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ENGINEERING RECONNAISSANCE FOLLOWING THE AUGUST 24, 2016 M6.0 CENTRAL ITALY EARTHQUAKE

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Abstract

An earthquake with a moment magnitude reported as 6.0 from INGV (Istituto Nazionale di Geofisica e Vulcanologia); occurred at 03:36 AM (local time) on 24 August 2016 in the central part of Italy. The epicenter was located at the borders of the Lazio, Abruzzi, Marche and Umbria regions, about 2.5 km north-east of the village of Accumoli and about 100 km from Rome. The hypocentral depth was about 8 km (INGV). We summarize preliminary findings of the Italy-US GEER (Geotechnical Extreme Events Reconnaissance) team, on damage distribution, causative faults, earthquake-induced landslides and rockfalls, building and bridge performance, and ground motion characterization. Our reconnaissance team used multi-disciplinary approaches, combining 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 enabled by state-of-the-art geomatics technology. We anticipate that results from this study, will be useful for future post-earthquake reconnaissance efforts, and improved emergency response.

Keywords: Central Italy earthquake, post-earthquake reconnaissance, Ground motions, Multidisciplinary approach

1. Introduction

The central Italy earthquake occurred on 24 August 2016 at 03:36 AM local time. The magnitude is listed as **M**6.0 by INGV and **M**6.2 by USGS. Although initially reported as occurring at relatively shallow depths, the current source model from INGV places the hypocentral depth at 8 km [1], which is not especially shallow for shallow crustal earthquakes.

The earthquake was located in a gap between two earlier damaging events, the 1997 **M**6.1 Umbria-Marche earthquake to the north-west and the 2009 **M**6.1 L'Aquila earthquake to the south-east. This gap had been recognized prior to the event as a zone of elevated risk (GdL Istituto Nazionale di Geofisica e Vulcanologia, hereafter INGV, 2016). The present event and those that preceded it occurred along the spine of the Apennine Mountain range on normal faults and had rake angles ranging from -80 to -100. Each of these events produced substantial damage to local towns and villages; the present event most strongly affected Arquata del Tronto, Accumoli, Amatrice, and Pescara del Tronto, with a loss of life as of this writing of 298, generally from collapses of unreinforced masonry dwellings.

The NSF-funded Geotechnical Extreme Events Reconnaissance (GEER) association, with co-funding from the B. John Garrick Institute for the Risk Sciences at UCLA and the NSF I/UCRC Center for Unmanned Aircraft Systems (C-UAS) at BYU, mobilized a US-based team to the area from 5-9 September 2016. The US 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 ReLUIS, Centre of Competence of Department of Civil Protection and the DIsaster RECovery Team of Politecnico di Torino. In subsequent phases of reconnaissance, researchers from Greece and the U.K. mobilized to the area to undertake detailed mapping of structural damage in specific villages where such data was thought to be of high value. The objective of the Italy-US GEER team was to collect and document perishable data that is essential to advance knowledge of earthquake effects, which ultimately leads to improved procedures for characterization and mitigation of seismic risk.

The GEER team was multi-disciplinary, 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 enabled by state-of-the-art geomatics technology. This combination of reconnaissance techniques provides opportunities for innovative future study.

Figure 1 shows the most strongly affected region. Our activities focused on the following aspects of the earthquake event:

1. Surface fault rupture
2. Recorded ground motions
3. Locations of landslides and rockfalls. Mapping specific case histories.
4. Performance of bridge structures
5. Performance of building structures, with an emphasis on damage patterns

Our observations related to each of these aspects is elaborated upon in the sections that follow. This paper is adapted from a Version 1 GEER reconnaissance report [2]. A more detailed reconnaissance report (Version 2) is in preparation.

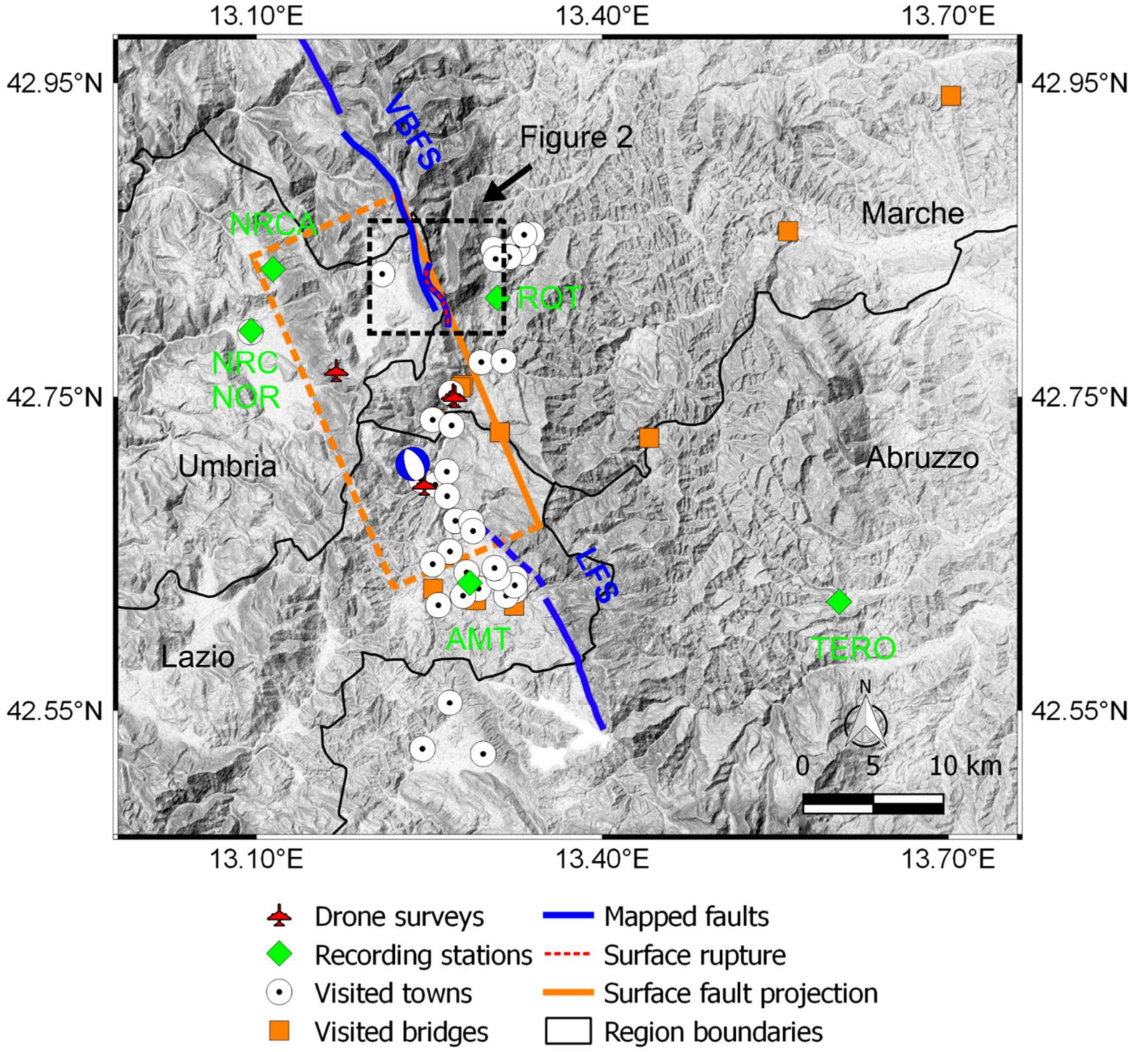

Fig. 1 – Regional map showing the Mt. Vettore–Mt. Bove fault system (VBFS, modified from Pizzi and Galadini [3]), and the Laga fault system (LFS, modified from Galadini and Galli [4]), finite fault model from Tinti et al. [5] and epicenter, ground motion station locations, and locations of various earthquake effects discussed in this report (adapted from Stewart et al., [2]).

2. Surface Faulting

The mainshock occurred in either a bend or a stepover zone between two previously mapped normal faults – the Mt. Vettore fault and the Amatrice fault, which is the north extension of the Laga Mountains fault. These faults are shown in Figure 1.

Surface rupture occurred over a 4.8 km portion of the Mt. Vettore fault, as shown in Figure 1 and 2. Working with researchers at INGV (especially co-authors Galadini, Gori, and Falcucci), displacements on the primary rupture were measured as generally in the range of 10-25 cm. These displacements were down-dip, generally with no appreciable along-strike component. Figure 3 shows a general view of the fault trace (Figure 3a) and a typical displacement measurement on the fault (Figure 3b). We did not see secondary breaks on the hanging wall. Aerial imagery of the surface rupture is pending.

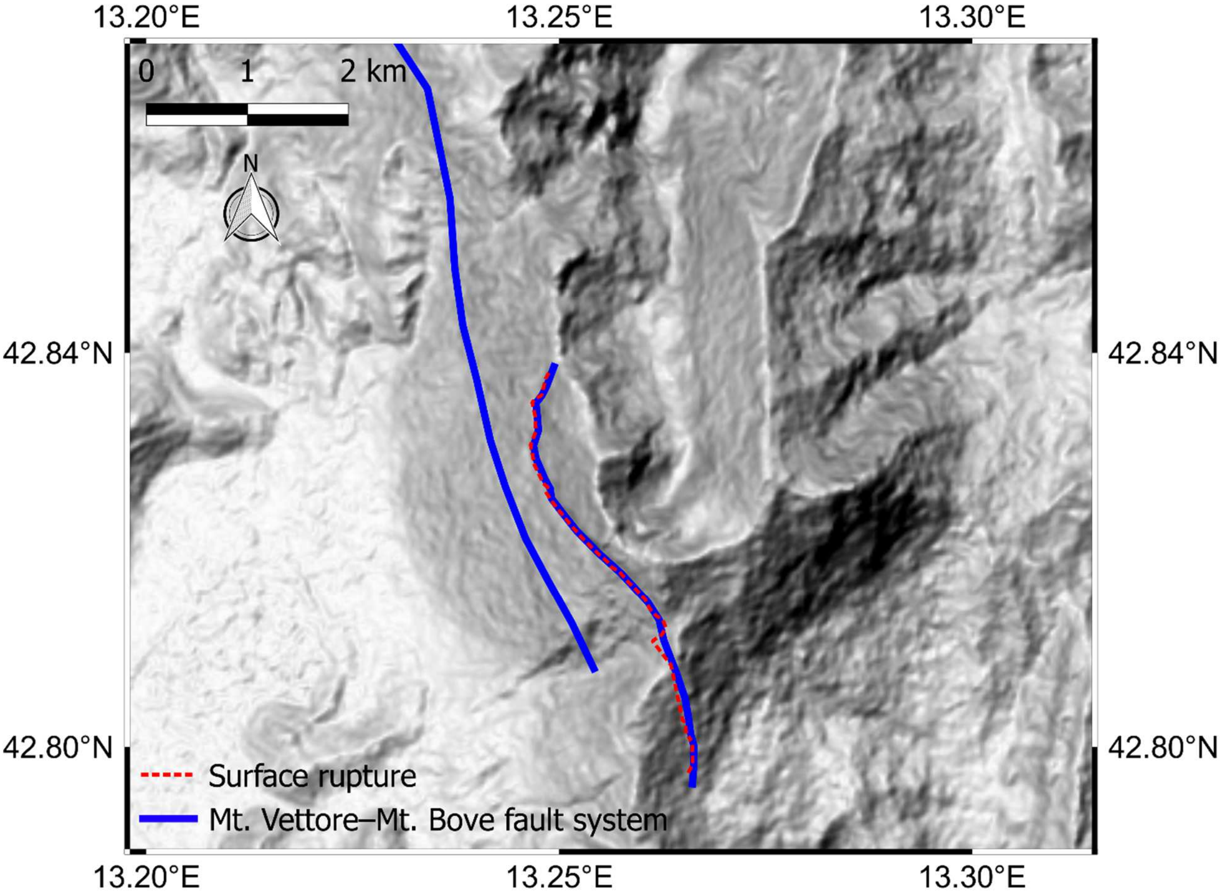

Fig 2 – Detail map of surface fault rupture and pre-event mapping of Mt. Vettore-Mt. Bove fault system (adapted from Pizzi and Galadini, 2009).

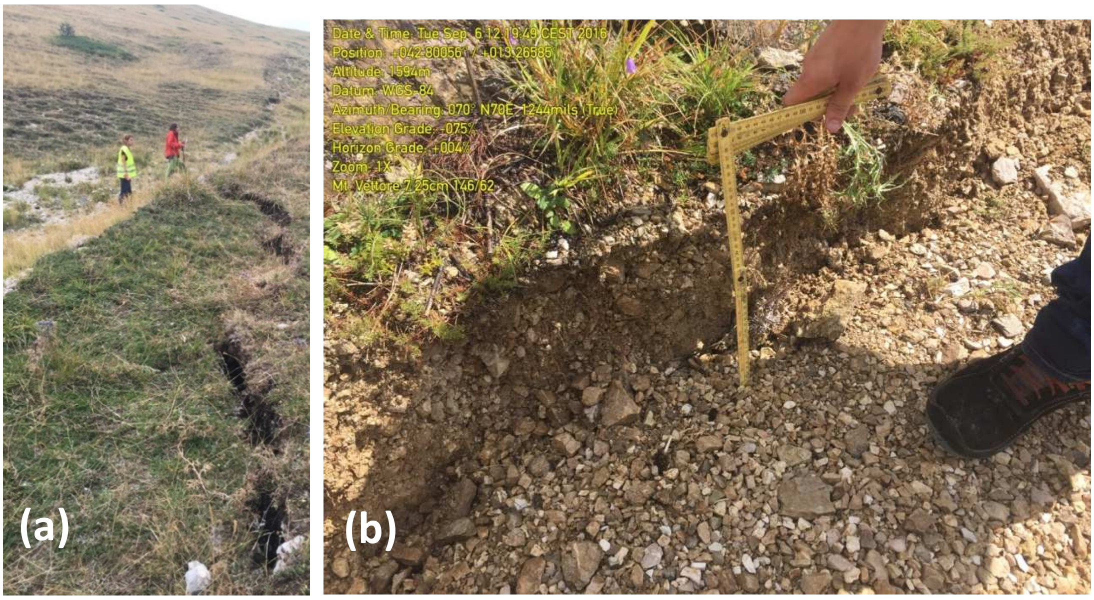

Fig 3 – (a) photographs of surface rupture on trace of Mt. Vettore fault (N42.79953, E13.26634, 5 September 2016) and (b) typical measurement (N42.8056, E13.26585, 6 September 2016).

3. Ground Motions

Two ground motion networks operate widely in Italy: INGV and Dipartimento della Protezione Civile (DPC). Data from these networks are disseminated at http://esm.mi.ingv.it.

In collaboration with the Pacific Earthquake Engineering Research (PEER) center, we downloaded volume 1 (digital uncorrected) data from the mainshock and aftershocks on 8/24 and 8/26 with INGV magnitudes **M**5.4, and 4.8. In total, 257 records were downloaded on 1 September 2016 and processed using standard PEER processing Ancheta et al. [6], which removes any static offset effects that might otherwise be present. We are aware of 105 additional records now available, which will be considered subsequently. We are presently compiling site parameters for stations without shear-wave velocity measurements, which may include some geophysical testing using surface wave methods at selected sites. Our Ver 2 report will present analysis of the data.

Figure 4 shows pseudo-acceleration response spectra (PSA) from the two stations most proximate to the mainshock rupture plane (AMT and NRC), which are shown in Figure 1. The corrected ground motions have been rotated into fault normal (FN) and fault parallel (FP) components. The two ground motions are of comparable amplitudes (NRC slightly higher), despite substantially different damage levels (details below). The AMT ground motion shows evidence of polarization in the FN direction at short oscillator periods (< 1.0 sec), while the NRC motion is stronger in the FN direction at long periods (> 1.0 sec).

We have visited the AMT and NRC sites. The instrument shelters at neither site appears to have been damaged by the earthquake, and both shelters are small structures unlikely to appreciably affect the recordings. Generally, the damage patterns near the AMT site were also suggestive of stronger shaking in the FN direction, which will be detailed in our Ver 2 report.

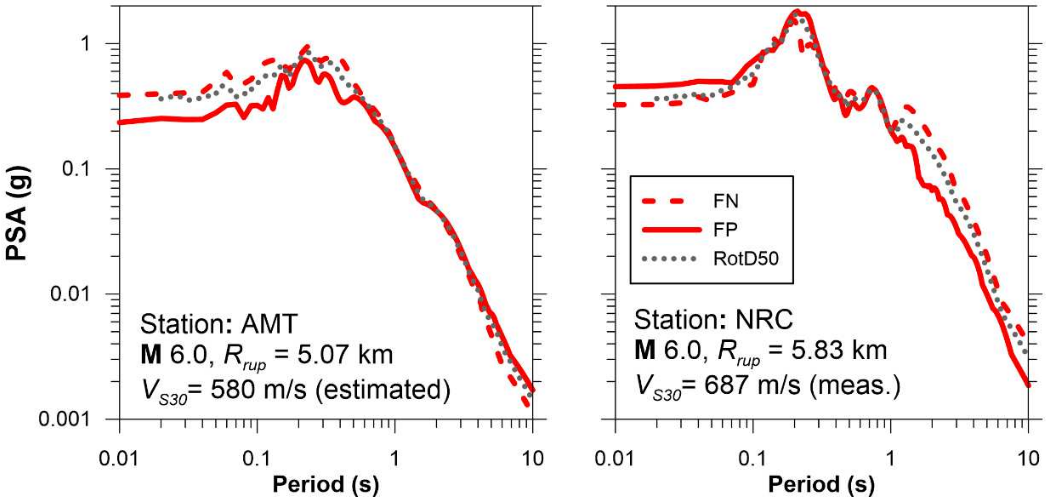

Fig 4 – Mainshock pseudo acceleration response spectra (5% damping) for Amatrice (AMT) and Norcia (NRC) sites. Fault strike taken as 150 deg for computation.

3. Landslides and Rockfalls

Figure 5 shows locations of known rockfalls and landslides. Prior to deployment of the GEER team, we reviewed reports of rockfalls from ISPRA [7] and CERI [8]. We found a limited number of landslides beyond those identified in the preliminary reports.

We overlaid the ISPRA and CERI locations on a map of multi-epoch (pre- to post-earthquake) deformation based on InSAR coherence changes (Damage proxy maps, ARIA project, JPL-Caltech, available at: http://aria-share.jpl.nasa.gov/), as shown in Figure 5. Our approach to reconnaissance activities was to initially visit sites of mapped deformation, but no prior rockfall observations, followed by more detailed mapping activities for high-value case histories.

Using direct visual observation where possible, in combination with aerial drone based imaging, we found no detectable landslide activity in the high-deformation zones shown in Figure 5 without prior landslides.

Using a DJI™ Phantom 4 drone, a customized Align™ T-Rex 800 drone, and an Ebee Sense Fly drone, we imaged the four locations shown in Figure 1. These data will be used also for high resolution digital map creation (ortophoto) Digital Surface Model (DSM) and 3D models of the acquired areas. Information on where to find down-sampled video for two of these locations (Accumoli and Pescara del Tronto) are provided on the Central Italy Earthquake event page within the GEER Association website (www.geerassociation.org). Figure 6 shows aerial photos taken by drones at Accumoli (Figure 6a) and Pescara del Tronto (Figure 6b).

Observed landslides were mainly small rock failures (wedge slides, topples and slides in intensely fractured/weak rocks) which very often generated rockfalls. One of the largest failures occurred on a slope that, in the past, was involved in similar instability phenomena (Pescara del Tronto, just above the Salaria State road, Figure 6b). In several instances (specifically Tufo, Pescara del Tronto and Accumoli, Figure 6a), retaining structures underwent displacements and rotation (toppling) with consequences to the backfill and hence to the areas behind (including roads).

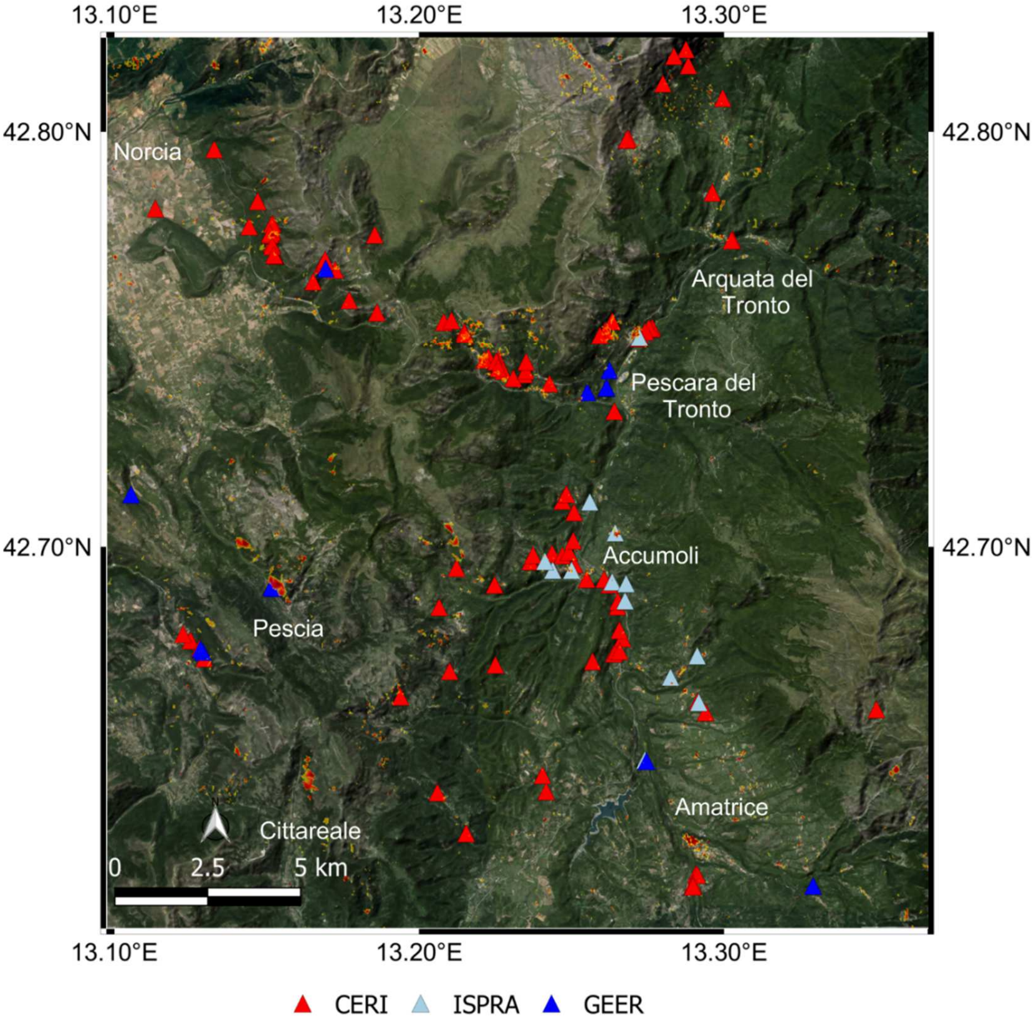

Fig 5 – Mapped rockfalls and landslides from ISPRA (red triangles), CERI (blue triangles), and GEER (this study; white triangles), along with the damage proxy map of the area produced by the ARIA project (Google earth kmz files used to produce this Figure are available at: http://aria-share.jpl.nasa.gov//events/20160824-Italy_EQ/DPM/, last accessed October 30, 2016).

Fig 6 – Aerial photos taken by drones at: (a) Accumoli (N42.69425, E13.24993, 9 September 2016); and (b) Pescara del Tronto (N42.750401, E13.272109, 9 September 2016).

4. Bridges

GEER worked in close collaboration with Consortium ReLUIS to inspect 11 bridges at the locations shown in Figure 1. These bridges have a variety of configurations, but can be broadly viewed as relatively contemporary structures (constructed since approximately the 1960s) and older arch masonry structures. The contemporary bridges inspected are reinforced concrete (RC) and composite RC and steel structures, generally built in the 1960s. The contemporary bridges inspected include:

- RC bridge located along the Strada Provinciale (SP) 7 (km 16+150), in Boscomartese;

- RC bridge located along the SP 173, in the belt of Offida;
- RC bridge located along the SP 20, in Colle.
- Composite steel and concrete bridge located along the SP in Colle, also known as Ponte Ramazzotti.

We found no evidence of damage to any of the contemporary bridges. We found damage to two arch masonry bridges at the locations shown in Figure 1. One of these bridges is near the village of Tufo on the Roman-era Trisungo route. The bridge had some cracking and spalling of exterior masonry elements, apparently exacerbated by settlement at the east support of the arch, as shown in Figure 7.

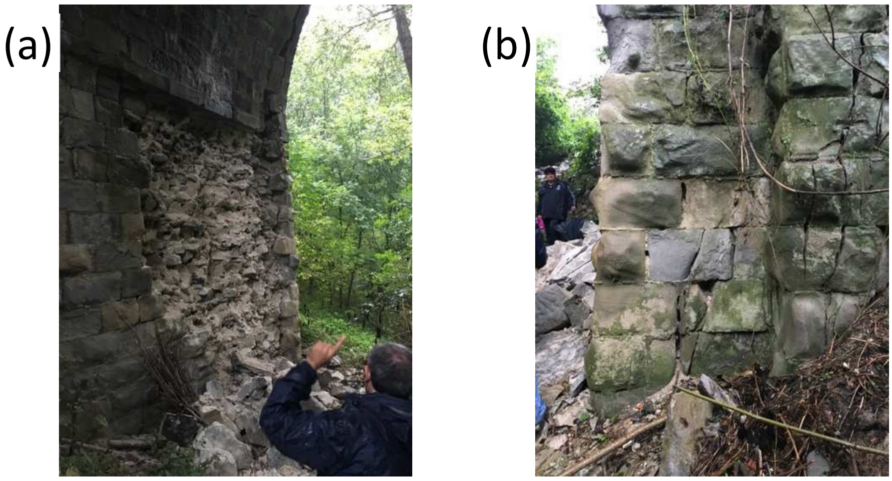

Fig 7 – Roman-era bridge along the Trisungo route (Tufo area – Arquata del Tronto): (a) spalling and (b) cracking of exterior masonry elements. (N42.735389, E13.253611, September 7 2016).

A second damaged bridge is the Ponte a Tre Occhi (Three eyes) near Amatrice, which is a critical lifeline for the access to the village of Amatrice. One of the arches exhibited cracking, but the most severe damage occurred to approach structures of *muratura a sacco* masonry construction, in which portions of the outer layer of masonry were lost, leading to lateral relaxation and settlement of the bridge deck (Figure 8). The bridge remained closed as of the date of our last site visit (8 September 2016).

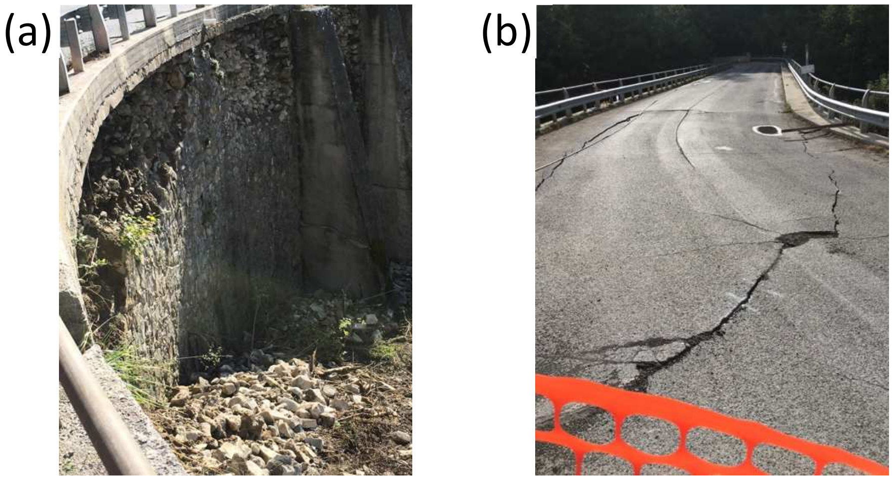

Fig 8 – Ponte a Tre Occhi (Amatrice): (a) spalling of the outer layer of the masonry and (b) settlement of the road surface. (N42.62067, E13.290278, September 8 2016).

5. Damage to Building Structures in Villages

The earthquake produced devastating effects on dwellings in the villages of Arquata del Tronto, Accumoli, Amatrice, and Pescara del Tronto, the overwhelming majority of which are of masonry construction. The motivation of the GEER work in these, and other, areas was to document patterns of damage and non-damage, and specific case histories of special interest. From a geotechnical and seismological perspective, these findings have potential application for inference of ground motion spatial distribution, including site effects (especially topographic effects). Moreover, as some of the initial engineering researchers to access the region, we also recognized our responsibility to support broader reconnaissance efforts for this earthquake in relation to the performance of buildings.

Prior to field deployment of the GEER team, we overlaid locations of structural damage as assessed by the Copernicus EMS Rapid Mapping service (http://emergency.copernicus.eu/), which is based on high-resolution orthophotos taken on 08/25/2016 at 10 UTC, with a pixel separation distance of 0.1m. That mapping delineated for each structure a damage classification as follows:

- Red: destroyed;
- Light red: highly damaged;
- Orange: moderately damaged;
- Yellow: Negligible to slight damage.

This mapping was provided for 29 villages by the Copernicus project.

We secured access to about 40 villages shown in Figure 1, and performed detailed mapping at six of these villages: (Amatrice, Arquata del Tronto, Pescara del Tronto, Tufo, Norcia, and Castelluccio). One objective of the detailed mapping was to validate the Copernicus damage assessments. Analysis of this data remains in progress.

We also performed detailed aerial imaging of the Pescara del Tronto village, which will support the development of a 3D model for subsequent damage studies. Aerial flights were not authorized over the structures in the village of Accumoli during our reconnaissance. Close range photogrammetric survey for Digital Surface Model generation was also completed for the Sant'Agostino church and its bell tower in Amatrice (Figure 9), which can be used to generate 2D or 3D models of the structure.

A consistent pattern of our observations pertains to the effectiveness of retrofitting for collapse avoidance of masonry structures. In the most heavily impacted villages, retrofitting was sparse. One compelling example is to compare Amatrice with Norcia. The devastation in Amatrice is well known, and retrofit in the historic center was lacking. The ground motions in Norcia appear to have been of similar or even greater intensity (Figure 4), but damage was sparse. Most masonry dwellings in Norcia have been retrofitted under a government program implemented following earthquakes in 1979 and 1997.

We observed a number of retaining wall failures in the villages of Amatrice, Accumoli, and Pescara del Tronto. These will be further documented in subsequent publications.

6. Next Steps

We have been in contact with other reconnaissance teams operating in the area, including EERI, ReLuis, and EUCentre. We have held a public briefing on the results of reconnaissance activities by each of these teams (available here). We are presently working on the Version 2 GEER report, while also planning reconnaissance activities related to the 26 Oct 2016 **M**5.9 event and the 29 Oct 2016 **M**6.5 event (INGV magnitudes).

Fig 9 – 3D textured model of the Sant'Agostino church and its bell tower in Amatrice. (N42.628, E13.2914, September 7 2016).

7. Acknowledgements

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