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SIMULATION OF EARTHQUAKE LIBRARIES FOR RISK-TARGETED AND PERFORMANCE-BASED DESIGN CONCEPTS

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Abstract

For the study area of Central Europe, an intensity-based hazard and risk assessment model is developed. The procedures implemented are structured in a modular system. Probabilistic Seismic Hazard Analyses are performed using the program PSSAEL, which calculates Earthquake-Libraries on the basis of Extreme-Value statistics and GUMBEL-Parameters (m, τ, σ, M_{max}). The HAZARD module enables the Monte Carlo simulation of earthquake libraries for different hazard levels, which are representative for the evaluation or design requirements. A set of empirical-statistically derived relationships between macroseismic intensity, distance, and source parameters has to be regarded as an essential element of the general approach. The quality of risk analysis and seismic design parameters depends on the quality of the catalogs and applied seismic source models. The definition of the seismic source zones is one of the key decisions to consider the inherent model uncertainties.

The parameters of the simulated earthquakes can be directly related to ground motion prediction models. A new method is presented by linking results of site investigations (H/V spectra) with a self-designed strong-motion database including recordings from sites with instrumentally verified subsoil conditions. A cluster analysis is performed, taking H/V spectra from the target site measurements as search and evaluation criterion. Each measurement is providing a target function (H/V spectra) which is the basis for a ranking of the best fitting strong-motion recording sites. With the focus on return periods specified for a set of different limit states (or performance levels), characteristic damage grades can be postulated to establish the link to performance-based design concepts (on an empirical basis).

About the return periods user demands (life-time) or the building category and the site-specific circumstances can be taken into account. Uncertainties of the modules seismic HAZARD and SOIL amplification can be applied to the predominant building types.

In case of masonry structures the damage grades are predicted for all simulated scenarios on the basis of numerical simulations and further evaluation criteria implemented in the subroutines of the VULNERABILITY evaluation tool. Model sites and target areas (raster elements) within different seismic regions are investigated. In addition to the seismic active region of the Swabian Alb also low seismic metropolitan areas in Southeast Germany are considered.

Keywords: Simulation of earthquake libraries, Modular risk assessment tools, Performance-based design

1. Introduction

The implementation of seismic risk analysis requires the appropriation of characteristic input parameters and data levels which are usually afflicted by uncertainties. It is still not sufficiently and systematically studied how and in which extent the uncertainties of the individual input parameters affect the results, which are of engineering interest, i.e. the level and local distribution of damage, and their probability of being exceeded due to model uncertainties.

The scatter of results is in so far not adequately quantified. Therefore, the existing modular system is modified and extended by new elements, correlations, and definitions that allow a multi-directional treatment of uncertainties. The system is based on the following principles [1, 2, 3]:

- separate treatment of uncertainties in each module,
- maintaining scatter of interim results within the input for the subsequent modules, and
- quantification of influence on the scatter arising from the individual modules as well as module changes for the interim and the final results.

The paper gives preference to a more detailed presentation of the HAZARD module, where different source region models are implemented, and of the VULNERABILITY module, where a new technique for the determination of damage grade functions is presented. In previous studies, an approach for the quasi-self-generation of Site-specific Ground Motion Prediction Equations (SGMPE) has been developed which is implemented in the modules SEISMIC ACTION and SITE [2]. These equations are in particular applicable to target regions where instrumentally site measurements are available or can be performed with low effort. Combining the results from HAZARD and VULNERABILITY the earthquake hazard and risk assessment tool using Monte Carlo simulation techniques is now finalized and open for studies of more refined building typologies.

2. Basics

2.1 Data base

The magnitude based earthquake catalog for Germany and adjacent areas EKDAG - enhanced “Ahorner catalog” is preliminary finalized with version 2.0 (as of December 2014, Figure 1). Consisting of the parts A (basics and remarks), B (earthquake catalogue), and C (macroseismic maps) the earthquake catalog EKDAG [4] stands only exemplary for currently published catalogues for Central Europe in the context of several European or national research projects.

2.2 Raster elements and model sites

To link the different survey lines and evaluate the Probabilistic Seismic Hazard Analysis (PSHA), it was decided to analyze the data on the level of raster elements (s. Figure 2). The size of the raster elements is based on the density of information available for the element and therefore to the grade of the specific seismic hazard (cf. [7]). The survey lines include the available macroseismic maps, site specific intensity increments, and last but not least the implementation of the modular damage models and risk assessment tools [2, 5, 6].

Model and target sites are easily assigned to these raster elements.

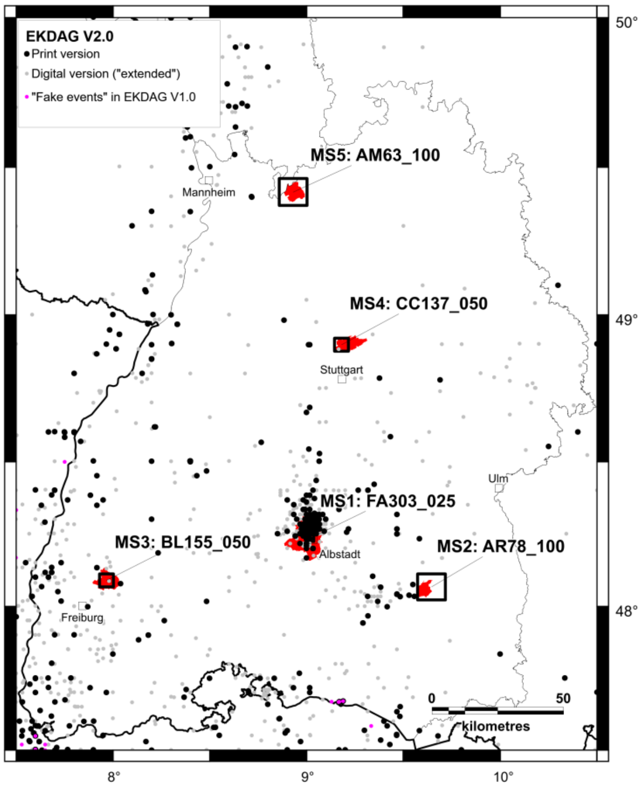


Fig. 1 – earthquake catalogue EKDAG [1]

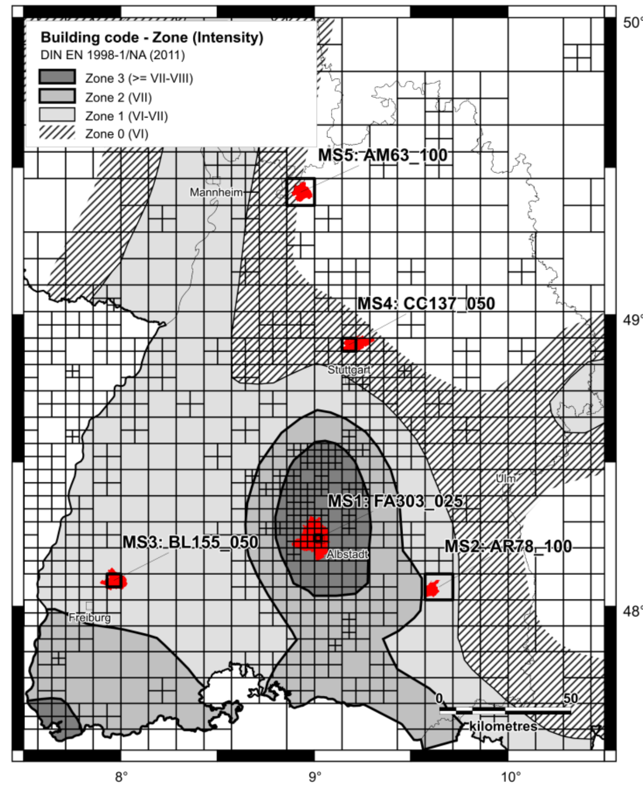


Fig. 2 – Overview of the used raster to evaluate the result of the PSHA [11]

Exemplary five model sites (MS) and related raster elements (RE) with different level of seismic hazard, which is characterized by the zone of the earthquake building code (Fig. 2; column "Zone" in Table 1), are selected. Some locations belong to a specified zone, while others are located in transition areas. In addition to the seismically active region of the Swabian Alb (MS1) also low seismic conurbations in Southwestern Germany are considered. The locations altogether therefore cover the spectrum of possible situations in the practical building application.

The choice of model sites is, however, not only related to hazard level; meso- or even micro-scale building stock surveys are available for the study areas, which were carried out in the context of developing an insurance-directed damage model [6, 8].

Table 1 – Investigated raster elements (see Fig. 2)

Model site MS		Lon.	Lat.	Raster element RE		Zone of German building code
MS1	Albstadt	9.01°	48.26°	RE1	FA302_025	3
MS2	Bad Buchau	9.65°	48.07°	RE2	AR78_100	1 (2)
MS3	Waldkirch	7.97°	48.09°	RE3	BL155_050	1
MS4	Ludwigsburg	9.20°	48.90°	RE4	CC137_050	0
MS5	Schönbrunn	8.93°	49.42°	RE5	AM63_100	- (0)

The knowledge of the building stock is a requirement to evaluate in a systematic approach the statistically relevant "model types or objects" of the existing building stock. For the purpose of this study, sample or "model objects" are derived from the building stock surveys in Albstadt (see [6, 9, 10]) and transferred to the other model sites. The simulations of damage to buildings show that different locations (exposed to a certain hazard) have an impact on the damage prognosis for a given (same) return period for the same model object. The results relate to the coordinates of the center for the grid elements (see [3, 7]).

2.3 Models of seismic source zones

The quality of seismic hazard analysis and the related engineering seismological design values depend largely on the seismic source zones model applied. The classification and delimitation of seismic source zones is seen as an element of uncertainty. In the developed methodological approach, it is the responsibility of the user to select the models according to the objectives and the demands on the study subject. As outlined in [3], it is possible to distinguish between zone-related and zoneless models, small-scale models (Small Scale Model, SS) or large-scale, more on tectonic regime aligned divisions (Large Scale Model, LS). In principle, the approach includes the use of modern methods of spatial data collection and interpretation, which clarifies the model selection, restricted or hereafter - if justifiable - may be supplemented by weighting factors (see [5]). One preferred approach with respect to engineering-standard tasks (residential buildings) provides a practically self-generating (mainly objectified) model development based on the epicenter density and VORONOI zones (Fig. 4) and the delineation of corresponding **E**pi**C**enter **D**ensity classes (ECD-n; n- number of classes; see [11]).

The authors show in [3], thereby the possible influence of used earthquake catalogs to the modeling. The article draws solely on calculations using the catalog EKDAG [4] as well as the models AR04 by [12] and Gru06 by [13] as shown in Fig. 3.

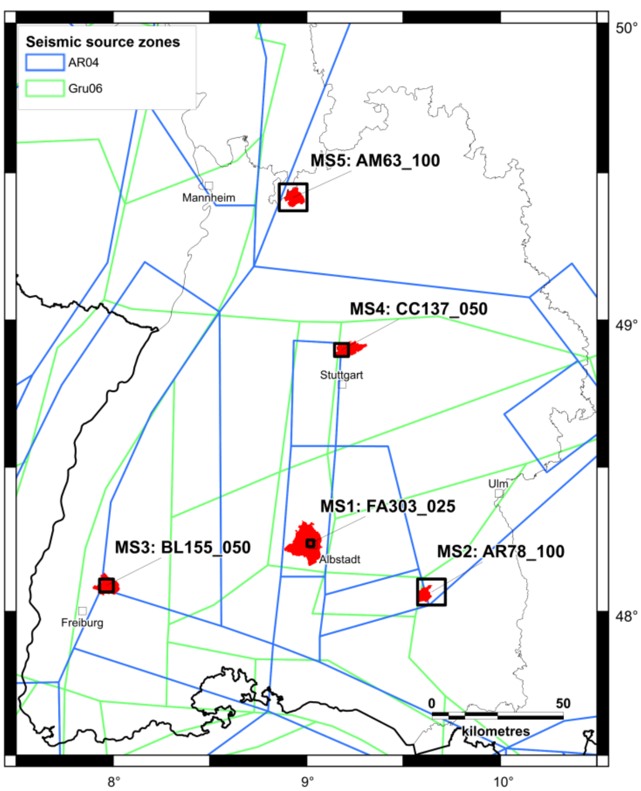


Fig. 3 – Model sites and seismic source zones AR04 (SS1) acc. to [12] and Gru06 (SS3) acc. to [13]

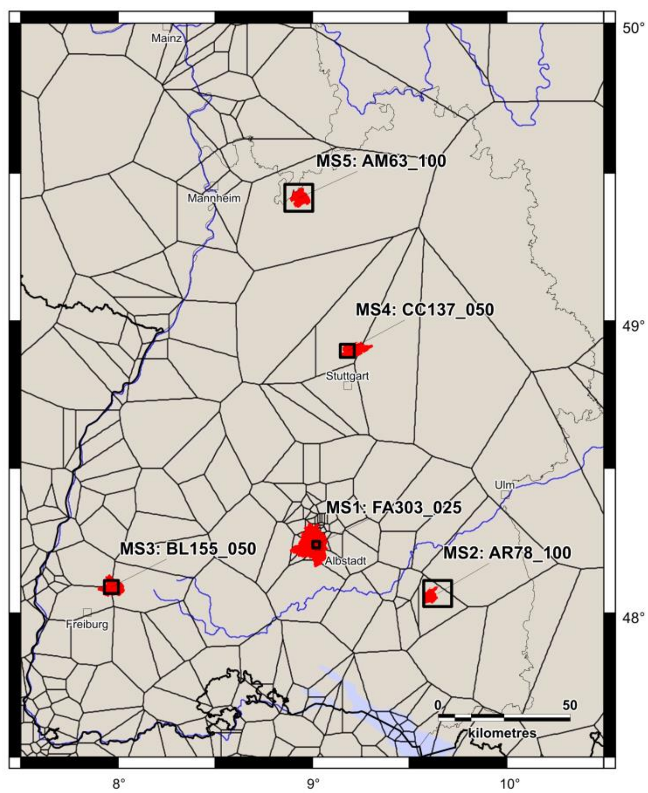


Fig. 4 - Model sites and VORONOI regions following **E**pi**C**enter **D**ensity (ECD) calculations (“zoneless”: ZL-No of ECD classes) acc. to [11]

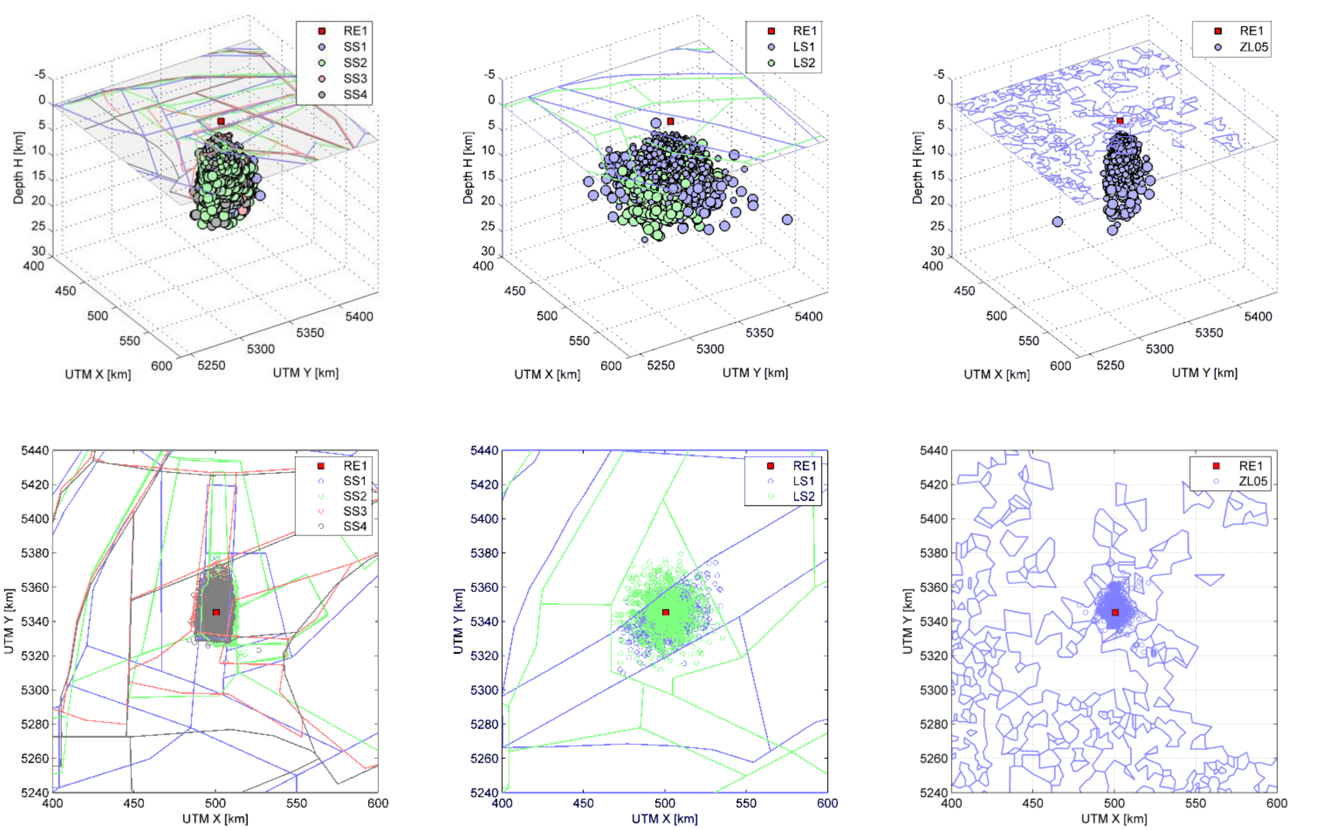
3. Results of the Probabilistic Seismic Hazard Analysis (PSHA)

3.1 Applied simulation program

Probabilistic Seismic Hazard Analysis is performed using the program PSSAEL [14]. For each zone element of the applied seismicity models (SS, LS), the magnitude exceedance rates are calculated on the basis of Extreme-Value statistics and GUMBEL-Parameters (m, τ, σ, M_{max}) using recently elaborated catalogue EKDAG [4]. The intensity exceedance rates are calculated for the center of the raster elements (see Fig. 2). For practical reasons, damaging intensities are of interest, only.

Earthquake libraries are simulated for predefined exceedance rates or intensities, enabling the link to return periods relevant for design purposes (and corresponding limit states). For each of the successfully simulated earthquakes, the information of epicenter (coordinates), magnitude, epi- and hypocentral distance, focal depth and epicentral intensity are available. The simulated earthquake libraries are used as input to model scenarios for model sites or raster elements, and for the investigation of individual objects of the existing building stock.

Uncertainties in the hazard analysis are supported by the investigation of various models and by taking into account magnitude-spread in the catalog entries of EKDAG in the form of modeling different variants. Uncertainties in the magnitude-frequency relations (of the zones) as well as regional characteristic of the focal depth distribution and attenuation relationships may be taken into account within allowed parameter range of the Monte Carlo simulations.



a) Small Scale Models (SS1, SS2, SS3, SS4) b) Large Scale Models (LS1, LS2) c) Epicentral density (zoneless) approach

Fig.5 – Simulated earthquake libraries with PSSAEL; superimposed by models for the model site MS1 (RE 1) with a mean return period of T_R= 475 years

3.2 Simulation of earthquake libraries

Shaking effects (intensities) describe the regional or local hazard. Following the descriptions of EMS-98 [15], slight to moderate structural damage has to be expected by shaking effects between intensity I_{EMS} = VI (6) and VIII (8). The PSSAEL tools enable the Monte Carlo simulation of earthquake libraries. For each intensity level a list of about 2000 successful trials (from several millions generated) seems to be representative for the hazard level under consideration. Each data point (earthquake) is described by a magnitude-distance pair and its epicentral coordinates as well as source depth (see Fig. 5).

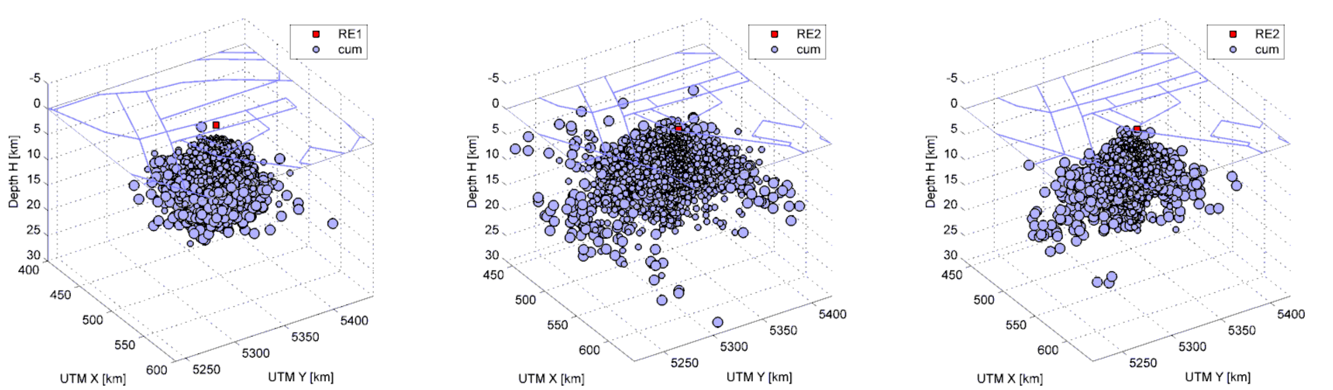
The simulated earthquakes related to the zonation models are spatially distributed equally pitted in each tectonic region or source zone. For further evaluation, only the simulated earthquakes for a given model site are selected which have the characteristic intensity of the predetermined probability of exceedance. The models are evaluated separately (single model) or in their combination (multi model approach). Figure 5 display the regional distribution and focal depth of the simulated earthquakes for the models acc. to Fig. 3 and an average return period of T_R = 475 years.

The cumulative distribution of magnitudes and distances for all seismic zone models (SS, LS and ZL) are illustrated in Fig. 6 for different raster elements and mean return periods. Due to the high seismicity concentration within a rather limited zone including the study area, the differences in the hazard are mainly related to the magnitude M_L.

3.3 Combination of earthquake libraries of different models

A methodology is developed by [5] that allows to combine simulated earthquakes from calculations of different models and/or catalogs for a given exceedance rate as model combinations. This approach is transferred to the damage prognosis of masonry type buildings and reinforced concrete structures.

The earthquake libraries deliver the condensed information about the uncertainties of the site-dependent hazard estimate. The parameters of the simulated earthquakes can be related to ground motion models (attenuation functions), directly. They have to be regarded as one key element of the procedure predetermining the scatter within spectral amplitudes on the action side and damage grades in case of analytical investigations of individual buildings of the predominant structural system.



a) Raster element RE1 T_R = 475a (see Figs. 5a, b, and c) b) Raster element RE2; T_R = 475a c) Raster element RE2; T_R = 2475a

Fig. 6 – Simulated earthquake libraries with PSSAEL; cumulated from all models in Fig. 5

4. Damage prognosis of the model sites and selected buildings

4.1 Seismic action

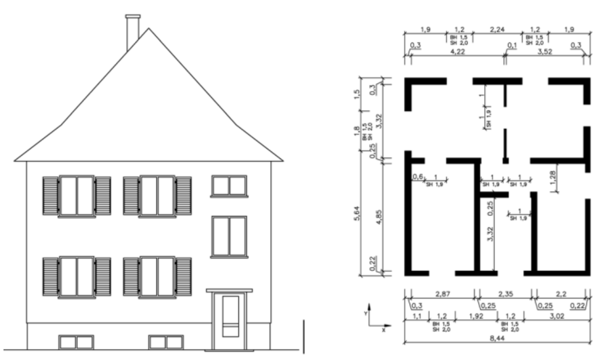
The availability of earthquake libraries generated by individual or combined simulations for each interesting return period enables the generation of spectral input parameters for each event by site-specific ground motion models.

It must be seen as an advantage of the developed procedure that the hazard analyzes, determining the impact and damage analysis can be performed modularly coupled (see [1, 2, 3]). Insofar there is the possibility to visualize user-friendly the impact side and to be free to decide on the degree of the considered spreading widths. In the synopsis of simulated earthquakes there are different methods available for evaluating and taking into account existing uncertainties (see [5]).

The contribution is limited to rock conditions. If the ground conditions of the model site are known, the DIN-compliant ground motion models (see [16]) or their refinements can be used. (Note: For model site Albstadt (MS1) the site measurements and results of site response analysis are already available in a comprehensive classification of subsoil classes and a corresponding assignment in database format [6, 7, 8].) The ground motion models acc. to [17, 18] for subsoil class A-R (DIN) or A (EC 8) are used, which are elaborated for rock sites with shear wave velocities v_s greater than 800 m/s.

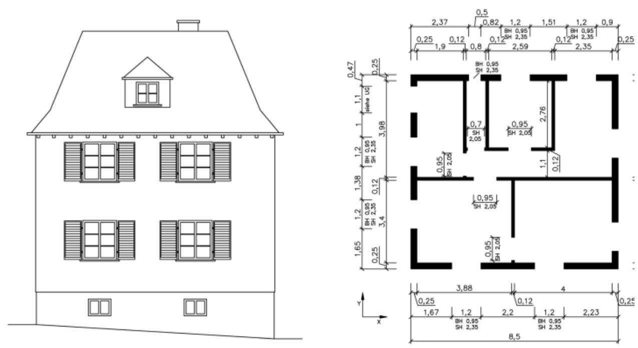
4.2 Investigated masonry buildings

Analytical studies of existing buildings have been conducted in the project DIMEBRA [10]. 50 representative buildings were selected from the total building stock for these investigations, digitally processed and modeled for the pushover analysis. The model parameters are - where possible - taken from the construction plans. This is the building layout, including the configuration of the walls, openings and type of ceiling, and information on the wall material. Possible and plausible ranges for the material strength of the bricks and the mortar are used. The method of construction of the masonry walls and the vertically acting loads were determined using historical material tables.



a) Front view b) Ground floor

Fig. 7 – Example building 1



a) Front view b) Ground floor

Fig. 8 – Example building 2

Fig. 9 – Damage Grades (DG) according to EMS-98 and corresponding examples from the September 3, 1978 Albstadt (Southern Germany) Earthquake; taken from [6, 15]

4.3 Damage grades

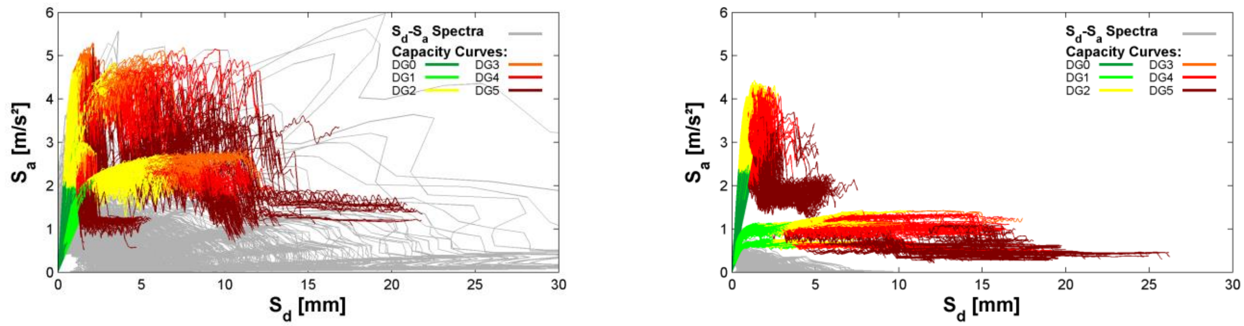
The damage prognosis refers to the damage grades acc. to EMS-98 [15]. Referring to the peripheral analysis of the existing buildings affected by 1978 Albstadt earthquake and the decisions taken in [10] (depending on the respective software), assignments are done between the analytically determined damage progression (displayed in the capacity curves) and the empirical EMS-98 compliant description. Results from the research project DIMEBRA [10] are taken to show the influence of the uncertainties of the modeling and structural analysis on the prognoses of damage grades (DG).

4.4 Capacity curves for different model assumptions

For the typical building representatives (Figs. 7 and 8) the response is predicted by quasi-static nonlinear pushover-analysis using various software solutions for all simulated scenarios. A calibration factor is used [1]. The factor is related to the effective level of ground motion in case of unreinforced masonry structures. It accounts for the observed discrepancy between the outcome of analytical studies and the occurred damage grades at Albstadt September 3, 1978 earthquake statistically investigated by [3, 5, 10].

The calculations of the capacity of the building take into account knowledge of uncertainties in form of spreading widths. For this purpose, samples are created, taking into account the material strength in 8 variants (LB-1 to LB-8) uniformly distributed over the determined range of values. Further, the method of construction of masonry walls with 2 samples (materials Mat-I, Mat-II) and the vertical loads with 2 samples (load levels LS-A, LS-B) are taken into account. The selected parameters are completely given in a tabular form (see [10]).

The Pushover load is applied in all 4 directions (-X, + X, -Y, + Y). Further, uncertainties in the building layout via a 5% eccentricity of Pushover load in positive and negative axis direction (pos. ex., neg. ex.) were recognized. The determined capacity curves are divided into sections of five damage grades acc. to EMS-98 [8] (see Fig. 9). The result (cf. Fig. 10) is a group of capacity curves which are evaluated in each case with the spectra of the simulated earthquakes. The predicted damage grades depend on location, return period and scaling factors of the ground motion.



a) Example building 1 (Fig. 7) in MS1 (RE1)

b) Example building 2 (Fig. 8) in MS2 (RE2)

Fig. 10 – Capacity curves (and defined ranges of Damage Grades (DG) according to EMS-98) overlapped with S_a-S_d-spectra for the simulated EQ libraries, T_R = 475 years and rock conditions

To assess the structural damage of a building the S_a-S_d-spectrum of a randomly chosen earthquake and a randomly chosen capacity curve of this building are assigned and evaluated by a procedure acc. to FEMA 440 [19].. Depending on the point of intersection of S_a-S_d-spectrum and capacity curve according to the coloring of the capacity curve a resulting damage grade is determined, which is included in the cumulative view of the expected damage (cf. Fig. 11). This procedure is done with 1000 repetitions. The color scheme is retained in the graphics for the probability of non-exceedance of damage grades (DG) for given return periods (here: T_R = 475 and T_R = 2475 years; see Figs. 11 and 12).

The results take into account the scatter and uncertainties of the seismicity models (module HAZARD) [in the form of the generated models from different earthquake libraries (Figs. 5, 6)], from the seismic action (module GMPE) [in the form of permitted spreading widths in the ground motion models], vulnerability (module VULNERABILITY) [determined in the form of different assumptions about the material characteristics and capacity curves by various software solutions (or masonry specific tools)]. Spectra are processed uniformly in the contribution for rock conditions; relations acc. to [17] will be used. These results are also available for the subsoil conditions of the building standard for German earthquakes zones [16, 18].

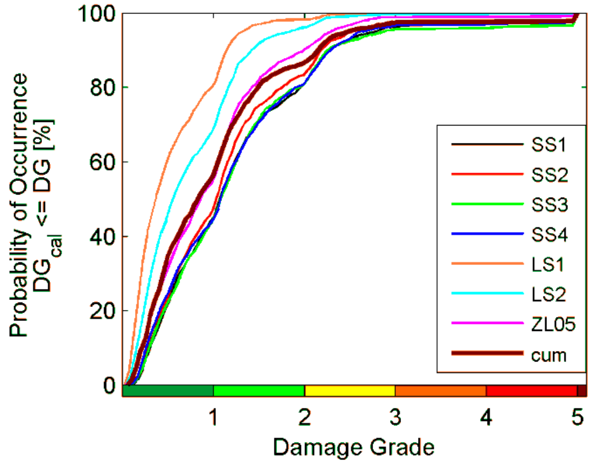
4.5 Result of the simulations

The risk analysis for a typical masonry building with wooden and R.C. floors is done by simulation of 1000 scenarios with randomly changing input parameters for each hazard level (return period). Uncertainties of seismic hazard (expressed by the earthquake libraries and generated for the used seismic zone models) and soil amplification are combined in hazard-consistent, site-specific ground motions applied to the structural system.

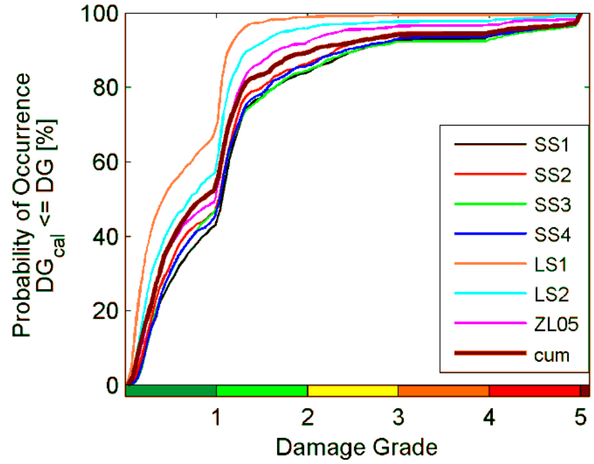
Results for the different sites and mean return periods are illustrated by the damage probability curves in Figs. 11 and 12. Using the proposed simulation technique, damage probability curves can be generated for different sites and mean return periods, which can be related to performance-based design levels.

From the in [10] modeled existing buildings more (60 in total) example buildings are selected by [5]. A distinction is made between the number of floors and the type of ceiling (for example, wooden or reinforced concrete ceiling). The damage acc. to the Albstadt-earthquake in 1978 is understandable by the detailed survey [6, 7] and can be used as a comparison and assessment scale respectively here especially for the calibration of the calculation results.

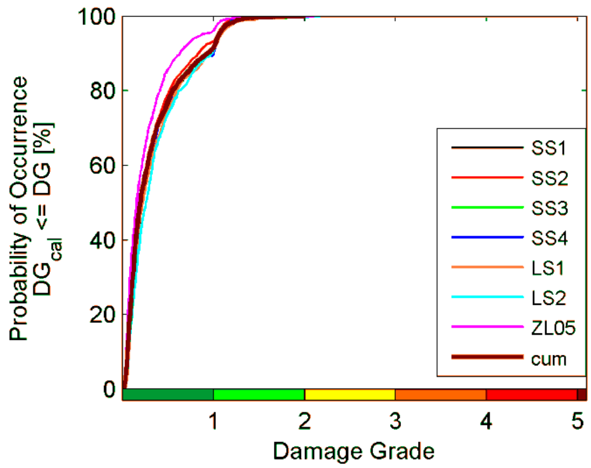
Figs. 11 and 12 provide an idea of the vulnerability of the exemplary selected masonry buildings if the existing buildings are subjected to numerical simulations. Damage prognosis relates to the model sites MS1 and MS4 and the two example buildings of Fig. 7 and Fig. 8 (dimensions, ground and elevation plan are given in [9], respectively [10]).



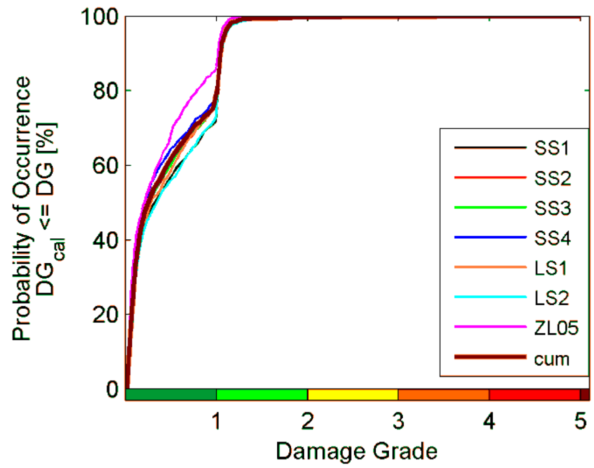
a) Example building 1 (Fig. 7) in MS1 (RE1)



b) Example building 2 (Fig. 8) in MS1 (RE1)



c) Example building 1 (Fig. 7) in MS4 (RE4)



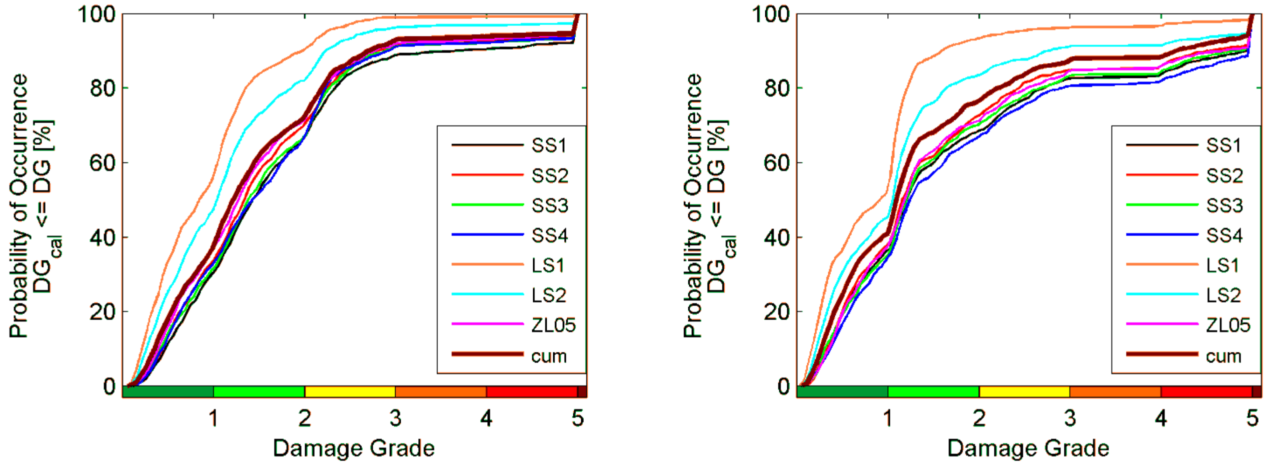
b) Example building 2 (Fig. 8) in MS4 (RE4)

Fig. 11 – Probability of Damage Grades (DG) for the model sites MS1 and MS4 (see Table 1, Figure 1) using PSHA results (simulated EQ libraries) from different seismicity models (Small Scale SS, Large Scale LS; zoneless approach (5 epicenter density classes: “ZL05”) and cumulated (“cum”) for T_R = 475 years

5. Interpretation and Conclusions

Results for the model sites MS1 to MS 5 reflect the particular differences in the grade of seismic hazard (cf. Figs. 1 and 2). They are plausible in the grading of the loss prognosis for the particular example building.

With regard to the number of floors and depending on the ceilings configuration of the example buildings in Figs. 11 and 12 interesting effects and phenomena are shown that can be generalized after evaluation of the currently ongoing work. It is notable that in case of increasing the impact (via the return period T_R = 2475 years, Fig. 12) only a moderate, partly nevertheless abrupt increase in the damage degree is visible. The here randomly selected buildings with wood-beamed ceilings have with larger impact (T_R = 2475 years) an increased likelihood of damage with damage grade 2 and higher. The behavior of a 2-storey masonry building with wood-beamed ceilings would be compatible with the protective goals of the German building standard for the design of structures for earthquake resistance.



a) Example building 1 (Fig. 7) in MS1 (RE1) b) Example building 2 (Fig. 8) in MS1 (RE1)

Fig. 12 – Probability of Damage Grades (DG) according to EMS-98 for the model site Albstadt (see Table 1) using PSHA results for a mean return period T_R = 2475 years

For the study area of Central Europe, an intensity-based hazard and risk assessment model has been developed. The modular system enables simulations and statistical simplifications within each of the basic elements as well as the transmission of the results between the linked modules. Making use of the simulated earthquake libraries calculated by the Probabilistic Seismic Hazard Analysis and the implemented empirical-statistically derived relationships between macroseismic intensity, distance and source parameters, damage prognosis can be used for hazard levels which are of importance for the further promotion of performance-based design concepts.

The parameters of the simulated earthquakes can be directly related to ground motion prediction models. Transferring the seismic action for all simulated events of the earthquake library to individual building representatives (in our study: unreinforced masonry systems) damage probability curves for different site clusters and hazard levels (mean return periods) can be elaborated. The procedure can be repeated for the whole building typology to come up with a new kind of risk mapping.

In the applied modular procedure results of PSHA can be coupled to the analysis of vulnerability and converted into prognosis of damage grades. Results in the contribution show the influence of source zones or seismicity models. Uncertainties in vulnerability assessment are additionally impaired for masonry buildings due to significantly different results in various software solutions [10].

There is still a lack of basic principles and systematically processed empirical data, to reflect the real spatial resistance quality of masonry buildings in between too optimistic and conservative unfavorable model approaches.

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The maps were created with the programs GMT and MapInfo Professional 12.5. The capacity curves were calculated with the software AmQuake Vers. 2.2.