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On the modeling of ground-motion field for seismic loss assessment of urban areas and lifelines for regions with a lack of strong-motion data

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ABSTRACT

Parameters of the probability distribution function for the seismic loss to portfolios and spatially-distributed structures (lifelines) during an earthquake are affected by ground-motion variability and correlation. In many seismically active regions, the strong motion data of real engineering significance are completely unavailable or very scarce. The absence of necessary data requires utilization of empirical correlation models obtained in other regions, and development of criteria for the proper selection from available correlation models is very important. In this paper we analyze influence of within-earthquake variability and correlation on uncertainty in estimation of seismic losses for residential buildings in one of the seismically active regions in Central Europe, which is characterized by the extreme shortage of the observed data, namely – South-Western Germany. Recommendations for practical calculations of seismic damage and loss in the regions with a shortage of ground-motion data are provided.

1. INTRODUCTION

In the past decade increasing attention has been focused on studies of ground-motion correlation (see Sokolov and Wenzel 2013, for collection of recent works). The term is related to similarity of ground-motion variability, or residuals between observations and results of modeling, for different earthquakes (between-earthquake correlation) and different locations (within-earthquake, or spatial, correlation). Correlation of ground motion reflects a non-random component in the residuals, which is caused by factors not accounted for by the ground-motion model and which constitutes epistemic uncertainty, i.e. uncertainty attributable to incomplete knowledge.

Parameters of the probability distribution function for the seismic loss during an earthquake to widely-located building assets (portfolios) and spatially-distributed structures (lifelines), which are very important for decision making and mitigation activities, are affected by ground-motion variation and correlation. A higher between-earthquake correlation and a higher within-earthquake correlation results in a larger

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variation in losses to a portfolio and a higher probability of extreme loss values; this would lead to a high variability in total loss.

In many seismically active regions, the strong motion data of real engineering significance are completely unavailable or very scarce. An appropriate ground-motion prediction equation (GMPE), which was developed using the data from other regions, or which is based on world-wide data, may be used for assessment of seismic hazard and loss. However, the within-earthquake correlation should be evaluated for a given area empirically. The information required for development of correlation models is not available in the regions with a lack of strong-motion data, therefore it is necessary to obtain upper and lower bound estimates by assuming the extreme characteristics of correlations, i.e. spatially uncorrelated ground motion and perfect correlation, and then, if necessary, to make some assumptions about realistic correlations based on the models developed for other regions. Sokolov et al. (2010, 2012) showed that the level of within-earthquake correlation may vary significantly depending on site classes, general geological conditions and earthquake magnitude. Thus, a single generalised model of within-earthquake correlation across geologically heterogeneous regions may not be adequate in some cases. In practical application a sensitivity analysis is required to check the influence of variations in parameters of within-earthquake correlation on the seismic hazard and risk estimations.

In this paper we analyze influence of within-earthquake variability and correlation on uncertainty in estimation of seismic losses for residential buildings in one of the seismically active regions in Central Europe, which is characterized by the extreme shortage of the observed data, namely – South-Western Germany. The earthquake prone areas are densely populated and highly industrialized, therefore assessments of seismic losses are highly desirable (Tyagunov et al. 2006). A few single events, so-called "scenario" earthquakes, were used in our study as the source of seismic influence. The impact of ground-motion variability and within-earthquake correlation on uncertainty in the loss values was analyzed in respect to the level of damage. The recently developed relationships between the within-earthquake correlation and gross geological and local soil characteristics, and earthquake magnitude (Sokolov et al. 2010, 2012) were considered as the factors allowing reducing uncertainty, which is related to a proper selection of the input correlation model. Recommendations for practical calculations of seismic loss in the region are provided.

2. GROUND-MOTION MODELING CONSIDERING CORRELATION

2.1 Basic definitions

The ground-motion parameter Y at n locations during m earthquakes is represented by

$$\log Y_{i,j} = f(e_i, s_{i,j}) + \eta_i + \varepsilon_{i,j} \quad i = 1, 2, ..., m; \quad j = 1, 2, ..., n; \qquad (1)$$

where e_i denotes variables that are properties of the earthquake source, $s_{i,j}$ are the properties of site location j during earthquake i, and f is a suitable function that describes the dependence of the mean value of ground-motion parameter $\overline{Y}_{i,j}$ on the magnitude, distance, local site conditions, etc. (i.e., $\overline{Y}_{i,j} = f(e_i, s_{i,j})$). The random variables η_i and $\varepsilon_{i,j}$ represent the between-earthquake and within-earthquake components of variability (independent and normally distributed with variances ${\sigma_\eta}^2$ and σ_ε^2), respectively. The value of η_i is common to all sites during a particular earthquake i, and the value of $\varepsilon_{i.j}$ depends on the site j. Assuming the independence of the two random terms, the total variance ${\sigma_T}^2$ is given by ${\sigma_T}^2 = \sigma_\eta^2 + \sigma_\varepsilon^2$.

The between-earthquake correlation of earthquake ground motion, or the similarity of ground-motion variability during different earthquakes at the same site, is determined by the relation between the components of variability (e.g. Wesson and Perkins 2001):

$$\rho_\eta = \frac{\sigma^2{}_\eta}{\sigma_\eta^2 + \sigma_\varepsilon^2} = \frac{\sigma^2{}_\eta}{\sigma^2{}_T}. \tag{2}$$

Two close sites may exhibit correlation of ground motion during an earthquake due to the commonality of wave paths (within-earthquake site-to-site (spatial) correlation), which depends on the site separation distance Δ. The empirical correlation coefficient calculated for within-earthquake $\varepsilon_{i,j}$ values separated by a distance Δ is usually represented as

$$\rho_\varepsilon(\Delta) = [\exp(a\Delta^b)], \tag{3}$$

where a and b are the region-dependent coefficients. The so-called “correlation distance” R_C may be considered a characteristic of the correlation (Wang and Takada 2005). The correlation distance shows the site-to-site distance for which the correlation coefficient $\rho_\varepsilon(\Delta)$ decreases up to 1/e = 0.368. For earthquake i and site j, the total correlation in $\varepsilon_{i,j}$ values is the following (e.g. Park et al. 2007; Goda and Hong, 2008):

$$\rho_T(\Delta) = \frac{\sigma_\eta^2 + \rho_\varepsilon(\Delta)\sigma_\varepsilon^2}{\sigma_T^2} = \rho_\eta + \rho_\varepsilon(\Delta)\left(\frac{\sigma_\varepsilon^2}{\sigma_T^2}\right), \tag{4}$$

where ρ_η is the between-earthquake correlation coefficient (Eq. 2), and $\rho_\varepsilon(\Delta)$ is the within-earthquake site-to-site (spatial) correlation coefficient (Eq. 3). When estimating the correlated ground motion, in addition to the median value of ground motion $\overline{Y}_{ij}$, it is necessary to generate the standard normal variates (errors) of η_i and $\varepsilon_{i,j}$ (Eq. 1).

Descriptions of the procedure for generation of the *k*-site random field of ground-motion error values that are spatially correlated may be found in many sources (e.g.

Park et al. 2007)

2.2 Ground motion models

In this study three earthquakes with moment magnitudes 5.5, 6.0 and 6.5 were selected as scenario events. The strongest earthquakes that shook South-Western Germany were the Basel (Switzerland), 1356, earthquake (M_W 6.4, maximum intensity in epicentral area I_{MAX} up to IX MSK, Gisler et al. 2006), and two earthquakes in Swabian Alb: the Ebingen, 1911, earthquake (M_W 5.7, I_{MAX} up to VIII MSK, Fiedler 1954) and the Albstadt, 1978, earthquake (M_W 5.2, I_{MAX} up to VIII MSK, Schwarz et al. 2005). We applied regional intensity-based vulnerability functions (Tyagunov et al. 2006) for estimation of damage (see next section), therefore seismic input has been modeled in terms of seismic intensity. Two models for calculation of intensity distribution were used. The first model (hereinafter referred to as the SG2009 model) is empirical attenuation relationship (Stromeyer and Grünthal 2009) developed using the data collected in Germany, France, the Netherlands, and the Czech Republic from earthquakes with moment magnitude up to 5.7. The equation describes intensity at particular site I_i as the function of so-called “calibration” intensity I_*, epicentral distance R and focal depth H of earthquake as follows

$$I_i = I_* - 2.80 \cdot \log\left(\frac{\sqrt{R^2 + H^2}}{H}\right) - 0.00126 \cdot \left(\sqrt{R^2 + H^2} - H\right) + \sigma \tag{5}$$

The variabilities in the model can be described by normal distribution with a standard deviation σ of about 0.7 intensity units. The “calibration” intensity I_* may be related to magnitude as $I_* = 0.875\,(\pm 0.49) + 1.061\,(\pm 0.11) M_W$ for reference focal depth 15 km (Feskova 2010). The magnitude-dependent I_* values should be increased or decreased at 0.25 units for every 5 km difference between the considered depth and the reference depth. In our study the SG2009 model was used for scenario earthquake of moment magnitude 5.5, and modeled intensity distribution for the earthquake and source depth 5 km is shown in Fig. 1.

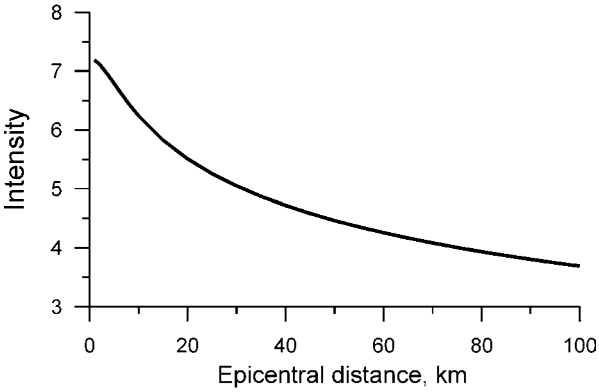

Fig. 1 Intensity attenuation curve obtained using the generalized SG2009 model, M_W 5.5, depth 5 km.

Sokolov and Wenzel (2008) developed a ground-motion prediction model for South-Western Germany. The model is based on the regional source-scaling and attenuation models for Fourier Amplitude spectra (FAS), frequency-dependent site amplification parameters, and stochastic simulation (Boore 2003). Besides the engineering parameters of ground motion (peak amplitudes, response spectra, etc.), the model allows estimating macroseismic intensity in terms of MSK scale directly from Fourier amplitude spectra of ground motion (Sokolov 2002). The model (hereinafter referred to as the FAS model) is based on so-called Very Hard Rock (VHR) spectrum calculated for given magnitude and distance and the frequency-dependent model of site amplification. The characteristics of the VHR spectral model are listed in Sokolov and Wenzel (2008).

The soil classification, which is used in German Seismic Codes (Keintzel 2005), includes three generalized types (or classes) describing deep geology (depth more than 20 m, ***Untergrund***) and shallow soil up to 20 m (***Baugrund***) conditions. The following deep geology classes are considered: rock (R); deep sediments (S); shallow sediments and transitions zones (T). The shallow soils are divided into rock or hard soil (A); firm coarse-grained soil (B); soft fine-grained soil (C). Thus, the following combinations are used: A-R, B-R, C-R, B-T, C-T, and C-S. The most territory of Baden-Württemberg is characterized by deep geology class R; class S covers a linear area in the western part (so-called the Upper Rhine zone) and an area in the south-eastern part of Baden-Württemberg; class T represents transition zones areas between areas R and S, or shallow basin area with thin sedimentary layers.

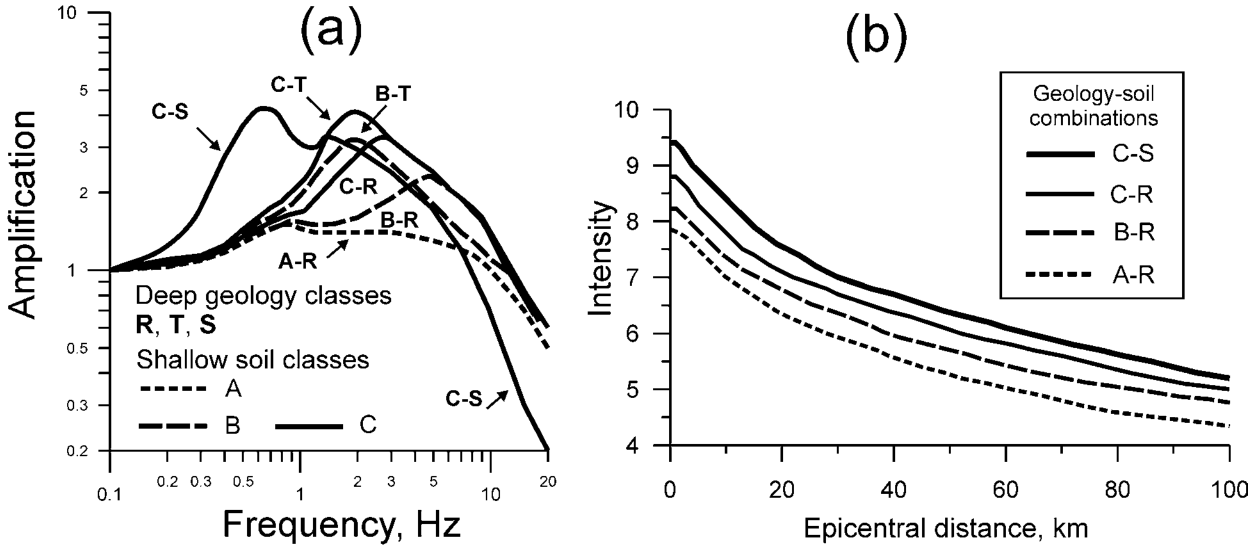

Fig. 2 The generalized site-dependent ground-motion models (see text for description of the labels). (a) Site-amplification functions for typical site classes in Baden-Würrtemberg. (b) Intensity attenuation curves obtained using the FAS model for different geology-soil classes, M_W 6.0, depth 5 km.

Brüstle and Stange (1999) calculated frequency-dependent site amplification functions of possible combinations of the deep geology and shallow soil classes using geotechnical characteristics, which are typical for Baden-Württemberg. The generalized site amplification functions for the soil classes are shown in Fig. 2a. In our study the FAS model was used for scenario earthquakes of moment magnitude 6.0 and 6.5; the examples of intensity distribution calculated for different generalized site classes are shown in Fig. 2b. Standard deviation σ of ground-motion residuals can not be defined for the semi-empirical FAS model, therefore we accepted σ = 0.7, as that in the SG2009 model. On the other hand, consideration of gross geological and local soil conditions may slightly reduce the standard deviation of residuals, therefore we also applied a smaller value σ = 0.5 for comparison purposes.

3 DAMAGE AND LOSS ESTIMATIONS

A set of residential buildings was constructed based on total number and relative percentage of buildings in the urban area belonging to four vulnerability classes that are typical for Germany (Tyagunov et al. 2006), namely: 15000 residential buildings, 1 % of which belongs to vulnerability class A; 40 % - to class B; 50 % - to class C; and 9 % - to class D. The urban area of 18 km x 22 km was divided into cells of 1 km x 1 km and the buildings were distributed across the area randomly; a uniform distribution has been considered to avoid uncertainty related to building grouping in every particular case. Fig. 3a shows the scheme of studied region, location of the urban areas and epicenters of the scenario earthquakes.

We used intensity-based vulnerability functions, which relate degree of damage (ratio between cost of repair and cost of replacement, or damage ratio) and intensity of seismic shaking (Tyagunov et al. 2006). The degree of damage for construction of particular vulnerability class and given intensity level is a random variable characterizing by a probability distribution function (normal or beta distribution). In this study we concentrated on analysis of influence of within-earthquake variability and correlation of ground motion on estimations of seismic losses, therefore we did not consider other sources of uncertainty in such estimations. First, we assumed that all variability is within-earthquake, i.e. $\sigma_\eta = 0$ in Eq. 4. Second, we did not consider damage probability distribution for given ground-motion intensity and structure-to-structure loss correlation of damage. To avoid uncertainty in replacement cost when converting damage to monetary loss, we estimated losses in terms of mean damage ratio (MDR). For a given ground-motion intensity Int generated for a cell i, a single value of expected direct loss $EDL_{i,j,VC}$ was estimated for every building j of particular vulnerability class VC as follows

$$EDL_{i,j,VC} = VF_{MDR}(VC, Int) \tag{6}$$

where $VF_{MDR}(VC, Int)$ is vulnerability function in terms of mean damage ratio for particular vulnerability class VC (Fig. 3b). The loss values, which had been estimated for all buildings within a particular cell, were summarized to obtain a cell-specific loss. Then, a single aggregated loss value $LOSS_{MDR}$ for a given generation of the ground-motion distribution was obtained as the normalized sum of losses from all cells

$$LOSS_{MDR} = (\sum_{i=1}^{N_C} \sum_{j=1}^{N_{CB}} \sum_{VC} EDL_{i,j,VC}) / N_{TB} \, , \tag{7}$$

where N_{CB} is the number of buildings within the cell i; N_C is the total number of cells; and N_{TB} is the total number of buildings in portfolio. The generated set of aggregated loss values (10,000 generations) is used for the estimation of the probability density function (PDF) and cumulative probability function (CPF), and the analysis of the parameters of loss distribution. Note that in this study the aggregated loss values were calculated for all vulnerability classes jointly and separately for particular classes.

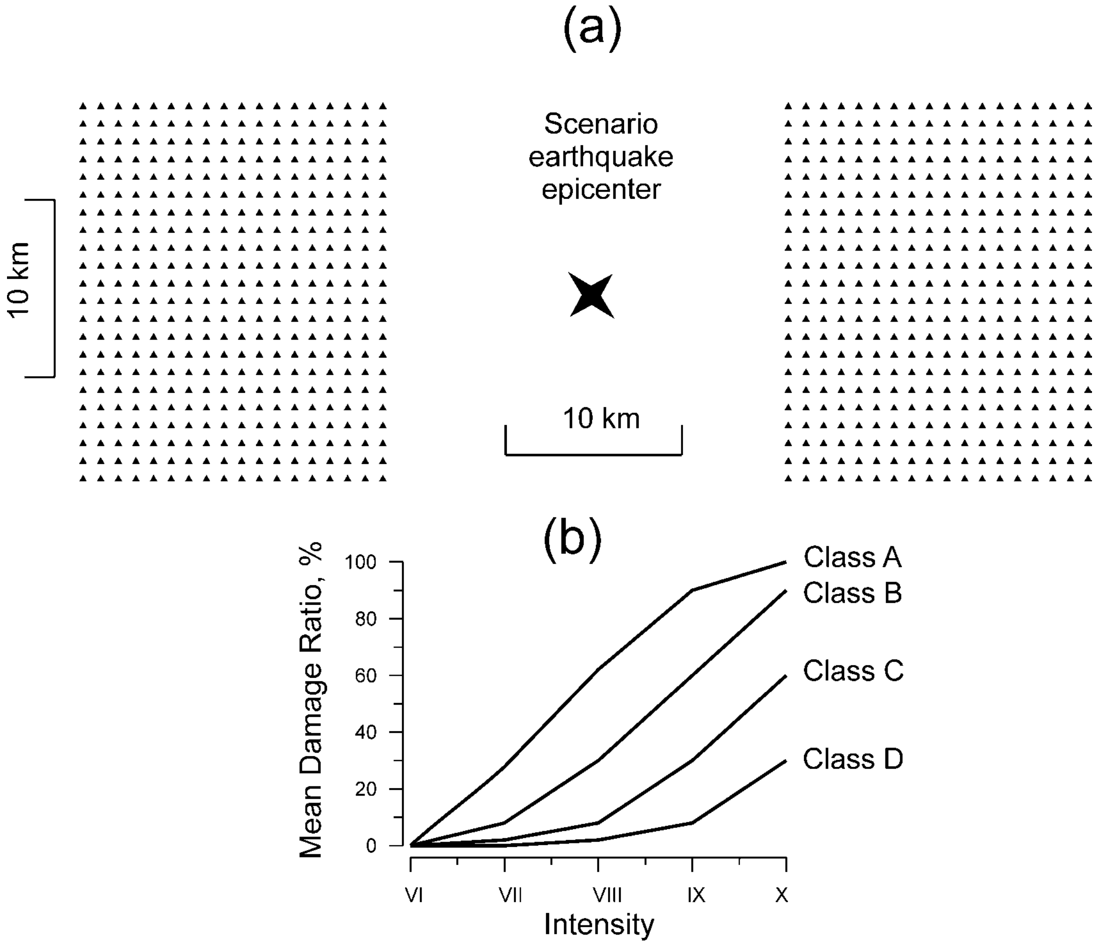

Fig. 3. Characteristics of the portfolios. (a) Studied area (two portfolios) divided into cells of 1 km x 1 km (triangles) and the location of epicenters of scenario earthquakes. (b). Vulnerability functions for different vulnerability classes (Tyagunov et al. 2006).

We calculated ground-motion parameters (seismic intensity) from a single scenario earthquake across a wide region, which includes models of two similar urban areas (hypothetical cities). The generation has been performed using Monte Carlo technique using the procedure described above and considering several models of within-earthquake correlation $\rho_{\varepsilon}(\Delta)$, in which the correlation distances R_C vary from 5 km to 40 km. The models also include extreme cases, namely: perfect correlation ($\rho_{\varepsilon}(\Delta)=1$, for all separation distances Δ , and spatially uncorrelated ground motion ($\rho_{\varepsilon}(\Delta)=0$ for all separation distances Δ except for Δ = 0 km). Obviously, the perfect spatial correlation should be considered an unrealistic and extreme case, and it was included here only for comparison purposes as the upper limit of the estimations.

4. RESULTS AND DISCUSSION

Knowing probability distribution of the portfolio loss is necessary for a seismic risk assessment and risk management. For example, primary insures are concerned with the central part of the distribution (mean and median values), while re-insurers deal mostly with the right tail of the distribution, because it is necessary to estimate probability of extremely negative outcomes of an earthquake. Therefore, a sufficiently smooth and accurate estimate of the loss probability function is of great importance. The loss probability distribution in terms of mean damage ratio is defined on the interval 0 % - 100 %, therefore the beta distribution Beta (α , β) is preferable for this case. The shape parameters α and β of theoretical beta distribution are estimated using the mean and the variance determined from the calculated distribution of expected losses (see examples below). The analytical expression allows drawing exact shape of the distribution and analysis of necessary parameters, like skewness, which is a measure of the asymmetry of the probability distribution. In this study, instead of analysis of parameters of beta-distribution, we are working with parameters determined from the modeled loss distributions.

We considered the following parameters of loss distribution: the mean value of loss $LOSS_{MEAN} = \sum_{i=1}^{N} LOSS_i \Big/ N$, where $LOSS_i$ is the aggregated loss value for the i simulation, and N is the total number of simulations; the median value, for which the cumulative probability function equals 0.5; and the particular values of loss with a certain probability of not being exceeded, e.g., 90% (LP_{90}), 95% (LP_{95}), and 99% (LP_{99}).

4.1 Influence of ground-motion variation on estimations of mean expected loss

It is worth to note that in several cases the loss calculations for portfolios, aiming to estimations of mean expected losses, are performed for scenario earthquakes using only mean values of predicted ground-motion parameters from corresponding GMPE without consideration of ground-motion variability (e.g. Lang et al. 2012; Tyagunov et al. 2006). Indeed, the mean expected loss for a portfolio does not depend on characteristics of ground-motion correlation (Sokolov and Wenzel 2011), however, as it will be shown below, the influence of ground-motion variability on estimations of mean expected loss should be analyzed in every particular case.

We calculated aggregated mean expected loss in terms of mean damage ratio (AMDR) for the portfolios (urban areas) considering buildings of all vulnerability classes A, B, C, and D jointly and separately for every vulnerability class. Three scenario earthquakes, different ground motion models, and different levels of within-earthquake variability, i.e. standard deviation σ_{ε} (0.0, 0.25, 0.5, and 0.7), were used. Initially we assumed that both portfolios are characterized by similar geological conditions.

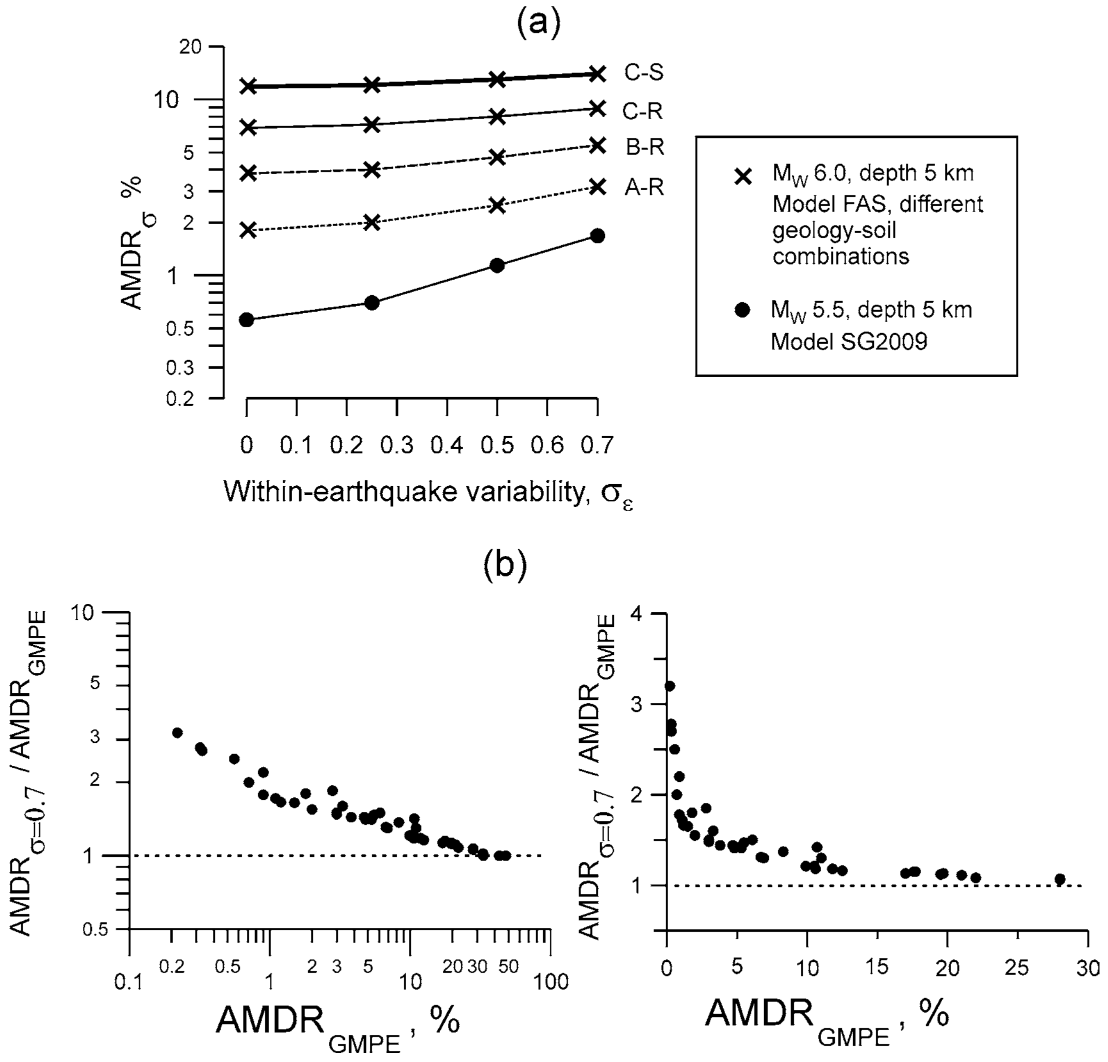

Fig. 4 Influence of within-earthquake variability on estimations of mean expected losses. (a) Aggregate mean expected losses in terms of mean damage ratio (AMDR) calculated using different ground-motion models and earthquakes for different values of within-earthquake standard deviation σ_ε. Zero standard deviation corresponds to mean values of predicted ground-motion intensity. (b) Relative difference between the loss estimations obtained using the mean values of predicted ground-motion intensity ($AMDR_{GMPE}$) and considering the within-earthquake variability ($AMDR_\sigma$, $\sigma_\varepsilon = 0.7$), all earthquakes, ground-motion models, and vulnerability classes.

Fig. 4a compares the AMDR values (examples) estimated using various models of ground motion. In general, values of the mean expected loss increase with the increase of within-earthquake standard deviation; however the degree of the increase is not similar for different levels of damage, which in turn depend on earthquake magnitude and location, ground-motion model, and characteristics of portfolios (considered vulnerability classes). To describe the dependence, we calculated the ratio between the

AMDR values estimated using maximum applied value of standard deviation $\sigma_{\varepsilon} = 0.7$ ($AMDR_{\sigma=0.7}$) and the values estimated using the mean values of predicted ground motion ($AMDR_{GMPE}$) taken from GMPE. Distribution of the ratios versus $AMDR_{GMPE}$ values is shown in Fig. 4b in bi-logarithmic and linear scales. It is possible to define a threshold $AMDR_{GMPE}$ level, starting from which the estimations of mean losses may be performed without consideration of the within-earthquake variability, i.e. the difference between $AMDR_{\sigma=0.7}$ and $AMDR_{GMPE}$ becomes negligible. For example, if for a given application the 20 % error in estimations of mean losses (i.e. ratio $AMDR_{\sigma=0.7} / AMDR_{GMPE}$ = 1.2) can be accepted as negligible, than the threshold level $AMDR_{GMPR}$ is about 10 % ; for the 10 % error - $AMDR_{GMPE}$ is about 20 % , etc.

4.2 Influence of within-earthquake correlation

In this section we study the influence of within-earthquake correlation on the loss probability distribution. Fig. 5a shows examples of probability distribution and cumulative probability functions of loss calculated for the portfolios (all vulnerability classes) using different levels of the within-earthquake correlation (moment magnitude 6.0, site model C-S, within-earthquake standard deviation 0.7). An example of approximation of the calculated loss probability distribution by beta distribution is shown in Fig. 5b. The influence of within-earthquake correlation is expressed in skewing of the shape of loss distribution. Consideration of within-earthquake correlation results in the long right tail of the distribution – the larger the level of correlation (correlation distance), the longer the tail. The general relationship between the considered characteristics of the loss distribution and the within-earthquake correlation is shown in Fig. 5c. While the median values of loss distribution slightly decrease with the increase of the correlation level (correlation distance), the particular values of loss with a certain probability of not being exceeded increase with the correlation level.

The influence of within-earthquake correlation on estimations of aggregated loss depends on level of damage, which, in turn, is a function of characteristics of portfolio (vulnerability classes of buildings and their numbers) and level of ground motion, i.e. site-dependent ground-motion model and earthquake characteristics. Thus, in practical calculation when it is necessary to analyze loss distribution for a portfolio, a sensitivity analysis, which considers influence of possible variations in the characteristics of within-earthquake variability (standard deviation and correlation) on the parameters of the loss distribution, is an essential procedure.

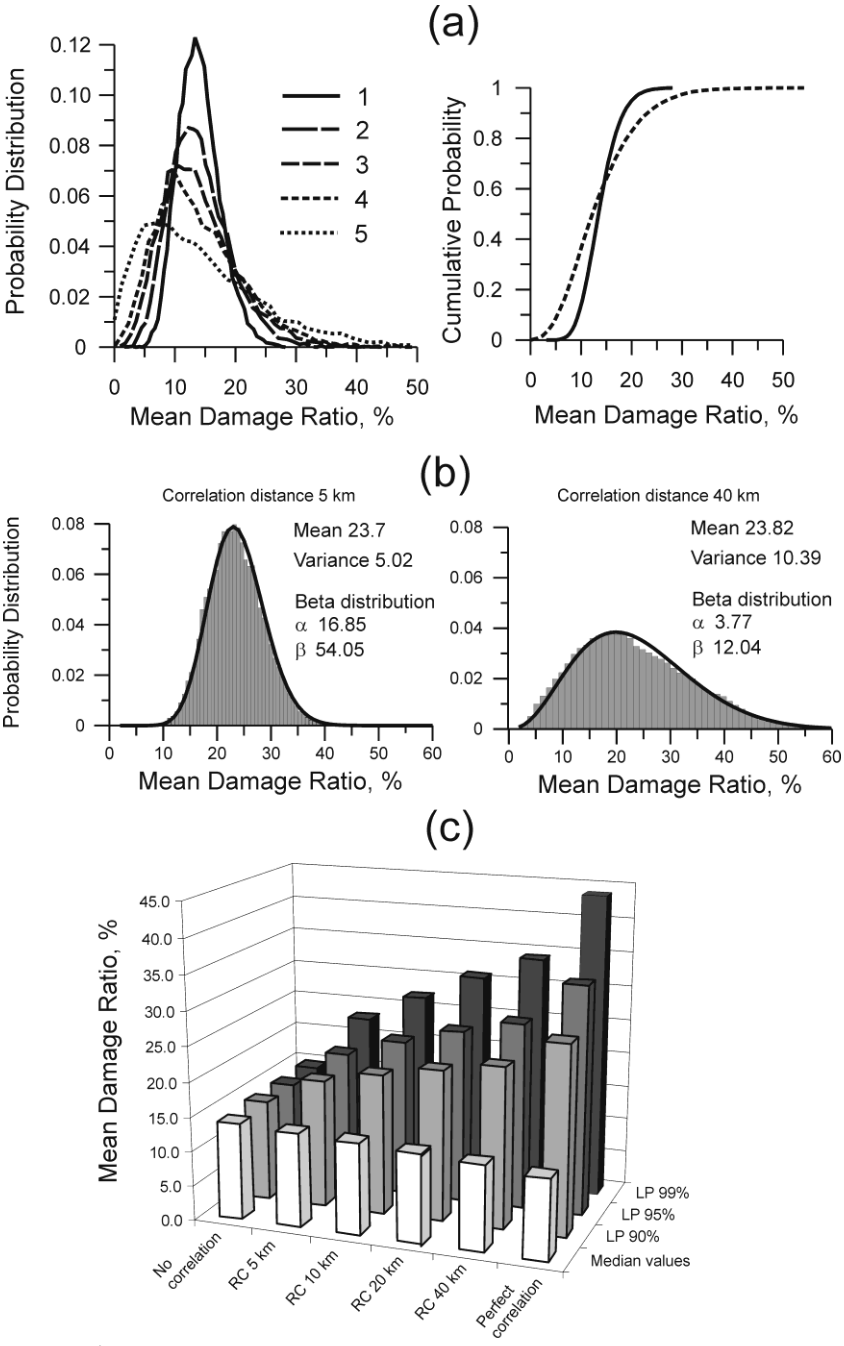

Fig. 6. Influence of within-earthquake correlation on aggregate loss distribution. (a) Examples of probability distribution and cumulative probability functions of loss: 1 – correlation distance R_C 5 km; 2 - R_C 10 km; 3 - R_C 20 km; 4 - R_C 40 km; 5 – perfect correlation. Magnitude 6.0; site model C-S; within-earthquake standard deviation 0.7. (b) Examples of approximation of calculated loss distribution by analytical beta distribution (solid lines). Magnitude 6.5; site model C-S; within-earthquake standard deviation 0.7, different within-earthquake correlation distances R_C, vulnerability class C. (c) Parameters of loss distribution estimated for various within-earthquake correlation distances R_C.

4.3 Selection of within-earthquake correlation model

Let us assume that two portfolios are characterized by different geological conditions, namely: the first portfolio is located in a hilly area mostly on rock covered by firm coarse grained soil and partly on narrow basins with shallow firm sediments (e.g. Black Forest foothills), and the second portfolio - on deep sedimentary basin (e.g. the Upper Rhine basin). Two generalized ground-motion models (site class B-R for the hilly area and site class C-S for the basin, see Fig. 2) with correspondent within-earthquake correlation models should be applied for calculation of losses. However, what correlation model (or models) should be used in this case when a lack of empirical data does not allow analyzing the region-dependent ground-motion correlation?

The models of within-earthquake correlation described in literature (see, for example, Sokolov and Wenzel 2011, for short review, and Sokolov et al. 2010, 2012) are characterized by different rates of decay of correlation with separation distance. Estimations of correlation distances may vary from 1-2 km to 40 (and even more) km. Therefore, it is necessary to consider epistemic uncertainty, which reflects the incomplete knowledge in the input correlation models, and which can be incorporated into probabilistic assessments using the logic tree method.

Fig. 6 compares the results of loss estimation (particular values of loss with certain probability of not being exceeded), which were obtained using extreme models of the within-earthquake correlation, namely: perfect correlation and spatially uncorrelated ground motion. These estimations may be considered as the upper and lower bound estimates, respectively. The absolute difference between the bound estimates may reach tens of percent depending on the level of damage and on the ground-motion variability. Selection of the within-earthquake correlation models, which allow reducing uncertainty and which result in realistic loss estimations, may be performed using recently developed relationships between the correlation and gross geological and local soil characteristics, and earthquake magnitude (Sokolov et al. 2012). First, a “basic” or “most likely” correlation distance is selected using the relationships. Second, several correlation distances around the “basic” distance may be taken into account and the weights for correlation models in the logic tree scheme are assigned inversely proportional to the difference between the “basic” distance and the actual correlation distances in the used models.

The intensity attenuation model, which has been developed by Stromeyer and Grünthal (2009) and which was used in our study for relatively small M_W 5.5 earthquake, does not include, as the input parameters, characteristics of geological and local site conditions. However, the geological characteristics of the area may be taken into account in selection of the within-earthquake correlation model. The correlation distances estimated by Sokolov et al. (2012) for relatively stiff soils in extended hilly area in Taiwan are less than 10 km. At the same time, the correlation distances are even smaller for areas with large spatial variations in thickness of deposits. The thick sediments with relatively soft surface soils are characterized by a higher level of within-earthquake correlation: the estimated values of correlation distance for such areas in Taiwan are about 20 - 30 km depending on geotechnical properties of surface soil. Therefore, in the loss estimations using the SG2009 intensity model we accepted the following parameters of within-earthquake correlation: the basic correlation distance

R_{CB}= 5 km for site class B-R (Black Forest foothills), and R_{CB} = 20 km for site class C-S (the Upper Rhine basin).

The FAS model considers influence of generalized geological conditions on earthquake ground motion (see Fig. 2). Sokolov et al. (2012) showed that empirical correction factors, which take into account local site characteristics (site class or averaged shear-wave velocity for the upper 30 m) and which are used together with correspondent GMPEs for calculation of site-dependent ground motions, would reduce the level of within-earthquake correlation for areas covered by soft sediments. It is reasonable to suppose that the site-dependent FAS model also reduces the correlation for site class C-S.

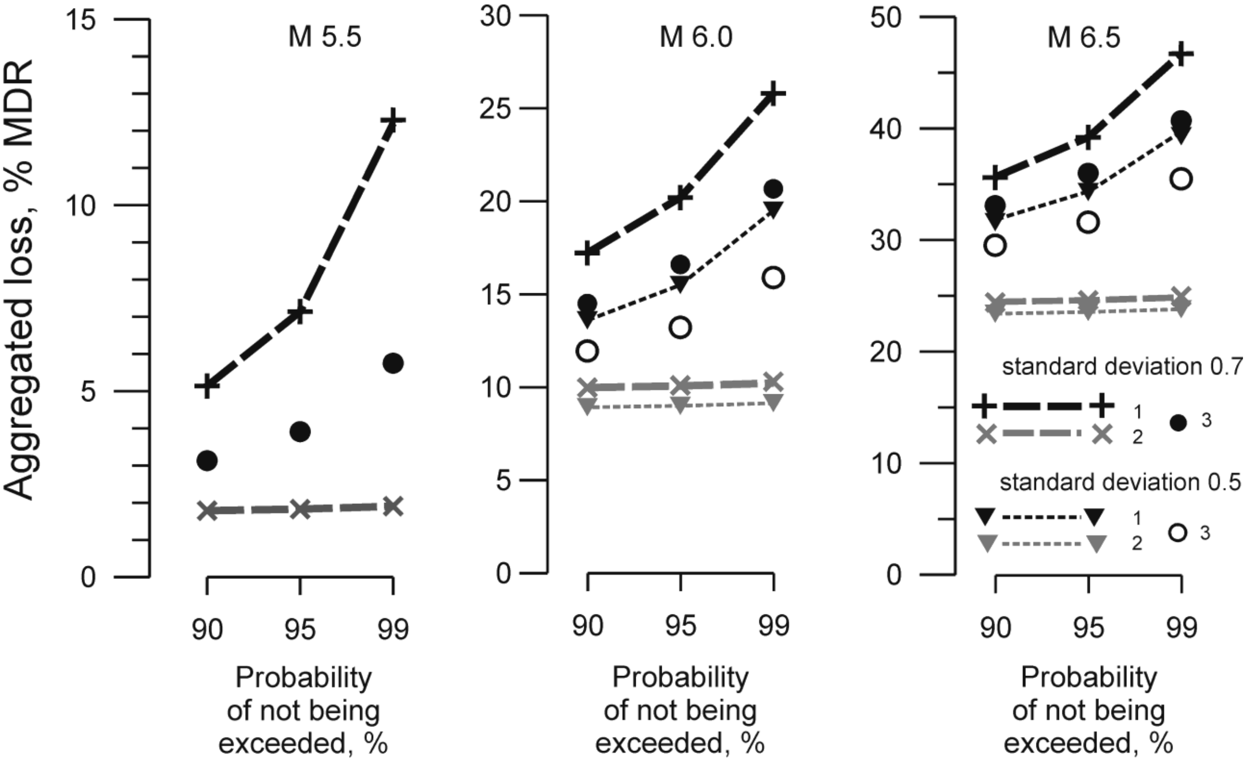

Fig. 6. Estimations of aggregated loss values for different probabilities of not being exceeded using considered scenario earthquakes with magnitudes M_W and two values of ground-motion standard deviation σ_ε. The upper and lower bound estimations, i.e. obtained using the perfectly correlated and spatially uncorrelated ground motions, are marked by crosses (σ_ε = 0.7), triangles (σ_ε = 0.5), and dashed lines (1 – perfect correlation, 2 – no spatial correlation). Circles (3) denote the loss values estimated using the geology-dependent correlation models.

It is necessary also to consider dependence of the within-earthquake correlation on earthquake magnitude – the level of the correlation increases with the increase in magnitude, and the dependence is more prominent for thick sediments. For example, the correlation distances estimated by Sokolov et al. (2012) for the area of thick sediments in Taiwan using the data from intermediate-to-large earthquakes (M_W > 6.0) may vary from 35 km to 60 km depending on properties of surface soil. Similar estimations of correlation distances for the hilly area vary from 10 km to 20 km. Based on the results, in our loss estimations using the FAS model we accepted the following parameters of the within-earthquake correlation: M_W = 6.0, the basic correlation distance R_{CB} = 5 km for site class B-R and R_{CB} = 20 km for site class C-S; M_W = 6.5, R_{CB} = 10 km for site class B-R and R_{CB} = 40 km for site class C-S. Results of application of the selected geology-dependent models of within-earthquake correlation for the loss estimations are shown in Fig. 6 together with correspondent upper- and lower-bound estimates. Note, that only the basic correlation distances were used in these calculations.

4. CONCLUSION

In this paper we analyze influence of within-earthquake variability and correlation on uncertainty in estimation of seismic losses for residential buildings in one of the seismically active regions in Central Europe, which is characterized by the extreme shortage of the observed data, namely – South-Western Germany. A set of the buildings was constructed based on total number and relative percentage of buildings in the urban area that are typical for Germany. The buildings belong to four vulnerability classes and regional intensity-based vulnerability functions were used for estimation of the losses. Two similar portfolios located on different typical geological conditions were considered and three scenario earthquakes were used in our study as the source of seismic influence. Two recently developed ground-motion models were used for calculation of intensity distribution.

The results of the modeling show that consideration of the within-earthquake variability and correlation of ground motion is essential when estimations of the loss distribution are required. Even if only the mean expected loss is the goal of calculation, the within-earthquake variability should be taken into account, and the total loss distribution should be estimated using appropriate (e.g. Monte Carlo) technique with consequent estimations of the distribution mean. Otherwise, estimation of the mean losses, which were obtained using only the mean predicted values of ground motion, should be considered as the lower-bound estimations of mean expected losses. In general, the calculated values of mean loss increase with the increase of within-earthquake standard deviation; however the degree of the increase is not similar for different levels of damage, which in turn depend on earthquake magnitude and location, ground-motion model and vulnerability characteristics of a portfolio.

The within-earthquake correlation causes an asymmetry of loss probability distribution. The degree of skewness depends on the level of damage and the ground motion variability. The lower and upper bound estimations of loss values, i.e. estimations obtained using the uncorrelated and perfectly correlated ground motions, for particular probability of exceedance may differ up to tens of percents in terms of mean damage ratio. The correspondent monetary loss may be very high depending on characteristics of portfolio. Thus, the proper choice of the within-earthquake correlation model is critical in estimations of portfolio loss distribution. The impact of ground-motion variability and within-earthquake correlation should be analyzed in every particular case with correspondent sensitivity analysis. Skipping the ground-motion variability and within-earthquake correlation leads to underestimation of loss.

Selection of the correlation models, which allow reducing uncertainty in the choice and which result in realistic loss estimations, may be performed using the recently developed relationships between the correlation and gross geological and local soil characteristics, and earthquake magnitude (Sokolov et al. 2010, 2012). The scheme of the selection, which applies the logic tree technique, may be the following. First, a “basic” or “most likely” correlation distance is selected using the relationships. Second, several correlation distances around the “basic” distance may be taken into account and the weights for the correlation models in the logic tree scheme are assigned inversely proportional to the difference between the “basic” distance and the actual correlation distances in the used models.

We realize that there are shortcomings in our study. The results should be considered as rather qualitative because of several simplified and arbitrary assumptions related to construction of the portfolios. In practical application requiring the estimation of the absolute values of loss, these assumptions have to be reconsidered. The joint influence of other sources of uncertainty in such calculations, e.g. damage probability distribution for given ground-motion intensity, structure-to-structure loss correlation, uncertainty in replacement cost, etc., have to be taken into account. The assumption should be verified separately.

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