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PROBABILISTIC SEISMIC HAZARD MAPS AND INDIVIDUAL LARGE EARTHQUAKES: “MULTI-SCALE HAZARD” AS A TOOL FOR ESTIMATION OF THE UPPER LEVEL OF GROUND MOTION WITHIN PARTICULAR AREA

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ABSTRACT

In this work we introduced a new product of probabilistic seismic hazard analysis (PSHA) and analyzed potential of the product to improve interpretation of the PSHA results for seismic classification of the territory and to validate PSHA with individual earthquakes. The discussed product is developed using area-based hazard estimations, i.e. annual rate of ground motion level exceedance in at least one site of several sites of interest or within in an area. We call these multiple-site estimations as a “multi-scale” hazard instead of the term “regional hazard” (Iervolino, 2013). Procedures of generation and interpretation of the product are discussed on example of the 2008 Wenchuan (China) M_W 7.9 earthquake occurred on 12 May 2008. We showed that the multi-scale hazard assessment provides reasonable estimations of the upper limit of ground motions, which may occur during the earthquakes, parameters of which are close to maximum possible events

INTRODUCTION

Earthquakes disasters of the 20th century (e.g., the 2004 Aceh-Sumatra M=9.3, 2008 Sichuan M=7.9, 2010 Haiti M=7.0 and 2011 Tohoku M=9.1 earthquakes), which occurred in areas predicted by earthquake hazard maps to be relatively safe, caused extensive discussions related to apparent weakness in current probabilistic seismic hazard assessments (PSHA) (e.g., Stein et al., 2012; Hanks et al., 2012; Stirling 2012; Iervolino, 2013; Wong, 2013; Wyss and Rosset, 2013). There is a mutual agreement that objective testing of PSHA results is necessary to judge the hazard assessment performance. However, the task may be difficult because there are no generally agreed criteria for the judgment (e.g. Stein et al., 2012). On one hand, PSHA considers a multitude of earthquake occurrences and ground motions, and produces an integrated description of seismic hazard representing all events. The predicted PGA corresponding to the total annual probability of exceedance is a statistical measure, and it does not have a clear physical meaning. On the other hand, ground motion record obtained during a single earthquake may be related to any value within a broad range of possible values determined by inherent between-earthquake and within-earthquake variability of ground shaking.

For validation or confirmation of PSHA using observed ground-motion records, a control period of consecutive observations is necessary (e.g., Albarello and D’Amico, 2008; Beauval et al., 2008;

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Miyazawa and Mori, 2009; Stirling and Gerstenberger, 2010; Mezcua et al., 2013; see also a short review in Stein et al., 2012, and discussion in Iervolino, 2013). However, the direct comparison of ground-motion records obtained during a single earthquake with the probabilistic seismic hazard model may allow to understand, whether the model is consistent with observations (e.g. Sokolov et al., 2004; Crowley et al., 2010; Masi et al., 2011). The comparison may result not only in compilation of new hazard maps and consequently in new seismic zonation to be used in building codes, but together with analysis of building damages and collapses, also in revision of the current design requirements (e.g., Chai et al., 2009; Wang, 2010).

In this paper we introduced and discussed a new product of probabilistic seismic hazard, which may allow performing validation of probabilistic seismic hazard with individual earthquakes. The product is based on multiple-site probabilistic hazard (i.e. annual rate of PGA exceedance in at least one site inside a particular area) estimations. Procedures of generation and interpretation of the product are discussed on example of the 2008 Wenchuan (China) M_W 7.9 earthquake occurred on 12 May 2008.

INPUT DATA AND ANALYSIS

The Wenchuan Earthquake and Building Code provisions for the area

The 2008 Wenchuan M_W 7.9 earthquake occurred on 12 May 2008 in the Wenchuan region, Sichuan Province of China, with the epicenter close to the town of Yingxiu (31.0^0 N, 103.4^0 E). The epicentral intensity during the Wenchuan earthquake was estimated to be more than X in Chinese Seismic Intensity scale. The maximum-recorded horizontal ground acceleration exceeded 950 gal (Li et al., 2008). According to official report the number of deaths was estimated as about 70,000 (as of 11 August 2008) and the estimated direct loss is as high as 100 billion US$. The study of damage to different types of constructions erected at different time periods (e.g., Wang, 2008) showed that the most of the buildings that were designed and constructed in the late 1990s according to the Chinese National “Code for Seismic Design of Buildings GBJ 11-89” did not collapse, however, they suffered from severe and moderate damage.

The seismic intensity was used in the CBJ 11-89 code, and the design intensity VI-VIII was assigned for the area affected by the earthquake. The revised version of the code GB 50011-2001 is based on peak acceleration with 10% probability of exceedance in 50 years (return period 475 years) for ground site-class type II (medium-stiff soil). Hereafter the value is referred as PGA_{475}. As provided by the Seismic Ground Motion Parameter Zonation Map of China (GB 18306-2001), the area around the seismogenic source of the Wenchuan earthquake is characterized by PGA_{475} about 0.15 g - 0.2 g. However, after the Wenchuan earthquake the earthquake zoning parameters and seismic design categories have been modified for over 70 cities and counties in Sichuan, Gansu and Shaanxi provinces; for example, PGA_{475} has been increased up to 0.3 g (e.g., Wang, 2010; Chen and Wang, 2010)

Probabilistic seismic hazard analysis

We employ the Monte-Carlo approach in probabilistic seismic hazard assessment (e.g., Musson, 1999; Sokolov and Wenzel, 2011; Assatourians and Atkinson, 2013). This approach is based on generation of a long-duration synthetic earthquake catalog, or which is more convenient, a large number of synthetic earthquake sub-catalogs, for given seismic source parameters (geometry, magnitude recurrence, hypocentral depth). Every synthetic sub-catalog representing a possible variant of seismic process has a specified duration and contains significant number of earthquakes compatible with knowledge about the regional seismicity. The distribution of ground motion for each seismic event in each synthetic sub-catalogue is calculated using specified ground motion prediction equation (GMPE) and correspondent characteristics of ground-motion residuals (between-earthquake and within-earthquake standard deviation and, when necessary, site-to-site correlation). To obtain the hazard curve, i.e. annual frequency of exceedance of each considered ground-motion amplitude level in particular site, it is necessary to count the number of exceedances in the generated ground-motion database and to divide these numbers by the equivalent total duration of the generated seismic process (number of synthetic sub-catalogs x duration of the sub-catalogs).

Procedure of generation of synthetic sub-catalogs for the region has been described in detail elsewhere (Sokolov and Ismail-Zadeh, 2014). Here we note that the necessary input data for probabilistic seismic hazard analysis in the region were collected from several sources, which used (a) the observed seismicity (Bhatia et al., 1999: Nath and Thingbaijam, 2012) and (b) modeled extreme events (Ismail-Zadeh et al., 2007) in the Tibet-Himalayan region. We use the same GMPEs and the logic tree framework as Nath and Thingbaijam (2012; see Table 2 and Fig. 3 in the article) for our seismic hazard computation considering rock and hard-soil conditions. The GMPE were selected by Nath and Thingbaijam (2012) for different tectonic provinces in the region using the suitability testing (e.g., Bommer et al., 2010).

Fig. 1a shows hazard curves, i.e. the annual frequency of exceedance of a given PGA threshold for a point (31.20 N, 103.70 E) located in the epicenteral area of the Wenchuan earthquake; Table 1 lists PGA estimations for different return periods. Two site conditions were considered, namely: rock (average shear wave velocity for the upper 30 m column, Vs_{30} = 1000 m/s) and hard soil (Vs_{30} = 400 m/s). Note that our estimations of the design PGA_{475} values are close to the value assigned for the area after the Wenchuan earthquake (see previous section). It is necessary also to emphasize that the large earthquakes (M > 7.0) in the synthetic catalogues used in our seismic hazard assessment were modeled using the data available in the regions before the Wenchuan earthquake (Ismail-Zadeh et al., 2007).

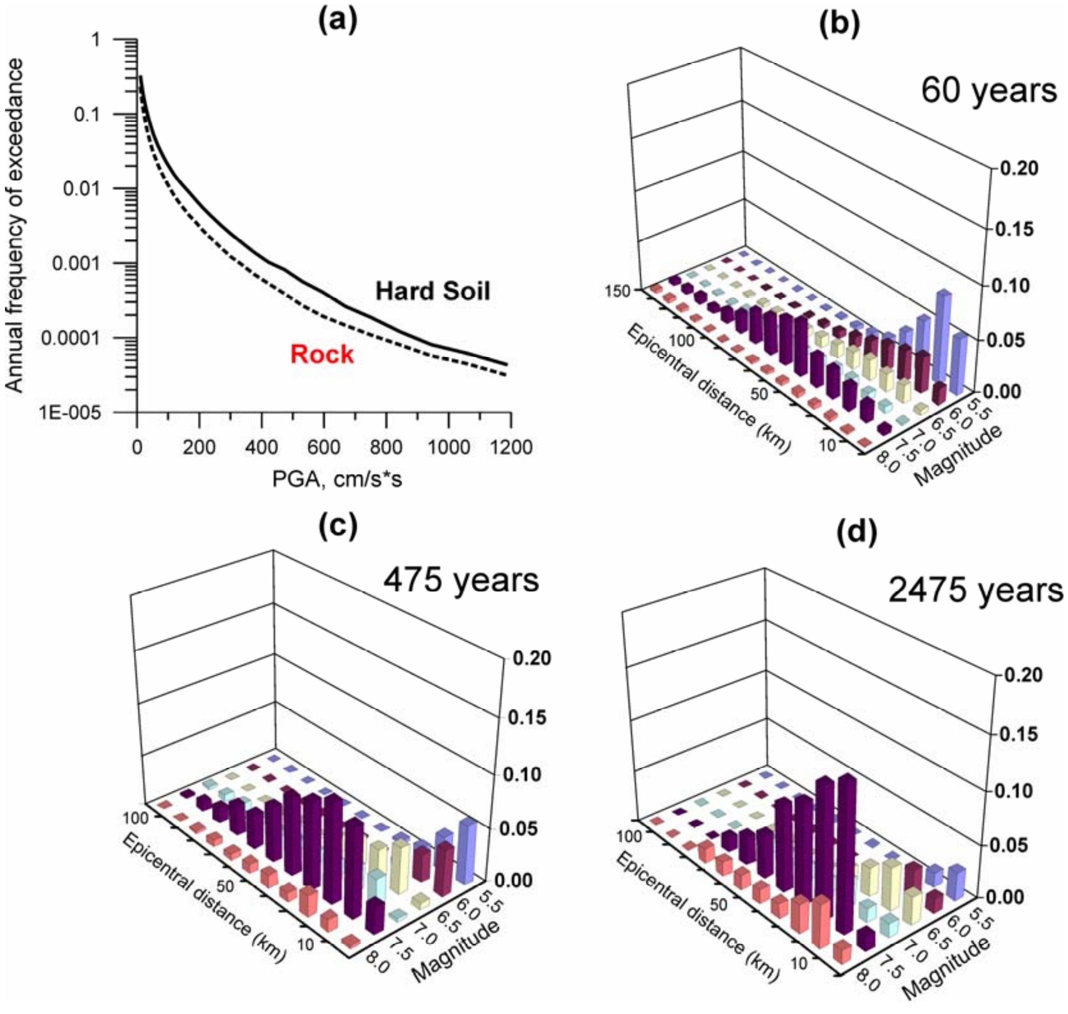

Figure 1. Results of PSHA for epicentral area of the 2008 Wenchuan earthquake (Sokolov and Ismail-Zadeh, 2014). (a) The hazard curves obtained for two generalized types of local site condition. (bcd) The contribution of different magnitude-distance bins to the PGA hazard for different return periods.

Table 1. Results of probabilistic seismic hazard assessment for a point located in the epicentral area of the 2008 Wenchuan earthquake

Site Condition	Return period, years				
	60	475	1000	2475	10000
	PGA, cm/s^2				
Rock	70	240	330	470	750
Hard Soil	100	320	430	600	900

Figures 1b-d show examples of deaggregation calculation for the considered site. As can be seen, earthquakes of magnitude more than 7.0 - 7.25 located at different epicentral distances bring considerable contribution to exceedances, which is comparable with nearby smaller events, even for small return period: in average about 40% of all exceedances for return period 60 years were produced by large magnitude events. Ground motion level for return period 475 years and 2475 years would be much frequently exceeded during nearby earthquakes of magnitude more than 7.0 - 7.25 than by the smaller earthquakes; the relative contribution to hazard, i.e. number of exceedances, from the large events is about 60 % and 70 % correspondingly. Influence of the largest possible events (M > 7.5 – 7.75) becomes important for relatively large return periods: these events bring about 15 % of all exceedances for return period 2475 years. As can be seen, parameters of the Wenchuan earthquake (magnitude M 7.9 and the source location, i.e. epicentral distance less than 30 km) are among the range of those described by the seismic source model accepted in the analysis (Sokolov and Ismail-Zadeh, 2014); the occurred earthquake was not unexpected event or isolated "*black swan*" (see discussion in Stein et al., 2012).

MULTIPLE-SITE HAZARD ANALYSIS

As a rule, the comparison between results of probabilistic seismic hazard assessment and records of real earthquake implies consideration of the highest amplitudes recorded close to earthquake source. These high amplitudes may correspond to relatively high positive values of within-earthquake variability caused by local site effect, peculiarities of rupture propagation, etc. When discussing the problems related to the comparison, Iervolino (2013) suggested considering ground-motion intensity, which has a specific annual rate of exceedance in *at least one* of several sites of interest, and the author called the estimations as "regional hazard". It has been noted, however, that the "regional hazard" estimates would be higher than the results of classical PSHA, and therefore the author was warning against utilization of the estimations for risk evaluation at specific sites. The difference between the standard point-wise hazard estimations and the estimations performed considering several sites, or the "multiple-site" hazard, would depend on number of sites considered (or area of region), characteristics of ground motion variability (GMPE standard deviation, both between-earthquake and within-earthquake components, and ground-motion correlation) (e.g., Rhoades and McVerry, 2001; McVerry et al., 2004; Sokolov and Wenzel, 2011) and level of hazard (Sokolov and Wenzel, 2011).

To analyze the discrepancy between the point-wise and the multiple-site hazard, in our study we calculated multiple-site hazard curves, i.e. annual rate of PGA exceedance in at least one site, for areas of different size (about 10 km^2, 25 km^2, 100 km^2, and 200 km^2) in the epicentral region of the Wenchuan earthquake. We considered a square area, which is located near the epicenter of the Wenchuan earthquake within a zone with intensity more than VIII (center of the area 31.2^0 N, 103.7^0 E). The area was divided into cells with dimension 0.01^0 x 0.01^0 (approximately 1 km x 1 km), and multiple-site hazard was evaluated considering peak acceleration values calculated for the centers of the cells. Only within-earthquake component of ground-motion variability with standard deviation 0.25 units of common logarithm ($\log_{10}$) has been considered.

Five models of within-earthquake correlation were applied assuming various levels of the within-earthquake correlation (correlation distances; see, for example Sokolov and Wenzel, 2013a, for definitions), namely: correlation distances (CD) 0 km; 5 km; 10 km; 20 km, and 40 km. As shown by

Bommer and Crowley (2006), among others, ground-motion variability in the classical (point-wise) Cornell-McGuire PSHA is implicitly assumed to be entirely between-earthquake, i.e. ground motions at different sites are perfectly correlated. However, ground-motion characteristics at separate sites are neither perfectly dependent (perfectly correlated) nor perfectly independent (uncorrelated) (e.g. McGuire, 2004). Therefore, the case of spatially uncorrelated ground motion (CD 0 km), should be considered as an unlikely and extreme case and it has been used here for comparison. Note, that the correlation distance of 40 km is not an unlikely value - the correlation distances estimated for the area of thick sediments in Taiwan and Japan 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 (Sokolov et al., 2012; Sokolov and Wenzel, 2013b).

Influence of the size of considered areas and the level of within-earthquake correlation on multiple-site hazard for different return periods is shown in Fig. 2. Distribution of PGA values (geometric mean of the horizontal components) recorded in epicentral area of the Wenchuan earthquake and the result of point-wise classical probabilistic estimation ($PGA_{475} \approx 300$ cm/s^2), is also shown in the figure. It is seen that the greater the area and the lower level of within-earthquake correlation (i.e. the smaller correlation distances), the greater the difference between the hazard estimates for individual sites and the multiple-site hazard. Estimates of ground-motion level, which will be exceeded in at least one site within the relatively small territory (10 km^2 – 25 km^2), obtained for return period 475 years and correlation distances less than 20 km are larger than the most of recorded peak amplitudes. The estimates for the relatively large territory (more than 100 km^2) are comparable (and even higher) with the highest recorded peak amplitudes. Note that a 100 km^2 area is suggested by Malhotra (2007) for estimation of so-called “aggregate risk” (i.e. risk to multiple locations) to be considered for seismic design load.

The multiple-site hazard estimations performed in our study did not take into account possible near-fault effects (e.g. directivity), which may increase level of high-frequency radiation and result to the higher PGA values. However, the effects are indirectly considered when applying models with low levels of ground-motion correlation, which allow large difference between values of ground-motion variations for neighboring sites.

CONCLUSIONS

In this work we introduced a new product of probabilistic seismic hazard analysis and analyzed potential of the product to improve interpretation of the PSHA results for seismic classification of the territory for needs of seismic design, estimation of seismic loss and risk assessment. The product is developed using area-based hazard estimations, i.e. annual rate of PGA exceedance in at least one site of several sites of interest or within in an area. We call these multiple-site estimations as a “multi-scale” hazard instead of the term “regional hazard” (Iervolino, 2013). On example of the 2008 Wenchuan earthquake we have shown that the multi-scale hazard assessment, when being performed for standard return period 475 years even for relatively small areas (e.g., territory of industrial development or a city district, size of area about 10 km^2 – 25 km^2), provides reasonable estimations of the upper limit of possible ground motions. Consideration of the larger areas (e.g. area of a city or large district of a city, more than 100 km^2), as well as low level of the within-earthquake correlation, allows estimating the worst case ground motion, i.e. high-amplitude ground motion resulted from peculiarities of rupture propagation along the extended earthquake source and local site effect with high amplification.

Depending on the considered area, the term “town-scale”, “district-scale”, or “city-scale hazard” may be used. We believe that the multi-scale hazard estimations are extremely useful for analysis of damage for critical elements of lifelines (e.g., hospitals, bridges, electrical substations, gas and water supply stations, etc.) located along large territories and for analysis of lifelines performance. Such estimations, together with standard point-wise assessments, may be performed using Monte-Carlo approach and considering between-earthquake and within-earthquake variability of ground shaking for urban or industrial areas, or zones of particular economic and social importance. The suitable models of ground-motion correlation may be selected on the basis of regional and local geological conditions and event magnitude (Sokolov et al., 2012; Sokolov and Wenzel, 2013b).

Note that our assessments were obtained for the case of a single earthquake. Analysis of other large earthquakes, which occurred in regions with recent PSHA and which provided strong-motion data (e.g., the 2009 L'Aquila M_L 6.3 earthquake and the 2011 Christchurch M_L 6.3 earthquake), are the task of future research.

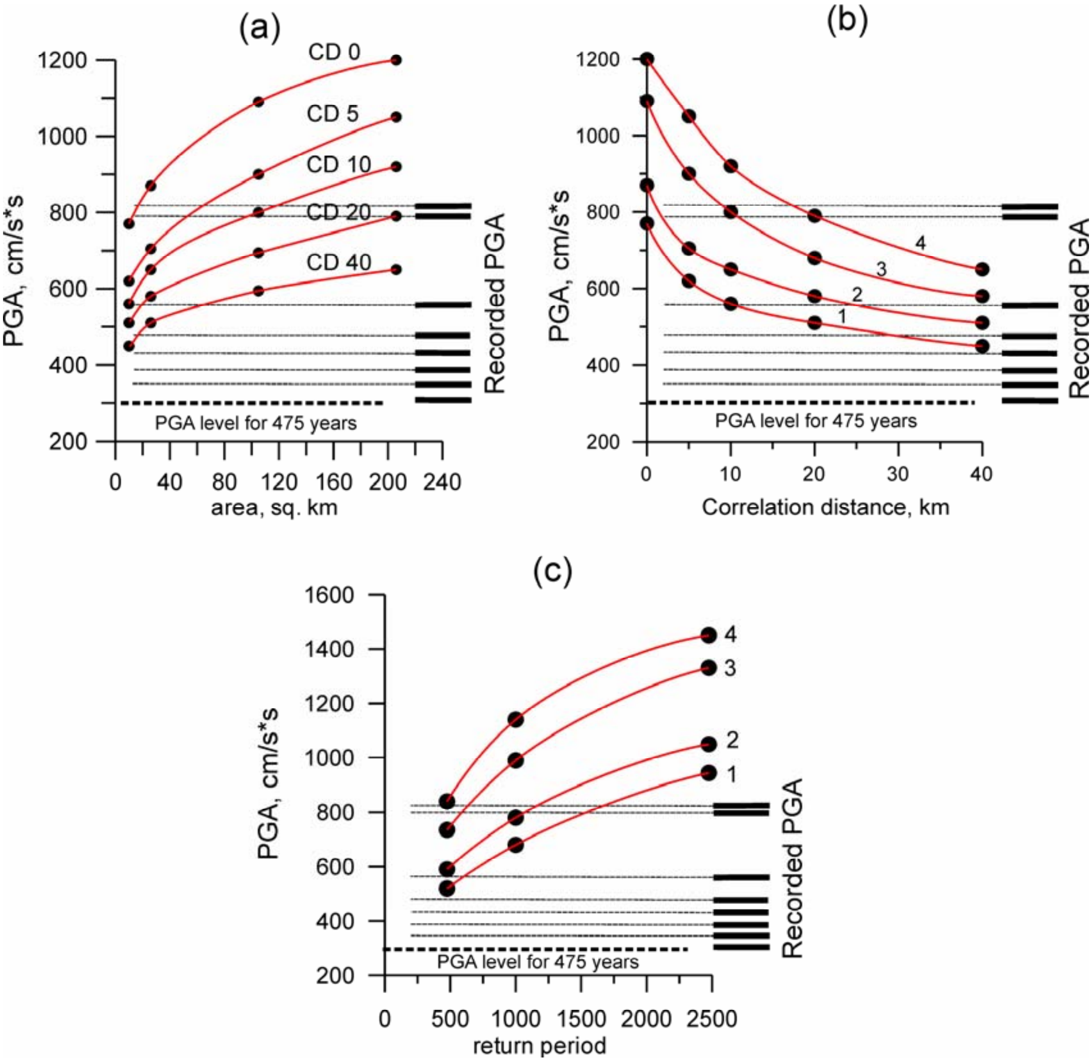

Figure 2. Estimations of multiple-site hazard PGA_{MSH}, i.e. PGA exceeded in at least one point within particular area, and comparison of the estimations with distribution of peak accelerations (geometric mean of the horizontal components, thick short segments in the right side of graph) recorded in epicentral area of the Wenchuan earthquake (Li et al., 2008). Black dots show individual estimations of PGA_{MSH} values and curves denote the spline interpolation between the estimations. (a) Multiple-site hazard estimated for return period 475 years and different within-earthquake correlation models (correlation distances, CD, 0 km, 5 km, 10 km, 20 km, and 40 km), dependence on the size of area. (b) Multiple-site hazard estimated for return period 475 years and different size of area 10 km^2 (1), 25 km^2 (2), 100 km^2 (3), and 200 km^2 (4), dependence on the within-earthquake correlation distance (c) Multiple-site hazard estimated for within-earthquake correlation CD=10 km, and various sizes of area 10 km^2 (1), 25 km^2 (2), 100 km^2 (3), and 200 km^2 (4), dependence on return period.

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