IMPROVING SHAKEMAP PERFORMANCE BY INTEGRATING RECORDED DATA WITH SYNTHETIC ESTIMATES OF GROUND MOTION

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The ShakeMap software, developed by the U.S. Geological Survey (USGS) earthquake Hazard Programs (Wald et al. 1999), automatically generates maps of the peak ground motion parameters (peak ground acceleration (PGA), peak ground velocity (PGV), and spectral acceleration (SA)) and of instrumental intensity in near real time, after an earthquake. The recorded ground motion parameters (PGMs) are fundamental in order to obtain accurate results. If no observations are available, ShakeMap relies on ground motion predictive equations (GMPEs) and information of site amplifications. However, local site amplifications are based on the S-wave velocities in the uppermost 30 m (Vs30), which, as known, suffer from low accuracy (e.g.,Wald and Mori 2000; Gallipoli and Mucciarelli 2009). In Italy, the ShakeMap software has been implemented and customized by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in the framework of a project financed by the Italian Civil Protection Department (Michelini et al. 2008). The project has also involved a number of other Italian seismological institutions (Istituto Nazionale di Oceanografia e Geofisica Sperimentale–OGS, among the others) that rapidly exchange ground motion parameters in near real time and compute ShakeMaps in the monitored area.

The main purpose of ShakeMap is to provide maps for post-earthquake response and recovery, other than for public and scientific information; therefore, they must be generated in near real time after the earthquake as their relevance decreases as information about actual damage becomes available. The rapidity of computation can be achieved only by calculating a first-order assessment of the ground shaking. As a consequence, there are multiple sources of uncertainty in producing a ShakeMap, including sparse ground motion measurements, approximate representation of fault finiteness and directivity, empirical ground motion predictions, numerical interpolation, and site corrections not included (Lin et al. 2005). However, it is possible to associate appropriate levels of confidence to ShakeMaps as part of their post-earthquake critical decision making process. Some studies (e.g., Lin et al. 2005; Douglas 2007; Bragato 2009) evidenced that, despite the complexity of the matter, requiring consideration of the nominal or dominant frequency content of each input parameter, of the earthquake size (weak versus strong motions), and of the distance to the nearest observations, ShakeMap uncertainties are usually dominated by two aspects: (1) the spatial variability of peak ground motions near recording stations (and thus, station density) and (2) the aleatory uncertainty associated with the GMPE used to estimate the shaking between stations (Lin et al. 2005; Bragato 2009). Several authors (e.g., Moratto et al. 2009; Ameri et al. 2010) claim the need to integrate recorded data and GMPE with synthetic PGM that account for the main features of the seismic source. To be effective, the computation of synthetics, as well as of the finite fault, should be done in near real time. Therefore the rapidity of calculation is linked to a number of assumptions, and simplifications that need testing before to proceed in automatic mode.

In this study, we suggest a procedure to account for source effects in ShakeMap by computing synthetic seismograms to be used for integrating observations and GMPEs, when near-source data are not available. To achieve the main features of the rupture model we use the modified Kikuchi and Kanamori method (2003) based on a finite fault inverse algorithm that deconvolves complex body waves using teleseismic long period P waves, together with the Time Domain Moment Tensor inverse code (TDMT_INVC, Dreger, 2003) to determine fault plane solutions. For the computation of synthetic seismograms we employ the "EXSIM" (Boore 1983; Motazedian and Atkinson, 2005), a stochastic approach that models the finite-fault ground motions. The whole procedure requires a calibration based on information about the structural model, the path duration and the attenuation factor related to the studied zone.

To assess the performance of our procedure, we performed a retrospective validation analysis considered as case study of the 2009 L'Aquila Mw=6.3 earthquake (Moratto and Saraò, 2011). The first Shakemaps, generated by INGV a few minutes after the event, suffered large uncertainties on ground motion estimates in an area closer to the epicenter due to the lack of near-field data (Faenza et al., 2011). To verify our approach, we recomputed ShakeMap for the L'Aquila earthquake, integrating data available soon after the earthquake at different elapse times with synthetic estimate of PGM, and we compared our results with the final ShakeMap, obtained when all the data were available. For the rapid source model of the L'Aquila event, we used regional and teleseismic waveforms. The advantage of using teleseismic data is their easy availability through the web database (e.g. IRIS Data System). The simplified model resulting from our inversion achieves information compatible with results found by Cirella et al. (2009) as of the maximum slip on the fault, the source duration and the position of the rupture plane (i.e. directivity) with respect to the hypocenter (Moratto and Saraò, 2011). This outcome could be used as an additional input parameter in ShakeMap, prior to computing synthetics

After validating through comparisons the simulated with the observed acceleration within the frequency range of interest (0.1–25 Hz), we computed ShakeMap integrating the INGV data with the finite fault approximation and synthetic PGMs. The misfit values related to the comparison of each test with the final ShakeMap, obtained when all the data were gathered by INGV, improve as we add more details (M_w, finite box, near-field recordings) to the ShakeMap input. The usage of the finite fault approximation reduces the misfit of 40% with respect to the ShakeMap computed in the point approximation, while uncertainties (within 5 km) on the dimensions of the rupture area produce negligible effects on the ShakeMaps. We proved that synthetic PGMs, which include finite source effects, could improve the accuracy of ShakeMap, unless strong site effects exist, as, without a-priori knowledge, we are not able to reproduce them. Also, synthetics computed on a regular grid around the epicenter can lead to an improvement of shaking.

Our findings, related to the L'Aquila earthquake, can be generalized beyond this particular case study. Testing the performance of synthetics for the ShakeMap of the Mw=6.9 2008 Iwate-Miyagi (Japan) earthquake, Ameri et al. (2010) reached similar conclusions. Recorded data are the irreplaceable ingredient to obtaining accurate shaking maps soon after an earthquake, but in the case where any near-source data are missing, the integration of observations with synthetics can improve the ShakeMap performance. The procedure that we applied sounds promising for near real-time application since it provides a rough finite source model and synthetic seismograms in a short time. Furthermore, being based on open-source software, it can be easily implemented in earthquake areas where the station coverage is poor. However, the application in real time is possible only after the whole procedure is tuned for a specific region. In principle, every step can operate in an automatic mode, but some programming work is still needed. As mandatory prerequisites, the ShakeMap software must be properly customized for the region under investigation together with a well-calibrated velocity model and a robust moment tensor solution computed in real time.

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