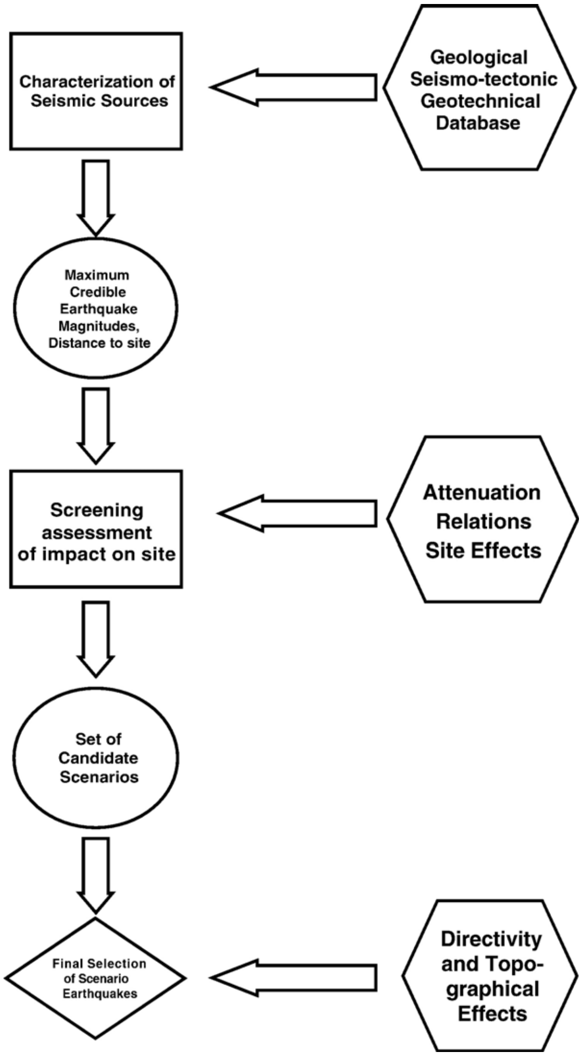

Fig. 2. Work-flow for the selection of scenario earthquakes.

but also relevant for any other methodology, are discussed below.

The size or magnitude of an earthquake can be estimated by several approaches. Fault length, area and displacement for known faults have been empirically correlated with moment magnitudes (Wells and Coppersmith, 1994). Improved correlations have been made possible by separating the data for different fault types. These relationships have been applied to seismogenic faults for estimating MCE magnitudes. An important assumption is the fault length used for MCE estimation (Mualchin, 1996). Empirical correlations for the assessment of earthquake magnitudes should not be applied outside the region they have been developed for. It should also be noted that fault mechanics (Scholz, 2002, p. 207) demonstrated different size regimes with respect to the scaling of moment and slip to the aspect ratio (length to width) of the source area, indicating different similarity regimes for earthquakes.

Correlations like Wells and Coppersmith (1994) are based on mixed data across these regimes and are compromise fits (Scholz, 2002). The use of mixed data can be a source of systematic error considered by some analysts as epistemic uncertainty. The different scaling regimes can be attributed, in part, to the way of propagation of the fault rupture. Seismic events with length less than the thickness of the brittle crust can propagate in all directions within a planar surface. Larger earthquakes, that rupture through the entire brittle crust (to the top of the ductile zone) can propagate farther only in the horizontal dimension. Thus, small and larger seismic events may be self-similar, but not to each other, and source scaling for interplate and intraplate tectonic regimes are different. Therefore, empirical correlations between magnitude and fault length should be based, as much as possible, on regional information. Fig. 3 shows magnitude dependence on fault length from global earthquake data.

In low seismic areas, the assessment of maximum credible earthquake magnitudes is more complicated. The solution to this problem is based on observed data. The data is based on seismic catalogues compiled from written records (historical approach). Fortunately, enough strong and damaging events in civilized areas are well recorded both in oral and written tradition. Statistical methods for the treatment of extreme values provide a meaningful means to assess maximum credible earthquake magnitudes in a region of interest. Possible methods are available, for example, by Noubary (2000):

- bootstrap techniques (re-sampling of the distribution of observed maximum magnitude values),
- threshold theory leading to the application of a Generalised Pareto Distribution (GPD),
- traditional extreme value statistics like the Gumbel distribution.

Additionally available information (e. g. from paleo-seismology) can be easily incorporated into the analysis. For example, paleo-seismological assessments of maximal magnitudes with the associated assessment of frequency (or recurrence period) can be incorporated into the empirical distribution of observed maximum values, which is re-sampled using a corresponding Monte Carlo-Procedure. It is recommended to use the 95%-quantile of the re-sampled distribution as the maximum credible earthquake magnitude.

In practical applications for high seismic areas with pronounced and well mapped seismic faults, magnitudes

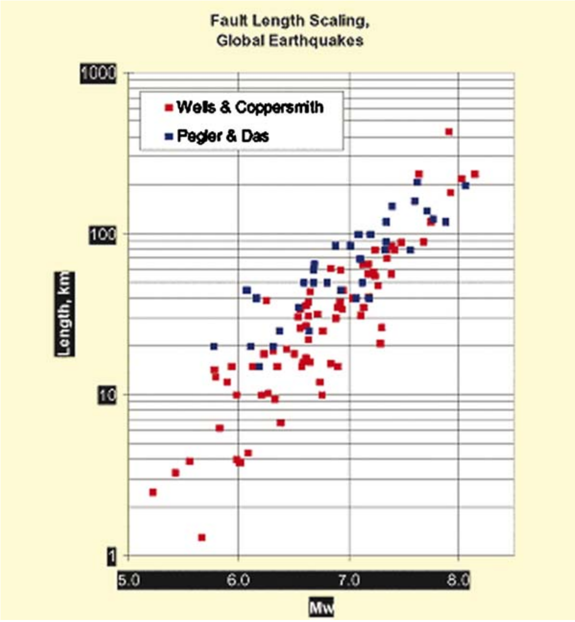

Fig. 3. Fault length scaling to magnitudes based on Wells and Coppersmith (1994) and Pegler and Das (1996).

are approximated up to the nearest quarter magnitude, reflecting the imprecision of magnitude scale (e.g. Calcagnile and Panza, 1973; Panza and Calcagnile, 1974; Herak et al., 2001), the limited data sets used to establish the relationships, and conservatism needed for seismic hazard estimates. It is easy to demonstrate that errors or changes in fault length by 100%, 50%, and 25% correspond to changes in magnitude estimates by only .3, .2, and .1 magnitude units, respectively. Therefore, typical MCE magnitudes, rounded off to a quarter of magnitude, are extremely stable and not likely to change for particular faults or earthquake sources. A stable estimate of MCE magnitude is a special feature of the deterministic scenario-based method, which is desirable for critical infrastructure design and construction.

4. Application of scenario-based seismic hazard analysis for risk analysis

For some applications, such as for safety analysis of critical infrastructures or for insurance companies, it is necessary to perform a detailed risk analysis. Such an analysis can be beneficial to assess the efficiency of design measures as well as to identify potential vulnerabilities especially for existing facilities. Risk analysis therefore provides a meaningful complementary tool to traditional safety analysis and deterministic design procedures. It is a common but erroneous belief that *only* a probabilistic seismic hazard analysis (traditional PSHA) is able to provide the required input for a probabilistic risk assessment (PRA) for critical infrastructures. People often prefer to believe in names (such as "probabilistic" seismic hazard analysis) instead of analysing the essential points of a topic. Even in official technical standards (Budnitz et al., 2003), this wrong belief is common. Unfortunately, the question is not that simple and is worth investigating in more detail. A deterministic scenario-based seismic hazard analysis result is appropriate to perform detailed risk analysis, as demonstrated below.

The key elements of a risk analysis (Kaplan and Garrick, 1981) are:

1. Identification of events that can occur and have adverse consequences.
2. Estimation of the likelihood of those events occurring.
3. Estimation of the potential consequences.

Therefore, the results of a risk analysis can be presented as a set of triplets:

$$R = \langle H_i, P_i, C_i \rangle \quad (8)$$

H_i represents the set of i events with possible adverse consequences.

P_i represents the associated probabilities of their occurrence.

C_i represents the associated intolerable consequences.

This means that a seismic hazard analysis shall provide the following information as an input for PRA:

- The events which may potentially endanger our infrastructure.
- The frequency or probability of occurrence of these events.

The consequences of these events are evaluated by the risk model of the plant, which essentially represents a logic model mapping the hazards to be investigated to their consequences. What does a traditional PSHA provide? The standard output consists of a uniform hazard spectrum and a set of hazard curves, which represent the convoluted impact of a large amount or infinite (Wang, 2005) number of earthquakes with respect to the chances of causing certain level of ground accelerations at the site of interest. Therefore, PSHA is not delivering the required frequency of events but exceedance probabilities of secondary properties. It is important to note that frequently damaging effects of an earthquake cannot be described by only a single secondary property (e.g. hazard curves expressed in terms of averaged spectral acceleration or even PGA). The impact of an earthquake event has to be described in the risk model of the plant, which can easily accommodate other impact effects besides the effects of acceleration (e.g. liquefaction, surface rupture below the basement). It is obvious that PSHA output does not correspond to the data necessary for providing the frequency of events causing damage required by modern risk analysis (Klügel, 2005e).

In the early development of seismic risk studies, hazard curves and uniform hazard spectra from PSHA were indeed used directly as an input for seismic PRA (Klügel et al., 2004) due to a lack of better alternatives. This approach could be justified as a conservative attempt to provide a worst-case assessment of the possible risk associated with seismic hazard. At this early time of seismic PRA, the hazard curves developed by PSHA for PGA or average spectral accelerations were mostly intensity-based. Therefore, they were better suited as a damage index for risk study. The replacement of intensity-based mean PGA values ("peak-damped") by uniform hazard spectra based on statistically extreme time-history recordings loosing the logical link to the damaging effects of earthquakes in the traditional PSHA methodology does not justify using this simplified approach anymore. Traditional PSHA methodology tries to resolve the problem by disaggregating the obtained seismic hazard into magnitude and distance pairs to be interpreted as scenario earthquakes. The problem here is that any source specific information is lost in the process of analysis and the disaggregation results are completely non-informative. As discussed in Section 2.3, if the disaggregation is based on spectral accelerations instead of energy measures, inappropriate controlling earthquakes may be selected as scenario earthquakes.

The scenario-based seismic hazard analysis methodology presented in this paper is much better suited to provide the required and correct input for a seismic PRA. The scenario earthquakes developed essentially represent the hazard events to be considered in the risk study. The frequency of smaller earthquake events can be taken into account in the calculation of the frequency of occurrence of the stronger scenario earthquakes which envelope the impact of smaller events, by using a classification system. This corresponds exactly to how probabilistic risk assessments of nuclear power plants are performed for other initiating events (IAEA (1995), IAEA (2002a,b), DOE (1996), Tregoning et al. (2005), Poloski et al. (1999)). A nuclear power plant has, for example, a large amount of pipes in the reactor coolant circuit, which potentially could break causing a loss of coolant accident (LOCA) inside the reactor containment. The calculation of all possible scenarios associated with each single possible pipe break is not possible. Therefore, pipe breaks causing similar consequences are combined together and modelled by an enveloping, conservative, accident scenario. The frequency of the scenario is calculated as the sum of the frequencies of all underlying pipe breaks, assigned to the same class (e.g., small break LOCA, medium break LOCA, large break LOCA, etc.). The same approach is used in PRA for airplane crash analysis. Airplanes are classified by their impact characteristics and the risk contribution of airplane crashes is calculated as the sum of the contributions of each of the classes. The frequency assigned to each of the classes is developed from real data of airplane crashes and represents the total frequency of all crashes of airplanes belonging to the considered class.

Let us have a look how the frequency of scenario earthquakes can be calculated starting from the most general case for an area source, A, which completely encloses our site of interest (e.g., area with radius/distance of 300 km or less from the site). Because the occurrence of earthquakes is not invariant in time and space, the calculation of an average frequency of occurrence for a certain earthquake (magnitude) class requires the solution of the following equation:

$$F(M_i) = \frac{1}{T_{\mathrm{life}}} \int_A \int_0^{T_{\mathrm{Life}}} \int_{M_{\mathrm{low}}}^{M_{\mathrm{upper}}} f_1(r, m, t)\,\mathrm{d}m\,\mathrm{d}r\,\mathrm{d}t \tag{9}$$

Here, $M_i \in (M_{\mathrm{low}}, M_{\mathrm{upper}})$ is the magnitude value associated to the considered earthquake class, M_{low} is the lower interval limit for the considered class, M_{upper} is the upper interval limit for the considered earthquake class, F is the average frequency of the earthquake class, r is the distance from a point seismic source located inside the seismic area source A to the site, f_I is the multivariate frequency density distribution of earthquakes within the considered area source, T_{Life} is the expected (residual) life time of the infrastructure analysed in the study, m is the magnitude, t is time. It is easy to understand that only a few earthquake classes have to be considered in a risk analysis (not more than 3 or 4). The impact assigned to each of the earthquake classes can be defined by the solution of the optimisation problem:

$$\mathrm{find}(r_{\mathrm{opt}}) \rightarrow \max \int_A \int_0^{T_{\mathrm{Life}}} \int_{M_{\mathrm{low}}}^{M_{\mathrm{upper}}} f_1(m, r, t) g(r|m)\,\mathrm{d}m\,\mathrm{d}r\,\mathrm{d}t \tag{10}$$

where $g(r|m)$ calculates the value of the selected impact parameter (energy-based measure, spectral acceleration, etc.) as a function of the distance from the location of the earthquake with magnitude m to the site. The calculated r_{opt} defines the location of the deterministic scenario earthquake considered for this class. In many practical cases, a simplification of the problem is possible by separating the spatial distribution of seismicity from the frequency distribution of earthquakes depending on magnitude size and time. This means that the frequency density distribution f_1 can be represented as:

$$f_1(r,m,t) = f_2(m,t)f_3(r|m) \tag{11}$$

Eq. (9) reflects the assumption that the spatial distribution of seismic activity is invariant with time. This is of course a rather strong assumption, which for a short-lived structure can be justified by the assumption of stable seismotectonic conditions in the area of interest. The required density distribution f_2 can be obtained much more easily, for example, using bivariate extreme value distributions (Noubary, 2000) or Markoff or Semi-Markoff models.

In cases where the seismic activity can be allocated to specific faults, the problem is simplified to a very large extent. The frequency of an earthquake belonging to the class i can be calculated as:

$$F(M_i) = \frac{1}{T_{\mathrm{Life}}}\sum_{j=1}^{N}\int_0^{T_{\mathrm{Life}}}\int_{M_{\mathrm{Lower}}}^{M_{\mathrm{Upper}}} f_j(m,t)\mathrm{d}m\mathrm{d}t \tag{12}$$

Here, j is the summation index for the relevant faults and N is the total number of faults potentially contributing to the magnitude class i. The optimisation problem of Eq. (10) can also be simplified under these conditions by making the bounding assumption that the shortest distance between fault and site will be selected.

Once the probabilistic scenario earthquakes are selected and their frequency is calculated (this is the required frequency of an initiating seismic event), it is easy to calculate scenario-specific hazard spectra, which will provide the input for subsequent analysis within the framework of a seismic PRA. Within this probabilistic framework it is possible to calculate uncertainty bounds on the average frequencies obtained from Eq. (9) or (12) by performing sensitivity analysis. It is also possible to calculate uncertainty bounds for the hazard spectra associated with each magnitude class, taking into account the total empirically observed uncertainty associated with the attenuation of seismic waves in the region of interest. Such estimates can easily be performed by propagating the uncertainties associated with the lack of knowledge of the values of the model parameters used through the model. Direct Monte Carlo analysis or response-surface analysis techniques can be used in dependence of the complexity of the model.

It is important to note that the proposed probabilistic extension of the deterministic scenario-based method is in full compliance with the likelihood principle, the basic principle of any meaningful risk analysis. In its original mathematical formulation it says (Edwards, 1972, p. 30): "Within the framework of a statistical model, ***all*** the information which the data provide concerning the relative merits of two hypotheses is contained in the likelihood ratio of those hypotheses on the data… For a continuum of hypotheses, this principle asserts that the likelihood function contains all the necessary information."

A shorter "common sense" formulation is:

All information on any subject submitted to an investigation is contained in the data about this subject.

Traditional PSHA violates this principle for the following reasons:

- The decomposition of the multivariate probability distribution of occurrence of earthquakes (size (magnitude), epicentre location and time being the most important variates) into a set of independent univariate probability distributions (introduced by Cornell, 1968) leads indirectly to the assumption of the existence of a "hidden" earthquake undetectable by any scientific means near a site. Any earthquake of any size can occur anywhere in space and at any time with some frequency.
- Negative evidence is ignored (e.g. in many cases there is no geological or geomorphological evidence for the "controlling scenario earthquakes" derived from a traditional PSHA especially in the near-site area, but this is ignored in the analysis).
- Replacement of observable scientific data by subjective probabilities (SSHAC, 1997) derived from expert judgement without empirical control.

The proposed probabilistic extension of the scenario-based seismic hazard analysis method removes the simplifying decomposition of the problem introduced by Cornell. Furthermore, it is focussed on the output as typically requested by risk analysts (frequency of critical events instead of exceedance probabilities of secondary hazard parameters).

5. A question of names

Abrahamson (2006) repeated a frequent argument of proponents of PSHA that deterministic seismic hazard analysis by its true nature is also a probabilistic method. This is a misrepresentation of the question.

Deterministic seismic hazard analysis is called "deterministic" because it is based on facts, data and physical models, describing the behaviour of earthquakes. Statistical (probabilistic) techniques, which are based on data analysis, are a natural part of this type of "deterministic" analysis. Therefore, the term "deterministic" is used in this paper to characterise approaches which are based on an increasingly deeper understanding of the underlying phenomena.

6. Summary and conclusions

The methodology presented here for a deterministic scenario-based seismic hazard analysis incorporates all available information (in a geological, seismotectonic and geotechnical database of the site of interest), and advanced physical modelling techniques can provide a reliable and robust basis for the development for a deterministic design basis of civil infrastructures. The robustness of this approach is of special importance for critical infrastructures. At the same time, a scenario-based seismic hazard analysis can produce the necessary input for probabilistic risk assessment (PRA), as required by safety analysts and insurance companies. The scenario-based approach removes the ambiguity of the results of traditional probabilistic seismic hazard analysis (PSHA) which relies on the projections of Gutenberg–Richter (GR) equation, as practiced in some countries. The problems in the validity of G–R projections, because of incomplete to total absence of data for making the projections, are still unresolved. Consequently, the information from G–R must not be used in decisions for design of critical structures or critical elements in a structure. The methodology discussed here is strictly based on observable facts and data and complemented by physical modelling techniques, which can be subjected to a formalised validation process. By sensitivity analysis, knowledge gaps related to lack of data can be resolved rapidly as scenarios are limited. In its probabilistic interpretation, the scenario-based approach is in full compliance with the likelihood principle, and therefore meets the requirements of modern risk analysis. The methodology of scenario-based seismic hazard analysis can easily be adjusted, so that its output is the required and correct information for safety analysts and civil engineers. The methodology incorporates parameters appropriate for damage index in the design of critical infrastructures and components, and thus supersedes outdated and inappropriate assessments of spike instrumental accelerations.

In a nutshell, scenario-based seismic hazard analysis should be preferred over the traditional PSHA for all applications because of its flexibility, robustness, use of physically meaningful data, reasonable conservative results and for PRA when required by safety analysts and insurance companies.

Acknowledgements

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Appendix A. Numerical Example

A numerical example will illustrate the suggested scenario-based procedure. For simplicity, the solution of the optimisation problem will be performed, using the simplifying assumption of Eq. (11) (numbering refers to the one in the main paper).

A.1. Task specification

Fig. A1 illustrates the task. A critical infrastructure shall be designed against earthquakes. It is located in the centre of the circle shown in Fig. A1. From the responsible project engineers it is known that modern design rules ensuring a ductile design of structures will be applied. It is also known that the characteristic first natural frequencies of the new structures are expected to be in the range of 3 Hz. The design lifetime of the critical infrastructure is 40 years. The very detailed site investigation performed allows the definition of an exclusion zone with respect to

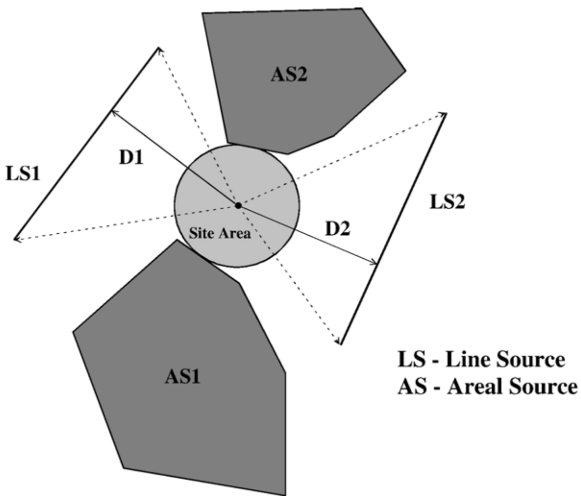

Fig. A1. Illustration of the numerical example.

the existence of active, capable faults within a radius of 5 km around the site. This means that inside this area only small and deep earthquake events are feasible ($M_w<5.0$). From the available geological and seismological database, it was concluded that in the surroundings of the site two significant linear sources (faults) have to be considered. The shortest distances to site are D1 = 30 km and D2 = 25 km. The length of surface projection of the first fault (line source LS1) is 21 km and of the second fault (line source LS2) is 15 km. For simplicity, it is assumed that the perpendicular from the site to the faults subdivides the fault surface projections of both line sources into two parts at a ratio of 2:1. Available data does not indicate any preferred location of epicentres along both faults, therefore a non-informative distribution of epicentre location has to be assumed. Based on historical data two areal sources (AS1 and AS2) with some past seismic activity have been discovered, which have to be considered in the analyses. The shortest distance of both areal sources to the site is 5 km (joining the exclusion zone). Areal source AS1 is extended up to a distance of 65 km, while areal source AS1 is extended up to a distance of 98 km from the site. Detailed statistical analyses have been performed to develop temporal and spatial frequency distributions of earthquake occurrences at the different sources including spatial distributions of epicentres for the areal sources. For simplification, the model of bivariate exponential distributions (Gumbel Type 2, see Noubary, 2000) is used both for the temporal distributions as well as for the spatial distributions. Detailed statistical analysis showed that the 95%-quantil of the magnitude distribution corresponds to a magnitude of 5.9 for source AS1 and 6.3 for source AS2.

The joint distribution function of the bivariate exponential distribution (X, T being the variates) is given as:

$$F(x,t) = \left(1-e^{-\lambda_1 x}\right)\left(1-e^{-\lambda_2 t}\right)\left[1+\alpha e^{-(\lambda_1 x+\lambda_2 t)}\right] \qquad (1)$$

The joint density is given as:

$$f(x,t) = \lambda_1\lambda_2 e^{(-\lambda_1 x-\lambda_2 t)}\left[1+\alpha(2e^{\lambda_1 x}-1)(2e^{\lambda_2 t}-1)\right] \qquad (2)$$

Maximum likelihood estimators for the parameters λ_1 and λ_2 are based on the empirical mean of X and T and calculated simply as:

$$\hat{\lambda}_1 = \frac{1}{\overline{\overline{X}}} \qquad (3)$$

and

$$\hat{\lambda}_2 = \frac{1}{\overline{\overline{T}}} \qquad (4)$$

α is calculated based on the empirical correlation coefficient ρ:

$$\hat{\alpha} = 4\hat{\rho} \qquad (5)$$

In our application the random parameter X has the meaning of magnitude, while the random parameter T corresponds either to the elapsed time between two earthquakes (temporal distribution) or to the distance between epicentre location and site. Other statistical distributions, continuous as well as discrete ones, can be used in dependence of the results of data analysis.

Upper limit estimates for the statistical models can be provided by accounting for the error in the magnitude and location estimates. The simplest procedure consists of an estimate of the upper limit for the maximum magnitude (e.g. mean + 2σ, or 95%-quantile) and the lower limit for the distance (in case of a spatial distribution for an areal source, e.g. mean − 2σ). The procedure is similar with respect to the elapsed time between events.

Statistical analysis was performed in units of moment magnitudes, years (time) and km (distance).

Table 1 shows the information available for the line sources. Tables 2a and 2b shows the available information for the areal sources for the considered case.

In addition, for our example it is assumed that

- detailed physical modelling has confirmed that for the relevant sources a simple amplitude-decay model for ground motion attenuation is acceptable,
- validated attenuation models for each of the sources have been established in terms of ground motion (spectral accelerations).

With respect to attenuation equations a set of four source-specific equations is available, reflecting the different topographical and directivity conditions with respect to seismic wave propagation from the different sources to the site. The general format for these equations is:

$$\log(S_a) = a + bM_w + c\log(R) + dR + \sigma P \qquad (6)$$

with $R=(D_{JB}^2+h^2)^{0.5}$ and D_{JB} representing the Joyner–Boore distance.

Table 3 shows the coefficients of the equation for the line source LS1, Table 4 for LS2, Table 5 for the areal source AS1 and Table 6 for the areal source AS2. These equations have been developed especially for this analysis by modifying the baseline equation of Table 3. They are not to be used for any other purpose. For simplicity a constant standard deviation for all equations of 0.28 (in log-scale) is assumed.

Table 1
Data for line sources

Source	Fault length, km	Fault length error, standard deviation in km	Shortest distance to site, km	Applicable statistical model for f_2 (see Eq. (11))	Parameters of the model			Parameters of the model for f_2, upper limit		
					λ_1	λ_2	α	λ_1	λ_2	α
LS1	25	5	30	Bivariate exponential (Gumbel)	0.17	0.009	0.79	0.15	0.013	0.79
LS2	17	3	25	Bivariate exponential (Gumbel)	0.23	0.0051	0.69	0.20	0.0082	0.68

For our example, it is assumed that from the information in the geological and seismological database the following correlations for the relationship between fault rupture length and moment magnitude as well as between fault length and moment magnitude have been established.

$$\log(L_{\mathrm{R}}) = -3.6 + 0.75M + P\sigma \qquad (7)$$

with $\sigma=0.1$ and

$$\log(L_{\mathrm{fault}}) = -3.25 + 0.72M + P\sigma \qquad (8)$$

with $\sigma=0.1$.

It is also assumed that the regression technique used for the development of these equations possesses the property of orthogonality.

A.2. Deterministic scenario-based analysis

According to the procedure of the deterministic scenario-based seismic hazard analysis, the first step consists in the evaluation of the maximum credible earthquake.

A conservative way of performing this task consists in the assumption that the whole fault length established by measurement could rupture. Additionally, the uncertainty of the measurement should be considered. The analysis is performed for a critical infrastructure. Therefore, we base our analysis on the mean $+1\sigma$ value of the estimated fault length as well as on the mean -1σ value (inverse problem) obtained from Eqs. (7) and (8).

So, we obtain for the linear source LS1 a MCE-value of $M_{\mathrm{w}}=6.9$. In case we want to base our analysis on the more realistic correlation between fault length and magnitude, removing the assumption of a complete rupture of the fault, the result would be $M_{\mathrm{w}}=6.7$. Therefore, the difference is not very large. Neglecting the uncertainty but keeping the assumption that the fault can rupture completely results in a magnitude value of 6.8. So the discussion confirms that MCE-magnitudes behave robustly with respect to a modification of data on fault or rupture lengths.

Therefore, we accept the following value

$$\mathrm{MCE}_{\mathrm{LS1}} = 6.9.$$

Repeating the same procedure for line source LS2, we obtain a magnitude value of

$$\mathrm{MCE}_{\mathrm{LS2}} = 6.7.$$

The next task consists in the evaluation of the MCE-magnitudes for the areal sources. According to our procedure we use the 95%-quantile of the historical magnitude distribution as the magnitude value for the MCE. The resulting MCE for the areal source AS1 is

$$\mathrm{MCE}_{\mathrm{AS1}} = 5.9$$

Accordingly, we obtain for the second areal source:

$$\mathrm{MCE}_{\mathrm{AS2}} = 6.3.$$

Once we have established the maximum credible earthquakes (in practical applications the values may be rounded off to the next larger quarter of a magnitude unit, therefore the final values would be 7.0, 6.75 for the line sources and 6.5 and 6.0 for the areal sources), we

Table 2a
Data for areal sources, distributions for f_2 (Eq. (11) in main paper)

Source	Shortest distance to site, km	Applicable statistical model for f_2 (see Eq. (11))	Parameters of the model for f_2			Parameters of the model for f_2, upper limit		
			λ_1	λ_2	α	λ_1	λ_2	α
AS1	5	Bivariate exponential (Gumbel)	0.35	0.132	0.84	0.32	0.143	0.81
AS2	5	Bivariate exponential (Gumbel	0.31	0.124	0.89	0.28	0.17	0.88

Table 2b
Data for areal sources, distributions for f_3 (Eq. (11) in main paper)

Source	Shortest distance to site, km	Applicable statistical model for f_3 (see Eq. (11))	Parameters of the model for f_3			Parameters of the model for f_3, upper limit		
			λ_1	λ_2	α	λ_1	λ_2	α
AS1	5	Conditional probability, based on a bivariate exponential model (Gumbel)	0.35	0.031	0.8	0.32	0.035	0.65
AS2	5	Conditional probability, based on a bivariate exponential model (Gumbel)	0.31	0.022	0.72	0.28	0.03	0.64

are able to calculate the corresponding hazard spectra and the associated CAV-values assuming the shortest distance between source and site.

Because in our case we know that the new construction will correspond to modern requirements of a ductile design, we may use the CAV-value as the criterion which scenario to select for the design of the new infrastructure. The alternative could simply consist in the use of an envelope of the hazard spectra for all four MCE-scenarios using the source-specific attenuation models. The later approach is more conservative. It is close to the approach frequently used by practitioners, where the most conservative of all attenuation equations for a region is used if source specific models are not available.

Fig. A2 shows the resulting hazard spectra for the 4 scenario earthquakes based on the mean regression models. Fig. A3 shows the same comparison for the mean $+1\sigma$ value. It is observed that at lower frequencies the hazard is dominated by the line source 2, while in the higher frequency range the areal sources contribute to the hazard envelope. Nevertheless, a design based on scenario 2 only, is sufficient, because it results in the highest spectral acceleration values in the range of the first natural frequency of the considered construction. Furthermore, the differences to the other scenarios at higher frequencies are low. Additionally, we may prefer to consider the information available with respect to the epicentre distribution in the areal sources. They indicate that the expected value for the distance to the site is much higher than 5 km (28.6 to 33.3 km, according to the statistical analysis). This consideration would allow the exclusion of the areal sources from further consideration.

Fig. A4 shows the enveloping hazard spectra for the mean regression and the mean $+1\sigma$ model.

It is interesting to observe that the most critical scenario results from line source LS2 with a smaller maximum credible magnitude than line source LS1. This is the result of the shorter minimal distance and the large differences between the source-specific attenuation equations of the two sources. This emphasises the importance of the development of a source-specific attenuation model or the use of detailed wave propagation models (e.g. the use of synthetic seismograms).

Note that any smaller seismic event at any of the four sources will not exceed the enveloping hazard developed from the scenarios.

Table 3
Coefficients of attenuation model for LS1

Spectral frequency, Hz	*a*	b	c	d	h
PGA (50)	−1.5537	0.2396	−0.62494	−0.0081622	5.4294
35	−1.5558	0.2648	−0.66713	−0.0085626	5.658
25	−1.6455	0.27332	−0.63828	−0.0087011	5.0448
20	−1.3713	0.23727	−0.63121	−0.0086357	4.9516
13.33	−1.3756	0.24517	−0.63336	−0.0086132	5.268
10	−1.2412	0.23763	−0.63708	−0.0086018	5.607
6.67	−0.96632	0.21371	−0.62504	−0.0083936	6.1966
5	−1.0168	0.21242	−0.57166	−0.0082279	5.8137
4	−1.103	0.22025	−0.56614	−0.0081654	6.765
2.5	−2.053	0.31787	−0.50505	−0.0079937	4.8624
2	−2.5039	0.35523	−0.46556	−0.0079405	4.6353
1.34	−2.6029	0.357	−0.45591	−0.0078623	4.617
1	−3.0338	0.38841	−0.42746	−0.0078021	4.0694
0.667	−3.521	0.42579	−0.41148	−0.0077495	4.5939
0.5	−3.9299	0.46231	−0.41078	−0.0077495	4.7113

A.3. Probabilistic scenario -based hazard analysis

A.3.1. Introductory discussion

Note that an upper limit for the probability of the critical scenario 2 (this is not to be set equal to the total frequency of scenarios in the same magnitude class as described in the main paper) can be assessed with the help of the recommended bivariate exponential model (neglecting for simplicity the truncation at the "physical limit of $m=6.7$" in our introductory discussion). The conditional probability of occurrence of an earthquake with magnitude X exceeding a specified value given a certain length of time (the lifetime of our structure) for the bivariate exponential model is calculated as:

$$P(X>m|T>T_{\mathrm{Life}}) = \frac{P(X>m, T>T_{\mathrm{Life}})}{P(T>T_{\mathrm{Life}})} \tag{9}$$

Table 4
Coefficients of attenuation model for LS2

Spectral frequency, Hz	*a*	b	c	d	h
PGA (50)	−1.320645	0.27554	−0.687434	−0.0081622	6.6294
35	−1.32243	0.30452	−0.733843	−0.0085626	6.858
25	−1.398675	0.314318	−0.702108	−0.0087011	6.2448
20	−1.165605	0.2728605	−0.694331	−0.0086357	6.1516
13.33	−1.16926	0.2819455	−0.696696	−0.0086132	6.468
10	−1.05502	0.2732745	−0.700788	−0.0086018	6.807
6.67	−0.821372	0.2457665	−0.687544	−0.0083936	7.3966
5	−0.86428	0.244283	−0.628826	−0.0082279	7.0137
4	−0.93755	0.2532875	−0.622754	−0.0081654	7.965
2.5	−1.74505	0.3655505	−0.555555	−0.0079937	6.0624
2	−2.128315	0.4085145	−0.512116	−0.0079405	5.8353
1.34	−2.212465	0.41055	−0.501501	−0.0078623	5.817
1	−2.57873	0.4466715	−0.470206	−0.0078021	5.2694
0.667	−2.99285	0.4896585	−0.452628	−0.0077495	5.7939
0.5	−3.340415	0.5316565	−0.451858	−0.0077495	5.9113

By using $F(x,t)$ and the marginal distribution of T, yields

$$P(X>m|T>T_{\mathrm{Life}}) = e^{-\lambda_1 m}\left[1+\alpha(1-e^{-\lambda_1 m})(1-e^{-\lambda_2 T_{\mathrm{Life}}})\right] \quad (10)$$

The conditional probability of earthquake occurrence within an interval (m_1,m_2) is given as:

$$P(X>m_1|T>T_{\mathrm{Life}})-P(X>m_2|T>T_{\mathrm{life}}) \quad (11)$$

The averaged annual frequency is obtained dividing the result by the lifetime of the structure. This approach can also be used for line source 1 and, in a similar way, for the areal sources neglecting the spatial distribution of seismic activity and for other magnitude values. Combining the obtained frequencies with the worst-case scenario (deterministic scenario earthquake at LS2 with magnitude 6.7) and summing up over all frequencies of the corresponding magnitude class leads to a conservative risk model for the infrastructure for the considered seismic initiating event, because the impact is maximized under our assumptions

- the scenario earthquake it located at the shortest distance to the site,
- analysis of seismic wave attenuation indicated the applicability of a simple amplitude-decay model.

Risk analysts are interested in a more realistic assessment. Therefore a more detailed probabilistic analysis following the procedure in the main paper is required.

A.3.2. Detailed probabilistic analysis

In a first step it is necessary to scale the suggested probabilistic models (the bivariate exponential distribution), which in principle allow infinite values of X (meaning magnitude or distance to site), for application in

Table 5
Coefficients of attenuation model for AS1

Spectral frequency, Hz	*a*	b	c	d	h
PGA (50)	−1.70907	0.27554	−0.812422	−0.0081622	5.4294
35	−1.71138	0.30452	−0.867269	−0.0085626	5.658
25	−1.81005	0.314318	−0.829764	−0.0087011	5.0448
20	−1.50843	0.2728605	−0.820573	−0.0086357	4.9516
13.33	−1.51316	0.2819455	−0.823368	−0.0086132	5.268
10	−1.36532	0.2732745	−0.828204	−0.0086018	5.607
6.67	−1.062952	0.2457665	−0.812552	−0.0083936	6.1966
5	−1.11848	0.244283	−0.743158	−0.0082279	5.8137
4	−1.2133	0.2532875	−0.735982	−0.0081654	6.765
2.5	−2.2583	0.3655505	−0.656565	−0.0079937	4.8624
2	−2.75429	0.4085145	−0.605228	−0.0079405	4.6353
1.34	−2.86319	0.41055	−0.592683	−0.0078623	4.617
1	−3.33718	0.4466715	−0.555698	−0.0078021	4.0694
0.667	−3.8731	0.4896585	−0.534924	−0.0077495	4.5939
0.5	−4.32289	0.5316565	−0.534014	−0.0077495	4.7113

Table 6
Coefficients of attenuation model for AS2

Spectral frequency, Hz	*a*	b	c	d	h
PGA (50)	−1.39833	0.2396	−0.718681	−0.0081622	5.4294
35	−1.40022	0.2648	−0.7671995	−0.0085626	5.658
25	−1.48095	0.27332	−0.734022	−0.0087011	5.0448
20	−1.23417	0.23727	−0.7258915	−0.0086357	4.9516
13.33	−1.23804	0.24517	−0.728364	−0.0086132	5.268
10	−1.11708	0.23763	−0.732642	−0.0086018	5.607
6.67	−0.869688	0.21371	−0.718796	−0.0083936	6.1966
5	−0.91512	0.21242	−0.657409	−0.0082279	5.8137
4	−0.9927	0.22025	−0.651061	−0.0081654	6.765
2.5	−1.8477	0.31787	−0.5808075	−0.0079937	4.8624
2	−2.25351	0.35523	−0.535394	−0.0079405	4.6353
1.34	−2.34261	0.357	−0.5242965	−0.0078623	4.617
1	−2.73042	0.38841	−0.491579	−0.0078021	4.0694
0.667	−3.1689	0.42579	−0.473202	−0.0077495	4.5939
0.5	−3.53691	0.46231	−0.472397	−0.0077495	4.7113

an interval. Due to the correlation between X and time, the calibration factor K is time dependent. The factor can be calculated from the joint distribution function (Eq. (1)):

$$K(t) = \left(\frac{F(\infty, t) - F(0, t)}{F(x_u, t) - F(x, t)}\right) \tag{12}$$

For $t \to \infty$ the calibration coefficient obtains its usual univariate format:

$$K = \frac{e^{-\lambda_1 x_1}}{1 - e^{-\lambda_1 (x_u - x_l)}} \tag{13}$$

Here, x_u and x_l are the upper and lower limits of the random variable X (here meaning magnitude or distance).

The first step in our risk analysis consists in the calculation of the frequency of initiating events for each class of events. After the initial seismological analysis, we decided to consider the following event classes:

- magnitude between 6.5 and 6.9 — magnitude class 1
- magnitude between 6.0 and 6.5 — magnitude class 2
- magnitude between 5.5 and 6.0 — magnitude class 3.

Because the design of the considered infrastructure will be very robust (designed against a conservative MCE-scenario), it is not necessary to consider more events in the analysis.

First, we calculate the frequency of class 1 events. Only the linear sources LS1 and LS2 contribute to this class. Additionally, the magnitude truncation at magnitude 6.7 has to be considered for LS2. Therefore, the

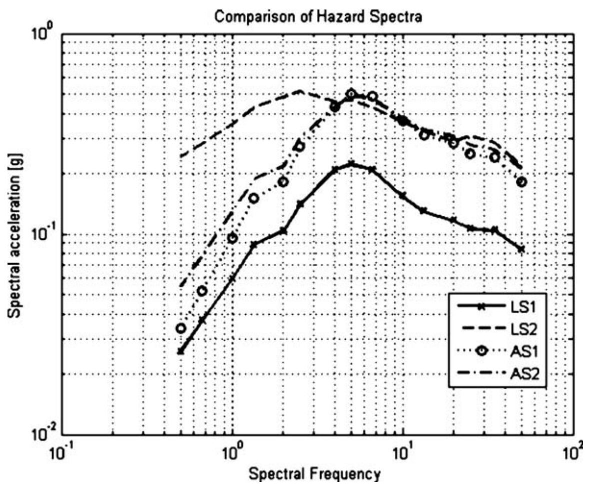

Fig. A2. Comparison of scenario hazard spectra — mean regression model.

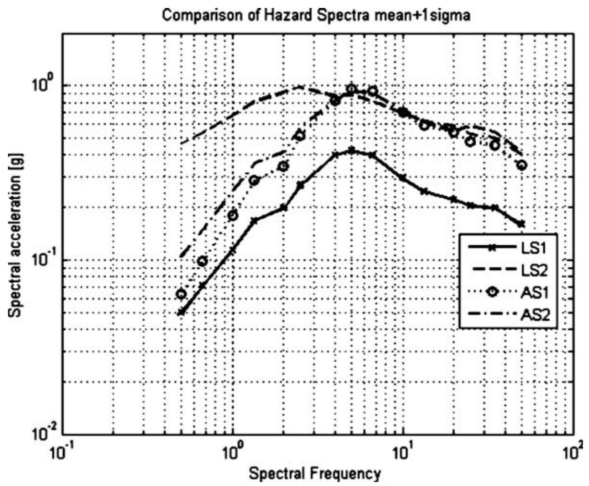

Fig. A3. Comparison of scenario hazard spectra — mean+1 sigma model.

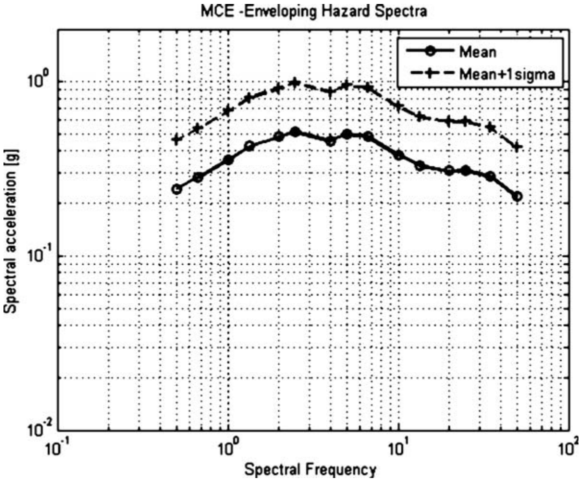

Fig. A4. Comparison of enveloping hazard spectra.

frequency of the events in class 1 can be calculated as the integral over time of a sum of two integrals:

$$F(6.5 \le m \le 6.9) = 1/T_{\rm life} \int_0^{T_{\rm life}} \left[\int_{6.5}^{6.9} f_{\rm LS1}(m,t){\rm d}m + \int_{6.5}^{6.7} f_{\rm IS2}(m,t){\rm d}m \right] {\rm d}t \qquad (14)$$

Here, $f_{\rm LS1}$ and $f_{\rm LS2}$ are the calibrated joint density functions of the bivariate exponential model for the line sources LS1 and LS2 correspondingly.

For event class 2 areal source AS2 has to be considered additionally besides the line sources. Because our analysis is based on Eq. (11) of the main paper, an integration over the area is not required for the evaluation of the total frequency of earthquake events in this class. Therefore, the resulting equation is again an integral over time of a sum of integrals:

$$F(6.0 \le m \le 6.5) = 1/T_{\rm life} \int_0^{T_{\rm Life}} \left[\int_{6.0}^{6.5} (f_{\rm LS1}(m,t) + f_{\rm LS2}(m,t)){\rm d}m + \int_{6.0}^{6.3} f_{\rm AS2}(m,t){\rm d}m \right] {\rm d}t \qquad (15)$$

Similarly we obtain the frequency for the event class 3:

$$F(6.0 \le m \le 6.5) = 1/T_{\rm life} \int_0^{T_{\rm Life}} \left[\int_{6.0}^{6.5} (f_{\rm LS1}(m,t) + f_{\rm LS2}(m,t) + f_{AS2}(m,t)){\rm d}m + \int_{5.5}^{5.9} f_{\rm AS1}(m,t){\rm d}m \right] {\rm d}t \qquad (16)$$

The calculation's results of the frequency of events are shown in Table 7. A lower magnitude level of $m_1 = 2.0$ was used in the analysis.

A.3.3. Solution of the optimisation problem

For a more realistic derivation of the scenarios the optimisation problem according to Eq. (10) in the main paper has to be solved. The optimisation problem can be simplified under certain conditions. For example, if

- the selected ground motion characteristic follows a simple amplitude-decay model,
- and the spatial distribution over the source is non-informative (uniform distribution or beta-distribution with shape parameters smaller than 1 within the distance interval), then the scenario earthquake can be assumed to occur at the shortest distance between source and site. Under these conditions a simple comparison between the resulting hazard spectra (as performed for the deterministic case in Section 2) is sufficient to identify the critical scenario for each magnitude class.

In our example, these conditions are fulfilled for the line sources but not for the areal sources. Because the first natural frequency of the considered infrastructure is in the range of 3 Hz, we solve the optimisation problem with respect to the spectral acceleration at 3 Hz.

A.3.3.1. Magnitude class 1. Only the two line sources actually contribute to this magnitude class. According to the task description we don't have any relevant information on the spatial distribution of seismicity along the faults. Therefore the earthquake scenario to be considered in the risk study corresponds to the deterministic scenario earthquake occurring at the closest distance between line source LS2 and the site. Fig. A5 shows the corresponding hazard spectrum (regression mean).

A.3.3.2. Magnitude class 2. Contributors to this class are both line sources and the areal source AS2. For the areal source a probabilistic model for the spatial distribution of seismicity is given. For the line sources once again a simplified analysis is sufficient assuming the occurrence of the candidate scenario earthquakes at the shortest distance

Table 7
Initiating event frequencies of the scenario earthquakes

Scenario earthquake (magnitude class)	Magnitude range	Frequency (best estimate)	Frequency, upper limit
1	6.5–6.9	0.00107	0.00113
2	6.0–6.5	0.0284	0.14
3	5.5–6.0	0.0742	0.316

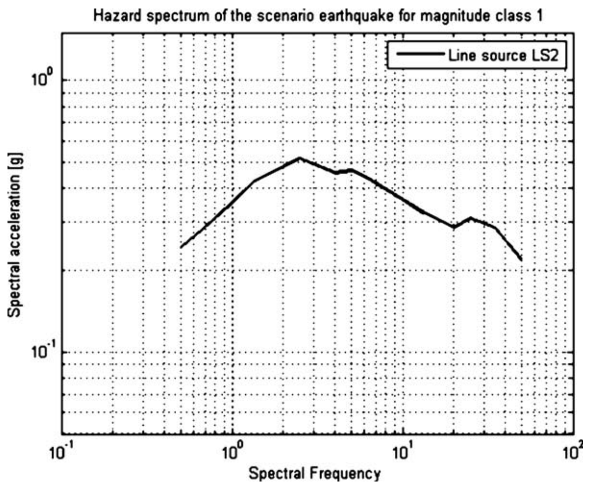

Fig. A5. Hazard spectrum of the scenario earthquake of magnitude class 1.

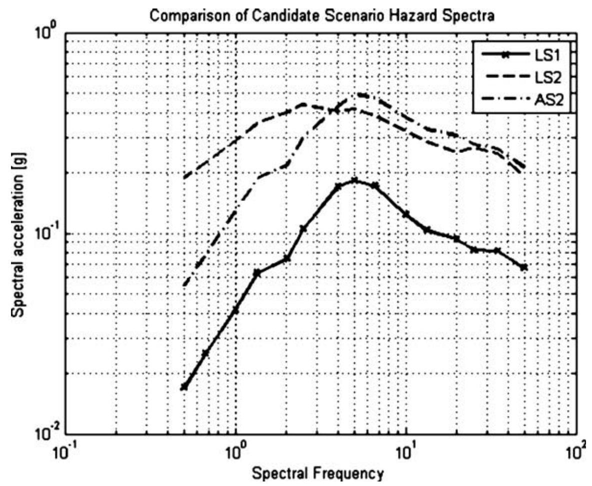

Fig. A6. Hazard spectra of the candidate scenario earthquakes of magnitude class 2.

to the site. Therefore, the optimisation problem converts into the task of finding the location of the candidate scenario earthquake for area source 2 and a comparison of the hazard spectra of all candidate scenarios. Because for the areal source we also apply an amplitude-decay model it is sufficient to solve the reduced optimisation problem

$$\text{find}(r_{\text{opt}}) \rightarrow \max \int_0^{T_{\text{Life}}} \int_{5.5}^{5.9} \int_{r_{\min}}^{r_{\max}} f_{\text{AS2}}(m,t) f_{\text{AS2}}(r|m) \, \text{d}m \, \text{d}r \, \text{d}t \tag{17}$$

to find the candidate scenario earthquake for the areal source 2. The integration variable can be separated. Therefore, it is possible to perform a further reduction of the optimisation problem:

$$\text{find}(r_{\text{opt}}) \rightarrow \max \int_{r_{\min}}^{r_{\max}} f_{\text{AS2}}(r|m) \tag{18}$$

The conditional probability can be calculated in analogy to Eq. (10). For the solution it is sufficient to find the location r_{opt} maximising the conditional probability for the lower magnitude value of the considered interval (5.5). From Eq. (10) it can be concluded that the candidate scenario earthquake for the areal source AS2 is also located at the boundary of the source (the modal value is located at the shortest distance). Therefore, for the final selection of the scenario earthquake for magnitude class 2 we have to compare the hazard spectra from the 3 contributing sources LS1, LS2 and AS2. For the line sources, the magnitude values to be considered are $m = 6.5$, while for the areal source the magnitude value is 6.3 (maximal value). Fig. A6 shows the comparison of the hazard spectra for the 3 candidate scenarios. The hazard spectrum of candidate scenario from line source 2 shows the highest value for the spectral acceleration at 3 Hz although the corresponding value for areal source 2 is close. Because the candidate scenario earthquake from line source LS2 is associated with a larger magnitude value (with a larger energy content), the candidate scenario from line source LS2 has to be selected as the final scenario earthquake for magnitude class 2.

A.3.3.3. Magnitude class 3. The solution of the optimisation problem for magnitude class 3 follows the discussion in Section A.3.3.2. All sources do contribute to this magnitude class. Once again the candidate scenario earthquakes are located at the boundary of the areal sources and at the shortest distance between the line sources and the site. Therefore, the final scenario earthquake is to be selected by a comparison of the hazard spectra of the candidate scenarios from each source. Fig. A7 shows the

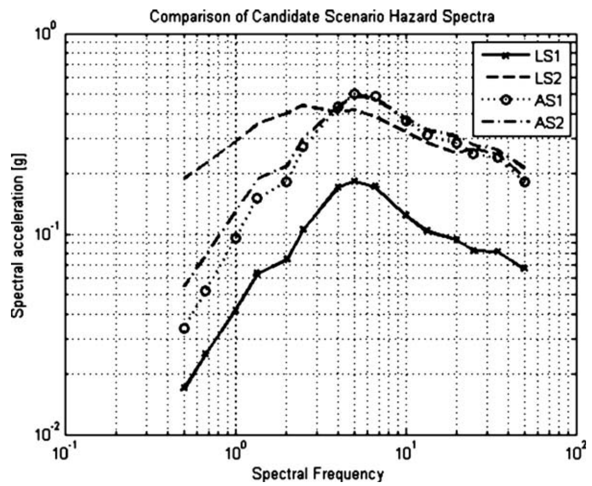

Fig. A7. Hazard spectra of the candidate scenario earthquakes of magnitude class 3.

comparison. Again the candidate scenario earthquake of line source LS2 leads to the largest spectral acceleration at 3 Hz. Therefore, it has to be selected as the final scenario earthquake for magnitude class 3.

A.4. Seismic risk evaluation

Most seismic risk studies (e.g. for nuclear power plants) as well as the corresponding software are based on hazard curves. The new methodology does not require the development of hazard curves because the frequency of seismic initiating events is calculated directly. Instead of hazard curves it is required to calculate the conditional probability of exceedance of the scenario earthquakes' hazard spectra including the corresponding uncertainty distribution. Together with the calculated frequencies of initiating events this allows to use the existing risk software to perform a seismic PRA (Probabilistic Risk Assessment).

For the calculation of the conditional hazard spectra exceedance probability it is possible to use the model of a lognormal distribution of spectral accelerations for a given scenario earthquake. To use this model correctly, we have to adjust the uncertainty values of our attenuation equations. Attenuation equations represent multivariate distributions of spectral accelerations in dependence of magnitude, distance and additional parameters not used explicitly as explanatory variables in the equation. The uncertainty caused by these additional explanatory variables is frequently confused with inherent randomness of earthquakes and named aleatory uncertainty (Abrahamson, 2006; SSHAC, 1997). Because this uncertainty is epistemic by nature, it is more appropriate to call this uncertainty "(temporarily) irreducible epistemic uncertainty". This irreducible part has to be treated as random in our model. The contribution of uncertainty of magnitude and distance can be eliminated from our probabilistic model because the selected scenarios are characterised by a fixed (upper estimate) and known magnitude value and a fixed and known distance between the earthquake location and the site. Furthermore, the selected scenarios are conservative with respect to all scenarios within the same magnitude class. Considering that the error term in our attenuation Eq. (6) can be represented as

$$\sigma = \sqrt{\left(\frac{\partial g(m,r)}{\partial m}\sigma_m\right)^2 + 2\rho\sigma_m\sigma_r + \left(\frac{\partial g(m,r)}{\partial r}\sigma_r\right)^2 + \sigma_{\text{ired}}^2} \tag{19}$$

we can calculate the irreducible, residual part of uncertainty σ_{ired} to be considered in the probabilistic model. g is the attenuation equation functional form (Eq. (6)). The correlation coefficient ρ can be set to 1, because a strong physical correlation exists between magnitude and epicentre location at the fault rupture plane. Furthermore, these two parameters are correlated in our case because the scenarios in terms of magnitude and distance pairs represent the solution of an optimisation problem. The errors of magnitude and distance can be evaluated. As an example we perform the calculation for magnitude class 1. For σ_m we have to consider a value of 0.4 magnitude units, because the selected scenario earthquake completely envelopes all scenarios within this magnitude class with respect to the used impact parameter (S_a). The value for σ_r should be evaluated from the spatial distribution of seismicity in the area surrounding the site. For magnitude class 1 we have to consider the two line sources as contributors. For our analysis we use the minimal value for σ_r of both faults (conservative assessment). Based on the data in our example and the theorem of Pythagoras we get for each of the line sources the following relation for the error

$$\sigma_r = \sqrt{a^2 + D^2} - D \tag{20}$$

where a is the larger of the two fault sections formed by the perpendicular between the line source and the site; D is the length of the perpendicular (shortest distance in our example).

In our example we obtain the value of $\sigma_r = 1.9$ km for line source LS2.

It is important to mention that the location uncertainty associated with an areal source is much higher than for a line source.

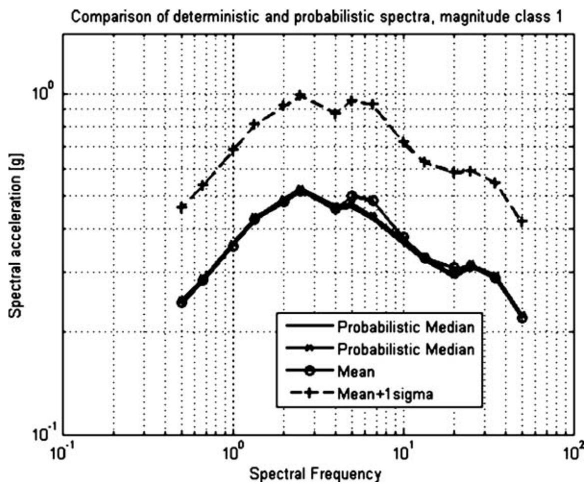

Fig. A8. Comparison of probabilistic (magnitude class 1) and deterministic hazard spectra.

The partial derivatives can be calculated from the source-specific attenuation equations.

In our example, all considered scenarios originate from line source LS2. Therefore, we have to use the attenuation equation for the line source LS2 for the calculation of the partial derivatives. The partial derivative for m is just the coefficient b in our Eq. (6). For simplicity, we evaluate the uncertainty (as an example) for the spectral frequency of 2.5 Hz. Therefore, $b=0.31787$. Then the resulting contribution of magnitude uncertainty to the uncertainty of the attenuation equation is 0.127. The partial derivative with respect to r is:

$$\frac{\partial g(m,r)}{\partial r} = c\frac{1}{r\ln(10)} + d \tag{21}$$

We evaluate the derivative for r at the shortest distance between fault and site neglecting the contribution of depth:

$$r \approx D_{\mathrm{JB}} = 25$$

Because the coefficient d is very small we can neglect its contribution. For $c=0.556$ (line source LS2, 2.5 Hz) we obtain for the resulting contribution of location uncertainty to the uncertainty of the attenuation equation a value of 0.02. Based on Eq. (20) we can calculate the irreducible part of uncertainty. This irreducible uncertainty is $\sigma_{\mathrm{ired}}=0.191$ (instead of 0.28 obtained from regression). Using the model of a lognormal distribution of spectral accelerations for a given scenario, we can calculate a "mean" hazard spectrum and the required quantile spectra.

We can also calculate the conditional probability of exceedance of our design spectrum. This delivers the required information for a subsequent probabilistic risk assessment.

Fig. A8 shows a comparison between the probabilistic "mean" hazard spectrum with the "median" (from our attenuation Eq. (6) representing the regression mean) and with the deterministic design spectra (the "mean" spectrum and the "mean+1σ" spectrum). The comparison shows that the probabilistic "mean" spectrum always lies below the deterministic "mean+1σ" spectrum and is very close to the deterministic "mean" spectrum. Considering the uncertainty reduction in the example it can be concluded that the deterministic "mean+1σ"-spectrum effectively corresponds to a "median+1.5σ" spectrum in the probabilistic analysis. The likelihood that a deterministic design spectrum, which is based on the "mean+1sigma" approach, will be exceeded is very low.

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