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IMPACT OF TIME-DEPENDENT HAZARD MODELLING ON PORTFOLIO LOSS ASSESSMENT

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Abstract: *The homogeneous Poisson process (HPP), which is a memoryless model, is a commonly used model for representing earthquake recurrence in the case of area-source models. However, when a single fault is of concern, time-dependent models, accounting for the time elapsed since the last event* $\left(t_e\right)$*, may be more appropriate. The aim of this study is to quantify the impact of time-dependent hazard modelling on seismic loss estimates for a case-study reinforced concrete (RC) building portfolio. Five case-study faults are used for estimating probabilistic seismic hazard in terms of spectral ordinates as a function of* t_e *using a simulation-based procedure. The considered fault parameters are representative of those characterizing actual faults in Central Italy. Both the Brownian Passage-Time (BPT) and the HPP models are considered for characterizing earthquake recurrence on these faults. Expected seismic losses are estimated by using a catastrophe modelling approach for a synthetic building portfolio located close to each case-study fault. A typical exposure for Italy, consisting of mid-rise RC buildings belonging to three vulnerability classes (i.e., Pre-code, Low-code, and Special-code), is considered. The vulnerability model is built by combining analytical fragility curves for each considered vulnerability class with a damage-to-loss model specifically calibrated for Italy. Results from this study show that the expected losses obtained using a BPT model can be more than twice the ones predicted by the HPP model, when the fault is 'overdue', i.e., when the time elapsed since the last event is large in comparison with the mean recurrence period of the fault. On the other hand, if the time elapsed since the last event is about half of the mean recurrence time of the fault, the BPT model leads to similar results to the HPP model.*

Introduction and motivations

The homogeneous Poisson process (HPP) is the most used approach to model earthquake recurrence in Probabilistic Seismic Hazard Analysis (PSHA) and seismic risk assessment, particularly when several (independent) sources contribute to the seismic threat for a given site. It assumes that the occurrence of events is independent of the number of past events and that the probability of occurrence only depends on the size of the time window, thus representing a memoryless process (e.g., Convertito and Faenza, 2014). However, historical data seems to suggest that the recurrence of earthquakes on a specific fault is not a memoryless process, generally depending on the time elapsed since the last event, t_e.

Very few studies have quantified the impact on expected seismic losses when considering time-dependent models for PSHA (e.g., Williams et al., 2008; Papadopoulos and Bazzurro, 2018). Therefore, there is a lack of information on how the different modelling assumptions could affect the estimated losses for building portfolios. This issue is investigated here.

Developing and providing guidance on improved methodologies for risk assessments (for both natural and man-made single and multiple hazard) is one of the objectives of the Sendai Framework for Disaster Risk Reduction 2015-2030 (UNDRR, 2015). Hence, improved earthquake risk modelling can in turn support managing and reducing seismic risk, a significant challenge for various stakeholders (e.g., governments, (re)insurance) aiming to achieve seismic resilience.

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Methodology

To assess the impact of different modelling assumptions regarding earthquake recurrence on seismic risk estimates, five case-study faults, representative of actual faults in Central Italy in terms of their characterizing parameters, are used here. The time-dependency of characteristic earthquakes on each considered fault is modelled using a BPT model (e.g., Convertito and Faenza, 2014); the results from the analysis are compared with those obtained using the HPP model. It is worth noting that the long-term mainshock occurrence is considered here, neglecting other cases as the short-term aftershock sequence modeling.

The BPT model, as proposed by Matthews, Ellsworth and Reasenberg (2002), considers a two-parameter Inverse Gaussian distribution for modelling the inter-arrival time, T , between earthquakes; the two parameters are the mean recurrence time (also referred to as the *return period*), usually denoted with T_{mean}, and the aperiodicity α, which is the shape parameter. The aperiodicity is the coefficient of variation (CoV) of the distribution, i.e., $\alpha = {}^{\sigma_T}\!/_{T_{mean}}$, where σ_T is the standard deviation of T. The hazard function associated to this distribution (i.e., frequency with which earthquakes occur) shows that the probability of having an earthquake is essentially zero at the beginning of the cycle (soon after an earthquake), then it increases until it reaches a maximum near T_{mean}, and finally decreases asymptotically to a constant value that depends on the fault (e.g., Convertito and Faenza, 2014). This means that the probability of occurrence becomes time-independent when the time since the last event is large. Moreover, the mode of the distribution is located to the left of T_{mean}, implying that it is more likely to have events with lower inter-arrival time than the mean recurrence time.

To estimate the seismic hazard due to a characteristic earthquake of a single fault (i.e., when the considered source may produce a specific magnitude; e.g., Schwartz and Coppersmith (1984)), a simulation-based procedure is used. Stochastic catalogues of events are produced by randomly generating inter-arrival times, magnitude and source-site distance values, and earthquake-induced ground-motion intensity measures (IMs) considering their respective probability distributions. Specifically, the time of occurrence of events (T) is simulated assuming a given time frame, i.e., $t_e \le t \le t_e + \Delta t$ where $\Delta t = 50$ years is the time window chosen for the purposes of this study. Then, for each event in each stochastic catalog, an earthquake moment magnitude (M) is simulated assuming a uniform probability distribution with magnitudes in the range $M = M_{mean} \pm \sigma_M$, where M_{mean} is the mean maximum characteristic magnitude of the fault, and σ_M is its standard deviation. Additionally, values of the source-site distance (R) are computed for each site assuming that any point within the fault has equal probability of being a focus. The type of distance defined (e.g. epicentral, hypocentral, Joyneer-Boore distance) depends mainly on the selection of the specific ground-motion model (GMM). Subsequently, for each pair [M, R], an IM values is simulated based on the median values determined from the selected GMM and the associated covariance matrix, accounting for the IM variability and the spatial correlation between sites (e.g., Park, Bazzurro, and Baker (2007)). In this case, the selected IM is $S_a(T_1)$, i.e., the spectral pseudo-acceleration at a representative fundamental period for the considered building class (in this case, $T_1 = 1\,\text{s}$), considering the ground-motion models (GMMs) for Italy recently developed by Huang and Galasso (2019). The resulting seismic hazard is expressed as function of the time elapsed since the last event $\left(t_e\right)$. The methodology used here is summarized in Figure 1.

The expected losses for a case-study building portfolio are estimated using the catastrophe modelling approach (e.g., Grossi and Kunreuther, 2005) considering ground-shaking intensities derived using both the BPT model and HPP at the different sites defined by an exposure grid. Specifically, a generic 10 km x 10 km exposure grid (with 1 km spacing in both directions) on stiff soil located at an average source-to-site distance $R_{JB} = 10$ km is considered, where R_{JB} is the Joyner-Boore distance, i.e., the closest distance from the surface projection of the fault to the site The exposure is defined according to a model developed by Minas et al. (2018) for the city of Avellino, considering that it is representative of a typical Italian building stock in several medium-to-large size cities. In this model it is assumed that the inventory consists only of mid-rise RC buildings categorized in three vulnerability classes: Pre-code, Low-code, and Special-code; see Minas et al. (2018) for details.

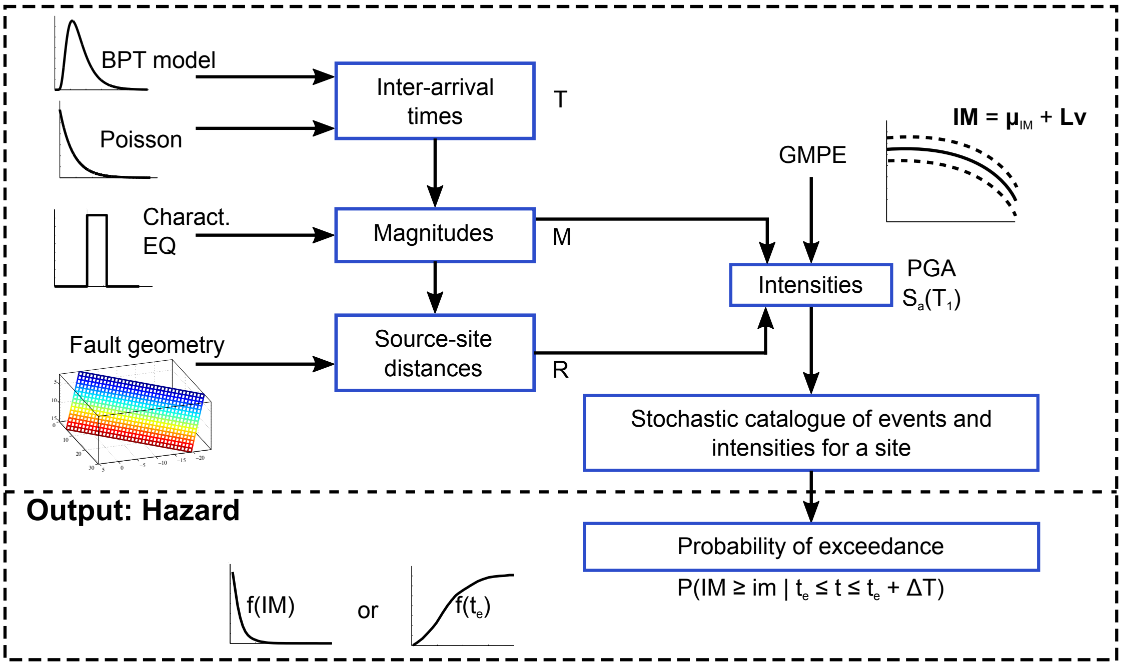

Figure 1. Simulation-based procedure for estimating the seismic hazard due to a single fault for a given site.

A fragility model is defined using the curves derived by Minas et al. (2018), based on the same vulnerability classes considered above. Then, a vulnerability model is built by combining those fragility curves with damage-to-loss ratios adapted from Di Pasquale and Goretti (2001). The considered fragility curves for three damage states (DSs) and the resulting vulnerability curves used in this study are shown in Figure 2. For simplicity, the uncertainty in the vulnerability model is neglected, i.e., only the mean values of the fragility curves and means damage-to-loss ratios are considered, in order to 'isolate' the uncertainty on the hazard model only.

Case-study faults

A sensitivity analysis is performed to investigate the impact of the ratio between the time elapsed since the last event and the return period $\left({}^{t_e}\!/_{T_{mean}} \right)$ on the estimation of seismic hazard and losses. The aim is to understand if the results obtained for a generic fault, at least in terms of trends, can be generalized to any fault.

To this aim, five normal faults are considered for illustrative purposes with different values of mean maximum magnitude (for the characteristic earthquake) M_{mean} and T_{mean}. The considered case studies are summarized in Table 1. The area of each fault is computed based on the Wells and Coppersmith (1994) relationships for normal-fault type. Based on the available data for normal faults in Italy (e.g., Faure Walker et al., 2018), it is assumed that the seismogenic thickness is $h = 12\text{ km}$, hence the width of the fault is limited by ${}^{h}\!/_{\sin(\delta)}$, where δ is the dip angle. Then, to demine the dimensions of each considered fault, it is assumed that the fault grows as a square until the width reaches its maximum value. For all cases, it is considered that the upper dip of the fault is at $H = 2\text{ km}$ depth and that the dip and strike angles are 60° and 0°, respectively. An example of case-study fault geometry and exposure grid considered in this study are shown in Figure 3.

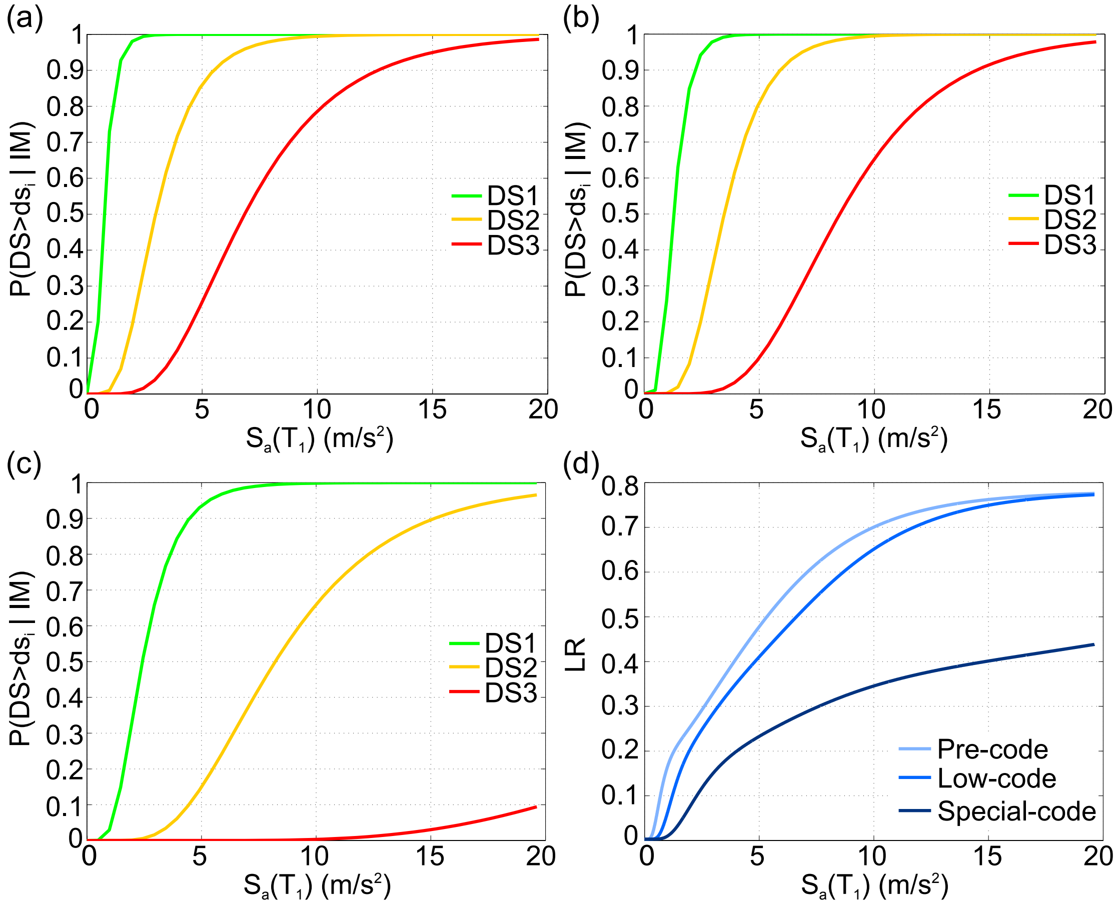

Figure 2. Fragility curves for mid-rise RC buildings for the three vulnerability classes (Minas et al., 2018): (a) Pre-code, (b) Low-code, and (c) Special-code. Vulnerability model (d)

			Fault geometry		
Case	**T_{mean} (yrs)**	**M_{mean}**	**Area (km^2)**	**Length (km)**	**Width (km)**
1	50	5.5	43.65	6.61	6.61
2	100	6.5	288.40	20.81	13.86
3	200	6.5	288.40	20.81	13.86
4	500	6.5	288.40	20.81	13.86
5	1000	7.0	741.31	53.50	13.86

Table 1. Considered case-study faults

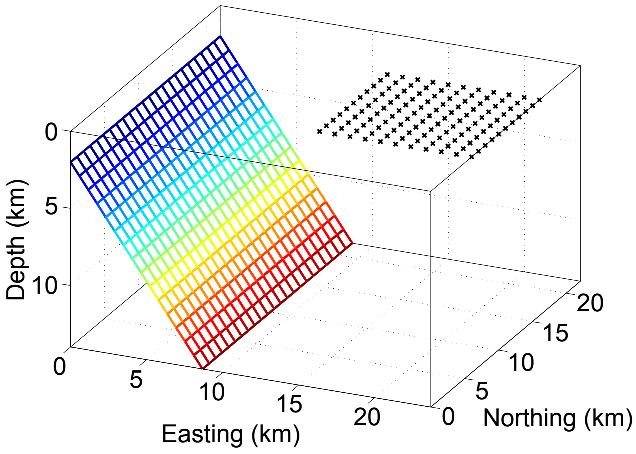

Figure 3. Example of a case-study fault geometry and exposure grid considered in this study.

The estimation of seismic hazard as function of the time elapsed since the last event $\left(t_e\right)$ is performed by considering different ratios of t_e/T_{mean} for each fault. The values of this ratio are set between 0 to $1.5 \cdot T_{mean}$ assuming a discretization of 0.02. Therefore, 76 different values of t_e are used for each case. For defining the BPT model, the generic value of aperiodicity $\alpha = 0.5$ is assumed (Ellsworth et al., 1999). Also, it is assumed that $\sigma_M = 0.3$ hence the earthquakes magnitudes are generated considering the range $M = M_{mean} \pm 0.3$.

Results and discussion

Expected seismic losses are estimated using the methodology described above, considering the estimated seismic hazard for each case-study fault, and the exposure and vulnerability models introduced above. It is assumed a replacement cost is 1,300 Euros/m2, which is the typical value for Italy (e.g., Minas et al. (2018)). Figure 4 shows the total expected loss for the considered building portfolio as function of the ratio t_e/T_{mean} considering the hazard estimated using the BPT model $\left(E\left[L|t_e/T_{mean}\right]_{BPT}\right)$, normalized to the expected losses estimated through the HPP model $\left(E\left[L|t_e/T_{mean}\right]_{HPP}\right)$:

$$\Delta E\left[L|t_e/T_{mean}\right] = \frac{E\left[L|t_e/T_{mean}\right]_{BPT}}{E\left[L|t_e/T_{mean}\right]_{HPP}} \tag{1}$$

It is observed from Figure 4 that the expected losses estimated using the BPT model can be as much as the double of the loss estimated obtained using the HPP model when the ratio t_e/T_{mean} is large. Moreover, in consistency with the results in terms of seismic hazard (not shown here for the sake of brevity), the normalized losses are close to one when the ratio t_e/T_{mean} is around 0.3 - 0.5. The methodology employed for analyzing the influence of t_e on the hazard (and losses) leads to consistent results for the different case studies.

Conclusions

This study has quantified the impact of time-dependent hazard modelling on seismic loss estimates for a case-study reinforced concrete (RC) building portfolio. Five case-study faults were used for estimating probabilistic seismic hazard and expected losses as a function of t_e using a simulation-based procedure.

Results from this study showed that the ratio t_e/T_{mean} is a key parameter to a) determine whether it is relevant to use time-dependent models for characterizing earthquake recurrence; and b) quantify the under-/overestimation of expected losses when a conventional HPP model is employed. For instance, the expected losses obtained using a BPT model can be more than twice the ones predicted by the HPP model, when the fault is ‘overdue’, i.e., when the time elapsed since the last event is large in comparison with the mean recurrence period of the fault. On the other hand, if the time elapsed since the last event is about half of the mean recurrence time of the fault, the BPT model leads to similar results to the HPP model, leading to acceptable estimates of the expected losses.

A full PSHA, considering a set of faults and background seismicity, would be required to further analyze the actual impact of time-dependent hazard modelling on the total expected losses.

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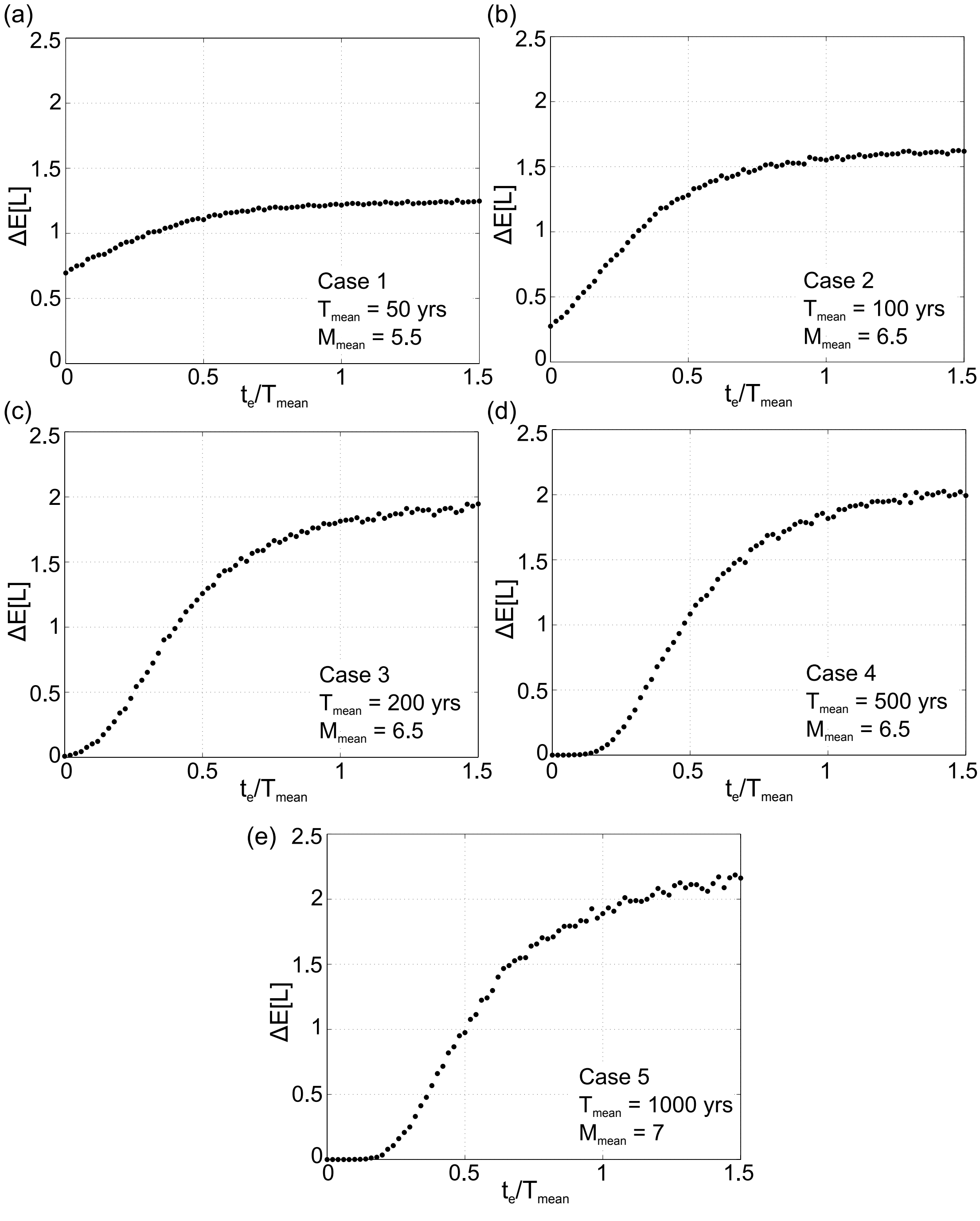

Figure 4. Total expected losses normalized to the losses estimated through the HPP model, for the five-case study fault and the considered building portfolio.

References

Convertito, V. and Faenza, L. (2014), Earthquake Recurrence, *Encyclopedia of Earthquake Engineering*. Springer. doi: 10.1007/978-3-642-36197-5.

Di Pasquale, G. and Goretti, A. (2001), Vulnerabilità funzionale ed economica negli edifici residenziali colpiti da recenti eventi sismici nazionali, in *Proc X Ital Conf Earthq Eng*.

Ellsworth, B. W. L., Matthews, M. V, Nadeau, R. M., Nishenko, S. P., Reasenberg, P. A. and Simpson, R. W. (1999), *A Physically Based Earthquake Recurrence Model for Estimation of Long-Term Earthquake Probabilities*.

Faure Walker, J. P., Visini, F., Roberts, G., Galasso, C., Mccaffrey, K. and Mildon, Z. (2018), Variable Fault Geometry Suggests Detailed Fault-Slip-Rate Profiles and Geometries Are

Needed for Fault-Based Probabilistic Seismic Hazard Assessment (PSHA), *Bulletin of the Seismological Society of America*, 109(1). doi: 10.1785/0120180137.

Grossi, P. and Kunreuther, H. (2005), *Catastrophe modeling: A new approach to managing risk*. 1st edn. Boston: Springer US. doi: 10.1007/b100669.

Huang, C. and Galasso, C. (2019), Ground-motion intensity measure correlations observed in Italian data, in *13th International Conference on Applications of Statistical and Probability in Civil Engineering*. Seoul, South Korea.

Minas, S., Sousa, L., Galasso, C. and Rossetto, T. (2018), Sensitivity of probabilistic regional seismic loss to hazard and vulnerability modelling options, in *16th European Conference on Earthquake Engineering*. Thessaloniki, Greece.

Papadopoulos, A. N. and Bazzurro, P. (2018), Sensitivity analysis of earthquake loss estimation using the space-time etas model for seismicity, in *16th European Conference on Earthquake Engineering*. Thessaloniki, Greece.

Park J., Bazzurro P., and Baker J.W. (2007). Modeling spatial correlation of ground motion intensity measures for regional seismic hazard and portfolio loss estimation, in 10th International Conference on Application of Statistic and Probability in Civil Engineering (ICASP10), Tokyo, Japan, 8 pp.

Schwartz, D. P. and Coppersmith, K. J. (1984). Fault behavior and characteristic earthquakes: Examples from Wasatch and San Andreas fault zones, *Journal of Geophysical Research*, 89(B7), pp. 5681–5698.

UNDRR (2015). Sendai Framework for Disaster Risk Reduction. Available at: https://www.unisdr.org/we/inform/publications/43291 (Accessed 17/06/2019).

Wells, D. L. and Coppersmith, K. J. (1994), New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement, *Bulletin of the Seismological Society of America*, 84(4), pp. 974–1002.

Williams, C. R., Aslani, H., Molas, G., Seneviratna, P. and Windeler, D. S. (2008), Impact of Time Dependent Recurrence Modeling on Seismic Risk Assessment: California Case Study, in *The 14th World Conference on Earthquake Engineering*. Beijing, China.