LESSONS LEARNED FROM 2016 AMATRICE EARTHQUAKE (ITALY) ON ISSUES OF ESG

Giovanna Cultrera[1], Fabrizio Cara[1], Giuseppe Di Giulio[1], Daniela Famiani[1], Chiara Felicetta[1], Giuliano Milana[1], Francesca Pacor[1], Maurizio Vassallo[1], Alessandro Todrani[2], Amatrice Working Group[1]
1 Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy (giovanna.cultrera@ingv.it)
2 Department of Sciences, Roma Tre University, Rome, Italy

ABSTRACT

The Amatrice earthquake (Mw 6.0, Italy) occurred on August 24th 2016, and started a long seismic sequence in Central Italy, severely affecting four Italian regions (Lazio, Abruzzo, Umbria and Marche) and causing 299 fatalities and about 30.000 homeless. It was followed by two mainshocks of Mw 5.9 and Mw 6.5 two months later, the latter being the largest earthquake recorded in Italy in the last 40 years.
Since the early hours from the first mainshock, several Italian Institutions were involved in the field to collect seismic data and to carry out geophysical, geomorphological, geological, geotechnical surveys, with the final goal of studying the site effects of the epicentral areas. In this paper we focus on the Amatrice municipality, where the impressive amount of data can increase the understanding of correlation between seismic recordings and geological/geophysical properties of the ground.

Keywords: Amatrice earthquake, site effects, seismic recordings, microzonation

INTRODUCTION

The historic center of Amatrice village (Italy), together with many villages in the mountainous areas of Central Italy, has been badly damaged by a Mw 6.0 earthquake, occurred on August 24th, 2016 (Fig.1). The earthquake started a long seismic sequence in Central Italy, causing 299 fatalities and about 30.000 homeless and severely affecting four Italian regions (Lazio, Abruzzo, Umbria and Marche). It was followed on October 26th 2016 by the Mw 5.9 Visso earthquake, to the North, and on October 30th by the largest event, the Mw 6.5 Norcia earthquake, that nucleated in between the source regions of the two previous mainshocks; the activated zone is about 70-km-long and 10-km-thick, and trends NNW-SSE parallel to the axis of the central-northern Apennines (Fig. 1; BSI working group, 2018, and Improta et al., 2019).
The damage in the epicentral area of the Amatrice earthquake appeared rather complex and strongly dependent on the high vulnerability of the traditional building stock, as well as on the critical geological conditions like for example poor geotechnical properties of terrains, landslides and other geomorphological instabilities (Fiorentino et al., 2018; Rossi et al., 2019; Graziani et al., 2019). Between the investigated municipalities, the town of Amatrice has received particular attention because its historical center was affected by heavy damage to total collapses reaching 85% of the whole building stock. The elevated level of destruction was mainly caused by the high vulnerability of the masonry buildings, but its spatial distribution was not uniform.
This variability may be due to the different vulnerability of the building heritage or to a ground motion variability within a few hundreds of meters, possibly due to the vicinity of the seismic source and the peculiar site effects. To address these issues, several Italian Institutions were involved in the field to collect seismic data and to carry out geophysical, geomorphological, geological, geotechnical surveys. Among the various Institutions, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) mobilized the Emersito task force in the first days of the seismic emergency. The aim of Emersito is to investigate possible site effects, caused by seismic events of moderate–to-large magnitude in the Italian territory, by means seismic monitoring and preparatory activities for seismic microzonation in the emergency phase (Cultrera et al., 2016; http://emersitoweb.rm.ingv.it/index.php).

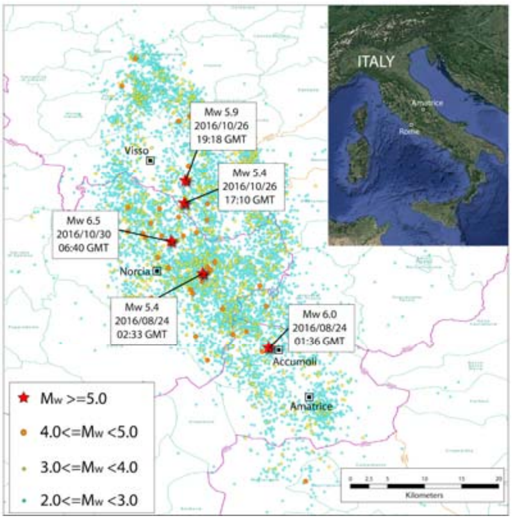

Figure 1. Central Italy seismic sequence (August 24 - November 30, 2016). The inlet shows the map of Italy with the position of Amatrice. The epicentral locations are from the INGV web service (http://terremoti.ingv.it). Redrawn from Cara et al., 2019.

Later on, the Italian Department of Civil Protection (DPC; www.protezionecivile.gov.it) commissioned the Center for Seismic Microzonation and its applications (CMS, Centro per la Microzonazione Sismica e le sue applicazioni; www.centromicrozonazionesismica.it) to coordinate seismological, geophysical, geomorphological, geological, and geotechnical surveys, with the final goal of performing seismic microzonation (SM) in 142 municipalities stroke by the earthquakes (Hailemikael et al., 2020). These microzonation activities were finalized to the assessment of local seismic hazards by identifying the zones of a given geographic area with homogeneous seismic behavior due to local geological conditions (SM Working Group 2015).
In this paper we focus on the efforts of looking for site effects by means of an impressive collection of both earthquakes and noise recordings in the municipality of Amatrice.

DATA COLLECTION

The Amatrice village was built on an alluvial terrace 60-80 m higher than the surrounding valley (Amatrice basin) and elongated in NW–SE direction with a length of about 2000 m and a maximum width of about 600 m (Fig. 2). It is bounded both at NE and SW by two river valleys and bordered by a steep slope to the North and to the West, and by a gentler slope to the South. This morphology, together with the low cohesion and the poor geotechnical properties of the covering terrain, causes landslides especially on the North flank of the downtown (Vignaroli et al., 2019; Milana et al., 2020).
In the following we list the most important data collection in the Amatrice municipality (Fig. 2):

- A dense seismic network was deployed in the most damaged hamlets, at sites representative of the geological conditions that can affect the ground motion characteristics (network 3A, https://doi.org/10.13127/SD/ku7Xm12Yy9). It operated during few months after the first mainshock and recorded strong magnitude events such as the Mw 6.5, as well as hundreds of other aftershocks of magnitude larger than 3.0 in near source region (Cara et al., 2019).
- An extensive campaign of 60 single-station ambient noise measurements was performed in order to determine the spatial variability of the fundamental frequency peak from the horizontal-to-vertical spectral ratio. Occasionally, it recorded also few small-magnitude earthquakes (Milana et al., 2020).
- Down-Hole measurements and non-invasive methods, such as Multichannel Analysis of Surface Waves (MASW) and 2-D array of ambient noise on the top of the Amatrice terrace and around

it, were aimed at obtaining Vs profiles down to a depth of few tens of meters (Milana et al., 2020; Felicetta et al., 2021; Famiani et al., 2021).

- A 1:5,000 scale geological survey was performed in the area and 31 geological cross-sections focused on the description of the stratigraphic architecture of the Quaternary continental deposits of the Miocene substratum and the spatial distribution of the main fault systems (Vignaroli et al., 2020).

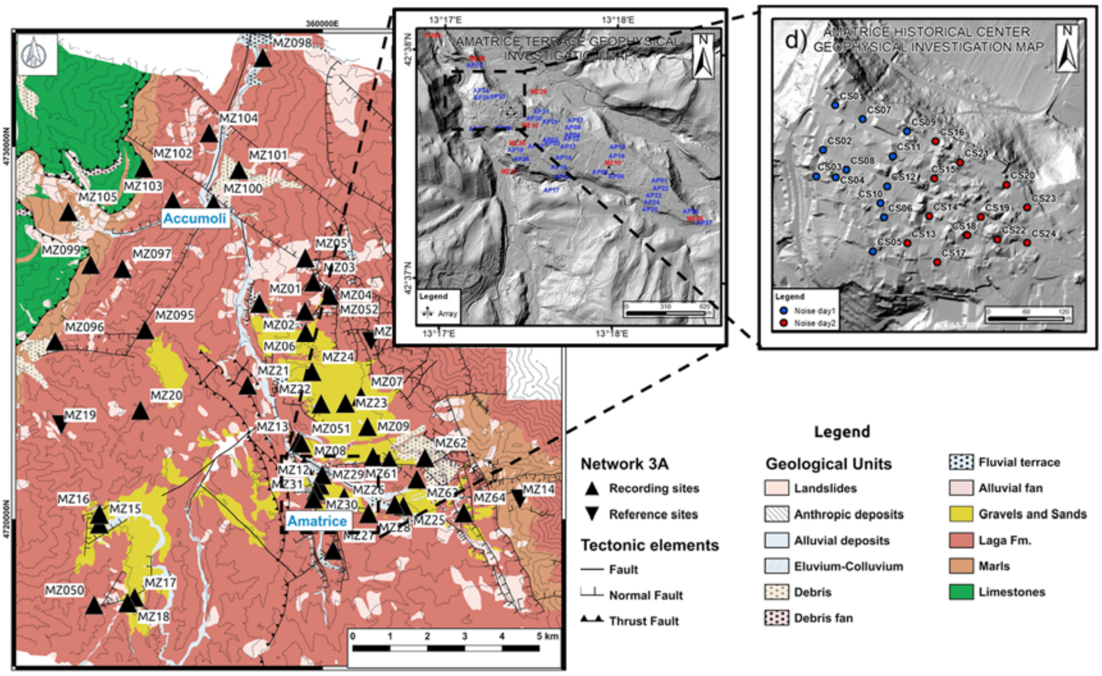

Figure 2. Position of the seismic stations of the network 3A on a simplified geological map. The inlets show a first zoom of the Amatrice terrace and second zoom of the historical center, with the location of seismic stations used for noise measurements. Redrawn from Cara et al. (2019) and Milana et al. (2020).

SITE EFFECTS STUDIES

The huge amount of data has been used mainly for supporting seismic microzonation studies in Central Italy, to quickly provide information and suggestions for the management of the early post-emergency and reconstruction phase in the 142 damaged municipalities identified by the Italian Civil Protection, including Amatrice.

Site effects studies benefited from the recordings of continuous waveforms dataset of the 3A temporary network (Cara et al., 2019) installed in tens hamlets of Amatrice and Accumoli municipalities which experienced a high level of damage. Priolo et al. (2020) provided quantitative information about the site response representative for each locality, by inferring several site parameters, such as the resonance frequency, amplification factors and empirical transfer functions from earthquake and noise recordings. Luzi et al. (2020) identified potential reference rock sites, i.e. stations installed on outcropping rock with a flat site response, and selected suites of spectrum-compatible accelerograms, that has been used by Pagliaroli et al. (2020) as input motion for calculating site amplifications through 1D and 2D simulations at selected sites which suffered the greatest damage. Felicetta et al. (2021) analysed the ground-motion amplification at the recording sites and the site response parameters (i.e., resonance frequencies, empirical amplification functions and amplification factors in different period ranges) for finding common behaviors among the sites and testing the use of available site condition proxies for site response classification.

Together with the earthquake recordings, used to empirically evaluate ground-motion amplification effects through spectral ratios, ambient noise measurements have been collected on the Amatrice terrace for defining the spatial distribution of the resonance frequencies (Fig. 3). The data analysis of Milana et al. (2020) reveals a spatial variation of site effects and a diffuse amplification of ground motion. The spectral amplification reaches its maximum values in the downtown area, at the western limit of the Amatrice terrace, with a resonant frequency of about 2.0-2.5 Hz. Then, it tends to decrease in the central part of the terrace and increases again moving towards its eastern edge, with a clear shift towards higher frequencies and a directionality of the amplification. Different conclusions are reached by Del Gaudio et al. (2021), that individuate variable maxima directions of the HVNSR computed from Instantaneous Polarization analysis: according to them, the observed variations could reflect wavefield polarization properties controlled by noise sources and a consequent lack of a pronounced anisotropy in site response.

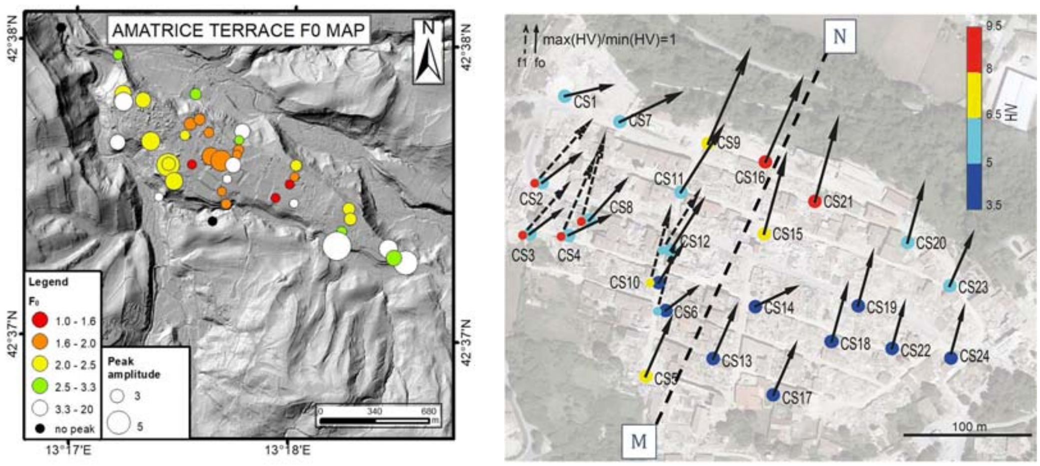

Figure 3. Results from Horizontal-to-Vertical spectral ratio on noise (HVNSR): (left) Map of the fundamental peak frequencies (f0); (right) Polarization effects from rotated HVNSR. Arrows: direction of maximum peaks at f0=1.8-2.7 Hz (plain) and f1=2.7-3.2 Hz (dashed); their length is proportional to the amplification variation respect to the minimum amplification (i.e. the bar length increases for sites with strongly polarized effect). The circle color relates to maximum amplitude of HVNSR peak, the dashed line (MN) represents a geological cross-section trace available in Vignaroli et al. (2019). Redrawn from Milana et al., 2020.

Several Vs profiles were performed in the area (Di Giulio, 2018; Milana et al., 2020; Felicetta et al., 2021; Famiani et al., 2021), providing information down to more than a hundred meters and showing the complexity in the structure of the subsoil: few meters thick of colluvium and anthropogenic deposits overlay the early-to-middle Pleistocene conglomerated and sandy lithologies (Amatrice-Sommati Unit), which sits on the geologic bedrock (i.e., Laga Formation); this latter shows a large Vs variability, from 600 to 1500 m/s, and average values of about 760 m/s in the upper 15 m.

These observations suggest a lateral variability of the geological conditions in the terraced area that, combined with the presence of topographic effects due to the morphology, probably played an important role in the damage produced by the August 24th event (Milana et al., 2020). To this purpose, Hailemikael et al. (2021) compared theoretical 1D transfer functions computed from site characterization information with the available empirical amplification functions at selected sites of the 3A network. The latter were computed by weak-motions spectral ratios using either a reference site (SSR) or horizontal-to-vertical ratios (EHV); the theoretical curves were computed using a 1D code under the linear-elastic assumption. In most of these sites, these authors found a poor match between empirical and theoretical amplification functions, suggesting that many of the 3A stations are difficult to classify based on the knowledge of the shallow subsurface (<50 m) and according to wave propagation 1D assumptions.

Moreover, the vicinity of the fault that ruptured during the Mw 6.0 mainshock should be taken into account, as the closest accelerometric station to Amatrice recorded a PGA of 8.5 m/s^2, largely exceeding the Italian code spectrum in the range of periods corresponding to 2–3 storeys buildings, which constitute the majority of the constructions in Amatrice (Fiorentino et al., 2018). A way to merge source and site effects, for simulating the ground shaking of the Mw 6.0 earthquake in downtown Amatrice, is described by Todrani & Cultrera (2021): these authors evaluated, in the Amatrice historical center, PGA and PGV values clearly above 1 standard deviation of the expected accelerations, suggesting that mainly the eastern part of downtown has been subjected to a severe ground shaking larger than the expected average.

CONCLUSIONS

The Mw 6.0 Amatrice earthquake, and the long seismic sequence that hit Central Italy in 2016-17, triggered a fruitful collaboration within many Italian and foreign Institutions. The huge collection of many different data (seismological, geological, geophysical and building damage recognition) turned out to be successful in terms of timely intervention during the emergency phase and the planning of the post-emergency recovering. It constitutes a unique set of information to be used in several research fields. In particular, the availability of seismological recordings, both earthquake and noise, demonstrates the importance of this kind of data for assessing the local site response and the correlation with more simple proxies.
This paper is intended to be a short review of the studies performed in the Amatrice area on the perspective of surface geology effects on seismic motion, but it is not exhaustive of all the efforts made in the area by many other researchers.

ACKNOWLEDGMENTS

We would like to thank all the researchers and technicians that contributed to the data collection and analysis of the presented studies. Our thoughts go to the victims and to the people who are still struggling with the devastating consequences of the earthquakes.

REFERENCES

BSI working group, (2018). *Bollettino Sismico Italiano settembre - dicembre 2016*, https://doi.org/10.13127/BOLLETTINO/2016.03

Cara, F., Cultrera, G., Riccio, G. et al. (2019). “Temporary dense seismic network during the 2016 Central Italy seismic emergency for microzonation studies”, *Sci Data*, **6**, 182. https://doi.org/10.1038/s41597-019-0188-1

Cultrera, G. et al. (2016). “Site effect studies following the 2016 Mw 6.0 Amatrice Earthquake (Italy): the Emersito Task Force activities”, *Ann. Geophysics*, **59**, Fast Track 5, https://doi.org/10.4401/ag-7189.

Del Gaudio, V., Wasowski, J., Pierri, P., Moretti, A., Ferrini, G. (2021). “Multitemporal analysis of ambient noise polarization to characterize site response in the town of Amatrice, shattered by the 2016 central Italy earthquake”, *Geophysical Journal International*, 224, 739-759. https://doi.org/10.1093/gji/ggaa335

Di Giulio, G., Bordoni, P., Cultrera, G., Milana, G., Vassallo, M. (2018). “VS profile derived from surface-wave and down-hole methods: comparison at some case studies in Central Italy”, *36th General Assembly of the European Seismological Commission*, 2-7 September 2018, La Valletta, Malta.

Famiani, D., Cornou, C., Cultrera, C., Kawase, H. (2021). “High-resolution seismic arrays in amatrice village for a better estimation of site effects”. This conference

Felicetta, C., Mascandola, C., Spallarossa, D., Pacor, F., Hailemikael, S., Di Giulio G. (2021). “Quantification of site effects in the Amatrice area (Central Italy): Insights from ground-motion recordings of the 2016–2017 seismic sequence”, *Soil Dynamics and Earthquake Engineering*, **142**, https://doi.org/10.1016/j.soildyn.2020.106565.

Fiorentino, G., Forte, A., Pagano, E., Sabetta, F., Baggio, C., Lavorato, D., Nuti, C., Santini, S. (2018). “Damage patterns in the town of Amatrice after August 24th 2016 Central Italy earthquakes”, *Bull Earthquake Eng*, **16**, 1399-1423. https://doi.org/10.1007/s10518-017-0254-z

Graziani, L., del Mese, S., Tertulliani, A., Arcoraci, L., Maramai, A. & Rossi, A. (2019). “Investigation on damage progression during the 2016–2017 seismic sequence in Central Italy using the European Macroseismic Scale (EMS-98)”, *Bull Earthquake Eng*, **17**, 5535–5558 (2019). https://doi.org/10.1007/s10518-019-00645-w

Improta, L., Latorre, D., Margheriti, L. et al. (2019). “Multi-segment rupture of the 2016 Amatrice-Visso-Norcia seismic sequence (central Italy) constrained by the first high-quality catalog of Early Aftershocks”, *Sci Rep*, **9**, 6921. https://doi.org/10.1038/s41598-019-43393-2

Hailemikael, S., Amoroso, S. & Gaudiosi, I (2020). “Guest editorial: seismic microzonation of Central Italy following the 2016–2017 seismic sequence”, *Bull Earthquake Eng*, **18**, 5415–5422. https://doi.org/10.1007/s10518-020-00929-6

Hailemikael, S., Di Giulio, G., Felicetta, C., Mascandola, C., Pacor, F., Spallarossa, D. (2021). "Suitability of the 1D assumption for ground response analysis in the epicentral area of the 2016 Mw 6.0 Amatrice earthquake (Central Italy)". This conference

Luzi, L., Pacor, F., Lanzano, G. et al. (2020). “2016–2017 Central Italy seismic sequence: strong-motion data analysis and design earthquake selection for seismic microzonation purposes”, *Bull Earthquake Eng*, **18**, 5533–5551. https://doi.org/10.1007/s10518-019-00676-3

Milana, G., Cultrera, G., Bordoni, P. et al. (2020). “Local site effects estimation at Amatrice (Central Italy) through seismological methods”, *Bull Earthquake Eng*, *18*, 5713–5739. https://doi.org/10.1007/s10518-019-00587-3

Pagliaroli, A., Pergalani, F., Ciancimino, A. et al. (2020). “Site response analyses for complex geological and morphological conditions: relevant case-histories from 3rd level seismic microzonation in Central Italy”, *Bull Earthquake Eng*, **18**, 5741–5777, https://doi.org/10.1007/s10518-019-00610-7

Priolo, E., Pacor, F., Spallarossa, D., Milana, G., et al. (2020). “Seismological analyses for the seismic microzonation of the 138 municipalities damaged by the 2016-2017 seismic sequence in Central Italy”, *Bull Earthq Eng*, **18,** 5553–5593. https://doi.org/10.1007/s10518-019-00652-x (2019).

Rossi, A., Tertulliani, A., Azzaro, R., Graziani, L., et al. (2019). “The 2016-2017 earthquake sequence in Central Italy: macroseismic survey and damage scenario through the EMS-98 intensity assessment”, *Bull Earthquake Eng*, **18**, 2407-2431. https://doi.org/10.1007/s10518-019-00556-w

SM Working Group (2015). *Guidelines for seismic microzonation, conference of regions and autonomous Provinces of Italy - Civil Protection Department, Rome*, Last Accessed July 2018 (Original Italian Edition: Gruppo di lavoro MS, Indirizzi e criteri per la microzonazione sismica, Conferenza delle Regioni e delle Province autonome—Dipartimento della protezione civile, Roma, 2008, 3 vol. e Dvd): http://www.protezionecivile.gov.it/httpdocs/cms/attach_extra/GuidelinesForSeismicMicrozonation.pdf.

Todrani, A. and Cultrera, G. (2021). “Near-source simulation of strong ground motion in Amatrice downtown including site effects”, submitted to *Geosciences* on Feb. 2021 to Special Issue "Engineering Analysis of Near-Source Strong Ground Motion".

Vignaroli, G. et al. (2019). “Geology of the central part of the Amatrice Basin (Central Apennines, Italy)”, *Journal of Maps,* **15**, 193–202, https://doi.org/10.1080/17445647.2019.1570877