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Reconnaissance of 2016 Central Italy Earthquake Sequence

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ABSTRACT

The Central Italy earthquake sequence nominally began on 24 August 2016 with a M6.1 event on a normal fault that produced devastating effects in the town of Amatrice and several nearby villages and hamlets. A major international response was undertaken to record the effects of this disaster, including surface faulting, ground motions, landslides, and damage patterns to structures. This work targeted the development of high-value case histories useful to future research. Subsequent events in October 2016 exacerbated the damage in pre- viously affected areas and caused damage to new areas in the north, particularly the relatively large town of Norcia. Additional reconnaissance after a M6.5 event on 30 October 2016 documented and mapped several large landslide features and increased damage states for structures in villages and hamlets throughout the region. This paper provides an overview of the reconnaissance activities under- taken to document and map these and other effects, and highlights valuable lessons learned regarding faulting and ground motions, engineering effects, and emergency response to this disaster.

INTRODUCTION

Between August and November 2016, three major earthquake events occurred in Central Italy. The first event (M6.1) occurred on 24 August 2016, the second (M5.9) on 26 October 2016, and the third (M6.5) on 30 October 2016. Each event was followed by numerous after-shocks, some exceeding M5.

As shown in Figure 1, this earthquake sequence occurred in a gap between two earlier damaging events, the 1997 M6.1 Umbria-Marche earthquake to the northwest (NW) and the 2009 M6.1 L'Aquila earthquake to the southeast. This gap had been previously recognized as a zone of elevated risk (GdL INGV sul terremoto di Amatrice 2016). These events occurred along the spine of the Apennine Mountain range on normal faults and had rake angles ranging from 80 to 100 deg. Each of these events produced substantial damage to local towns and villages. The 24 August 2016 event caused heavy damage to the villages of Arquata del Tronto, Accumoli, Amatrice, and Pescara del Tronto. In total, there were 299 fatalities, generally from collapses of unreinforced masonry dwellings. The October events caused significant new damage in the villages of Visso, Ussita, and Norcia, and almost complete destruction of the villages of Arquata del Tronto, Accumoli, Amatrice, and Pescara del Tronto. The October events did not produce fatalities, as the area had largely been evacuated and the tourist season had ended.

As described in the next section, the postevent reconnaissance involved two teams working in a coordinated manner. The first and largest team, with whom most of the authors of this paper were associated, was organized under the auspices of the Geotechnical Extreme Events Reconnaissance (GEER) Association, which is funded by the United States (U.S.) National Science Foundation (NSF). We conducted major reconnaissance activities in collaboration with many partnering organizations in Italy and elsewhere, with a focus on the scientific and engineering aspects of the events. The second team was organized by the Earthquake Engineering Research Institute (EERI) under the leadership of coauthor Silvia Mazzoni, which worked with several Italian partnering organizations. The EERI team also documented structural damage, although their principal focus was emergency response and medium- and long- term recovery and reconstruction efforts from a societal-resiliency perspective.

This paper describes the organization and objectives of the reconnaissance and high- lights some of the most significant findings, which are explained in more detail in other papers within this issue. Those papers have been prepared to document what we believe to be the most significant findings of the reconnaissance by the GEER and EERI teams. More information about the seismological and engineering aspects of the events are available in two detailed reports (GEER 2016, 2017).

RECONNAISSANCE ACTIVITIES

The NSF-funded GEER Association, with co-funding from the B. John Garrick Institute for the Risk Sciences at the University of California, Los Angeles and the NSF Industry–University Cooperative Research Centers Program (NSF IUCRC) Center for Unmanned Aircraft Systems (C-UAS) at Brigham Young University (BYU), mobilized the U.S.-based team to the area in two main phases: (1) following the 24 August 2016 event, from early September to early October 2016; and (2) following the October events, between the end of November and the beginning of December 2016. The U.S. team worked in close collaboration with Italian researchers organized under the auspices of the Italian Geotechnical Society, the Italian Center for Seismic Microzonation and its Applications, the Consortium of the Laboratories University Network of seismic engineering (ReLUIS), which is a Center of Competence of Department of Civil Protection, and the DIsaster RECovery Team of Politecnico di Torino. The objective of our Italy– U.S. GEER team was to collect and document perishable data. This work included the traditional GEER responsibilities for documenting geological, seismological, and geotechnical effects, as well as documenting the performance of buildings, bridges, and other structures.

The Italy–U.S. GEER team was multidisciplinary, with expertise in geology, seismology, geomatics, geotechnical engineering, and structural engineering. Our approach was to combine traditional reconnaissance activities of on-ground recording and mapping of field conditions with advanced imaging and damage detection routines. The three- dimensional (3-D) imaging was performed using unmanned aerial vehicles (UAVs) and has produced 3-D models of landslide features, surface faulting, and structural damage patterns. Links to the 3-D models resulting from this work are available at the BYU-PRISM website, available at http://prismweb.groups.et.byu.net/gallery2/2016%20Central%20Italy%20Earthquakes/ (last accessed 12 September 2018).

The EERI team undertook additional reconnaissance of the events, in coordination with the GEER team and in collaboration with the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) in Pavia and the ReLuis consortium. They visited the area in October 2016 and, again, in May 2017. The EERI team focused on emergency response and recovery, in combination with documenting the effectiveness of public policies related to seismic retrofit. The EERI team visited numerous short- and long-term temporary housing sites, ranging from short-term tem- porary tent camps (Tendopoli) to locations where the ground was being prepared for long-term (5–10 yr) temporary homes, to long-term housing locations where people had been living for a month, to L’Aquila, where these residences had been in use for over five years.

Both the GEER and EERI reconnaissance teams required access to heavily damaged “Red Zones,” which was facilitated by coordination on the part of EUCENTRE and ReLuis with the Italian government for the assessment of buildings and infrastructure. In particular, we worked closely with the Italian Department of Civil Protection to gain (in some cases, escorted) access to these restricted areas. This level of coordination and cooperation was essential to the reconnaissance effort.

OVERVIEW OF MAJOR FINDINGS

The initial objective of the GEER team was reconnaissance related to ground failures (surface fault rupture, landslides, and other ground deformations); soil–structure interaction (e.g., retaining wall failures); and indicators of site response effects (such as localization of damage, often in a manner consistent with topographic features). However, for both the August and October events, our mission broadened to include documentation of structural performance for a variety of rea- sons including: (1) it supported our mission of evaluating damage patterns; (2) the structural performance data was indeed perishable, and as the principal reconnaissance team in many of the visited areas, we felt a duty to document the broader impacts of these events.

Papers in this issue present significant technical findings related to the seismological, geotechnical, and structural engineering aspects of these events. A few highlights, with refer- ences to the respective manuscripts, are as follows:

EARTHQUAKE PROBABILITIES

When a large earthquake occurs, there are two schools of thought regarding its effect on the risk of subsequent large events. One is that stress release lowers earthquake rates relative to the long-term (Poisson) rate until stresses can again build up on the fault. Another is that stress release on one portion of the fault may increase stress on adjoining portions of the same fault segment or adjacent segments. This could locally increase earthquake rates (and hence short-term probabilities) relative to the long-term rate. This subject is of substantial practical significance for regional risk assessment. As shown in Figure 1, the August 2016 and October 2016 events occupy a gap along the NW striking Apennine chain between the locations of the 1997 Umbria-Marche and 2009 L'Aquila events. The occurrence of this cluster of earthquakes suggests that the latter (probability increasing) mechanism occurred and may continue into the future. This important topic is elaborated upon by Galadini et al. (2018).

FAULTS AS SEISMIC SOURCES

The portions of the Apennines affected by the Central Italy events are undergoing extension accommodated by numerous normal faults, many of which are well expressed at the surface. Galadini et al. (2018) show that the main shock events occurred on the Mt. Vettore–Mt. Bove fault system and the Amatrice fault in the Laga Mountains. Both of these faults had been recognized prior to the 2016 event sequence, but were not considered in previous Italian national seismic hazard studies. A review of these and other faults suggests that while most are expected to rupture separately (not cross between faults in a single event), the Laga Mountains faults and Mt. Vettore–Mt. Bove fault system are an exception and, in fact, did rupture together in the 24 August 2016 main shock. Galadini et al. (2018) encourage the use of seismic source models that utilize fault sources as a principal driver of hazard when those sources are well-characterized, as is the case in the subject region of Italy.

SURFACE FAULT RUPTURE

Gori et al. (2018) describe data on surface faulting from this event sequence and its association with prior geologic mapping. The M6.1 24 August 2016 event produced vertical offsets on the Mt. Vettore–Mt. Bove fault system that ranged from 0–35 cm over a 5-km interval of the fault near its southern end. The M6.5 30 October 2016 event ruptured a 15-km-long section of the fault, with vertical offsets typically ranging between 70 and 200 cm. Data compiled for the three main shocks (24 August 2016, 26 and 30 October 2016) will be a valuable resource for modeling surface rupture characteristics of normal fault earthquakes.

GROUND MOTIONS

Zimmaro et al. (2018) describe the ground motion database developed from recordings of these events. Those ground motions significantly extend the worldwide inventory of normal fault recordings in tectonically active regions. Zimmaro et al. (2018) describe important near- fault aspects of the ground motions and provide maps showing spatial variations of ground motion from main shock events. They demonstrate that the data exhibits fast anelastic attenuation at large distances (>100 km), which is predicted by Italy-adjusted global models, but not by Italy-specific models.

LANDSLIDES

Franke et al. (2018) describe how landslide effects were relatively modest in the August 2016 events, but were appreciable from the October events. They describe phased reconnaissance that combines traditional methods (i.e., existing landslide maps and manual inspection and measurement) and innovative approaches (i.e., satellite imagery, interferometry, and UAVs images). The geometry of the landslide source zones, as well as depositional areas, are documented with 3-D models from UAVs. Franke et al. (2018) show that such models can be used to evaluate landslide ground movements in complex topographic geometries and boulder runout distances from rock falls. The geology of these areas is also documented, although subsurface characterization data is currently unavailable. Two aspects of these case histories of interest to future work include: (1) the occurrence of landslides in some events but not others (predictive models should be able to forecast both) and (2) the landslide fall/runout distances.

MASONRY STRUCTURE FRAGILITY

Sextos et al. (2018) describe reconnaissance to document damage and nondamage to building structures in numerous villages and hamlets affected by the event sequence. Through both fieldwork and interpretation of 3-D imagery, they document structural performance according to a common classification scheme at high resolution—in many cases, a full inventory of performance of every structure within a hamlet or village (or portions thereof) was developed. Moreover, the damage mapping is multi-epoch, meaning that the performance of the same structures was recorded following the August 2016 events and the October

2016 events. Detailed multi-epoch structure-by-structure damage mapping and statistics are shown for many towns in the epicentral area, including Amatrice, Norcia, and Accumoli. We anticipate that empirical structural fragility models (e.g., Rossetto and Elnashai 2003, Rota et al. 2008, Sabetta et al. 1998) will be reevaluated in consideration of the data from these events.

SITE EFFECTS

Sextos et al. (2018) compare damage distributions within selected villages and hamlets with geological and topographic conditions. They describe horizontal-to-vertical spectral ratios (HVSR) from microtremor measurements and their azimuthal dependence, which were measured in selected areas with pronounced topographic relief and concentrated damage. These results reveal apparent site amplification polarized in the direction normal to the slope, which may have been responsible for some damage concentrations. A representative detailed example of this approach is presented for the small hamlet of Fiume. These findings will guide the selection of sites to be investigated with numerical ground response analyses for seismic microzonation.

RETROFIT EFFECTIVENESS

Mazzoni et al. (2018) describe the history of seismic design and retrofit of building structures in the area, and how the similarly-sized towns of Amatrice and Norcia had vastly different levels of preparation for these events and different levels of structural performance. They describe how the historical center of Amatrice, which largely lacked retrofit measures, was damaged extensively by the August event. Destruction in Amatrice was almost complete following the 30 October 2016 event. In contrast, the historical center of Norcia, for which retrofit programs had been implemented, did not experience significant damage from the August event, and even following stronger shaking in the 30 October 2016 event, the damage was largely limited to one collapsed church and distress to several historical buildings. Mazzoni et al. (2018) describe several individual case studies that show the effectiveness of retrofit measures that were tested across multiple events.

BRIDGE PERFORMANCE

Durante et al. (2018) describe the characteristics of bridges in the strongly shaken regions, including traditional masonry construction and relatively modern reinforced concrete and steel structures. They show that failures were confined to masonry structures and the modes of deformation that were observed, typically in abutments.

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REFERENCES

Chiaraluce, L., Amato, A., Cocco, M., Chiarabba, C., Selvaggi, G., Di Bona, M., Piccinini, D., Deschamps, A., Margheriti, L., Courboulex, F., and Ripepe, M., 2004. Complex normal fault- ing in the Apennines thrust-and-fold belt: The 1997 seismic sequence in Central Italy, Bulletin of the Seismological Society of America 94, 99–116.

Durante, M. G., Di Sarno, L., Zimmaro, P., and Stewart, J. P., 2018. Damage evaluation of road-way infrastructure during the 2016 Central Italy earthquake sequence, Earthquake Spectra 34, 1721–1737. doi:10.1193/101317EQS205M.

Franke, K. W., Lingwall, B. N., Zimmaro, P., Kayen, R. E., Tommasi, P., Chiabrando, F., and Santo, A., 2018. A phased reconnaissance approach to documenting landslides following the 2016 Central Italy earthquakes, Earthquake Spectra 34, 1693–1719. doi:10.1193/082117 EQS165M.

Galadini, F., Falcucci, E., Gori, S., Zimmaro, P., Cheloni, D., and Stewart, J. P., 2018. Active faulting in source region of 2016–2017 Central Italy event sequence, Earthquake Spectra 34, 1557–1583. doi:10.1193/101317EQS204M.

GdL Istituto Nazionale di Geofisica e Vulcanologia (INGV) sul terremoto di Amatrice, 2016. Primo rapporto di sintesi sul Terremoto di Amatrice Ml 6.0 del 24 Agosto 2016 (Italia Centrale), Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy. doi:10.5281/ zenodo.61121 (in Italian).

Geotechnical Extreme Events Reconnaissance (GEER), 2016. Engineering Reconnaissance of the 24 August 2016 Central Italy Earthquake, Version 2 (P. Zimmaro and J. P. Stewart, eds.), Geotechnical Extreme Events Reconnaissance Association Report No. GEER-050B. doi:10.18118/G61S3Z.

Geotechnical Extreme Events Reconnaissance (GEER), 2017. Engineering Reconnaissance following the October 2016 Central Italy Earthquakes, Version 2 (P. Zimmaro and J. P. Stewart, eds.), Geotechnical Extreme Events Reconnaissance Association Report No. GEER-050D. doi:10.18118/G6HS39.

Gori, S., Falcucci, E., Galadini, F., Zimmaro, P., Pizzi, A., Kayen, R. E., Lingwall, B. N., Moro, M., Saroli, M., Fubelli, G., Di Domenica, A., and Stewart, J. P., 2018 Surface faulting caused by the 2016 Central Italy seismic sequence, Earthquake Spectra 34, 1585–1610. doi:10.1193/111417EQS236MR.

Mazzoni, S., Castori, G., Galasso, C., Calvi, P., Dreyer, R., Fischer, E., Fulco, A., Sorrentino, L., Wilson, J., Penna, P., and Magenes, G., 2018. 2016–17 Central Italy earthquake sequence: Seismic retrofit policy and effectiveness, Earthquake Spectra 34, 1671–1691. doi:10.1193/100717EQS197M.

Piatanesi, A., and Cirella, A., 2009. Rupture Process of the 2009 Mw6.3 L’Aquila (Central Italy) Earthquake from Nonlinear Inversion of Strong Motion and GPS Data, Working Report (Version 2), Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy.

Rossetto, T., and Elnashai, A., 2003. Derivation of vulnerability functions for European-type RC structures based on observational data, Engineering Structures 25, 1241–1263.

Rota, M., Penna, A., and Strobbia, C. L., 2008. Processing Italian damage data to derive typological fragility curves, Soil Dynamics and Earthquake Engineering 28, 933–947.

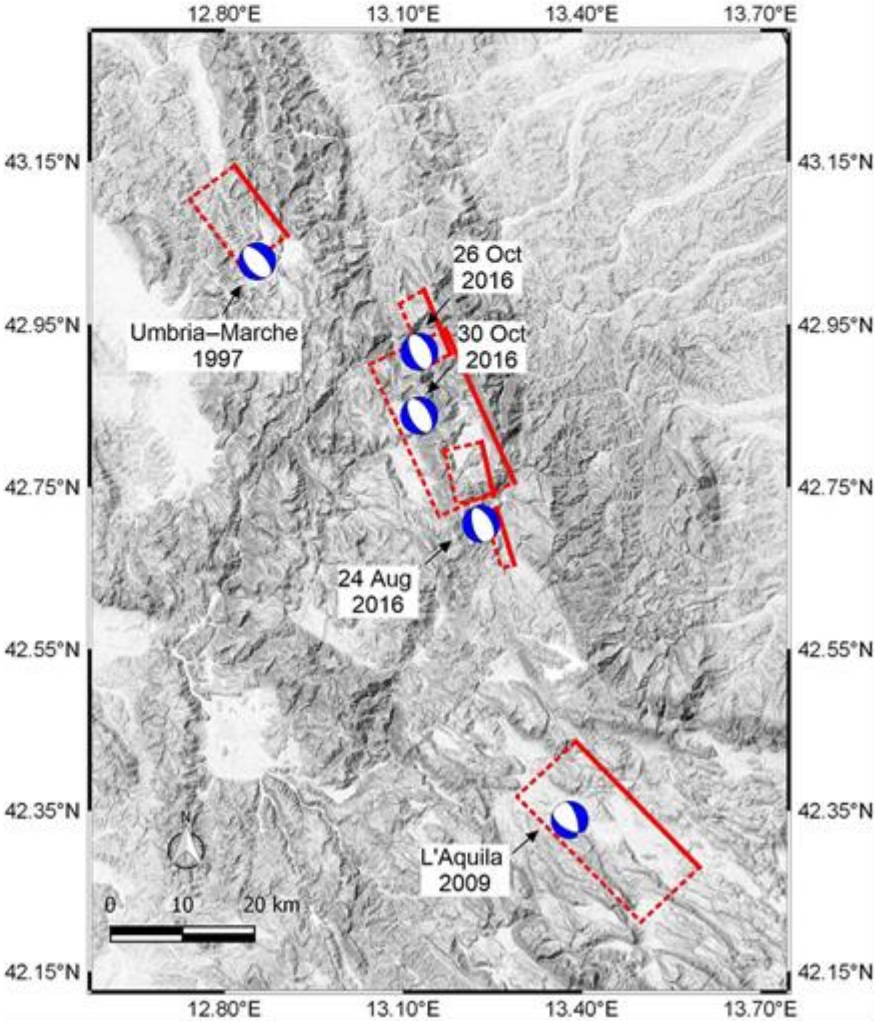
Sabetta, F., Goretti, A., and Lucantoni, A., 1998. Empirical fragility curves from damage surveys and estimated strong ground motion, in Proceedings of the 11th European Conference on Earthquake Engineering, 6–11 September 1998, Paris, France.

Sextos, A., De Risi, R., Pagliaroli, A., Foti, S., Passeri, F., Ausilio, E., Cairo, R., Capatti, M. C., Chiabrando, F., Chiaradonna, A., Dashti, S., De Silva, F., Dezi, F., Durante, M. G., Giallini, S., Lanzo, G., Sica, S., Simonelli, A. L., and Zimmaro, P., 2018. Local site effects and incremental damage of buildings during the 2016 Central Italy earthquake sequence, Earthquake Spectra 34, 1639–1669. doi:10.1193/100317EQS194M.

Zimmaro, P., Scasserra, G., Stewart, J. P., Kishida, T., Tropeano, G., Castiglia, M., and Pelekis, P., 2018. Strong ground motion characteristics from 2016 Central Italy earthquake sequence, Earthquake Spectra 34, 1611–1637. doi:10.1193/091817EQS184M.

FIGURE CAPTIONS

Figure 1. Map of central Italy showing moment tensors of major earthquakes since 1997 and the intermediate gap areas. Finite fault models for 1997 Umbria-Marche and 2009 L’Aquila are from Chiaraluce et al. (2004) and Piatanesi and Cirella (2009). Finite fault models for Central Italy events are from Galadini et al. (2018).


12.80°E
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13.70°E
43.15°N
42.95°N
42.75°N
42.55°N
42.35°N
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30 Oct 2016
Umbria–Marche 1997
24 Aug 2016
L'Aquila 2009
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10
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Figure 1.