A scenario-based approach to generate empirical shaking maps in Central Italy from non-ergodic ground motion models

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Generation of seismic shaking maps as a tool to support decision making at a given site is a key-topic for civil protection planning and engineering purposes. Currently, shaking fields are based on Ground-Motion Models (GMMs), which estimate the intensity measures as a function of several parameters dependent on the reference earthquake scenario (magnitude, distance, soil category, etc.). However, GMMs are usually provided under the assumption of ergodic standard deviation (i.e. the spatial variability at many sites is assumed identical to the variability at a single site; Anderson and Brune, 1999). This assumption implies higher level of uncertainty associated to the model predictions, due to the fact that ergodic GMMs are calibrated on geographical areas where more records are available, thus neglecting region-specific features of ground motion behavior. However, in case of site-specific PSHA purposes or engineering applications at local scale (i.e. loss assessment and risk analyses of structures and infrastructures) there is the need to improve the ground motion prediction performance. In these cases, the simplified assumption of ergodicity may be not reliable to describe regional properties of the ground shaking (i.e. magnitude scaling, distance attenuation characteristics and site effects). More accurate predictions can thus be computed by relaxing the ergodic assumption in favor of non-ergodic approaches, in which the repeatable terms of variability due to source-, path- and –site effects are used to provide region-specific corrections of the median predictions, as well as to transfer part of the aleatory variability into epistemic uncertainty (e.g., Rodriguez-Marek et al., 2013; Villani and Abrahamson, 2015; Baltay et al., 2017; Lanzano et al., 2017).
Following this concept, we propose a methodology for generating empirical shaking maps of the acceleration spectral ordinates based on a non-ergodic GMM calibrated on Central Italy, in which the systematic contributions of the variability are decomposed. The obtained corrective terms are then mapped by means of spatial correlation models to provide the local adjustments of the ground shaking, following the approaches proposed for California (Landwear, 2019; Sahakian et al., 2019) and Emilia region in Italy (Sgobba et al., 2019).
We finally simulate the ground shaking empirically, by adding up the ground motion intensity field predicted by the GMM and the spatially correlated fields of the site (δS2S), source region (δL2L) and path (δP2P) effects computed at any point of a regular grid.
Implementation of such a modelling clearly requires a dense dataset in order to compute robust estimation of the repeatable terms. For this reason, we focus our study on Central Italy, where a huge quantity of high-quality strong-motion records (more than 30.000 waveforms) has become available after the occurrences of significant events in the last 10 years.
Results show peculiar spatial patterns of the site and path effects in the region, that can be related to physical aspects not fully captured by the GMM. The impact of the corrections on the shaking pattern and spectral intensity amplitudes is also shown through empirical simulations of the ground motion scenarios related to past earthquakes.

Dataset

Dataset is composed by accelerometric and velocimetric earthquake signals, recorded by stations and events located in Central Italy since 2008 and including data of the 2009 L'Aquila and the 2016-2017 Central Italy sequences. It is composed by more than 30,000 records of about 450 earthquakes in the magnitude range 3.4 – 6.5 and more than 460 stations within 250 from the epicenters.
The huge number of waveforms is due to the great effort made during the last seismic sequences in 2016 (Amatrice Mw 6.0 – Visso Mw 5.9 - Norcia Mw 6.5) by the Italian Department of Civil Protection (DPC), the Istituto Nazionale di Geofisica e Vulcanologia (INGV) and several academic and research institutions that installed more than 100 stations with the aim of improving the event locations and monitoring the site effects (Priolo et al., 2019; Cara et al., 2019).

Region-specific GMM

In order to calibrate an ad-hoc non-ergodic GMM in the study area, a mixed effect model is applied similarly to the one recently proposed for Italy (ITA18, Lanzano et al., 2019), where the "fixed" effects account for magnitude scaling and for geometric and anelastic decay with distance, while the "random" effects are related to event, site, source and path. The median prediction of this GMM is assumed to be referred to the ground motion intensity level predicted for the reference sites (i.e. the sites characterized by a flat site response and an amplification factor around unity) identified according to the procedure by Felicetta et al. 2018.

The GMM is calibrated for the geometrical mean of the horizontal components of the Peak Ground Acceleration (PGA) and 70 acceleration response spectral ordinates (SA) in the period range 0.04-2s.

With respect to the predictions, three correction contributions of the systematic and repeatable effect of ground motion are estimated through the residual analysis:

- the site-to-site residual term (δS2S) defines the systematic bias of ground motions recorded at a specific stations with respect to the GMM predictions (fixed-effects) at reference sites; in this way the δS2S can be considered as a proxy of the amplification function of the station;
- the location-to-location term (δL2L) defines the systematic bias of the source regions. The location terms are here computed by means of two different procedures: (i) GRID approach: the study area is divided into a regular grid with any cell representing the source region in which the events are averaged; (ii) CLUSTER approach: the events are aggregated and averaged within polygonal areas identified on the basis of spatial-temporal criteria of clustering. δL2L may be related to the average stress-drop within the source region (Baltay et al., 2017; Bindi et al., 2018);
- the path-to-path term (δP2P) defines the systematic deviations along one source-to-site path and is related to anomalies in crustal velocity, density or in the attenuation function (Baltay et al., 2017). δP2P are here computed on the basis of the two different procedures used to identify the source areas (models GRID and CLUSTER).

Geostatistical analysis of the residual terms

To investigate and model the spatial dependence of the corrective terms, a traditional geostatistical analysis is applied. Under the hypothesis of univariate normal distribution and intrinsic stationarity (for the site terms) while non-stationarity (for the path terms), a spatial correlation model is built by fitting the sample semivariograms. A Kriging interpolation technique is applied as a predictor to estimate the value of the corrective terms on the unsampled locations of the computation grid (1.6x1.6 km resolution) and then to reconstruct the fields of the corrections.

Maps of such residuals show remarkable path effects: as exemplified in Figure 1 for L'Aquila source area, the spatial distribution of the δP2P for PGA are positive over about 30 km of correlation distance for the seismic waves travelling from the Apennine chain to the Adriatic coast (red contours), whereas deamplification is observed towards the Tyrrhenian coast (blue contours). Maps of interpolated δS2S terms are characterized instead by smaller correlation distances at almost all investigated periods. In any case, the variability of these terms was found to be relevant (in the range 0.1-0.15 log10 units), when removed from the aleatory uncertainty.

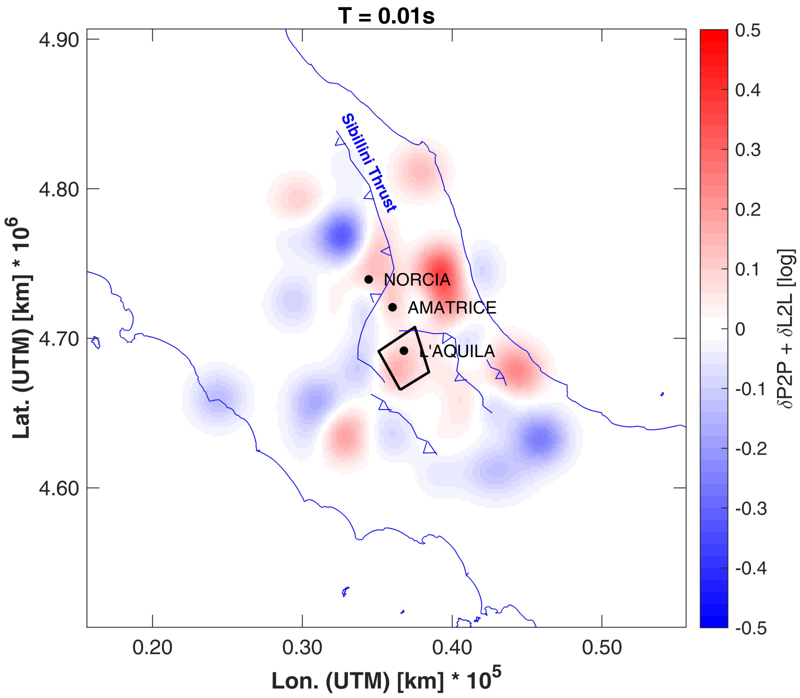


Fig.1. Example of spatially correlated fields of the path and location terms computed for L'Aquila area (CLUSTER model) at PGA.

Example of empirical simulation and discussion

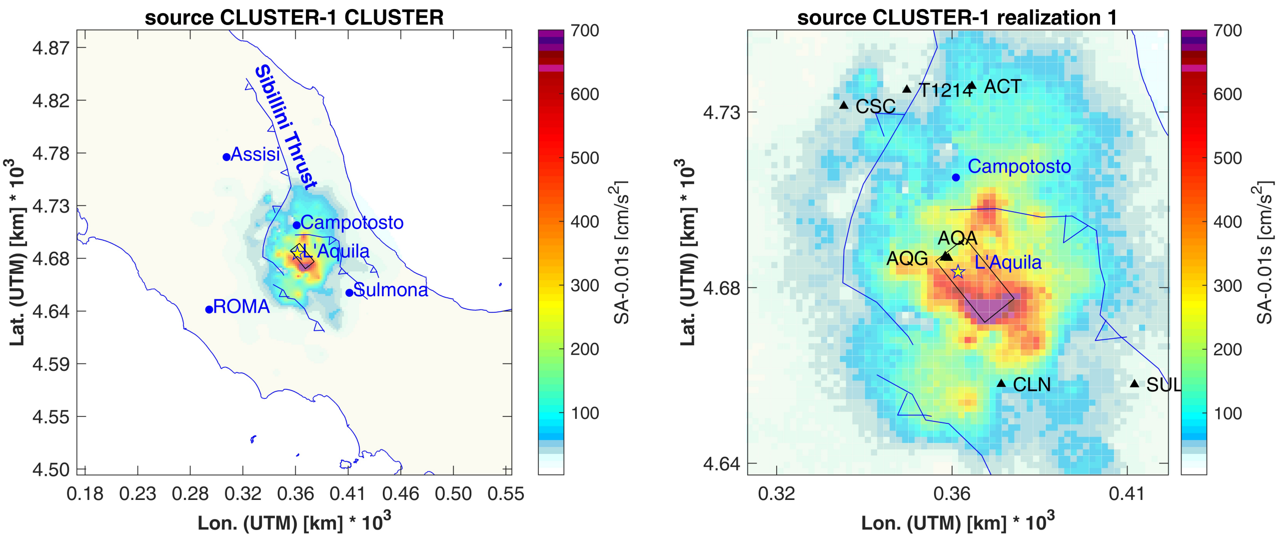
Once built the non-ergodic model and obtained correlated fields of the corrective terms through geostatistical analysis, we are able to compute the pattern of the ground shaking by summing each contribution (median prediction and residual corrections) at any point of the regular grid. Here we show an example of shaking map (mean field) related to the scenario of L'Aquila M_w 6.1 earthquake occurred on 6th April 2009 for PGA (Fig.2a). Following the proposed method, equiprobable realizations of the shaking maps are obtained by incorporating the prediction uncertainty (accounting both for the spatial interpolation variance and the residual aleatory variability) at different percentiles (Sgobba et al., 2019); as shown in Fig.2b for L'Aquila example.

A comparison of the acceleration spectral ordinates with the observed values for different recording stations, performed in terms of different error metrics (Root Mean Squared Error and R-squared error), confirms the reliability of the GMM predictions adjusted for the regional corrections, with small differences between the GRID and the CLUSTER models.

The obtained spatial distribution reproduces the main ground motion patterns as documented in the literature for the event of L'Aquila with reference to instrumental data or according to macroseismic observations (see Ameri et al., 2011 for example). The most relevant similarity with the patterns proposed in the literature can be found on the systematic amplification effect observed at the south edge of the surface projection of the fault, which maybe more likely related to combined effects of site and path.

Other tests have been performed also on independent events (i.e. not included in the dataset calibration), confirming the good agreement between predictions and observations. Some inconsistencies (average residual ~0.3 log10 units) have been detected at longer periods for events with larger magnitudes and conversely at short periods for smaller events at stations above or in the proximity of the faults, thus suggesting that the ground motion is here affected by more complex near-source effects, not fully captured by the adjusted model. This may be due to the fact that near-source effects mainly depend on the specific source and thus cannot be mapped into the repeatable terms of variability.

Further improvements of the proposed approach include the implementation of the directivity effects into GMM by modelling the azimuthal distribution of the aleatory residuals (i.e. the final residuals after removing the systematic components). The procedure could also take advantage from the application of advanced geostatistical techniques to obtain more accurate spatial interpolation of the corrective terms.



(a) (b)

Fig.2. Example of shaking maps simulation of the Mw6.1 L'Aquila earthquake (median field – 50° percentile) at PGA (a); zoomed map around the fault area (random field realization at 65° percentile) (b). Star indicates the epicenter of the event whereas black triangles indicate the recording stations. Continuous blue lines inside the area represent the main thrusts.

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