Improving Models of Spatial Correlation of Earthquake Ground Motion

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Earthquake ground motion

The ground motion of interest to engineering is often the transient ground shaking that occurs during an earthquake. It is evaluated in terms of one or more scalar intensity measures (IMs), such as the peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD) at a specific site. Figure 1 shows the acceleration, velocity and displacement time histories, respectively.

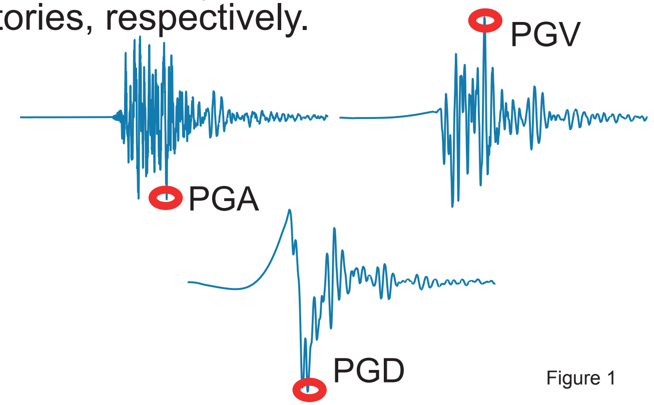

Figure 1

The ground motion can be expressed also by the acceleration response spectrum SA, which represents the maximum response of a single-degree-of-freedom system of oscillators, characterised by different periods T and damping values, and subject to an earthquake ground motion time history.

Ground Motion Prediction Equaton (GMPE)

Traditional seismic hazard and risk analysis tools usually employ ground motion prediction equations to estimate the ground shaking at a given site. GMPEs relate a ground motion IM to a set of explanatory variables describing the source (e.g. magnitude and faulting mechanism), the wave propagation path (e.g. distance metric and regional effects) and the site conditions (e.g. soil classification).

IMs are modelled as lognormally-distributed random variables:

$$\log_{10} Y_{ij} = \log_{10} \overline{Y_{ij}}(M, R, S, \theta) + \varepsilon_{ij} + \eta_i$$

where Y_{ij} is the IM of interest at site ith due to the jth event and $\bar{Y}_{ij}$ is the predicted median function of magnitude (M), distance from the source (R), local-site conditions (S) and other explanatory variables (θ). η denotes the between-event residual term, whereas ε is the within-event residual term.

Correlation

It quantifies the degree to which two variables (e.g. IMs) at different sites separated by a given distance (h) are related. It is usually represented by a semivariogram, a geostatistical tool, which measures the average dissimilarity between two variables.

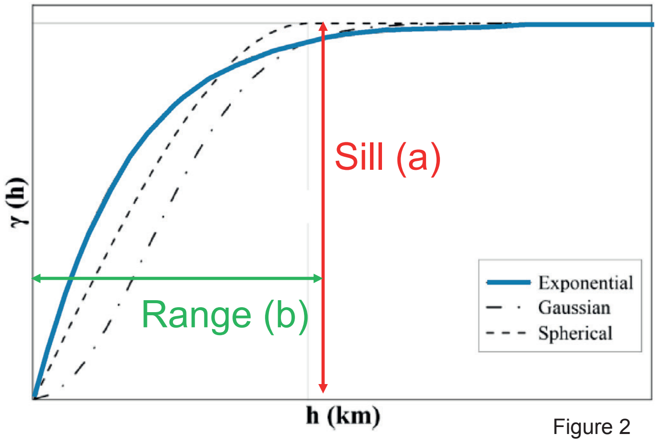

Figure 2

$$\gamma(h) = a[1-\exp(-3h/b)]$$

Need for spatial correlation models

Traditional seismic hazard and risk analysis tools use GMPEs to estimate the ground shaking at a given site and are grounded on the hypothesis of independency between IMs at closely spaced sites. Standard Probabilistic Seismic Hazard Assessment is now a well-established tool.

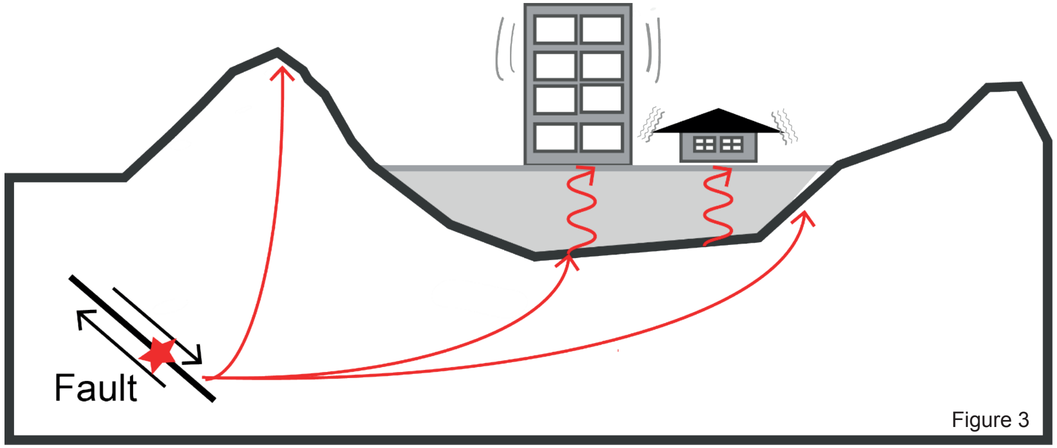

Figure 3

However, the quantification of the seismic performance of spatially distributed infrastructures over a region requires not only the estimation of independent IMs values at different sites, but it also requires defining, simultaneously, correlated ground motions at multiple locations during the same earthquake. Understanding the spatial characteristics of the ground motion is thus needed to provide a more accurate representation of ground-motion fields.

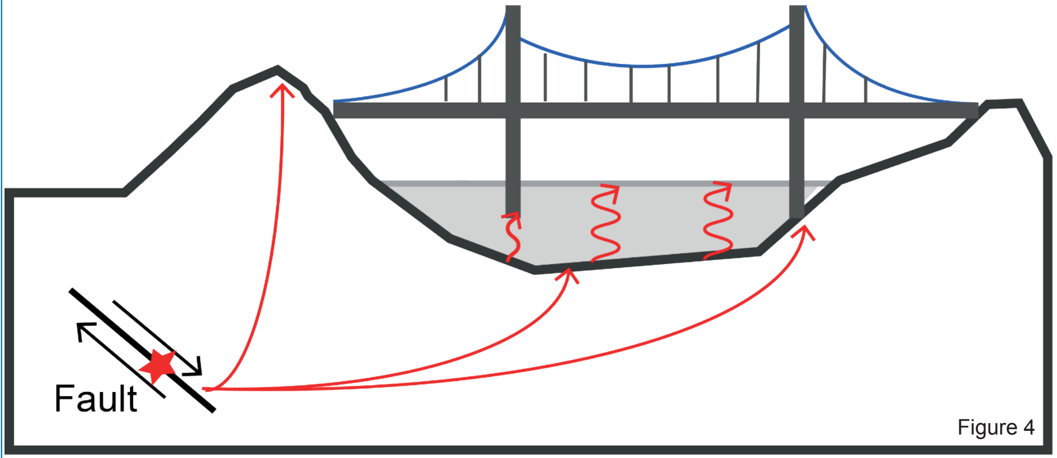

Figure 4

Importance of spatial correlation

Stakeholders, such as government, search-and-rescue organizations and private companies, require a reliable evaluation of the ground motion field to support decision making for civil protection emergency planning as well as long-term and rapid loss and risk assessment.

Earthquake ground motions in epicentral areas are often recorded at only a handful of seismometers separated by many kilometres (Figure 5a). Therefore, knowledge of how the ground motion varies spatially is required to predict ground-motion IMs at unobserved locations to generate shaking scenarios. (Figure 5b).

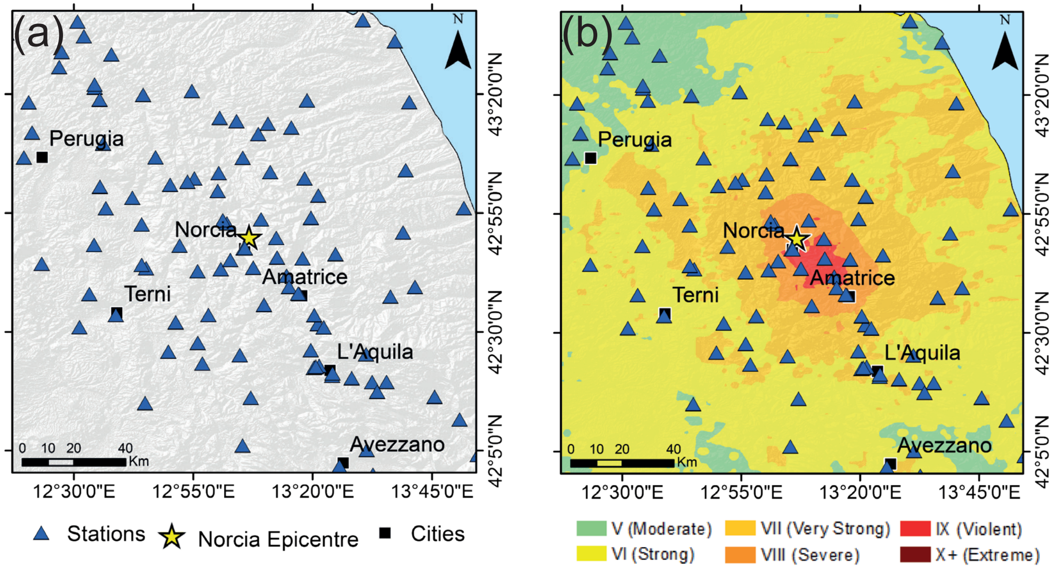

Figure 5

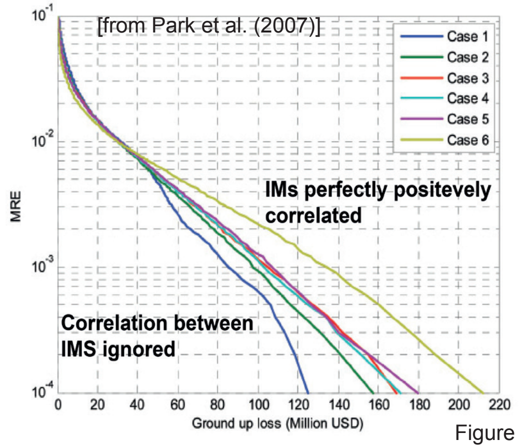

Figure 6

The importance of defining spatially-correlated ground-motion fields is demonstrated by several authors [e.g. Park et al. (2007)]. Neglecting the spatial correlation, for example, may cause a bias in loss estimates, overestimating the most likely losses and underestimating rare losses.

Which factors most influence the spatial correlation of earthquake ground motion?

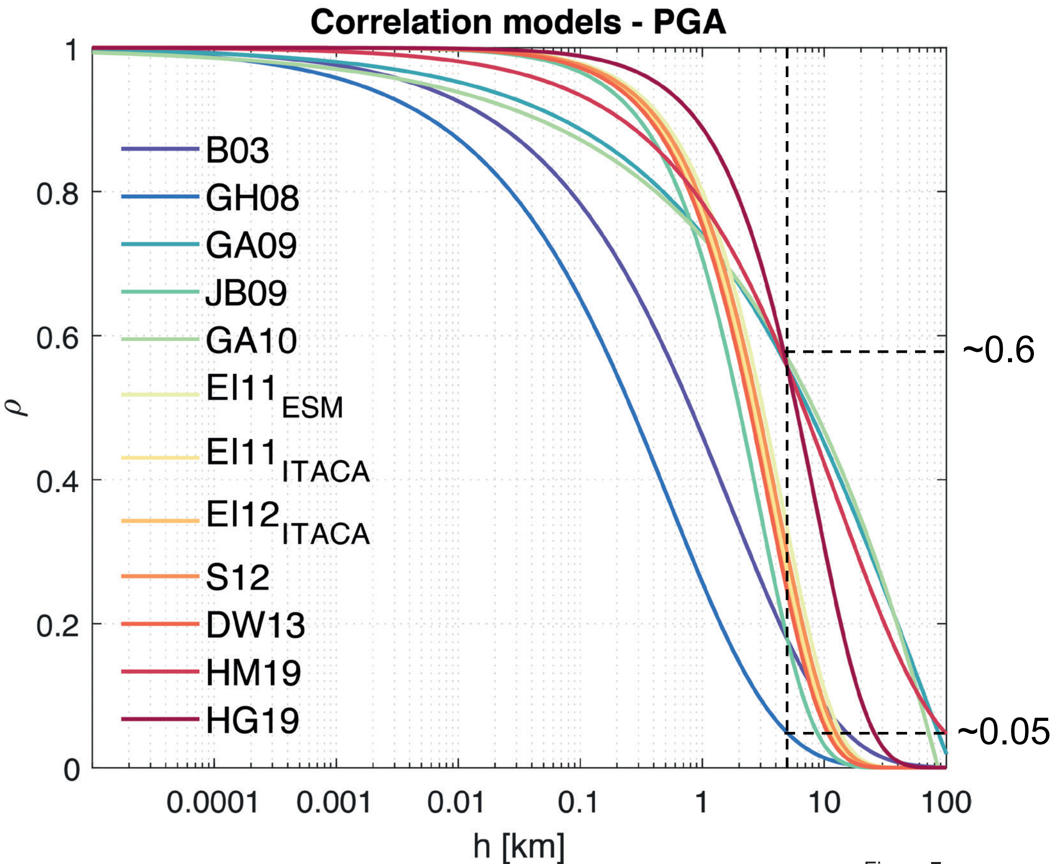

Figure 7

EI11 (ESM): Esposito and Iervolino (2011) based on the ESM database; EI11 and EI12 (ITACA): Esposito and Iervolino (2011,2012) based on the ITACA database; GH08: Goda and Hong (2008); GA09 and GA10: Goda and Atkinson (2009, 2010); JB09: Jayaram and Baker (2009); B03: Boore et al. (2003); HM18: Heresi and Miranda (2018).

→ MAGNITUDE
→ ESTIMATION METHOD
→ GEOLOGICAL STRUCTURE
→ SITE EFFECTS
→ PERIOD
→ GMPE
→ NUMBER of RECORDING STATIONS
…

Dependence on Magnitude

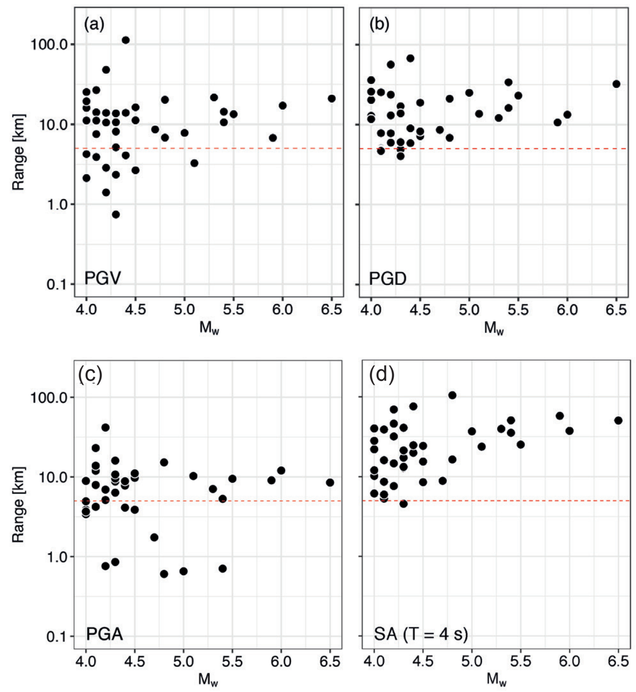

Figure 8

In figure 8, we compare the ranges obtained for each Mw ≥ 4.0 earthquake belonging to the 2016-2017 Central Italy seismic sequence as a function of magnitude. The results do not suggest any clear relationship between range and magnitude, at least for this Mw interval, in agreement with the findings of Jayaram and Baker (2009). We believe that other factors should be considered to explain the variability in terms of correlation length, especially when the same seismic region is considered, as suggested by Stafford et al. (2018), who demonstrated that the rupture process of events of equal magnitude has a significant contribution on the variability in the range. We are carrying on further studies on this aspect, using 3D physics based ground motion simulations.

Dependence on Period

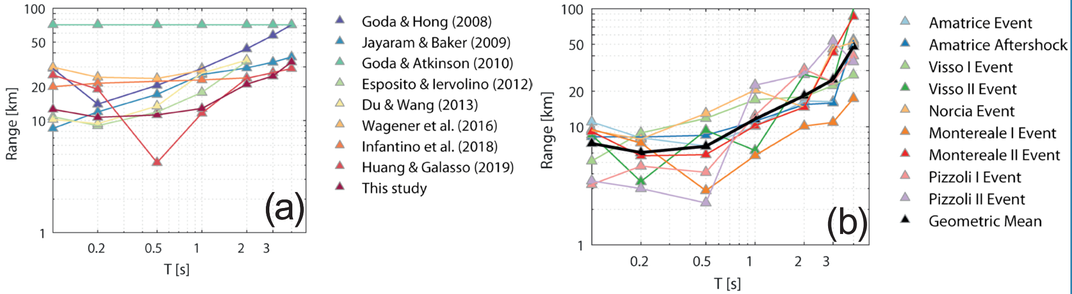

Figure 9

Figure 9a provides an overview of the range as a function of period of different studies along with the correlation model obtained using data from the 2016-2017 Central Italy seismic sequence. Range and period are directly proportional, in agreement with studies on ground-motion coherency. In figure 9b, we observe the increasing trend with period for all Mw ≥ 5.0 events of the sequence taken individually, as well.

Dependence on local site effects

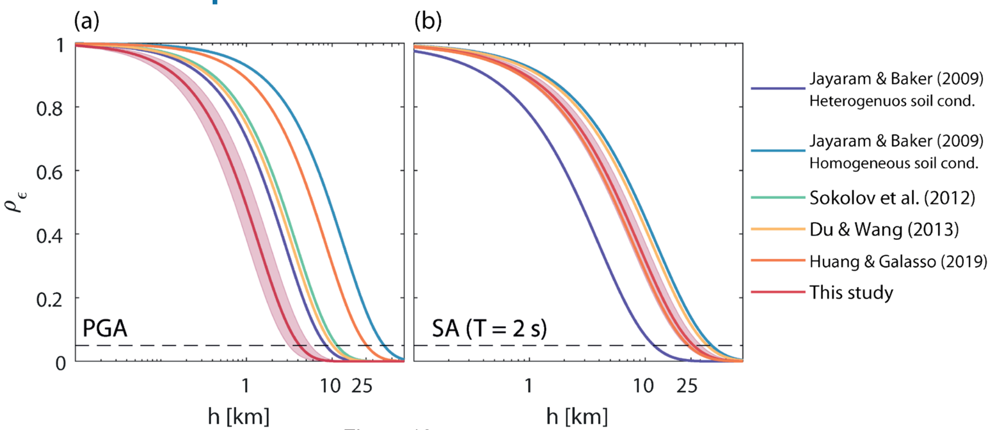

Figure 10

Several studies indicated that the level of correlation is strongly influenced by site conditions, especially when short-period IMs (e.g. PGA) are of interest. Our results agree with those found in literature. In particular, the comparison between the Huang and Galasso (2019), based on Italian data, and Central Italy models suggests that the correlation strongly depends on the geological characteristics of the considered specific area.

Conclusions

In this work, we aim to provide insights into the spatial correlations of earthquake ground-motion intensity measures. We critically summarize the main findings of previous studies and we attempt to address the primary questions about ground-motion spatial correlation:

1) We do not find any relationship between magnitude and correlation distance. We believe that other source effects, such as directivity and azimuth should be accounted for, as outlined in Stafford et al. (2018);

2) We find a positive correlation between the range and response spectral period, as expected from the literature;

3) We analyse the dependency of the spatial correlation on local-soil conditions, illustrating that the influence of local-site effects is period-dependent, as demonstrated already by several authors. We also believe that region-specific spatial correlation models should be derived since we demonstrate that a single rate of decay of the correlation is not suitable for seismic hazard and risk assessment, even though all the data came from the same country (Italy in this case).

The reader should refer to Schiappapietra and Douglas (2020) [a, b] for more details.

References

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