Outline of the Damage of Transportation Facilities and Geotechnical Structures by the 2009 L'Aquila, Italy Earthquake

by

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ABSTRACT

This is a reconnaissance report on the damage to transportation facility and geotechnical structures caused by the 2009 L'Aquila, Italy earthquake. Site investigation was conducted by the authors during the period of April 18-21, 2009. Presented is a discussion on the damage of transportation facilities. Geotechnical damage and ground motions are also presented.

1. INTRODUCTION

A strong earthquake with M_L=5.8 and M_W=6.2 occurred near L'Aquila, Central Italy, at 03:32 local time on April 6, 2009 as a result of 15 km long NW-SE striking normal fault. The fault dips southwest and the city of L'Aquila is located on the hanging wall of the causative fault. Damage in L'Aquila and its vicinity was extensive with about 10,000-15,000 buildings heavily damaged. Approximately 294 people were killed, with over 1,000 injured.

The population of L'Aquila was about 70,000. The city center spreads over terrace of calcareous conglomerates while Aterno River cuts through the terrace down to lower elevations. The terrace is about 100 m higher than the elevations of lowland along Aterno River.

A joint reconnaissance damage investigation team consisting of ten members from Japan Society of Civil Engineers, Japanese Geotechnical Society, Architectural Institute of Japan and Japan Association for Earthquake Engineering was sent. The authors conducted a field investigation on the geotechnical and geological damage as well as investigation on the damage to transportation facilities and other structures in the regions of L'Aquila and its vicinity including Ocre, Onna, Paganica and Coppito during April 18-21, 2009. Based on the field investigation, feature of the damage including their damage mechanisms are presented here.

It should be however noted that since the field investigation was conducted without prior information on design drawings and analysis, it is highly possible that the interpretation of the failure mechanism by the authors might not be accurate. Moreover, because access to the extensively damaged regions including the old city of L'Aquila, Onna and Paganica was restricted, there were a number of structures which could not be investigated thoroughly.

2. GEOLOGICAL AND SEISMOLOGICAL CONDITIONS

The stratigraphy of L'Aquila consists of schists, limestone, lacustrine deposits, conglomeratic deposits and Holocene deposits from bottom to top. Schists are best seen at the east portal of Gran-Sasso tunnel. Schists are overlain by limestone, which is the main rock unit constituting Gran-Sasso Mountain ridge. The basin of L'Aquila consists of lacustrine clayey deposits. Conglomeratic deposits cover these deposits. The inclusions of conglomeratic deposit originate from limestone and other rocks from nearby mountains. Matrix of conglomeratic deposits is clayey or calcareous, which can be easily dissolved by

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ground water flow. Fig. 1 shows the geological profile along the SW-NE cross section of L'Aquila. All these deposits are covered by Holocene deposits from Aterno River Valley. Holocene deposits are a mixture of clay, silt, sand and gravel, and they are widely distributed along Aterno River. Paganica, Onna and Fossa village where extensive damage was developed are on Holocene deposits.

Historically large earthquakes occurred in 1315, 1349, 1461, 1703, 1706 and 1915 in the vicinity of L'Aquila. The 1915 event named as Fucino earthquake (M_S=7) resulted in victims of 33000. The most recent events were 1984 Greco earthquake (M_L=5.8) and 1996 Umbria (Ms=6.1). The nearest event occurred in 1461. Bagh et al. (2007) reported that earthquakes in the close vicinity of L'Aquila were either due to purely normal faulting or oblique faulting with a normal component. They pointed out that there was no large seismic event since the 1915 Fucino event, implying that the region might suffer a large event in near future.

Based on parameters by various seismological institutes worldwide, the L'Aquila earthquake was caused by a 15-20km long and 10-15km wide normal fault as shown in Fig. 2. The estimated rupture duration ranged between 6.8 and 14 s.

Surface ruptures were observed at Paganica, Lake Sinizzo, and two bridges at Onna and Fossa as shown in Fig. 3 and Photo 1. Surface ruptures were observed at three sites in Paganica. Most fractures at Paganica indicated the opening of surface cracks with a normal displacement. The authors also observed cracks on the road to Lake Sinizzo, which is thought to be the southeast end of the earthquake fault. There were also surface cracks in the vicinity of a bridge near Fossa (refer to Photo 11) as shown in Fig. 7. Some cracks were in compression while most of them were in tension.

3. STRONG MOTION RECORDS

Based on the Italian National Strong Motion Network (Accelerometric National Network (RAN)), 56 strong motion records triggered during the earthquake were so far released. In the

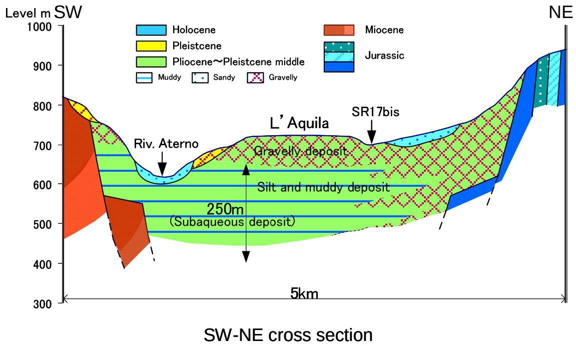


Fig. 1 Geological profile along the SW-NE cross section under L'Aquila

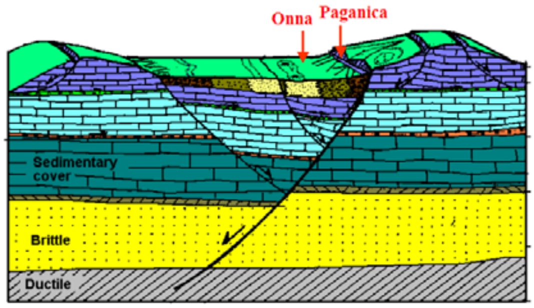


Fig. 2 Schematic illustration of size and surface effects of M6 class graben earthquakes (modified from Dramis and Blumetti, 2005)

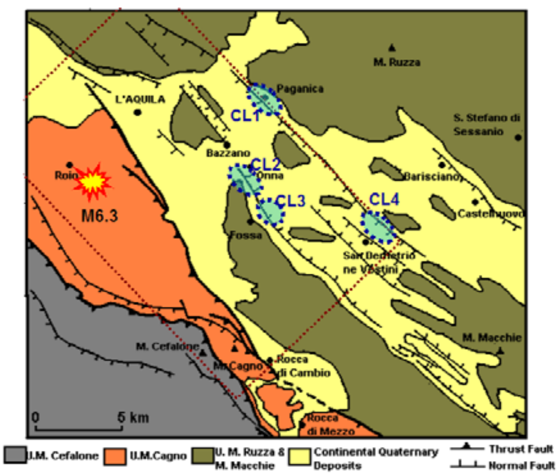


Fig. 3 Locations of surface ruptures

(a) CL1 (b) CL2 (c) CL3 (d) CL4

Photo 1 Surface ruptures in the area of Aterno River to the west of Onnna town (refer to Fig. 3 for locations of CL1-CL4))

Table 1 Main strong motion records

Station name	Station code	Latitude	Longitude	Type of ground	R_e (km)	V_{s30} (m/s)	PGA (m/s^2)
Aquil Park	AQK	42.345	13.401	Conglomerate	5.6	455	3.66
V. F.Aterno	AQV	42.377	13.337	Fluvial	5.8	475	6.46
Colle Grilli	AQG	42.376	13.339	Limestone	4.3	1000	5.05
V.&F. Aterno	AQA	42.345	13.401	Fluvial	4.8	475	4.78

close vicinity of L'Aquila City, there are four strong motion stations as shown in Table 1; AQV (GX066-B), AQG (FA030-B), AQA (CU104-B) and AQK (AM043-C). They were all on the hanging wall side of the earthquake fault. The equivalent shear wave velocity between the ground surface and 30 m from the ground surface, V_{s30}, is in the range of 455-1000 m/s. The largest peak ground acceleration of 6.46 m/s^2 was recorded at AQV.

Fig. 4 shows the acceleration records at AQV and AQK stations. It is of great interest that the amplitude of ground accelerations are not symmetric and their forms are different each other although the epicentral distances and the equivalent shear wave velocity V_{s30} of ground are almost the same.

Fig. 5 shows the acceleration records at GSA and GSG stations, which are reportedly founded on Eocene limestone with a shear wave velocity of 1 km/s. The GSA station is at Assergi and the GSG station is located in an underground gallery. Although the epicentral distances and ground conditions are the same, the acceleration at ground surface is amplified almost 15 times that in the underground gallery.

Acceleration spectra at some selected strong motion stations (AQV, AQK, AQA, AQG, MTR, FMG, GSA and GSG) are shown in Fig. 6. The predominant periods of the recorded accelerations range between 0.05s and 0.4s in the lateral components. The predominant period of about 0.8 s at AQG station is noted as was pointed out by Luca et al. (2005). The spectral accelerations of vertical component are high at natural periods ranging between 0.05s and 0.1s.

4. GEOTECHNICAL DAMAGE

1) Horizontal movements and cracking in the area of Aterno River

Horizontal movements and cracking were observed in the area of Aterno River to the west of Onna town. The embankments on both sides of Aterno River moved towards the river creating separation cracks as well as some compression cracks in the vicinity of the damaged bridge on Aterno River as shown in Fig. 7 and Photo 2. The cracks and movements on the east side of the river were more intensive as the ground was inclined towards west. Nevertheless, any sand boiling was not observed in the area. It would be quite speculative on the cause of these movements.

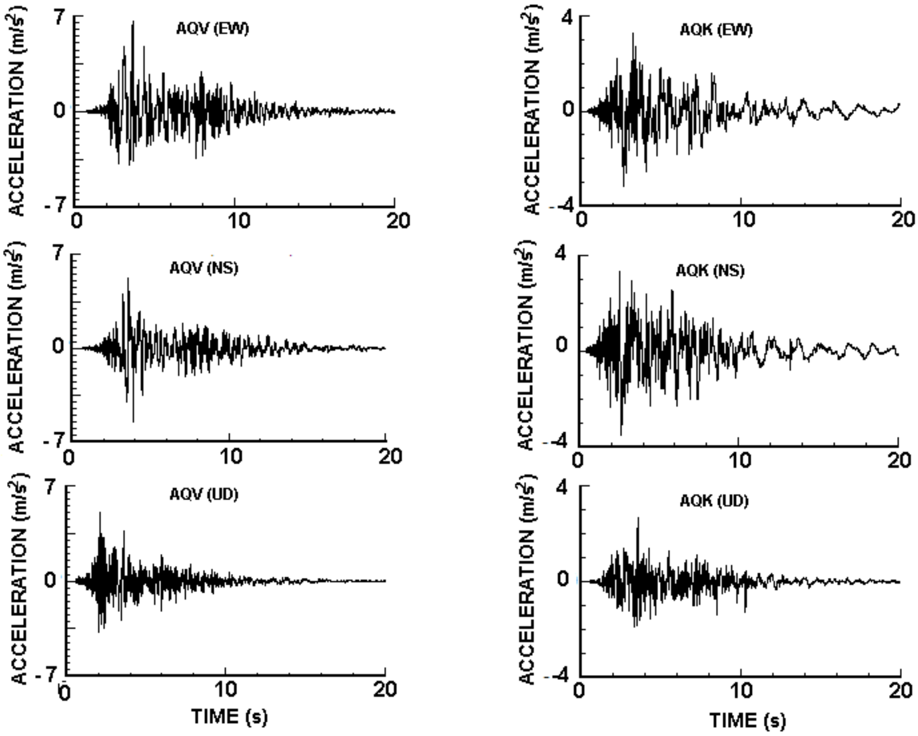


Fig. 4 Acceleration records at AQV and AQK stations

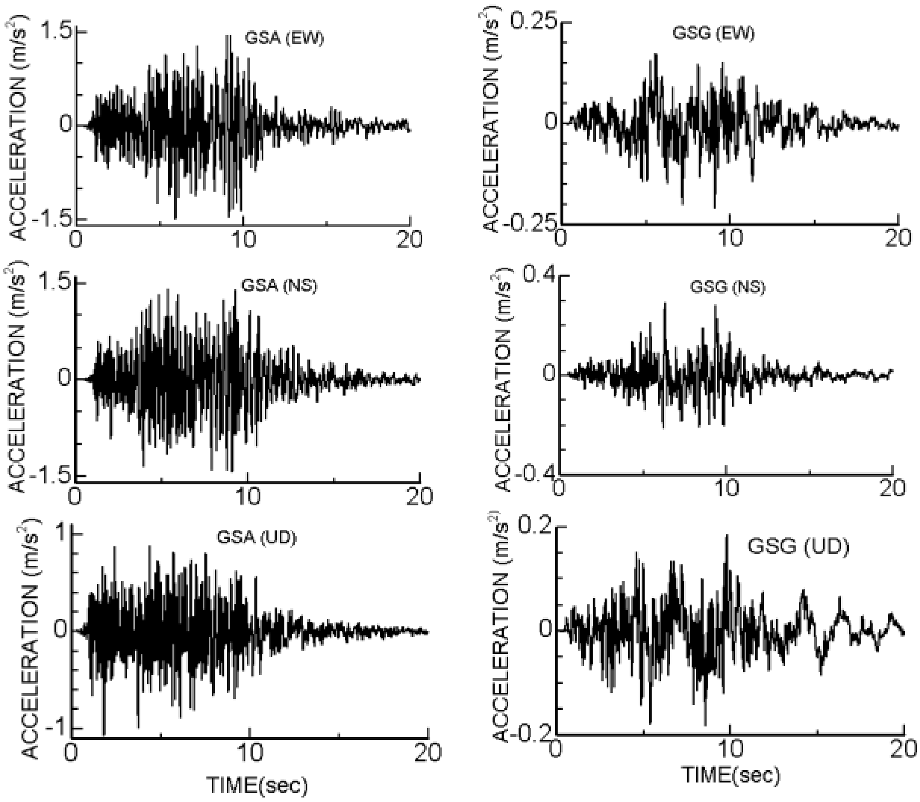


Fig. 5 Acceleration records at GSA and GSG strong motion stations

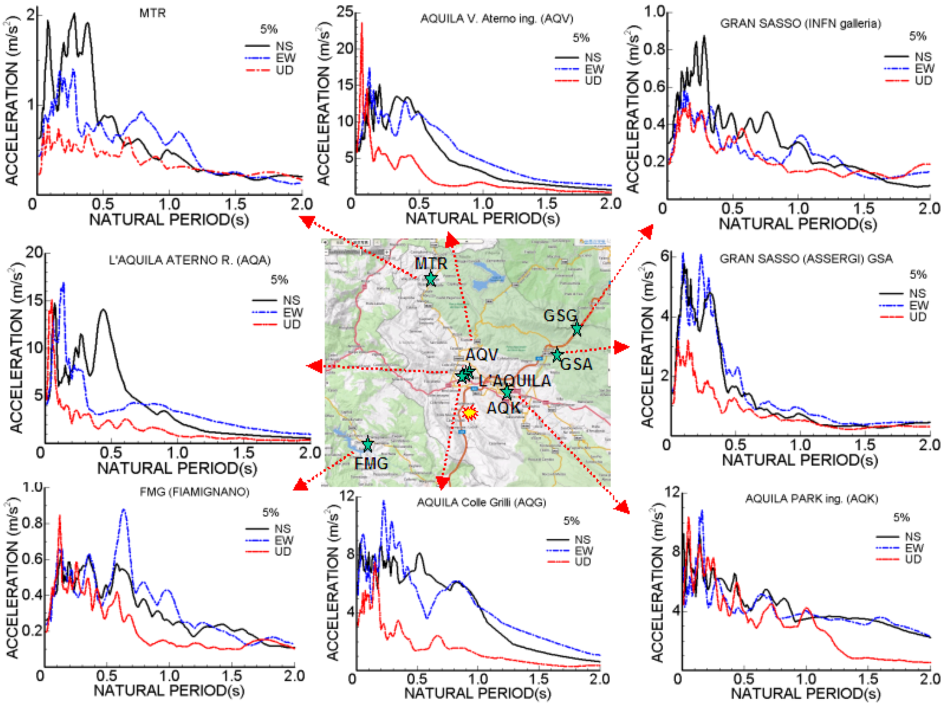
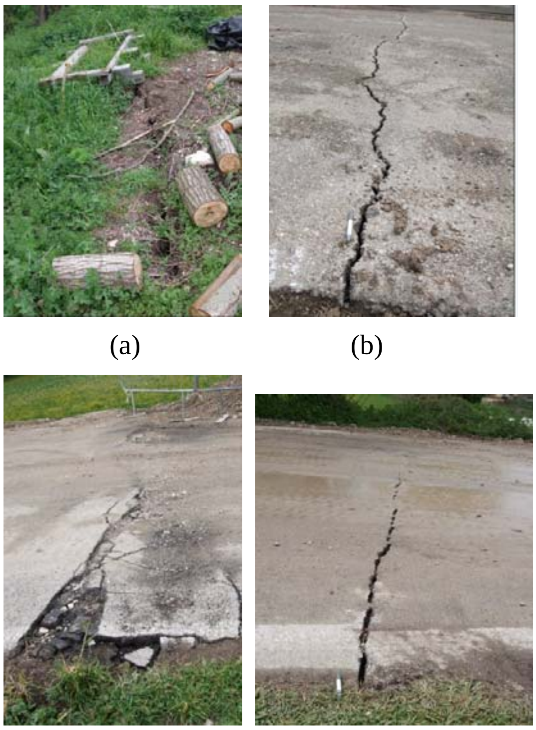


Fig. 6 Acceleration response spectra of selected strong motion stations

Based on InSAR evaluation, ground movements are large in the close vicinity of Aterno River near Onna town. Tectonic movements, ground liquefaction or both might cause the movement in this area. If ground liquefaction is involved, it is likely that there is a thick impermeable silty and clayey layer on top of the liquefiable ground below.

Fig. 7 Cracks in the vicinity of a damaged bridge on Aterno River (Refer to Photo 2)



(c) (d)

Photo 2 Surface cracks on the east side of Aterno River (Refer to Fig. 7 for locations)

2) Lateral spreading and sliding along shoreline of Sinizzo Lake

There are a number of sinkholes in the vicinity of L'Aquila featuring the Karst topography of the area. Sinizzo Lake with about 120 m diameter is probably one of the sinkholes. Extensive lateral spreading occurred along the shoreline of Sinizzo Lake as shown in Photo 3. Around the north shore, several parallel blocks were bounded by continuous cracks due to large lateral spreading of the surface ground and they moved toward the lake as shown in Photo 4. The ground at the west shore moved 22 m towards the lake. Two famous beautiful springs at the north-eastern shore dried up after the earthquake, however a new spring was formed close to the original two springs. The fact that the original ground water flow paths were blocked and a new water flow path was formed due to ground deformation during the earthquake implies that the ground water table was high and close to the ground surface. Based on this evidence, it is considered that the lateral spreading was resulted from yielding of the ground due to intensive earthquake shaking as well as degradation of shear strength of the ground due to generation of the pore water pressure.

Extensive surface rock sliding on the mountain on east side of the lake was developed as shown in Photo 5.

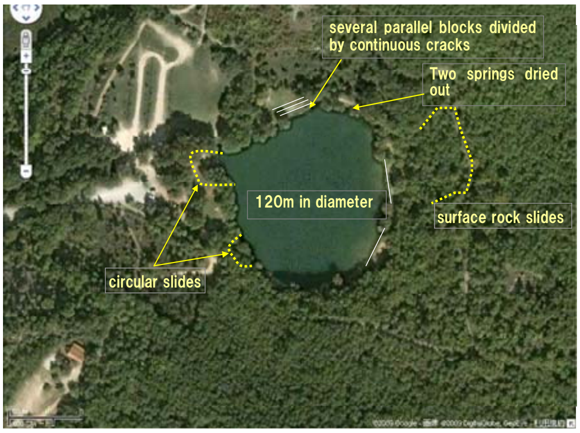


Photo 3 Lateral spreading around Lake Sinizzo (added on Google map)

Photo 4 Separated blocks due to lateral spreading

Photo 5 Surface rock sliding on the mountain (east of the Sinizzo Lake)

3) Rock falls in Stiffe

Two large rock falls occurred in Stiffe. The estimated mass and size of one of the rock blocks was 12 t and 1.5m x 1.6m x 1.9m, respectively. This rock block hit and destroyed the wall of a small building in the park near Grotte di Stiffe as shown in Photo 6. Photo 7 shows a broken tree, a shallow dent on the ground and the damaged wall, lined up along the path of the fallen rock block. The velocity and energy at the instance of collision is estimated in view of the jumping distance as 15 m/s and 2,700 kJ, respectively. The collision energy was large enough to destroy the wall of a building. The other fallen rock block reached the bottom of the park.

It is important to assess the sources of falling rocks so that stability of neighboring rock masses or isolated rocks remaining on a slope can be evaluated. By assessing the collision energy of possible unstable rock masses, the risk to human lives and properties can be evaluated. It may be effective to prepare a check sheet to record information on the height of rock fall sources, size, geological conditions, protection measures and possible fall path.

Photo 6 A 12 ton fallen rock with 1.9m long, 1.6m wide and 1.5m tall

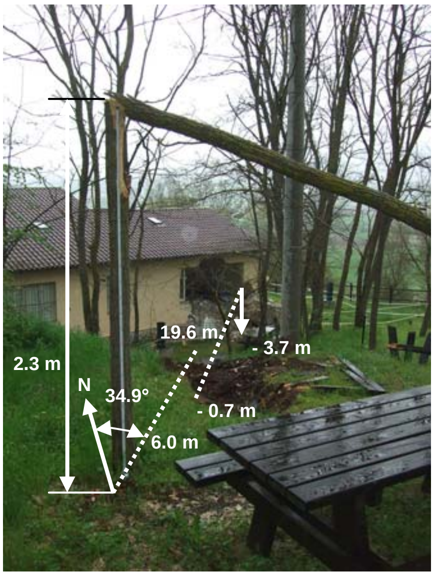


Photo 7 A broken tree, a shallow dent on the ground and a collapsed wall of the building along the path of a fallen rock.

It is noted that there are several large sinkholes and sparsely distributed gorges probably due to subterranean drainage in a mountainous terrain in the vicinity of the above rock fall. The good drainage indicates the presence of numerous cracks and caves in the soluble rock formation, and this may have contributing factor in rock falls. It is likely that there may be lots of unstable rocks in source areas. Detailed in-situ investigation to identify rock fall hazard locations will be necessary for a rational rehabilitation.

4) Sinkholes on roads due to caving

In the old city of L'Aquila, two sinkholes appeared on roads due to the earthquake and a vehicle fell into a sinkhole as shown in Photo 8. One of the sinkholes was already back-filled with soils for stabilizing the surrounding ground. However the other sinkhole was only partially back-filled as shown in Photo 9 and the authors had the chance to investigate it. Fig. 8 shows the dimensions of the sinkhole. The deepest point from the road surface was measured as 13m near the east edge of the sinkhole. However the cave tended to become deeper towards west. The roof of the cave roughly consists of four horizontal layers. From the bottom to top, they are (1) well cemented calcareous conglomerate, (2) clayey conglomerate, (3) clay, and (4) backfill. It is noted that a sewage conduit was constructed after excavating a 3.7m deep vertical trench reaching to the level of the calcareous conglomerate. This trench excavation has eventually notched the upper surface of the conglomerate roof of the cave, which could further reduce its effective thickness. The scenario mentioned above may have been responsible for the formation of the sinkhole during the earthquake shaking.

After experiencing the intense shaking, there are probably a number of unstable thin roofed caves remaining underground in the old city of L'Aquila. Thorough sounding of the condition of foundation rock mass may be important for a safe and rational rehabilitation of the city. Among many techniques available, the surface wave tomography may be effective and it may yield shear wave velocities of ground, which are directly related to its mechanical properties.

Photo 8 Sinkhole immediately after the earthquake (from Web page)

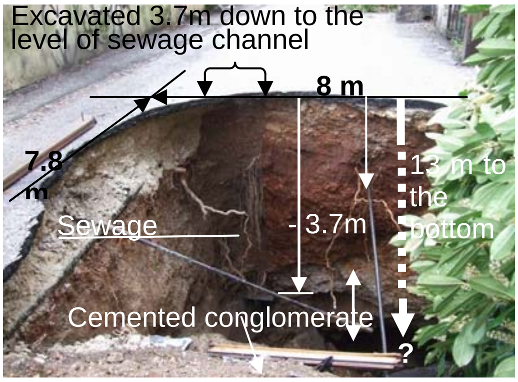


Photo 9 Sinkhole in a road, old city of L'Aquila (refer to Fig. 8)

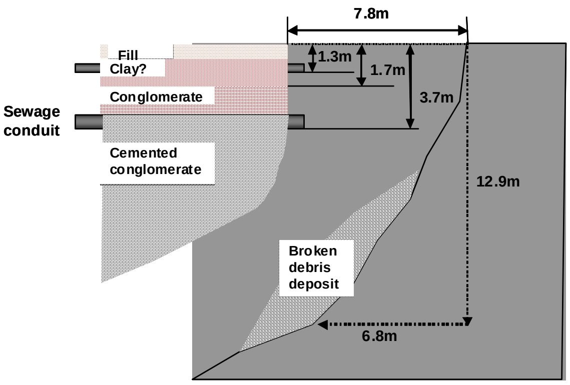


Fig. 8 Section of a sinkhole (Refer to Photo 9)

5) Soil Liquefaction

Soil liquefaction is caused by the generation of the pore water pressure and it is often observed when ground consists of fully saturated sandy soil. Alluvium deposits are geologically formed along Aterno River in the epicentral area. During investigations, the authors found sand boils along Aterno River in the area called Martini, which is just south of the hill on which the old downtown of L'Aquila City is located. The river meanders in the area and it is likely to have resulted in sandy deposits at those meanders. At Martini district liquefaction created many NE-SW trending fractures parallel to the river embankment and they opened up as shown in Photo 10. Sand boiling as thick as 150 mm was observed in various locations. The movement of ground was towards SE direction. Table 2 and Fig. 9 show some physical properties and grain size distribution of sand boils, respectively, based on laboratory tests at Tokai University, Japan and Pamukkale University, Turkey. Boiled sand is almost homogenous and its grain size distribution falls within the easily-liquefiable bounds according to Japan Port and Harbour Research Institute classification (1997).

The liquefaction induced lateral spreading. The sum of crack openings from the adjacent field towards the river embankment ranged between 250-350mm. There were several depot-like structures and bridges for railways and roadways in the area where soil liquefaction was observed. However there was no visible damage on the structures probably because the foundations were resting on deep stiff soils.

Photo 10 Liquefaction at Martini district of L'Aquila

Table 2 Properties of liquefied soil sample collected from sand volcanoes

Dry unit weight (kN/m^3)	13.11-13.80
Porosity (%)	39.0-41.6
Mean grain size D_{50} (mm)	0.5-0.6
Friction angle (degree)	32-35

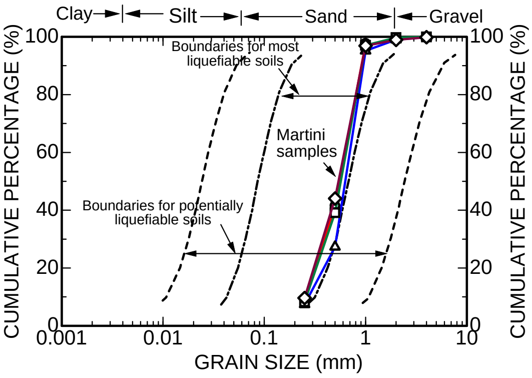


Fig. 9 Grain size distribution and comparison of liquefaction bounds

5. DAMAGE OF TRANSPORTATION FACILITIES

1) Damage of bridges

A 35 m long 5 m wide three-span continuous reinforced concrete bridge collapsed as shown in Photos 11 and 12. It was located at the crossing of SR261 on Aterno River for approaching Fossa Town. Four reinforced concrete pile-bent columns with a hexagonal section failed at a height slightly above the river surface, and they shifted sideway and penetrated the deck slab as shown in Photos 13 and 14. A column had six 17 mm diameter round main bars at each corner of the hexagonal section as shown in Photo 15. Several 9 mm diameter round bars were also set to fix the top of columns to the reinforced concrete girders. 6 mm diameter round hoops were provided at about 300 mm interval. The strength of concrete in columns was most likely less than 20 MPa. Photo 16 shows a broken pile-bent as well as a girder next to the bent at the right downstream column. Plastic hinge did not form in the column because of the low reinforcement. It seems that damage of the column which was induced prior to the earthquake progressed during the earthquake. Steel bars exposed due to very thin covering concrete were extensively corroded prior to the earthquake. Both left and right river dykes were protected by stone masonries at inside facing to river flow. The river dykes suffered almost no damage due to the earthquake. This feature of damage reminds us of a similar damage of the Struve Through Bridge in the 1989 Loma Prieta Earthquake, California, USA (Lew, 1990).

Photo 11 Collapse of a three span continuous bridge near Fossa Station

Photo 12 Section of the fallen deck

Photo 13 Damage of pile-bent pier

Photo 14 Pile-bent piers which punching sheared the deck slab

Photo 15 Top of a pile-bent pier

Photo 16 Failure of a pile-bent pier

A 20 m long 4 m wide three-span continuous bridge located in the suburbs of Onna Village suffered damage at the top of frame piers as shown in Photos 17 and 18. Plastic hinge did not form at the beam-column connection. The damage which was developed prior to the earthquake progressed during the earthquake. Embankment right behind the abutment settled and a cast-iron water pipe attached on the bridge suffered damage at the connection between the bridge and the embankment. Several cracks occurred on the river dyke due to soil sliding.

Photo 17 A 20 m long bridge near Onna Village

Photo 18 Damage of a frame reinforced concrete pier

A 2 m long, 2.5 m tall stone masonry arch culvert collapsed and was temporarily repaired by filling crushed lime stone into the culvert as shown in Photos 19 and 20. How the arch culvert suffered damage was not known because it was already repaired. However it is likely that a part of stone masonry arch members lost the equilibrium and collapsed during the earthquake. Because the embedment of the arch was shallow without covering masonries on the arch, the arch members had less stability.

Photo 19 Emergency repair of a stone masonry arc culvert (SR261)

Photo 20 Road temporarily repaired by filling crashed limestone

A part of the A24 viaduct in L'Aquila as shown in Photo 21 also suffered damage. The viaduct is a 37 m long simply supported PC box-girder bridges supported by 11-20 m tall reinforced concrete columns. It is supported by steel fixed (sliding) and movable (roller) bearings or elastomeric bearings. The viaduct was separated in the upper and lower bound bridges. Vertical gaps as large as 200 mm were seen at numerous expansions as shown in Photo 22. A number of decks drifted by nearly 200 mm in the longitudinal and transverse directions as shown in Photo 23. The bearings where gaps occurred at expansion joints or decks drifted could hardly be investigated, but it is likely that the gaps at expansions were developed by failure of bearings. Drift of the decks is generally developed due to residual deformation of elastomeric bearings. A part of the covering concrete spalled as shown in Photo 24 at the bottom of a pier. It is likely that the pier nearly yielded. Photo 25 shows damage of a shear connector at the end of a deck.

Photo 21 A viaduct of A24 in L'Aquila

Photo 22 Gap at an expansion joint

Photo 23 Residual drift of two bridges in the longitudinal direction

Photo 24 Spalling of a part of covering concrete

Photo 25 Damage of a shear connector

2) Damage of retaining wall

Settlement of road surface occurred at a number of locations in the lowland along Aterno River. One of the two lanes of SS17 at the intersection with SR615 was partly restricted for traffic because the road embankment locally subsided by 350mm and the upper part of the stone masonry retaining wall leaned as shown in Photos 26 and 27. The retaining wall was propped by wood bars for resisting the earth pressure. The detour lane was being constructed adjacent to the affected lane.

Photo 26 Subsidence of a road embankment at the intersection of Route SS17 and Route SR615

Photo 27 Emergent repairing of damaged embankment

6. SUMMARY

The L'Aquila earthquake provided valuable lessons on how transportation facilities behaved under an M_w=6.2 low probability and high consequence event. Historically L'Aquila and its vicinity were subjected to at least eight earthquakes since the 14th century. During this earthquake, extensive damage was developed in the old city of L'Aquila and the surrounding towns and villages including Onna, Paganica, Fossa and Ocre. The L'Aquila basin was covered by conglomeratic clayey or calcareous deposits underlay by lacustrine clayey deposits.

Inherent to the unique soil condition, settlements and sliding of ground and soil structures occurred at numerous locations in the lowland along Aterno River, and a number of sliding and rock fall occurred in the nearby mountainous regions. Two sinkholes were found in the old city of L'Aquila due to collapse of thin roofed caves in conglomeratic calcareous deposits.

As was apparent from the lessons in the past events, old unreinforced masonry buildings were extremely vulnerable to earthquake. In particular, unreinforced masonry buildings with soil joint suffered extensive damage.

Extensive corrosion of steel bars in reinforced concrete structural members was widely observed not only in bridges but also in buildings. Concrete cover was so thin for preventing corrosion. There were even cases when concrete cover was not virtually provided. Corrosion of bars resulted in direct loss of tension strength as well as loss of bond strength between concrete and bars.

A local and probably old three-span continuous short-span bridge collapsed, and several bridges suffered damage. At A24 viaduct in L'Aquila, residual drift of decks and vertical gaps of expansion joints occurred at number of spans possibly due to damage of bearings. Failure of shear connectors was also observed. However damage of bridges was generally less significant because most of bridges in the damaged area were small supported by short columns.

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