Physics-based ground shaking scenarios for seismic fragility analyses: the case study of the 2009 L'Aquila earthquake

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Abstract: This works aims at exploring the use of ground shaking scenarios generated by means of 3D physics-based numerical simulations (PBS) for seismic fragility analyses. To this end, the case study of the 2009 L'Aquila earthquake is considered because of the availability of a detailed database of post-earthquake damage surveys, as well as of a validated numerical model for ground shaking prediction. Empirical fragility curves were derived for both masonry and Reinforced Concrete building typologies by statistical processing of damage data in correlation with the PBS ground shaking scenario. Fragility curves were derived for Peak Ground Acceleration and compared with those obtained by characterizing the ground shaking using ShakeMaps. The prediction capability of the two sets of fragility curves, one from PBS and the second from ShakeMaps, is tested by comparison of damage predictions with respect to the observed damage at the scale of the L'Aquila municipality. Results of this study validate the use of PBS for empirical fragility studies and shed light on the advantages of simulation-based approaches for ground motion characterization, especially when strong-motion recordings are insufficient or not available, as for historical earthquakes.

Keywords: seismic risk, fragility curves, physics-based numerical simulation, damage scenarios

1. Introduction

With the ever-increasing computational power, 3D physics-based numerical simulations (PBS) are becoming a more and more appealing tool to provide realistic site-specific scenarios of earthquake ground motion, in alternative to the commonly used empirical ground motion prediction equations (GMPE), based on statistical regressions from regional or worldwide records. More specifically, PBS are the key approach towards production of urban and regional risk scenarios, as it is the case for the ShakeOut (Porter et al., 2011) and Haywired (USGS, 2017a and 2017b) experiments in California, as well as for the Scenario Earthquake Shaking Maps (available at https://www.j-shis.bosai.go.jp) suitable for prefecture emergency plans in Japan, in order to pinpoint target areas and target facilities needing maintenance for earthquake disaster prevention.

Engineering validation of PBS results has already found considerable attention (e.g., Galasso et al., 2012; Tsioulou and Galasso 2018; Petrone et al., 2021a; 2021b). However, in view of the seismic risk applications at urban scale (see e.g., Smerzini and Pitilakis 2018; Stupazzini et al., 2021; Riaño et al. 2021), it is also crucial to verify whether a PBS scenario is suitable to provide not only a reliable prediction of the level of damage observed in an urban area during a historical earthquake, but also a suitable basis for calibration of empirical fragility curves when instrumental information on ground shaking is not sufficient to reliably correlate the observed level of damage to the estimated ground motion intensity.

As a matter of fact, the spatial distribution of ground motion intensity is typically inferred either by ShakeMaps (Wald et al. 2021; Michelini et al. 2020), in case a sufficient number of records is available, or by empirical GMPEs (Erdik 2017), as it is often the case for historical earthquakes with no instrumental records. In all such cases, there is a large level of uncertainty when a ground motion level is associated to the specific site where an earthquake effect is observed. Besides, the estimated ground motion is typically available only through its peak values, with no information on other parameters related to the time history itself, such as duration and frequency content. Instead, once suitably validated, the PBS ground motion scenario may provide a complete picture of the variability of the ground motion waveforms, supporting the derivation of empirical fragility curves with a wider set of intensity measures (IM), including multi-component input.

With this background, the main aim of this paper is to explore and validate the use of PBS ground shaking scenarios for the calibration of empirical fragility curves, with application to the Mw6.2, Apr 6 2009, L'Aquila earthquake. This case study is selected because of the availability, on one side, of a database of post-earthquake damage surveys with an unprecedented level of detail (Dolce et al. 2019; Rosti et al. 2021a; 2021b), and, on the other, of a validated numerical model for PBS ground motion scenarios (Evangelista et al., 2017).

2. Case study: damage database and 3D physics-based simulation of the L'Aquila earthquake ground motion

On April 6, 2009, a Mw 6.2 earthquake hit L'Aquila city, one of the largest urban centers in the Abruzzo region (Central Italy) with about 70,000 inhabitants, causing 308 deaths and vast destruction in the town itself and surrounding areas. The post-earthquake macroseismic survey revealed a maximum intensity degree of IX-X in the Mercalli-Cancani-Sieberg (MCS) scale in the towns of Onna and Paganica, while other 14 towns and villages, including L'Aquila, reached an intensity degree between VIII and IX (Galli et al. 2009).

This study makes use of the up-to-date version of the damage database originally examined by Rosti et al. 2018 and 2020. The database, now available in the Observed Damage Database - DaDo (Dolce et al. 2019), was also analysed in Rosti et al. 2021a and 2021b. For the objective of this study, which is to compare the effect of different approaches for the characterization of ground shaking in the empirical fragility analysis, we considered a subset of the damage dataset corresponding to the detailed study area depicted in Fig. 1. The considered dataset, hereafter referred to as detailed dataset, counts 7987 residential buildings, 4564 (57%) of which refer to masonry, whereas 3423 (43%) are RC buildings (see Fig. 1). The dataset adopts the typological building classification of Table 1 and the height classification of Table 2.

In this work, a 3D physics-based numerical approach, through the spectral element code SPEED (Mazzieri et al. 2013, http://speed.mox.polimi.it/), is used to simulate the seismic wave propagation during the L'Aquila earthquake and, hence, to construct the ground shaking scenario for fragility analysis. The 3D spectral element model of the L'Aquila earthquake derives from a previous study (Evangelista et al. 2017), which was focused on the calibration and the validation of the numerical model against the available recordings. To overcome the frequency limit of the numerical model, the ANN2BB technique proposed by Paolucci et al. (2018) and further improved in Paolucci et al. (2021), is used to enrich the PBS signals at high frequency.

Fig. 2 shows the map of Peak Ground Acceleration (PGA) obtained from PBS (left) and from the up-to-date version (v4) of the ShakeMap according to Michelini et al. (2020) (right). The maximum horizontal component (Hmax) is shown to enable a consistent comparison between the two approaches, since ShakeMaps are released only for the Hmax component. To understand the differences between PBS and ShakeMap, it is worth recalling that the former is derived by computing the peak values directly from the broadband waveforms (simulated by SPEED and enriched by the ANN2BB technique at high frequencies) on an arbitrarily dense grid of receivers, while the latter is generated by combining, through suitable geospatial interpolation algorithms, the recorded ground motion values at the available stations with the GMPEs predictions, where data are not available. From the comparison of Fig. 2, it is apparent that the PBS provides a realistic spatial distribution and correlation of PGA values, which reflects the physical features of the source rupture and of local site response, while the ShakeMap provides a smooth pattern with limited spatial variability. Furthermore, it is noted that, at local scale, PGA from PBS tends to be smaller than that from ShakeMaps, which is conditioned on the relatively high values of shaking recorded at the Aterno Valley transect.

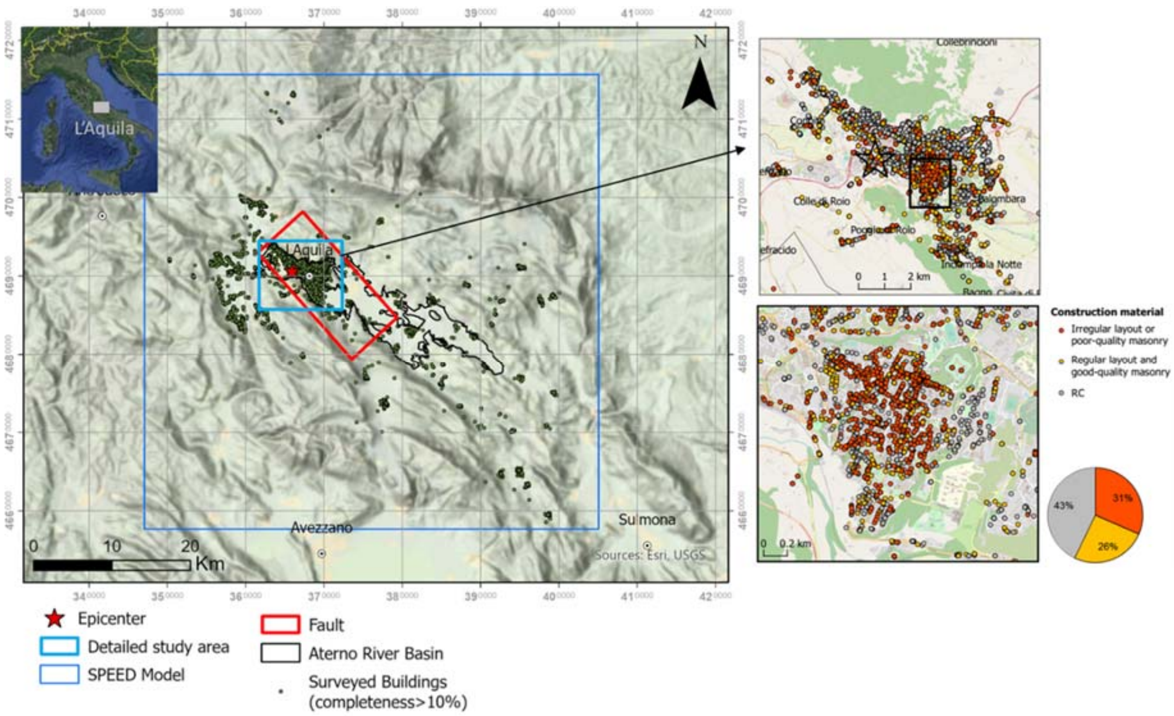

Fig. 1 – The 2009 L'Aquila earthquake: overview of the case study (left) and damage database in the detailed study area addressed in this work (right).

Table 1. Typological building classification adopted in this study.

Building typology	Construction Material	Masonry type	Intermediate diaphragm	Connecting Devices?	Design Level
IRR/F/NCD	Masonry	Irregular layout o poor-quality (IRR)	Flexible (F)	No (NCD)	-
IRR/F/CD				Yes (CD)	-
IRR/R/NCD			Rigid (R)	No	-
IRR/R/CD				Yes	-

REG/F/NCD		Regular layout and good-quality (REG)	Flexible (F)	No	-
REG/F/CD				Yes	-
REG/R/NCD			Rigid (R)	No	-
REG/R/CD				Yes	-
RC/Seismic-Pre81	RC	-	-	-	Seismic-Pre 1981
RC/Seismic-Post81			-	-	Seismic-Post 1981

Table 2. Height classification adopted in this study.

Height Class	Construction material	No. Storeys
L	Masonry	1-2
MH		>2
L	RC	1-2
M		3-4
H		>4

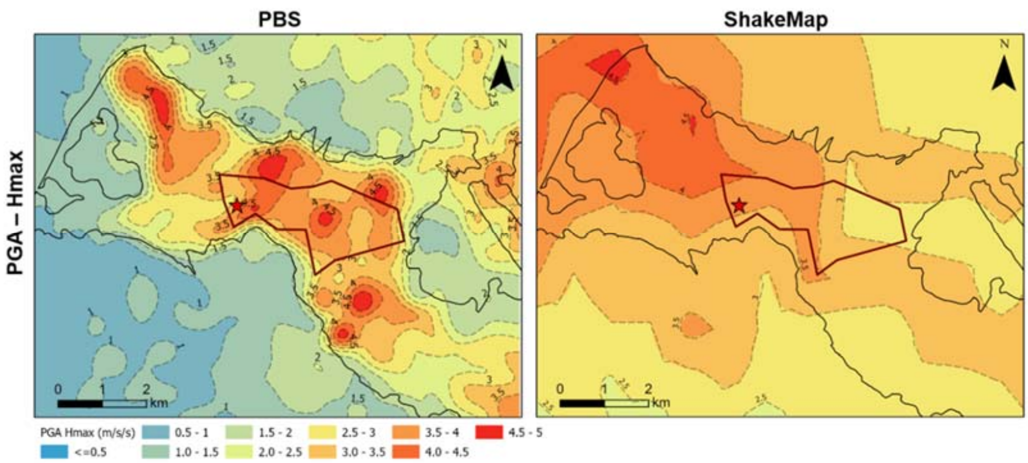

Fig. 2 – Comparison between the map of PGA-Hmax in the detailed study area from PBS (left) and from the ShakeMap (right).

3. Fragility curves estimated from PBS and ShakeMap

Empirical fragility curves are derived for the building typologies listed in Table 1 by statistical processing of the damage database. In line with existing literature studies (e.g. Rota et al. 2008; Del Gaudio et al. 2017), the cumulative lognormal distribution is adopted for describing the probability of reaching or exceeding a preselected damage level, as a function of the seismic intensity measure:

$$P\left(DS \geq ds_i | IM = im_j\right) = \Phi\left[\frac{\log(im_j/\theta_{ds_i})}{\beta}\right] \quad (1)$$

where θ_{dsi} is the median value of the selected intensity measure associated with damage level ds_i whereas β denotes the logarithmic standard deviation.

Considering its extensive use in seismic vulnerability and risk applications (e.g. Dolce et al. 2021), PGA (Hmax component) is selected for representing the severity of the ground motion shaking. To overcome the lack of PBS results outside the detailed study area, a hybrid strategy is pursued for defining seismic input at different building locations of the damage database. Specifically, the ground shaking is locally estimated using PBS at buildings sited in the detailed study area (see Fig. 2, left), whereas the ShakeMap is used for estimating seismic input at undamaged buildings located in the municipalities less affected by the ground shaking (i.e. non surveyed municipalities and partially-surveyed municipalities with completeness ratio lower than 10%), which were added to the post-earthquake database for suitably accounting for the negative evidence of damage (e.g. Rosti et al. 2021a, b).

Fig. 3 shows the fragility functions in terms of PGA, estimated using PBS (solid lines), for mid/high-rise masonry building typologies, in comparison with those entirely based on the ShakeMap (dashed lines). This comparison serves as validation of the use of ground shaking scenarios from PBS to construct empirical fragility. The two sets of curves (PBS Vs ShakeMap) turn out to be consistent, although some differences are found. Specifically, PBS-derived fragility curves tend to be less conservative for masonry buildings (especially for the MH class), while a reverse trend is found for RC buildings (not shown herein for sake of brevity).

The accuracy of the adopted simulation procedures to reproduce the observed damage is globally assessed in terms of damage distribution within the detailed study area, see Fig. 4. In the figure, predicted global damage distributions for all buildings (masonry + RC) are compared to the observed ones. Predicted damage distributions are obtained by combining the PBS (or ShakeMap) ground motion scenario with the corresponding fragility model. Results show that both approaches, PBS and ShakeMap, generally well reproduce the observed seismic damage in the detailed study area. Predictions are aligned with observations for all levels of damage from DS2 to DS5, indicating the general fitness of both procedures to reproduce observed seismic damage.

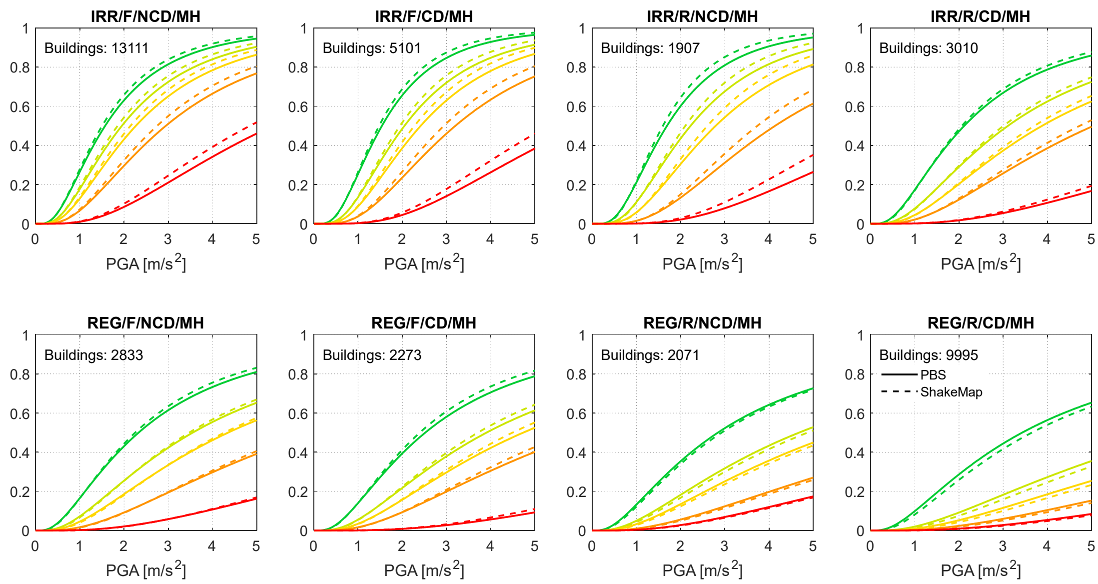

Fig. 3 –Comparison of empirically-derived fragility curves of mid-/high-rise masonry building typologies. IM: PGA estimated from PBS (solid lines) and by ShakeMap (dashed lines).

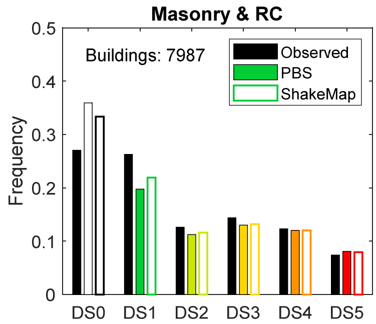

Fig. 4 – Observed and predicted global damage distributions for all buildings (masonry + RC) in the detailed study area.

4. Conclusions

This work presents a novel set of empirical fragility curves for the 2009 L'Aquila earthquake by exploiting the availability, on the one side, of a comprehensive database of post-earthquake damage observations, and, on the other side, of a 3D numerical model for physics-based ground shaking scenarios. The numerical model of the L'Aquila earthquake, validated against strong-motion recordings, includes a detailed 3D seismic wave propagation model, encompassing a finite-fault kinematic source model, as well as the 3D site response model of the Aterno River Valley.

Fragility curves were empirically-derived for both masonry and RC buildings, by characterizing the ground shaking within the L'Aquila municipality using the broadband shaking scenarios from the PBS. The ground motion intensity measures selected for the fragility analysis include PGA, which is the reference ground motion intensity measure used in the Italian national platform for seismic risk assessment (Borzi et al. 2021).

The comparison of the fragility curves derived from PBS with those obtained from the ShakeMap available for the L'Aquila earthquake highlights that the PBS-based fragility analysis does not show any systematic bias with respect to standard approaches. The validation of the PBS approach is confirmed also by the comparison of damage predictions with the post-earthquake observations. This study points out the advantages of simulation-based seismic shaking scenarios for empirical fragility studies, particularly when strong-motion recordings are insufficient or not available, as for historical earthquakes. These aspects will be the subject of future research in the framework of the 2022-2024 ReLUIS Projects (see Masi et al. 2021).

Acknowledgements

This work has been carried out in the framework of the 2019-2021 DPC-ReLUIS Project WP4 "MARS – Seismic Risk Maps" funded by the Italian Civil Protection Department.

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