Damage of 2009 L'Aquila, Central Italy Earthquake

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This is a reconnaissance report on the damage to buildings, bridges and other structures caused by the 2009 L'Aquila, Italy earthquake. The authors conducted site investigation during the period of April 18-21, 2009. A detailed discussion on the damage of buildings, bridges and other facilities as well as possible damage mechanisms is presented. Geotechnical damage and ground motions are also presented.

Key Words : *L'Aquila earthquake, Earthquake damage, Damage survey, Failure mechanism, Buildings, Bridges, Geotechnical damage, Seismicity, Faults, Ground motions*

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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 as shown in Fig. 1 (Institute for Environmental Protection and Research 2006). Geology at the fault zone which will be described later is also shown here. 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.

Reconnaissance damage investigation was conducted by a joint-team of Japan Society of Civil Engineers, Japanese Geotechnical Society, Architectural Institute of Japan and Japan Association for Earthquake Engineering. The authors conducted a field investigation on the geotechnical and geological damage as well as investigation on the damage to buildings, 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 and 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 structures which could not be investigated thoroughly.

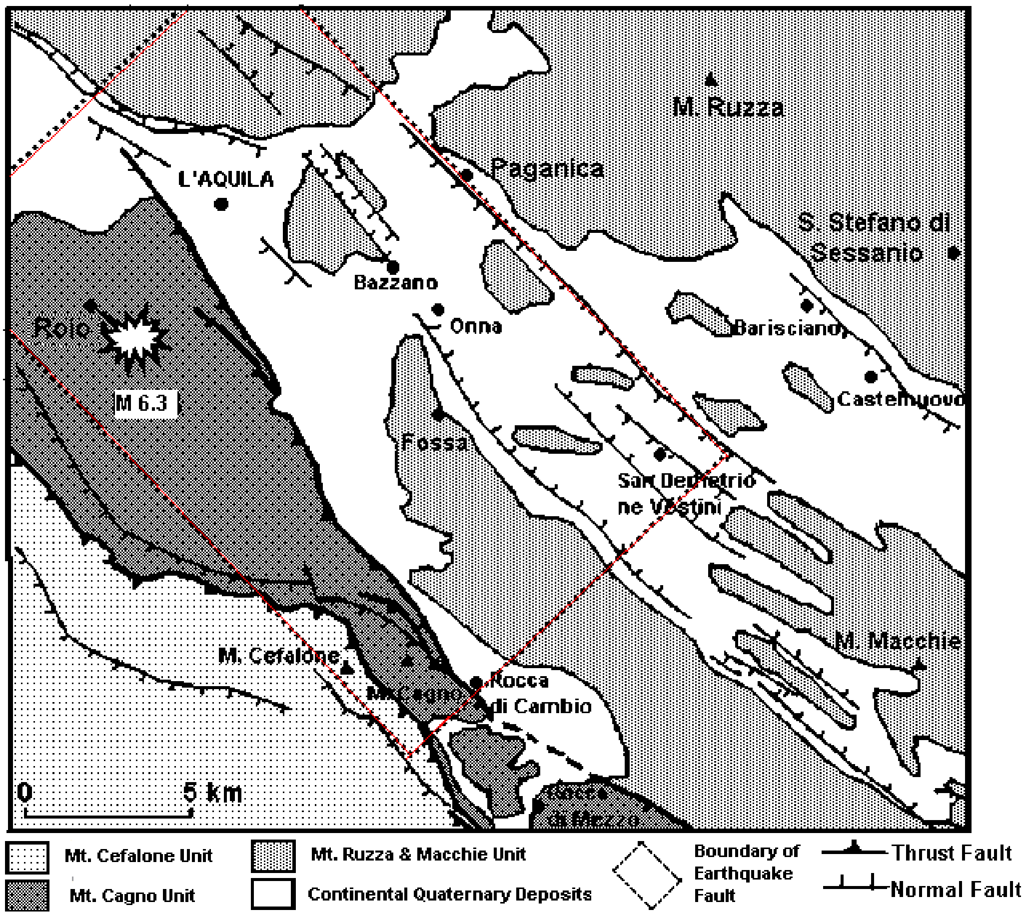


Fig. 1 Geology of the epicentral area and localities (modified from Institute for Environmental Protection and Research 2006)

2. GEOLOGICAL AND SEISMOLOGICAL CONDITIONS

Fig. 1 shows the geology in the vicinity of L'Aquila (Institute for Environmental Protection and Research 2006). The earthquake affected area consists of Meso-Cenozoic carbonate platforms and quaternary deposits. There are two Meso-Cenozoic depositional systems. The first one is characterized by Mesozoic carbonate platforms (limestones and dolomites). This evolves into carbonate slope and basin environments (calcarenites and marls). Its deposition continued until the mid-Miocene. The second one consists of silico-clastic deposits (clays and sandstones) belonging to the Upper Miocene-Pliocene interval. The stratigraphy of L'Aquila consists of schists, limestone, lacustrine deposits, conglomeratic deposits and Holocene deposits from bottom to top. Holocene deposits are a mixture of clay, silt, sand and gravel, and they are widely distributed along Aterno River. Paganica, Onna and Fossa villages where extensive damage occurred are on Holocene deposits. 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 ground water flow.

Historically large earthquakes occurred in the vicinity of L'Aquila in 1315, 1349, 1461, 1703, 1915, 1984 and 1997 as shown in Table 1. The 1915 event (Fucino earthquake (M_S=7)) resulted in victims of 33000. The most recent events were 1984 Lazio-Abruzzi earthquake (M_L=5.8) and 1997 Umbria-Marche earthquake (Ms=6.1). The events which occurred close to L'Aquila were 1461 L'Aquila earthquake (M_L=6.5) and 1703 Norcia L'Aquila earthquake (M_L=6.7). The Mercalli Intensity was IX in L'Aquila during both earthquakes. 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 (refer to Fig. 1). The estimated rupture duration ranged between 6.8 and 14 s.

Table 1 Major earthquakes in the vicinity of L'Aquila in Central Appenines

Earthquakes	Year	Magnitude	Distance from L'Aquila (km)	Maximum Mercalli Intensity	Mercalli Intensity at L'Aquila
Sulmano	1315	M_L=6.0	62	IX	VIII
Aquilano	1349	M_L=6.5	29	IX	IX
L'Aquila	1461	M_L=6.5	15	X	IX
Norcia-L'Aquila	1703	M_L=6.7	16	XI	IX
Fucino	1915	M_S=7	57	XI	VII-VIII
Lazio-Abruzzi	1984	M_L=5.8	88	VIII	VI
Umbria-Marche	1997	Ms=6.1	88	IX	VII

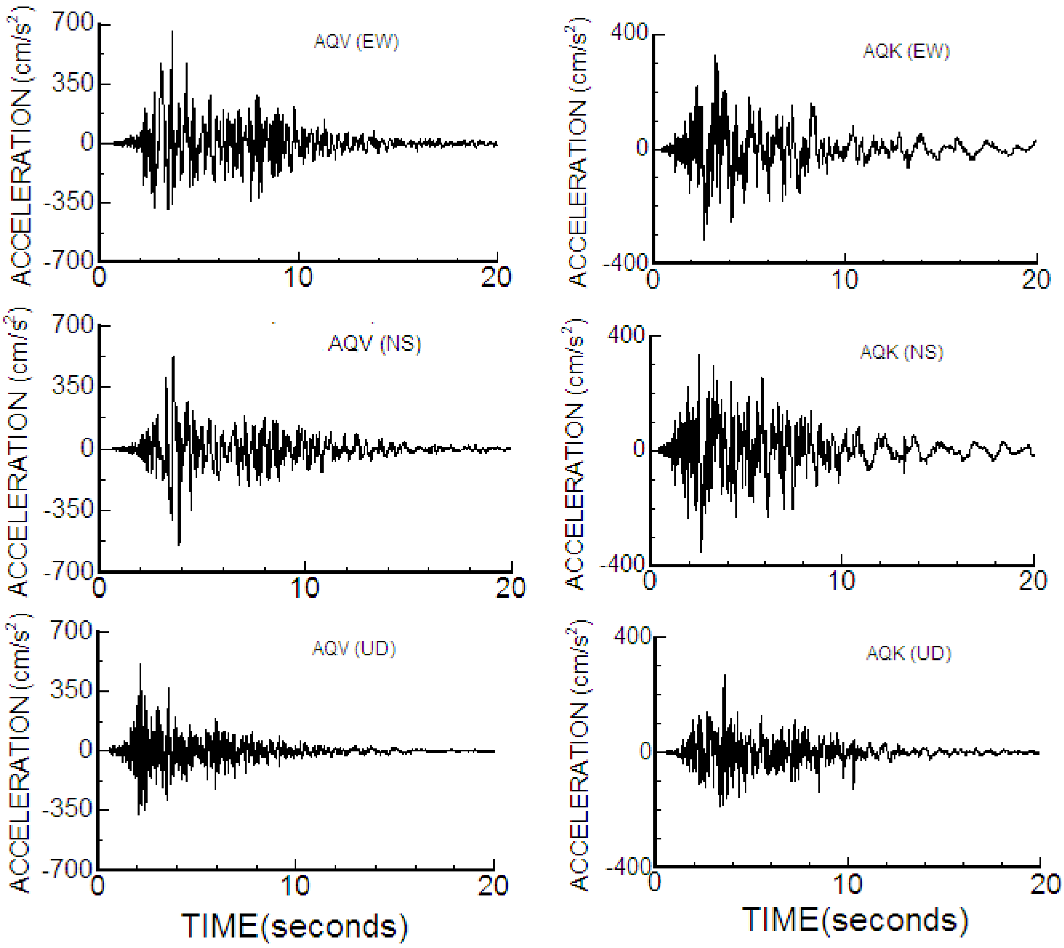
3. STRONG MOTION RECORDS

Based on the Italian National Strong Motion Network (Italian Department of Civil Protection), 56 strong motion records triggered during the earthquake were released. In the close vicinity of L'Aquila City, there are four strong motion stations as shown in Table 2; AQV (Centro Valle, GX066-B), AQG (Colle Grilli, FA030-B), AQA (Fiume Aterno, CU104-B) and AQK (Aquil Parking, 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 (Stewart 2009). The largest peak ground acceleration of 6.46 m/s^2 was recorded at AQV.

Fig. 2 shows the acceleration records at AQV and AQK stations. It is of great interest that the amplitude of ground accelerations are not symmetric with respect to time axis, which may imply strong directivity effect, and their forms are different each other although the epicentral distance and the equivalent shear wave velocity

Table 2 Strong motion stations in the vicinity of L'Aquila

Station code	Latitude	Longitude	Ground	R_e (km)	V_{s30} (m/s)	PGA (m/s^2)
AQK	42.345	13.401	Conglomerate	5.6	455	3.66
AQV	42.377	13.337	Fluvial	5.8	475	6.46
AQG	42.376	13.339	Limestone	4.3	1000	5.05
AQA	42.345	13.401	Fluvial	4.8	475	4.78



(a) AQV (b) AQK

Fig. 2 Acceleration records at AQV and AQK stations

V_{s30} of ground are close.

Acceleration spectra at some selected strong motion stations (AQV, AQK, AQA, AQG, Fiamignano, Montereale, Gran Sasso (INFN Galleria) and Gran Sasso (Assergi) of Italian Strong Motion Network - RAN) are shown in Fig. 3. The predominant periods of the recorded accelerations range between 0.05s and 0.4s in the lateral components. However it is noted that the lateral components of response acceleration were nearly or over 5 m/s^2 at 0.5 s at AQV, AQK, AQA and AQG stations where response accelerations were high. The high response accelerations around 0.5 s are likely to develop extensive damage in standard-size structures. The spectral accelerations of vertical component are high at natural periods ranging between 0.05s and 0.1s.

4. GEOTECHNICAL DAMAGE

1) Lateral spreading and sliding along shoreline of Sinizzo Lake

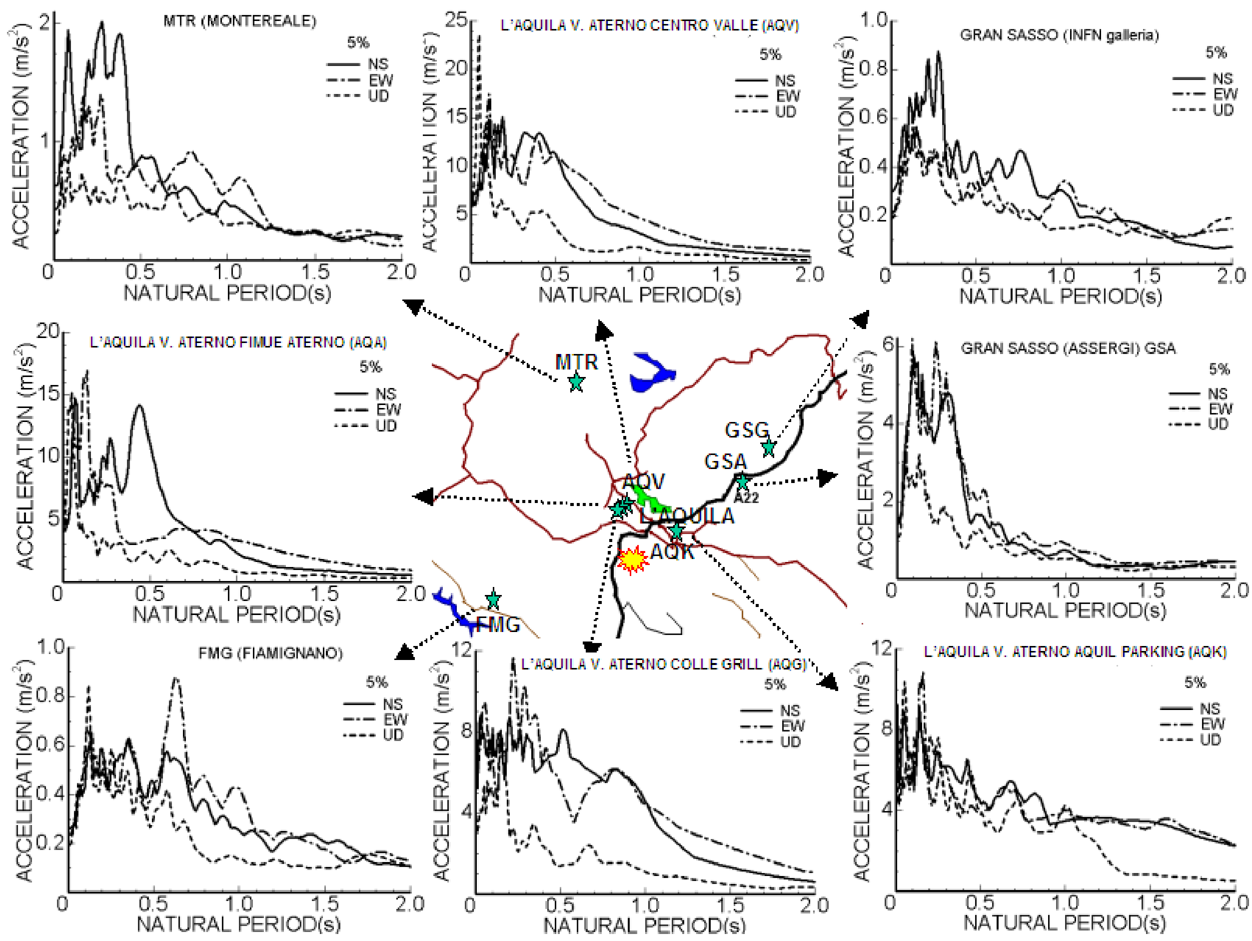


Fig. 3 Acceleration response spectra of selected strong motion stations

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 1. 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 2. 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 occurred on the mountains on east side of the lake as shown in Photo 3.

2) 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 4. Photo 5 shows a broken tree, a shallow dent on the ground and the damaged wall, along the path of the fallen rock block. The velocity and energy at the instance of collision is estimated based on 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 1 Lateral spreading around Lake Sinizzo (added on Google map)

Photo 2 Separated blocks due to lateral spreading

Photo 3 Surface rock sliding on the mountain (east of the Sinizzo Lake)

Photo 4 A 12 ton fallen rock with 1.9m long, 1.6m wide and 1.5m tall

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.

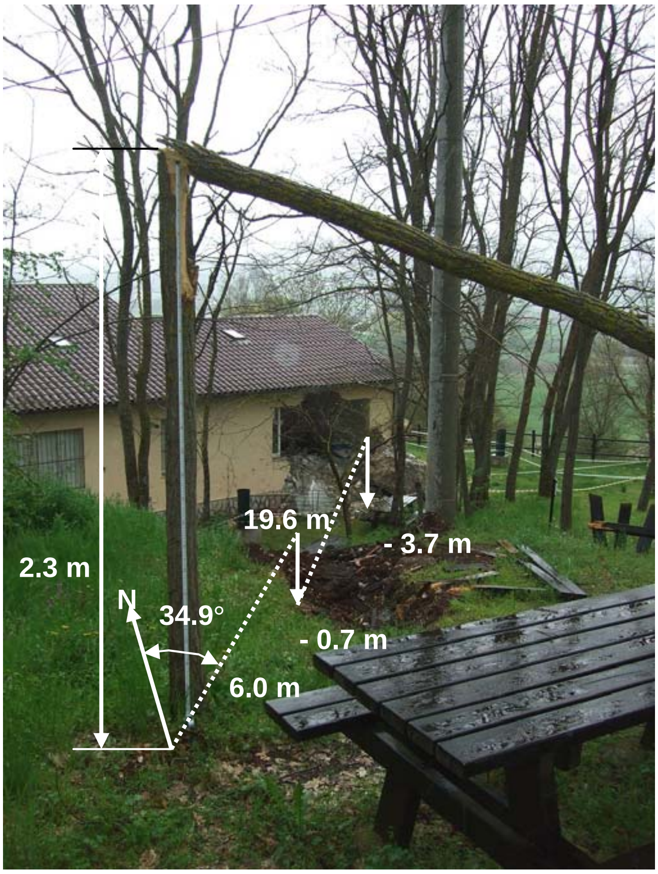


Photo 5 A broken tree, a shallow dent on the ground and a collapsed wall of the building along the path of a fallen rock.

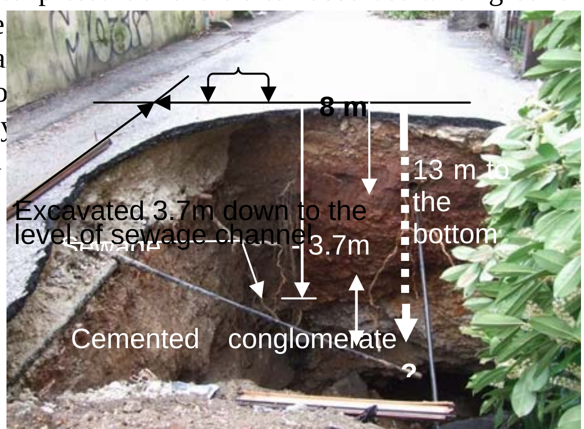
3) Sinkholes on roads due to caving

In the old city of L'Aquila, at least two sinkholes nearly 60 m apart developed on roads due to the earthquake and a vehicle was about to fall into one of the sinkholes as shown in Photo 6. This sinkhole was already back-filled with soils for stabilizing the surrounding ground. However the other sinkhole was only partially back-filled as shown in Photo 7 and it was possible to investigate it. The deepest point was 12.9m from the road surface near the east edge of the sinkhole (refer to Fig. 4). However the cave tended to become deeper towards west. The roof of the cave 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 was observed 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.

4) Soil Liquefaction

Soil liquefaction is caused by the generation of the pore water pressure and it is often observed when ground … s are … d sa … d do … sandy … allel



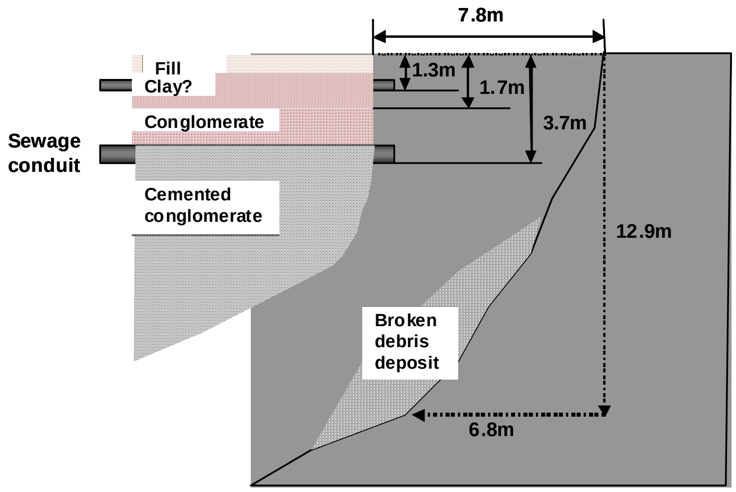


Fig. 4 Section of a sinkhole (Refer to Photo 7)

Photo 8 Liquefaction at Martini district of L'Aquila

shown in Photo 8. Sand boiling as thick as 150 mm was observed in various locations. The movement of ground was towards SE direction. Table 3 and Fig. 5 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 and stiff soils.

Table 3 Properties of liquefied soil samples collected from sand volcanoes

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

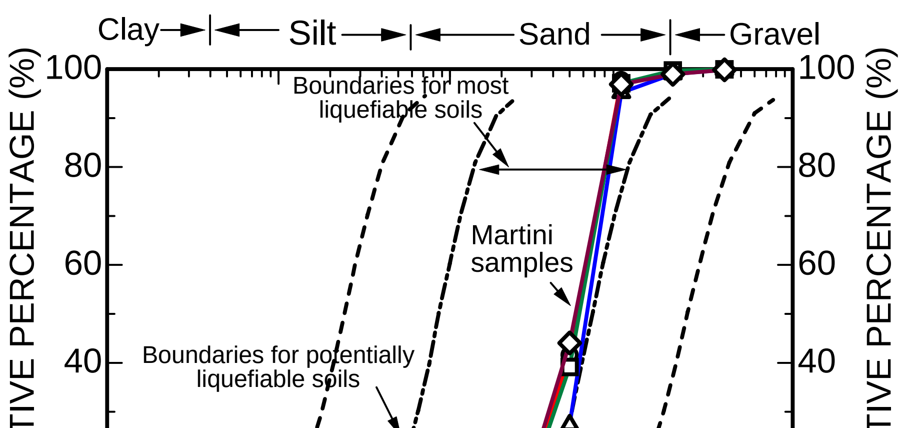


Fig. 5 Grain size distribution and comparison of liquefaction bounds liquefaction bounds

5. DAMAGE OF BUILDINGS

1) Damage of RC frames with unreinforced brick infill walls

Damage of reinforced concrete buildings were investigated based on Japanese standards and guidelines for evaluation of existing buildings (BRI 2001a, BRI 2001b, BDPA 2005). Photo 9 shows a part of five-story student dormitory which totally collapsed resulting in eight victims. Two extended buildings which did not collapse were connected to the collapsed building by stairs and beam bars as shown in Photo 10. Round 10 mm main bars and 6mm stirrup with 250 mm spacing were set in the beam. Slab bars with 4 mm diameter were set in the ribs under the membrane as shown in Photo 11. Because concrete cover was very thin, bars were all corroded. Compression strength of concrete based on Schmidt Hammer test indicated 14MPa at the foundation in another collapsed building in Photo 12.

Photo 13 shows damage of a three-story building. The joint failed and masonry wall leaned in the out-of-plain direction. In many buildings, finishing materials and outer wall panels fell away and masonry walls suffered shear cracks as shown in Photo 14. It was found that middle-rise buildings suffered damage at the middle story as shown in Photo 15. Photo 16 is another typical example of such damage of middle story buildings. Size of the column section changed at the second and forth stories, where damage occurred. However, it is important to note from minor falling of cover concrete and vertical deformation that damage of RC frames was very limited.

Visible damage from outside of the buildings included cracking and falling of bricks in walls and peeling of finishing-mortar cover in beam-column joint panels as shown in Photo 17. Most steel bars exposed after falling of cover concrete were extensively corroded as shown in Photo 18 due to very thin cover concrete. There were even cases in which there was almost no cover concrete. Photo 19 shows an example of the first story collapse of a building in which construction joint was placed at the top of the column near the beam-column joint as shown in Photo 20. Photo 21 shows shear cracks of a short column in the first story of a two story RC building shown in Photo 22.

Photo 9 Collapsed dormitory and two extended buildings

Photo 10 Connection with extended buildings

Photo 11 Debris from the collapsed building

Photo 12 Schmidt hammer test at a foundation of the building

Photo 13 Damage of joints and masonry walls

Photo 14 Damage of finish and outer wall panels

Photo 15 Damage of middle stories

Photo 16 Fall of masonry walls in a six-story building

Photo 17 Unveiled reinforcements

Photo 18 Corrosion of longitudinal bars in a beam

Photo 19 Shear failure of a column at the top

Photo 20 Beam-column joint with construction joint at the top of the column

Photo 21 Shear cracks of a short column in the first story

Photo 22 Collapse of a two-story RC building

Photo 23 The church and convent of S. Angelo d'Ocre

Photo 24 Cracks and residual drift of an arch

Photo 25 Fall of wall bricks and finishing mortar of an unreinforced masonry building

Photo 26 Collapse of unreinforced masonry buildings in Onna village

2) Damage of masonry

Photos 23 and 24 show damage of Cenvent and Church of S. Angelo d'Ocre. Shear cracks on wall, residual drift of an arch and cracks on vault were developed. Damage level of the Convent and the Church was evaluated as "slight to moderate damage" based on the damage assessment sheet of cultural heritage for palaces and churches (Decree of the President of the Council of the Ministers 2006). A number of unreinforced masonry buildings were seriously damaged as shown in Photos 25 and 26.

6. DAMAGE OF TRANSPORTATION FACILITIES

1) Damage of bridges

Damage of bridges was investigated referring to Japanese guidelines for repair and restoration of road facilities (JRA 2007). A 35 m long 5 m wide three-span continuous reinforced concrete bridge at the crossing of SR261 on Aterno River for approaching Fossa Town collapsed as shown in Photo 27. Four reinforced concrete pile-bent columns failed slightly above the river surface, and they shifted sideway and penetrated the deck slab as shown in Photos 28 and 29. A column had six 17 mm diameter round main bars as well as 6 mm diameter round hoops at about 300 mm interval. 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. The river dykes suffered almost no damage due to the earthquake. Both left and right river dykes were protected by stone masonries at inside facing to river flow. 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).

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 Photo 30. 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.

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 Photo 31. 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.

A part of the A24 viaduct in L'Aquila as shown in Photo 32 suffered slight damage. The viaduct is a nearly 37 m long simply supported PC box-girder bridges supported by 11-20 m tall reinforced concrete columns. It is supported by steel fixed and movable roller bearings or elastomeric bearings. Vertical gaps as large as 200 mm were seen at numerous expansions. A number of decks drifted by nearly 200 mm in the longitudinal and transverse directions as shown in Photo 33. It is likely that the gaps at expansions were developed by failure of bearings and the drift of the decks was developed due to residual deformation of elastomeric bearings.

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 Photo 34. The retaining wall was propped by wood bars for resisting the earth pressure.

Photo 27 Collapse of a three span continuous bridge near Fossa Station

Photo 28 Damage of pile-bent pier

Photo 29 Pile-bent piers which punching Village

Photo 30 A 20 m long bridge near Onna the deck sheared the deck slab

Photo 31 Emergency repair of a stone masonry arch culvert (SR261)

Photo 32 A viaduct of A24 in L'Aquila

Photo 33 Residual drift of two bridges in the intersection of Route SS17 and Route SR615

Photo 34 Subsidence of a road embankment at the

7. DAMAGE OF INDUSTRIAL FACILITY

Nearly 20 m tall 4 m diameter silos for storing polypropylene pellets in VIBAC manufacturing plant suffered damage as shown in Photo 35. There were two types of silos built at different times. The first was a group of 8 silos founded on a common pile foundation and supported by a steel frame structure. The other was 12 silos set in two rows on cylindrical skirt resting on 1.2m thick concrete slabs on pile foundations. The cylindrical skirt is fixed to the pile cap with anchor bolts. The silos were made of 6mm structural aluminum.

According to the director of the plant, the silos that were full with the material collapsed during the earthquake, while those with 65% of their full capacities did not collapse. During the earthquake, the silos pounded with the adjacent warehouse partially leaving a dent of impact on its wall. The broken bottom skirts with the silo cones developed the diamond buckling with a circumferential wave number of approximately 6 as shown in Photo 36.

8. SUMMARY

The L'Aquila earthquake provided valuable lessons on how buildings, bridges and other structures behaved under an M_w=6.2 low probability and high consequence event. 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. Failure of outside wall finish and fracture of brick walls were predominant in reinforced concrete frame buildings with unreinforced brick masonry wall. Some administrative buildings having larger structural sections with good construction quality inside the old city of L'Aquila suffered only limited damage. There were middle-rise buildings which suffered damage at the middle stories because size of the column section changed at those stories. There were buildings in which the first story collapsed due to insufficient construction practice of beam-column joints.

Extensive corrosion of steel bars in reinforced concrete structural members was widely observed not only in buildings but also in bridges. Concrete cover was very thin for preventing corrosion. There were even cases where 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 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.

Photo 35 Buckled silos at VIBAC

Photo 36 Buckled bottom of a silo

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