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Chapter 30

3D Spectral Element Model for Numerical Simulation of the Seismic Ground Motion in the Aterno Valley (Italy)

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In this chapter, we present 3D Spectral Element simulations of the 2009 *L'Aquila* earthquake aimed at defining a physics-based seismic input for site response analysis. The numerical description of the Aterno basin was built on the subsurface geological model and on the dynamic soil properties of the filling material. We adopted a kinematic description of the rupture that fits near source observations. The comparison between synthetics and recorded accelerograms shows that the simulated signals reproduce with a satisfactory accuracy the real data in the frequency range 0.1–0.7 Hz, consistently with the adopted source model. Simulations were performed by the cluster SCoPE at University of Napoli Federico II.

1. Introduction

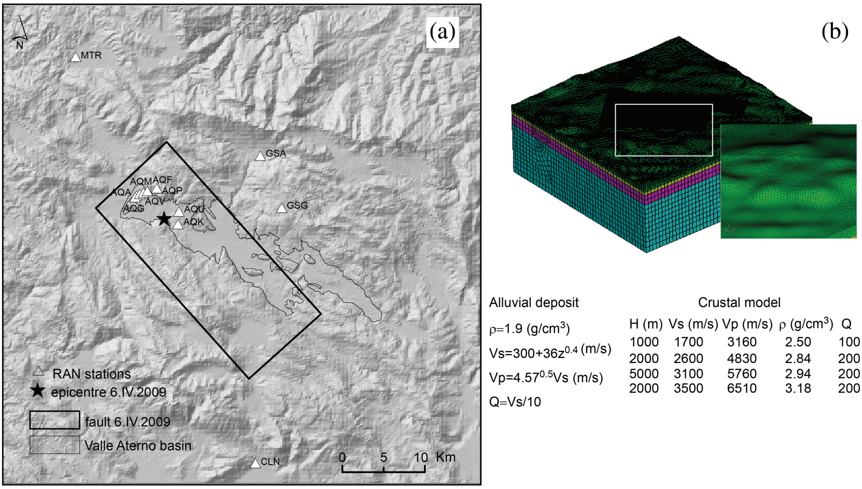
With the development of large supercomputer facilities and workstations, physics-based source-to-site 3D numerical simulations of seismic ground motion are becoming a viable tool to construct ground shaking scenarios for earthquakes. These simulations aim at coupling the modeling of seismic source, propagation and site effects, to provide simulations of earthquakes for seismic hazard studies and earthquake engineering applications. We performed an advanced 3D numerical simulation of the 2009 Mw = 6.3 *L'Aquila* earthquake, to be used as an input in the framework of the RELUIS project (see acknowledgments).

The selected numerical tool was the code Spectral Elements in Elastodynamics with Discontinuous Galerkin (SPEED), developed at *Politecnico di Milano*[6] and designed for the simulation of large-scale seismic wave propagation problems including a kinematic description of the rupture, the propagation through a heterogeneous Earth, localized geological irregularities such as alluvial basins and topography.

2. 3D Spectral Element Model of the Aterno Basin

The area hit by the 2009 *L'Aquila* earthquake is located in an intra-Apenninic basin, elongated in NW–SE direction, crossed by the Aterno river, and surrounded by the Gran Sasso and the Velino-Sirente mountains. The bedrock consists of Meso-Cenozoic carbonate rocks, generally outcropping along the sides of the valley and on ridges located within the Aterno River basin. The maximum thickness of the Quaternary deposits is estimated as high as 500 m.

Through the collection and interpretation of geophysical and geotechnical investigations,[7] a simplified shear waves velocity model of the Aterno basin was defined. We assumed an outcropping bedrock outside the boundaries of the basin. A crustal model, based on the profile suggested by Ameri *et al.*[1] was adopted. Moreover, the S-wave velocity value of the shallower layer was reduced according to the results of site investigation (Working Group AQ-MS)[8] to mimic the impedance contrast at the bedrock.



H (m)	Vs (m/s)	Vp (m/s)	ρ (g/cm^3)	Q
1000	1700	3160	2.50	100
2000	2600	4830	2.84	200
5000	3100	5760	2.94	200
2000	3500	6510	3.18	200

Fig. 1. 3D model of the *L'Aquila* basin: (a) area extension of the analysis domain, (b) Numerical mesh consists of 263,936 hexahedral elements.

The 3D numerical model of the *L'Aquila* basin extends for 58 km in the NS and EW directions with a maximum depth of 20 km (Fig. 1). It was discretized to provide a mesh of 263,936 hexahedral elements (Fig. 1b). The size of the elements ranges from a minimum of 133 m, within the quaternary basin, up to 400 m in the outcropping bedrock. The mesh was generated to propagate up to about 2 Hz for a spectral degree 3. The software ParMetis[5] was used to partition the mesh over the selected number of threads.

2.1. *Kinematic Source Model Along the Paganica Fault*

To represent the rupture process of the *L'Aquila* earthquake, the fault plane and the focal mechanism (strike 133°, dip 54°, rake 102°) were fixed[4] leading to a fault size of 28×20 km^2. The kinematic model is shown in Fig. 2, within the misfit between real data (black records) and synthetics (red records). The model shows a major slip patch between 5 and 10 km southwards of the hypocenter. A smaller asperity in the upper part of the fault with slip as large as 50 cm is instead responsible of the up-dip directivity observed at *L'Aquila* and GSA

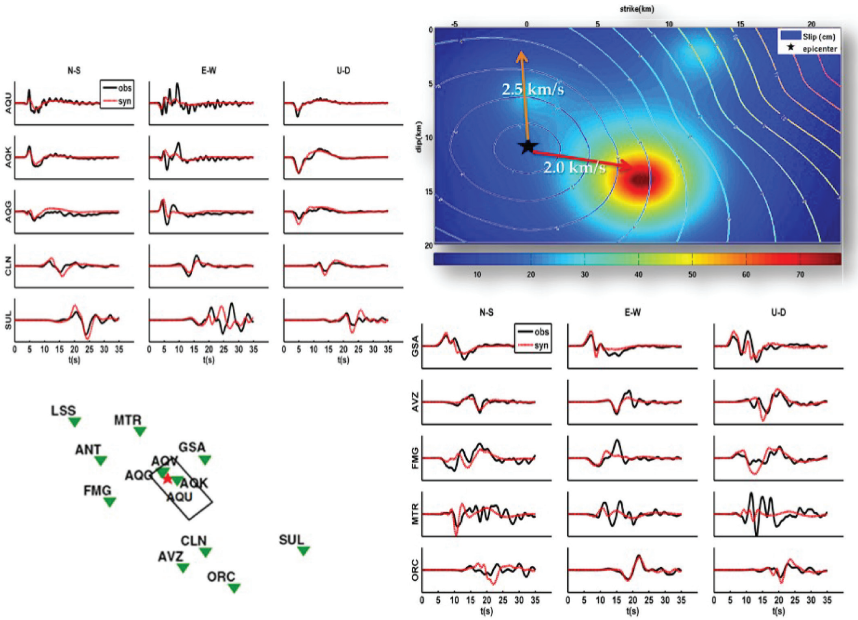


Fig. 2. Final slip distribution and isolines of rupture time from kinematic inversion of *L'Aquila* earthquake data. Comparison of real data (black records) and synthetics (red records) is also shown for some stations.

stations (see Fig. 2). To extend the kinematic model at higher frequencies, the low frequency slip was coupled with a high frequency k^{-2} distribution.[3] We found that the slip roughness does not significantly affect the spectral shape at near and far fault stations, while randomization of the rise time, with a uniform distribution and a mean of 0.75 s, significantly improves the spectral fit, mostly at near fault distances.

3. Numerical Simulation of the 2009 Abruzzo Earthquake

The numerical simulations were carried out assuming the source model described in Sec. 2.1. The SPEED code run on the SCoPE cluster at University of Napoli Federico II on 128 cores, task for nodes 4 and number of threads equal to 2, with a total time of about 3 hours for a single run. In Fig. 3, the contours of E–W velocity component are

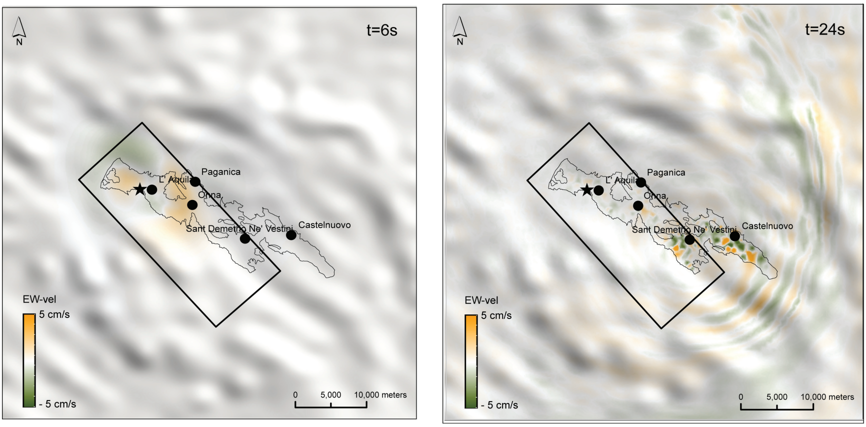


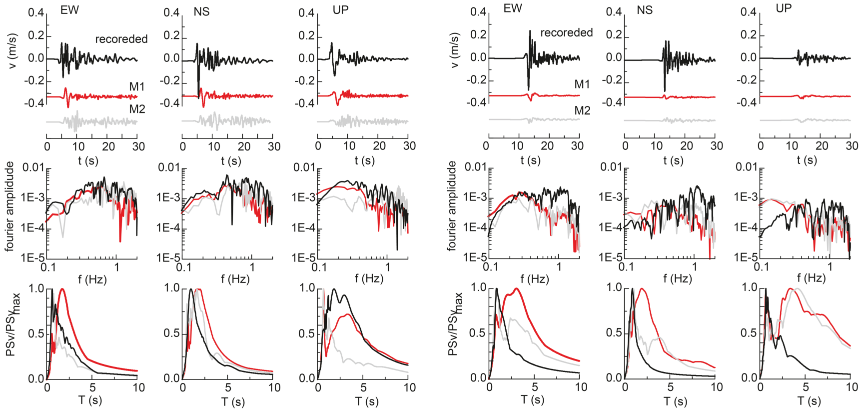
Fig. 3. Contours of E–W velocity component at 6 s and 24 s.

plotted at 6 s and 24 s, showing that the numerical model reproduces the up-dip rupture propagation and a wave focalization within the basin, particularly where the deepest depocenters are located.

The results of 3D analyses are shown as time histories of displacement monitored at selected stations of the Italian Accelerometric Network reported in Fig. 1. The numerical results are then compared with the records of the mainshock in terms of velocity, Fourier and normalized response spectra. To properly compare the observed and simulated data, the waveforms were processed with an acausal band-pass filter Butterworth between 0.1 and 2 Hz, according to the maximum propagated frequency.

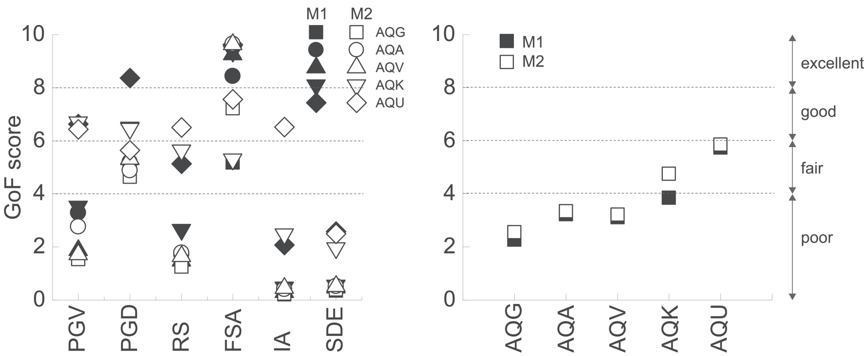
Figure 4 shows the comparison between numerical and observed signals at the stations AQU and AQG, considering the 3 components (EW, NS and UP). The data clearly show that the energy content of the recorded signals is not consistently reproduced by numerical simulations while the frequency content is described coherently with the adopted source models, particularly at AQU (Fig. 4a). At the station AQG (Fig. 4b), instead, the simulations underestimate the amplitude of the signal. The shape of the recorded response spectra are well reproduced by the numerical simulations.

The comparison is also summarized in terms of Goodness-of-Fit scores, GoF.[2] For each monitored station, the GoF scores of peak



(a) (b)

Fig. 4. Comparison of recorded and simulated signals at the RAN stations: (a) AQU and (b) AQG.



(a) (b)

Fig. 5. Goodness-fit-scores in the frequency band between 0.1 and 2 Hz: (a) for the five monitored stations; (b) average values of the six metrics for each stations.

ground velocity (PGV), peak ground displacement (PGD), response spectral acceleration (RS), Fourier amplitude spectrum (FSA), Arias intensity (IA) and SDE (Energy density) are evaluated in the bandwidth 0.1–2 Hz (Figs. 5a and 5b). In Fig. 5, we also compare the results provided by the low frequency source model (M1) and by the coupled k^{-2} model (M2).

The scores of the 6 metrics are assessed as the average value of the 3-components for each station. The results clearly show a misfit between recorded and numerical waveforms, that cannot be ascribed to the simplified model adopted for the deposit filling the basin (see Sec. 3), but could be due to the lack of high-frequency energy content of the source model.

4. Conclusive Remarks and Future Activities

In this work, we performed numerical simulations of the *L'Aquila* earthquake with the code SPEED, based on the spectral element method.

We obtained an updated geological model of the Aterno river basin, suitable to devise a 3D numerical model for seismic wave propagation analyses. Then we included a kinematic description of the earthquake rupture based on the inversion of strong motion data. These ingredients were used to generate a numerical mesh of the region that was used by the code SPEED to simulate the ground motion during the earthquake, by exploiting the high performance computing (HPC) cluster SCoPE.

Several features of the near source ground motion were reproduced by the model, such as the low to intermediate frequency Fourier and response spectral amplitudes, peak ground velocities and accelerations. Nevertheless, loss of high frequency energy and un-modeled impulsive response at near source stations require a better description of the source and propagation. For this purpose, future research activities will be addressed to provide pre-processing tools to SPEED that, based on a relatively rough information on the fault geometry, hypocenter location and spatial distribution of the main fault asperities, with the goal of providing a numerical slip distribution consistent with the high-frequency radiation of seismic energy and to improve results of the numerical simulation of the *L'Aquila* earthquake by comparing several kinematic models available from literature.

Acknowledgments

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