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VULNERABILITY AND RISK ASSESSMENT FOR EARTHQUAKE PRONE CITIES

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SUMMARY

Urban seismic risk is steadily increasing world-wide. This is true as well for the countries of low and moderate seismicity, taking into account that the risk value depends not only on the hazard level, but also on the aggregate elements at risk (both in human and economic terms) and their vulnerability to probable seismic influence. Thus, the proper approach to the problem of risk assessment and risk management should include consideration of all the contributing factors.

The Center for Disaster Management and Risk Reduction Technology (CEDIM), established as a joint initiative of the GeoForschungsZentrum (GeoResearchCenter) in Potsdam and the University of Karlsruhe, conducts an interdisciplinary study aimed at assessment and mapping of different kinds of risks for the territory of Germany, including the seismic risk. Considerable part of the territory of Germany is related to seismic prone zones, where earthquakes are probable, producing shaking intensity up to VIII. These seismic prone zones are densely populated, industrialized and have a high concentration of developed infrastructure, which implies a challenge for future disaster preparedness and risk mitigation activity. The paper presents some results of the seismic risk subproject of CEDIM.

The quantitative approach to the problem of risk analysis correspondingly implies the proper hazard, vulnerability and exposure evaluation. This paper is dedicated mainly to consideration of vulnerability analysis, including methodological aspects of the approach at the country level. Vulnerability composition models were constructed for the building stock of communities of different population classes, which can serve prototypes for the risk analysis. Using these models on GIS platform we computed and mapped specific damage distribution and estimated distribution of seismic risk potential over the territory of Germany.

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INTRODUCTION

The Center for Disaster Management and Risk Reduction Technology (CEDIM), established as a joint initiative of the GeoForschungsZentrum Potsdam and the University of Karlsruhe, conducts an interdisciplinary study aimed at assessment and mapping of different kinds of risks for Germany, including the seismic risk. The quantitative approach to the problem of risk analysis correspondingly implies the proper hazard and vulnerability evaluation. The seismic risk team of CEDIM includes the group of the GeoForschungsZentrum Potsdam, concentrated on hazard aspects, and the group of the University of Karlsruhe, concentrated on vulnerability aspects. This paper presents some results of the seismic risk subproject, the main current goal of which is assessment and mapping of seismic risk for Germany. The conceptual framework of the developed GIS-based approach to the problem of risk analysis includes consideration of the main contributing factors, namely, hazard (H), vulnerability (V) and exposed values (E) at the regional and national scale.

Considerable part of the territory of the Federal Republic of Germany (total area of the country is approximately 357 thousand square kilometers with population about 82 million as can be seen from Table 1) is related to seismic prone zones, where earthquakes are probable, producing shaking intensity up to VIII.

Table 1. Population and communities of Germany

Administrative Division	Area (sq.km)	Population (thousand)	Density per sq. km	Communities
Baden-Württemberg	35 751.64	10 601	297	1 111
Bavaria	70 549.93	12 330	175	2 102
Berlin	891.76	3 388	3 800	1
Brandenburg	29 476.16	2 593	88	1 474
Bremen	404.23	660	1 632	1
Hamburg	755.16	1 726	2 286	1
Hesse	21 114.19	6 078	288	430
Mecklenburg-Western Pomerania	23 172.96	1 760	76	1 000
Lower Saxony	47 616.48	7 956	167	1 054
North Rhine-Westphalia	34 081.87	18 052	530	396
Rhineland-Palatinate	19 846.74	4 049	204	2 306
Saarland	2 568.45	1 066	415	52
Saxony	18 413.30	4 384	238	544
Saxony-Anhalt	20 446.69	2 581	126	1 289
Schleswig-Holstein	15 761.40	2 804	178	1 132
Thuringia	16 171.94	2 411	149	1 017
Germany	357 022.90	82 200	231	13 912

Distribution of the main seismically hazardous zones, as given in the National Seismic Code (E DIN 4149 [1]) and can be seen in Figure 1, coincide, in particular, with the Federal States of Baden-Württemberg, Rhineland-Palatinate, North Rhine-Westphalia, Saxony and Thuringia, most of which are densely populated, industrialized and have a high concentration of developed infrastructure.

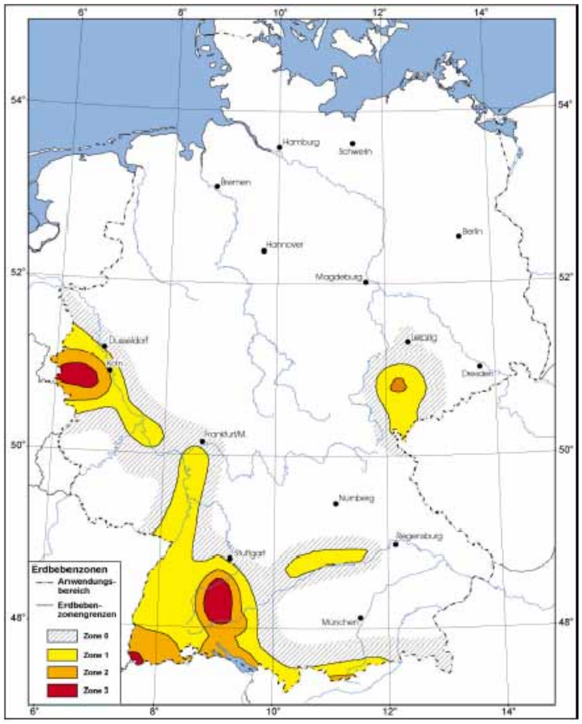

Figure 1. Seismic zoning of the territory of Germany (E DIN 4149 [1])

The seismically hazardous zones of the country, which are shown in Figure 1, were identified on the basis of so called D-A-CH map (Grünthal [2]), which was constructed for non-exceedance probability of 90% in 50 years (average return period of 475 years) in terms of seismic EMS-98 intensity (Grünthal [3]) for the D-A-CH countries (Germany, Austria and Switzerland). The expected level of seismic intensity in the Seismic Code is identified for the four zones as follows: zone 0 ($6 < I < 6.5$), zone 1 ($6.5 < I < 7$), zone 2 ($7 < I < 7.5$) and zone 3 ($7.5 < I < 8$).

Thus, one can say that the seismic risk in Germany represents a typical problem with a low occurrence probability, but potentially high consequences, and there is a demand for meticulous attention to the problem (Allmann [4]).

METHODOLOGY OF VULNERABILITY AND RISK ANALYSIS

There is a general agreement that the term "earthquake risk" refers to the expected losses to a given element at risk over a specified future time period. According to the way in which the element at risk is defined, the risk may be measured in terms of expected economic loss, or in terms of human lives lost, or in terms of physical damage to property, where appropriate measures of damage are available. Risk may be expressed in terms of average expected losses or in probabilistic manner and should include proper consideration of vulnerability and exposed values. In the recent years there was growing recognition of the problem and the change in emphasis from hazard to risk caused development of procedures and techniques for vulnerability and risk analysis at different scale, e.g. Carniel [5], Faccioli [6], Fäh [7], FEMA-NIBS [8], Frolova [9], Papadopoulos [10], Schwarz [11], Tyagunov [12], Vaseva [13], Young [14], Zonno [15] and many others.

The approach to the problem of risk analysis as well as to the constituents (hazard, vulnerability, exposure) depends on the scale. For individual existing buildings or construction sites the analysis can be conducted in detailed manner, taking into account geotechnical information about the site, location of probable hazard sources and estimated seismic influence, using advanced numerical or simplified methods of structural analysis and considering all relevant elements at risk. Obviously, this is a finance and time-consuming procedure and it is applicable only for individual sites, in particular for critical buildings and facilities. The next level (microzonation) is applicable for urban areas on the basis of available hazard microzonation maps and building stock inventory. Depending on the problem under consideration the inventory of the building stock is implemented building by building as a rule using visual screening procedures and representative buildings for simplification. In the same manner distribution of the exposure at risk can be estimated. For the next level corresponding to regional or national scale, another set of input data and more generalized methods of analysis are used. As it was mentioned above, the current problem under consideration of CEDIM corresponds to the country level. Therefore, below we describe the developed GIS-based procedure in more detailed manner.

Classification of communities

Taking into account the scale of the problem we consider communities of the country as units at risk. For the purposes of the study we classified the whole family of about 14,000 communities of Germany (Table 1) into five population classes depending on the number of inhabitants, namely, P1 (less than 2,000 inhabitants), P2 (2,000 – 20,000), P3 (20,000 – 200,000), P4 (200,000 – 800,000) and P5 (more than 800,000). The GIS layer with the classified communities is shown in Figure 2.

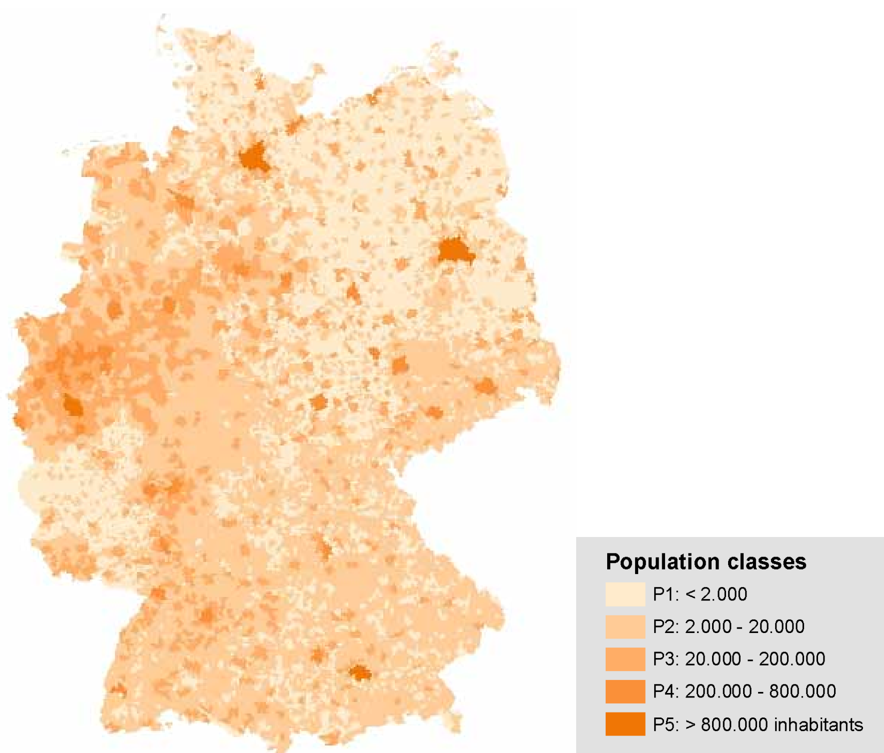

Figure 2. Population distribution in communities of Germany

It is worth mentioning that comparison of the data of population distribution (Figure 2) with the map of hazard zones (Figure 1) shows that the most densely populated areas, in particular, west (Lower Rhine Embayment in North Rhine-Westphalia) and south-west (Baden-Württemberg) parts of the country, coincide with the earthquake prone zones.

Seismic hazard input

At the first stage of the study we use the above-mentioned D-A-CH map as hazard input data. The seismic intensities of the D-A-CH map given for a grid of points over the territory of Germany were recalculated for the centers of communities using interpolation tools. The corresponding GIS layer with the hazard input data is shown in Figure 3.

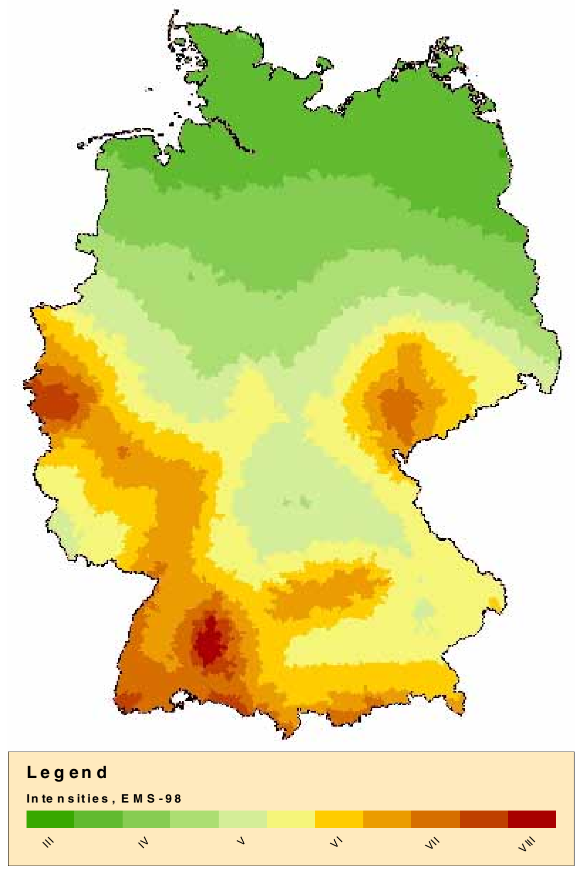

Figure 3. Seismic hazard distribution (for non-exceedance probability of 90 % in 50 years)

Vulnerability of the existing building stock

Another part of the procedure is dedicated to analysis of seismic vulnerability. The seismic vulnerability implies the expected degree of damage to a given element at risk resulting from a given level of seismic hazard. There are two principal approaches to vulnerability assessment, which include observed vulnerability and predicted vulnerability. Observed vulnerability refers to assessment based on statistics of past earthquake damage. Predicted vulnerability refers to assessment of expected performance of buildings based on engineering computations and design specifications or, if no other method is available, on engineering judgement. Obviously the second way is more suitable for the areas of low and moderate seismicity, where, as a rule, there is no data regarding the observed vulnerability. In the case of Germany, despite the experience of damaging Albstadt (1978) and Roermond (1992) earthquakes there is not sufficient data about seismic performance of the existing building stock of German communities. On the other hand, there is growing interest in the national engineering community to the problem of vulnerability assessment of the existing building stock in Germany (e.g. Meskouris [16], Raschke [17], Sadegh-Azar [18], Schwarz [19]).

Analysis of seismic vulnerability in our study was conducted using the vulnerability classification of buildings in terms of the European Macroseimic Scale (EMS-98), (Grünthal [3]), where six vulnerability classes were introduced and for different types of structures a most likely vulnerability class and probable ranges were indicated. The indication of probable uncertainties in seismic performance of structures is due to the fact that besides the type of structure and construction material there are many other factors affecting the seismic vulnerability of buildings, such as quality and workmanship, geometrical and structural regularity (in plan or in elevation), local soil conditions, state of preservation of the buildings, their position with respect to other buildings, earthquake resistant design (ERD), etc. These factors should be taken into consideration, in particular, when conducting vulnerability assessment with the use of visual screening procedures like (FEMA [20, 21]) and making inventory of the building stock of communities.

Prototype communities

In our study the building stock of communities is considered as a unit ("a piece of a puzzle") composing the whole picture of the country and vulnerability analysis is conducted in accordance with the classification of communities into population classes. We considered a few communities of different size, which are listed in the Table 2. All these communities are located within seismic prone zones and we assume that they can serve as prototypes for the five selected population classes.

Table 2. Considered prototype communities

Community	Population class	Zone (E-DIN 4149, [1])
Cologne	1 020 000 (P5)	1 (6.5 < Intensity < 7)
Schmölln	13 000 (P2)	2 (7 < Intensity < 7.5)
Albstadt	48 000 (P3)	3 (7.5 < Intensity < 8)
Lörrach	47 000 (P3)	3 (7.5 < Intensity < 8)
Karlsruhe	283 000 (P4)	1 (6.5 < Intensity < 7)
Stupferich (Karlsruhe)	3 000 (P2)	1 (6.5 < Intensity < 7)
Ettlingen	39 000 (P3)	1 (6.5 < Intensity < 7)
Schluttenbach (Ettlingen)	(P1)	1 (6.5 < Intensity < 7)
Schöllbronn (Ettlingen)	(P2)	1 (6.5 < Intensity < 7)
Spessart (Ettlingen)	(P2)	1 (6.5 < Intensity < 7)

For some of these communities we used information available from publications, in particular, Cologne and Schmölln were case study cities considered in the framework of the recent DFNK (Deutsches Forschungsnetz Naturkatastrophen - German Research Network Natural Disasters) project and a detailed vulnerability analysis was conducted for the building stock of these communities (Schwarz [12, 19], Raschke [17], Stricker [22]). For the other communities and their parts (Albstadt, Lörrach, Karlsruhe, Stupferich, Schluttenbach, Schöllbronn, Spessart) information about the existing building stock was collected using simplified visual screening procedures and other available data. While conducting visual screening analysis for test areas of the selected communities, the most probable vulnerability class of the

EMS-98 vulnerability table was assigned taking into account the above-mentioned factors affecting the seismic vulnerability.

Vulnerability composition models

Thus, based on available information and using engineering judgement we compiled the following matrix (Table 3) describing vulnerability composition models for the building stock of German communities corresponding to different population classes.

Table 3. Vulnerability composition models of the building stock of communities

Population classes (number of inhabitants)	Percentage of buildings of different vulnerability classes (EMS-98)			
	A	B	C	D
P1 (< 2 000 inhabitants)	Few	Most	Few	Very few
P2 (2 000 – 20 000)	Few	Most	Many	Very few
P3 (20 000 – 200 000)	Very few	Many	Very many	Very few
P4 (200 000 – 800 000)	Very few	Many	Most	Few
P5 (> 800 000)	Very few	Many	Most	Few
Very few - (0-5 %); Few - (5-20 %); Many - (20-40 %); Very many - (40-65 %); Most - (65-100 %)				

It is stated that the building stock of German communities is presented by the range of the vulnerability classes from A to D. The experience shows that in some cases for buildings with mixed structural types additional transitional classes can be introduced for making inventory, in particular, it can be useful for microzonation studies. However for the purposes of this study we did not consider any transitional classes. As for the vulnerability classes E and F, which are related to the structures with an increased level of earthquake resistant design (ERD), they are not presented in the table because they are not representative for Germany. The data in Table 3, describing the vulnerability composition models as percentage of buildings of different vulnerability classes, are given as a probable range just to emphasize that there are no two identical communities and one should be aware of the existing uncertainty.

Using the data in Table 3, the following (averaged) vulnerability models were constructed and used in the study (Figure 4). The pie diagrams in Figure 4 show (clockwise) percentage of buildings corresponding to the vulnerability classes A, B, C, D in the building stock of communities of different population classes and at this stage of the study the models were assumed to be representative for the whole country.

Vulnerability (damageability) functions

For the vulnerability classes A, B, C and D, which (in different proportions) are representative for the existing building stock of German communities, the damage probability matrices (DPM) were constructed following the ideas of the European Macroseismic Scale (EMS-98), where the description of damage distribution in terms of “few”, “many”, “most” is given in definition of the intensity degrees. Though, it should be mentioned, that in the intensity definition of the EMS-98 such description of the damage occurrence probabilities is given only for the highest damage grades. Therefore, in our study the percentage of buildings suffering lower damage grades was estimated, using the guidelines to the EMS-98 and also results of other studies (e.g. ATC-13 [23], Nazarov [24]). It is appropriate to mention here that supplementation of the damage distributions, given in the EMS-98, for the whole range of probable damage grades at different intensities and for the whole family of the vulnerability classes is an important problem requiring additional investigations, including analysis of both observed and predicted vulnerability for different types of buildings. Collection and processing of such data is indispensable for improvement of the damage probability matrices and vulnerability functions and therefore for the vulnerability and risk analysis.

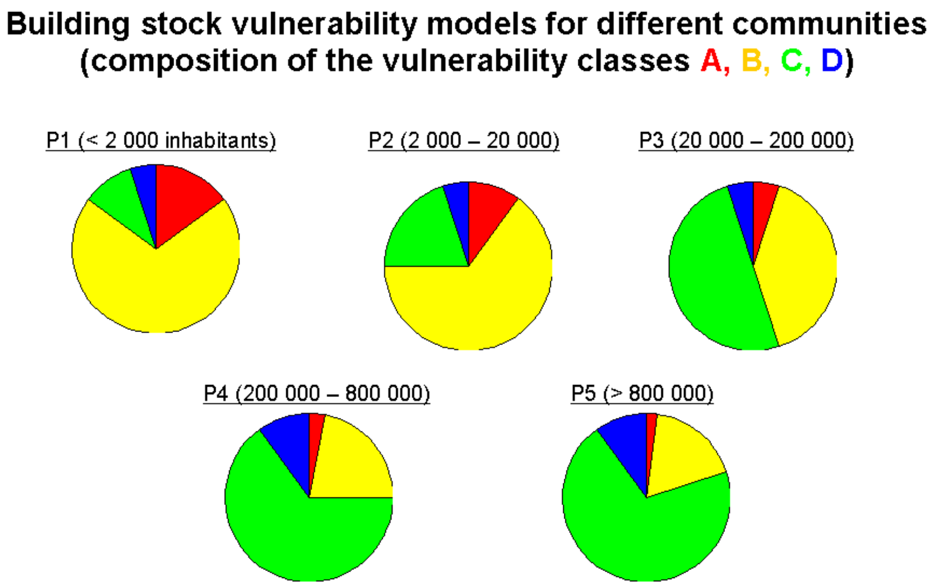

Figure 4. Building stock vulnerability models for different communities

We constructed vulnerability functions for each of the considered vulnerability classes (from A to D) in terms of the mean damage ratio (MDR) versus intensity of ground shaking. For computation of the MDR, which is considered as the cost of repair over the cost of replacement, the damage ratio range was assigned to the damage grades classified in the EMS-98 as presented in Table 4. In addition to the five damage grades from 1 to 5 the grade 0 was introduced to consider the full range of the damage states in the algorithm of risk analysis. Using these averaged data in our study, we are aware of the necessity of more detailed consideration of the damage ratio, considering all relevant peculiarities of different buildings, which can be especially important at the level of individual sites and microzonation studies, in particular, for the purposes of cost-benefit analysis.

Table 4. Classification of damage and damage ratio

Classification of damage	Damage Ratio, %	Central Damage Factor, %
Grade 0: No damage	0	0
Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)	0-1	0.5
Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)	1-20	10
Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)	20-60	40
Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)	60-100	80 (100)
Grade 5: Destruction (very heavy structural damage)	100	100

The constructed vulnerability functions for the vulnerability classes A, B, C and D and for the considered interval of seismic intensities from V to IX (EMS) are shown in Figure 5.

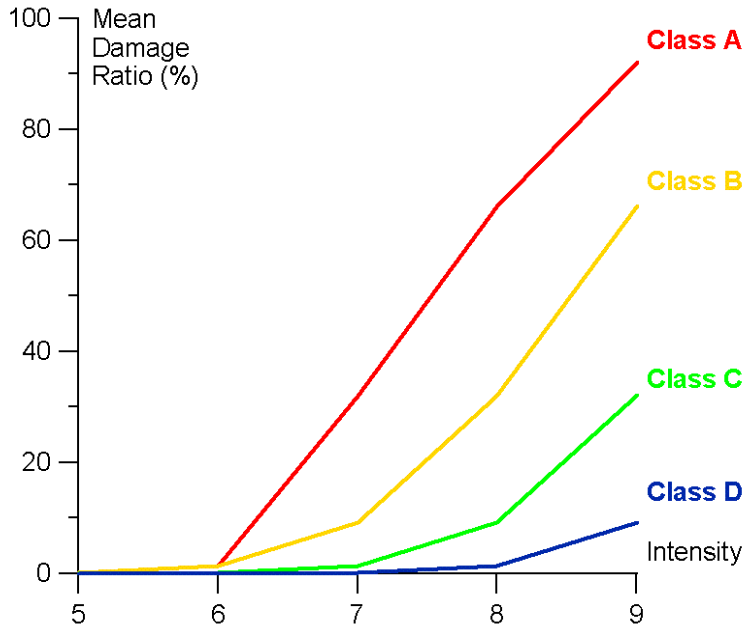

Figure 5. Vulnerability functions for the different vulnerability classes

Further these vulnerability curves (Figure 5) were combined with the building stock vulnerability models (Figure 4). By summing the product of the percentage of different vulnerability classes and corresponding mean damage ratio for the considered interval of intensities the vulnerability (damageability) curves were constructed for the selected five classes of communities (Figure 6).

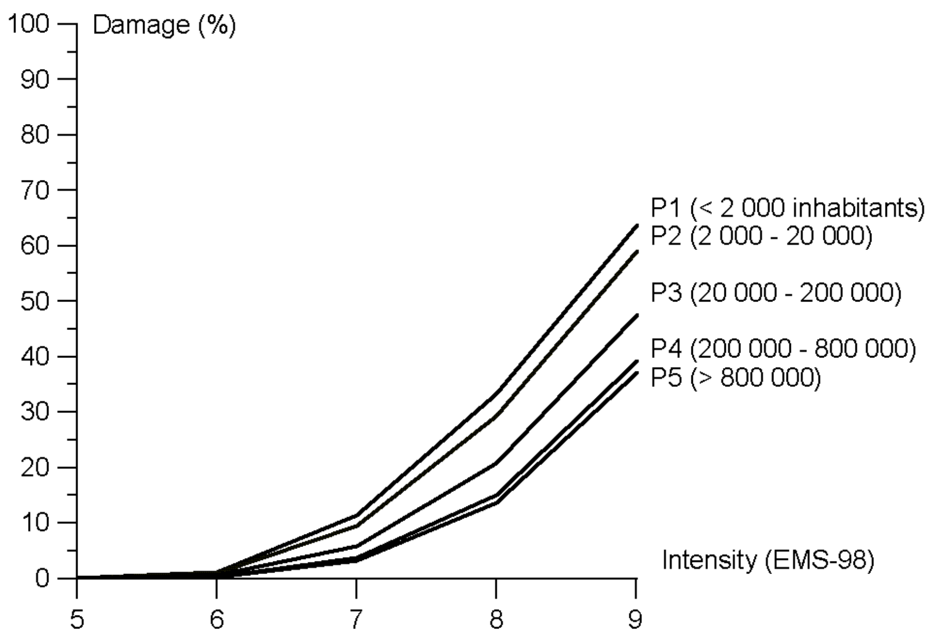

Figure 6. Vulnerability (damageability) functions for the building stock of different communities

These curves indicate expected damage (percentage) to the building stock versus seismic intensity. As it was already stated, for the problem of country level the building stock of communities is considered as a unit and, correspondingly, the averaged seismic input is referred to the centers of the communities.

From consideration of the curves in Figure 6 we can roughly judge about the damage potential of different communities located in earthquake prone zones. That is, for example, at the averaged seismic input of intensity VIII about 30% of the existing building stock of small communities (villages) will be destroyed, at the same time for larger communities (their parts) at this level of ground shaking about 10-15% of the buildings will be lost. At the level of intensity VII the percentage of probable damage to the building stock makes up about 10-12 % for small communities and about 4-6 % for larger cities. For rapid calculations of probable earthquake damage the following hints can be helpful. If we compare the curves in Figure 5 and Figure 6, we can see that the damageability curves for smaller communities (P1 and P2) approximately correspond to the curve of the vulnerability class B, whereas the damage to the building stock of larger communities (P4 and P5) can be approximately described by the curve of the vulnerability class C. The damageability curve for the population class P3 (which represents the most of German communities) is between these curves.

Damage and risk estimation

Having combined the constructed vulnerability models (Figure 6) with the distribution of communities of different population classes (Figure 2) and preliminary seismic hazard input (Figure 3), we computed specific damage distribution, which is also obtained as a GIS layer and shown in Figure 7. The range of estimated damage values over the territory of the country is from 0 to about 36%, which depends on combination of hazard and vulnerability characteristics.

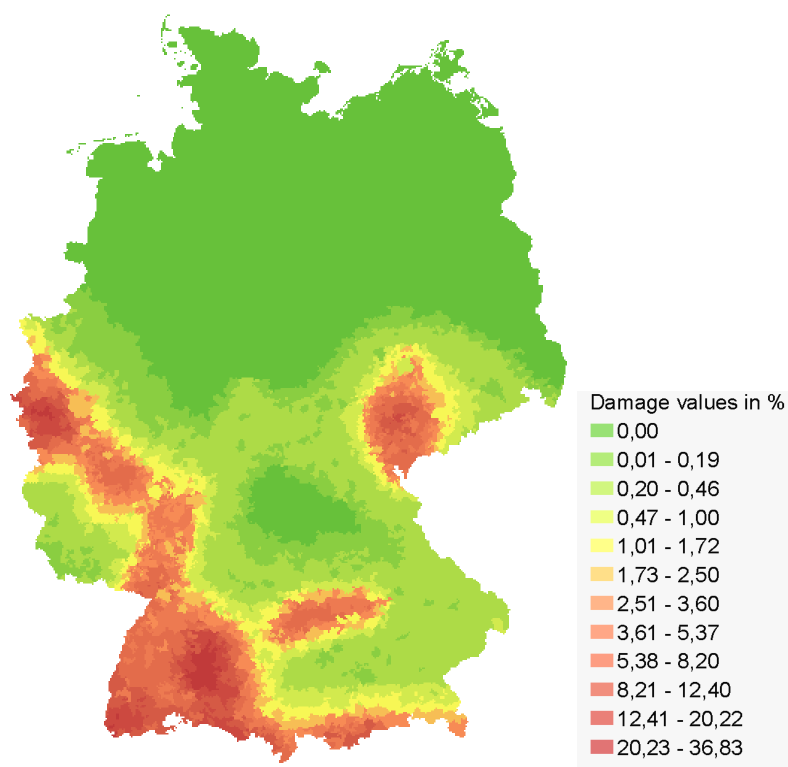

Figure 7. Estimated specific damage distribution (percentage of damaged buildings)

The specific damage means estimated percentage of the existing building stock, but it does not consider the number of buildings in the community. In other words, this is a combination of hazard and vulnerability input, but without consideration of exposed values. Therefore, in Figure 7 one cannot see distribution of risk or expected losses, because the value of the mapped specific damage can be equal for a densely populated area and for a waste.

At the present time the CEDIM team is engaged in collecting data about distribution of values at risk in the country, which are necessary for the purposes of risk analysis and will be used for assessment of other kinds of risks as well. Since currently the data is not available we cannot assess the existing level of seismic risk. At the same time just to have a rough idea about distribution of risk potential we estimated it as the product of the specific damage (Figure 7) and number of inhabitants in the communities, because, indeed, it sounds reasonable to assume that the amount of values in a community is proportional to the number of inhabitants. The outcome is shown in Figure 8. Certainly this picture is rough as it was obtained on the basis of many above-listed assumptions, but it provides the first estimation of seismic risk distribution over Germany.

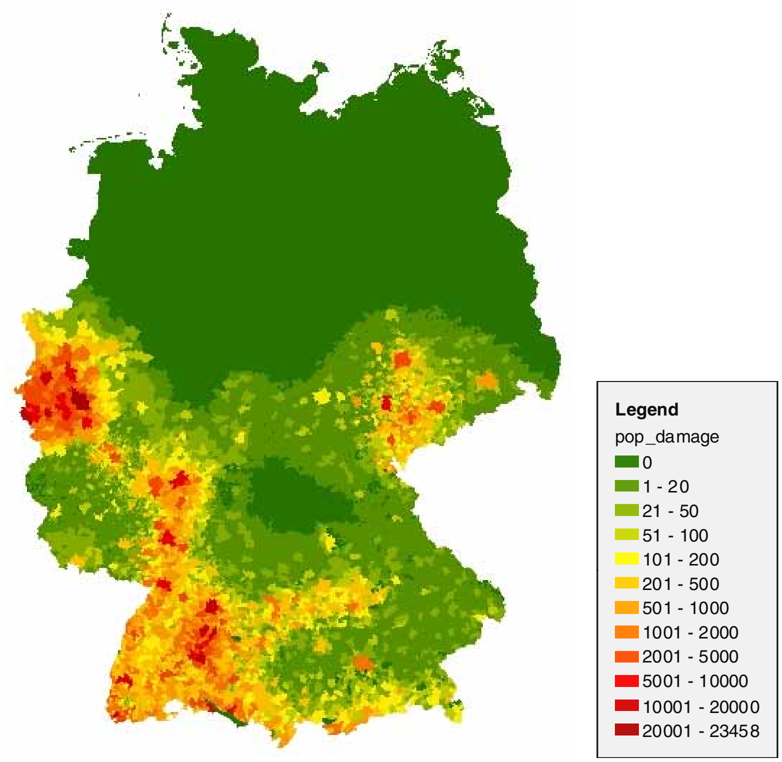

Figure 8. Estimated distribution of seismic risk potential over Germany

Unlike the picture of specific damage distribution (Figure 7), the picture in Figure 8 is more variegated ("spotty") and attracts attention to the places, which it would seem in the previous Figure 7 are out of interest for risk mitigation. First of all this concerns the large cities. At the same time the less populated and uninhabited areas, colored reddish in Figure 7, turned green in the map of risk potential, for the example the area of Bodensee (Lake of Constance).

The obtained results show that, on the one hand, the smaller communities are characterized by more vulnerable composition of their building stock and, therefore, higher percentage of damaged buildings can be expected there in case of probable future earthquakes. On the other hand, the larger communities located in earthquake prone areas, even with more favourable building stock composition and smaller estimated damage percentage, are characterized by higher level of risk potential because of higher concentration of exposed values there.

CONCLUSIONS

The principal emphasis of the first stage of the study was to work through the methodology of seismic risk assessment at the national scale while the process of data collecting is underway. Collection and analysis of data and improvement of the preliminary models concern all aspects of the problem, including hazard, vulnerability and exposure. For the present the constructed vulnerability composition models and damageability curves for the communities of different population classes should be considered as preliminary. Besides, a new hazard assessment will be made following basically what has been made within the DFNK project (Grünthal [25]).

It is worth-while to compare the maps of seismic hazard (Figure 3), specific damage (Figure 7) and risk potential (Figure 8). Though the distribution of specific damage and risk potential generally follow the hazard distribution, one can see a clear-cut distinction of the pictures. The estimated specific damage to the building stock, which is a combination of hazard and vulnerability input and can be interpreted as percentage of damaged buildings in the communities, does not consider the real number of buildings and other values at risk in the community. Therefore, the picture is rather smooth and provides no idea about potential losses in the area. At the same time the map of risk potential (where distribution of exposed values was taken into consideration in a rough manner) introduces new gradations and provides a better vision of the problem, which is important for the purpose of disaster preparedness and risk management.

The obtained preliminary results show, in particular, that, on the one hand, the smaller communities are characterized by more vulnerable composition of their building stock and, therefore, higher percentage of damaged buildings can be expected there in case of probable future earthquakes. On the other hand, the larger communities located in earthquake prone areas, even with more favourable building stock composition and smaller estimated damage percentage, are characterized by higher level of risk potential because of higher concentration of exposed values.

The future steps of the seismic risk program of CEDIM include:

- Improvement of the seismic hazard input data. The presented results were obtained using seismic input based on the D-A-CH map providing estimate of seismic intensity distribution corresponding to non-exceedance probability of 90% for the period of 50 years. The intended improvement of seismic hazard input data includes computation and mapping of probability distribution functions corresponding to different fractiles in terms of both seismic intensities and PGA (Grünthal [25]).
- Improvement of the vulnerability input data. On the one hand, it means improvement of the used generalized vulnerability models (building stock composition, damage probability matrices, loss functions for different types of buildings). On the other hand, it is intended to develop and apply methodology of vulnerability analysis on the basis of available GIS data about the actual building stock distribution in communities.
- Collection and analysis of data about spatial distribution of values at risk. Extension of the methodology for analysis of direct and indirect losses.

All these listed activities are to be effected bearing in mind the main goal of the project – assessment and mapping of seismic risk for Germany and its states.

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