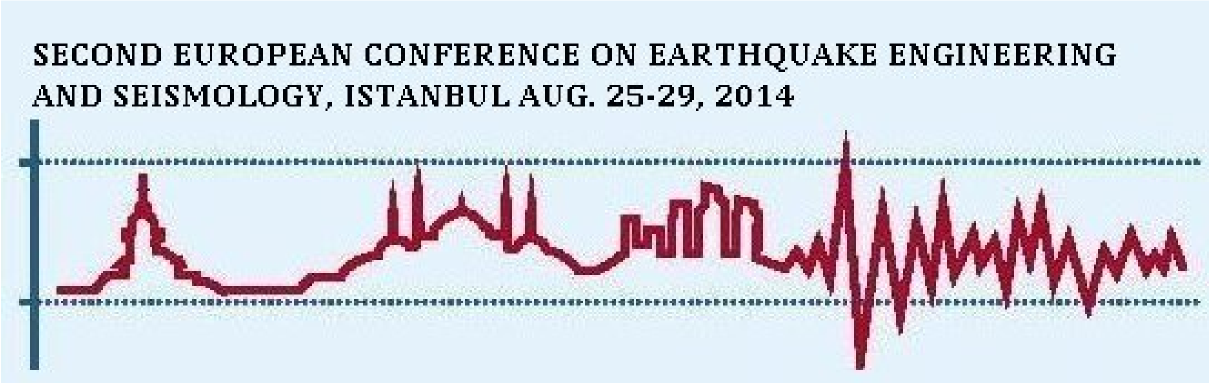

MACROSEISMIC INTENSITY CONSTRAINT FOR PROBABILISTICALLY BASED SHAKEMAPS

Emilia FIORINI[1] and Paolo BAZZURRO[2]

ABSTRACT

In this work we present footprints of ground motion intensity for a set of historical Italian earthquakes that were produced using a selected GMPE and an empirically-based spatial correlation model. The ground motion fields have been constrained by instrumental observations where available, following a well established methodology, firstly published by Park, Bazzurro and Baker (2007), that allow one to produce spatially correlated ground motion fields consistent with recorded shaking intensities for a given earthquake. That approach has been expanded in this study to include amongst the constraints of the random fields also the “imperfect” observations related to macroseismic intensities.

INTRODUCTION

The focus of this study is to provide a probabilistic representation of the regional ground motion generated by selected Italian historical earthquakes that is informed by all available data, namely accelerograms and macroseismic intensity observations. This representation takes the form of a map of median ground motion conditioned on all the information available supported by a set of correlated ground motion random fields of peak ground acceleration that are also statistically consistent with the available data. The set of random fields provides a depiction of the uncertainty about the actual but unknown level of ground motion generated by these earthquakes. Usually only the conditional median map is computed (i.e., a ShakeMap in the terminology of USGS) In this article, we will present our proposed methodology for computing such random fields and we will show them for the Mw 6.3 L’Aquila 2009 Earthquake. The median map along with simulated random fields around the median values are the best probabilistic representation of ground motions generated by a past event. A set of such maps, which models the variability of the ground motion generated and not only our “best” guess, is very valuable for multiple applications, such as loss estimation for portfolio of buildings. If the full variability of the ground shaking is not modelled, a full probabilistic estimation of losses is hindered.

Shakemap scenarios could be obtained by complex kinematic or dynamic rupture models that can reproduce quite well for a given rupture the pattern of shaking in the nearby region. However, such models require detailed knowledge of the rupture parameters, have not been completely tested, do not capture the nonlinearity of the soil response, and provide dependable ground motion only for relatively long periods. A more pragmatic and routinely used way to produce scenario of ground motion intensity measures (IMs) for a given earthquake is to use a Ground Motion Prediction Equation (GMPE), which takes into account the variability related to both earthquake characteristics and site effects. The conventional use of GMPEs, however does not take into account the effect of spatial correlation of IMs from site to site.

[1] Dr, EUCENTRE, Pavia, emilia.fiorini@eucentre.it
[2] Prof, IUSS, Pavia, paolo.bazzurro@iusspavia.it

There is empirical evidence that ground motion IMs from a single event are spatially correlated from site to site. The production of the ground motion random fields is based on published research on spatial correlation of conditional and unconditional ground motion IMs, as well as on available geological and seismological data for the historical earthquakes, such as fault data, soil maps and instrumental datasets.

SPATIALLY CORRELATED INTENSITY MEASURES

Intensity measures from a single event are spatially correlated from site to site due the characteristics of the generating earthquake (e.g., stress drop, rupture velocity), path effects, and near fault effects, such as proximity to fault asperities for sites close to the fault plane (Park, Bazzurro and Baker 2007). Spatially correlated random fields can be produced either without any observation constraining the resulting ground motion (unconditional random fields, typically used for modelling future events) or, if available, by using data of observed IMs to constrain the resulting ground motion (i.e., conditional random fields). The general methodology for both cases is described in detail in Park, Bazzurro and Baker (2007).

The simulation of spatially correlated random fields of ground motion relies on the general framework of Ground Motion Prediction Equations (Loth and Baker, 2013), defined for an earthquake j at site *i* as,

$$lnY_{ij} = \overline{lnY_{ij}} + \sigma_{ij}\epsilon_{ij} + \tau_j\eta_j \quad (1)$$

where $\overline{lnY_{ij}}$ is the mean of the log ground motion predicted by the model, as a function of magnitude, distance, site conditions. η and ε are standard normal error terms that model the between event (a.k.a. inter) and within event (a.k.a. intra) variability of ground motion, while τ and σ are the corresponding standard deviations estimated by the selected GMPE. For a given earthquake j the η term is assumed to take on the same value at all sites, while the within-event residuals are different from site to site and display a spatial correlation that depends on the inter-site distance h. This spatial correlation has been empirically investigated by several authors (Jayaram and Baker, 2009; Goda and Hong, 2008; Loth and Baker, 2013) and formulations exist that can be included in the modeling of ground motion fields.

If intensity measures from recording stations are available, they influence the values of ε at sites nearby the observations to an extent that is dictated by the adopted spatial correlation model, and can therefore be included in the modeling to produce conditional random fields of ground motion.

MACROSEISMIC INTENSITIES

Macroseismic intensities can be used to supplement the observations of ground motion for historical earthquakes where few or sparse records are available to constrain the random fields of IMs. Macroseismic intensities, however, are not direct observations of ground motion IMs but they can be correlated to ground motion IMs via vulnerability models. However the conversion from macroseismic intensities to a so-called instrumental IM of ground motion, such as PGA, bear large uncertainties. Unlike the IM measurements at recording stations, which are considered to be known with certainty, the levels of IM inferred from the macroseismic intensity observationss are spatially correlated among each other and with the values of nearby recorded ground motions. One possible method to introduce macroseismic intensity measures in the modeling of random fields, consistent with the above requirements, is the method proposed by Ebel and Wald (2003), which applies the Bayes theorem to estimate the probability that a certain ground motion level is experienced at a site where a given macroseismic intensity has been reported, using the following formulation

$$P(GM_o|MMI) = \frac{P(MMI|GM_o)P(GM_o)}{\sum_{GM} P(MMI|GM)P(GM)} \quad (2)$$

The method utilizes empirical probability distributions $P(MMI|GM_o)$ derived from an intensity-ground motion dataset of Californian earthquake, and use these in conjunction with the prior probability distribution of ground motion $P(GM_o)$ derived from a GMPE to estimate the updated probability distribution of ground motion for a given MMI level, $P(GM_o|MMI)$. In the context of modeling random fields of IM, the unconditional prior probability distribution from the GMPE is modified based on the spatial correlation with the nearby recorded ground motion values, if available, and with the other macroseismic intensity observations. In this way the PGAs obtained from the macroseismic intensities are allowed to vary in a manner consistent with the spatial correlation structure adopted in the modeling. The PGAs obtained from the conversion of the macroseismic intensities are then used as a constraint in addition to the available strong motion observations, for the production of the conditional random fields of IMs. In the present work the simulated PGA value at each macroseismic intensity site is the median of the updated conditional distribution of GM|MMI.

HISTORICAL FOOTRPINTS FOR ITALIAN EARHTQUAKES

In this section we show an example of the application of the proposed methodology to produce the ground motion footprint of L'Aquila 2009 earthquake (Mw 6.3). PGA values from recording stations have been used in the conditional simulation of the random fields. Also macroseismic intensities have been converted to PGA, using the procedure outlined above, and used as a soft constraint in the modelling.

Fig. 1 shows a comparison of the PGA obtained with our conversion procedure with the PGA obtained using the conversion equations of Worden (2012) and Faenza and Michelini (2010). For this earthquake the PGA obtained with Equation 2 is more consistent with the values of from the Worden equation. This is not true, however, for other events in our study that display a better fit with the Faenza and Michelini equation. The scatter of the converted PGA data is comparable with the scatter of the original dataset used in the development of the Faenza and Michelini conversion equation.

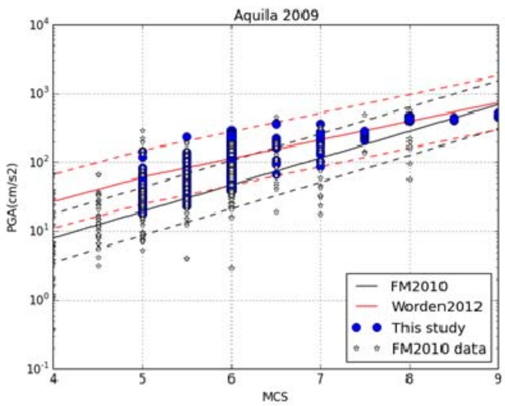

Figure 1. Macroseismic Intensity (MCS) versus PGA conversion of this study, compared with the relations of Faenza and Michelini, 2010 (FM2010) and Worden et al. 2012 (Worden2012).

Fig. 2 shows the median PGA of the random fields produced for the L'Aquila 2009 earthquake using the spatial correlation model of Jayaram and Baker (2009). The Akkar et al. (2013) GMPE has been used to calculate the median ground motion and the residuals of observations. The ground motion records have been downloaded from ITACA1.1 (Working Group ITACA, 2010), while the macroseismic intensity data come from the DBMI11 (Italian Macroseismic Database, Locati et al, 2011). The local site conditions are derived from a 1:100k soil map developed by the INGV (Di Capua et al., 2011), modified for this work by using available microzonation studies and the Vs30 available for some of the ITACA recording stations. It is worth noting that the maps produced in this study represent the geometric mean of PGA, rather than the PGA of the largest horizontal component as it is usually done in the ShakeMaps from the USGS.

In the maps of Fig.2 it is possible to see how the otherwise rather regular PGA contours are modified by the presence of the PGA observed at recording stations and by the conditional median

PGA inferred from the macroseismic intensity observations. The map shows a pronounced asymmetry of the PGA contour lines in the NW-SE direction, following the damage pattern which is distributed along the same direction, mainly SE of the fault, as described by many authors (Galli and Camassi 2009; Ameri et al., 2011). It is also possible to notice how patches of PGA higher than the surroundings are visible in correspondence of Onna, Villa Sant'Angelo and Castelnuovo, where MCS intensities of 9/9.5 have been reported. These patches of higher than expected shaking may not be so isolated but these are the only locations where MCS observations are available.

Table 1 shows the median PGA estimated for these locations in the present study, compared with the PGA values obtained from the INGV Shakemap (http://shakemap.rm.ingv.it/shake/2206496920/pga.html), and with those estimated with the conversion equation of Faenza and Michelini that, as stated earlier, does not fit well the damage caused by this earthquake. In particular Table 1 shows the same comparison for Castel di Ieri, a location about 25 km away from the fault, with a reported MCS of 6.5. This location belongs to a set of points with MCS 6.5 - 7 aligned SE of the fault. Although the INGV Shakemap displays the largest horizontal component of motion, our values for Onna, Castelnuovo and Villa Sant'Angelo are all higher than the INGV Shakemap, consistent with the large damage data reported for these sites. The PGA for Castelnuovo, the site farthest from fault among the three, is up to 3.8 times higher than the corresponding value in the INGV Shakemap.

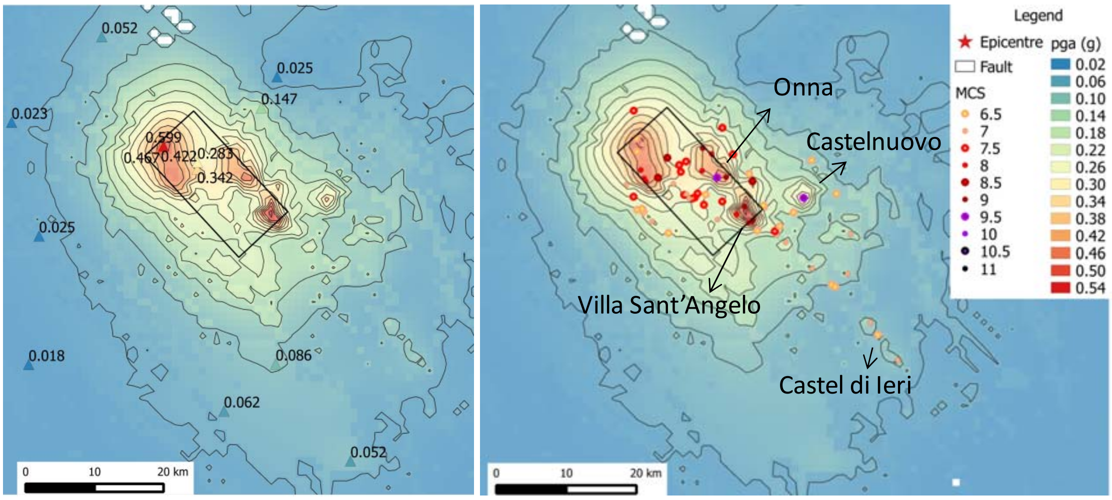

Figure 2. Median PGA of the random fields produced for L'Aquila 2009 Mw 6.3 earthquake, constrained by PGA observed at recording stations (blue triangles, left) and by macroseismic observations (right)

Table 1. Comparison of PGA from MCS intensities from different sources

Location	MCS	This Study	INGV Shakemap	Faenza and Michelini
Onna	9.5	0.47	0.30	1.1
Castelnuovo	9.5	0.38	0.10	1.1
Villa Sant'Angelo	9.0	0.52	0.19	0.7
Castel di Ieri	6.5	0.07	0.04	0.07

CONCLUSIONS

In this paper we have presented a methodology for the simulation of spatially correlated random fields of ground motion intensities that are statistically consistent with all available data on the level of ground shaking, both in terms of recorded ground motion values and in terms of macroseismic intensity data. The method proposed for the conversion of macroseismic intensities to PGA yields values that are spatially correlated with the available recorded observations, as well as with the other existing intensity points. Accounting for the latter source of information is particularly useful to improve the estimate of ground motion fields generated by older events, for which strong motion records are unavailable, or by more recent ones whose ground motion was recorded only at few stations. The latter is the case of the L'Aquila 2009 earthquake, whose ground motions in the high damaged areas south east of the fault was not recorded by any station. The example application described in this paper has shown how the development of historical footprints that include macroseismic intensities as if they were "imperfect" observations of IMs, is valuable in improving the estimates of ground motion from past earthquakes. The main application of spatially correlated random fields of ground motion IMs is in risk assessment of portfolio of buildings and lifelines. Random fields of correlated ground motion IMs constitute the most robust input to the probabilistic calculation of damage and loss caused by historical earthquake. This calculation serves the essential purpose of calibrating or validating earthquake loss estimation models. The calibration or validation of risk models usually utilises single ShakeMaps of median ground motion IMs that do not exploit the knowledge of macroseismic intensity observations. No random fields, such as those shown in Fig. 3, are used. The lack of consideration for the variability in ground motion IM results in a underestimation of the loss variability and possibly in a bias of mean loss estimates given to the nonlinear nature of the IM to loss relationships. The use of spatial correlation in the simulation of many random fields for the same earthquake conditional on all the observations available allows one to explore the effects of higher than median and lower than median ground motion on the distribution of losses at a regional scale.

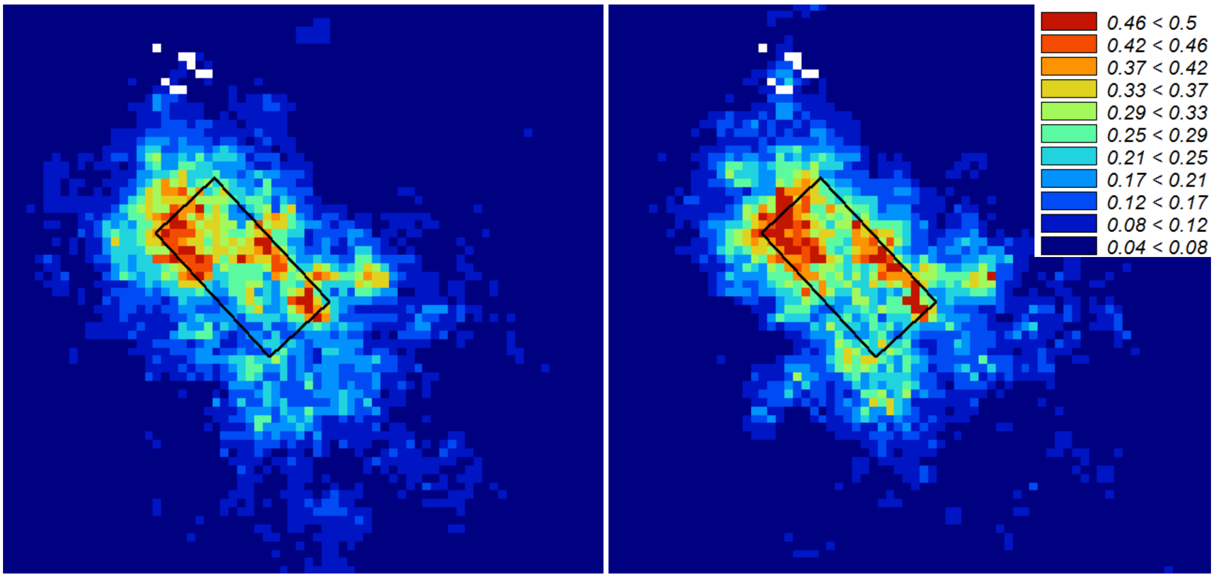

Figure 3. PGA for two of the random fields produced for L'Aquila 2009 Mw 6.3 earthquake

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