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COMPARATIVE SEISMIC RISK STUDIES FOR GERMAN EARTHQUAKE REGIONS DAMAGE AND LOSS ASSESSMENT FOR THE CITY OF COLOGNE

Jochen SCHWARZ[1], Tobias LANGHAMMER[2], Holger MAIWALD[3] and Anselm SMOLKA[4]

SUMMARY

In current research quantifying loss potentials for German city regions basic tools for GIS-based seismic risk assessment technologies have been developed and applied to the building stock and regional particularities of German earthquake regions. Different study areas with comparable levels of seismic hazards were investigated, but they had varying numbers of inhabitants and degrees of urbanization. This paper focuses on the case study of Cologne as an example for a larger city, and is related to results of the German Research Network Natural Disasters DFNK-project [1].
Seismic risk maps were prepared for different EMS- intensities. The impact of model assumptions and the step-wise refinement of input variables on the distribution of expected building damage are recognized as leading to different risk maps. Furthermore, the zones of higher risk are identified. An integrated approach combining data from official and insurance statistics was used to develop an inventory of exposed values in Cologne. A loss estimation procedure was applied converting results of refined vulnerability and damage assignments into mean damage ratios for the 370 municipalities.
Results are available for different scenario events (with return periods T_R between 475 and 10.000 years). Results support the prognosis that in the case of strong earthquakes the loss might rise to maximum values between 25 and 30 billion US $ for the city, and up to 60 billion US $ (and still higher) if all whole surrounded regions are considered. This estimate is consistent with previous lower bound estimates by Allmann et al. [2]. The extent to which extent the loss varies due to scenario event, local site effects, the vulnerability of building types, the assigned asset, and the implied correlation between damage and loss is also shown.

[1] Head of Earthquake Damage Analysis Center (EDAC), Bauhaus University 99421 Weimar, Germany. Email. schwarz@bauing.uni-weimar.de
[2] Research Assistant, Earthquake Damage Analysis Center (EDAC), Bauhaus University Weimar, Germany.
[3] Research Assistant, Earthquake Damage Analysis Center (EDAC), Bauhaus University Weimar, Germany.
[4] Head of Geological/Geophysical Risks Geo Risks Research Dept. Munich Reinsurance Company, 80791 Munich, Germany

INTRODUCTION

There has been a tremendous increase in the number of seismic risk studies; not only for high seismicity regions and places of particular seismic exposure, but also for European (often so-called) low seismicity areas. The progress in seismic risk mapping and the reasonable limitation of the unreliable quantified damage potential can be attributed to the development of GIS-Tools (Geographic Information Systems) and more refined data bases.

Recent studies for California [3], Northern Italy [4] or for the city of Basel [5] indicate that, among only minor other factors, applied vulnerability functions predetermine the quality of damage scenarios as compared to other factors. By studying damage data for different building types and earthquakes it can be concluded that commonly used standardized vulnerability functions deviated severely from the observed damage distributions [6].

The inherently empirical approach of the European Macroseismic Scale EMS-98 [7] provides new possibilities for seismic risk studies. One of the major advantages of the EMS scale is that it is based on the experience of world-wide macroseismic investigations, and that the vulnerability table for different building types has been proved over the years of its [6]. Furthermore, the scale supports the calibration of the building vulnerability and seems to be robust concerning the scatter.

SEISMIC RISK STUDIES IN GERMAN EARTHQUAKE REGIONS

For earthquake regions in the Federal Republic of Germany there is almost no data or experience available for the vulnerability of the currently existing building stock, consequently there is no method for calibrating the results of seismic risk analyses or damage scenarios. Current research on the quantification of realistic damage potentials for German city regions outline that assessing the building stock requires considerable efforts and is inadequately prepared in respect of the evaluation of vulnerability. The earthquake resistance of the building stock or its vulnerability is usually unknown. Buildings of special importance for general safety, such as facilities and institutions necessary for coping with catastrophes (hospitals, fire brigades, etc.), have not yet been checked [1].

Within the framework of recent research projects, basic tools for GIS-based seismic risk assessment technologies were developed and applied to the building stock and regional particularities of different German earthquake regions [1], [8], [9], [10], [11]. One of these case studies, the town Schmölln in Eastern Thuringia, [10] seems to be representative for the majority of smaller towns in Germany. Likewise the case study of Cologne stands for larger cities. Due to similarities of hazard and scenario intensities, the considerable differences do not only require proper decisions on the appropriate methods and acceptable efforts, they also enable conclusions about future research strategies and needs for disaster reduction management. This paper focuses on the city of Cologne and illustrates the impact of model assumptions and the step-wise refinements of such input variables as site conditions, building stock, or vulnerability functions on the distribution of expected building damage. Furthermore and in contrast to common research strategies, results support the conclusion that in the case of stronger earthquakes the damage will be less concentrated due to particular site conditions and/or the decreased vulnerability of the building stock. Due to the effect of deep sedimentary layers and the composition of building types, the urban center of Cologne (Köln) will be less affected by an earthquake of comparable intensity than other smaller cities in Thuringia or the Swabian Alb [1], [11].

Studies of the Earthquake Damage Analysis Center at the Bauhaus-University Weimar (EDAC) in the test area Cologne and results of comparative risk assessments [12] are subsequently referred to.

BASICS METHODOLOGY

Hazard Assessment

The seismicity of the test area and the degree of seismic hazard can be derived from the zoning map of E DIN 4149 [13] or its former, still valid version, DIN 4149 [14]. According to the new version of the DIN 4149 [13], Cologne is located in zone 1, or in the transition area to zone 2 (Figure 1). Figure 2 shows the results of a probabilistic hazard assessment for Cologne recently performed by Grünthal and Wahlström [15]. In this assessment, uncertainties of the input data are explicitly processed using a logic-tree approach. It could be justified that the mean hazard-curves correspond to results of previous studies which also serves as the basis for the current hazard zoning map of DIN 4149 [16].

Following the given hazard curves scenario events for different return periods can be used in the risk studies (among others mean return periods T_R = 475, 2475 and 10000 years). Furthermore, sufficiently conservative upper bound scenarios can be determined taking into consideration the scatter/uncertainties of probabilistic hazard assessment

Results of the probabilistic hazard assessment for the area of Cologne/Aachen in terms of 50% fractile of intensity for return periods T_R = 475 (10 % probability of exceedance in 50 years) and 2475 years (10 % probability of exceedance in 50 years) are given in Figure 3.

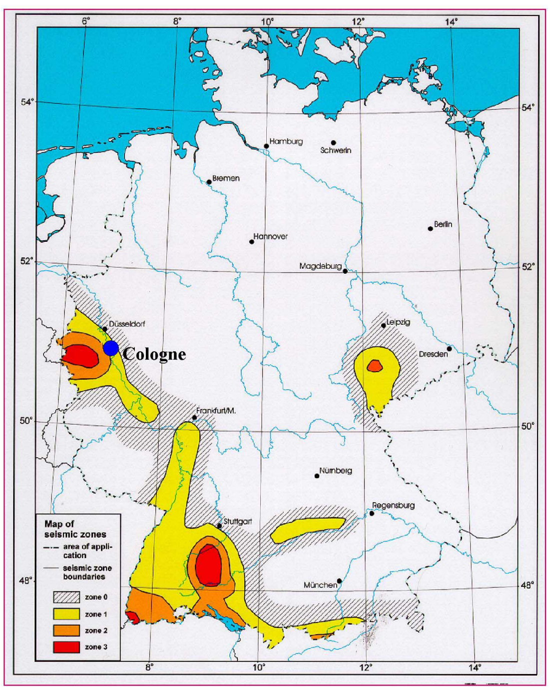


Figure 1. Hazard zoning map for new German Seismic Code DIN 4149 [1]

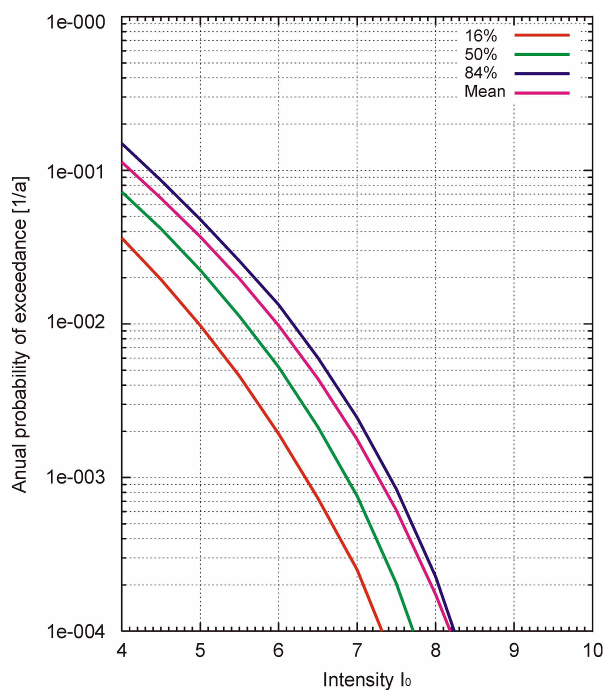
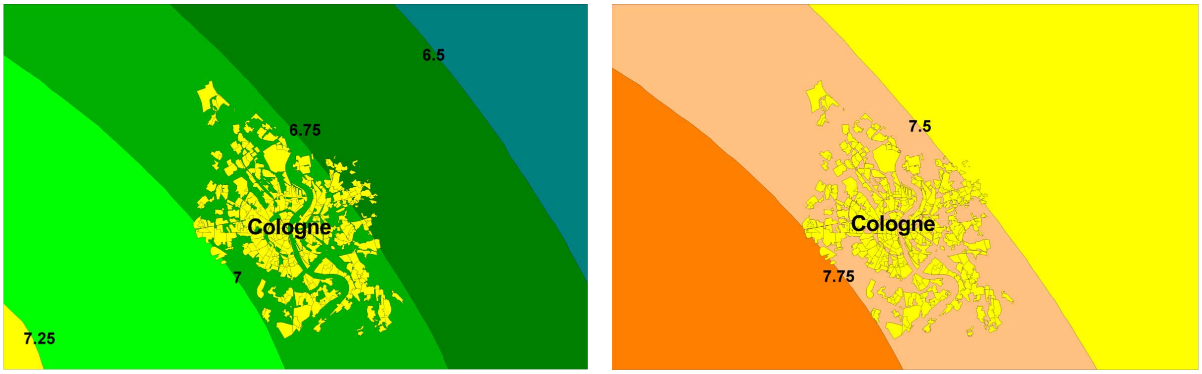


Figure 2. Hazard curves for Cologne (6.95°E, 50.93°N) taken from Grünthal and Wahlström [15])

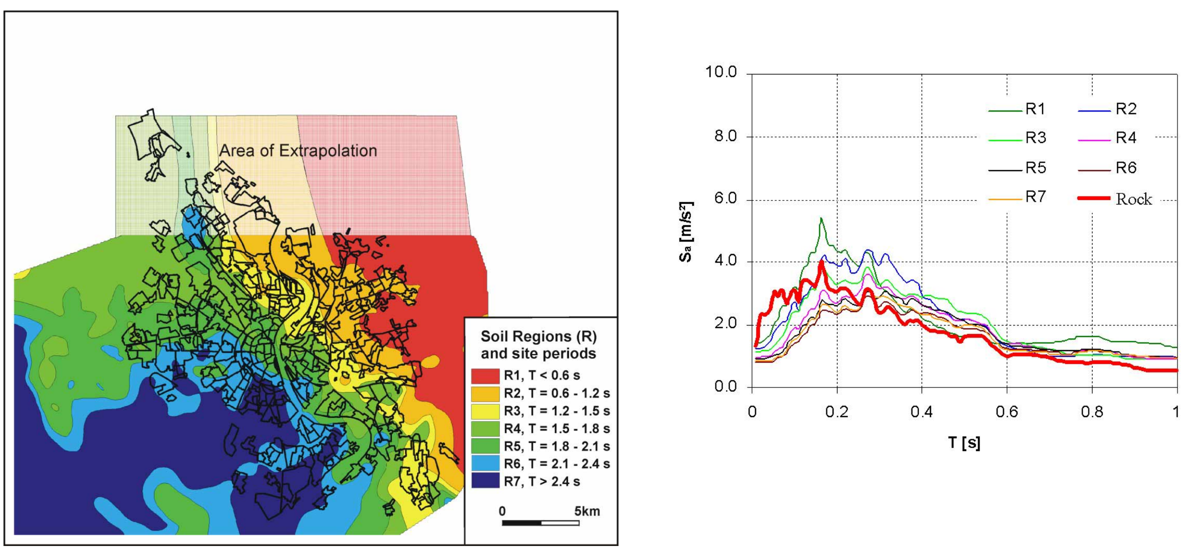


a) T_R = 475 a b) T_R = 2475 a

Figure 3. Results of probabilistic hazard analysis for the area of Cologne/Aachen (Grünthal and Wahlström [15]); here used as probabilistic scenarios for damage assessment and loss estimation

Interpretation and Mapping of Geologic and Subsoil Conditions

For the GIS-modeling the investigation area was subdivided into a grid (raster) of 500m x 500m and available geological and topographical maps were processed. Based on grid units with details about geological layers (borehole data, geological maps) profiles for the neighbouring grid units were extrapolated. As a whole, seven types of depth profiles were distinguished depending on the ranges of site periods [11]. In the site response analyses for these profiles variations of shear wave velocities and geological layering were considered. The dominant site periods as well as amplification functions and local ground motion of the classified and mapped profiles (grid map) due to different event scenarios were calculated. This procedure ensured that site conditions were considered appropriately (Figure 4a).



a) Dominant site periods, amplification functions, and local ground motion of the classified and mapped profiles (grid map)

b) Spectra from site response analyses for the seven soil profiles [11]

Figure 4.

The investigation area in the region of Cologne is characterized by relatively homogenous topography and subsoil conditions or, smooth transitions. The very deep sedimentary layers in Cologne have a damping effect in the period range characteristic for average buildings. The variety of spectra derived from the site investigations for application in the whole city area is illustrated in Figure 4b.

Vulnerability of Building Types and Damage Assessment

Vulnerability of Building Types

The quality of the seismic risk assessment and mapping is dependent strongly on the quality and accuracy of the digitized and geo-codified building inventory. Therefore, maps of the building stock were elaborated on the basis of aerial photo images. A test area with approximately 800 buildings in the city's center was surveyed in detail. (In Figures 8, 9, and 10, which relating to the scenarios, the test area in the center is specially marked.)

The vulnerabilities of the various building types and techniques is evaluated on the basis of the European Macroseismic Scale EMS-98 [7] and their dynamic characteristics.

Buildings were inspected and identified in respect to their building type, category, importance, and state of maintenance. On this basis the most probable vulnerability class according to the European Macroseismic Scale EMS-98 (A, B, C, D) was assigned to each building, on this basis, while additional transitional classes (A-B, B-C, C-D) were introduced for buildings with mixed types of construction (see Table 1).

a) b)

Figure 5. Examples of typical building types in the study area

Composition of Building Inventory

It must be stressed that the building stock in Cologne was affected by severe destruction from the Second World War and its aftermath. The greatest part of the building stock was erected in the past 50 years (Figure 5). Consequently, buildings and construction types of low vulnerability dominate: 80% of the buildings can be assigned to vulnerability class C and less than 14% to vulnerability class B.

The composition of the building stock for the test area according to EMS-98 was determined in respect of vulnerability classes. In the sense of geostatistical extrapolation, it was also applied to the entire city area with consideration of the given age structure of the buildings in the city quarters concerned. This approach is based on the assumption that the distribution of vulnerability classes within the building stock and erected in a given amount of time is comparable.

The regional distribution of the surveyed building stock and the assigned vulnerability classes are illustrated in Table 1. Here "mixed" building types are assigned to a specific vulnerability class. Detailing of the transitional classes was not carried out, as these only represent a small fraction of the total building stock.

Table 1. Composition of building inventory with respect to building type and vulnerability class according to EMS-98 [1]

Building Type [1)]	Test area of Cologne [%]	Vulnerability classes [%]						
		A	A-B	B	B-C	C	C-D	D
Masonry	71.0	0.2	1.1	16.7	2.5	79.2	-	0.2
Masonry + Reinforced Concrete	8.9	-	-	-	3.6	94.6	-	1.8
Reinforced Concrete	7.8	-	-	-	-	100.0	-	-
Reinforced Concrete + Masonry infill	8.7	-	-	1.8	-	94.5	-	3.6

[1)] only those with a contribution of more than 2.0 % are given

Definition of damage grades and damage distribution

In the European Macroseismic Scale EMS-98 expected values for building damage are assigned to every intensity and vulnerability class, while its value range (few, many, most) relates to the maximum damage. Thus only “incomplete” and rough damage distributions or vulnerability (fragility) functions are initially available for each vulnerability class. It belongs to the essential achievements of this study that these damage distributions were supplemented. Therefore, the analyses are based on models with “complete” damage distributions, which, among others, refer to evaluations in the context of field investigations and damage surveys of the German Task Force Earthquake [6].

The earthquake scenarios developed in the context of risk assessment mainly express building damage (structural) according to the scaling and definitions of damage grades in EMS-98. The single damage grades are therefore described by damage specifications that refer to the structural system and building type.

The estimated damage distribution for the given scenarios is described using the mean damage grade D_m, but can also be illustrated by showing the shares of every single damage grade D_i (i damage grade according to EMS-98). The connection between damage expectation and locally differentiated intensities is achieved by application of vulnerability functions, which in the comparisons carried out here are based on a methodological approach outlined in [17].

Regional variation of seismic action with respect to predominant building types

Building periods are predicted on the basis of empirical formulas given in DIN 4149 [13], which only consider the height of a building and its structural systems. It must be stressed that the fundamental building periods serve as the main link between site-dependent ground motion and building response (damage). In this context, the calculated, site-specific spectra (cf. Figure 4b) are sorted into period ranges corresponding to main periods of selected building types or groups. The mean value of the spectral accelerations in this ranges is calculated and introduced into the further mapping procedure as prominent values for the applicable grid unit. Figure 6 gives the spectral acceleration in the period range of T = 0.1 to 0.2 s, which can be seen as representative for low residential buildings, an in this case two-story masonry (brickwork) buildings (see Figure 5).

For the city of Cologne it seems appropriate to assume uniform input values over large areas. Such a situation is doubtlessly advantageous for the quality of seismic risk analyses. However, in most cases the local conditions will be subject to strong variations, which will also lead to greater requirements and efforts to achieve realistic modeling. Thus the case of Cologne reflects an exceptional rather than standard situation.

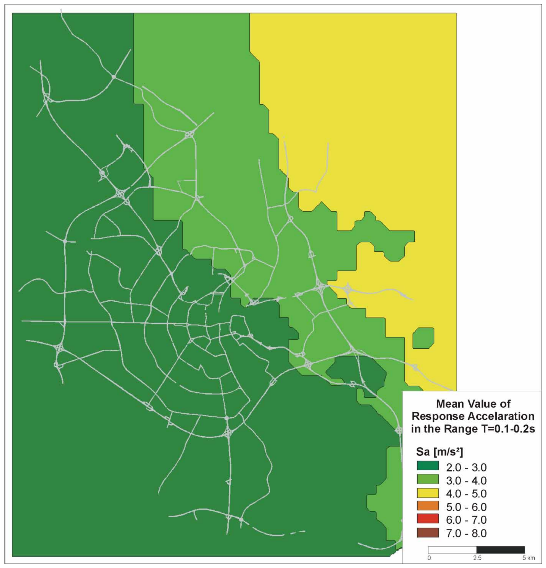


Figure 6. Probable spectral accelerations in the period range between T = 0.1 s to 0.2 s: average values for the investigated grid elements within the test areas of Cologne (section 11 km x 10 km)

APPROACHES TO DAMAGE SCENARIOS

Variation and refinement of input parameters

The vulnerability of the existing building stock was described in terms of the damage probability, whose calculation depends on the severity (intensity) and quality (spectral acceleration) of ground shaking. Due to the application of various methods and the recognition of the scatter of ground motions (due to scenario events and site conditions), vulnerability of building types and building periods resulted in a multitude of scenarios, that were simulated and mapped in the course of the investigations. Subsequent examples outline the influence of the different approaches in respect of the refinement of input parameters (levels) and the basic description of the scenario itself (deterministic, probabilistic).

Seismic risk maps were prepared for different EMS-intensities. The impact of model assumptions and the step-wise refinement of input variables from level I to III (such as site conditions, building stock or vulnerability functions) on the distribution of expected building damage are considered in more detail below. The estimated damage distribution for the given scenarios is described using the mean grade of damage D_m for each municipality.

Level I: site-independent approach

In these scenarios, only the attenuation of intensity depending on distance is considered. Seismic action will be assumed more or less undifferentiated. The impact of site-dependent seismic action on the damage distribution is not considered.

Level II: site-dependent approach

This basic data allows the processing of site-specific seismic action (cf. Figure 4), which can also be specified in the period ranges of the dominant building types (cf. Figure 6). Site-specific spectral accelerations are calculated in tightly spaced grid elements; the local intensity is differentiated with relations developed specifically for this task. These intensity increments can be understood as correction values for the site intensity, and they were finally inserted as such into the calculation of the mean damage grades D_m for each municipality.

Level III: More refined approach with additional consideration of dynamic building characteristics
In recent case studies, a procedure was developed to transform the site-specific description of seismic action and the composition of building height within each of the vulnerability classes into “Delta-Intensities” [17]. Therefore, the regional damage distribution according to level II is slightly modified. This more refined approach is well suited to indicate zones that could be identified as critical to higher damages.
The three levels are connected with different demands to the required input parameters. Their preparation and evaluation can be realized only as a long-term task and depends strongly on the users interest. In general, damage scenarios will not reach the quality of level III. It also has to be emphasized that the kind and refinement of the presented results do not only depend on purely scientific criteria. There are many reasons to avoid an overly detailed map of damage distribution indicating the grade of expected or simulated damage for each particular building. In many cases, political and social reactions and economic interests have to be anticipated [9],[10]. Therefore, results for the extreme scenarios are presented as mean damage grades for defined areas following the municipal areas.

Deterministic approach
Location of assumed epicenters of scenario events
The damage scenarios for the city of Cologne were developed by taking the historical seismic activity and the geological conditions (faults) into account for five hypothetical epicenters as illustrated in Figure 7:
- The epicenters E1 and E2 were determined at about 10 km from the city center in a western or southwestern direction.
- Epicenter E3 was assumed at a distance of about 15 km southwest of the town center, immediately at the Erft-fault line.
- The epicenters E4 and E5 correspond to the source location of historic earthquakes: E4 earthquake on August 26,1878 at Tollhausen (I=8.0); E5 earthquake from October 24, 1841 at Cologne (I=7.0 according to catalogue entries, but this seems questionable).

Changing the earthquake’s epicenter (north of Cologne at scenario E1, southwest at E2) definitely affects regarding the municipality that would suffer the heaviest damage [1].
Figure 8 provides an impression of the damage distribution and the grades of damage, should historic earthquake events in site proximity repeat themselves (scenarios E4, E5). As the results confirm, only slight damage is expected. The mean damage grade is between 0.5 (or less) and 1.0 (see legend in Figure 9d). This corresponds with the data from historic reports and damage statistics.

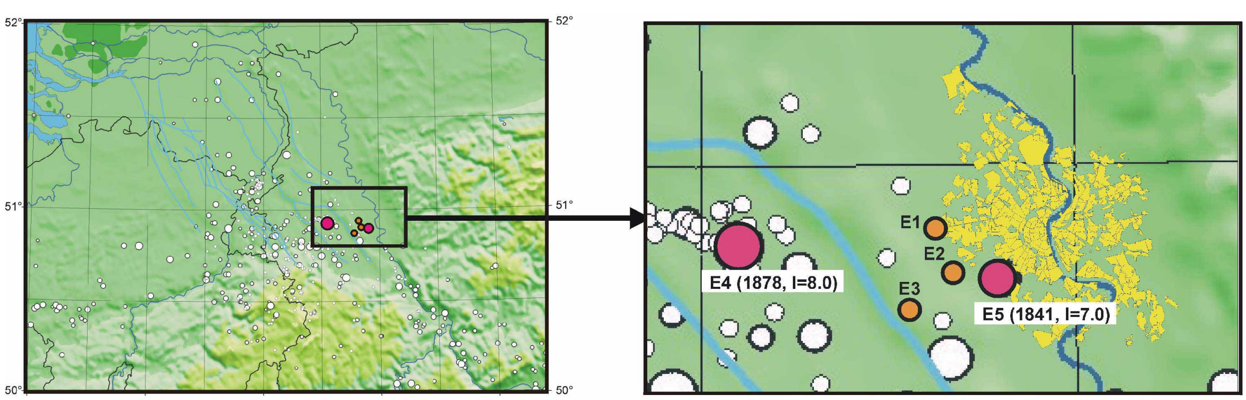
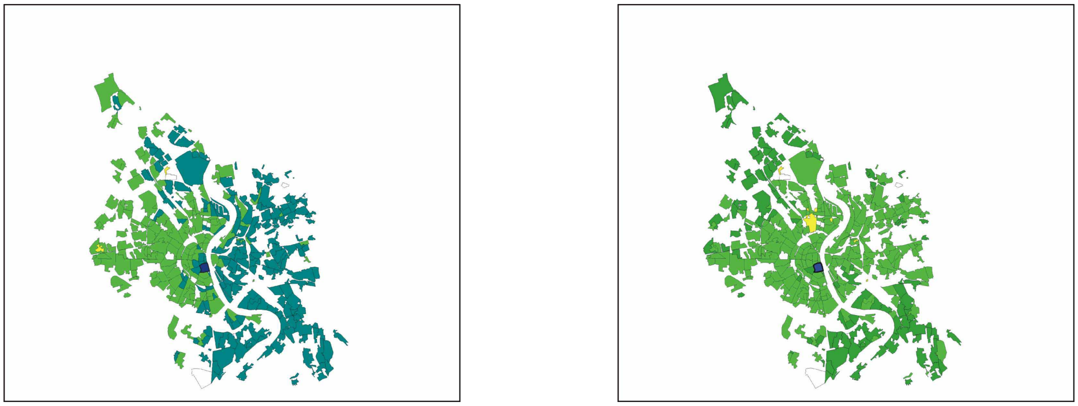


Figure 7. Epicentral map of Lower Rhine Valley (Northrhine-Westphalia) and location of selected deterministic scenario events (E1 to E5) partially following coordinates of historic earthquakes



a) Reference Intensity I I(EMS) = 8.0 (E4) b) Reference Intensity I I(EMS) = 7.0 (E5)

Figure 8. Mean damage grades for deterministic scenario events E4 and E5: repetition of historical earthquakes based on the site-independent level I approach (for legend see Figure 9d)

Level of refinement of input parameters

Figure 9a shows the change in the damage distribution in the city area for scenario E5 assuming a site intensity of I = 8.0. As outlined in Figure 9b, local subsoil conditions can significantly influence the distribution of damage. Compared to the scenario without specific consideration of the site subsoil (level I in Figure 9a) damage-increasing as well as damage-reducing effects can be observed.

In Figure 9b and Figure 9c mean damage grades are presented for the more refined approaches that consider the effect of specific site conditions (level II in Figure 9b) an the effect of building height (level III in Figure 9c) by introducing site and period-dependent intensity modification increments, [1], [16]).

For practical reasons and for comparing deterministic with probabilistic results, two calculations for each scenario were performed. The first attempt assumes the basic intensity in the coordinates of the historic epicenters; the second one is related to a postulated basic scenario intensity in the city center. Therefore, the epicentral intensities in E1 to E5 have to be increased to values leading to the intended reference intensities in the center of the city.

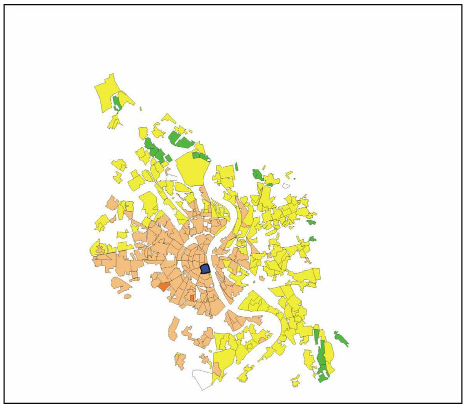
Probabilistic approach

Results of a probabilistic hazard analysis for the area of Cologne/Aachen [15] given in Figure 3 are used as probabilistic scenarios for damage assessment. This means that intensity differentiated in steps of 0.25 grades was applied to the building stock, or more accurately to the particular composition of vulnerability classes within each municipality.

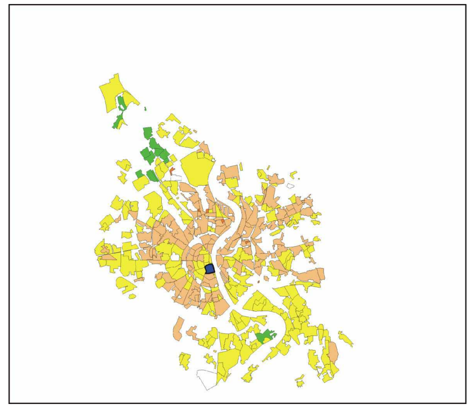
From these investigations, it can be concluded that such modifications have an impact on the distribution of damage but are of minor importance for the total loss integrated over the city of Cologne.

The results offer a direct introduction into the evaluation of regions with e high risk. The prognostic element of the statements could flow into decisions concerning both short-term catastrophe management and long-term site development, e. g. the planning of new constructions or the reinforcement of existing buildings. Implementing of the results in terms of concerted actions is a matter for the public authorities and other institutions responsible for planning.

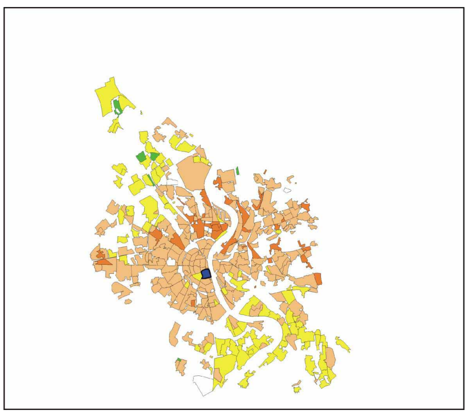
With the differentiated presentation of the mean damage grade D_m the risk studies lead to parameters relevant for insurance companies. As will be shown in future contributions [13], damage potentials can be quantified on a new, realistic basis. In this context it must be noted that further investigations regarding the estimation of damage potentials should be extended to nonstructural and consequential damage, as well as on methodological basics for the determination of the evaluation parameters.



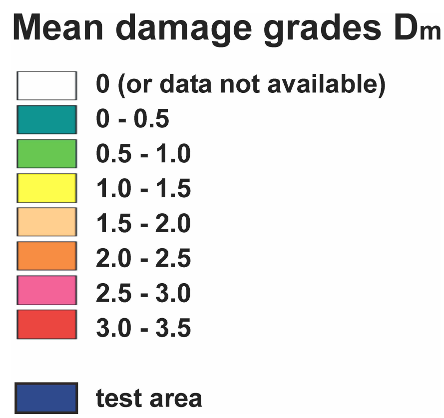
a) site-independent approach (level I)



b) site-dependent approach (level II)

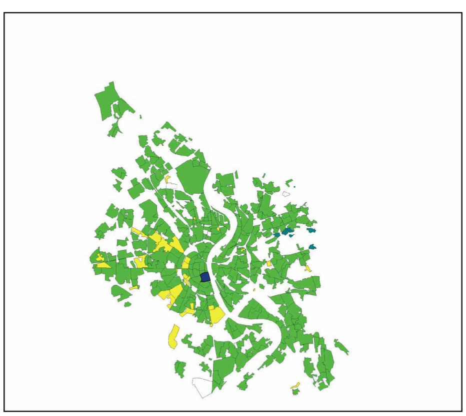


c) More refined approach considering dynamic building characteristics (level III)

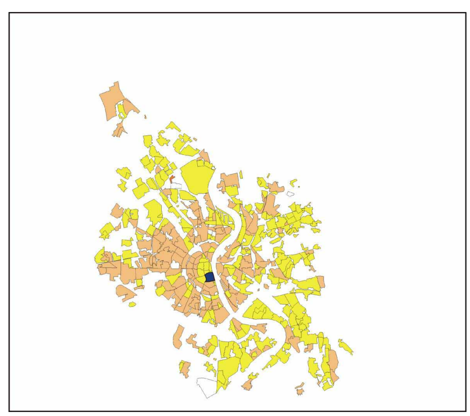


d) Legend

Figure 9. Mean damage grades D_m for deterministic scenario event E5 and increased reference intensity of I(EMS)=8.0 dependent on the approach (level of refinement of input parameters)



a) Mean return period T_R=475 years



b) Mean return period T_R= 2475 years

Figure 10. Mean damage grades D_m for probabilistic scenarios (according to Figure 3), For the legend see Figure 9d

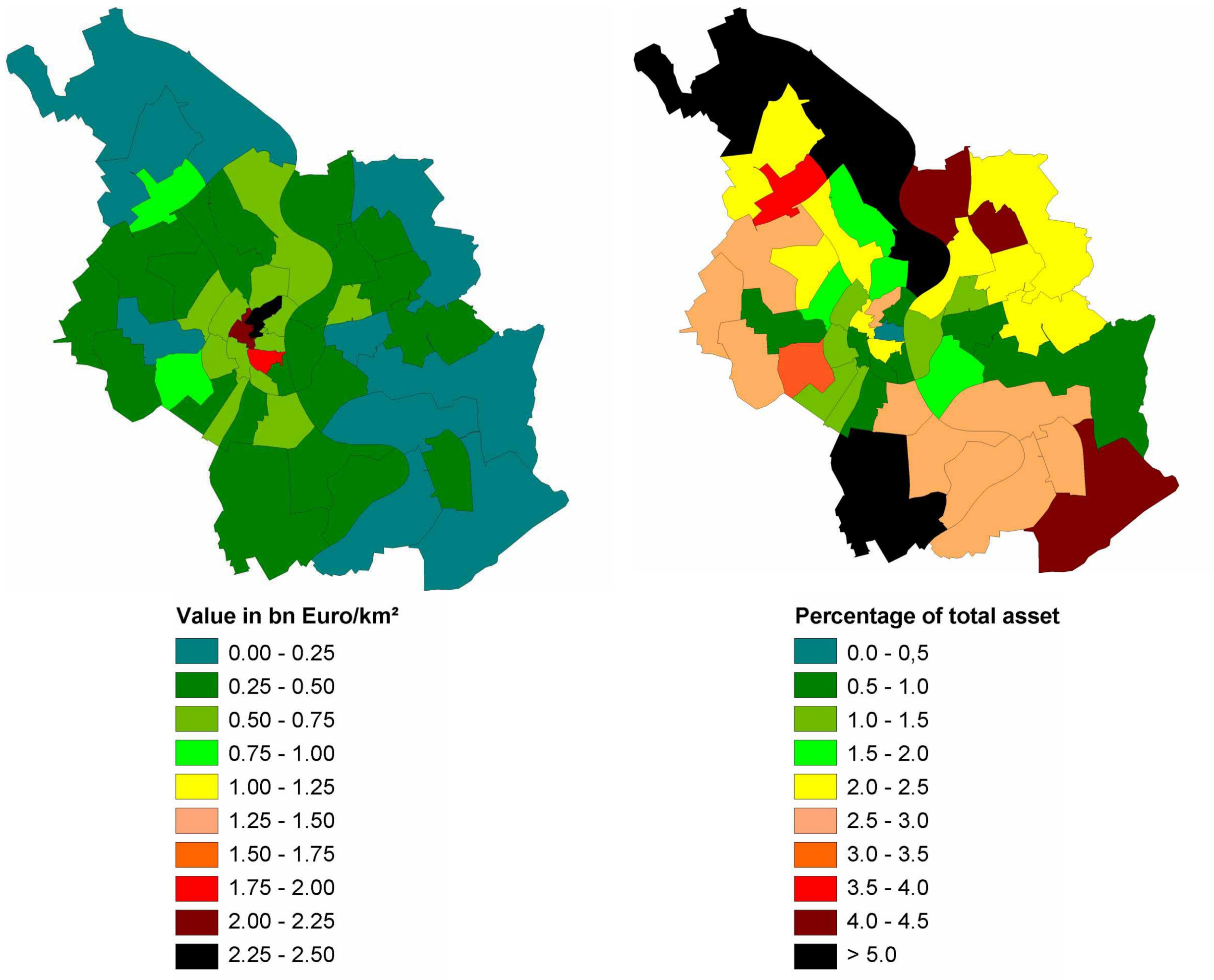


Figure 11. Distribution of values

PROCEDURE OF LOSS ESTIMATION

Estimation of total assets

In order to estimate direct losses caused by earthquakes, an inventory of potentially exposed assets in the area under consideration is required as a first step. In a second step, then, mean damage ratios have to be applied to the assets. The asset values used for the following loss estimation were taken from a comparative risk assessment for the city of Cologne [12]. As it is outlined by Grünthal et al. [12] in more detail, different approaches for the estimation of assets can be applied. They can be based on official statistics on the gross stock of fixed assets and on the number of inhabitants or on insurance data. E.g., insured values per capita can be derived from data gathered by primary insurers. Eventually a hybrid approach was chosen, using official statistics for the commercial sector and a combination of official statistics and insurance data for private housing. In this way, total values for the city area were estimated. These total values were then distributed within the municipalities on the basis of ATKIS, the official German topographic-cartographic information system. Since there is no exact correspondence between the economic sectors in the national accounts and the ATKIS land use codes, finally a scheme developed by MURL [18] was applied for assigning ATKIS land use classifications to economic sectors. The resulting spatial pattern of economic sectors in Cologne is shown in Figure 11. The calculated object values per

ATKIS object were aggregated within five-digit postal codes and for Cologne as a whole which resulted in a total amount of € 133 billion.. It has to be recognized that insurer's data support the conclusion that the average building value in Cologne is probably higher than the values which can be derived from official gross stock of fixed assets. Therefore, the above mentioned € 133 billion probably represent a rather low estimate of the total values in Cologne.

Deriving loss percentages from damage grades

In order to calculate absolute losses it is necessary to translate the assessed average damage grades per zip code into expected loss percentages or mean damage ratios (MDR). An empirical approach is followed for this purpose. It is based on the damage pattern per damage grade as defined in the EMS scale of 1998.
Cologne would be affected by damage grades not exceeding a value of 2, even when the worst earthquake scenario is considered. Damage grade 1 stands for negligible to slight damage, grade 2 for moderate damage. For such low damage grades the corresponding expected loss percentages can be well approximated by a potency function. Applying a function of the expected loss, for example.

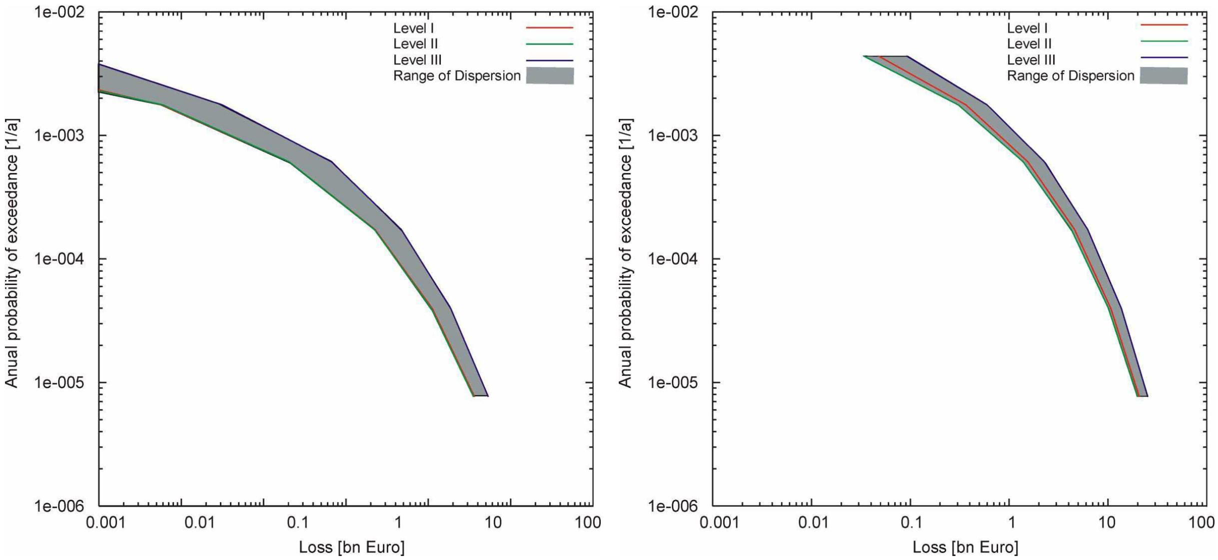
$$EL \text{ in } \% = 0{,}969 * DG^{3{,}0756}$$

results in 1% for damage grade 1, 8% for grade 2, and 28% for grade 3 (EL=expected loss, DG=damage grade; the exact calculated values have been rounded to the next integer, or first decimal value). Higher damage grades are neither expected in the Cologne region, nor anywhere else in Germany.

Table 2. Expected losses per damage grade for three different functions, representing the range of loss percentages covered by each class

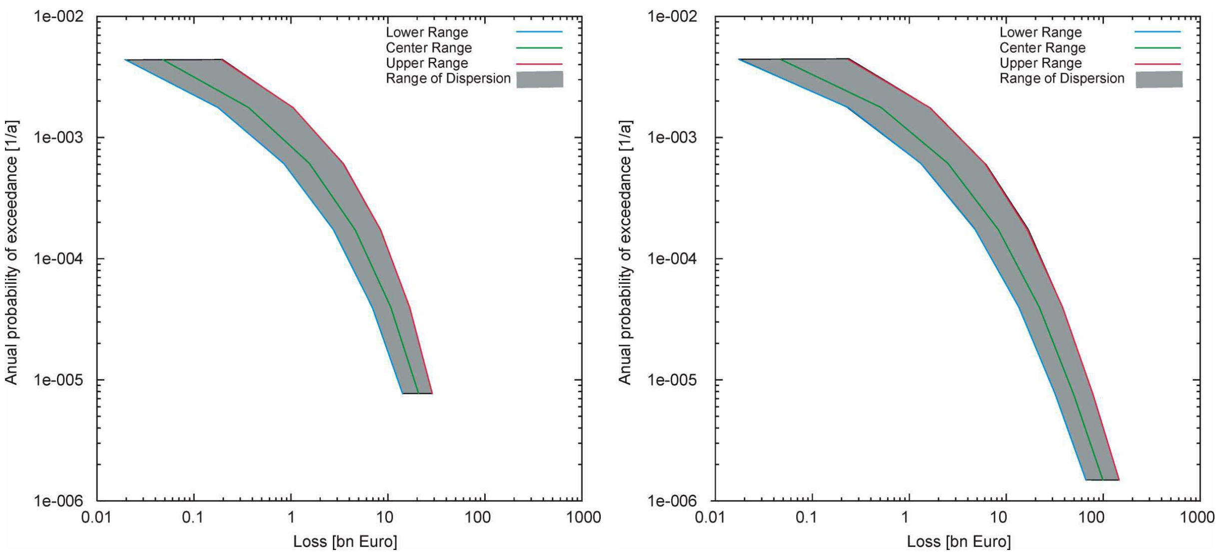
Damage grade DG	Loss % (range)	Probable lower range	Center	Probable upper range
1	0.5-5	0.5	1	2.5
2	5-10	5	8	10
3	10-50	20	28	40

The center values satisfactorily agree with loss ratios per intensity degree as derived from an (unpublished) evaluation of earthquake losses that was produced by the 1978 Albstadt earthquake in Southern Germany. The affected building inventory can be considered as a good representative for Central European conditions, and accordingly, for the Cologne region as well. As already stated, not even grade 3 is reached in Cologne itself. Table 2 shows expected losses per damage grade for three different functions, representing the range of loss percentages covered by each class. The exact calculated values have been rounded to the next integer, or first decimal value. This gives an idea of the uncertainties involved in the process of assigning loss percentages to damage grades.
Due to the composition of the building inventory and the dominance of masonry buildings (see Table 1), only one correlation between the damage grade and expected loss was applied. For each municipality the mean damage grades D_m were transformed into Mean Damage Ratios MDR (indicating the loss as a percentage of the replacement value). The losses are summed up for all the municipalities. Assuming that within each municipality the intensities according to the scenario maps are representative the loss can be expressed in terms of annual probabilities of exceedance corresponding to the mean or other statistical fractile intensities given by Figure 2. Deterministic results according to the different approaches (levels of refinement of input data, see Figure 9) are given in Figure 11. For comparing earthquake losses with those of other hazards, such as like storms or floods [12] probabilistic scenarios as depicted in Figure 10 were used. Surprisingly, probabilistic and deterministic scenarios exhibit only minor differences.



a) Scenario E4 b) Scenario E5

Figure 12. Economic loss curves for deterministic scenario events in dependence on the level of refinement of input parameters (location of epicenters taken from to Figure 7)



a) City area of Cologne alone b) Cologne and the adjacent areas of North Rhine Westphalia (NRW)

Figure 13. Economic loss curves for deterministic scenario event E5 (location of epicenter in vicinity of Cologne, see Figure 7) for both Cologne alone and for Cologne and the adjacent areas of North Rhine Westphalia (NRW). The scatter in the loss functions is related to table 2

CONCLUSIONS

Seismic risk maps have been prepared for different scenario intensities recognizing the scatter and uncertainties of site-dependent ground motion and of the applied vulnerability functions. The developed GIS-based seismic risk assessment technologies have been proven as powerful and applicable for the assessment of seismic damage potential in larger cities and other regions.

In order to simulate a specific and simultaneously random distribution of earthquake damage for the test area, different methods have been developed and applied to establish a connection between the specific local conditions and model earthquakes defined by intensities. Due to the diverse methods and the scatter in ground motion and vulnerability of building types, numerous scenarios resulted, which can lead to results that deviate widely. It must therefor be emphasized that the calculated building damage can only be the result of a scenario and the relations with which the various layers of the GIS-model are connected. The quality of the risk study does not lie in the estimation of damage for a specific building, but rather in depicting realistically the entire damage situation including regional and local distribution.

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