ShakeMap constrained by observed damage

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Introduction

ShakeMap provides ground shaking intensity estimates in the region hit by a seismic event. It has been recently shown that information about the ground shaking intensity can be also obtained from observed damage to the construction hit by the event. This study explores this issue further, discussing how much damage information affects the shaking estimates and reduces its uncertainty using the example of the L'Aquila 2009 earthquake in Italy.

Methodology

To build a ShakeMap means estimating, at each site of the area hit by a seismic event, a ground motion intensity measure. At the state-of-the-art, such an estimate is obtained modelling the logarithms of ground motion intensity measure (IM), at the sites of interest, as a Gaussian random field (GRF) conditional to the earthquake magnitude and location, and the observed recordings at the monitoring stations (Worden et al. 2018). Typically, ShakeMap displays the exponentials of the expected value of the GRF at each site (i.e., the median IM at each site).

Four kinds of sites can be identified in the area where the ShakeMap is calculated: (i) sites with seismic monitoring stations where the shaking was recorded; (ii) sites where the structural damage to the buildings has been observed, but no ground shaking was instrumentally measured; (iii) sites with damaged buildings, and for which shaking records is also available; (iv) sites where neither damage nor intensities were known.

Recent research (e.g., Iervolino et al., 2024) has shown that damage information at sites of type (ii) provides information about the shaking that caused the surveyed damage. This is because buildings work as seismic stations recording shaking in terms of damage states rather than acceleration or velocity. Consequently, it is possible to use the damage information to inform the ShakeMap. To do so, a probabilistically consistent procedure, based on sequential Monte Carlo method, was developed and the results it produces are preliminarily presented herein.

Starting from the GRF assumption of the classical ShakeMap, conditional on source information and records, the algorithm generates an arbitrary number of realizations of the random field at the damage-surveyed sites. Then it iteratively selects those most compatible with the observed damage, based on a maximum likelihood criterion. Finally, the selected damage-informed random field realizations are used to generate IM realizations at the sites where neither damages nor shaking records are available, that is those of type (iv), through the GRF. This enables deriving the damage-informed distribution of the IM in the area, from which damage-informed ShakeMap are obtained.

Two relevant implications of the approach developed are that: (a) the damage-informed intensity in the area does not form a GRF anymore; (b) at sites where a recording station is present, that is those of type (iii), possible damage information is irrelevant for updating the ShakeMap. In other words, these sites are equivalent to those of type (i) for the purposes of ShakeMap development.

Case study

The case study of the L'Aquila earthquake, occurred on the 6th of April of the 2009, with a moment magnitude equal to 6.1, is considered. In fact, building damage information was collected in the Da.D.O. database (Dolce et al. 2019). Herein, damage to the reinforced concrete buildings with three and four storeys, designed for seismic actions before 1981, was considered. Observed data consists of 5247 buildings located at 1058 sites. For the ideal application developed herein, only 50 sites were selected out of 1058. Moreover, instead of the real number of buildings at each site, two different cases were considered, at each site there are: (1) 10 buildings; (2) 100 buildings.

The classical ShakeMap (i.e., without considering damage) for this earthquake was first developed, considering the peak ground acceleration (PGA) as the IM, using the ground motion prediction equation (GMPE) of Bindi et al. (2011), with the spatial correlation model of intra-event residual of Esposito and Iervolino (2011). The recordings to inform the ShakeMap are from 51 monitoring stations within the applicability limits of the selected GMPE. Fig.1-a) shows the median PGA of the GRF at the selected 50 surveyed sites.

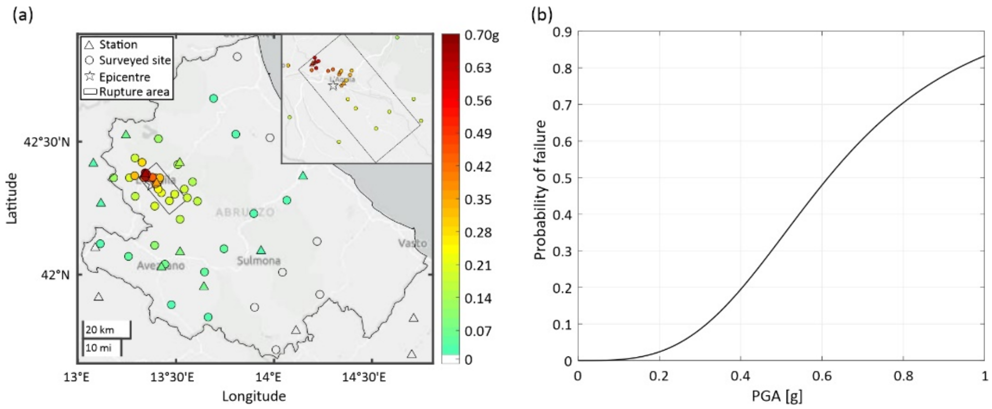

Fig. 1 – (a) Median PGA of the original GRF at the surveyed sites; (b) semi-empirical fragility curve to simulate DS3 or worse damage (from Iervolino et al., 2024).

To evaluate the damage-informed ShakeMap, it needs to know the damage to the buildings at the 50 surveyed sites. For this application, the damage at the buildings was simulated using the semi-empirical fragility curve, for DS3 damage level, from the work Iervolino et al. (2024), which is shown in Fig.1-(b). To simulate damage to inform ShakeMap, each building at each surveyed

site was assigned a *damaging* PGA (where damage means DS3 or worse) value simulated sampling the fragility curve. This sampled PGA, causing building damage, was then compared to the PGA value experienced by the building site, which was single realization of the original GRF. Each building is considered damaged if the simulated PGA at the site from the GRF is larger than its damaging PGA.
The simulated damage to the buildings was used as input to the sequential Monte Carlo method to obtain 10,000 damage-informed shaking fields in the area. The median PGAs map from these realizations was compared with the original (classic) ShakeMap.

Results
Fig.2 shows the effect of the structural damage on the ShakeMap for the two considered ideal cases. More specifically, the figure shows the median PGA estimate for a regular grid around the source of the earthquake. Fig.2-(a) shows the median original ShakeMap, while panels (b) and (c) the damage-informed median ShakeMap for the cases of 10 buildings and 100 buildings at each surveyed site, respectively. The surveyed sites are denoted by circles, and the corresponding greyscale colour indicates the percentage of damaged buildings at each site (i.e., number of buildings in DS3 from simulation over the total number of buildings at the site).

It is apparent that the percentage of damaged buildings affects the ShakeMap the more the site of interest is distant from the recording stations. In other words, the effect of damage in constraining the ShakeMap is especially noticeable for sites in areas where no recordings are available.

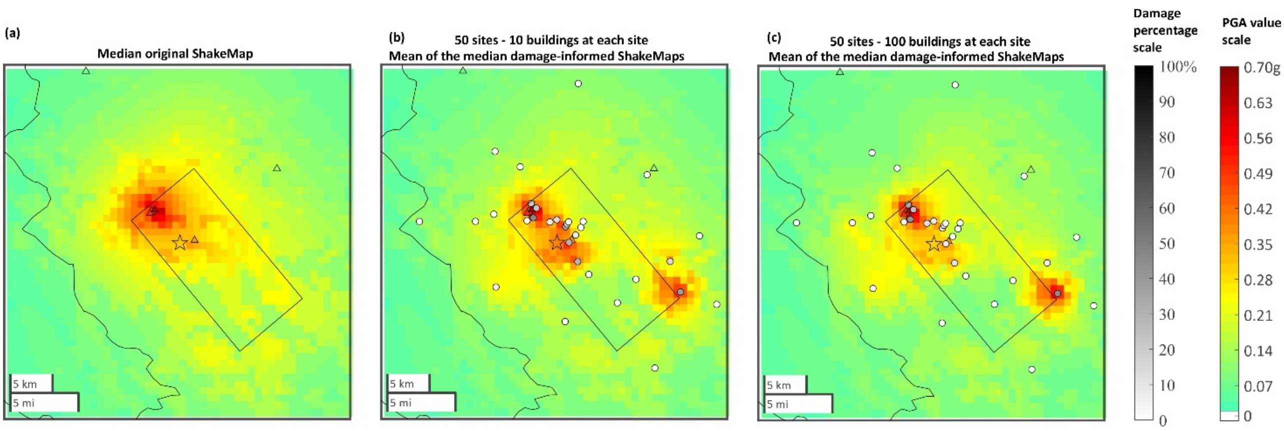

Fig. 2 – (a) Median ShakeMap conditioned to the measurements to the stations. Mean of the median damage-informed ShakeMap for the case of: (b) 10 buildings and (c) 100 buildings at each surveyed site.

To understand how damage affects ShakeMap, Fig.3 shows the probability density functions estimate (PDFs), approximated by histograms, of the IM at selected sites. The grey PDFs are those from the GRF, that is, only conditional on magnitude, location and accelerations at the recording stations (i.e., classic ShakeMap). The red histograms represent the damage-informed PDFs at the same sites from the sequential sampling algorithm. The black and the red dashed lines are the median of the grey and red distributions, respectively. The blue dashed line represents the value of PGA used to simulate the damage, which, therefore, can be considered as the *true* PGA at the site.

Three surveyed sites are considered in the figure, in particular the sites (a) and (b) are located near to the stations, while the site (c) is far. Site (a) experienced a *true* PGA lower than the median value of the PDF from the classic ShakeMap; site (b) experienced a value of PGA about equal to the median of the classic ShakeMap PDF; site (c) experienced a *true* PGA larger than the median value of classical ShakeMap PDF. It is observed that: (1) the median damage-informed IM is always closer to the *true* PGA value, with respect to the classic ShakeMap; (2) damage information reduces the uncertainty IM estimates, except when the *true* PGA is far in the tail of the classic ShakeMap distribution; (3) the uncertainty reduction is larger for sites with a larger number of buildings.

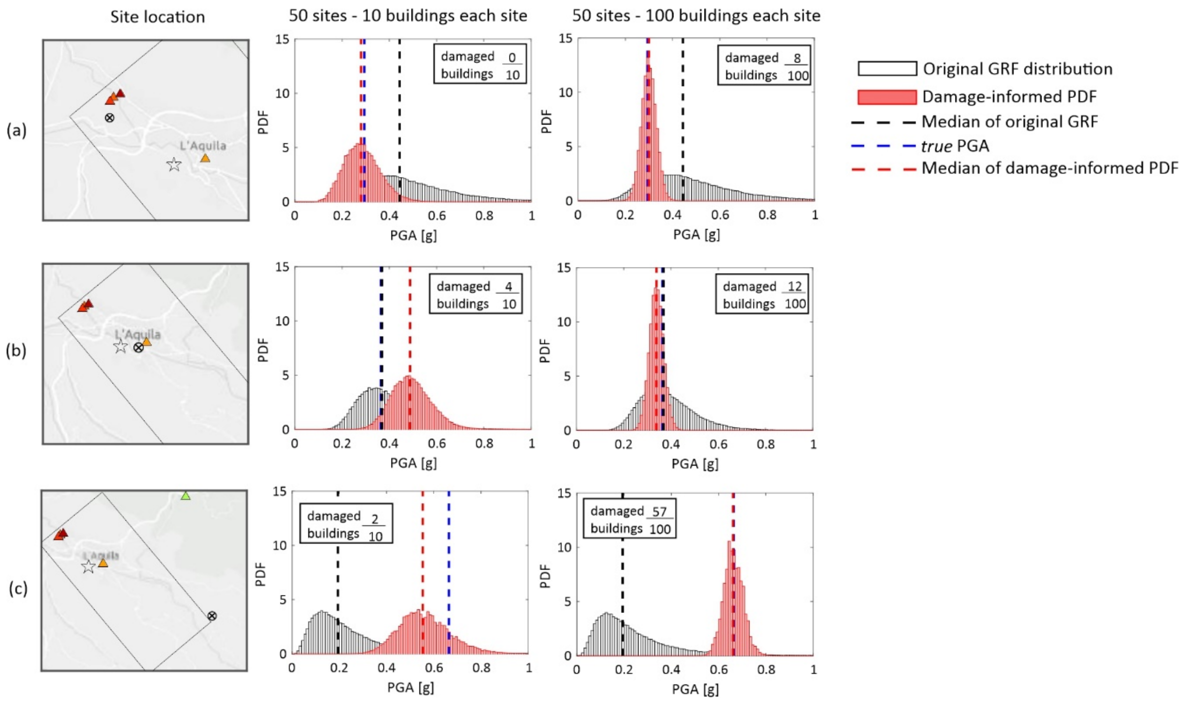

Fig. 3 – PDFs for three damage-surveyed sites.

Conclusions

This preliminary work quantitatively demonstrates the effect of structural damage information on ShakeMap. Such an effect depends mainly on the percentage of damaged buildings at the surveyed site and on the distance surveyed site from the recording stations. The key findings are that: (1) the knowledge of damage tends to decrease the uncertainty on the estimate of the IM in the area, except in those cases where the true IM is very atypical according to the classical ShakeMap; (2) neglecting the damage information tends to provide biased shaking intensity estimates in the area.

References

Bindi D., Pacor F., Luzi L., et al., 2011: Ground motion prediction equations derived from the Italian strong motion database. *Bull Earthquake Eng.*

Dolce M., Giordano F., Borzi B., et al., 2019: Observed damage database of past Italian earthquakes: the Da.D.O. *WebGIS*. *Boll. Geof. Teor. Appl.*

Esposito S., Iervolino I., 2011: PGA and PGV spatial correlation models based on European multievent datasets. *Bull Seismol Soc Am*.

Iervolino I., Rosti A., Penna A., Giorgio M., 2024: Damage-informed ground motion and semi-empirical fragility assessment. *Earthquake Engng Struct Dyn.*

Worden B.C., Thompson E.M., Baker J.W., et al., 2018: Spatial and spectral interpolation of ground-motion intensity measure observations. *Bull Seismol Soc Am*.

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