EFFECTS OF THE RUPTURE DIRECTIVITY ON THE PROBABILISTIC SEISMIC HAZARD MAPS IN THE SOUTHERN APENNINES, ITALY

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Introduction. In planning the design of structures in a region of potential seismic activity, a specification of the earthquake ground motion “intensity” is strongly needed. The earthquake occurrence and its effects on ground shaking is described as a stochastic process and thus its analytical representation is based on a number of state variables defined over a known space. Those variables which are called explanatory variables are linked together by a continuous function, the ground motion predictive equation (GMPE). The GMPEs have a significant role in the standard hazard practice as the hazard maps are based on a probabilistic assessment of such an empirically derived prediction. However, despite the relevance of the GMPEs in capturing first-order effects of the ground motion variability (e.g. attenuation with distance, dependence on magnitude, modulation due to the faulting style) and the fact that their characterization has greatly improved within the NGA project (Power et al., 2008) GMPEs are still incomplete; large azimuthal variations, ascribed to the complexity of the rupture propagation on a finite fault, are predicted and observed in the ground motion distribution (e.g., Benioff, 1955; Kasahara, 1960). Those spatial-temporal features of the ground motion variability generally lump together into the term “directivity effect” (Ben-Menahem, 1961). Several authors have introduced directivity in PSHA computations (Somerville et al., 1997; Abrahamson 2000; Rowshandel et al., 2006; Chiocciarelli and Iervolino, 2012 and references therein). In this work we follow the strategy proposed by Spagnuolo et al. (2012) who use the corrective factor for directivity proposed by Spudich and Chiou (2008). The advantage of the latter method is that the Spudich and Chou’s corrective factor is based on the physical meaning of rupture directivity that is: the energy radiated between the hypocenter and the closest point to the site is modulated as a function of the elapsing time; if this time is short the energy is time compressed, a directivity pulse is formed and the spectral amplitude is amplified. In order to retain this essential physics, Spudich and Chiou (2008) have developed a predictor for directivity by simplifying the computation of synthetic seismograms to an analytical expression. This analytical expression allows to make predictions even in absence of a direct empirical specification of the occurrence of a directivity effect.

The correction for rupture propagation. The analytical model of Spudich and Chiou (2008, hereafter SC2008) acts as a corrective factor - an additive term to the logarithmic expression of the ground motion intensity measure, i.e. spectral acceleration (SA) - in the GMPEs and its functional form is searched over both an empirical data-set and a database of synthetic simulations: the use of synthetic simulations guarantees a complete azimuthal coverage and, more generically, an efficient sampling that accounts for a statistically consistent combination of source parameters. SC2008 is based on a formalism derived from the isochrones theory (Bernard and Madariaga, 1984; Spudich and Frazer, 1984) - a high frequency representation of the seismic rupture where the source contribution at any given time and station is represented by a line on the fault plane called an isochrone. The isochrone velocity is directly proportional to the isochrone spacing and it is defined along the entire fault. In the two-dimensional case, the reciprocal of the isochrone velocity, the isochrones slowness, is equal to the usual seismic directivity function. The finite fault radiation pattern is approximated by a single point source radiation pattern corresponding to the hypocenter. In summary, the SC2008 corrective factor accounts for the fraction of rupture surface lying between the hypocenter and the point on fault closest to the site (s), for the isochrone velocity ratio (c’) and for the radiation pattern (p) which spatially modulates the ground motion amplitudes. The SC2008 depends on the spectral period (T), ranging between [0.5-10] seconds. It can be synthesized as follows:

\[ f_{SC008}(T) = f_M(M) f_R(R) [a(T) + b(T) IDP] \]  

(1)
IDP = C (c’) S (s) P (p)

where S, C and P are functional forms of s, c’ and p respectively; a(T) and b(T) are regression parameters; \( f_M \) and \( f_R \) are tapering functions depending on magnitude (M) and distance (R), respectively. Moreover, the authors provide an analysis of the inter-event residuals against several independent variables to resolve the most relevant parameters for the corrective factor. They reported no significant correlation of inter-event residuals with rupture velocity to shear velocity for all events; as a consequence they indicated 0.8 as an appropriate number. No significant correlation is found for magnitude, S-wave velocity in the first 30 meters (\( V_{S30} \)), fault dip or rake, which therefore can be introduced independently in the proposed strategy.

**The hazard model implementation.** In this study we have implemented and modified the USGS seismic hazard computer code adding the SC2008 factor to one of the existing NGA equations, the Boore and Atkinson (2008). The application to other GMPEs of the package (Akkar and Bommer, 2010; Bindi et al., 2012; Cauzzi and Faccioli, 2008) needs ad-hoc calibrations. Note that the SC2008 is effective from \( T \geq 0.5 \) up to \( T=10 \) s. The highest is the period the highest the efficacy of the correction. As a first test we focused on a single fault segment treated as an extended fault. The entire fault extension was explored by a “moving sub-fault” with magnitude-dependent dimension.

GMPEs used in the PSHA standard practice do not account for the nucleation position whereas the SC2008, which is based on rupture propagation from the hypocenter to the closest point to the site, strongly depends on it. Because each point of the sub-fault (the grid spacing is 1 km) has the same probability of nucleating an event (it is assumed an uniform distribution for the nucleation position), and each nucleation point would produce a specific corrective model, the PSHA computation would end in a number of corrected models equals to the number of the nucleation point considered times the number of each sub-fault. Our choice, in this preliminary analysis, was to keep the nucleation position which gave the maximum of the SC2008 correction within each sub-fault. An alternative for further implementation is either to mediate for the effect of a uniform distribution of nucleation points, or assigning a proper probability density function for the distribution of the hypocenters (Spagnuolo et al., 2012).

**Results.** In order to test the impact of the corrective factor on seismic hazard (10 % probability in 50 yrs) we first considered its effect on a normal fault (dip=45°, M=6.6) and on a strike slip fault.
fault (M=6.6). Seismic hazard is given in terms of SA at 3 s. Fig. 1 reports the percentage ratio between the seismic hazard computed with the SC2008 (a directivity model) and the seismic hazard resulting from the standard practice (using a null-directivity model) normalized to the latter. It is presented as a relative difference in percentage, computed as:

$$\frac{[\text{PSHA}_{\text{corrected}} - \text{PSHA}_{\text{standard}}]}{\text{PSHA}_{\text{standard}}} \times 100.$$ (2)

The corrective factor affects mainly the spatial distribution. A positive contribution (which increases the PSHA up to 35%) was achieved at sites in a (namely) directive direction: for a normal fault, the up-dip rupture direction along the surface exposure of the fault; for a strike slip fault, the along strike direction. A decrease (up to 20%) was achieved in the backward direction. Part of this effect is modulated by the nodes and lobes of the radiation pattern (Spagnuolo et al., 2012). Beside, the correction proposed by SC2008 reduces the uncertainty sigma (the record-to-record standard deviation) of a value estimated around 4%. This reduction itself affects the PSHA computation even in regions where the corrective factor is negligible.

We have applied this corrective factor to the DISS (Basili et al., 2008) faults in the Southern Apennines. The percentage change between seismic hazard spectral acceleration at 1 s and 3 s is presented in Fig. 2 (left panel and right panel respectively). At 3 s the increment of the seismic hazard estimation was up to 25% and it was achieved along the entire system of faults. A significant reduction (up to 10%) was achieved in the region north to Naples (Campania), and in the Gargano national park (Puglia). At 1 s the effectiveness of the corrective factor is lower; the increase is up to 10% and the decrease is up to 5%. The areas affected by the modifications were approximately the same.

**Conclusions.** In this study we improved the seismic hazard maps in the near source region incorporating rupture complexity (i.e. directivity) in the ground motion prediction. We have implemented and modified the USGS seismic hazard computer code adding the SC2008 factor to one of the NGA equations, the Boore and Atkinson (2008). The application to other GMPEs of the package (Akkar and Bommer, 2010; Bindi et al., 2012; Cauzzi and Faccioli, 2008) is also feasible but needs ad-hoc calibrations which are planed for a future activity.

![Fig. 2– Representation of the ratio between seismic hazard at a) 1 s and b) 3 s SA (%10 in 50 yrs) with directivity and null-directivity models calculated using the database DISS of individual fault segments, respectively. The correction was applied to the ground motion predictive equation of Boore and Atkinson (2008, BA08), to the spectral acceleration (SA) at 1 s and 3 s. In red: positive amplifications. In blue: negative amplifications.](image)
We observed that the effect of the rupture directivity is to increase the seismic hazard estimations up to 25% and predict a reduction up to 10% in the southern Apennines. The effectiveness of the correction for directivity depends on the period of the spectral acceleration. Its effect is lower at shorter periods.

The strategy proposed in this work has the advantage that it is suitable to be updated anytime that a new information is available from catalogs; as an example, in this preliminary study the nucleation position was fixed to the value which gave the maximum correction at the considered site; however it is possible to vary the nucleation position inside the sub-fault by assigning a proper density distribution which is not necessarily uniform (Mai et al., 2005). Moreover, the incorporation of the Spudich and Chiou (2008)'s corrective factor is able to predict the spatial variability of ground motion due to rupture complexity even in regions where a specification of the directivity effect is not directly available from observations. Our results show that the complexity of the rupture process is effective also in presence of small faults, thanks to the probabilistic treatment of a physical process.

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