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The 2009 L'Aquila earthquake (Italy): Its characteristics and implications for earthquake science and earthquake engineering

L'Aquıla (İtalya) depreminin özellikleri ve deprem bilimi ve mühendisliği açısından önemi

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ABSTRACT

The 2009 L'Aquila earthquake that occurred in the Abruzzi region of Central Italy had a moment magnitude of 6.3. The earthquake caused the loss of 294 lives with casualties being particularly heavy in the old city of L'Aquila. The authors were able to investigate the damage caused by this earthquake soon after the event. The earthquake was caused by a normal fault and the heaviest damage was mainly on the hanging-wall side of the causative fault. This study describes the characteristics of this earthquake and its implications to earthquake science and earthquake engineering. Furthermore, the main causes of the heavy structural damage as well as the prediction of the earthquake are discussed. A close inspection of prediction claims indicates that the prediction did not really satisfy the requirements for earthquake prediction. The causes of the heavy damage were low seismic resistance of structures and lack of implementation of modern seismic design code.

Keywords: Damage, L'Aquila earthquake, liquefaction, normal faulting, paleoseismology.

ÖZ

Moment büyüklüğü 6.3 olan L'Aquila depremi, İtalya'nın orta kesimindeki Abruzzi bölgesinde 6 Nisan 2009'da meydana gelmiştir. Deprem 294 kişinin yaşamını yitirmesine ve L'Aqulia kentinde ağır hasar meydana gelmesine neden olmuştur. Yazarlar, depremden hemen sonra depremin neden olduğu hasarı incelemişlerdir. Deprem normal bir faydan kaynaklanmış olup, özellikle fayın tavan bloğu üzerinde bulunan yerleşimlerde oldukça ağır hasarlara neden olmuştur. Bu çalışmada, L'aquila depreminin özellikleri ve deprem bilimi ve mühendisliğindeki önemi ile etkileri sunulmuştur. Bunun yanı sıra, yapılarda görülen ağır hasarlar ile bunların nedenleri sunulmuş ve tartışılmıştır. Ayrıca deprem tahmini yapıldığına ilişkin haberlerin doğruluğu bilimsel olarak incelenmiş ve bu öngörünün deprem tahmini için gerekli koşulları sağlamadığı görülmüştür. Gözlenen hasarlarının başlıca nedenleri, yapıların depreme karşı dirençlerinin düşük olması ve deprem yönetmeliklerinin uygulanmamış olmasıdır.

Anahtar Kelimeler: *Hasar, L'Aquila depremi, sıvılaşma, normal faylanma, paleosismoloji.*

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INTRODUCTION

An intra-plate earthquake with a moment magnitude of 6.3 occurred in L'Aquila in Central Italy, at 3:32 local time on April 6, 2009. The earthquake was caused by a normal fault along the Apennines mountain chain. 294 people were killed in the city of L'Aquila and in nearby villages and towns. The village of Onna was completely destroyed by the earthquake.

Although the magnitude of the earthquake was intermediate, the damage to the old part of L'Aquila, Onna and the towns of Paganica and Tempara that are located on the hanging-wall side of the causative fault was extremely heavy. The earthquake's effects were distinctly observed over a 20 km long and 10 km wide area. Some surface ruptures were observed along the expected surface trace of the earthquake fault. Nevertheless, the surface ruptures were not distinct.

This earthquake was quite important in terms of scientific and engineering. The magnitude and the structural effects anticipated from paleoseismological studies and evaluations can be actually validated by this earthquake. The performance of and damage to historical architectural structures also have important implications for assessing the magnitude of historical earthquakes inferred from their damage reports.

The authors investigated this earthquake between April 19th and 23rd, 2009. Although the time was short and there were many restrictions to access to the damaged areas, the authors were able to evaluate the characteristics of this earthquake in terms of earthquake science and earthquake engineering. The evaluations and studies of various reports and the regional seismicity of the region before the main shock were of great significance for earthquake predictions, for scientifically evaluating the claims of the prediction of this earthquake by a technician involved with radon monitoring. This earthquake also demonstrated the vulnerability of natural rock structures during earthquakes, besides the damage to engineered structures. In this study the authors present the outcomes of their investigations.

GEOLOGY AND SEISMO-TECTONICS

The lithological units of the earthquake area are schists, limestone, lacustrine deposits, conglomeratic deposits and Holocene deposits, from bottom to top. Schists are best seen at the east portal of the Gran-Sasso tunnel. The schists are overlain by limestone, which is the main rock unit constituting the Gran-Sasso Mountain ridge (Figure 1). The basin of L'Aquila consists of lacustrine clayey deposits Covered by conglomeratic deposits. The components of the conglomeratic deposits originate from limestone and other rocks from nearby mountains. The matrix of the conglomeratic deposits is clayey or calcareous, and can be easily dissolved by groundwater flow. All these deposits are covered in the Aterno River Valley by Holocene deposits consisting of a mixture of clay, silt, sand and gravel (APAT, 2006; Bigi et al., 1990; Pettitta and Tallini, 2003).

The Italian Peninsula is an anti-clockwise rotating platelet squeezed between the Euro-Asian and African plates. The Adriatic platelet, which subducts beneath the Italian Peninsula and the Eurasian plate, is also anti-clockwise rotating (Figure 2). Nevertheless, the northeast motion of the African plate governs the main driving sources of the motions of these platelets. These motions resulted in the formation of the Tyrrhenian back arc basin, inducing the plate thinning. As a result, the thinning action together with the anti-clockwise rotation of the Italian Peninsula causes earthquakes with the current normal faulting regime in the Appenines Mountain Range and volcanic eruptions in the vicinity of Sicily Island.

Large historical earthquakes occurred in 1315, 1349, 1461, 1703, 1706, and 1915 in this earthquake affected region. The 1915 event is named the Fucino earthquake and it had a surface magnitude of 7 (Figure 3a). The most recent events are the 1984 Greco earthquake (ML:5.8) and the 1996 Umbria earthquake (M_s:6.1). The event closest to L'Aquila was the 1461 event. Bagh et al. (2007) studied the faulting mechanism of earthquakes in the close vicinity of L'Aquila and found that the earthquakes were due either to purely normal faulting or to ob-

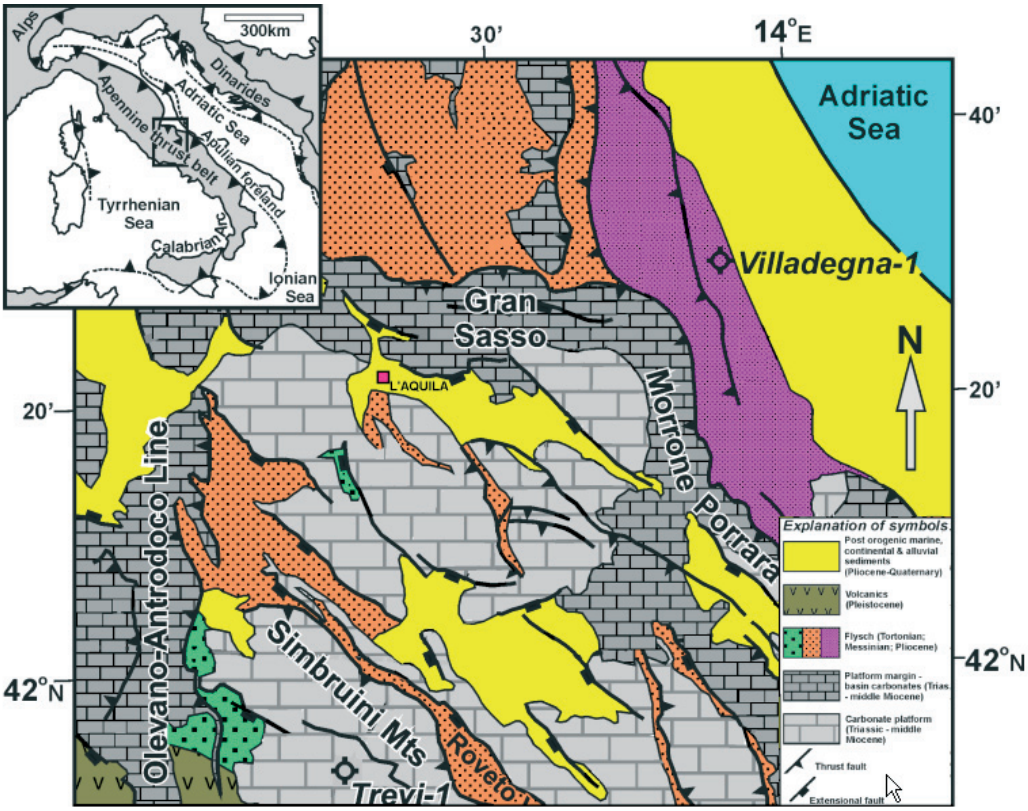


Figure 1. Regional geological map of the earthquake-affected region (modified from Bigi et al., 1990).
Şekil 1. Depremin etkilediği alanın bölgesel jeoloji haritası (Bigi vd., 1990'dan değiştirilerek).

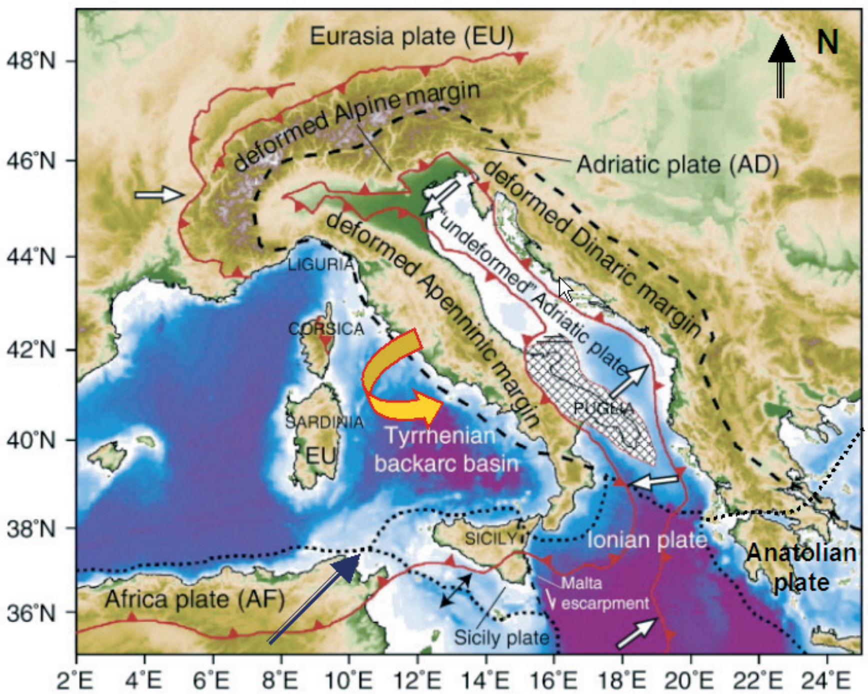


Figure 2. Map showing the main plates in Italy and its vicinity (slightly modified from Devoti et al., 2008).
Şekil 2. İtalya ve çevresindeki başlıca plakaları gösteren harita (Devoti vd., 2008'den biraz değiştirilerek).

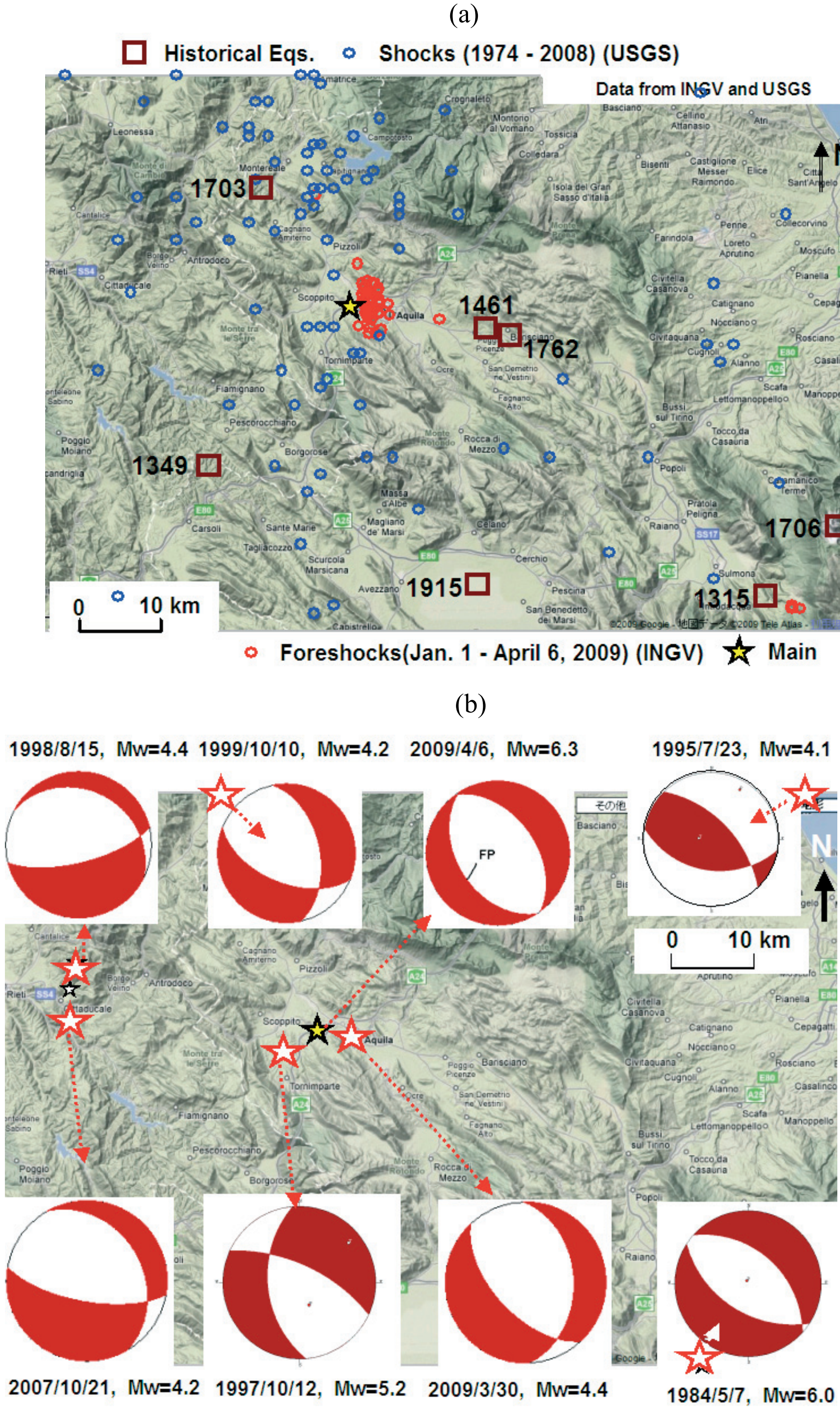


Figure 3. (a) Major past earthquakes and regional seismicity before the L'Aqulia earthquake, and (b) focal mechanisms of some earthquakes (compiled from HARVARD, USGS and INGV).

Şekil 3. (a) L'Aqulia depreminden once meydana gelmiş başlıca eski depremler ile bölgesel depremsellik ve (b) bazı depremlerin odak mekanizmaları (HARVARD, USGS ve INGV'den düzenlenmiştir).

lique faulting with a normal component (Figure 3b). They pointed out that there had been no large seismic event since the 1915 Fucino event, implying that the region may suffer a large event in the near future. This implication was justified by the 2009 L"Aquila earthquake. However, they had foreseen a maximum magnitude of the earthquake of about 7. Such an earthquake could be produced by the slippage of larger faults in the region, such as the Campo Imperatore fault.

CHARACTERISTICS OF THE EARTHQUAKE

Faulting and Surface Ruptures

The fundamental parameters of the 2009 L'Aquila earthquake have been determined by various seismological institutes worldwide and the results are summarized in Table 1 (ERI, 2009; Yamanaka, 2009; USGS, 2009; HARVARD, 2009; INGV, 2009). These estimations indicated that the earthquake was caused by a normal fault 15-20 km long and 10-15 km wide (Figure 6), and the estimated rupture duration ranged between 6.8 and 14 s. In the same table, the parameters estimated from empirical relations proposed by Aydan (2007) and parameters measured by the reconnaissance team of an active fault cutting through the most recent sedimentary deposits (probably of Holocene age) at Paganica are also given, and Figure 4 shows results calculated using Aydan (2000)'s method. It was particularly interesting to note that the parameters of the active fault observed at Paganica were almost the same as those of the focal plane solutions estimated by several seismological institutes.

Surface ruptures were observed during the reconnaissance at the localities of Paganica, Lake Sinizzo, Onna and Fossa Bridge (Figure 5). Surface ruptures were also observed at three locations in Paganica town. Most fractures in Paganica indicated the opening of surface cracks with a normal displacement.

The authors observed cracks on the road to Lake Sinizzo, which is thought to be the southeastern end of the earthquake fault. There were also surface cracks in the vicinity of damaged or collapsed bridges on the Aterno River near Onna and Fossa.villages Some of the cracks were of a compressive type while most of them were of an extension type. As the permanent ground displacement inferred from the InSAR technique (INGV, 2009) concentrates along the Aterno River, the surface ruptures seen in these localities may also imply the extension of the L'Aquila basin in a NE-SW direction, (this is a graben structure) and that the Aterno River flows along a course at the lowest elevation of the basin. The INGV (2009) geological group also reported that surface fractures occurring at Paganica extended to the north of the A24 Motorway, which may imply that some surface ruptures might pass beneath the via-

Table 1. Fundamental parameters of earthquake estimated by different institutes.
Çizelge 1. Depremin değişik kuruluşlarca tahmin edilmiş temel parametreleri.

Institute	M_w	Strike (°)	Dip (°)	Rake (°)	Slip (cm)	Duration (s)	Length (km)	Width (km)
USGS	6.3	127	50	-109		6.8		
HARVARD	6.3	147	43	-88		7.0		
CEA	6.4	139	43	-93		8.4	20	
INGV	6.3	147	43	-88	40		18	16
ERI	6.2	147	44	-99	50	14	25	15
NU	6.3	145	41	-94	60	10	20	10
Aydan (2000)	6.3	140	52	88	45	8.3	17.5	13.7

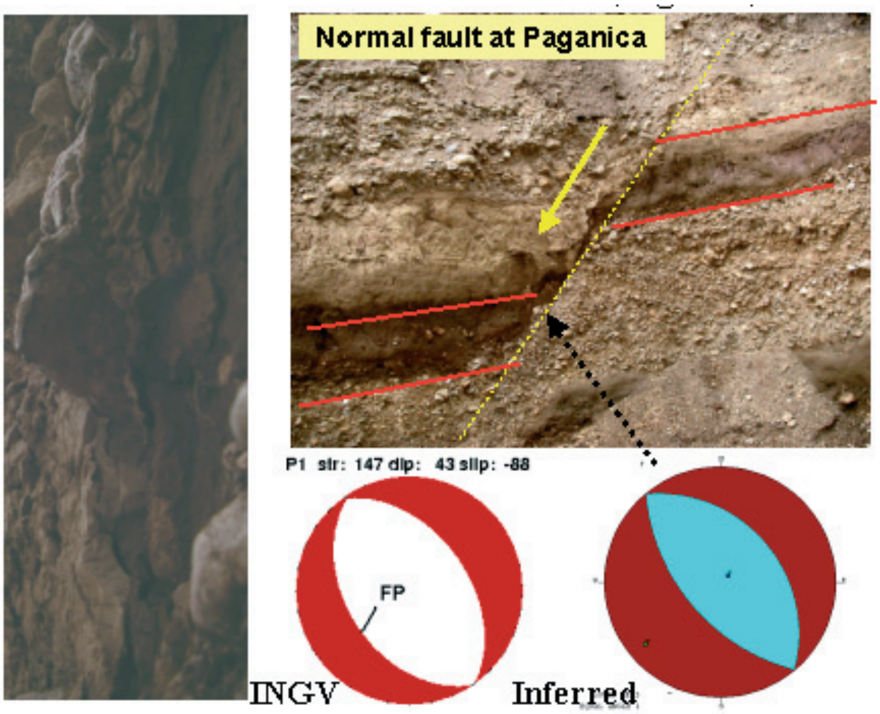


Figure 4. A very young fault in Paganica and comparison of inferred focal mechanism.
Şekil 4. Paganica'daki çok genç bir fay ve odak mekanizmasının karşılaştırılması.

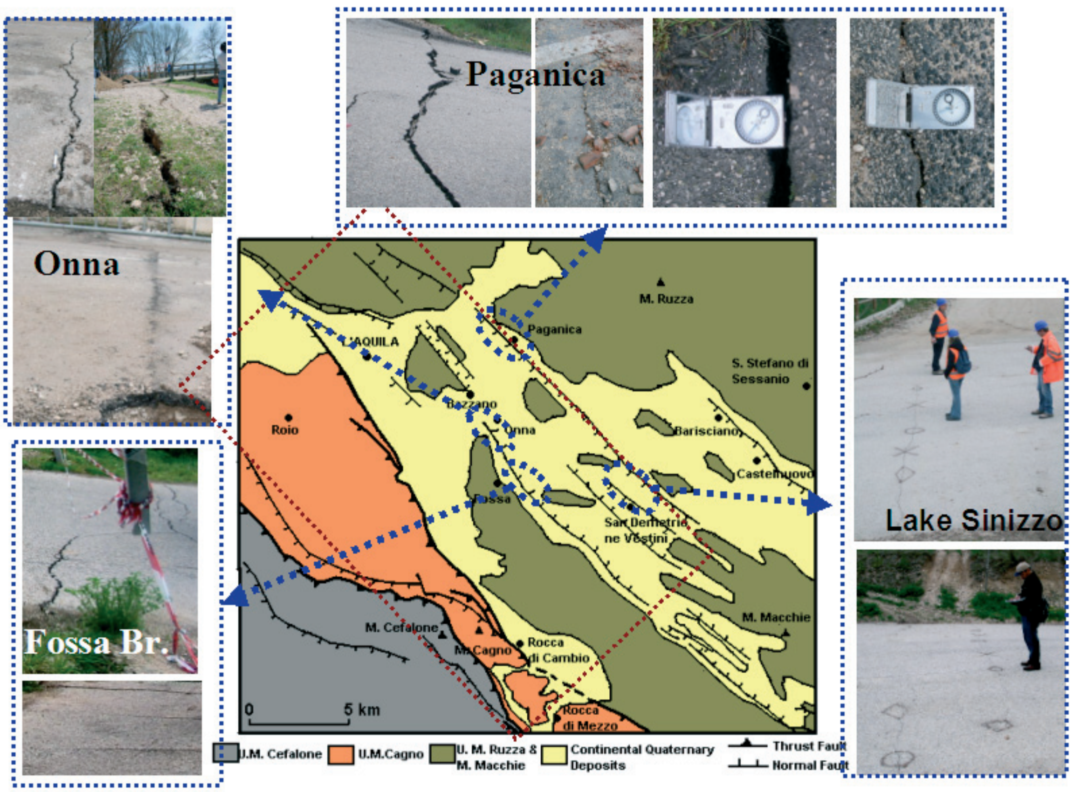


Figure 5. Locations and pictures of surface ruptures.
Şekil 5. Yüzey kırıklarının yerleri ve görüntüleri.

ducts of the A24 Motorway. In addition, they reported surface ruptures near Bazzano as well as north of L'Aquila.

Shocks and Faulting Mechanism

The area is seismically active and it is really difficult to define the time of foreshock activity. Nevertheless, the seismic activity (M>3) was relatively quiet until 2008 (see Figure 4). The seismic activity started to increase from March 10, 2009 and reached a peak activity on March 30, 2009 (Figure 6). The activity continued during April when there was a foreshock with a magnitude of 4.0 at a distance of 10 km northeast of the main shock. G. Giuliani, the technician from Gran Sasso's National Institute of Nuclear Physics involved with radon monitoring, alarmed by this seismic activity and radon activity reportedly warned the people of the town of Sulmona, which is about 30 km south-east of L'Aquila, and claimed that an earthquake would occur on March 29, 2009. Nevertheless, no report of the monitoring results of radon and his scientific reasoning are available. The earthquake occurred on April 6, and 30 km away from the anticipated location. Although there were two foreshocks in the vicinity of Sulmona (see Figure 3 for location) most of the foreshocks were concentrated in the vicinity of the main shock. The anomaly of radon emission could undoubtedly be associated with the earthquake. This simple example shows that the use of a single parameter for earthquake prediction can not be decisive. Giuliani could have used the foreshock activity in addition to the monitoring of radon emissions. Therefore, none of the fundamental requirements for the prediction of earthquakes (i.e. location, time and magnitude) was fulfilled by the prediction of this technician.

The main shock with a moment magnitude of M6.3 (Ml=5.8) occurred at 03:33 AM local time on April 6, 2009 near L'Aquila. INGV (2009) estimated that the earthquake was a result of normal faulting on a NW-SE oriented structure about 15 km long. The fault dips toward the southwest and the town of L'Aquila is on the hanging wall of the fault just above it. This fault may be associated with the fault that INGV (2009) have named the Paganica fault.

Following the main event, several hundreds of aftershocks were recorded (Figure 7). Three large aftershocks with a local magnitude (Ml) of 4.8, 4.7 and 5.3 occurred on April 7 near L'Aquila and southeast of the town (close to the villages of Onna, Fossa, Ocre). None of the aftershocks on April 8 was larger than Ml 4. On

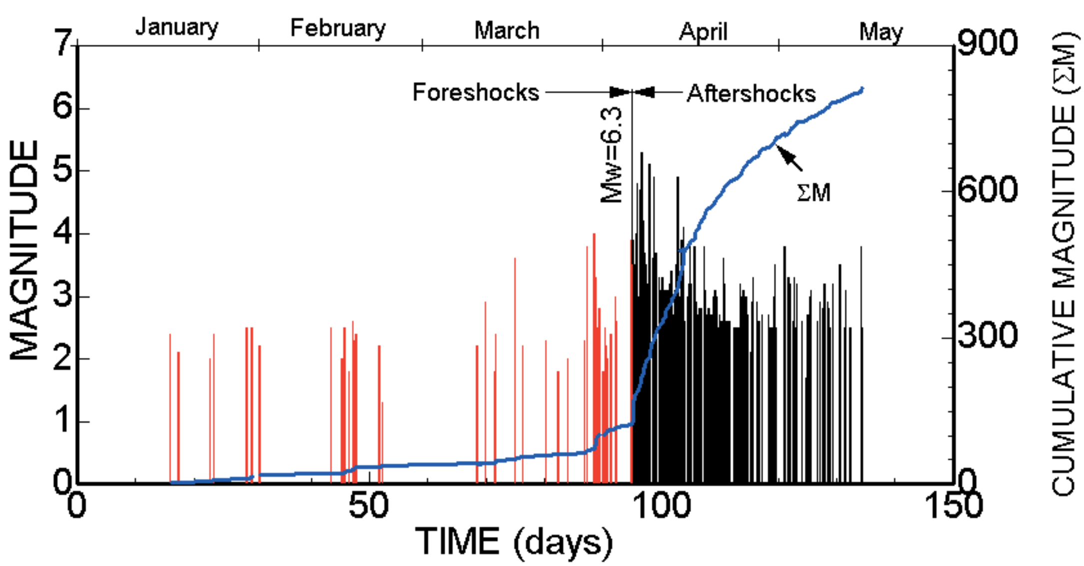


Figure 6. Time history of shocks.
Şekil 6. Sarsıntıların zamana bağlı değişimi.

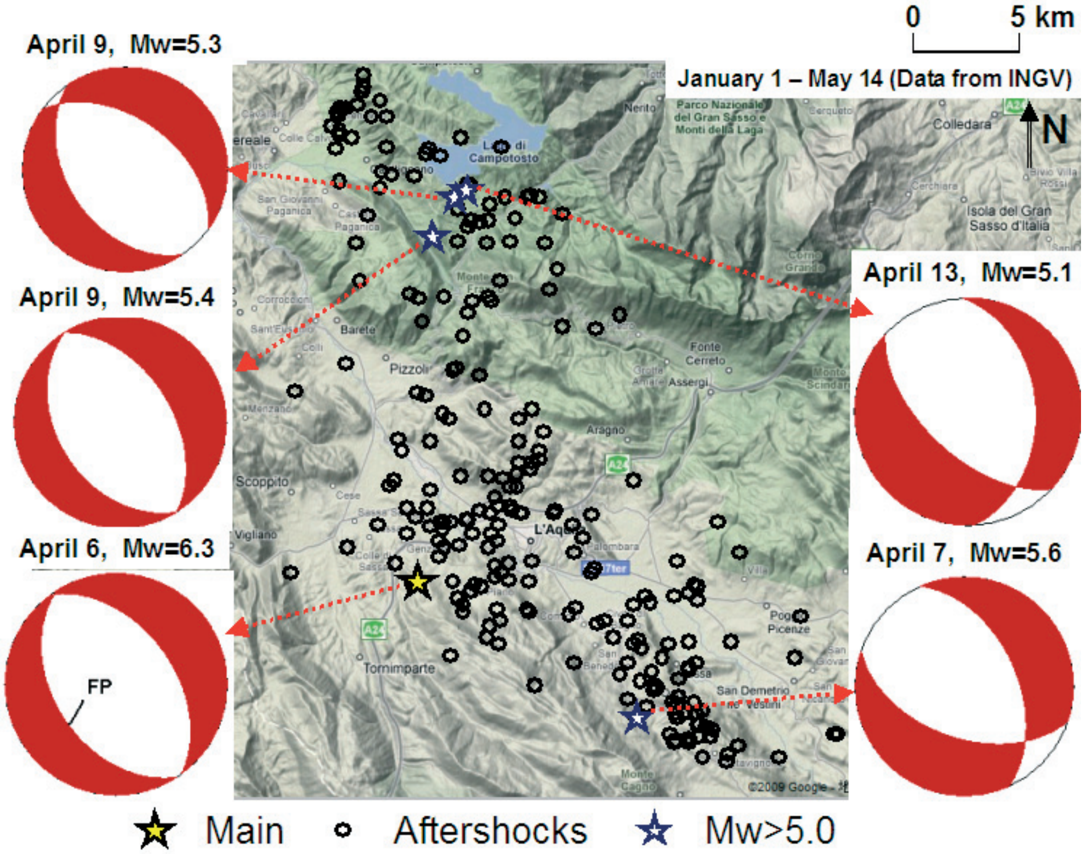


Figure 7. Epicenters of shocks and focal mechanism of some large aftershocks.
Şekil 7. Depremlerin merkez üstleri ve bazı büyük artçı depremlerin odak mekanizmaları.

April 9th, an aftershock with a magnitude (Ml) of 5.1 occurred to the north of L'Aquila, close to Barete, Pizzoli and Campotosto. This was probably the activation of another shorter segment of the normal fault system of Abruzzi Region, the Campotosto fault, and the extension of the accumulated seismic stress release towards the northwest. The projection of the aftershock activity on a cross-section perpendicular (NE-SW direction) to the Paganica fault implies that the L'Aquila graben was activated during this earthquake. The focal mechanisms of the aftershocks determined by INGV (2009) implied dominantly normal faulting. However, the dip of some of these aftershocks is expected to be northeast, in addition to aftershocks with southwest dipping faulting.

Strong Motion Records

Based on the Italian National Strong Motion Network (Accelerometric National Network, RAN, 2009), 56 strong motion records triggered during the earthquake have so far been released (Figure 12). In the close vicinity of L'Aquila City, there are four strong motion stations, as shown in Table 2; AQV (GX066-B), AQG (FA030-B), AQA (CU104-B) and AQK (AM043-C). They are all on the hanging wall side of the earthquake fault. The equivalent shear wave velocity 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.

Figure 8a shows the acceleration records at AQV and AQK strong motion stations. It is of great interest that the ground motions are not symmetric and their forms are different from

Table 2. Information for the strong ground motion stations in the vicinity of L'Aquila.
Çizelge 2. L'Aqulia çevresindeki kuvvetli yer hareketi kayıt istasyonlarına ait bilgiler.

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

each other although the epicentral distances and equivalent shear wave velocity (V_{s30}) of ground are almost the same. Although the details of the ground conditions at the stations are not available yet, the ground motion amplification estimations based on the V_{s30} approach may not be valid at all.

Figure 8b shows the acceleration records at GSA and GSG strong motion 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 to almost 15 times greater than that in the underground gallery.

The attenuation of maximum ground acceleration for two different models is shown in Figure 9. Figure 9 is a comparison of attenuation of maximum ground acceleration as a function of hypocentral distance using the various attenuation relations (Aydan, 1997; Joyner and Boore, 1981; Fukushima et al., 1988). As seen from this figure, attenuation based on spherical symmetry can not estimate a wide range of observational data. The attenuation relation proposed by Aydan and Ohta (2006) (see also Aydan, 2007), which includes a consideration of fault orientation and ground characteristics, provides better bounds for the observational data.

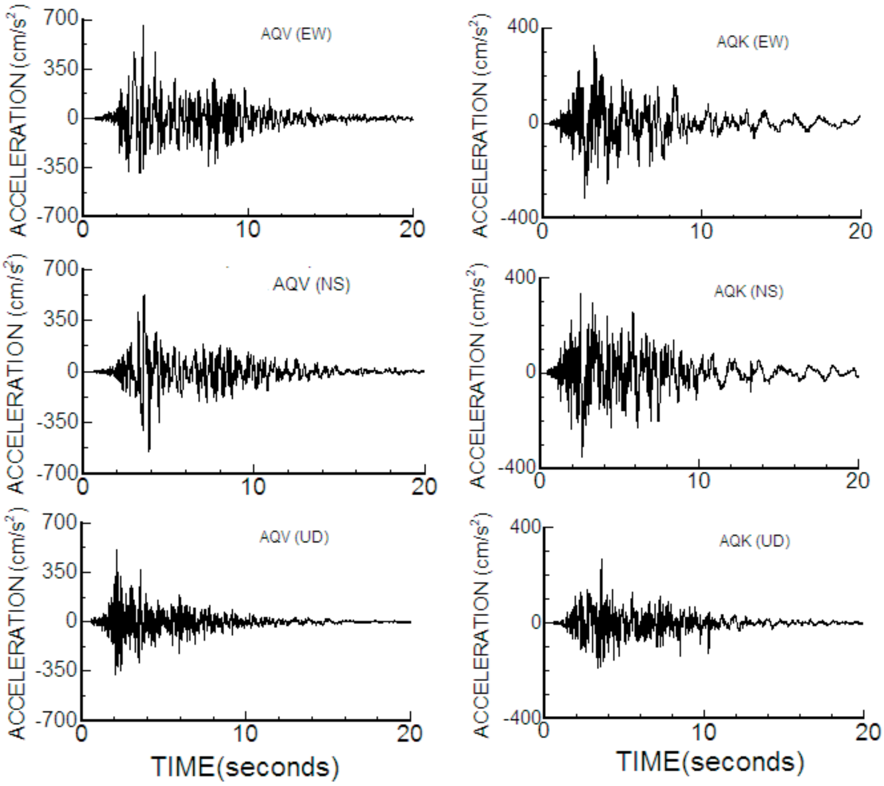
Figure 10 shows the acceleration spectra of selected stations in the vicinity of the epicenter. When the response spectra of records of strong motion stations in the close vicinity of L'Aquila are compared with the design spectra designated by the EC8, the actual response spectra exceed the designations within the period range of 0-0.4 s. The base ground acceleration is imaging to have ranged between 0.3-0.4 g in the of L'Aquila, in view of the ground motion records at AQK strong motion station as well as the damage to structures.

Acceleration spectra of some selected strong motion stations (AQV, AQK, AQA, AQG, MTR, FMG, GSA, GSG) are shown in Figure 10. As expected, the spectral accelerations of vertical component are high for natural periods ranging between 0.05 s and 0.1 s. As for the horizontal component, the natural periods range between 0.05 s and 0.4 s. Nevertheless, very long period components are particularly noted for AQG station, which is located over the bedrock of limestone and has previously been pointed out by Luca et al. (2005).

Permanent Ground Deformations

An attempt was made to estimate the permanent ground deformations from strong motion records using the EPS method proposed by Ohta and Aydan (2007a, 2007b). The most important aspect of these methods is how to assign parameters for numerical integration. The record is divided into three segments. Filtering is imposed in the first and third segments while the integration is directly applied to the second segment if the acceleration record does not drift. The duration of the second segment is directly based on the

(a)



(b)

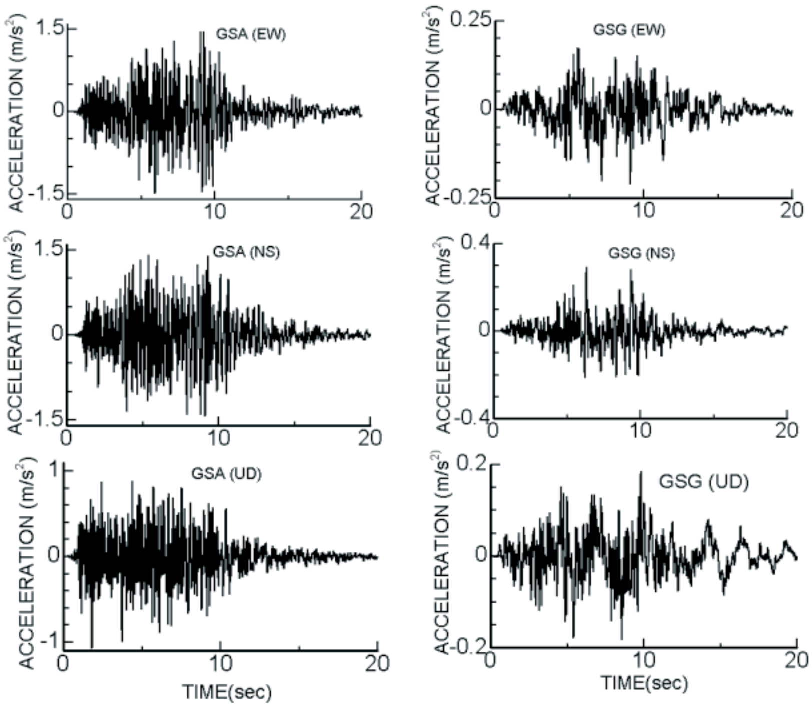


Figure 8. (a) Acceleration records at AQV and AQK strong motion stations, and (b) acceleration records at GSA and GSG strong motion stations.

Şekil 8. (a) AQV ve AQK ve (b) GSA ve GSG kuvvetli yer hareket istasyonlarında alınmış ivme kayıtları.

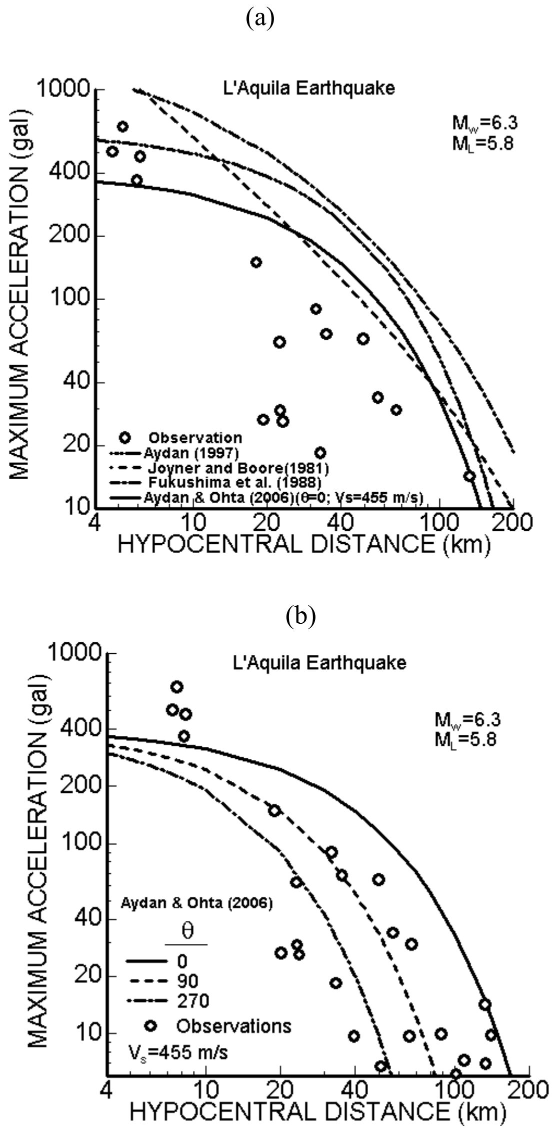


Figure 9. Comparison of attenuation relations with observational data.

Şekil 9. Azalım ilişkileri ve gözlemsel verinin karşılaştırılması.

rupture process of the earthquake fault. In view of the rupture process estimated by several institutes and the relation proposed by Aydan (2007), the rupture time was selected as 10 s and the filtering of acceleration levels for the first and third segments were ± 1 and ± 5 gals. The computed results for the stations AQA and GSG, which are perpendicular to the fault strike, are shown in Figure 11a. Figure 11b shows the horizontal permanent ground deformations which are comparable with GPS measurements.

GEOTECHNICAL DAMAGE

Horizontal Movements and Cracking in the Area of the River Aterno

Horizontal movements and cracking were observed in the area of the Aterno river, to the west of Onna village. The embankments on both sides of the Aterno moved towards the river, creating separation cracks as well as some compression cracks in the vicinity of the damaged bridge over the Aterno. The cracking on the east side of the river was more intensive as the ground was inclined towards the west. Nevertheless, any sand boiling, which may be an indicator of liquefaction, was not observed in the area. Based on InSAR evaluation, ground movements are large in the close vicinity of the Aterno, near Onna. Tectonic movements, ground liquefaction or both might have caused the movement in this area. If ground liquefaction were involved, it is likely that there would be a thick impermeable silty and clayey layer on top of the liquefiable ground below.

Ground Failure at Sinizzo Lake

The Abruzzi region is karstic and many sinkholes and dolines exist in the epicentral area. Lake Sinizzo is a doline lake with embankment reinforcement on its northwest side. The lake is 9.8 m deep and it has an average diameter of 122.7 m (Bertini et al., 1989). Extensive ground failures took place around the shore of Lake Sinizzo (Figure 12). Although the surrounding ground is mainly calcareous conglomerate, the lakebed is composed of Holocene deposits.

Slope Failures and Rockfalls

Slope failures caused by the 2009 L'Aquila earthquake may be classified into three categories: a) soil slope failures; b) surficial slides of weathered rock slopes c) rock slope failures (planar sliding, wedge sliding failure and flexural or block toppling) and d) rockfalls (Figure 13). As the magnitude of the earthquake was small and the duration of shaking was short, the scale of the slope failures was small, too. Nevertheless, rockfalls induced damage to structures and roadways. Soil slope failures were obser-

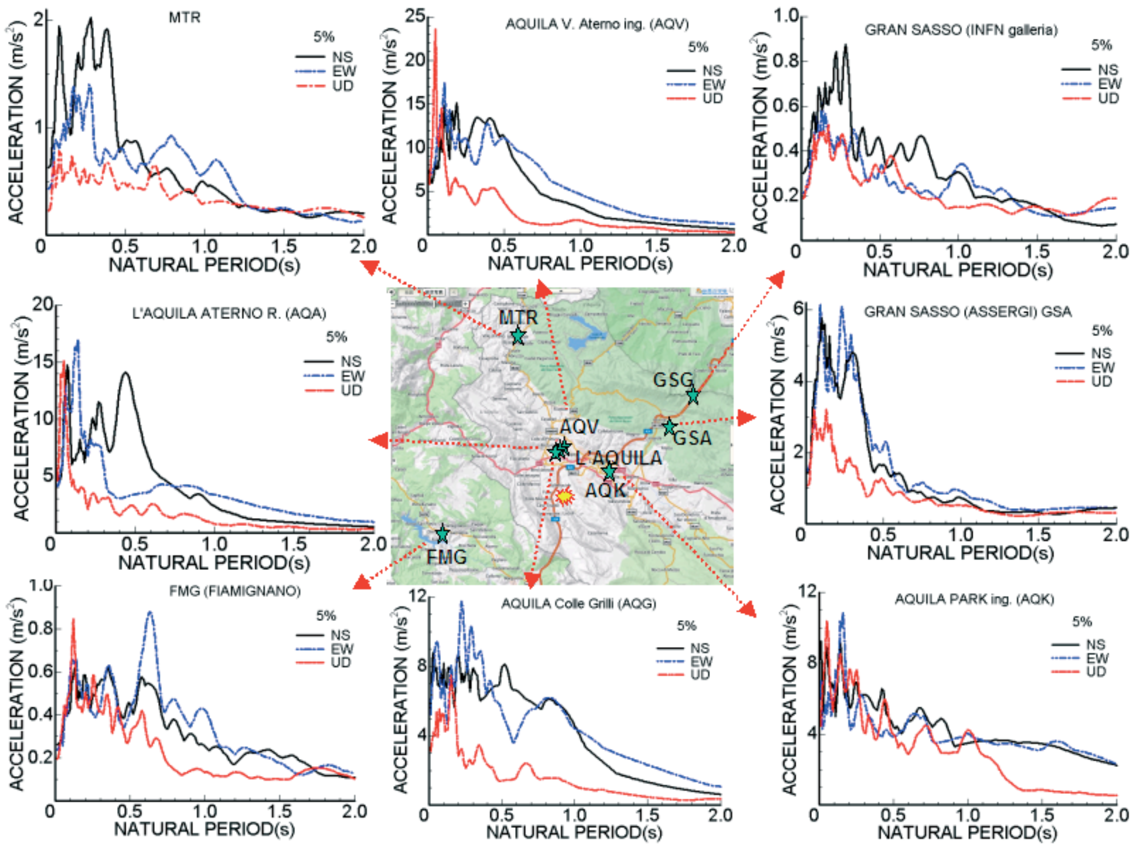


Figure 10. Acceleration response spectra of selected strong motion stations.
Şekil 10. Seçilmiş kuvvetli yer hareketi istasyonlarının ivme tepki spektrumları.

ved along the Aterno River's shores in mountainous areas such as in the vicinity of Campotosto. Figure 13a shows a soil slope failure along the Aterno River in the Martini District.

Weathered rock slope failures are of a surficial sliding type and rock generally consists of weathered marl, limestone and conglomerate. Particularly marl is very prone to weathering due to cyclic wetting and drying. Furthermore, as the elevation of the epicentral region is very high, the effect of freezing and thawing should be another cause of heavy weathering of the rocks. Failures of rock slopes were observed in the vicinity of Lake Sinizzo, quarries near Bazanno and Fossa and in roadway cut slopes.

Most of the rock slope failures involve natural discontinuities such as faults, joints and bedding planes. Depending upon the orientations of rock discontinuities, the slope failures may be classified as planar and/or wedge sliding failures, toppling or combined sliding and toppling failures. Aydan (2007) and Aydan et al. (2009) have recently proposed some empirical formulas to use in assessing the bounds for slope failures in relation to their natural state and the relative position of slopes with respect to hypocenters and earthquake faults, considering the hangingwall and footwall effects. These empirical relations are applied to observations concerning this earthquake together with previous case histories, as shown in Figure 13c. As seen from the figure, the observations made in the L'Aquila earthquake are generally in accordance with empirical bounds and other previous case history data.

Rockfalls were observed in the areas where steep rock slopes and cliffs outcrop. Large scale rock falls were observed in the vicinity of Stiffe, San Demetrio and Lake Sinizzo, and Paganica (Figure 13b). Some of these rockfalls induced damage to structures. Nevertheless, the rock-

(a)

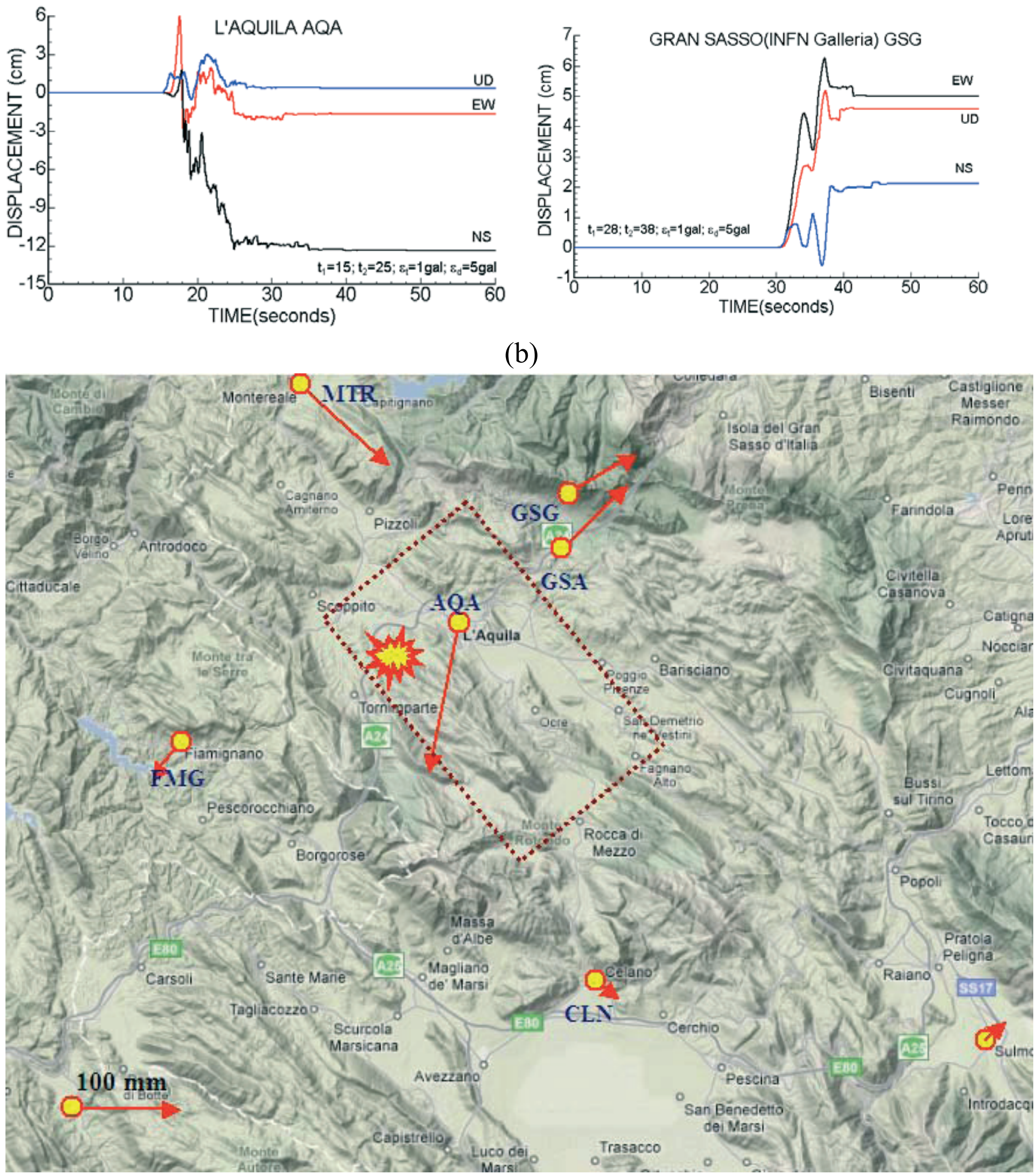


Figure 11. (a) Estimated ground movements during earthquake at selected points, and (b) estimated permanent ground displacements by EPS method.

Şekil 11. (a) Seçilmiş noktalarda deprem sırasında tahmin edilmiş yer hareketleri ve (b) EPS yöntemiyle tahmin edilmiş kalıcı yerdeğiştirmeler.

falls occurred by the fall of individual blocks which have failed in the modes of sliding, toppling or combined sliding and toppling.

Aydan et al. (1989), Aydan and Kawamoto (1987, 1992), Kumsar et al. (2000) and Aydan and Kumsar (2009) presented some methods that can be used to analyze the various modes of failure of rock slopes. Figure 14 compares computational results with observational data from stable and unstable slopes. The data compiled by Aydan et al. (1989) from the

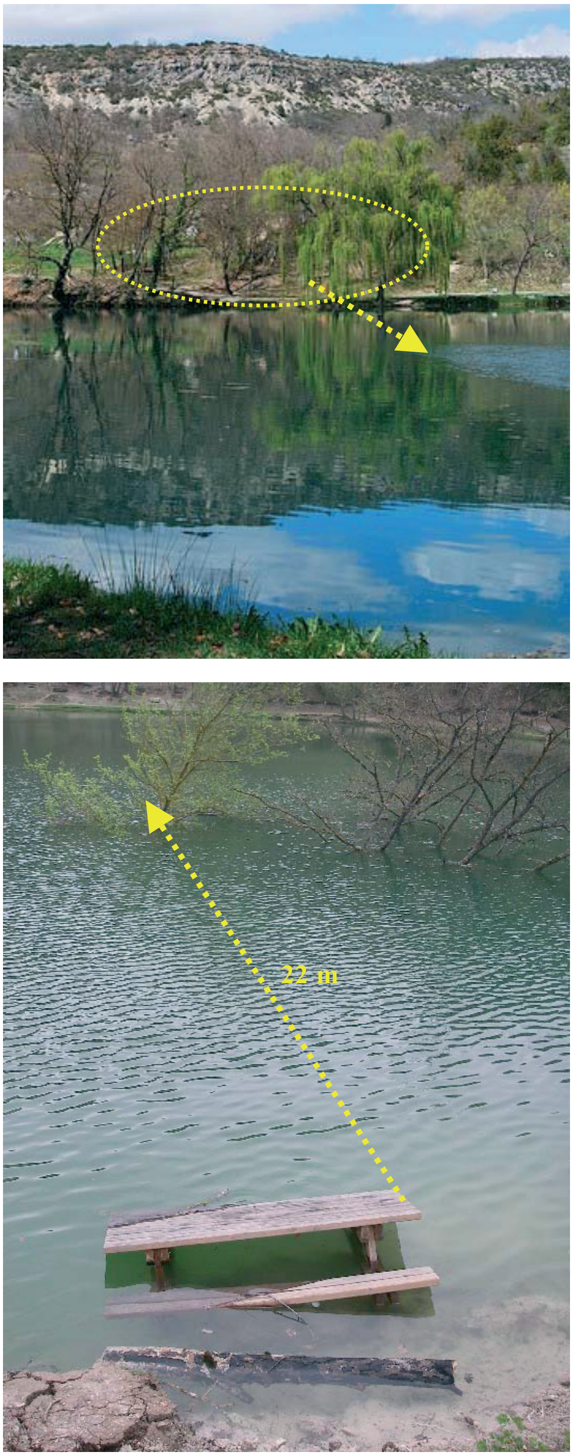


Figure 12. Views of the ground failure before and after the earthquake.
Şekil 12. Depremden önce ve sonra yüzeydeki yenilmeden görüntüler.

natural rock slopes of the Apennine Mountains are also plotted together, as the mountains of the region belong to the Apennine mountain ridge. The Apennines are composed of mainly limestone and other calcareous rocks of different geologic ages. As a result, their stability is influenced by the orientation of bedding planes as well as normal faults. During the compilation of data, it was noted that when layers are thin, it seems that the slope angle for stability under natural conditions is drastically reduced. Furthermore, when layers dip into a slope, the natural stable slope angle tends to be almost equal to that of the bedding plane. As for layers dipping into the mountainside, the stable slope angle is almost equal to, or greater than, the normal angle of the bedding planes. When it is greater than the normal angle of bedding plane, its value ranges from 5° to 35°. When the slope becomes higher, the stable slope angle tends to converge to that of the norm of the bedding plane. The repose angle of slope debris ranges between 30° and 40°. Figure 14 is considered as a guideline for local engineers when selecting the slope-cutting angle in the actual restoration of the failed slopes.

Sinkholes

The geology of L'Aquila city involves limestone at its base, lacustrine clay and continental debris in the form of conglomerate and breccias and Holocene alluvial deposits from bottom to top. The L'Aquila breccia of Pleistocene age is known to contain karstic caves. Karstic caves are geologically well-known to form along generally steep fault zones and fractures due to erosion and/or solution by groundwater (i.e. Aydan and Tokashiki, 2007; Tokashiki and Aydan, 2008). During reconnaissance, the authors found two large karstic caves very close to the AQK strong motion station. The height of one of these caves is about 5 m. Along the same road one can easily notice the remnant of a karstic cave on a rock-slope cut. It seems that karstic caves are a well-known problem in L'Aquila. One can find reports of searches for potential karstic caves using various geophysical methods (i..e Tallini et al., 2004a, 2004b). The 2009 L'Aquila earthquake caused two sink-

(a)

(b)

(c)

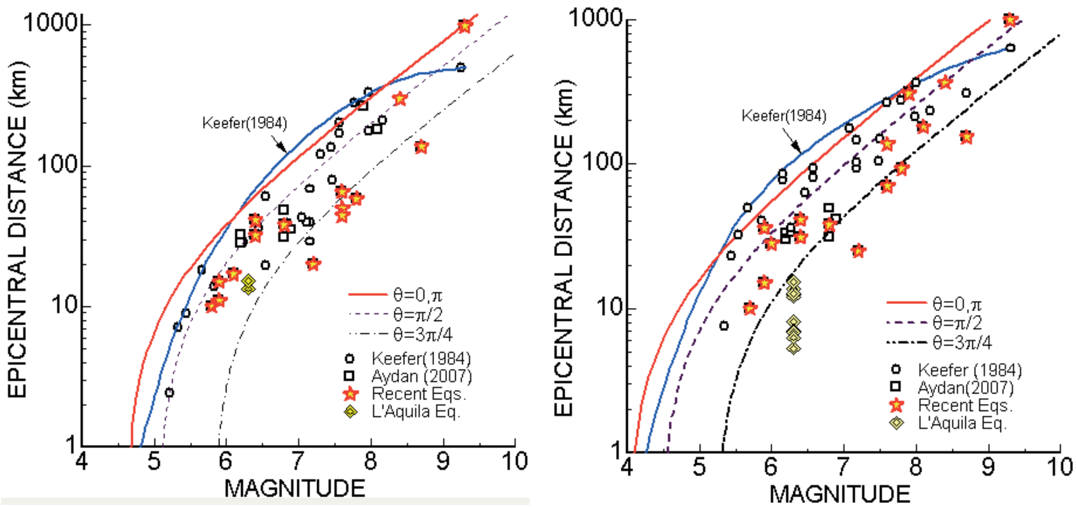


Figure 13. (a) Soil slope failure at Martini district, (b) rockfall at Stiffe, and (c) comparison of data of L'Aquila earthquake with empirical bounds (coherent slopes and disturbed slopes).

Şekil 13. (a) Martini bölgesinde bir zemin şevi duraysızlığı, (b) Stiffe'de kaya düşmesi ve (c) L'Aqulia depremi verisinin görgül ilişkilerle karşılaştırılması (sıkı şevler ve örselenmiş şevler).

holes in L'Aquila (Figure 15a). One of the sinkholes was well publicized worldwide. The width of this sinkhole was about 10 m and its depth is not well-known. A car fell into this sinkhole. The second sinkhole was about 50 m away and its size was slightly smaller. Its length and width were about 8 m and 7 m, respectively. The depth of the sinkhole was about 10 m. The layers between the roof and road level were breccia with calcareous cementation, breccia with clayey matrix and top soil from bottom to top. A side trench was excavated to a depth of 3 to 4 m from the ground surface on the south side of the sinkhole. Another sinkhole occurred in Castelnuovo, and it had a length and width of 5 and 3 m with a depth of 5 m. The thickness of the roof of this sinkhole was about 1.5-2.5 m.

Ground Liquefaction and Lateral Spreading

Soil liquefaction is caused by generation of pore water pressure and it is often observed when the ground consists of fully saturated sandy soil. Alluvial deposits are geologically formed along the Aterno River in the epicentral area. During their investigations, the authors found sand boils along the Aterno in the area called Martini, which is just south of the hill on which the old city centre of L'Aquila is located. The river meanders in the area sandy deposits are li-

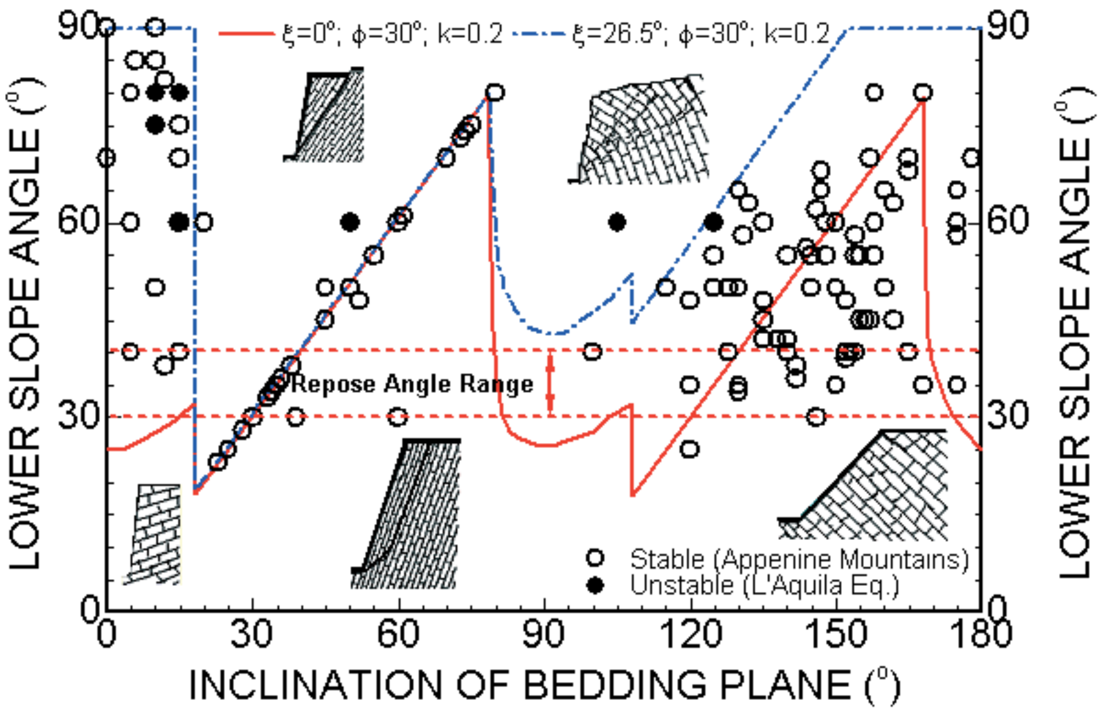


Figure 14. Comparison of observational data with computational results prom previous studies (ξ : intermittency angle; *k*: horizontal seismic coefficient; ϕ : friction angle).
Şekil 14. Gözlemsel verinin önceki çalışmalarda elde edilmiş hesaplama sonuçlarıyla karşılaştırılması (ξ : aralık açısı; k: yatay sisimik katsayı; ϕ : sürtünme açısı).

(a) (b)

Figure 15. (a) A sinkhole in L'Aquila, and (b) liquefaction in Martini district.
Şekil 15. (a) L'Aquila'da karstik bir çökme ve (b) Martini bölgesinde sıvılaşma.

kely to have resulted in the locations of the meanders. In the Martini district, liquefaction created many NE-SW trending fractures parallel to the river embankment, as shown in Figure 15b. Sand boiling as thick as 150 mm was observed in various locations. The movement of ground was towards a SE direction. Boiled sand is almost homogenous and its grain size distribution falls within the easily-liquefiable bounds according to the classification issued by the Port and Harbour Research Institute of Japan (1997).

The ground liquefaction also induced lateral spreading. The sum of crack openings from the adjacent field towards the river embankment ranged between 250-350 mm. 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 to the structures, probably because the foundations were resting on deep stiff soils.

Figure 16a compares the authors' observations with the empirical bounds proposed by several researchers (Aydan et al., 1998; Aydan, 2007; Ambraseys, 1988; Kuribayashi and Tatsuoka, 1979) for the limit of ground liquefaction. The observations are within the limits of liquefiable ground. Since the data is quite limited now, new data may give more accurate results. An attempt was made to obtain data concerning the ground deformation due to liquefaction-induced lateral spreading, using several methods. Aydan et al. (2008) proposed a new method based on the maximum ground velocity obtained from the strong motion records. Figure 16b compares the estimation of ground deformation for different layer thicknesses. The comparison with the observational data implies that the thickness of liquefied ground in the Martini district should range between 1.5 and 2 m. Additional comparison is based on the use of ground motion data in the close vicinity of the liquefaction site in the Martini district.

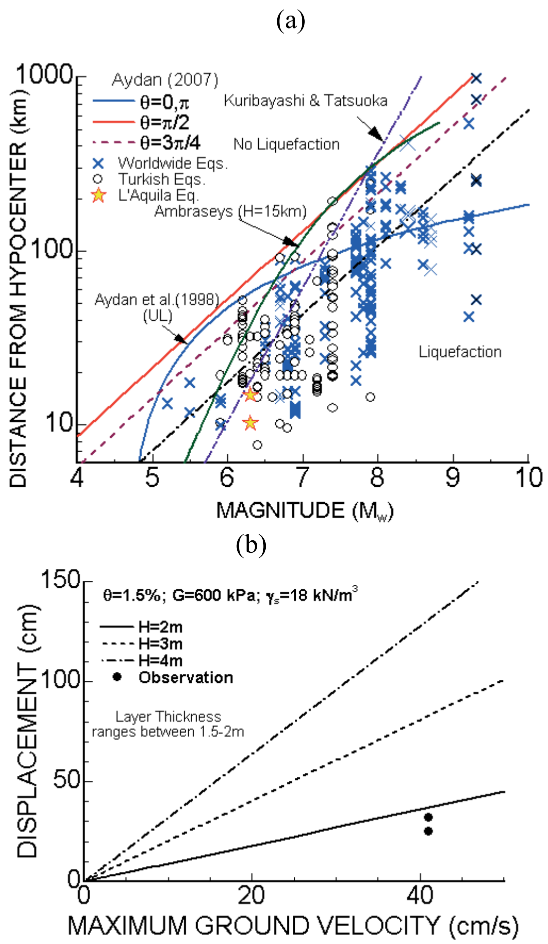


Figure 16. Comparison of observations with estimations from the method proposed by Aydan et al. (2008) based on maximum ground velocity.

Şekil 16. Gözlemlerin Aydan vd. (2008) tarafından önerilen yöntemden elde edilmiş tahminlerle karşılaştırılması.

STRUCTURAL DAMAGE

Damage to Buildings

Masonry buildings can be grouped into two; specifically, residential buildings and cultural and historical masonry buildings (Figure 17a). Residential masonry buildings are generally two story buildings and in this area they were made of stone or brick, or a mixture of stone and brick. The mortar is mud or lime. Heavily damaged or collapsed buildings had almost no tie beams. Furthermore, the mortar of these buildings was mud. The main cause of the collapse or heavy damage to masonary buildings was out-of plane failure.

Cultural and historical buildings are of a larger scale and involve domes, towers and facades. The failure mechanism of these buildings is fundamentally quite similar to that of ordinary masonry buildings. The non-existence of tie beams make these buildings quite vulnerable to heavy damage or collapse. The dome of Santa Maria del Suffragio collapsed although wooden tie beams had been used. As the wooden tie beams were not continuous over the perimetry of the dome, the effect of the earthquake was disastrous. The masonary cylindrical tower at Stefano di Sessanio, which is about 20 km from the epicenter, had completely collapsed (Figure 17b). It was important to notice that another tower of almost same height and located at the foot of the same hill survived the earthquake. This may be related to a difference in the amplification characteristics of the top and the foot of the hill, as well as to the shape and shaking characteristics of the towers.

(a)

(b)

(c)

Figure 17. (a) An example of masonry building damage, (b) views of the tower of Stefano di Sessanio before and after the earthquake, and (c) an example of heavily damaged or collapsed reinforced concrete building.

Şekil 17. (a) Yığma yapılardaki hasara bir örnek, (b) Stefano di Sessanio kulesinin depremden önceki ve sonraki görüntüleri ve (c) ağır hasara maruz kalmış betonarme bir yapıya örnek.

Many reinforced concrete (RC) buildings had either collapsed or were heavily damage by the earthquake (Figure 17c). The reasons for the heavy damage or collapse are similar to those found in Turkey (Aydan et al., 2000a, 2000b) and elsewhere. The possible reasons are poor workmanship, design and construction mistakes, resonance, lack of professional ethics, the soft floor effect and collision. It was interesting to note, in some of heavily damaged buildings, that unwashed sea sand had been used for concrete mixture even though this place is 90 km away from the sea.

Damage to Transportation Facilities

A 35 m long and 5 m wide, three-span, continuous reinforced concrete bridge had collapsed, as seen in Figure 18a. It was located at the crossing of SR261 to Fossa on the Aterno River. Four reinforced concrete columns with hexagonal sections had been broken at their column-slab connections, and had slid sideways and penetrated the deck slab. The columns had six 17 mm diameter smooth bars at each corner of the hexagonal section. 9 mm diameter smooth bars had also been used to fix the top of the columns to the reinforced concrete girders. The stir-ups were 6 mm in diameter at a spacing of 300 mm. The vertical downward motion might have played an important role in the failure of this bridge.

A 20 m long and 4 m wide three span continuous bridge just the west of Onna suffered damage at the top of its frame piers. The superstructure of the bridge was damaged by tensile cracking due to the movement of the piers towards the center of the river, caused by movements of the embankment on both sides.

A 2 m long and 2.5 m high stone masonry arch bridge had previously collapsed and was repaired by filling crashed limestone into the collapsed section. The southwest side of abutments probably moved towards the west and this movement resulted in the loss of the arching effect of this masonry arch bridge, which collapsed again during the earthquake. An additional cause for the collapse of this small bridge may be that its infill cover was thin.

A part of the viaducts of the A24 expressway near L'Aquila was affected by the earthquake, although the expressway itself did not collapse

(a)

(b)

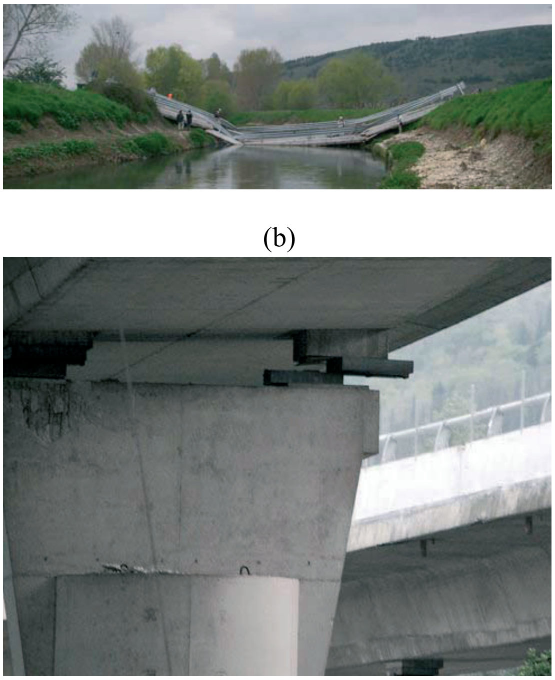


Figure 18. (a) A collapsed bridge, and (b) damage to A24 expressway.

Şekil 18. (a) Çökmüş bir köprü ve (b) A24 otoyolunda hasar.

anywhere (Figure 18b). The viaducts are simply supported PC box-girder bridges supported by reinforced concrete piers. They were supported by steel sliders and roller bearings or elastomeric bearings. The viaduct was displaced and there were gaps as large as 200 mm at numerous locations. A number of decks had drifted in the longitudinal and transverse directions. Some of these gaps were repaired by asphalt filling.

Damage to Retaining Walls

Road surface settlement occurred at a number of locations. One of the two lanes of the SS17 at the intersection with SR615 was partly restricted for traffic because the road embankment had locally subsided by 350 mm and the upper part of the stone masonry retaining wall was tilted. The tilted retaining wall was supported by a wooden support system.

Damage to Water Pipelines

Damage to pipes is generally caused by permanent ground deformation, which may result from faulting, slope failure and liquefaction-

(a)

(b)

Figure 19. (a) A pipe damaged by permanent ground movement near Onna, and (b) view of a buckled silo.

Şekil 19. (a) Onna yakınlarında kalıcı yer deformasyonu nedeniyle hasar görmüş bir boru ve (b) bükülmüş bir silodan görünüm.

induced lateral spreading. The authors observed damage to water pipes in Paganica and near Onna. (Figure 19a). The damage to water pipes in Paganica was caused by the combined effects of faulting and slope failure. Pipes were damaged due to the extensional movement of the surrounding medium. The damage to a pipe near Onna was caused by the movement of its surrounding ground towards the center of the bridge over the Aterno. The pipe was damaged on both sides of the river. Nevertheless, the movement was much larger on the eastern side of the bridge where the pipe was buckled.

Damage to Industrial Facilities

There are many industrial facilities in the area affected by the earthquake, but there was almost no damage to pre-cast industrial facility structures, which are generally vulnerable to earthquakes. The good design and construction of the beam-column joints of these pre-cast facility structures could be the main reason for their good performance and resulting undamaged state. However, 20 m high and 4 m diameter silos for storing polypropylene pellets in the VIBAC plant suffered from a severe buckling problem, as seen in Figure 19b.

There were two types of silos built at different times. The first one was a group of 8 silos founded on a common pile foundation and supported by a steel frame structure. The other group was 12 silos set in two rows on a cylindrical skirt resting on 1.2 m thick concrete slabs on pile foundations. The cylindrical skirt is fixed to the pile cap through anchor bolts. The silos were made of 6 mm thick aluminum plate. The silos that buckled were totally full during the earthquake, while those full to only 65% of their capacities did not collapse. During the earthquake, the buckled silos pounded into the adjacent warehouse. The damaged bottom skirts of the silo cones exhibited diamond-buckling modes.

CONCLUSIONS

The 2009 L'Aquila earthquake provided valuable lessons on how modern and historical buildings, bridges and other structures behave under an M_w=6.3 intra-plate basin earthquake. Historically, L'Aquila and its vicinity have been subjected to at least 8 earthquakes since the 14th century. During this most recent earthquake, extensive damage was done to the old city of L'Aquila and the towns and villages in its vicinity, including Onna, Paganica, Fossa and Ocre. The L'Aquila basin is covered by conglomeratic clayey or calcareous deposits underlaid by lacustrine clayey deposits.

The foreshock activity in the epicentral region was of great importance to the earthquake prediction. The claim of an earthquake prediction based on an observed radon anomaly by a technician associated with the Italian Physics Laboratory did not satisfy the fundamental requirements for earthquake prediction. This example clearly illustrates the fact that a multiparameter integrated scheme must be adopted for earthquake prediction.

The inferred faulting mechanism of very young faults observed in Paganica was quite similar to the faulting mechanism of the main shock and previous earthquakes. They deserve close attention in studying the faulting mechanism of potential earthquakes, and which may be of great importance for earthquake hazard assessments.

Settlements and the sliding of ground and geotechnical structures occurred at numerous locations in the lowland areas along the Aterno River, and a number of slope failures and rockfalls occurred in the mountainous regions. Two sinkholes were formed in the old city of L'Aquila.

Old unreinforced masonry buildings were extremely vulnerable to the earthquake. In particular, unreinforced masonry buildings with mud mortar suffered extensive damage. Out-of plane failure of walls was predominant in reinforced concrete frame buildings with unreinforced brick masonry walls. The reasons for the heavy damage or collapse of such buildings have a similarity with the reasons for earthquake damage seen in Turkey and elsewhere. The possible reasons are poor workmanship, design and construction mistakes, coincidence of fundamental natural periods of structures with the dominants of ground motions, a lack of ethics in the construction process, the soft floor effect and collision.

The failure mechanism of cultural and historical buildings is fundamentally quite similar to that of ordinary masonry buildings. The nonexistence of tie beams makes these buildings quite vulnerable to heavy damage and collapse. The dome of Santa Maria del Suffragio collapsed because non-continuous wooden tie beams had been used. The masonry cylindrical tower at Stefano di Sessanio, which is about 20 km from the epicenter, had completely collapsed while another tower of almost same height located at the foot of the same hill survived the earthquake. This may be related to a characteristic difference in amplification between the top and the foot of the hill, as well as to the shape and shaking characteristics of the towers. The damage done to cultural and historical buildings and structures by this earthquake may be used to re-evaluate the parameters of past seismic events.

Extensive corrosion of steel bars in reinforced concrete structural members was widely observed, not only in buildings but also in bridges. Their concrete cover was too thin to prevent corrosion.

A three-span continuous short-span bridge had collapsed, and several bridges suffered damage. At the A24 viaduct in L'Aquila, residual drift of decks and vertical gaps at expansion joints occurred due to damage to the bearings. However, damage to bridges and viaducts was generally less common.

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