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New Generation of Probabilistic Seismic Hazard Assessment for the Area Cologne/Aachen Considering the Uncertainties of the Input Data

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Abstract. A new earthquake catalogue for central, northern and northwestern Europe with unified M_w magnitudes, in part derived from chi-square maximum likelihood regressions, forms the basis for seismic hazard calculations for the Lower Rhine Embayment. Uncertainties in the various input parameters are introduced, a detailed seismic zonation is performed and a recently developed technique for maximum expected magnitude estimation is adopted and quantified. Applying the logic tree algorithm, resulting hazard values with error estimates are obtained as fractile curves (median, 16% and 84% fractiles and mean) plotted for pga (peak ground acceleration; median values for Cologne 0.7 and 1.2 m/s^2 for probabilities of exceedence of 10% and 2%, respectively, in 50 years), 0.4 s (0.8 and 1.5 m/s^2) and 1.0 s (0.3 and 0.5 m/s^2) pseudoaccelerations, and intensity ($I_0 = 6.5$ and 7.2). For the ground motion parameters, rock foundation is assumed. For the area near Cologne and Aachen, maps show the median and 84% fractile hazard for 2% probability of exceedence in 50 years based on pga (maximum median value about 1.5 m/s^2), and 0.4 s ($>2 \text{ m/s}^2$) and 1.0 s (about 0.8 m/s^2) pseudoaccelerations, all for rock. The pga 84% fractile map also has a maximum value above 2 m/s^2 and shows similarities with the median map for 0.4 s. In all maps, the maximum values fall within the area 6.2–6.3° E and 50.8–50.9° N, i.e., east of Aachen.

Key words: seismic hazard, Cologne/Aachen area, zonation models, maximum magnitude, parameter uncertainty

1. 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.

As a task within the project German Research Network Natural Disasters (DFNK),

the seismic hazard in an area enclosing the cities of Cologne (Köln) and Aachen, Germany has been calculated using a new databank with unified M_w magnitudes and intensities, state-of-the-art techniques in the assignment of input parameters and their specified uncertainties, and a logic tree calculation algorithm producing output hazard values with quantified errors (fractiles). The improved seismicity data, the more physical way of determining maximum expected magnitude and the introduction of input/output uncertainties via the logic tree processing entitles the notation “new generation” of hazard assessment.

The hazard assessments are made for rock surfaces in order to enable a combination with different microzonation analyses providing the influence of the sedimentary cover (Fäcke et al., 2006; Richwalski et al., 2006). Important goals are to provide basic data for the engineering groups of the DFNK and to present the hazard values in terms of intensities so that they are easily transferable for seismic risk evaluation from scenarios (Schwarz et al., 2002, 2006).

The earliest probabilistic seismic hazard maps for the study area were based on intensities (Ahorner and Rosenhauer, 1986; de Crook, 1993, 1996; Grünthal et al., 1998). Later maps relate to peak ground acceleration (Grünthal et al., 1999; and with almost similar results Leynaud et al., 2000; Atakan et al., 2001). None of these studies takes the uncertainties of the input parameters into account and therefore, in the best case, each study represents only one of the several thousand realizations of the present logic tree approach (Section 2.7.). A change of values for one of the input parameters may lead to a significant change of the resulting hazard map, a problem not discussed in the previous studies. Other improvements of the current study are the use of the new M_w databank by Grünthal and Wahlström (2003) (Section 2.1.) and the application of new distribution functions for maximum expected magnitudes (Section 2.5.).

2. Input Parameters – Methods and Improvements

Modern methods have been applied and in several cases further developed to provide realistic input parameters and models to probabilistic seismic hazard assessments. These include the specification of uncertainties for each input parameter. The different input alternatives for each parameter are weighted. Combining the uncertainties of all parameters in a logic tree results in quantitative error estimations of the calculated hazard values. Two categories of uncertainties 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 modifications with respect to earlier hazard calculations are described below.

2.1. SEISMICITY DATA

A databank for central, northern and northwestern Europe with unified M_w and maximum intensity 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 et al., 1999). The data processing includes discriminating event types, eliminating fake events and duplets, converting different magnitudes and intensities to M_w if this is not given by the original source, and converting magnitudes to intensities where the latter are lacking. The magnitude and intensity conversions are key tasks of the study and imply establishment of regression equations where no local relations exist (Grünthal and Wahlström, 2003; Stromeyer et al., 2004). A catalogue containing tectonic earthquakes from the databank within the area 44–72°N, 25–32°E and the time period 1300–1993, and with lower magnitude level at $M_w = 3.50$, is presented by Grünthal and Wahlström (2003), who also give further details about the databank. The catalogue, with more than 5000 events, contains only original intensities, but for the intensity based hazard assessments of the present study, converted intensities, as given in the databank, are assigned to events lacking macroseismic information. The seismicity parameters used in the present study are throughout based on this databank.

2.2. SEISMIC SOURCE ZONE MODELS

The seismic source zones define areas with certain characteristics where future earthquakes are expected to occur. They can have significant influence on the hazard calculations, especially for the areas where the sites for which the hazard should be calculated are located. The uncertainties in defining the seismic zones are captured by considering alternative models. The previous model used by the D-A-CH (Grünthal et al., 1998) and GSHAP (Grünthal et al., 1999) 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

Figure 1. The D-A-CH and GSHAP seismic source zones for western Central Europe, with seismicity. Source model *Gr* is made up by a subset of the zones. The target area of this study near the cities of Cologne and Aachen in the Lower Rhine Embayment is marked.

pattern and are based on tectonic studies by Legrand (1968), Colbeaux et al. (1980), Ahorner (1994), Geluk et al. (1994) and R. Pelzing (personal 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. Many source zones of the original D-A-CH model could be excluded after tests proved they do not contribute to the hazard of the investigated area near Cologne and Aachen. 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

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 et al. (1998), with seismicity including new data from R. Pelzing (personal communication).

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.

2.3. GROUND MOTION RELATIONS

Lacking local attenuation data for the Rhine area, the selected attenuation relations are based on data from tectonically similar regions. The dominant faulting mechanisms in the target area are normal faulting and a combination of normal faulting with strike slip. Therefore, the relations by Spudich et al. (1999) for extensional regimes and Boore et al. (1997) assuming strike-slip mechanism and not specified mechanism, respectively, are used. Calculations are performed for peak ground acceleration

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.

(pga) and spectral acceleration response at periods of 0.4 and 1.0 s assuming rock conditions. The velocity of 620 m/s used by Spudich et al. (1999) is applied also to the Boore et al. (1997) relations. Equal weight is assigned to each of the two studies and for the Boore et al. (1997) relations equal weight is in turn assigned to each mechanism type.

For intensity attenuation, the relation by Sponheuer (1960) is used, with alternative damping coefficients, $\alpha = 0.001$, 0.002 and 0.003. The alternatives are equally weighted.

2.4. FREQUENCY-MAGNITUDE/INTENSITY RELATIONS WITH STANDARD DEVIATIONS

The *a*- and *b*-values of the cumulative Gutenberg–Richter relation are calculated for

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).

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 $a \pm 1.41\sigma$ and $b \pm 1.41\sigma$ values. These values represent the medians of the $\pm\sigma$ tails of the normal distribution curve, i.e., the parts larger than $+\sigma$ (approximate 84% fractile) and smaller than $-\sigma$ (approximate 16% fractile), respectively. Therefore, the $a \pm 1.41\sigma$

and $b \pm 1.41\sigma$ values are weighted 0.16 each and the a and b entries are weighted the remaining 0.68 each.

Corresponding assignments of a and b and their standard deviations are made for the frequency–intensity relation for each source zone.

2.5. MAXIMUM EXPECTED MAGNITUDE/INTENSITY

A combination of two methods is used to calculate maximum expected magnitudes:

- (1) The method presented by Coppersmith (1994) and Cornell (1994) 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, the b -value of the Gutenberg–Richter frequency–magnitude relation and the number of “large” earthquakes in a source zone. This results in a posterior distribution function of maximum expected M_w magnitude for each zone, where the maximum observed magnitude marks the lowest value. This method has been applied in studies for Fennoscandia by Wahlström and Grünthal (2000, 2001).
- (2) The maximum M_w magnitude for a given fault area A (km²) is described by Wells and Coppersmith (1994):

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

$(M_w)_{\max}$ is calculated assuming failure along the whole zone, i.e., A is calculated as the length of a zone multiplied with the depth of the seismogenic part of the crust. These calculations are performed for all zones where this is tectonically justified. Based on the distribution of foci in the Lower Rhine Embayment, the seismogenic depth range is put at 30 km for the zones concerned.

(1) & (2) The posterior function from method (1) is cut by $(M_w)_{\max}$ from method (2) as its highest value, where such a value has been calculated (i.e., is tectonically justified). The corresponding area under the function is then subdivided in five equal areas and the gravity points of the areas give the five values used as input in the hazard calculations (Figure 5). Thus the – optionally modified – distribution function for each source zone has been discretized to give representative values of plausible maximum magnitudes.

For further discussion on maximum magnitudes see Chapter 4. Maximum expected intensities were derived in an analogous way.

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 and Coppersmith (1994) 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.

2.6. FOCAL DEPTH DISTRIBUTION

The focal depth of earthquakes has an obvious impact on the seismic hazard. In this study, its influence is considered as proposed in the manual of FRISK88M (1996). 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, equally weighted, depth values, used as input in the hazard calculations.

2.7. THE LOGIC TREE

The different uncertainties or alternatives of the assessed input parameters and models are combined in a logic tree, with estimated relative weights assigned (Figure 6). A slightly modified version of the FRISK88M (1996) computer program was used for the calculations. The data come from the new M_w and intensity databank (Section 2.1.). The individual seismic events were not associated with errors but their uncertainty is implicitly considered in the parameters of the frequency–magnitude/intensity relations. 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 (Section 2.2.).

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 et al. (1999) denotes normal faulting and “ss” and “all” by Boore et al. (1997) 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. For intensity based hazard, an analogous tree is used. The attenuation branches here contain the Sponheuer (1960) relation with equal weighting for $\alpha = 0.001, 0.002$ and 0.003 .

Each of the source zone models is combined with each of three attenuation functions (Section 2.3.). For strong ground motion, the models represent different tectonic regimes (normal, strike-slip and unspecified faulting) and are treated with their standard deviations. For intensities, three different a -coefficients are applied.

Further combination is made with the mean and $\pm$ one standard deviation values of a and b of the frequency–magnitude/intensity relations of each source zone. Their weights follow from the statistical considerations (Section 2.4.).

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/intensities (Section 2.5.) and with each of the five equal-weighted values of the focal depth distributions (Section 2.6.).

A study of the sensitivity of different input parameters used in seismic hazard studies was undertaken choosing a site at Aachen (Grünthal and Wahlström, 2001). The findings are valid for our whole study area. By varying the parameters one by one, their respective influence on the hazard was investigated.

3. Results – Seismic Hazard for the Cologne/Aachen Area

The combination of the branches of the logic tree gives a set of 3375 hazard solutions corresponding to a given occurrence probability. Based on the large number of combinations, fractile curves showing the spread of the solutions are obtained. In Figure 7, the hazard assessments for central Cologne are given as curves showing the mean, median and median $\pm$ 1 SD fractiles (84% and 16%), for pga, intensity and spectral accelerations at 0.4 and 1.0 s, and for annual probabilities of occurrence down to 10^{-4} , i.e., return periods up to 10,000 years. All ground motion calculations are made for rock foundation. These data should be the basis for seismic risk studies for Cologne.

Figure 7 shows that the 16%, median, mean and 84% values for a 10% probability of exceedence in 50 years (i.e., a return period of 475 years) are 0.5, 0.7, 1.0 and 1.0 m/s^2 , respectively, for pga, 0.5, 0.8, 1.3 and 1.2 m/s^2 at 0.4 s and 0.2, 0.3, 0.5 and 0.4 m/s^2 at 1.0 s. The corresponding values for a 2% probability of exceedence in 50 years (a return period of 2475 years) are 0.8, 1.2, 1.5 and 1.5 m/s^2 for pga, 1.0, 1.5, 2.4 and 2.3 m/s^2 for 0.4 s and 0.3, 0.5, 0.9 and 0.9 m/s^2 at 1.0 s. For larger return periods, the hazard pga values fall between the spectral values at 0.4 and 1.0 s. This agrees with other studies, see e.g., Adams and Halchuk (2003).

Earlier hazard uniform spectral accelerations for Germany were derived by

Figure 7. Mean, median and median ± 1 SD fractile (84% and 16%) hazard curves for the centre of Cologne based on: (a) peak ground acceleration; (b) intensity; (c) 0.4 s spectral acceleration; (d) 1.0 s spectral acceleration. Rock foundation is assumed for the ground motion based hazard.

Grünthal and Schwarz (2000) and Schwarz et al. (2001). The difference between median and mean values in our study, which increases with increasing hazard level, should be kept in mind when evaluating hazard results from other studies. Previous studies with which comparisons are made below present only mean hazard values. It is notable that in the present study all mean acceleration curves show agreement with the respective $+1$ SD curves (84% fractiles).

The intensity based hazard curve of Figure 7b shows values of 5.9 (16% fractile), 6.5 (median), 6.9 (mean) and 7.1 (84% fractile) for the 10% probability in 50 years level and correspondingly 6.8, 7.2, 7.7 and 7.8 for the 2% probability in 50 years level. In these cases the mean values are clearly smaller than those of the 84% fractile. These values are in good agreement with the mean hazard values from previous studies by Grünthal et al. (1998) and others mentioned in Section 1.

Hazard calculations were also 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% fractile hazard maps for pga are shown in Figures 8a and b, for 0.4 s spectral accelerations in Figures 8c and d and for 1.0 s spectral accelerations in Figures 8e and f. The median values can be considered the “best” estimate under the given circumstances and the 84% fractile values represent a conservative estimate. All calculations assume rock foundation. The map values provide basic input for other DFNK studies, e.g., of the influence of the sedimentary cover on the hazard (Fäcke et al., 2006; Richwalski et al., 2006).

Figure 8 shows that the tendency found for Cologne with pga values smaller than 0.4 s values but larger than 1.0 s values for larger return periods, in this case 2475 years, is valid throughout the target area. The largest hazard is found for the area near $6.2\text{--}6.3^\circ\text{E}$ and $50.8\text{--}50.9^\circ\text{N}$, i.e., east of Aachen, with median values about 1.5, above 2.0 and about 0.8 m/s^2 for pga, 0.4 and 1.0 s, respectively. The 84% fractile map for pga (Figure 8b) is in large parts similar to the 0.4 s median map (Figure 8c), not least for the Cologne area.

A map computed for the mean hazard at a return period of 475 years for pga shows good agreement with the GSHAP map (Grünthal et al., 1999), which uses the same criteria. The agreement should be viewed in the light of the different basic input parameters (source zones, attenuation relations, M_{max} , focal depth distribution) and that their uncertainties were not considered in GSHAP. This is an indication of the reliable selection of the most probable input values in the GSHAP study.

4. Discussion and Conclusions

The maximum possible magnitude is one of the most critical parameters in seismic hazard calculations. The values 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 (2001) based on paleoseismic and neotectonic data, deformation rates and fault dimensions suggest M_w values of 6.3 and 6.7 with return

Figure 8. Hazard maps for the area Cologne/Aachen for a probability of exceedence of 2% in 50 years: (a) peak ground acceleration, median values; (b) peak ground acceleration, 84% fractile values; (c) 0.4 s spectral acceleration, median values; (d) 0.4 s spectral acceleration, 84% fractile values; (e) 1.0 s spectral acceleration, median values; (f) 1.0 s spectral acceleration, 84% fractile values. Rock foundation is assumed.

periods of 4900 years and 18,000 years, respectively, for the Erft-Sprung, the fault system located closest to Cologne. Ahorner (2001) points out that due to (1) the distance of the city to the fault, (2) that only two segments of the system are important for the earthquake potential of the city and (3) that no aseismic creep is assumed, the given magnitudes may be overestimates. The geologic-tectonic values are on approximate level with those calculated from cumulative seismic moments of earthquakes according to Ahorner (2001).

Techniques to calculate maximum possible and maximum credible earthquakes based on total seismic and tectonic moment release rates and assuming the Gutenberg–Richter or the gamma distribution have been suggested by Main et al. (1999). Coppersmith (1994) lists a variety of methods to estimate the maximum possible magnitude.

A seismic source regionalization model with the current seismotectonic detailedness is used for the first time in a hazard study in Germany. Contemporary work at the geological surveys of several German states (“Länder”) is aiming at analogous detailed models for other parts of the country. Lacking adequate strong motion data for the region, the applied attenuation functions are selected with special consideration to the types of tectonics and fault mechanics of the Lower Rhine Embayment.

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 for Cologne for the first time. The results are in agreement with previous studies of the area (Table I). The ranges of values given in the Leynaud et al. (2000) and Atakan et al. (2001) studies correspond to several computations using different input sets. Their values basically confirm the GSHAP results (Grünthal et al., 1999).

Table I. pga based hazard at Cologne from this and previous studies.

Study	Probability of non-exceedence (%/years) and corresponding return period (years)		pga (m/s ²)
Grünthal et al. (1999)	90/50	475	1.0 mean
Leynaud et al. (2000)	90/50	475	0.6–1.0* mean
This study	90/50	475	1.0 mean; 0.5–1.0 median**
Atakan et al. (2001)		1000	0.7–1.3* mean
Leynaud et al. (2000)	90/250	2375	1.6 mean
This study	98/50	2475	1.5 mean; 0.8–1.5 median**

*Ranges of values from individual computations with different seismic source zone and/or attenuation models.

**Median $\pm$ 1 SD.

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