Originally published as:

Grünthal, G., Wahlström, R. (2001): Sensitivity of parameters for probabilistic seismic hazard analysis using a logic tree approach. - Journal of Earthquake Engineering, 5, 3, 309-328

DOI: 10.1142/S1363246901000376

SENSITIVITY OF PARAMETERS FOR PROBABILISTIC SEISMIC HAZARD ANALYSIS USING A LOGIC TREE APPROACH

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Received 28 June 2000

Revised 17 August 2000

Accepted 30 November 2000

The sensitivity of different parameters used in probabilistic seismic hazard calculation is investigated by different logic tree runs with alternative magnitude sets, source zone models and attenuation relations, and with different sets of values for the seismicity parameters and the σ -value. Also the influence from the different parameters on the hazard uncertainty, represented by fractiles, is investigated. The calculations are made for peak ground acceleration at a site near Aachen in the Lower Rhine Embayment. The model where the site is located in a larger source zone gives lower hazard values. This is typical for the case where the seismicity near the site is high relative to its surrounding. The hazard curves for the different attenuation functions are similar, an effect of the similarity of the functions themselves. However, a large sensitivity of this parameter is indicated for small mean return periods. An increased σ -value implies a moderate increase of the hazard at long mean return periods. The hazard is increasing for decreased focal depth, decreased β -value and increased maximum expected magnitude, respectively. However, the effects are noteworthy only at low hazard levels for variations in the focal depth and to some extent in the maximum expected magnitude. Finally, decreasing the minimum magnitude thought to be of engineering relevance causes a drastic increase of the hazard at small mean return periods.

Keywords: seismic hazard, parameter sensitivity, logic tree.

1. Introduction

From engineering aspects and for site studies, seismic hazard assessment is a necessary step to estimate the seismic risk, considered the most relevant measure of earthquake threat. The probabilistic seismic hazard treated in this study is expressed as the probability of exceedence (or non-exceedence) of different ground motion characteristics calculated for earthquakes of all sizes and locations within defined ranges. The parameters used in seismic hazard calculation are subject to different interpretations by different analyst groups. One and the same analyst may also want to use different hypotheses concerning one or more of the parameters. Modern techniques, such as the logic tree algorithm and non-regionalisation

models, facilitate greater flexibility in the assignment of the parameters and their uncertainties. The logic tree algorithm permits several values for each parameter and results in error estimates (fractiles) of the hazard. The flexibility is enhanced by the assignment of weights to the values. In practical applications, there should be a balance in the assignment of values and weights between the generous input options and a restraint to realistic settings. A non-regionalisation model, e.g. *Frankel* [1995], *Rüttener* [1995] or *Woo* [1996], can be an alternative in cases of poorly defined faults and other tectonic features. It avoids the specification of faults or source zones based on seismicity or geology data.

At the present time, only a few applications of the logic tree technique in probabilistic hazard calculation have been published in Europe, e.g. *Labák et al.* [1998] for the site of a nuclear power plant in Slovakia, *Musson and Winter* [1997] for the United Kingdom, *NFR/NORSAR and NGI* [1998] for Norway and its offshore area, and *Wahlström and Grünthal* [2000, 2001] for Fennoscandia.

The scope of the present study is to elucidate the influences of the various parameters and their uncertainties in seismic hazard calculation. *McGuire and Shedlock* [1981], *Atkinson and Charlwood* [1983], *Rabinowitz and Steinberg* [1991] and *Bender and Perkins* [1993] are examples of different previous approaches in sensitivity studies. As in the present study, *Atkinson and Charlwood* [1983] analyse the influences of individual parameters by varying them one at a time. Similar results are obtained in the two studies in many cases, however, the benefit of the present study, thanks to the logic tree technique, is the smoothing effect of introducing several values of each input parameter with the resulting measure of the uncertainty of the hazard through the spread of the output fractiles. There are two main sources of uncertainty in the parameters, the aleatory uncertainty related to the inevitable unpredictability of nature and the epistemic uncertainty related to insufficient knowledge of the parameters. Awaiting increased knowledge from more and better data, the impact of the latter type of uncertainty can be narrowed by the logic tree approach. The increase in hazard due to the aleatory uncertainty is mainly quantified through the use of σ , the standard deviation of the scatter of the data about the attenuation relations. However, there is sometimes hard to distinguish between the two types of uncertainty and also the aleatory type can be introduced in the logic tree approach.

Various source regionalisation models, magnitude sets and attenuation relations are applied in the present study. So are different σ -values for the spread in the attenuation data. By introducing different regionalisation models as allowed by the logic tree algorithm, interpretations of different seismotectonic hypotheses can be considered in the same calculation. This is preferred to a non-regionalisation model in this case. The division into source regions (zones) is based on a presumed homogeneity of the seismicity within each region. For each regionalisation model and source region, several values are assigned to each of the seismicity parameters maximum expected magnitude, earthquake recurrence parameters and focal depth. A fourth parameter, the minimum magnitude thought to be of engineering relevance, is assigned the same value for all regions and models. Using the logic tree algorithm, calculations are performed to obtain

Figure 1. Regionalisation models, source regions and source provinces. (a) *Ahorner* model; (b) *D-A-CH* model; (c) *GFZ* model. The provinces are marked by different hatching. Locations of earthquake epicentres in the GFZ database and of the test site at Aachen in the Lower Rhine Embayment are displayed in (c).

exceedence probabilities of horizontal peak ground acceleration (PGA) for a test site located roughly at Aachen (50.8°N, 6.1°E) in the Lower Rhine Embayment [Fig. 1(c)], one of the most intense seismic regions in Central Europe north of the Alps. By using one regionalisation model, magnitude set or attenuation relation at a time, or by changing the default values for a seismicity parameter or σ -value, the sensitivity of each input parameter for the seismic hazard can be investigated.

2. Calculation Algorithm

A revised version of the computer algorithm FRISK88M [*Risk Engineering*, 1996], applying the logic tree algorithm, is used in this study. The logic tree has different branches for different “global alternatives”, attenuation relations and values of each seismicity parameter needed. The global alternatives of the present study are combinations of regionalisation models and magnitude sets. The attenuation relations and the number of values of each seismicity parameter have to be the same for all regions within a global alternative. A seismicity parameter can be combined with the corresponding value (dependence) or every value (independence) of this parameter for every region. The number of solutions, i.e. branches on the logic tree, for each global alternative is $A \cdot M^S \cdot B^S \cdot HS$, A being the number of attenuation relations, M maximum expected magnitudes, B values of the frequency-magnitude relation parameters and H focal depths; S is 1 if a parameter (M , B , H) is dependent (in the sense described above) and is equal to the number of source regions if it is independent. The attenuation relation is always a dependent parameter. If there is a large number of regions, the number of branches (and computer time) increases drastically when independent seismicity parameters are used instead of dependent. Tests made on small samples show that the range of output hazard values shows only minor changes in the two cases. M , B and H are all dependent in the present study.

3. Source Regionalisation Models and Source Regions

A regionalisation model should consist of seismotectonic units in each of which the seismic activity is believed to remain constant in the long term, even though the existing seismic record may be insufficient to show this (cf. *Adams et al.* [1995a]). Two basic types of seismic sources are distinguished: regions and faults. Boundaries of seismic sources are frequently not sharp with respect to the seismic activity. Although based on criteria of many types besides seismicity - structural-geological, neotectonic, geodynamic, geophysical, etc., e.g. see *Autran et al.* [1998] - faults can often not be clearly defined, nor can source regions be sharply marked off from one another. The lack of a complete understanding of the long-term tectonic processes in many intraplate environments is another factor of uncertainty in the specification of seismic sources. The implications for the seismic hazard of the ambiguity of the boundaries of source regions are discussed by

Bender [1986]. In the present study, only source regions are used.

Musson [1997] introduces two types of source regions, one with larger zones and one with many small zones centred around individual epicentres or clusters of epicentres. In a similar fashion, *Adams et al.* [1995a] introduce two models, a geologically based with larger zones and a historical-seismicity based with smaller zones resolving the known seismicity pattern in greater detail. In both studies, there is a decrease of the hazard in the high-seismicity parts and an increase in the low-seismicity parts of the large-zone models in comparison to the small-zone models (see also *Bender and Perkins* [1993]). While *Musson* [1997] uses both models as different alternatives in one logic tree run, *Adams et al.* [1995a] run each of their models separately and select the maximum hazard value of the two for each site, the quasi-probabilistic so-called “robust” method with application to many Canadian sites (cities) [*Adams et al.*, 1999]. Generally, the importance of seismicity versus geology increases with decreasing time period over which the hazard is of interest, since it is less likely with sudden deviations from known seismicity patterns in the short course of time (cf. *Adams et al.* [1995a]). Note, though, e.g. the occurrence of several “surprise” earthquakes in eastern Canada in recent years, a main reason for the new conservative robust hazard algorithm [*Adams et al.*, 1995a, 1999]. If the long-term hazard must be taken into account, as for nuclear waste depositories, geological considerations should be more emphasised in the regionalisation.

Alternative hazard calculation procedures avoiding regionalisation are mentioned in the Introduction. It is doubtful if the “objectivity” can compensate for the ignorance of seismological, geological and seismotectonic knowledge by some of these techniques. For a critical discussion of *Franke*’s [1995] method, which currently is a standard procedure in USGS hazard calculations, see *Adams et al.* [1995b]. The option of the logic tree approach to use several regionalisation models is preferred in this study. This reduces the border effect to some degree. A fully probabilistic approach is kept by combining three different source regionalisation models for the Rhine region and its neighbouring area in one run:

- *Ahorner*: A slightly revised version of his PSSAEL model [*Ahorner and Rosenhauer*, 1986], L. Ahorner (personal communication, 1998), 15 selected source regions having significant influence for studying the selected site;
- *D-A-CH*: A slightly revised version of *Grünthal et al.* [1998, 1999], 12 selected source regions;
- *GFZ*: A new model by G. Michel, GeoForschungsZentrum Potsdam (personal communication, 1999), 13 selected source regions.

The source zone models represent slightly different interpretations of data of seismicity, seismotectonics and structural geology. Three or four source provinces are introduced in each model. A province consists of two to four neighbouring source regions assumed to be similar according to the criteria above. Some regions do not belong to a province. Regions and provinces of the selected source regionalisation models are plotted in Fig. 1. The area immediately north of the

Basel region in the GFZ model is part of two low-seismicity regions which are not included in this study.

4. Earthquake Data

The main database is the catalogue of European earthquakes compiled in the framework of the Global Seismic Hazard Assessment Program (GSHAP, *Grünthal et al.* [1999]) at the GeoForschungsZentrum Potsdam. The database is named “GFZ-mag” below. As an alternative set, data for some 200 events in the Middle Rhine area compiled by *L. Ahorner* (personal communication, 1998) have been incorporated, as new or alternative entries, and together with the unaltered events of “GFZ-mag” they constitute the “Ahorner-mag” database. Although the magnitudes of the vast majority of the events are identical in both databases and the Ahorner revisions are more of local than methodological interest, each set has been included as a branch of the logic tree. However, no sensitivity study is performed of this “parameter”.

The moment magnitude, M_w , is the most frequently used magnitude concept in attenuation relations. If not obtained directly from the seismic moment, M_w is computed from M_L , M_S , m_b and other types of magnitudes, or from macroseismic data, using transformation formulae described by *Grünthal et al.* [1999].

Two selection criteria are imposed on the events of each input set: (1) To assure Poissonian distribution of the events, as required by the probabilistic method, only the main shock is included in the case of an earthquake sequence. The events are then tested and the Poissonian distribution is verified with a high confidence level. (2) Different threshold magnitudes apply for different time periods to ascertain completeness of the events (Table 1). Since the M_w entries for the vast majority of the events in the two sets are identical and there is no big difference for most of the other events, the same threshold criteria are used for both magnitude sets (databases). Figure 1(c) includes earthquake epicentres in and near the source regions.

Each of the magnitude sets, “GFZ-mag” and “Ahorner-mag”, is combined with each of the source regionalisation models, *Ahorner*, *D-A-CH* and *GFZ*, to make up six global alternatives. The global alternatives are given equal weight.

Table 1. Completeness of magnitude data.

Year	1200	1300	1400	1500	1600	1700	1800	1900	2000	
Magnitude, M_w	5.3				4.3		3.8	3.3	2.8	2.3

5. Attenuation Relations

An empirical attenuation relation describes how the ground motion depends on the magnitude (or intensity) and the distance. Lacking an attenuation relation based entirely on data near the investigated site, three relations are used in the present study:

$$\ln a = -2.143 + 0.751 M_w - 0.815 \ln r - 1.04 \times 10^{-3} r; \sigma = 0.576$$

$$\text{(modified after Ambraseys et al. [1996])} \quad (5.1)$$

$$\ln a = -3.254 + 1.045 M_w - \ln r; \sigma = 0.437$$

$$\text{(modified after Sabetta and Pugliese [1996])} \quad (5.2)$$

$$\ln a = -0.522 + 0.527 M_w - 0.945 \ln r; \sigma = 0.542$$

$$\text{[Spudich et al., 1997]} \quad (5.3)$$

a being the horizontal peak ground acceleration (m/s^2), M_w moment magnitude, r distance (km) and σ standard deviation of $\ln a$. Equation (5.1) is based on extensive data compiled from earthquakes in Europe (mainly the southern part) and southwest Asia; Eq. (5.2) is based on Italian data and established in frequent engineering applications; Eq. (5.3) is applicable to a normal faulting regime, i.e. suitable for the Rhine area. Therefore, each of these relations seems useful for application in the study area. Lacking local data, also the σ -values in our study

Table 2. Attenuation relations for horizontal peak ground acceleration with valid distance and magnitude ranges.

Reference area/event type	Equation	Distance [km]	Magnitude, original	Magnitude, M_w
Ambraseys et al. [1996] Europe and adjacent areas	(5.1)	up to 200	$M_S = 4.0 - 7.5$	4.4 - 7.2
Sabetta and Pugliese [1996] Italy	(5.2)	up to 100	$M_L = 4.6 - 5.5^*$ $M_S = 5.5 - 6.8$	5.6 - 6.7
Spudich et al. [1997] extensional regime earthquakes	(5.3)	up to 105	$M_w = 5.0 -$	5.0 -

*Not used.

M_w is obtained from M_S using the relation $M_w = (M_S + 1.542)/1.25$, which implicitly includes the Hanks and Kanamori [1979] M_w definition.

M_w is obtained from M_L using the relation $M_w = (M_L + 0.7222)^2 \cdot 0.09 + 1.65$.

These conversion formulae have been established at the GeoForschungsZentrum Potsdam.

are taken from the equations above. Table 2 gives restrictions of the equations, the legitimacy of which is of geographical/geological or tectonic kind. Eq. (5.3) is the original whereas M_S was converted to M_w to obtain the Eqs. (5.1) and (5.2) (see Table 2). The three equations are given equal weight in the logic tree.

The σ -values in Eqs. (5.1)–(5.3) represent the scatter in the data from which the respective relation was derived. The nature of σ is likely made up by many components, such as travel path, azimuth, local geology, magnitude and distance. The attenuation relation and the σ -value are both of great importance for the assessed hazard (increased hazard for increased σ , most pronounced at low probabilities of exceedence), see, e.g. *Atkinson and Charlwood* [1983] and *Rabinowitz and Steinberg* [1991]. It is an important task for the future to record and compile local data to get an adequate relation and an adequate σ -value.

6. Seismicity Parameters

6.1. Seismicity recurrence parameters

Error sources in the values of the recurrence parameters, i.e. ν , the annual number of events with or above the assigned minimum magnitude of 4.0 (see Sec. 6.4), and β , the negative slope of the cumulative $\ln(\text{frequency})$ - M_w relation, are: inhomogeneous or incomplete catalogues in time and space, recurrence periods of large earthquakes exceeding the time span of the catalogue, location uncertainty (which may place an event in the wrong source region) and deficiency of the magnitude homogenization.

In this study, instead of assigning statistical error estimates, different sets of ν and β -values are computed for each source region and source province, and for the “gross zone” - an area encompassing the Rhine regions of the three regionalisation models, i.e. all regions except the southernmost and the two easternmost ones of each model (Fig. 1). This is done for each of the “GFZ-mag” and “Ahorner-mag” sets. For a few regions, there are not sufficient data to make an independent determination of the ν - and β -values and data from a neighbouring region are included. Freezing the β -values calculated for each source province and the gross zone, the corresponding ν -values are calculated for each region. The regional, provincial and gross zone values are assigned weights of 0.3, 0.4 and 0.3, respectively, i.e. the largest “homogeneous” unit, the province, is given a slight priority. If a region does not belong to a province (see Fig. 1), fictitious provincial ν - and β -values identical to the regional are introduced and assigned a weight of 0.4. For the regions of each model not belonging to the gross zone (see above), fictitious gross zone values identical to the provincial are assigned a weight of 0.3.

6.2. Focal depth

The focal depth distribution of events with magnitude, $M_w > 2.8$ in the “GFZmag” set is determined for each region. The lower magnitude limit is specified to avoid

uncertain data from small events. Many events lack a focal depth solution and cannot contribute. For one region [HUN2 of the *Ahorner* model; Fig. 1(a)], there is no depth solution and the distribution from the adjacent region (HUN1) is adopted. Like for the other seismicity parameters, the computer algorithm requires focal depth values to be assigned to predetermined weights, not vice versa. Based on the obtained depth distribution in each region, ten values are therefore assigned a weight of 0.1 each. One and the same value can occur several times. Since there are only small differences between the two M_w sets, the same depth assignments are adopted for the “Ahorner-mag” set.

6.3. Maximum expected magnitude

Various methods to calculate the maximum expected magnitude in the source regions are described by *Coppersmith* [1994]: Addition of an increment to the maximum observed magnitude, where the increment should depend on the β -value, still usually is assigned as a constant; extrapolation of the frequency-magnitude curve to a given recurrence interval and a normalised area, where the possible non-linearity over a longer magnitude interval is a source of uncertainty; extreme-value theory, where large data sets are needed to give some confidence; rate of strain or moment release, hard to estimate and uncertain if derived relationships between the rates and the maximum observed magnitude are analogous to the maximum expected magnitude; seismicity dimension, scaling relations between fault dimensions and magnitude are controversial; tectonic analogies with other similar provinces, uncertain classification of tectonic provinces. Ample references to the above methods are given by *Coppersmith* [1994].

The last technique, where space is substituted for time, is preferred by *Coppersmith* [1994] and *Cornell* [1994] and is adopted in a modified form in the present study. Normal distribution functions of maximum observed magnitudes in stable continental regions globally, of extended crust and non-extended crust, respectively (only the former applies in the present study), are multiplied with likelihood functions based on seismicity parameters in each source region: the maximum observed M_w , number of large earthquakes and β -value. From the resulting posterior distribution of maximum expected magnitude, M_{max} , for each region and magnitude set, five representative values are selected and assigned a weight of 0.2 each. An example showing how the M_{max} values are selected is given in Fig. 2.

As an option not used in this study, the long and detailed record of earthquake data in Europe, yet with no earthquakes near the size of the largest in some other stable continental regions, e.g. New Madrid, Missouri, US, 1811–1812 or Meckering, Australia, 1968, might suggest that the global function should be substituted by a “European” prior distribution function derived from continental domains in Europe. A study on this topic by the present authors is in preparation.

6.4. Minimum magnitude

The minimum magnitude thought to be of engineering relevance, M_{min} , has to be

Fig. 2. Example plot of a posterior likelihood function of maximum expected magnitude and the selection of five representative values (gravity points at hatched lines) from a partition into five areas of equal size (separated by solid lines). The example is for a source region with maximum observed $M_w = 4.4$.

set at one value in the input to the computing algorithm. Typically, a magnitude in the interval 3.75–5 is selected [Bender and Perkins, 1993], the higher-end values in calculations for sites of earthquake-resistant designed facilities like nuclear power plants, e.g. see Labák *et al.* [1998]. The default value of M_{min} is set at $M_w = 4.0$ in the present study.

7. Influences of Individual Parameters

Figure 3 shows the logic tree with all parameters set and weighted at the default values as described in the previous sections. The number of branches is 2700. Varying the parameters one at a time, their influences on the seismic hazard - the median and ± 1 standard deviation fractiles of PGA at Aachen - are elaborated. The sensitivity investigations are done in three different ways: (1) For the magnitude set, regionalisation model and attenuation relation, one alternative at a time is run while keeping all the other branches of the tree as in Fig. 3. The number of branches is thus smaller in these calculations. (2) For the seismicity parameters as well as the attenuation deviation, σ , the original values are varied or in-

Fig. 3. Logic tree for seismic hazard calculation (default settings). Explanations of symbols, values and equations are given in the text.

crements are added within the estimated realistic range of uncertainty for each parameter. For some parameters, the comparison is performed using only one global alternative (this is the case also for the attenuation), i.e. with a decreased number of branches. (3) For M_{min} , which is not variable within the logic tree, alternative values to the default, $M_w = 4.0$, are inserted in separate runs. This is done using one global alternative, i.e. again with a decreased number of branches.

The aim with the selected magnitude classes, source zone models and attenuation relations as well as the alternative values of the parameters under (2) and (3) has been to cover realistic input options and ranges of similar probability for the different parameters. There is inevitably some subjective component involved in the assignments and other investigators could motivate other selection sets.

M_w set. The hazard values obtained from each of the “GFZ-mag” and “Ahorner-mag” sets are nearly identical, as could be expected from the similarity of the two M_w sets. The difference is of local interest and not further elaborated here.

Regionalisation model. The smaller contribution to the total hazard from the GFZ model than from the other two models, shown in Fig. 4, is explained by the larger size of the source region in which Aachen is located, with a corresponding “smearing-out” effect of the seismicity. For other sites, there are other relative influences of the different models. With decreasing hazard level, there is an obvious increase in the spread of the fractiles with increasing fractile level. Figure 4 should be taken as a general illustration of the importance of regionalisation modelling.

Attenuation relation and σ . Seismic hazard curves based on each of the selected attenuation relations (Table 2) are similar (Fig. 5). Figure 6 shows the increase in seismic hazard for an increase in σ by 10% and 20%, respectively, for all three attenuation relations. The influence is small but increases slightly with increasing mean return period.

Fig. 4. Seismic hazard calculated from the three different regionalisation models. In Figs. 4–11, P denotes annual seismic hazard and PGA horizontal peak ground acceleration. In Figs. 4–10, median hazard curves are represented by full lines, 84% fractiles (+1 standard deviation) by long-hatched lines and 16% fractiles (-1 standard deviation) by short-hatched lines. Figures 4–12 all apply to Aachen.

Fig. 5. Seismic hazard calculated from each of the three attenuation relations used in this study (see Table 2). The influence from the various relations is similar.

Fig. 6. Seismic hazard calculated from three different sets of ν -values, original and with values increased by 10% and 20%, respectively.

Fig. 7. Seismic hazard calculated from three different sets of β -values, original and with values increased by 0.25 and 0.5, respectively. The differences between the curves remain virtually unchanged with changing hazard level.

Fig. 8. Seismic hazard calculated from three different sets of focal depths, original and with values multiplied by 0.75 and 1.5, respectively.

The β -value has a rather marginal influence, as seen in Fig. 7, where the hazard is computed from input files where the values of 0.25 and 0.5, respectively, are added to every β -value, and the corresponding ν -values are recomputed. A typical β -value is in the range 2–2.5. An increased β -value (a smaller fraction of large events) gives lower seismic hazard and the effect is virtually stable over a wide range of hazard levels (parallel curves). It is worth noting that the uncertainty does not change for different fractiles.

Focal depth values multiplied by factors of 0.75 and 1.5, result in increased and decreased hazard, respectively. This is noticeable particularly at low hazard levels, as visualised in Fig. 8. Like for the β -value there is no increase in the spread of the fractiles with increased fractile level.

The maximum expected magnitude, M_{max} , has an influence on the seismic hazard illustrated in Fig. 9. In this example, values of 0.5 and 1.0, respectively, are added to all M_{max} entries. The increase in the hazard is modest at small mean return periods but somewhat larger for lower hazard levels. There is practically no change in the uncertainty of the different fractile levels.

The minimum magnitude, M_{min} , is a sensitive parameter at small mean return periods, where a modest increase results in a large decrease in the seismic hazard, as shown in Fig. 10. In this example, the M_{min} values 3.5, 4.0 and 4.5 are compared. The difference becomes marginal at long mean return periods.

As a spin-off of the study, the mean hazard curve and the 16%, 37%, 50% (median), 63% and 84% hazard fractile curves for Aachen are shown in Figure 11. The fractiles correspond to deviations from the median of -1σ , -0.5σ , 0 , $+0.5\sigma$ and

Fig. 9. Seismic hazard calculated from three different sets of M_{max} values, original and with values increased by 0.5 and 1.0, respectively.

Fig. 10. Seismic hazard calculated from three different M_{min} values, 3.5, 4.0 and 4.5, respectively. The increase in the hazard for decreasing M_{min} is large for short mean return periods but marginal for long mean return periods.

Fig. 11. Seismic hazard mean and fractile curves (default settings). F0.84 denotes the 84% fractile, etc.

Fig. 12. Contribution, v , to the seismic hazard (mean values) of earthquakes with different magnitudes and at different distances, for a PGA of 1 m/s² (default settings). The lowest magnitude class represents $M_w \leq 4.5$ and the highest distance class $r \geq 100$ km.

$+1\sigma$, respectively. The default parameter settings described in Secs. 3-6 are applied. The relative contributions to the seismic hazard from various magnitudes and distances, at a PGA level of 1 m/s^2 , are shown in Fig. 12. The computing algorithm is designed to give mean values for the file used for Fig. 12. Typically they correspond approximately to the 63% fractile (see Fig. 11).

8. Conclusions and Discussion

Since there is a virtually linear dependence between each input parameter and the calculated hazard, the best hazard estimate results from the input of the mean value of each parameter [McGuire and Shedlock, 1981; Bender and Perkins, 1993]. However, different alternatives, hypotheses and interpretations may exist for the parameters and a logic tree technique is needed to take these into consideration. This flexibility, if confined to realistic parameter settings, is a big advantage to standard methods.

The sensitivities of individual parameters are summarised below, where reference is made to the different fractile curves plotted in Figs. 4-10:

- The choice of regionalisation model can have significant influence (Fig. 4), but the effect is modest when the same tectonic base is used for the regionalisation. The specification of the region where the investigated site is located is most important. The inclusion of several models may smooth unwanted effects from individual models. In the present case, the strong influence is underlined by the $+1$ standard deviation fractile for the model giving the lowest hazard (GFZ) being lower than the median hazard curves for the two other models for return periods up to about 1000 years. Atkinson and Charlwood [1983] found no large differences in the hazard calculated for their three different models, with the differences actually decreasing with decreasing probability.
- The three selected attenuation relations, suitable for the conditions of the study area, give similar hazard values (Fig. 5). Tests made with other relations showed a considerable variation of the hazard. There is an overlap of the fractile sets at shorter mean return periods even for our three similar relations, indicating a high sensitivity of this parameter for seismic hazard calculations. The increase in hazard with increased σ is small, the effect being slightly larger for longer mean return periods (Fig. 6), a result confirmed by, e.g. Atkinson and Charlwood [1983] and Bender and Perkins [1993]. The small difference between the median values is accentuated by the large jump to the other sets of fractiles. This can be interpreted as an insensitivity of σ , within realistic variations, to seismic hazard. The different σ -values for the three relations also imply different relative weighting for the different fractiles. Efforts should be made to obtain an attenuation relation based on local data.
- Increased β gives decreased hazard, but the effect is rather minor and virtually invariant to the hazard level (Fig. 7). A similar invariance was obtained in the study of Atkinson and Charlwood [1983]. There is a distinct difference between

each set of fractiles, underlining the only minor influence of this parameter for the hazard. *Arieh and Rabinowitz* [1989] and *Grünthal and Bosse* [1997] found the seismicity rate, ν , generally more influential than β , in the latter study particularly at small mean return periods.

- The focal depth distribution has influence, in particular for long mean return periods (increased hazard for decreased depth; Fig. 8). There is a corresponding spread of the ± 1 standard deviation fractiles, yet no overlap of the three sets in the plotted range of hazard levels. The uncertainty in catalogue depth assignments and the sparsity of depth data in some source regions contribute to the uncertainty in the calculated hazard values. Therefore, it may be sensible to calculate the depth distribution using data from larger areas, e.g. see *Wahlström and Grünthal* [2001]. The strong influence of this parameter in regions where the span of focal depths is large is demonstrated by *Atkinson and Charlwood* [1983].
- M_{max} has minor influence at short mean return periods, but the influence increases with increasing mean return period (Fig. 9), a tendency also obtained by, e.g. *Atkinson and Charlwood* [1983]. There is a clear separation of the three sets of fractiles, indicating the insensitivity of this parameter. Standard hazard computations show a considerable dependence on M_{max} . The logic tree approach allowing several values of M_{max} has a stabilising effect compared to standard approaches, as pointed out by, e.g. *Musson and Winter* [1997]. M_{max} might also be a more sensitive parameter in a different kind of region.
- M_{min} has a profound influence at short mean return periods (increased hazard for decreased M_{min} ; Fig. 10), as confirmed by, e.g. *Bender and Perkins* [1993]. Besides the large spread of the median hazard curves, the sensitivity is manifested as a significant overlap of the different fractile sets. For example, the $+1$ standard deviation fractile for $M_{min} = 4.5$ is much lower than the median curve for $M_{min} = 4.0$ for short mean return periods. For a general discussion of M_{min} in hazard calculation, see *Bender and Campbell* [1989].

These conclusions have general validity, although the detailed influences are to some extent dependent on the location of the investigated site. For statistical aspects of the importance of various parameters, see *Bender and Perkins* [1993].

To further investigate the influence of attenuation in combination with each of the other parameters, a relation with quite different characteristics, giving smaller hazard at short mean return periods and larger hazard at long mean return periods, is added to the three relations used in the previous calculations. The main effect is that the spread of the hazard curves for the different values set for each investigated parameter increases at long mean return periods. This effect is particularly notable for the source zone models and the σ -value. For the minimum magnitude, the spread decreases at short mean return periods. The distribution of the total hazard is more towards larger distances and to some extent larger magnitudes, as expected with the introduction of a ground motion relation giving more weight to longer mean return periods. *Rabinowitz and Steinberg* [1991] and *Rabinowitz et al.* [1993] elaborate on the combined influence of more than one

parameter on the hazard and find that this can be stronger than from the individual parameters.

Acknowledgements

We kindly thank Professor L. Ahorner who provided an updated earthquake catalogue file for a part of the Rhine area as well as a modified seismic source zone model for the study area. A subset of a new tectonic- and seismicity-based regionalisation model of Germany and its surroundings by G. Michel, GFZ, has been used. The technical support of our department colleague Ch. Bosse is much appreciated. Regards paid to the thorough comments of two reviewers have improved the text.

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