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The L'Aquila earthquake — A view of site effects and building behavior from temporary networks

Giovanna Cultrera, Marco Mucciarelli, Stefano Parolai

The idea of this Special Issue comes from a “joint venture” of research groups from several Italian and European Institutions (Istituto Nazionale di Geofisica e Vulcanologia and University of Basilicata, Italy; GeoForschungsZentrum-GFZ, Germany; CETE Méditerranée - LRPC Nice and OCA-UMR Géoazur, France) which coordinated a large seismic survey for site effect estimation in the wide area hit by the 2009 L'Aquila, Italy, earthquake (Figure 1).

The Mw 6.3 mainshock of April 6th, 2009, represented the most damaging event in Italy since the 1980 Irpinia earthquake (Mw 6.9). Several large aftershocks (Mw > 5) and thousands of smaller events occurred in the following months and the coordination of different rapid response seismic networks from Italy, France and Germany allowed the scientific community to collect a very large and high quality data set, probably the largest ever acquired during a normal fault seismic sequence (Margheriti et al., 2011).

Among many scientific issues, the L'Aquila earthquake seismic sequence represented a laboratory to understand the site effects in intra-mountain regions and their influence on damage distribution for traditional dwellings and recent residential reinforced concrete buildings (D'Ayala and Dolce, 2011). The macroseismic survey (Galli and Camassi, 2009) indicates that the strongest damages were observed in the city of L'Aquila and in the villages to the SE, in agreement with the rupture propagation pattern toward up-dip and SE (Cirella et al., 2009) and according to the orientation of the Aterno River Valley. In particular, sixteen localities including L'Aquila downtown, on the hanging-wall side of the causative fault, suffered damage greater than VIII degree of the Mercalli-Cancani-Sieberg intensity scale (MCS). The maximum observed intensity is IX-X MCS in the small villages of Onna and Castelnuovo (Figure 1).

The day after the mainshock, a temporary seismic network of 33 seismic stations was deployed in the middle Aterno river Valley, nearby or inside the damaged centers (Figure 1). **Bergamaschi** et al. (this volume) describe the cooperation frame of the different Institutions for this rapid response experiment, the ground motion database of the recordings and their analysis. The large variability of site responses at different locations in terms of spectral ratios is correlated with the geological and geotechnical information available from previous studies and from the seismic microzonation promoted by the Italian Department of Civil Protection soon after the L'Aquila mainshock (Gruppo di Lavoro MS-AQ, 2010).

The same dataset of earthquake recordings ($3.0 \leq M_L \leq 5.3$) has been used by **Ameri** et al. (this volume) to estimate the source parameters of these events and the seismic attenuation characteristics in a highly heterogeneous and fractured crust of the L'Aquila mainshock fault zone. The site amplification effects at the recording sites are consistent with the results of Bergamaschi et al., and highlight the amplification of the vertical component at a number of sites.

Different seismic survey were carried out in the urban centers suffering the highest damage. L'Aquila, the capital city of the Abruzzo Region (Figure 1), has about 75.000 inhabitants and many historical and modern buildings. The historical center suffered the collapse of several buildings, including some recent reinforced concrete ones, and severe damage for a big portion of public and residential buildings which were declared unusable. **Milana** et al. (this volume) collected and analyzed microtremor and aftershocks data to investigate the amplification effects in the city and to support the microzoning activities promoted by the Italian Civil Defense Department (Gruppo di lavoro MS_AQ 2010). Their results describe the presence of low-frequency amplification diffused in the historical center and whose amplitude varies within the area. This peak is related to peculiar geological setting of the city, which is build on a terrace of alluvial Quaternary breccias overlying lacustrine sediments of up to 200 meters thickness with a strong P and S waves impedance contrast.

The amplitude variability is related to the lateral variations in surface geology, in particular to the breccias outcropping in the northern area, characterized by a velocity reversal, which disappear toward South. This behavior has been modeled by **Bordoni** et al. (this volume) that performed 2D simulations on the same area. They found that the reversal of velocity acts as a low-pass frequency filter on the horizontal components reducing the amplification effect of the sediments. They also predict amplification at higher frequencies that could be related to damage clustering in the part of the city where soft sediments outcrop. Both papers show that the evaluation of amplification factors should take into account the heterogeneity of the surface geology that strongly affects recordings and simulations.

The small village of Onna (Figure 1) suffered an extremely heavy damage in the masonry structures, experiencing the largest intensity assigned for the L'Aquila earthquake (IX–X on the MCS scale). Within a distance of 2 km from Onna, the villages of Bazzano and Monticchio suffered a smaller level of damage (VIII and VI MCS, respectively). Starting from these observations, **Di Giulio** et al. (this volume) analyze the aftershock recordings at seismic stations deployed in this area, as part of the experiment described by Bergamaschi et al. (this volume). Seismic data indicate that the Onna area is exposed to high-frequency ground-motion amplification related to the alluvial sediments, and this can partially explain the severe damage during the 2009 mainshock. However, the Authors explain that the ground motion recordings at Onna are well reproduced by the predictive equation for the Italian territory.

Right above the hypocenter, the village of Poggio di Roio experienced an intensity of IX/X MCS degree, while the ancient villages in and around the semi-graben depression of the Roio plain (Figure 1) show a heterogeneous damage distribution. The study of **Bertrand** et al. (this volume) on the aftershocks recordings shows the presence of large amplification effects, detected not only at the stations located on alluvium but also at the stations lying on rocky sites at the edges of the plain.

The last three papers are dealing with some peculiar issues on site effects, such as the ground motion amplification due to cataclastic or fractured rock and the non-linear ground motion behavior. These studies were triggered again by some anomalous damage behavior in the Aterno valley area.

The first case is found in San Gregorio, a village sitting on an alluvial fan at the edge of the middle Aterno valley few kilometers east from Onna (Figure 1), which experienced intensity equal to IX MCS. The masonry ancient buildings of the historical center suffered heavy structural damages, whereas only one reinforced concrete (RC) building had the first floor collapsed following the April 6 mainshock. The study of the site effects performed by **Mucciarelli** et al. (this volume) returns a very high amplification of seismic motion along the same direction where the building was displaced of more than 70 cm. The detailed geotechnical survey has revealed the presence of an unexpected thickness of fault cataclastic material just below the building, not visible from a surface survey. The low resistance material incorporated in well-stratified calcarenites probably acted as soft layer causing a peculiar site effect.

Castelvecchio Subequo, a village located at about 40 km from the epicenter (Figure 1), stand out for an “anomalous”, relatively high degree of damage (7 MCS scale). The damage was mainly concentrated in the uppermost portion of the old village, where geotechnical surveys found sets of fractures that are related to the deformation zone. **Marzorati** et al. (this volume) detected the ground motion amplifications at the uppermost portion of the carbonate ridge on which the village is built. They also correlate the presence of seismic amplifications with the fracture opening, while no amplification is seen where the bedrock is densely fractured but no open joints occur.

The studies presented in this Special Issue used weak-to-moderate earthquake recordings and the majority of them tried to infer the ground motion values expected for the magnitude 6.3 earthquake in places where no strong motion instruments were available (see for example Milana et al. or Di Giulio et al.). During the mainshock, the few accelerometric stations within 6 km from the epicenter recorded peak acceleration values ranging from 0.3 to 0.7g (www.itaca.mi.ingv.it), suggesting that the strong shaking measured in the sediment filled valley of the Aterno river could be affected by non-linear soil behavior. **Puglia** et al. (this volume) look for the time variation of

amplification function and soil fundamental frequency over long and short time scale. However, the variations in frequency and amplitude seems not relevant from building design standpoint, except for a site in the Aterno valley NW of L'Aquila (AQV) which shows a consistent shift of the resonance frequency.

Data archive

The data recorded to evaluate site effects and to monitor building structures are archived by their reference Institutions. A set of events with $M_L > 3$ is shared by all participants and few of these waveforms are archived inside ITACA <http://itaca.mi.ingv.it/> the Italian accelerometric archive.

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References

- Ameri G., A. Oth, M. Pilz, D. Bindi, S. Parolai, L. Luzi, M. Mucciarelli and G. Cultrera (2011). Separation of source and site effects by Generalized Inversion Technique using the aftershock recordings of the 2009 L'Aquila earthquake. *Bull. Earthquake Eng.*, this issue.
- Bergamaschi F., G. Cultrera, L. Luzi, R. M. Azzara, G. Ameri, P. Augliera, P. Bordonì, F. Cara, R. Coglianò, E. D'Alema, D. Di Giacomo, G. Di Giulio, A. Fodarella, G. Franceschina, F. Galadini, M. R. Gallipoli, S. Gori, P. Harabaglia, C. Ladina, S. Lovati, S. Marzorati, M. Massa, G. Milana, M. Mucciarelli, F. Pacor, S. Parolai, M. Picozzi, M. Pilz, S. Pucillo, R. Puglia, G. Riccio, M. Sobiesiak, (2011). Evaluation of site effects in the Aterno river valley (Central Italy) from aftershocks of the 2009 L'Aquila earthquake. *Bull. Earthquake Eng.*, this issue.
- Bertrand E., A.-M. Duval, J. Régnier, R.M. Azzara, F. Bergamaschi, P. Bordonì, F. Cara, G. Cultrera, G. Di Giulio, G. Milana, J. Salichon. Site effects of the Roio basin, L'Aquila. *Bull. Earthquake Eng.*, this issue.
- Bordonì P., J. Haines, G. Milana, S. Marcucci and F. Cara, G. Di Giulio, (2011). Seismic response of L'Aquila downtown from comparison between 2D synthetics spectral ratios of SH, P-SV and Rayleigh waves and observations of the 2009 earthquake sequence. *Bull. Earthquake Eng.*, this issue.
- Cirella A, Piatanesi A, Cocco M, Tinti E, Scognamiglio L, Michelini A, Lomax A, Boschi E (2009) Rupture history of the 2009 L'Aquila (Italy) earthquake from non-linear joint inversion of strong motion and GPS data. *Geophys Res Lett* 36:L19304. doi:[10.1029/2009GL039795](https://doi.org/10.1029/2009GL039795)
- D'Ayala D., M. Dolce, (2011). Guest editorial: L'Aquila earthquake: seismic sequence of 6th April 2009, Abruzzo, Italy. *Bull Earthquake Eng* (2011) 9:1–10, DOI 10.1007/s10518-010-9240-4
- Di Giulio G., S. Marzorati, F. Bergamaschi, P. Bordonì, F. Cara, E. D'Alema, C. Ladina, M. Massa and The L'Aquila Experiment Team (Azzara R. M., Coglianò R., Cultrera G., Fodarella A., Luzi L., Milana G., Pucillo S., Riccio G.), (2011). Local variability of the ground shaking during the 2009 L'Aquila earthquake (April 6, 2009—Mw 6.3): the case study of Onna and Monticchio villages. *Bull. Earthquake Eng.*, this issue.
- Galli P, Camassi R (2009) Rapporto sugli effetti del terremoto aquilano del 6 aprile 2009; Dipartimento della Protezione Civile Istituto Nazionale di Geofisica e Vulcanologia QUEST Team. http://emidius.mi.ingv.it/DBMI08/aquilano/query_eq/quest.pdf

- Gruppo di lavoro MS_AQ (2010) La Microzonazione Sismica dell'area aquilana. 2 vol., + 1 DVD, Edited by Dipartimento Protezione Civile, Rome
- Margheriti L., L. Chiaraluce, C. Voisin, G. Cultrera, A. Govoni, M. Moretti, L. Luzi, R. Azzara, C. Chiarabba, R. Di Stefano, F. Pacor, G. Milana, M. Mucciarelli, G. Cecere, A. Amato, P. Bordonì, M. Sobiesiak, A. Strollo, A.M. Duval, P. Dominique, A. Paul, S. Husen, S. Parolai, V. Lauciani, S. Mazza, A. Delladio and G. Selvaggi. Rapid response seismic networks in Europe: the lesson learned from L'Aquila 2009 earthquake emergency. Submitted to Annals of Geophysics.
- Marzorati S., Ladina C., Falcucci E., Gori S., Saroli M., Ameri G., and Galadini F., (2011). Site effects "on the rock": the case of Castelvechio Subequo (L'Aquila, central Italy). Bull. Earthquake Eng., this issue.
- Milana G., R. M. Azzara · E. Bertrand · P. Bordonì, F. Cara, R. Coglianò, G. Cultrera, G. Di Giulio, A.M. Duval, A. Fodarella, S. Marcucci, S. Pucillo, J. Régnier, G. Riccio, (2011). The contribution of seismic data in microzonation studies for downtown L'Aquila. Bull. Earthquake Eng., this issue.
- Mucciarelli M., M. Bianca, R. Ditommaso, Marco Vona, M. R. Gallipoli, A. Giocoli, S. Piscitelli, E. Rizzo, M. Picozzi, (2011). Peculiar earthquake damage on a reinforced concrete building in San Gregorio (L'Aquila, Italy): site effects or building defects? Bull. Earthquake Eng., this issue.
- Puglia R., R. Ditommaso, F. Pacor, M. Mucciarelli, L. Luzi, M. Bianca, (2011). Frequency variation in site response over long and short time scales, as observed from strong motion data of the L'Aquila (2009) seismic sequence. Bull. Earthquake Eng., this issue.

Figure 1. Location of the experiments described in this Volume: red ellipses show the areas of the Aterno (Bergamaschi et al., 2011; Ameri et al., 2011) and the Roio experiments (Bertrand et al., 2011), square symbols indicate L'Aquila (Milana et al., 2011; Bordoni et al., 2011), San Gregorio (Mucciarelli et al., 2011), Castelvechio Subequo (Marzorati et al., 2011) and the accelerometric array (Puglia et al., 2011). Star is the epicenter of the April 6, 2009, mainshock.