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SPECTRAL AMPLITUDE BASED PROBABILISTIC SEISMIC HAZARD FOR THE AREA COLOGNE/AACHEN (GERMANY) CONSIDERING THE UNCERTAINTIES OF THE INPUT PARAMETERS

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SUMMARY

Probabilistic seismic hazard is calculated for an area near Cologne/Aachen (Germany) in the Lower Rhine Embayment. Using the logic tree technique, the uncertainties of the various input parameters and models are quantified in order to give a measure of the errors to the output hazard. Main input features are different combinations of seismic source zones derived from a detailed neotectonically founded regionalization model, seismicity parameters from a new earthquake databank with unified M_w, distributions of maximum expected magnitudes derived with a technique combining global and regional magnitude data, and attenuation relations selected to correspond to the faulting regime of the investigated area.

Medium (“best” estimate) and 84% fractile (“conservative” estimate) hazard maps for 2% probability of exceedence in 50 years are presented based on accelerations at 0.1s, 0.2s, 0.4s, 1.0s and 2.0s periods assuming rock foundation. The frequency dependence of ground acceleration for the cities of Cologne and Aachen are shown in diagrams for a wide range of exceedence probabilities.

INTRODUCTION

The quantification of the earthquake hazard for a site or an area restricts the preparedness and economic potential of earthquake protection to realistic levels. It also provides the earthquake engineers with guidelines of quality requirements for future buildings and other constructions. A principal problem in hazard assessments is that the different input parameters are not precisely known but affected by uncertainties.

A new earthquake catalogue for central, northern and northwestern Europe with unified M_w magnitudes (Grünthal [1]), in part derived from chi-square maximum likelihood regressions (Stromeyer [2]), forms the basis for seismic hazard calculations for the Lower Rhine Embayment. State-of-the-art techniques in the assignment of input parameters and models and their quantified uncertainties, and the application of

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a logic tree calculation algorithm, produce output hazard values with quantified errors (fractiles). To the input belong a detailed seismic zonation, maximum expected magnitudes calculated from a combination of globally and regionally observed magnitudes, and appropriate attenuation relations.

Earlier probabilistic seismic hazard maps for the area around Cologne and Aachen (Germany) were based on intensities (Ahorner[3]; de Crook [4, 5]; Grünthal [6]). Later maps relate to peak ground acceleration (Grünthal [7] and with almost similar results Leynaud [8] and Atakan [9]). None of these studies takes the uncertainties of the input parameters into account and therefore yields no error estimate of the calculated hazard.

Resulting acceleration based hazard maps for the study area depict the median and 84% fractile values, respectively, for 2% probability of exceedence in 50 years at frequencies between 0.1s and 2.0s. Mean, median and 84% fractile hazard curves are given for Cologne and Aachen.

All hazard assessments are made for rock surfaces. At a later stage, a combination with microzonation analyses providing the influence of the sedimentary cover will be taken into account.

INPUT PARAMETERS AND MODELS AND THEIR UNCERTAINTIES

Two types of uncertainties of the data can be distinguished, although sometimes they overlap: *aleatoric* denoting the variability and thus unpredictability in the nature of events and *epistemic* due to insufficient knowledge or incomplete models of the input parameters. The second type of uncertainty can be diminished by increased future information. The best assessments at present time of the input data and models, with uncertainties, are descibed below. The different input values can be assigned different weights to increase the flexibility.

Seismic source zone models

The seismic source zones define areas with certain characteristics where future earthquakes are expected to occur. The uncertainties in defining the seismic zones are captured by considering alternative models. The previous model used by the D-A-CH (Grünthal [6]) and GSHAP (Grünthal [7]) studies (Figure 1) are modified by introducing 14 small zones in the area of the Lower Rhine Embayment and the Ardennes. The 14 zones, shown in Figure 2, are practically an image of the neotectonic pattern and are based on tectonic studies by Legrand [10], Colbeaux [11], Ahorner [12], Geluk [13] and R. Pelzing, pers. communication. A subset of the zones of the D-A-CH model, here denoted *Gr*, is used as the first model in the present study. Although it uses first-order seismotectonic information, it is more strongly related to the observed seismicity than the other models (see below). Different combinations of the 14 small zones supplemented by surrounding zones from the D-A-CH model make up four additional source zone models, *Ga*, *Gb*, *Gc* and *Gd*. Figure 3 shows the new parts of the models. The simultaneous use of several source zone models, possible through the logic tree algorithm (see below), combines the influence of different seismotectonic hypotheses.

The five models are assigned different weights. The starting model *Gr* gets a neutral weight of 0.20. The combined model *Ga* and the most split up model *Gd* each gets the highest weight (0.23), since they follow the most likely NW-SE trending seismogene structures. It is less probable that the northern end of the neotectonic NW trending faults would be as seismically active as the central and southern parts. Therefore, model *Gc*, representing the combination of small zones in the NW, centre and SW in the Lower Rhine Embayment, is assigned a slightly lower weight (0.17). So is model *Gb*, with its block structure of zones.

Attenuation models

The dominant faulting mechanisms in the target area are normal faulting and a combination of normal faulting with strike slip. Lacking local attenuation data for the Rhine area, the relations by Spudich [14]

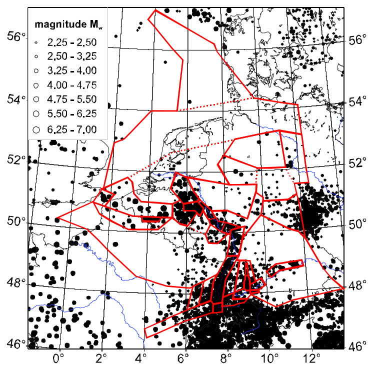


Figure 1. The D-A-CH and GSHAP seimic source zones for western Central Europe. Source model *Gr* is made up by a subset of the zones (see text).

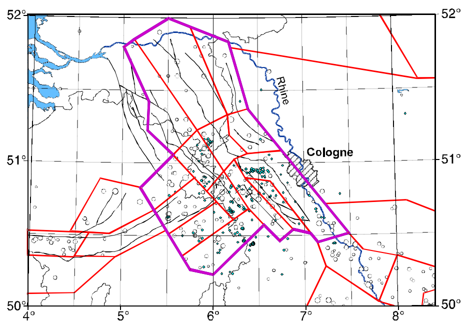


Figure 2. The 14 small seismic source zones as images of the neotectonic setting in the target area surrounded by the D-A-CH source zone model of Grünthal [6].

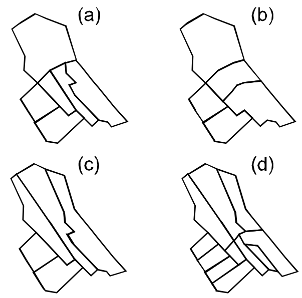


Figure 3. Parts of the zonation models (a) *Ga*, (b) *Gb*, (c) *Gc* and (d) *Gd* made up by different combinations of the new zones shown in Figure 2.

for extensional regimes and Boore [15] assuming strike-slip mechanism and not specified mechanism, respectively, are used. Calculations are performed for spectral accelerations at periods of 0.1s, 0.2s, 0.4s, 1.0s and 2.0s assuming rock conditions. The velocity of 620 m/s used by Spudich [14] is applied also to the Boore [15] relations. Equal weight is assigned to each of the two studies and for the Boore [15] relations equal weight is assigned to each mechanism type.

Seismicity data and parameters

A databank for central, northern and northwestern Europe with unified M_w has been obtained by analysis and revision of earthquake data in 25 local catalogues and 30 special studies. This work was related to the Global Seismic Hazard Assessment Program (GSHAP) for this area (Grünthal [7]). The seismicity parameters used in the present study are based on this databank.

The a- and b-values of the cumulative Gutenberg-Richter relation are calculated for each source zone using the maximum likelihood technique. Where the data are sparse, data from adjacent zones are included in the calculation of the b-value. Representative examples of frequency-magnitude relations and the data they are calculated from are given in Figure 4. The uncertainty of each a- and b-value is considered by introducing the a ± 1.41σ and b ± 1.41σ values. These values represent the medians of the ±σ tails of the normal distribution curve, i.e. the parts larger than +σ (approximate 84% fractile) and smaller than -σ (approximate 16% fractile), respectively. Therefore, the a ± 1.41σ and b ± 1.41σ values are weighted 0.16 each and the a and b entries are weighted the remaining 0.68 each.

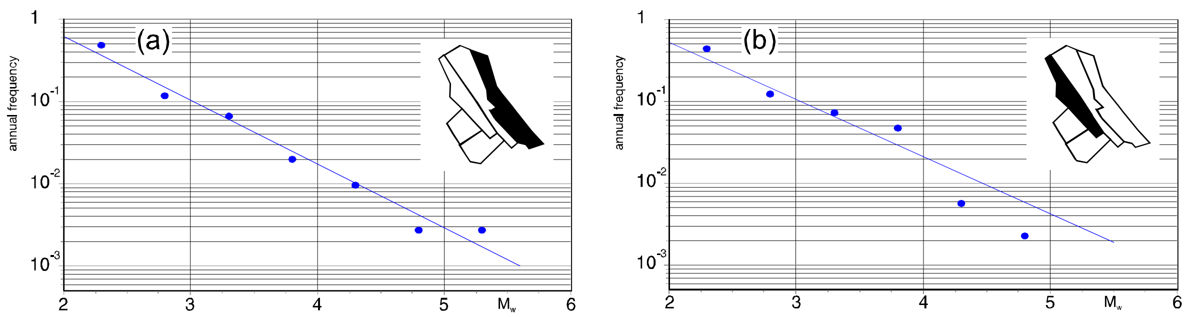


Figure 4. Examples of cumulative frequency-magnitude relations and the data they are based on: (a) Erft block and Viersen fault zone (from model *Gc*); (b) Feldbiss fault zone (from model *Gc*); cf. Figure 3.

The method by Coppersmith [16] and Cornell [17] multiplies prior global distribution functions of M_w magnitudes for extended and non-extended stable continental regions, respectively, with regional likelihood distribution functions determined by the maximum observed M_w magnitude, resulting in a posterior distribution function of maximum expected M_w magnitude for each zone. The maximum observed M_w marks the lower boundary of the posterior distribution.

Whereas the distribution in its higher end asymptotically approaches 0 in the Coppersmith [16] approach, the present study introduces a boundary as the maximum M_w calculated for a given fault area A (km^2) described by Wells [18]:

$$(M_w)_{max} = 4.07 + 0.98 \log A \qquad (1)$$

where A is set as the length of the zone times the depth of the seismogenic crust (30 km). Each distribution is then discretized between the boundary values to give five representative input values, reflecting the uncertainty. The values are given equal weight. Examples of expected maximum magnitude distributions are shown in Figure 5.

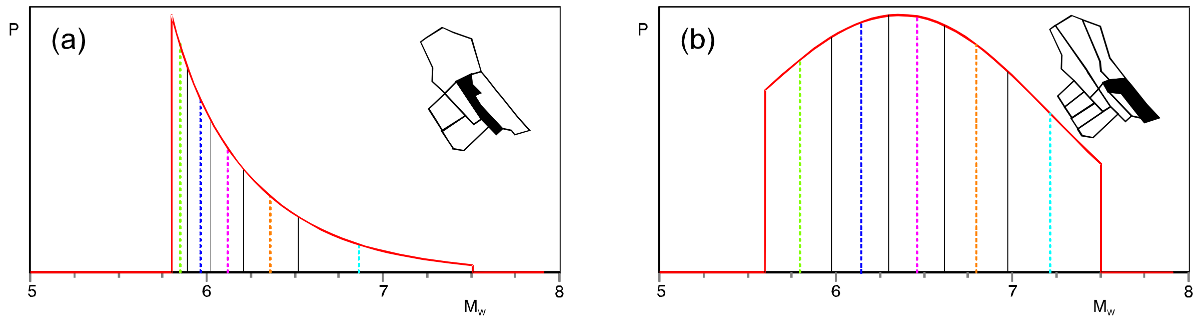


Figure 5. Examples of posterior probability distribution functions giving sets of maximum expected magnitudes: (a) Peel boundary fault, SE part, and the SW Erft block boundary fault zone (from model *Ga*); (b) Erft fault zone (from model *Gd*). The lower cut-off is the largest recorded magnitude in the zone and the higher cut-off represents the value calculated from the Wells [18] relation. The area under the curve is separated in five equally large parts, the gravity values of which (hatched lines) are used as input in the hazard calculations.

The depths of the largest earthquakes in each of five subregions in the Rhine area and its surroundings form the basis for selection of five representative focal depths for each subregion. Each source zone is assigned such a set of depth values as input, reflecting the uncertainty of the parameter. Again the five values are equally weighted.

THE LOGIC TREE ALGORITHM

The various input parameters/models with their uncertainties and weights are combined in a logic tree (Figure 6). A slightly modified version of the FRISK88M [19] computer program was used for the calculations.

The epistemic uncertainty in the selection of seismic source zones is taken into account through the five models, four of which are based on combinations of the small-unit model suggested in the present study.

Each of the source zone models is combined with each of three attenuation models (for different periods), representing different tectonic regimes.

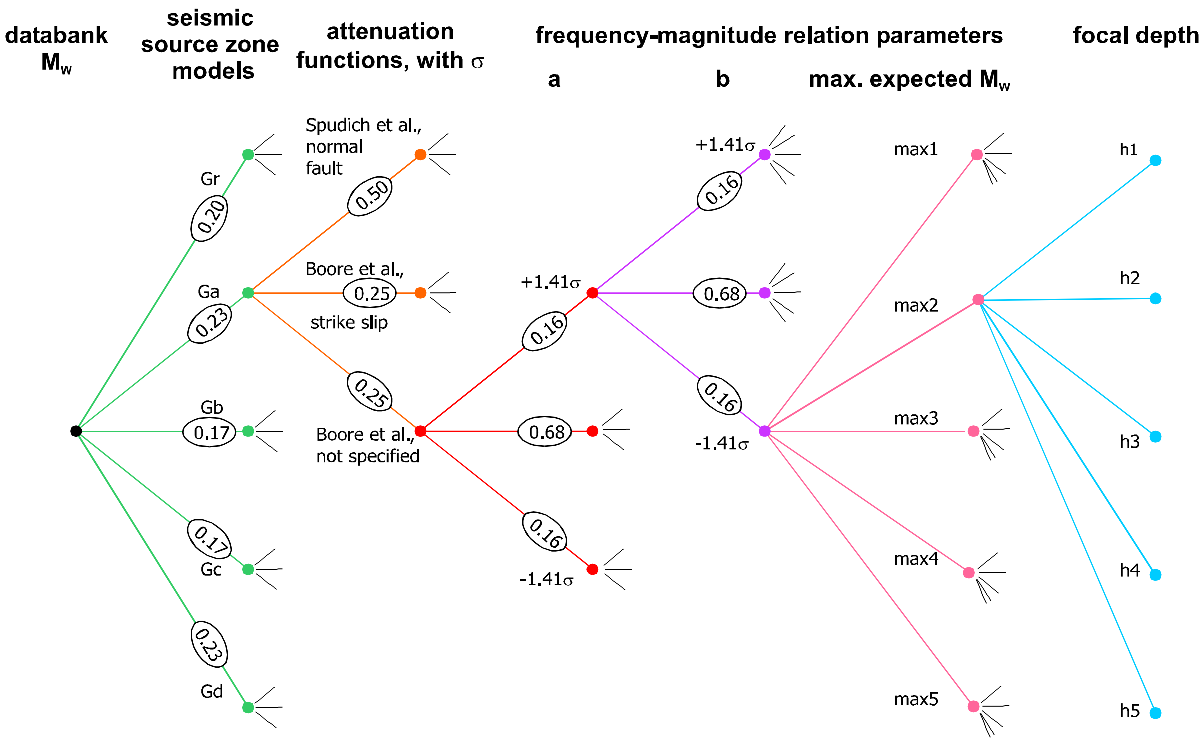


Figure 6. Logic tree showing the structure of input data for seismic hazard calculations in terms of ground motion. The attenuation functions are specified for different faulting types: "nf" by Spudich [14] denotes normal faulting and "ss" and "all" by Boore [15] denote strike-slip and unspecified mechanisms, respectively. The different weights of input parameter alternatives are given, except for the maximum expected magnitude and the focal depth, where equal weighting (0.2) is used.

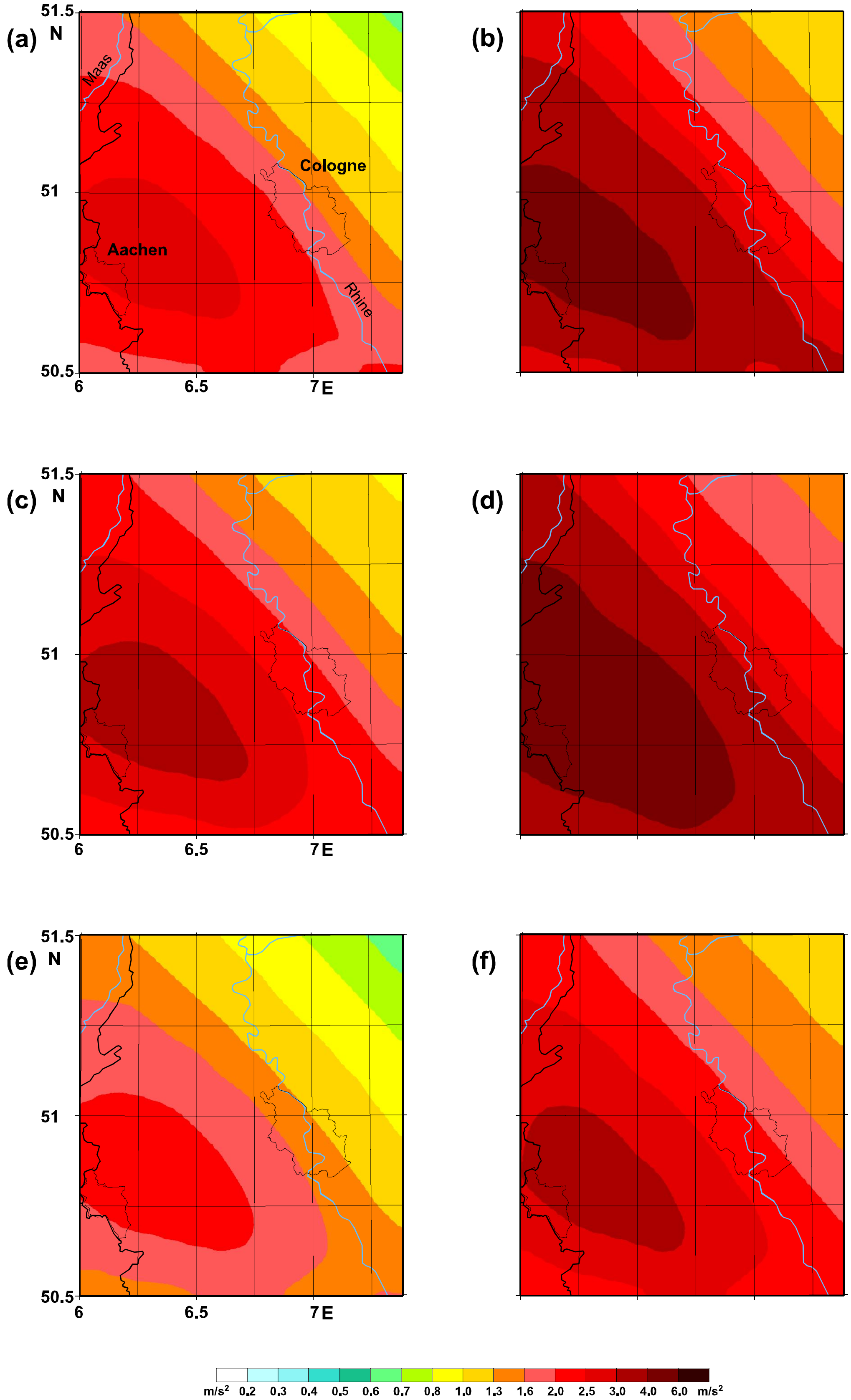
Further combination is made with the mean and ± one standard deviation values of a and b of the frequency-magnitude relations of each source zone. Their weights follow from statistical considerations. The magnitudes of the individual seismic events are not given errors but their uncertainty is implicitly considered in the use of several frequency-magnitude relations.

Finally, each of the previous combinations is combined with each of the five equal-weighted values of the discretized probability distribution functions of the maximum expected magnitudes and with each of the five equal-weighted values of the focal depth distributions.

RESULTS

Hazard calculations were performed for a grid of points with spacing 0.1° in latitude and longitude over the target area and for a probability of exceedence of 2% in 50 years. Median and 84% (median + one standard deviation) fractile hazard maps for spectral accelerations in the range 0.1s - 2.0s are shown in Figure 7. The median values can be considered the "best" estimate under the given circumstances and the 84% fractile values represent a conservative estimate. The largest hazard is found for the area near 6.2°E-6.3°E and 50.8°N-50.9°N, i.e. east of Aachen, with median values near 3 m/s^2 at 0.1s, over 3 m/s^2 at 0.2s and then falling to 0.5 m/s^2 at 2.0s.

In Figure 8, the hazard assessments for central Cologne are given as curves showing the mean, median and median + one standard deviation (84%) fractiles for the period range 0.1s to 2.0s and annual probabilities of occurrence down to 10^{-4}, i.e. return periods up to 10,000 years. Figure 9 gives the corresponding curves for Aachen. Table 1 gives a summary of the hazard accelerations for a probability of exceedence of 2% in 50 years.


(a)
(b)
(c)
(d)
(e)
(f)
51.5
51
50.5
N
6
6.5
7 E
Maas
Rhine
Cologne
Aachen
m/s²
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1.0
1.3
1.6
2.0
2.5
3.0
4.0
6.0
m/s²

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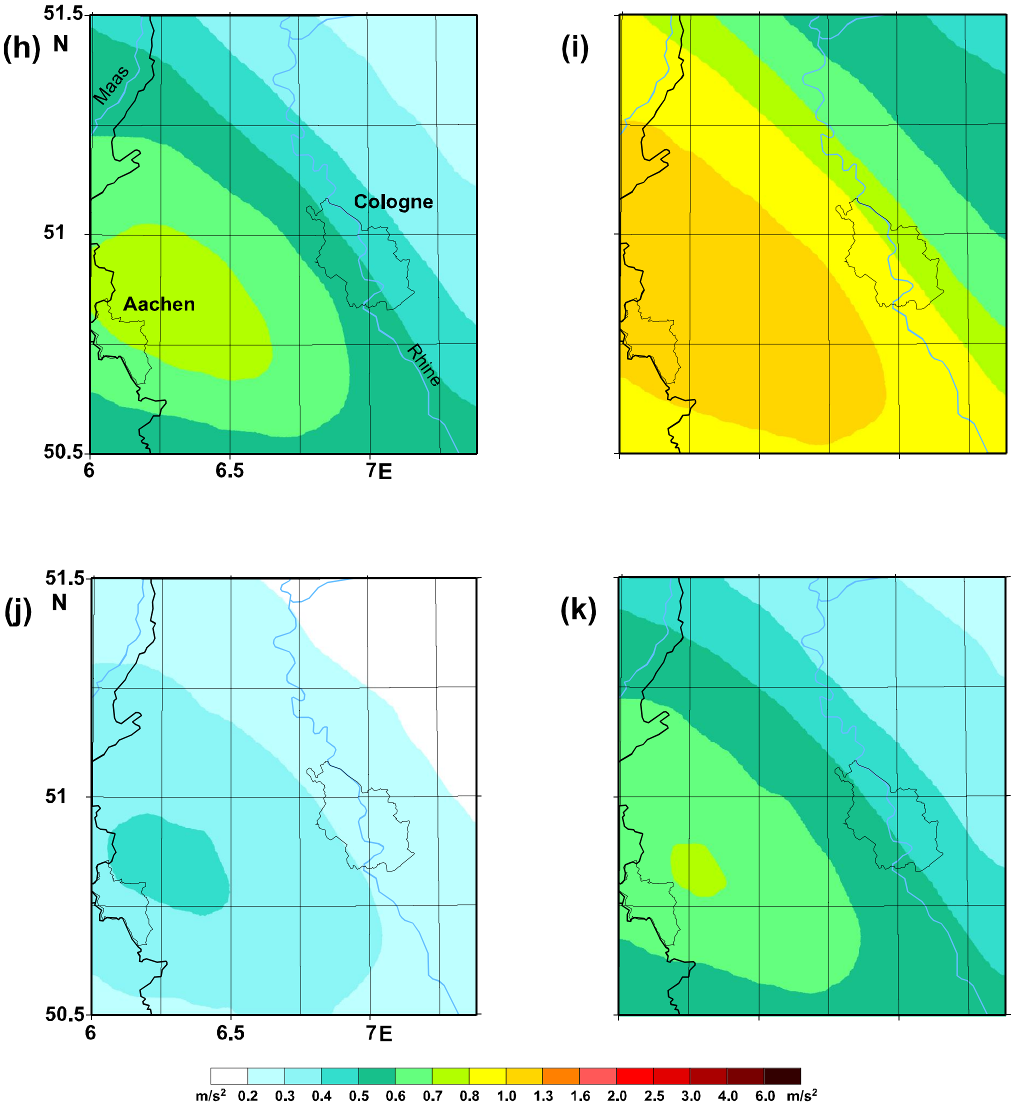

Figure 7. Spectral acceleration hazard maps for the area Cologne/Aachen for a probability of exceedence of 2% in 50 years and different periods and exceedence probabilities; rock foundation is assumed: (a) 0.1s / 50%; (b) 0.1s / 84%; (c) 0.2s / 50%; (d) 0.2s / 84%; (e) 0.4s / 50%; (f) 0.4s / 84%; (g) 1.0s / 50%; (h) 1.0s / 84%.; (j) 2.0s / 50%; (k) 2.0s / 84%.

Figures 7-9 and Table 1 show that the highest hazard for the respective fractiles and sites is obtaind at 0.2s period, that Aachen has one third to one half higher hazard values than Cologne at the lower periods and that the mean and 84% fractile values show good agreement for all periods and hazard levels. The results should be the basis for seismic risk studies for the two cities and the Lower Rhine region. As stated above, all calculations assume rock foundation.

DISCUSSION

A seismic source regionalization model with the current seismotectonic detailedness is used for the first time in a hazard study in Germany. By using alternative seismic source zone models and attenuation functions, and introducing uncertainties or distributions of the seismicity parameters, the logic tree technique results in a quantification of the uncertainty of the seismic hazard of the investigated area for the first time.

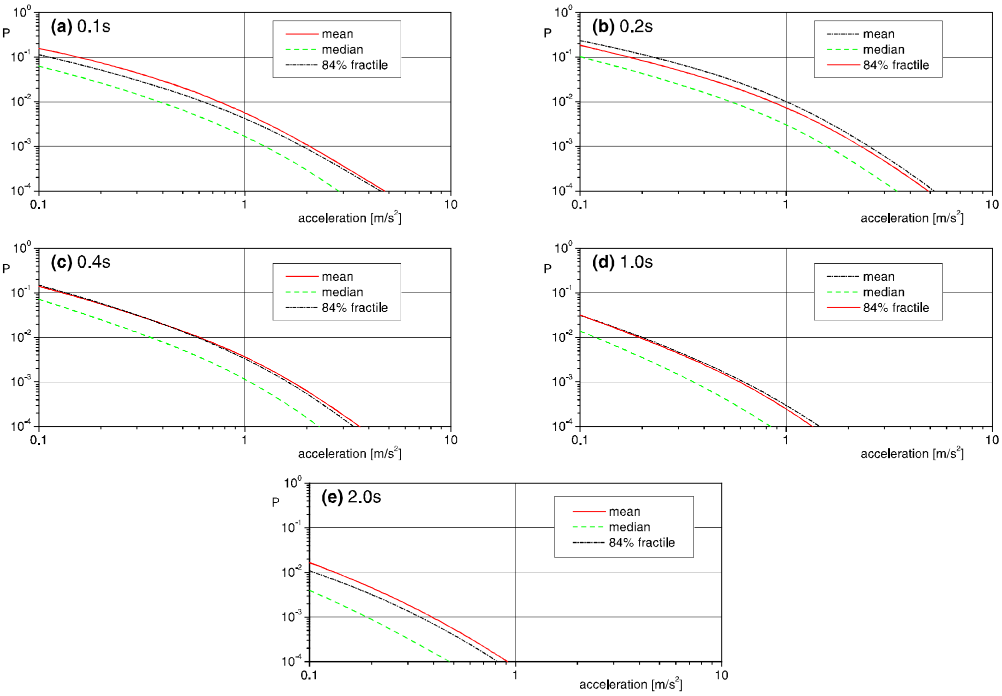

Figure 8. Mean, median and median + one standard deviation fractile (84%) spectral acceleration hazard curves for Cologne for different periods; rock foundation is assumed: (a) 0.1s; (b) 0.2s; (c) 0.4s; (d) 1.0s; (e) 2.0s. P is the annual occurrence rate.

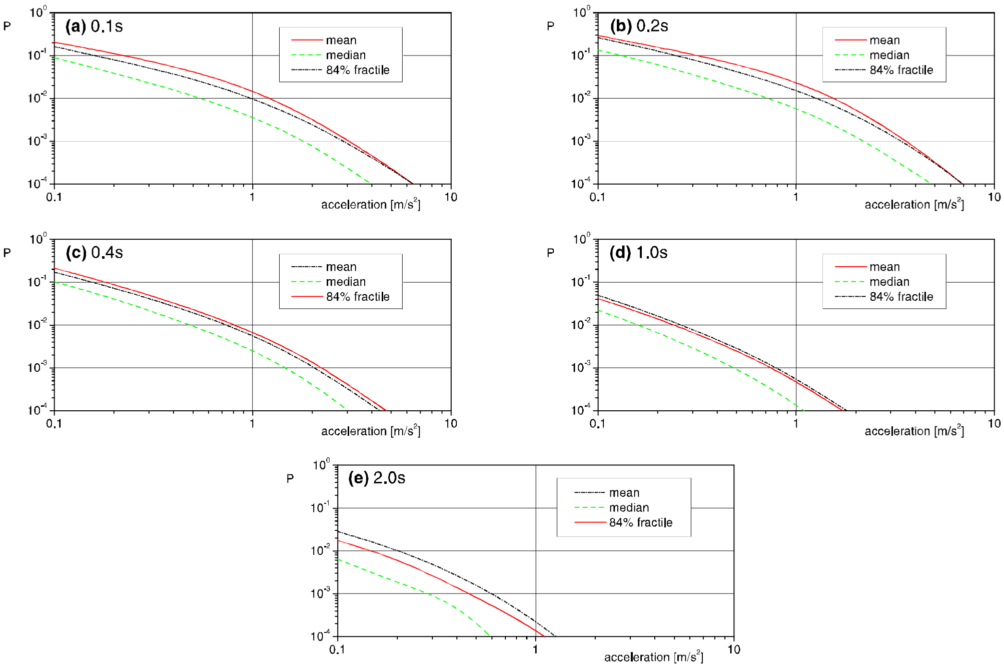

Figure 9. Hazard curves for Aachen corresponding to Figure 8.

Table 1. Spectral acceleration hazard levels (m/s^2) at Cologne and Aachen for a probability of exceedence of 2% in 50 years.						
Site	Fractile/mean	Period (s)				
		1	0.2	0.4	1.0	2.0
Cologne	50%	1.8	2.2	1.5	0.5	0.3
	mean	2.9	3.4	2.4	0.9	0.6
	84%	2.7	3.2	2.3	0.9	0.5
Aachen	50%	2.5	3.0	2.1	0.7	0.4
	mean	4.2	4.9	2.8	1.1	0.8
	84%	4.1	4.8	3.0	1.1	0.7

The maximum expected magnitudes obtained in this study are conservative estimates since the upper constraint relates to rupturing over the maximum length across a zone. In a study by Ahorner [20] based on paleoseismic and neotectonic data, deformation rates and fault dimensions suggest M_w values of 6.3 and 6.7 with return periods of 4,900 years and 18,000 years, respectively, for the Erft-Sprung, the fault system located closest to Cologne. Since this fault system is located several tens of km from Cologne with only two of its segments important for the earthquake potential of the city and since no aseismic creep is assumed in the calculations, Ahorner [20] points out that the these magnitudes may be too high for Cologne. However, the geologic-tectonic values are on approximate level with those calculated from cumulative seismic moments of earthquakes according to Ahorner [20].

The results of the present study are on level with those of previous studies, although a more thorough comparison is difficult to make since the latter mainly relate to peak ground acceleration and used different computational techniques and sets of input parameters (Grünthal [7], Leynaud [8], Atakan [9]).

A study of the sensitivity of different input parameters used in seismic hazard studies was undertaken chosing a site at Aachen (Grünthal [21]). The findings are valid for our whole study area. By varying the parameters one by one, their respective influence on the hazard was investigated.

REFERENCES

1. Grünthal G, Wahlström R. “An M_w based earthquake catalogue for central, northern and northwestern Europe using a hierarchy of magnitude conversions.” J. Seismol. 2003; 7: 507-31.
2. Stromeyer D, Grünthal G, Wahlström R. “Chi-square maximum likelihood regressions for seismic strength parameter relations, and their uncertainties, with applications to an M_w based earthquake catalogue for central, northern and northwestern Europe.” J. Seismology 2004; 8: 143-53.
3. Ahorner L, Rosenhauer W. “Regionale Erdbebengefährdung.” In: Realistische Seismische Lastannahmen für Bauwerke, Kap. 9, Abschlußbericht an das Institut für Bautechnik Berlin, König und Heinish, Beratende Ingenieure, Frankfurt/Erdbebenstation Bensberg der Universität Köln/Institut für Geophysik der Universität Stuttgart 1986.
4. de Crook Th. “Probabilistic seismic hazard assessment for the Netherlands.” Geologie en Mijnbouw 1993; 72: 1-13.

5. de Crook Th. “A seismic zoning map conforming to Eurocode 8, and practical earthquake parameter relations for the Netherlands.” Geologie en Mijnbouw 1996; 75: 11-18.
6. Grünthal G, Mayer-Rosa D, Lenhardt, W. “Abschätzung der Erdbebengefährdung für die D-A-CH-Staaten - Deutschland, Österreich, Schweiz.” Bautechnik 1998; 10: 19-33.
7. Grünthal G and the GSHAP Region 3 Working Group. “Seismic hazard assessment for Central, Northern and Northwestern Europe: GSHAP Region 3.” Ann. Geofis. 1999; 42: 999-1011.
8. Leynaud D, Jongmans D, Teerlynck H, Camelbeeck, T. “Seismic hazard assessment in Belgium.” Geologica Belgica 2000; 3/1-2: 67-86.
9. Atakan K, Ojeda A, Camelbeeck T, Megraoui M. “Seismic hazard analysis results for the Lower Rhine Graben and the importance of paleoseismic data.” Geologie en Mijnbouw 2001; 80: 305-314.
10. Legrand R. “Le Massif de Brabant.” Mémoires pour servir à l’explication des Cartes géologiques et minières de la Belgique1968; 9: 148 pp.
11. Colbeaux JP, Dupuis C, Robaszynski F, Auffret JP, Haesaerts P, Somme J. “Le détroit du Pas-de-Calais: un élément dans la tectonique de blocs de l’Europe Nord-Occidentale.” Bulletin d’information des Géologues du Bassin de Paris 1980; 17(4): 41-45.
12. Ahorner L. “Fault-plane solutions and source parameters of the 1992 Roermond, the Netherlands, mainshock and its stronger aftershocks from regional seismic data.” Geologie en Mijnbouw 1994; 73: 199-214.
13. Geluk MC, Duin EJTh, Dusar M, Rijkers RHB, van den Berg MW, van Rooijen P. “Stratigraphy and tectonics of the Roer Valley Graben.” Geologie en Mijnbouw 1994; 73: 129-141.
14. Spudich P, Joyner WB, Lindh AG, Boore DM, Margaris BM, Fletcher JB. “SEA99: A revised ground motion prediction relation for use in extensional tectonic regimes.” Bull. Seism. Soc. Am. 1999; 89: 1156-1170.
15. Boore DM, Joyner WB, Fumal TE. “Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work.” Seism. Res. Lett. 1997; 68: 128-153.
16. Coppersmith KJ. “Conclusions regarding maximum earthquake assessment.” The Earthquakes of Stable Continental Regions. Vol. 1: Assessment of Large Earthquake Potential, Electric Power Research Institute (EPRI) 1994; TR-102261-V1: 6-1--6-24.
17. Cornell CA. “Statistical analysis of maximum magnitudes.” The Earthquakes of Stable Continental Regions, Vol. 1: Assessment of Large Earthquake Potential, Electric Power Research Institute (EPRI) 1994; TR-102261-V1: 5-1--5-27.
18. Wells DL, Coppersmith KJ. “New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement.” Bull. Seism. Soc. Am. 1994; 84: 974-1002.
19. FRISK88M. “User's Manual, Version 1.79.” Risk Engineering, Inc., 4155 Darley Ave., Suite A, Boulder, Colorado, USA, 1996.
20. Ahorner L. “Abschätzung der statistischen Wiederkehrperiode von starken Erdbeben im Gebiet von Köln auf Grund von geologisch-tektonischen Beobachtungen an aktiven Störungen.” Deutsche Geophysikalische Gesellschaft e.V. Mitteilungen 2001; 2: 2-10.
21. Grünthal G, Wahlström R. “Sensitivity of parameters for probabilistic seismic hazard analysis using a logic tree approach.” J. Earthq. Engrg. 2001; 5: 309-328.