Damage to Roadway Infrastructure from 2016 Central Italy Earthquake Sequence

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The region of the central Apennines affected by the 2016 earthquake sequence has numerous towns, villages, and isolated dwellings connected by local secondary roads and a few state highways. The roadway network includes several bridges that are important to the economy of the region and play an important role in the post-earthquake resilience of local communities. Within this network, 12 bridges and a rockfall protection tunnel were inspected in coordination with local officials, with relatively cursory reconnaissance of most of the remainder of the network. All inspected reinforced concrete and steel–concrete composite bridges performed adequately. Two historic masonry bridges near Amatrice and Tufo suffered significant damage after the 24 August 2016 main shock, and collapsed after the 30 October 2016 event. Recovery strategies related to the bridge collapse near Amatrice, where two temporary bridges were built within 10 days from the first main shock in August, are discussed. An inspected rockfall protection tunnel experienced earthquake pounding effects. [DOI: 10.1193/101317EQS205M]

INTRODUCTION

This paper describes the performance of roadway infrastructure as observed in reconnaissance performed following two events within the 2016 Central Italy Sequence—the 24 August 2016 and 30 October 2016 main shock events. Further information on the broader reconnaissance effort are provided in GEER (2016, 2017) and Stewart et al. (2018). Additional details on the event sequence are given in Galadini et al. (2018). Roadway infrastructure networks are important for post-disaster response and longer-term community resilience. Recent studies show that bridge infrastructures in southern Europe are vulnerable to earthquake damage (e.g., De Risi et al. 2017, Di Sarno et al. 2017, and Pinto and Mancini 2009). Furthermore, the recent 2016 Kaikoura earthquake in New Zealand has shown that damage to roadway network infrastructure can impact social and economic activities (e.g., Davies et al. 2017 and Stevenson 2017) and that even recently designed bridges can suffer significant damage (Palermo et al. 2017).

The area struck by the Central Italy earthquake sequence is located in the inner central Apennine mountain chain. This is a sparsely populated area in which small villages and towns are typically connected by local secondary roads. This paper shows the performance

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of eight recently-designed reinforced concrete (RC) and composite steel–concrete bridges, four older masonry bridges (one of which was built in the Roman-era), and a rockfall protection tunnel. The assessment of bridge performance is based on detailed on-site visual inspections. For bridges located in the province of Ascoli Piceno, the inspections were performed in coordination with bridge officials affiliated with the local provincial government agencies. Based on interpolation procedures described in Zimmaro et al. (2018), ground motion levels at the bridge sites range from ~0.1 to ~0.55 g in the two most significant main shock events (**M**6.1 24 August 2016 and **M**6.5 30 October 2016), hence some damage might be inspected, even to bridges of relatively modern construction.

The following sections describe: (1) Ground motion demands at the transportation infrastructure sites considered in this paper; (2) seismic design criteria and performance of bridge structures and related considerations; (3) the performance of other inspected transportation infrastructure; and (4) recovery efforts related to the failure of an especially significant bridge structure near Amatrice.

SEISMIC DEMAND AT SITES OF INTEREST

In this section, the seismic demands for three main shocks of the 2016 Central Italy earthquake sequence (**M**6.1 24 August 2016, **M**5.9 26 October 2016, and **M**6.5 30 October 2016 events) at selected roadway infrastructure locations are estimated. Zimmaro et al. (2018) calculated the spatial distribution of peak ground acceleration and velocity (PGA and PGV, respectively) using a Kriging procedure applied to within-event residuals (i.e., a measure of the difference between observed and predicted ground motions at recording station locations). This approach is applied to estimate PGA and PGV at roadway infrastructure locations. In this analysis, ground motions are evaluated for a uniform reference value of the time-averaged shear wave velocity in the upper 30 m, V_{S30} of 580 m/s. This V_{S30} value corresponds to site class B according to the Italian building code (Ministry of Infrastructure 2008; hereafter *NTC08*). As a result, the ground motions calculated applying this procedure do not account for local site response effects, including the effects of topography.

Figures 1 and 2 show the spatial distribution of PGA and PGV, respectively, for the 24 August 2016 and 30 October 2016 main shocks along with locations of bridges and other infrastructure discussed in this paper. Table 1 shows PGA and PGV estimated at inspected roadway infrastructure locations. The outcomes of the calculations show that the highest values of PGA (~0.4–0.5g) and PGV (~30–40 cm/s) during the **M**6.1 24 August 2016 and the **M**6.5 30 October 2016 events occurred at the two masonry bridge sites in Amatrice (M1 and M2 in Figures 1 and 2) and at the two masonry bridge sites in Tufo (M3 and M4 in Figures 1 and 2). Ground motions were considerably smaller in the **M**5.9 26 October 2016 earthquake (Zimmaro et al. 2018).

PERFORMANCE OF BRIDGES

APPLICABLE CODES AND STANDARDS

Prior to 1974, bridge construction in Italy was not regulated by design codes that required consideration of seismic effects. Since 1974, areas considered seismically active were subject to code provisions affecting the design of bridges, retaining walls, and other transportation infrastructure (Italian Ministry of Public Works 1974 and 1975). The most recent version of these codes was adopted by the Ministry of Infrastructure (2008; *NTC08*) in 2009. Since 1974, all national seismic zonation maps and design codes consider the subject area of Central Italy as an active seismic zone characterized by moderate to high seismicity.

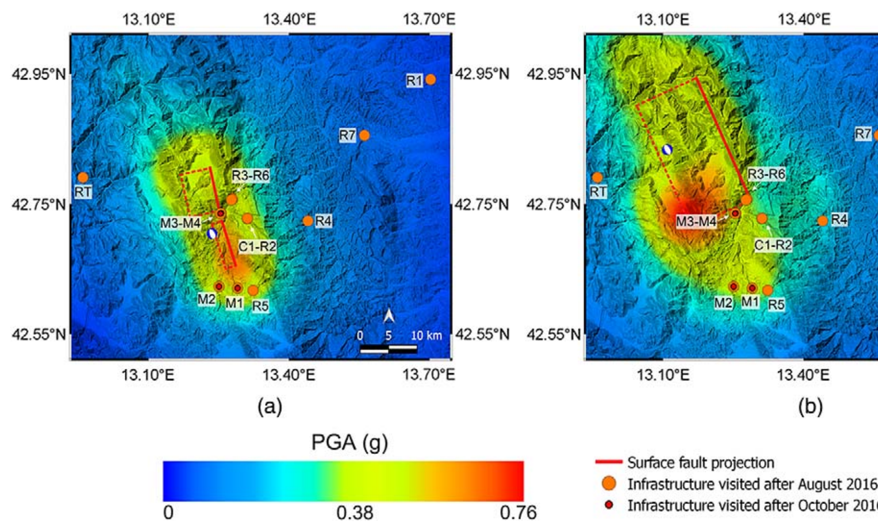

Figure 1. Map showing inspected infrastructure and spatial distribution of PGA for (a) the **M**6.1 24 August 2016 and (b) the **M**6.5 30 October 2016 main shocks.

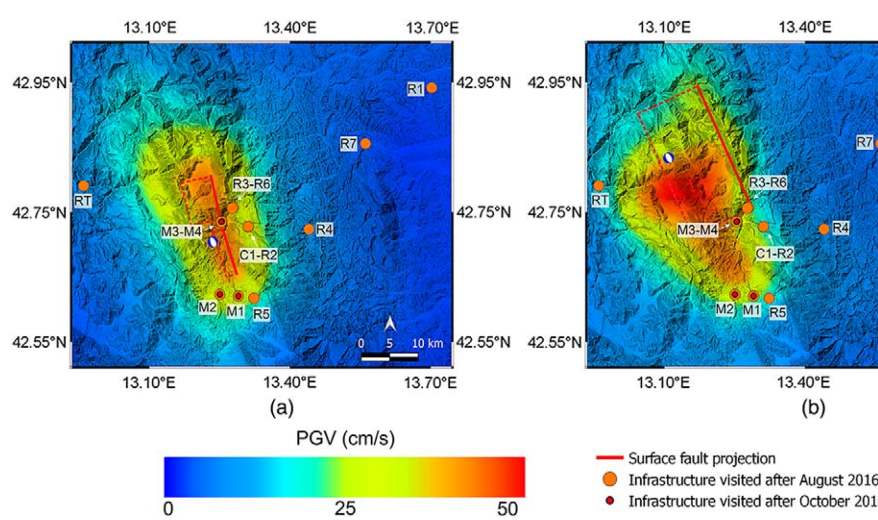

Figure 2. Map showing inspected infrastructure and spatial distribution of PGV for (a) the **M**6.1 24 August 2016 and (b) the **M**6.5 30 October 2016 main shocks.

Table 1. Details of the inspected roadway infrastructures

					M6.1 24 August 2016		**M**5.9 26 October 2016		**M**6.5 30 October 2016	
	ID	Construction type	Long (deg)	Lat (deg)	PGA (g)	PGV (cm/s)	PGA (g)	PGV (cm/s)	PGA (g)	PGV (cm/s)
SP 20, Colle (km 9+650) Ponte Ramazzotti	C1	Composite steel and concrete	13.3111	42.7276	0.41	29	0.081	3.8	0.29	19
SP173, Offida	R1	RC	13.7023	42.9417	0.048	3.4	0.034	2.8	0.062	6.9
SP 20, Colle (km 500)	R2	RC	13.3111	42.7278	0.41	29	0.081	3.8	0.29	18.5
SP129, Trisungo-Tufo (km 4+900)	R3	RC	13.2789	42.7577	0.45	35	0.10	4.5	0.30	21
SP7, Boscomartese (km 16+150)	R4	RC	13.4405	42.7241	0.16	9.5	0.092	3.1	0.22	8.0
SR577, Torrente Rionero	R5	RC	13.3233	42.6172	0.43	23	0.058	2.9	0.31	17.2
SS685, Tre Valli Umbre (km 2)	R6	RC	13.2771	42.7562	0.45	35	0.10	4.5	0.30	22
SS4, crossing the Tronto River Ascoli Piceno	R7	RC	13.5609	42.8558	0.079	3.6	0.053	1.9	0.11	5.1
SR260, Ponte a Tre Occhi, Amatrice	M1	Masonry	13.2902	42.6207	0.54	31	0.068	3.5	0.40	25
SR260, Ponte a Cinque Occhi, Amatrice	M2	Masonry	13.2504	42.6232	0.47	32	0.072	3.7	0.36	29
Roman-era SP129 Trisungo-Tufo, (1 span)	M3	Masonry	13.2549	42.736	0.53	42	0.094	4.3	0.41	31.0
Roman-era SP129 Trisungo-Tufo, (3 spans)	M4	Masonry	13.2537	42.7354	0.53	42	0.094	4.3	0.42	31.4
Rockfall protection tunnel SS685	RT	Composite steel and concrete	12.9594	42.7905	0.11	10	0.074	5.0	0.17	14.0

The general seismic design criteria in the 1974 code were based on static lateral load requirements, with the alternative of using linear elastic dynamic analysis. *NTC08* requires that the deck and foundation remain in the elastic range, while energy dissipation is provided by piers and/or specific devices (e.g., seismic isolators). The code also indicates that phenomena such as permanent structural displacements, loss of support, and earthquake pounding effects are to be avoided. *NTC08* does not mandate retrofit of existing bridges. When the decision is made to structurally modify an existing bridge, then the *NTC08* provisions become mandatory as part of the design of the modification.

As described further below, information on the specific design and construction dates of the inspected bridges were not available. The speculation of local officials, and the second author, is that most of the RC and steel bridges predate the 1974 standard, although some may have been designed using it. Regardless, none of the inspected bridges were designed in a contemporary manner that would include, for example, modern RC section detailing requirements. For this reason, satisfactory seismic performance under strong shaking would not necessarily be anticipated.

INSPECTION PROCEDURES

Periodic pre-event evaluations of strategic bridges are performed in Italy following specific inspection and analysis protocols (Italian Department of Civil Protection 2010). Strategic bridges are those designated as risk category IV infrastructure (per *NTC08*), which are defined as falling into one or more of the following categories: (1) Formally designated as critical by either national (Department of Civil Protection 2003) or local emergency plans (issued by regional councils); (2) required to provide post-earthquake life safety per *NTC08* protocols; or (3) damage can cause prolonged road closures per *NTC08*. These are typically bridges present on major state highways (types A and B according to *NTC08 – Autostrade* and *Strade Extraurbane principali*, respectively).

Post-earthquake damage inspections of bridges (strategic and otherwise) are required by government officials. However, no standard documentation protocols, such as those by Veletzos et al. (2006) for California, are publicly available. At the time of our field work, we were unaware of the distinction between strategic and nonstrategic bridges, and as a result, we made no specific effort to locate strategic bridges. As it turned out, the bridges that we inspected did not include strategic bridges, although we are aware of efforts by the National Autonomous Roads Corporation (ANAS, *Azienda Nazionale Autonoma delle Strade*) to do so. To our knowledge, none of the bridges inspected by ANAS were significantly damaged.

The bridge reconnaissance reported here is based on an *ad hoc* inspection procedure whereby, for each bridge, the road surface condition was checked and the main structural elements (such as piers, abutments, joints, and supports) and other nonstructural elements were inspected. Evidence of ground failure near foundations or abutments was noted when such areas were visible or accessible. Due to limited time and lack of access to specialized equipment for rappelling into deep canyons spanned by some bridges, it was not possible to access foundation piers and abutments in such cases. For similar reasons, in some cases, it was not possible to inspect the full lengths of bridge columns, nor the underside portion of deck supports. As a result, for some RC bridges, assessment of pounding effects could only be evaluated in an approximate manner by visual inspection of the deck and other readily visible areas.

RECONNAISSANCE FINDINGS

Inspected bridges are classified according to age: (1) Relative modern viaduct-type bridges, built around the 1960s using RC and/or composite RC and steel members; and (2) older masonry arch bridges, which, in some cases, date back to Roman times.

Twelve bridges were inspected following the 24 August 2016 earthquake. Most of the RC and composite bridges that were inspected did not experience significant seismically-induced damage. Conversely, the masonry bridges suffered extensive damage during the August events that affected roadway operations. The latter damaged bridges were revisited following the October seismic sequences together with an additional small masonry bridge along SP477. The investigated masonry bridges suffered substantial additional damage during the October seismic sequence. The locations of surveyed masonry bridges are shown in Figures 1 and 2; further details are given in Table 1.

RC and Composite RC Bridges

As shown in Table 1, the bridge likely to have experienced the largest ground shaking was the composite steel and concrete bridge along the Strada Provinciale (SP) 20 Colle (km 9+650), also called *Ponte Ramazzotti* (Figure 3). *Ponte Ramazzotti* (C1 in Figures 1 and 2) is formed by three composite steel and concrete spans, two RC piers, and two abutments. The bridge experienced some movements during the 24 August 2016 event (Figure 3). The movements have been accommodated by the bridge deck and did not affect the road surface or the structural components and, for this reason, limits on bridge utilization were not required.

Another interesting bridge that was inspected is the RC bridge along the SP173 in Offida (Figure 4). This bridge (R1 in Figures 1 and 2) had significant settlement of the roadway close to the abutments (Figure 4b), which caused damage at the structural elements (Figure 4c). These settlements, which existed before the earthquake, appear to have been exacerbated by seismic compression of backfill during the 24 August 2016 main shock. Thus it was suggested to limit the maximum load to be carried by the bridge until specific geotechnical improvements to stabilize the area could be performed.

The other RC bridges inspected did not show evidence of seismic-induced damage; no limits on bridge utilization were recommended. More details about the other inspected bridges are reported in GEER (2016, 2017).

Performance of Masonry Bridges

Two masonry arch bridges along the Trisungo route in Tufo village were inspected. These bridges are composed of an older (Roman-era) part and a relatively recent extension. The two bridges are located close to each other, so they likely experienced similar shaking intensities. The bridges were affected in a similar manner by the 24 August 2016 earthquake, but responded differently to the October 2016 sequence.

In the first inspection, a one-span masonry bridge along the Trisungo route near Tufo (M3 in Figures 1 and 2) presented cracking within load-bearing masonry elements within the arch

Figure 3. *Ponte Ramazzotti:* Composite steel and concrete bridge along the SP20 in Colle (42.7276 deg, 13.3111 deg). (a, b) overview of the bridge, (c) abutment, and (d, e, f) bridge support details.

Figure 4. RC bridge along the SP173 in Offida (42.9417 deg, 13.7023 deg): (a) Overview of the bridge; (b) settlement of the road; (c) crack; and (d) relative displacement of the abutment.

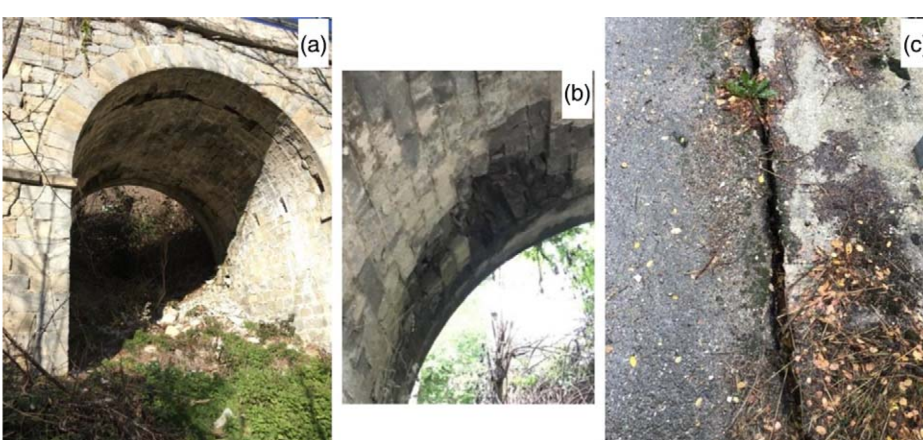

Figure 5. Roman-era bridge along the Trisungo route (1 span bridge, Tufo area, Arquata del Tronto: 42.7360 deg, 13.2549 deg): (a) View of the arch following the October event; (b) spalling of the interior of the arch; and (c) road cracks after the 24 August event,which grew slightly during the October event

(Figure 5a), including spalling (Figure 5b). Cracking adjacent to the roadway surface was observed immediately behind the wall, which increased slightly between the first and second inspections. Otherwise, the damage at this location were not appreciably different at the times of the two inspections.

In the first inspection, the three-span bridge (M4 in Figures 1 and 2, hereafter Tufo bridge) presented partial collapse of short walls above the roadway surface (Figure 6a and 6b), spalling of several elements in the central arch (Figure 6c), and significant cracks of some masonry elements on the east support of the central arch (Figure 6d). This damage occurred in relatively recently added sections of the bridge. The older Roman-era portions of the bridge did not exhibit obvious signs of damage.

The Tufo bridge was inspected again in December 2016 after the October 2016 sequence. Significant additional damage was observed (Figure 7). In particular, part of the central arch, already damaged after the first event, collapsed as a result of the October earthquakes. Figure 7a shows large longitudinal cracks on the roadway surface (not present following the 24 August earthquake). The masonry rail, which was damaged during the 24 August event (shown in Figure 6a and 6b), totally collapsed following the October events (Figure 7b).

Figure 6. Central arch of the Roman-era three arches masonry bridge along the Trisungo route (42.7354 deg, 13.2537 deg) as observed following the August 2016 event: (a, b) Partial collapse of the railing; (c) spalling; and (d) cracking of some masonry elements in the central arch.

Figure 7. Three-arches bridge along the Trisungo route (same location as in Figure 6) after the 30 October 2016 event (photos taken on 13 December 2016). (a) Large longitudinal cracks on the roadway surface (same location as Figure 6b); and (b) total collapse of the masonry rail (same location as Figure 6a). The collapse of the arch is not visible in the pictures.

The masonry bridge referred to locally as the *Ponte a Tre Occhi* in Amatrice (M1 in Figures 1 and 2) was inspected following the 24 August and 30 October earthquakes. This bridge crosses the Castellano River and represents a critical lifeline for access to Amatrice, and it was closed on the date of our first visit (8 September 2016). The bridge is formed by three arches and the main structure is composed of *muratura a sacco*, which is a typical method of masonry construction (Giuliani 1993). This method consists of using regular-shaped masonry elements on the external part of the construction, sometimes with between-element mortar. The interior part of the construction is composed of relatively irregularly-shaped cobbles, usually without mortar. During the 24 August 2016 earthquake, several sections of the external (regular-shaped) layer collapsed (Figure 8a and 8c). This resulted in a lack of confinement of the interior uncemented cobbles, which then underwent lateral relaxation and settlement that was observable on the roadway surface (Figure 8b). These diffuse transverse cracks along the road surface had maximum openings of about 5 cm and 2.7 cm horizontally and vertically, respectively. Some deformation of the road surface was evident before the main shock, as shown in Figure 8e and 8f (dated December 2011). Moreover, internal cracking was observed on all the arches of the bridge (Figure 8d).

As a result of the October events, the *Ponte a Tre Occhi* experienced additional damage, consisting mainly of spalling of outer layer masonry elements located along abutment areas (not involving the three arches; Figure 9a and 9b). At the time of the reconnaissance (2 December 2016), repairs had been carried out on one of the two abutments, while the bridge masonry and structure appeared to have not yet been repaired.

PERFORMANCE OF NON-BRIDGE TRANSPORTATION INFRASTRUCTURE

Reconnaissance of the broader region affected by the Central Italy events involved extensive travel over local road networks and regional highways by various members of

Figure 8. *Ponte a Tre Occhi*: Masonry bridge along the SR260 in Amatrice (42.6207 deg, 13.2902 deg). (a, c) Abutment deformations on two sides of the bridge, (b) road settlement, (d) cracks on the arch, (e) pre-event cracks along the SR260, and (f) bridge–abutment connection [source for (e, f): Google Maps (https://www.google.com/maps/; last accessed 13 September 2018)].

the GEER teams (GEER 2016, 2017). In general, the performance of the transportation network appeared to have been good, although there were incidents of retaining wall failures and slope failures, which are described elsewhere (Franke et al. 2018, GEER 2016, 2017).

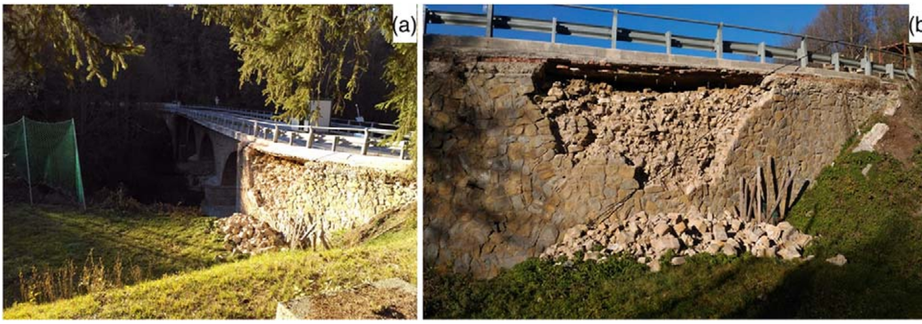

Figure 9. *Ponte a Tre Occhi* (same location as in Figure 8) after the 30 October 2016 event (photos taken of 13 December 2016): (a) Damage to abutment in same section shown in Figure 8c; and (b) closer view of masonry collapse along abutment.

In this section, we describe the performance of a composite steel and concrete rockfall protection tunnel located 10 km east of Norcia on highway SS685 (*Tre Valli Umbre*) after the **M**6.5 30 October 2016 event. Aside from wall and slope failures, this is the only example of non-bridge infrastructure damage that we encountered.

The performance of the rockfall protection tunnel along the *Tre Valli Umbre* highway before the 30 October 2016 event is unknown. As shown in Table 1, PGA values at the site for the three main shocks are 0.11g, 0.07g, and 0.17g for the 24 August 2016, 26 October 2016, and 30 October 2016 events, respectively (PGV values were similarly highest for the 30 October 2016 event). Figure 10 shows an overview of the structural arrangement of the

Figure 10. Overview of the composite steel–RC rockfall protection tunnel near Norcia.

Figure 11. (a, b) Close-up views of reinforced concrete beam-column joint and the steel frame.

rockfall protection tunnel, which consists of a combination of RC columns and RC and steel beam segments. Figure 11 shows details of steel–concrete joints. Prior to the earthquakes, some deterioration and spalling of concrete occurred, which exposed steel rebars (Figure 11a). As shown in Figure 11b, the structure suffered slight damage from pounding. This was evidenced by freshly spalled pieces of concrete.

RECOVERY FOLLOWING BRIDGE DAMAGE

The town of Amatrice is in a mountainous area with one major river (*Tronto River*), and three creeks (*Castellano, La Neia*, and *Rio Scandarello*) in the vicinity. Access to the town from the surrounding road network is provided by three access roads, all of which have over-river bridge crossings. The principal access is from the south, with two additional access points from the north and east, respectively. The damage to the *Ponte a Tre Occhi* bridge (M1 in Figures 1 and 2) from the **M**6.1 24 August 2016 earthquake compromised the south access. Furthermore, the east access was limited due to damage to the *Ponte Rosa* bridge, which experienced failure in shear to the masonry piers. The damage to these bridges initially limited the movement of first responders and threatened recovery activities, which was problematic due to the extensive damage to portions of the town (GEER 2016, Sextos et al. 2018).

As a result, a joint group formed by the National Civil Protection and the Italian Army built two temporary bridges within 10 days of the 24 August 2016 main shock. The first temporary bridge (Figure 12) was built to bypass the *Ponte a Tre Occhi*. The temporary bridge was built rapidly and traffic was opened within one week of the main shock. The construction of this temporary bridge started with a diversion of the river that allowed the construction of a concrete sublayer slab on the river bed and a placement of ten 3×3 m precast concrete void elements. Those elements were selected to allow the restored river flow to pass through them. Vehicle loads were distributed over the vertical webs of the precast elements through a cast *in situ* deck slab.

Figure 12. Temporary bridge bypassing the *Ponte a Tre Occhi* in Amatrice (Mr. Totaro, personal communication).

Figure 13. Temporary bridge near *Ponte Rosa*.

The second temporary bridge (Figure 13) was built to increase traffic capacity of the east access road and overcome traffic restrictions resulting from partial closure of the *Ponte Rosa*. It is a 12-m span Bailey bridge, a typical military construction typology that can be deployed quickly. This bridge is a modular construction, covering relatively small spans by assembling preformed steel frames connected into truss beams. Two truss beams are conncected by transverse steel beams forming the deck and the bridge parapets.

CONCLUSIONS

This paper presents the performance of roadway infrastructure in the mountainous areas strongly shaken by the 2016 Central Italy earthquake sequence. RC and composite RC and steel bridge structures performed well, despite some having been strongly shaken by multiple events. In contrast, masonry bridges near Amatrice and Tufo experienced significant damage that limited functionality. Damage to the *Ponte a Tre Occhi* in Amatrice required construction of temporary bridges to facilitate emergency response and recovery. Two masonry bridges near Tufo were inspected. A one-span bridge had similar levels of distress from inspections following the 24 August and 30 October events, while a three-span bridge suffered damage in both events, with the latter affecting load bearing elements, including the partial collapse of the central arch, causing road closure. We also described some pounding damage in a composite steel and concrete rockfall protection tunnel.

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