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Feasibility study of earthquake early warning systems: The case of tunnels of the Italian high-speed railway network

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ABSTRACT: The fragility curves commonly studied in the structural and geotechnical engineering can be used in the application of seismic Early Warning Systems (EWS) for the real-time estimation of the probability of damage of a structure and the implementation of safety procedures. This represents a valid tool for the mitigation of the seismic risk of the geotechnical work- system. This work presents an innovative approach for the study of the feasibility of a seismic Early Warning system applied to underground linear infrastructures. With this regard, the case of the high-speed railways Italian network has been considered. This is a probabilistic approach that exploits the disaggregation of the seismic hazard to define sets of virtual seismic sources potentially affecting railway's tunnels. Hence, the probability of seismic damage to tunnel structures and the time available for implementing real-time mitigation procedures can be calculated.

1 INTRODUCTION

The seismic vulnerability of underground structures, such as tunnels, is strongly influenced by the technology of their lining system (i.e. continuous or segmented tunnel lining), the type and intensity of the seismic event and the consequent effect of its interaction with the surrounding ground. The possibility to have reliable models for assessing the seismic vulnerability of the structure is certainly an element of great importance for the mitigation of the seismic risk. The fragility curves, for example, represent a valid tool for estimating the probability to overcome assigned damage levels of a structure subjected to an assigned seismic input, widely used in structural engineering, less used in geotechnical engineering due to the high computational effort to take into account the effects of the seismic soil-structure interaction.

In the technical literature there are some studies to evaluate the seismic vulnerability of tunnels based on empirical fragility curves (Hazus 1999; ALA 2001, Corigliano 2006) that derive from statistical analysis of observed damages on tunnels during past seismic events. Nevertheless, this approach does not allow to distinguish the structural typology of the tunnel nor the soil type. Less realistic but more reliable are instead the fragility curves based on the distribution of damages obtained by numerical analyses for different seismic scenarios, able to take into account the effects of the dynamic soil-structure interaction. Argyroudis & Pitilakis 2012 for instance, proposed a procedure to define fragility curves for continuous tunnel lining, based on pseudo-static numerical analyses in plane strain conditions. The authors proposed four categories of damage (D1: no damage, D2: minor damage, D3: moderate damage, D4: extended damage) for the specific structural typology, defining as damage index of the structure, DI, the ratio between the seismic demand and the capacity in terms of bending moment of the structural section of the continuous tunnel lining. Following the approach suggested by the authors, fragility curves were calibrated for the same structural type and for the same soil categories, based on the results obtained from non-linear coupled analyses (Fabozzi 2017).

The comparison between the two approaches shows how pseudo-static analyses can underestimate the probability of damage in such seismic conditions, compared with the coupled case, which was expected from some results that the authors presented (Argyroudis & Pitilakis 2012) and other literature studies (Tsinidis et al. 2016, Fabozzi et al. 2017a). Another examples of numerical fragility curves are those proposed by Salmon et al. 2002, Andreotti & Lai 2014, Argyroudis et al. 2016, Kiani et al. 2016 and Fabozzi et al. 2017b. Some of the numerical fragility curves presented here were used as a method to predict the probability of tunnel damage in correspondence of two target sites of the high-speed railways Italian network within a feasibility study of an Early Warning Seismic system, EWS.

The seismic EWS systems consist of hardware and software systems for the rapid notification of the seismic alarm (Iannaccone & Zollo 2010) and are useful tools for mitigating the impact of earthquakes on engineering systems. The principle on which EWS systems are based is the ability to locate and estimate the magnitude of a real-time event based on the content of energy of P waves. This is followed by the sending of alert messages to a series of sites to be protected before they are reached by seismic action capable to produce damage (S waves). In this way, the warning messages can be used to activate various types of protection actions. Therefore, the operation principle of this system is based on the velocity difference of the seismic waves (the speed of the S waves is about 1.7 times lower than that of the P waves) compared with the velocity of the radio waves that convey the information on the earthquake.

Typically, EWS system follows two basic approaches: 'regional' (or network based), and single station 'on-site' warning. Regional early warning systems are based on the use of a seismic network located near one or more known epicentral areas, for which the aims are to detect and locate an earthquake and to determine its magnitude from the analysis of the first few seconds of the arriving P waves at more stations (Satriano et al. 2011). The lead-time for a regional system is defined as the time difference between the S waves recorded in the source area and the arrival of first P waves at the target site, and the necessary computation and data transmission times. Onsite early warning systems, instead, are intended for target sites located too close to a seismogenic area, where the analysis of data recorded at more stations of a regional network determines a lead time too small to warn the target in case of an event. For this reason, on-site systems rely on seismic sensors installed directly at the target site and exploit only the information carried by the faster early P waves. In this case, the lead time is equal to the S-wave minus the P-wave arrival times.

This work describes a procedure that exploits the disaggregation of the seismic hazard to define sets of virtual seismic sources potentially affecting railway's tunnels. Hence, the probability of seismic damage to tunnel structures and the time available for implementing real-time mitigation procedures can be calculated. Such a procedure is applied to two tunnels of the high-speed Italian system with different structural layout, Bologna railway passage and La Botte tunnel respectively. The procedure suggests that for the considered tunnels, the best option for undertaking seismic risk mitigation measures would be an on-site threshold-based early-warning system. However, the foreseen probability of structural damage to the tunnel lining is low in both cases. The proposed methodology can be easily generalized to different targets to design the optimal configuration of an earthquake early warning system, and applied to control, manage and maintain the tunnel structures along the high-speed railway network.

2 METHODOLOGY

Using the fragility curves for different levels of damage states (DSs), from the PGA value recorded at a target sites (e.g. a tunnel) the probability of damage (Pf) can be estimated. Figure 1 shows a schematic application of the fragility curves for the estimation of Pf.

Whenever a dataset of past earthquake waveforms for a site of interest is not available, one simplest approach to assess the Pf that a structure can experience during its lifetime is to exploit the Probabilistic Seismic Hazard Analysis (PSHA) for extracting the ground motion level (i.e., the PGA for instance) that can occur at the structure site within a given reference

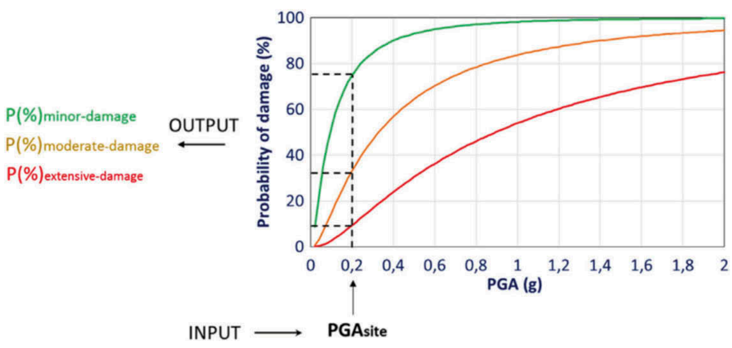

Figure 1. Schematic application of the fragility curves. (Modified after Fabozzi et al. 2018).

period and different exceedance probabilities (e.g. P_r = 81%, P_r = 63%, P_r = 10%, P_r = 5%, as proposed in the Italian code). This approach was applied to both tunnels considered for the case of study to calculate a "background" level of Pf.

While such a "background" Pf can be obtained straightforward from the PSHA, it is worth noting that this procedure does not provide any direct indications about the location of the seismic sources that contributed to the hazard. By contrast, during the design of seismic EWS, this is a key piece of information, being the location of seismic sources necessary to compute the leadtime, which in turn is needed to understand the effectiveness of the early-warning. A possible strategy to overcome this issue is to exploit the disaggregation of seismic hazard, as schematically shown in Figure 2, which provides insights into the earthquake scenarios driving

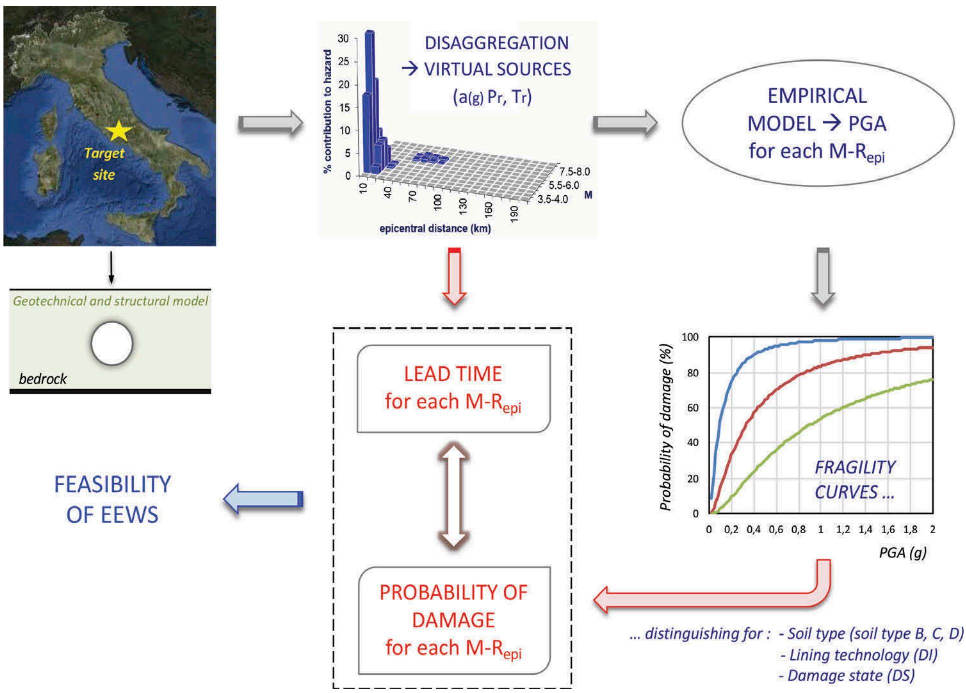

Figure 2. Layout of the proposed method based on the disaggregation of the PHSA to evaluate the probability of seismic damage of underground tunnels and the related feasibility of seismic EWS. (Modified after Fabozzi et al. 2018).

the hazard at a given ground motion level (Barani et al. 2009) as function of the selected intensity measure and the mean return period. The proposed procedure makes use of the disaggregation analysis applied to the PSHA defined for the Italian territory in terms of peak ground horizontal acceleration, PGA, to identify 'virtual sources' (i.e., in terms of epicentral distance and magnitude) that provide the higher contribution to the hazard at a target location. Disaggregation maps are, indeed, expressed in terms of magnitude (M), source-to-site distance (Repi) and the contribution (w%) to the hazard. Thus, the disaggregation analysis permitted to identify seismic events that from the hazard perspective are of interest for the structures at hand. Then, for each pair of (M-Repi) derived from the disaggregation analysis, the PGA at the target site where the tunnel is located is computed by a ground motion prediction equation (GMPE) (Figure 2); in this study the GMPE proposed by Bindi et al. 2011 for Italy has been adopted.

The set of PGA values obtained for the target site represents the input matrix for the fragility curves. By means of them, for each tunnel a matrix of probability of damage, Pf, is defined for each damage state. Furthermore, the set of virtual seismic sources are used also to estimate a leadtime matrix, which allows assessing the time available to implement protective actions at the target structure to be protected (and therefore it allows to select which seismic EWS approach between on-site and regional is most indicated). To this purpose, for each pair of (M-Repi) the lead-time is computed assuming: (i) P-wave and S-wave velocities of 5.5 km/sec and 3.0 km/s, respectively; (ii) a P-waves time window length of 1 s for estimating the magnitude until M = 7 (Brondi et al. 2015, Festa et al. 2017); (iii) the time spent for computation and telemetry together equal to 1 s, assumed on the basis of the experience with the seismic EWS and management system PRESTo operating in Southern Italy (Satriano et al. 2011); (iv) for each site, according to the seismic zone of the seismic hazard analysis where it is placed, a hypocentral depth is assumed equal to the "efficient depth", which is defined as the depth interval where 90% of the events occur.

For the two test-cases considered in this study, the lead-time and acceleration matrices have been computed. In turn, considering all M-Repi pairs, the PGA maps have been used in combination with the fragility curves to produce the final matrix with the probability of minor, moderate and extensive damage.

3 CASE STUDY

The proposed approach has been applied on two sites of the Italian High-Speed Rail System (HSR) system, (Figure 3) a tunnel along Bologna-Firenze link, Case 1, and la Botte tunnel along Roma-Napoli link (in Ceccano, near Frosinone), Case 2. These target tunnels have been chosen for their position with respect to the most seismic zones of the region, and because they are representative of two different tunnel lining technologies. Both the considered areas show an important historical seismicity (see data from the Parametric Catalog of Italian Earthquakes by Rovida et al. 2016 made available by the INGV, the Italian Institute of Geophysics and Volcanology; https://emidius.mi.ingv.it/CPTI15- DBMI15/description_CPTI15.htm).

Bologna railway passage (Case 1) belongs to the Bologna-Firenze stretch and represents one of the most important interchange node of the national HS network. The 94% of Bologna-Firenze line is excavated in bored tunnels crossing the Apennine chain, characterized by relatively steep mountainous reliefs, with very variable tunnel overburden up to about 600 m in correspondence of the Raticosa tunnel on the Tuscan side, where the geology is characterized by sedimentary rock formations (i.e., marly-sandy formations and clayey flysch).

Bologna railway passage is a very recent urban crossing long about 10 km, 6 km of which are in underground for the southern access to the HS station of the city. The latter consists of two parallel shallow tunnels excavated with an Earth Balance Pressure, EPB, Tunnel Boring Machine, TBM, of a diameter of 9.40 m. This technique was adopted to minimize interaction effects with the above structures of the urban area. The tunnel linings are segmented with 6 pre-cast concrete segments plus the key with a thickness of 0.40 m, while the internal diameter

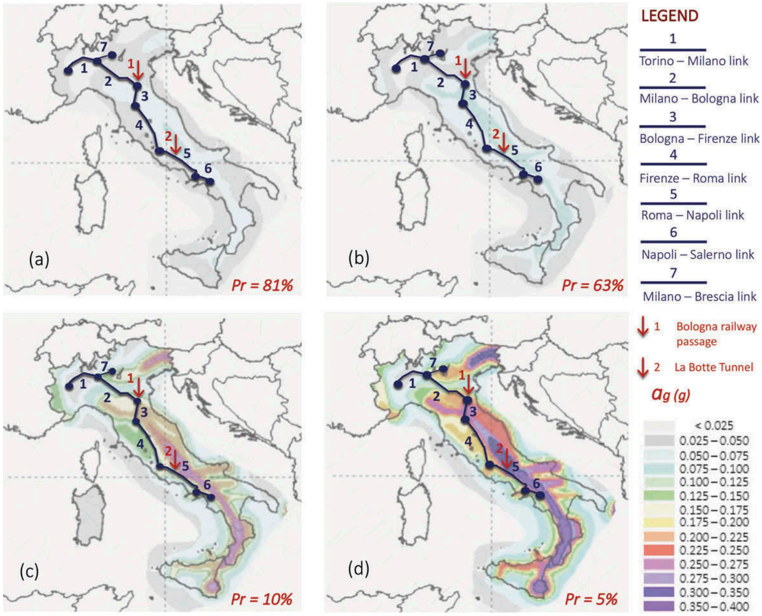

Figure 3. Italian high speed rail system (operational) combined with the hazard maps for a probability of exceedance equal to (a) 81% (return period TR = 30 y), (b) 63% (return period TR = 50 y), (c) 10% (return period TR = 475 y), and (d) 5% (return period TR = 975 y). (Hazard maps extracted from INGV, http://zonesismiche.mi.ingv.it). (Modified after Fabozzi et al. 2018).

of the tunnels is equal to 8.30 m. The tunnels were excavated through two main formations, one alluvial deposit of Savena River with deposits of clay, and one of sandy soil.

La Botte tunnel (Case 2) belongs to the Roma-Napoli stretch that develops into a geological context mainly characterized by volcanic (pyroclastic soil, tuff and lava) and sedimentary rocks (i.e., flyshes, marly-sandy formations, limestones). Along this stretch, the tunnels cover is very variable, but it does not exceed 110 m of maximum height. This structure is 1.5km long bored tunnel, excavated with traditional method and variable cover along the stretch (maximum cover equal to 44 m, minimum cover equal to 20 m). Depending on the tunnel axis depth and the crossed ground conditions, the tunnel has a variable structural section (both the invert and the crown have a thickness variable between 0.60 m and 1.00 m, the area of excavation is variable between 125.3 m^2 and 151.9 m^2). The tunnel crosses two different predominant lithotypes: volcanic and sedimentary ones. Due to variability of the tunnel geometry and properties, the most seismically vulnerable section has been considered (i.e., lining thickness equal to 0.60 m and cover equal to 20 m, in sedimentary ground).

4 RESULTS

In this section, a procedure to assess the probability of damage Pf based on a disaggregation of PHSA is presented. This is applied to a feasibility analysis for a loss-drive seismic EWS and rapid response system for the tunnels of CASE 1 and CASE 2. Figures 4 and 5 show the results of the disaggregation analysis through which indications about the location and magnitude of the seismic sources that mostly contribute to the hazard are derived.

Taking into exam CASE 1 for P_r = 63%, the disaggregation map in Figure 4a shows that the seismic threat responsible for the highest contribution to hazard is located at a distance between 10 and 20 km from the target site with a magnitude between 4.5 and 5. The peak ground acceleration (PGA) at the tunnel related to this scenario is equal to 0.04 g (Figure 4b),

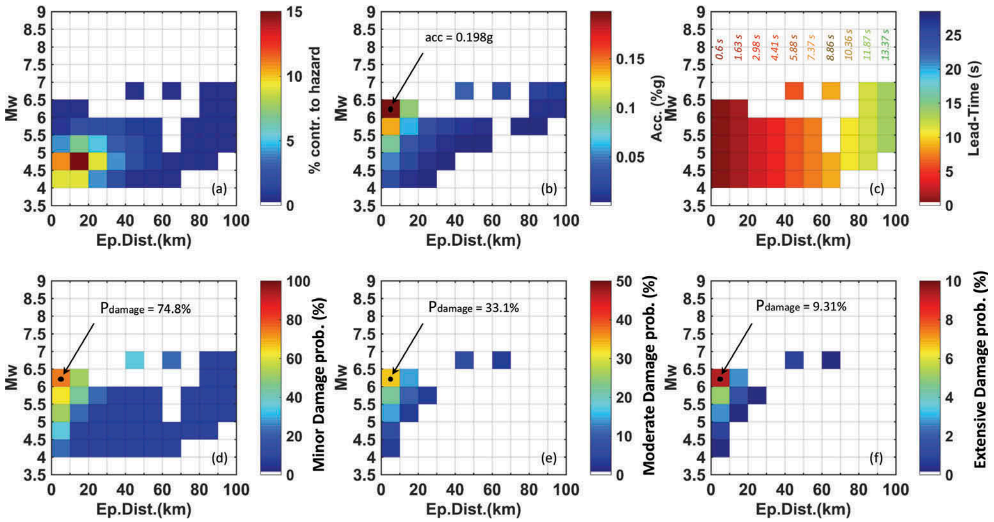

Figure 4. (a) Disaggregation (INGV, http://zonesismiche.mi.ingv.it), (b) acceleration and (c) lead-time maps of target site of Bologna HS railway passage and maps of probability of damage for (d) minor, (e) moderate and (f) extensive damage level (P_r = 63%). (Modified after Fabozzi et al. 2018).

which corresponds to a probability of minor, moderate and extensive damage equal to 20%, 0%, and 0%, respectively (Figure 4d-f). The correspondent lead-time instead, is equal to 1.6 s (Figure 4c). It is worth noting, however, that the maximum PGA expected at the target is about 0.2 g, to which corresponds a probability of minor, moderate and extensive damage equal to about 70%, about 35% and lower than 10%, respectively. This scenario corresponds to a source located at a distance between 5 km and 10 km from the site and a magnitude range from M = 6 to M = 6.5. Despite this scenario would be very important in terms of ground motion at the target site and damage probabilities, it is worth to consider that it is associated to a very low contribution to the hazard, and therefore it is very unlikely to occur. These two cases represent the end members (i.e. the one with the highest occurrence probability and the worst one in terms of PGA) of a wide number of possible scenarios. From this point of view, this approach is a very versatile tool, which allows to investigate different scenarios in terms of PGA and probability of occurrence. Considering the lead-time of 1.6s for the seismic threats with highest contribution to the hazard (Repi = 10-20 km, M from 4.5 to 5), our feasibility analysis suggests for CASE 1 a threshold-based on-site EWS system (i.e., a system made of 2-3 accelerometric stations installed nearby the tunnel).

It is worth noting that our definition of lead-time provides conservative values, being it based on the theoretical arrival time of the S-wave at the target site. Clearly other approaches could be followed, as for instance, the one proposed by Emolo et al. 2016 where the lead-time is measured on waveforms as the difference between the instant at which the ground velocity overcomes for the first time the threshold value of 3.4 cm/s (i.e., the lower boundary of the VII degree in the instrumental intensity scale proposed by Faenza & Michelini 2010 and the P-wave arrival. In this last case, the definition of the lead-time is related to the effective arrival of the ground shaking of interest for a seismic EWS and it would provide for the targets selected in this work larger lead- times. A similar analysis has been carried out also for CASE 2. Figure 5a shows that the seismic threat responsible for the highest contribution to hazard is located in this case at about 5 km from the target site, but again it is associated to a low magnitude (i.e., from M = 4 to M = 4.5). The correspondent PGA is equal to 0.05 g (Figure 5b), which would determine a probability of damage almost nil for minor, moderate and extensive damage state (Figure 5d-f). The correspondent available lead- time is equal to 0.6 s (Figure 5c). The maximum PGA expected at the target is 0.22 g and corresponds to a source

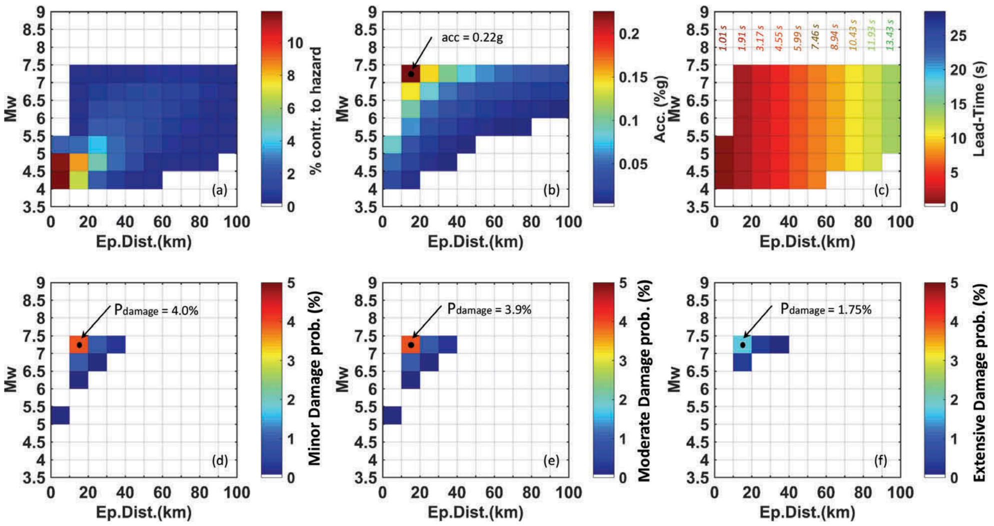

Figure 5. (a) Disaggregation (INGV, http://zonesismiche.mi.ingv.it), (b) acceleration and (c) lead-time maps of target site of La Botte HS railway tunnel and maps of probability of damage for (d) minor, (e) moderate and (f) extensive damage level (P_r = 63%). (Modified after Fabozzi et al. 2018).

located at about 15 km of distance from the site, magnitude in the range M = 7 to M = 7.5, but, like in the previous case, a very low contribution to the hazard. This threat is associated to a probability of minor, moderate and extensive damage equal to about 5%, about 4% and lower than 2%, respectively (Figure 5d-f).

Hence, for CASE 2 the seismic virtual threat to be considered more likely, that is the first mentioned threat with the higher contribution to the hazard (Repi = 0-10km, M = 4-4.5) would produce negligible damage. It should be noted that the low probabilities of damage associated to CASE 2 are due to the lower vulnerability of the continuous lining with respect to the segmental lining of CASE 1, of course for the same PGA level. As for CASE 1, also for CASE 2 the low lead-time associated to the seismic threat with the highest contribution to the hazard suggests the adoption of a threshold-based on-site seismic EWS.

5 CONCLUSIONS

A procedure for computing Pf at a target sites has been presented, where a direct indication about the location of the 'virtual seismic sources' and their contribution to the seismic hazard (i.e. M-Repi derived from the disaggregation analysis) are considered. The importance of considering these pieces of information (i.e., M-Repi) lies in the fact that they allow to assess Pf considering a specific hazard scenario (spatially constrained and probabilistically defined in time). Therefore, defining scenarios of interest for a target allows to evaluate the lead-time (i. e. the time available before the arrival of S-waves to the target), which in turn supports the design of the most effective seismic risk protection action to be implemented in real-time at the specific target.

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