FINITE SOURCE EFFECTS IN SHAKEMAP MODELLED THROUGH SYNTHETIC SEISMOGRAMS: TESTS ON THE 2009 M_W=6.3 L'AQUILA EARTHQUAKE

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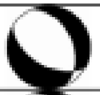
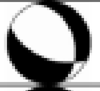
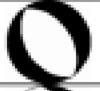
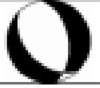
The ShakeMap software (Wald et al., 1999) automatically generates, in real-time, shaking maps using as input the epicentre location, the ground motion parameters (PGA, PGV and SA) extracted from the recorded waveforms and possibly the finite fault rectangle representing the rupture area. The software has been properly calibrated for the Italian territory by Michelini et al. (2008) at INGV.

The 2009 L'Aquila earthquake (Mw 6.3) occurred on April 6 at 01:32 UTC was the first important application of the ShakeMap in Italy and it gave the opportunity to test and improve the standard procedure. The earthquake was very well instrumented being recorded by many broadband and strong motion instruments placed in the near field but for different reasons, not all the data were soon available after the earthquake. The INGV broadband stations saturated up to 80-90 km from the epicentre whereas the strong motion station data of the Rete Accelerometica Nazionale (RAN) network were available only some hours after the event occurrence (Michelini et al., 2009). For these reasons, the first ShakeMaps generated for the L'Aquila earthquake in near real-time were incomplete and updated several times during the day, as new data were available (Michelini et al., 2009). Only few days later, it was possible to compute a ShakeMap including all the recorded data together with an accurate source model computed by waveform inversion (Cirella et al., 2009). The difference between the maps generated immediately after the earthquake and the latest ShakeMaps are noticeable: there are large uncertainties in the zone with more damages and casualties principally due to the lack of near field strong motion data in real time. Several authors (e.g. Moratto et al., 2009) claim the need to integrate records and ground motion empirical relations (GMPE's) with synthetic data including seismic source radiation effects to overcome the lack of data when this occurs. Nevertheless, to be effective the computation of synthetics should be done in near real time, and to include the source effects, also the main features of the source should be obtained in short time.

In this study, we compute rapid synthetics using a stochastic approach. The simplified finite source model is computed by inversion of teleseismic data. The synthetic data are then used to compute ShakeMap of the L'Aquila earthquake in order to test if the integration of synthetics could have really ameliorated the near real time ShakeMap of the 2009 L'Aquila earthquake.

Tab. 1 - Moment tensor computed for the 2009 L'Aquila earthquake by USGS (GS), Harvard (HRV), MedNet (MED) and OGS.

DATE	Lat	Long	Depth	Mw	Mo (Nm)	STR DP RAKE		DC%	Agency
2009.04.06 01:32:39.00	42.334	13.334	2.0	6.2	2.8e+18	113, 60, -118 340, 40, - 51		31	GS
2009.04.06 01:32:49.20	42.290	13.350	12.0	6.3	3.7e+18	336, 42, -62 120, 54, -113		85	HRV
2009.04.06 01:32:47.2	42.32N	13.32	12	6.3	3.7e+18	324, 47, -92 147, 43, -88			MED
2009.04.06 01:32:39	42.32N	13.32	6	6,3	3,5e+18	350, 50, -66 136, 45, -116		64	OGS

The rapid gross source features. To carry out the slip distribution, we applied the modified Kikuchi and Kanamori method (2003), based on a finite fault inverse algorithm that deconvolve complex body waves using teleseismic long period P waves. The advantage of using teleseismic data is their immediate availability through the database on the web (e.g. IRIS Data System).

In the slip inversion we fixed the focal mechanism (strike=136°, dip=45°, rake =-116°) that we computed by the Time Domain Moment Tensor inverse code (TDMT_INVC, Dreger, 2003) using data recorded at OGS in real time. Our moment tensor (Tab. 1) is well in agreement with the moment tensor obtained by other agencies (USGS, Harvard, MedNet). The fault dimension, a rectangular section 30 km long and 20 km wide was fixed by the Wells and Coppersmith (1984) empirical relation and oriented following the moment tensor solution. The rupture velocity was fixed at 3.0 km/s. 31 teleseismic broad-band P wave data were selected and analysed and a total seismic window of 80 s length was inverted. From this first inversion we got a single asperity showing a possibly unilateral fault with rupture propagating from NW to SE (Fig. 1) and maximum slip on the fault of 70 cm, in agreement with the model obtained by Cirella et al. (2009). On purpose we did not refine the slip inversion in order to test how good could be the information coming from a preliminary quick inversion results.

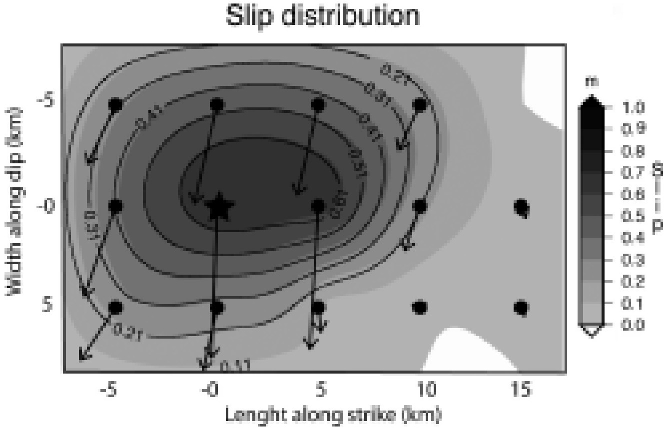


Fig. 1 - The slip distribution on the rupture area obtained by applying the Kikuchi and Kanamori (2003) approach. The black star represents the nucleation of the rupture; the fault is 30 km long and 20 km wide.

Modelling of synthetic data. The synthetic seismograms were computed applying the stochastic approach called "EXSIM" (Motazedian and Atkinson, 2005). EXSIM models the finite-fault ground motions dividing a large fault into subfaults, where each subfault is considered as a small point source. It requires a calibration based on information about the structural model, the path duration and the attenuation factor related to the studied zone; in this study we calibrated the software utilizing the parameters proposed for the L'Aquila region by Bindi et al. (2009). We computed synthetics for the following cases: 1) at the missing data stations with a maximum JB distance of 100 km (*test S1*) and 2) at bedrock receivers placed on a regular grid with nodes distant 0.1° each other with maximum epicentral distance of 50 km (*test S2*). In all tests the signals were filtered with a low pass cut-off frequency of 0.1 Hz and a high pass cut-off frequency of 25 Hz.

Test S1 mimics the lack of data due to transmission problems after an earthquake occurrence; such a data gap can produce large uncertainties in ShakeMaps especially in near field where the damages and human causalities can be relevant. The synthetic seismograms are computed for 22 accelerometric stations closer than 100 km from the epicentre. Finally the ground motion parameters (PGM) are extracted and used as input in the ShakeMaps generation.

Test S2 is a generic grid with 60 stations that can be easily developed around any earthquake epicentre.

ShakeMap computation: real data integrated by synthetic estimates. After the ShakeMaps generation, the comparison with final INGV ShakeMap (*test T1*) shows that *test S1* underestimates the ground motion in near field and above the rupture area because the data recorded at two stations (AQG and AQV) cannot be reproduced. If we remove the data of those two stations, the comparison between *test S1* and INGV ShakeMap (now called *test T2*) is very good: the maps are very similar in area close to the source and in far field. The differential map between the two ShakeMaps (Fig. 2A) evidences that the differences are limited within 5%g with more relevant variation in sites of recording stations placed above the fault.

The ShakeMaps, using data of *test S2* has large PGA (more than 25%g) towards SE at the end of finite fault. The related instrumental intensity maps estimates intensity larger than VIII° in zone above the rupture area in accordance with the macroseismic observations. The comparison between *tests S2* and *T2* evidences that the receivers grid underestimates the ground motion in the northern rupture area (close to epicenter) while overestimates the shaking at the end of the fault (SE from epicenter) where no recording stations is operating (Fig. 2B); this is the zone where the directivity effects are stronger and the absence of real data could take to relevant uncertainties on the ShakeMaps.

Conclusions. In this work we aim to verify if the integration of synthetics could have decreased the uncertainties of the first ShakeMap of the 2009 L'Aquila earthquake, computed without all the recorded data. To this purpose we integrated the ShakeMap of the L'Aquila earthquake with synthetics computed using a stochastic approach including a simplified finite source quickly retrieved using teleseismic data.

The comparison between our hybrid ShakeMaps, obtained using both recorded data soon available after the earthquake and synthetics, and the final INGV ShakeMap (*test T2),* computed with all the available information, reveal that our approach is promising in trying to overcome the lack of data: if we exclude two stations (AQG-AQV) that recorded anomalous PGA values (local site effects?) we obtain very similar maps. The ShakeMaps with the synthetic regular grid reproduce the maps generated with all recorded data. Such a computation on a regular grid can be easily implemented in the ShakeMap computation and can reduce the uncertainties in the near field area. It is

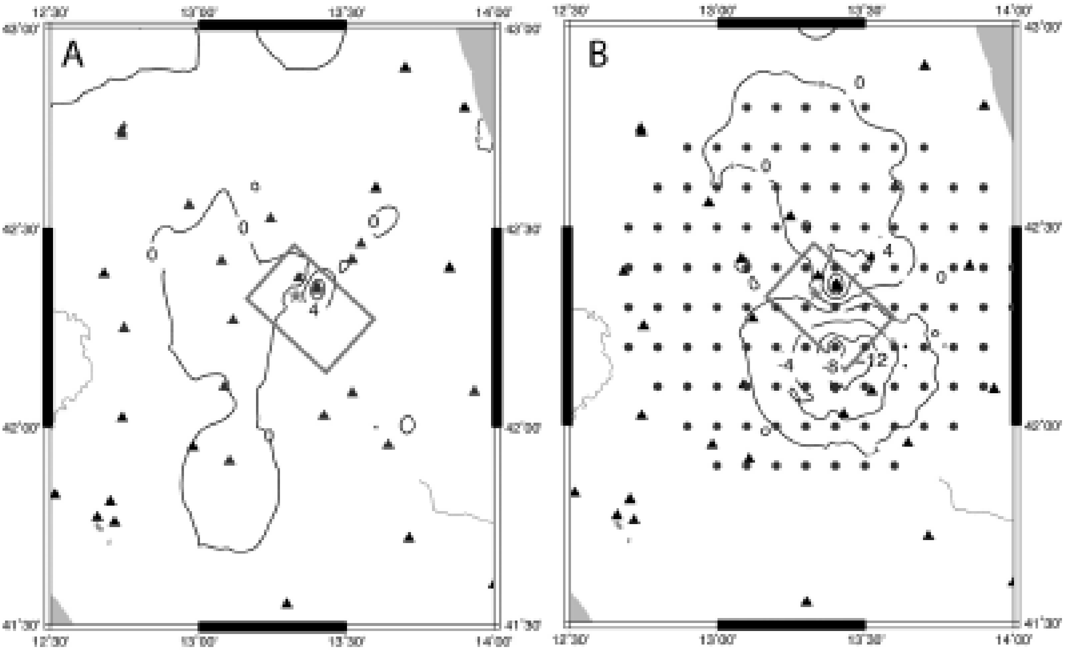


Fig. 2 - PGA (in %g) differential maps between T2-S1 (A) and T2-S2 (B). The triangles show the recording stations used to generate ShakeMap while the circles show the grid nodes where the synthetic seismograms were computed.

fundamental to highlight that, for Civil Defence purposes, the ShakeMaps must be generated as faster as possible. In this regard the methodology that we applied is particularly effective since we are able to invert the finite source and to compute synthetic seismograms in a short time compatible with the ShakeMap demands.

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