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OPERATIONAL-ORIENTED EXTREME GROUND-MOTION HAZARD SCENARIOS FOR CRITICAL INFRASTRUCTURES

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ABSTRACT

Among extreme natural hazards, earthquakes represent a major threat as sudden-onset events with limited, if any, capability of forecast, and high damage potential that could induce significant disruption to critical infrastructure (CI) networks. Seismic performance level and resilience of CIs can be analyzed by identifying the ground motions leading to failure of selected key elements. Main interest focuses on those exceeding the original design, which should correspond to low probability occurrence. A specific hazard methodology, based on Monte Carlo simulation, has been developed for low probability ground motions affecting CI networks. Through this approach, a representation of maximum amplitudes that follow a general extreme-value distribution can be obtained. This facilitates the analysis of the occurrence of extremes, i.e., very low probability of exceedance from unlikely combinations, for the development, among others, of stress tests. Extreme ground-motion scenarios have been developed for selected combinations of modelling inputs including seismic activity models (source model and magnitude-recurrence relationship), ground motion models (GMM), hazard levels, and fractiles of extreme ground motion. This approach to seismic hazard is at the core of the risk analysis procedure developed and applied to European CI transport networks within the framework of the European-funded INFRARISK project. Such an operational seismic hazard framework can be used to provide insight in a timely manner to make informed risk management or regulation of further decisions on the required level of detail or on the adoption of measures, the cost of which can be balanced against the benefits of the measures in question.

Keywords: Seismic Hazard; Earthquake Scenarios; Extreme Ground-Motion; Critical Infrastructures; Risk Management

1. INTRODUCTION

Concentration of high value assets and critical infrastructures (CIs) in vulnerable areas, increase the potential for severe and widespread impacts of rare but devastating and very high impact natural hazards. These events affect the well-being and security of society, but also can induce significant disruption of the economy with special impact on CIs, causing severe loss of function. Among them, earthquakes represent a major threat as sudden-onset events with limited, if any, capability of forecast, and high damage potential. CI failures depend not only on the particular event but also on the primary failure type of an infrastructure element or system, which could lead to cascading failures in local and regional interdependent systems.

Tools and methodologies for risk modeling and simulation are of great importance for owners, operators, and regulators of CIs. In most cases, available tools represent efforts tailored to the needs of a particular asset/region/state, lacking the features to be used on extended regions throughout Europe and as a consequence, lack the capability to scale to international level (EC 2014). In these cases, an operational assessment approach may provide sufficient insight in a timely manner to make informed risk management or regulating decisions for the application of more detailed risks analysis.

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We propose an operational-oriented approach to seismic hazard assessment specifically developed to consider low-probability extreme earthquake ground motions, which is directly applicable for extended linear infrastructures in regions in Europe (García-Fernández et al. 2018).

The approach is implemented through an improved version of the EqHaz suite of Assatourians and Atkinson (2013), and it is based on Monte Carlo simulation techniques, which have some advantages over conventional Probabilistic Seismic Hazard Analysis (PSHA): It has a more transparent procedure that facilitates the identification of events that contribute more to target amplitude levels (deaggregation at any probability level), and a more powerful and flexible handling of uncertainties, with a straightforward link with probabilistic risk analysis, where Monte Carlo simulation is a common tool (e.g., Musson 1999, 2000, 2012; Crowley and Bommer 2006; Hong et al. 2006; Shiraki et al. 2007; Atkinson and Goda 2013).

2. METHODOLOGY

In general, PSHA is performed using a single set of source zones, either areal (polygon) or fault source (line segments and dip), each of which is associated to a magnitude-recurrence relationship truncated at a maximum magnitude value (M_{max}). Expected ground motion amplitudes (PGA or spectral acceleration) are characterized by a set of ground motion models (GMM), with prescribed aleatory variability (sigma) and epistemic uncertainties, as a function of magnitude and distance, for some reference local site condition.

The EqHaz code we use, allows for modeling both epistemic and aleatory uncertainty in the input parameters separately (traditional approach to uncertainty); or, alternatively, treat them as equivalent (blended approach), which enables the treatment of ground motions using extreme-value statistics. We apply the second option in our implementation, first because the distinction between epistemic and aleatory uncertainty is not always clear (Atkinson 2011; Bommer et al. 2005; Bommer and Scherbaum 2008), and second, and most important, because it facilitates the analysis of the occurrence of extreme ground motions from unlikely parameter combinations (i.e. low-probability ground motion amplitudes). Regardless of the modeling of uncertainties, the mean hazard will be the same if the total uncertainty has been correctly estimated (Atkinson 2011). EqHaz is addressing PSHA for a single site, or a grid of sites, using three sequential programs: EqHaz1, EqHaz2, and EqHaz3.

EqHaz1 uses a source zone model and the seismic activity parameters (i.e., magnitude-recurrence relationships, focal depths, and maximum magnitude) to randomly generate a synthetic earthquake catalog for events greater than a minimum magnitude of interest M_{min}. EqHaz2 calculates expected ground motion amplitudes at the site and produces a catalog of ground motions and a mean hazard curve, using selected sets of GMMs. Aleatory variability is modeled by multiplying the GMM sigma by a random number (epsilon) drawn from the standard normal distribution and adding the value to the median log ground motions. EqHaz3 compiles statistics on maximum-amplitude values for a given set of hazard levels, along with information on motions that exceed the mean hazard amplitude and provides a table of fractiles of maximum motions with specified hazard levels, which is a core issue in the developed application.

The developed approach generates extreme-motion deterministic hazard scenarios by extracting the set of parameters that produce the extreme motion associated with a specific fractile (e.g., 90th percentile) and hazard level (e.g., 10^{-4}) at a selected site, and apply the same parameters for calculating the ground motion in a grid of points covering a defined area. This way, the generated deterministic scenario is consistent with the hazard level and fractile of extremes at the reference site.

In our application, seismic activity models (source model and magnitude-recurrence relationship) are derived from the area source model used in the European SHARE project (Woessner et al. 2015). Ground motion modeling is implemented through the Western North America (Wcrust) and Eastern

North America (ENA) three-branch GMM developed by Atkinson and Adams (2013) for the 2015 edition of the National Building Code of Canada. Hazard levels of 4×10^{-4}, 2×10^{-4}, and 10^{-4} per year (annual probability of ground motion exceedance) are considered, with 50th, 75th, and 90th percentiles of extreme ground motions.

Figure 1a is a sample PGA scenario developed following the above assumptions. The ground motion values show an isotropic distribution corresponding to the GMM applied. In real earthquakes, the contour lines of ground motion amplitudes are usually anisotropic due to the GMM intra-event spatial variability, which represents individual scattering at different sites due to different propagation paths and local site conditions (e.g., Goda and Hong 2008; Wagener et al. 2016). Jayaram and Baker (2008, 2009) showed that spatially distributed intra-event components of log of observed to predicted ratios of ground motions (intra-event residuals) can well be represented by the multivariate normal distribution.

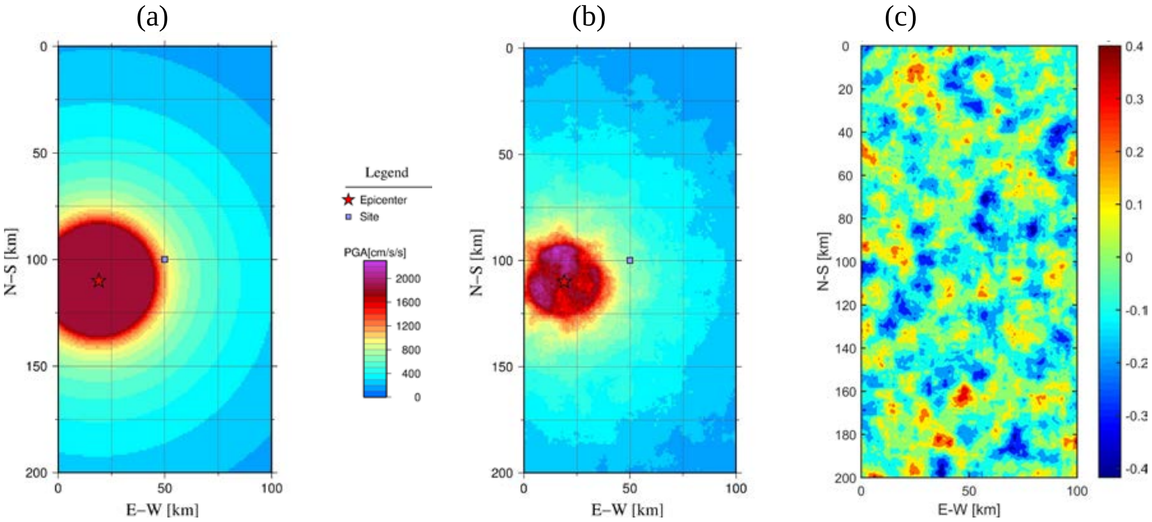

Figure 1. (a) Sample PGA map for 90th percentile extreme motions of 10,000-year block without applying spatial variability in the modeling. (b) Same as left panel but spatial variability/correlation is applied. (c) Two-dimensional Gaussian random field used for modifying Fig. 1a to Fig. 1b

We introduced an additional spatial random variability to the ground motion scenarios with the purpose of breaking the symmetry that would result from direct implementation of GMMs, while we maintain the degree of spatial correlation expected from Jayaram and Baker (2009). For generating two-dimensional random fields, we followed the approach of running a moving average disk of adjustable size over an equally-spaced grid of white noise matching the grid points of the defined scenario area. Then, we add the epsilon of the earthquake ground motion at the reference site to this random field to generate an epsilon field (or map) to be applied to the median ground motion map. This approach is run10,000 times with 5-km disk radius. From 32 realizations of Gaussian fields out of 10,000, which resulted in a very low value for the central grid point (reference site), 18 with near zero value (actually less than 2% distortion) are picked for this study. Figure 1b shows a modified version of Figure 1a after a realization of spatial variability is applied, using the Gaussian random field in Figure 1c.

3. MODELLING PARAMETERS

For implementing the proposed method in an end-user decision support tool, considering its operational-oriented character, we developed a generic application example, which includes a single rectangular seismic areal source of 400 km × 500 km with an elongated hazard region of 100 km × 200 km (simulating the location of a linear transportation network) centered inside (Figure 2). Extreme PGA hazard maps are calculated for this hazard region with a regular grid of 1-km spacing (20,301 sites), having a reference site at its center (Figure 2).

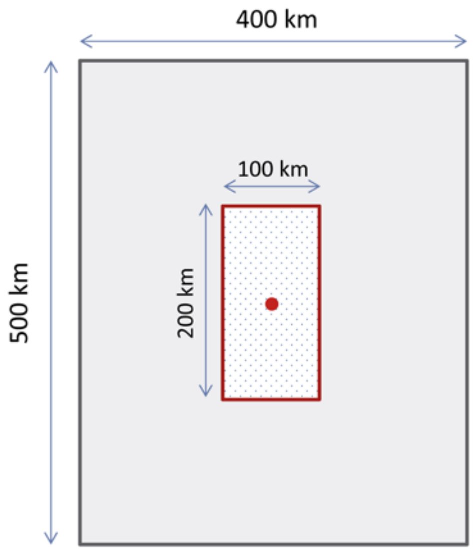

Figure 2. Single areal source of 400 km × 500 km, and hazard region of 100 km × 200 km. The red dot is the location of the reference site in the center of the hazard region. Extreme motion hazard is calculated for the reference site and associated ground-motions are calculated for the entire hazard region (grid of 1-km spacing)

The seismic activity of the single source is modeled by simplified representative models (Table 1) built upon the areal sources of the European SHARE project (Woessner et al., 2015). The SHARE model was selected because it is the most recent compilation and updated model of seismic sources at European scale.

Table 1. Representative seismic activity models, parameters and associated weights (based on SHARE areal source model). **N_0/year**: number of earthquakes with $M \geq 0$ per year in the 400 km × 500 km source area; **β**: beta parameter of the recurrence relation; **z**: focal depth; **M_{max}**: maximum magnitude.

Seismic Activity Model (*SHARE regime*)	**N_0/year; β [*weight*]**	**z(km) [*weight*]**	**M_{max} [*weight*]**
High (*SHARE_Active*)	28571; 1.95 [*0.10*] 28571; 2.30 [*0.60*] 107143; 2.00 [*0.10*] 107143; 2.30 [*0.10*] 214286; 2.30 [*0.10*]	2.5 [*0.10*] 10.0 [*0.40*] 18.0 [*0.50*]	7.00 [*0.50*] 7.20 [*0.20*] 7.40 [*0.20*] 8.00 [*0.10*]
Moderate (*SHARE_SCR-Ext*)	143; 2.150 [*0.15*] 2857; 2.303 [*0.85*]	uniform: 2-22	6.50 [*0.50*] 6.70 [*0.20*] 6.90 [*0.20*] 7.10 [*0.10*]
Moderate-to-low (*SHARE_SCR-NoExt*)	214; 2.30 [*0.50*] 2143; 2.30 [*0.50*]	uniform: 2-26	6.50 [*0.50*] 6.75 [*0.20*] 6.95 [*0.20*] 7.20 [*0.10*]
Low (*SHARE_SCR-Shield*)	264; 2.30 [*0.75*] 514; 2.30 [*0.25*]	uniform: 30-35	6.50 [*0.50*] 6.70 [*0.20*] 6.90 [*0.20*] 7.10 [*0.10*]

Two sets of the Atkinson and Adams (2013) GMMs developed for Canada are implemented in our approach: ENA (Eastern North America) and Wcrust (Western North America), to represent low- and high-attenuation models for crustal seismicity, respectively. Each set is composed of three weighted GMM sub-models or branches, lower, central, and upper, which account for epistemic uncertainty in our approach.

We followed Geological Survey of Canada's implementation of ENA GMMs for hazard analyses (Halchuk et al. 2014) for assigning weights of 0.20, 0.50, and 0.30 for lower, central, and upper branches, respectively, in the ENA GMM. The original Atkinson and Adams (2013) recommended weights of 0.25, 0.50, and 0.25 for lower, central, and upper sub-model, respectively, are used in the Wcrust GMM. The implemented GMMs provide ground motions for NEHRP B/C site class (i.e., V_{S30} = 760 m/s).

4. HAZARD SCENARIOS

In this application, example hazard scenarios are calculated for three hazard levels: 4×10^{-4}, 2×10^{-4}, and 10^{-4} per year; and for three fractiles of extremes: 0.50, 0.75, and 0.90. Several tests were performed to identify minimum duration of synthetic catalogs and maximum value of minimum magnitude, M_{min}, above the M4.0 threshold of engineering interest, for reducing computing time and memory allocation, and still ensuring that the catalog sampling is sufficient for producing reliable and stable results. Selecting 3-Myr catalogs with M_{min}=5.0, guarantee reliable results of controllable size with reasonable computing times and memory allocation.

Considering all possible combinations of the four activity models, two GMMs, three hazard levels, and three fractiles of extreme ground motion, up to 72 extreme-motion hazard scenarios are generated. It is clear that some of them could not be a realistic representation of the ground motions from real earthquakes (e.g., the structure and rheology in regions of high seismic activity does not usually favor low attenuation models of ground motion).

Using the selected 18 two-dimensional random fields with near zero value at the reference site for modifying randomly the original ground motion scenarios, a final set of 1296 extreme-motion hazard deterministic scenarios is obtained. As an example, Figure 3 shows the 0.90 fractile PGA scenarios with different activity models at 10^{-4} hazard level, using Wcrust GMM. Because the High model (SHARE_Active in Table 1) is way more active than the other three, the color scale is enlarged for this scenario.

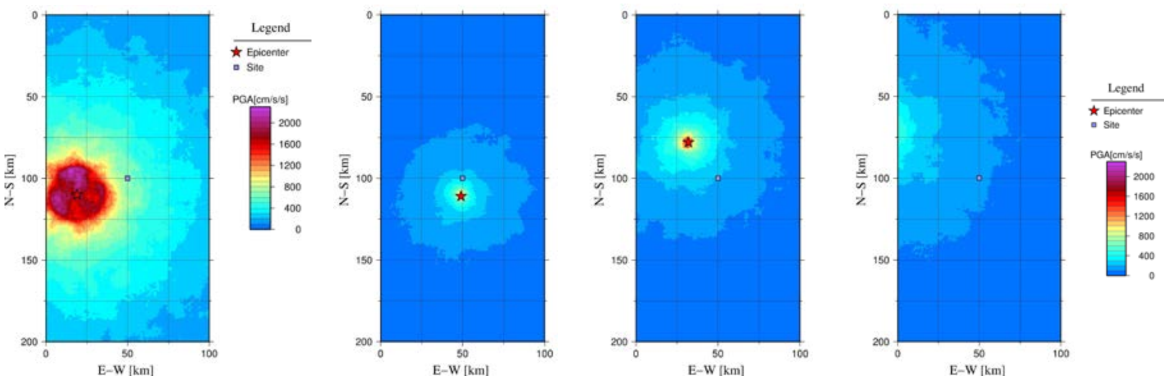

Figure 3. The 0.90 fractile extreme PGA hazard scenarios at 10^{-4} hazard level implementing the Wcrust GMM and the four seismic activity models. From left to rigth: High (SHARE_Active), Moderate (SHARE_SCR-Ext), Moderate-to-low (SHARE_SCR-NoExt), and Low (SHARE_SCR-Shield)

5. CONCLUSIONS

This paper describes a seismic hazard approach that has been developed to obtain low-probability extreme ground motions affecting critical transport infrastructure networks by generating extreme ground-motion scenarios for selected combinations of modeling inputs (García-Fernández et al. 2018). The approach is not intended to be substitutive of any specific hazard assessment with the required level of detail but rather constitutes an application-oriented option to seismic hazard assessment especially suited as a first stage in the risk analysis for more informed decision making when it comes to the evaluation of risk associated to low probability seismic hazard.

In the application example, the approach uses four seismic activity models derived from the European SHARE project (Woessner et al. 2015); two GMMs (Atkinson and Adams 2013) representing high and low attenuation, which account for epistemic uncertainty by including three branches (upper, central, and lower); three hazard levels; and three percentiles of extreme ground motion. Intra-event spatial variability is introduced by generating two-dimensional random fields and selecting those that result in near-zero value at the central grid point of reference.

Among the advantages in the application is the use of Monte Carlo simulation techniques which provides a more transparent and flexible procedure than conventional PSHA; allowing for handling low-probability ground motion amplitudes, as well as the generation of extreme ground motion deterministic scenarios for selected probability levels.

The different hazard deterministic scenarios can be compared and combined and the resulting risk scenarios assessed (according to a given risk metric) leading to a ranking and prioritization process to meet what may be considered a tolerable level of risk affecting the most critical elements in the infrastructure.

Two key aspects of the approach to emphasize are those in relation to its potential to improve risk management of infrastructures. First, it can be easily implemented as the first step in an operational analysis framework contributing to prioritize actions according to both resources and expected impact and at the same time, it increases the capacity at stakeholder level (regulators, managers, operators, etc.) aiding in the decision-making process and in the design of the most appropriate strategies. Second, it constitutes a robust first approximation to risk modeling and to the identification of weak elements in CI transportation networks. More detailed hazard scenarios can be then produced using region-specific parameters in the seismic source and GMMs. The approach is flexible enough to be adapted to different types of CIs, and it can be further modified for implementing alternative hazard models to generate deterministic scenarios.

The approach has been demonstrated through the implementation of the seismic hazard model derived in the described application example in a decision support tool. The final set of 1296 extreme-motion hazard generic deterministic scenarios have been implemented as a hazard model database in the INFRARISK Decision Support Tool, IDST (https://infrarisk.it-innovation.soton.ac.uk/), which is an online tool, developed within the framework of the European INFRARISK project ("Novel Indicators for identifying critical INFRAstructure at RISK from natural hazards") and aiming at assessing the risks to CI networks due to extreme natural hazard events, by analyzing their seismic performance level and resilience, and for further developing stress tests.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Assatourians K, Atkinson G (2013). EqHaz: An open-source probabilistic seismic –hazard code based on the Monte Carlo simulation approach. *Seismol Res Lett* 84(3): 516-524.

Atkinson G, Adams J (2013) Ground motion prediction equations for application to the 2015 Canadian national seismic hazard maps. *Can J Civ Eng* 40 (10): 988-998.

Atkinson G, Goda K (2013). Probabilistic seismic hazard analysis of civil infrastructure. In: Tesfamariam S, Goda K (eds) Handbook of Seismic Risk Analysis and Management of Civil Infrastructure Systems. Woodhead Publishing Ltd, Cambridge, pp 3-28.

Crowley H, Bommer JJ (2006) Modelling Seismic Hazard in Earthquake Loss Models with Spatially Distributed Exposure. *Bull Earthquake Eng* 4(3): 249–273.

EC (2014). Risk Assessment Methodologies for Critical Infrastructure Protection: Part II. A New Approach. European Commission Technical Report EUR 27332, 28 pp. ISBN 978-92-79-49246-4.

García-Fernández M, Assatourians K, Jiménez MJ (2018) An operational-oriented approach to the assessment of low probability seismic ground motions for critical infrastructures. *J Seismol* 22(1):123–136.

Goda, K, Hong HP (2008) Spatial correlation of peak ground motions and response spectra. *Bull Seismol Soc Am* 98(1): 354–365.

Hong HP, Goda K, Davenport AG (2006) Seismic hazard analysis: a comparative study. *Can J Civ Eng* 33(9): 1156-1171.

Jayaram N, Baker JW (2008) Statistical tests of the joint distribution of spectral acceleration values. *Bull Seismol Soc Am* 98(5): 2231-2243.

Jayaram N, Baker JW (2009) Correlation model for spatially-distributed ground-motion intensities. *Earthquake Eng Struct Dyn* 38(15): 1687-1708.

Musson RMW (1999) Determination of Design Earthquakes in Seismic Hazard Analysis Through Monte Carlo Simulation, *J Earthquake Eng* 3: 463-474.

Musson RMW (2000) The use of Monte Carlo simulations for seismic hazard assessment in the U.K. *Ann Geofisc* 43: 1–9.

Musson RMW (2012) PSHA validated by quasi observational means. *Seismol Res Lett* 83: 130–134.

Shiraki N, Shinozuka M, Moore II JE, Chang SE, Kameda H, Tanaka S (2007) System Risk Curves: Probabilistic Performance Scenarios for Highway Networks Subject to Earthquake Damage. *J Infrastruct Syst* 213(1): 43–54.

Wagener T, Goda K, Erdik M, Daniell J, Wenzel F (2016) A spatial correlation model of peak ground acceleration and response spectra based on data of the Istanbul Earthquake Rapid Response and Early Warning System. *Soil Dyn Earthq Eng* 85: 166-178.

Woessner J, Danciu L, Giardini D, Crowley H, Cotton F, Grünthal G, Valensise G, Arvidsson R, Basili R, Demircioglu MN, Hiemer S, Meletti C, Musson RMW, Rovida AN, Sesetyan K, Stucchi M, the SHARE consortium (2015) The 2013 European Seismic Hazard Model: key components and results. *Bull Earthq Eng* 13: 3553-3596.