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Review of the liquefaction cases triggered by the 2009 L'Aquila earthquake (Italy)

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ABSTRACT: This paper describes three cases of liquefaction triggered by the 2009 L'Aquila earthquake. The sites are located along the Aterno river banks, in alluvial soil deposits of common depositional environment, at various epicentral distances: L'Aquila – Ponte Rasarolo (1.5 km), Fossa (10 km) and Vittorito (45 km). Liquefaction analyses were carried out at each site, aimed at reproducing the observed phenomena, using simplified methods based on in situ test results. The paper illustrates comparatively the results of the liquefaction analyses at the three sites, taking into account the local soil conditions and the markedly different seismic demand.

1 INTRODUCTION

On April 6, 2009 a magnitude M_w = 6.1 earthquake heavily struck the city of L'Aquila and several villages of the middle Aterno river valley (central Italy), causing considerable damage over an area of approximately 600 km^2. The earthquake caused 309 victims, about 1,600 injured, over 65,000 homeless and huge economic losses. In addition to widespread damage to constructions, several effects on the physical environment, such as ground fractures and deformations, sinkholes, rock falls, landslides, and liquefaction, were also observed in the area (GEER Working Group 2009, Monaco et al. 2012). Among the various effects, liquefaction was definitely not a major concern. Few minor cases of liquefaction were reported, which involved mainly cultivated areas, with no significant liquefaction-induced damage to buildings, roads or pipelines. Nevertheless, there is some interest in analyzing these cases due to the lack of well documented case-histories of liquefaction in this region, which is one of the areas of highest seismic hazard in Italy. In fact, the available information is mostly based on historical description or catalogues of past earthquake-induced liquefaction evidence (e.g. Galli 2000, Fortunato et al. 2012).

Three cases of liquefaction triggered by the April 6, 2009 L'Aquila earthquake have been reported; all occurred along the Aterno river banks, in soil deposits of common depositional environment, at various epicentral distances (Figure 1): L'Aquila – Ponte Rasarolo (only 1.5 km from the epicenter), Fossa (about 10 km from the epicenter) and Vittorito (about 45 km far from the epicenter). The three cases are analyzed in this paper, as described in the following.

2 METHODS OF LIQUEFACTION ANALYSIS

2.1 *Procedure*

Liquefaction analyses were carried out in each investigated area, aimed at reproducing the liquefaction phenomena triggered by the April 6, 2009 earthquake. The analyses were

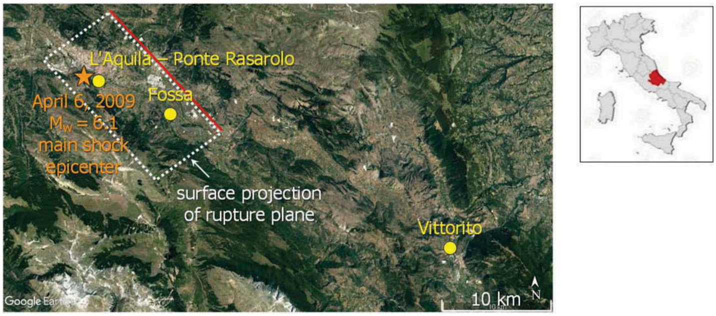

Figure 1. Location of the documented liquefaction cases induced by the April 6, 2009 earthquake.

performed by use of methods developed in the framework of the "simplified procedure" introduced by Seed & Idriss (1971), that is based on the comparison, at any depth, of the seismic demand (cyclic stress ratio *CSR*) and the capacity of the soil to resist liquefaction (cyclic resistance ratio *CRR*).

When *CSR* is greater than *CRR* liquefaction may occur. The liquefaction safety factor FS_{liq} in free field conditions at a given depth was calculated as:

$$FS_{liq} = \frac{CRR}{CSR} = \frac{CRR_{M=7.5} \cdot MSF}{CSR} \tag{1}$$

where $CRR_{M=7.5}$ is the cyclic resistance ratio for a reference magnitude M_w = 7.5 (conventionally adopted in the simplified procedure) and *MSF* is a magnitude scaling factor.

The "integral" liquefaction susceptibility at each test location was evaluated by means of the liquefaction potential index *LPI* (Iwasaki et al. 1982):

$$LPI = \int_{z=0}^{z=20m} F(z) \cdot w(z) dz \tag{2}$$

where z is the depth (in m) below the ground surface, $w(z)$ = 10 – 0.5 z is a depth weighting factor and the function $F(z)$ depends on the safety factor, according to Sonmez (2003).

In some of the cases examined in this study the in situ tests used to evaluate *CRR* and FS_{liq} did not reach the depth of 20 m, required to calculate *LPI* according to Eq. (2). In these cases *LPI* was calculated down to the maximum investigated depth, assuming that the soils below this depth could be reasonably considered as "non liquefiable".

2.2 *Evaluation of the cyclic stress ratio*

The analyses were carried out assuming the main shock recorded at 3:32 a.m. (local time) of April 6, 2009 as the event which triggered liquefaction. The magnitude of this event, initially estimated by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) as M_w = 6.3, has been later corrected into M_w = 6.1 (Scognamiglio et al. 2010). Therefore a magnitude M_w = 6.1 was assumed in this study. The location of the epicenter, which has been also adjusted by INGV after a preliminary evaluation, is about 2 km SW of L'Aquila city center (Figure 1). The hypocentral depth was estimated at about 8 km. The main shock was originated by a normal fault (Paganica) trending NW-SE for an extension of about 15 km.

According to the simplified procedure, the evaluation of the cyclic stress ratio *(CSR)* requires the determination of the maximum horizontal acceleration a_{max} induced by the earthquake at the ground surface. Despite the large amount of ground motion recordings provided by the Italian strong motion network (RAN, Rete Accelerometrica Nazionale), which are available from the Italian accelerometric archive (ITACA v 2.3, Luzi et al. 2017), the evaluation of a_{max} induced by the main shock at the three examined sites is affected by significant uncertainty. In fact, no single ground motion recording stations are located at or near these sites. Even when the site is not far from one or more stations (e.g. L'Aquila – Ponte Rasarolo), it appears problematic to extrapolate to the site the strong motion data recorded in quite different soil conditions.

Taking into account this uncertainty, in this study the seismic input was assessed by use of the ground motion prediction equation (GMPE) developed by Bindi et al. (2011) for the Italian earthquake database, considering the distance of each site from the seismogenic source of the April 6, 2009 main shock. In particular, the GMPE by Bindi et al. (2011) requires as input the Joyner-Boore distance R_{jb} which is defined as the shortest distance from the site to the surface projection of the rupture plane, and the ground type defined based on the shear wave velocity (V_S) profile. For L'Aquila – Ponte Rasarolo and Fossa, which are located in epicentral area, the Joyner-Boore distance was assumed as $R_{jb} = 0$, because both are positioned on the surface projection of the rupture plane, as identified by Ameri et al. 2012 (Figure 1). For Vittorito it was assumed $R_{jb} = 28$ km. For all three sites, based on the available V_S data, the ground type was estimated as C according to the Eurocode 8 (EN 1998-1:2004) classification. Based on the above assumptions, the values of a_{max} (as a fraction of gravity g) estimated at the three sites by use of the GMPE by Bindi et al. (2011) are respectively $a_{max} = 0.379\ g$ for L'Aquila – Ponte Rasarolo and Fossa, $a_{max} = 0.085\ g$ for Vittorito.

2.3 *Evaluation of the cyclic resistance ratio*

The cyclic resistance ratio (*CRR*) was estimated by use of empirical methods based on in-situ parameters from seismic dilatometer tests (SDMT, Marchetti et al. 2008), namely the measured shear wave velocity V_S and the horizontal stress index K_D, a parameter related to stress history obtained from DMT interpretation (Marchetti 1980). In particular, *CRR* was estimated from V_s using the correlations proposed by Andrus & Stokoe (2000) and Kayen et al. (2013), and from K_D using the correlations proposed by Monaco et al. (2005), Tsai et al. (2009), Robertson (2012) and Marchetti (2016). In the V_s-based methods, the magnitude scaling factors *MSF* were evaluated according to the specific formulations proposed by the Authors (Andrus & Stokoe 2000 and Kayen et al. 2013, respectively). In the K_D-based methods, *CSR* at each depth and *MSF* were calculated according to Idriss & Boulanger (2008). While the Vs-based methods account for different values of fine content (FC), the KD-based methods currently available are valid for clean sands (at present the *FC* correction for the CRR-K_D correlation is still under study).

3 VITTORITO SITE

The case-history of Vittorito, investigated by Monaco et al. (2011), is the best-known and documented of the three liquefaction cases triggered by the 2009 L'Aquila earthquake. Due to the relatively great distance (approximately 45 km) from the epicenter, the peak ground acceleration produced by the earthquake in this area was most likely very low, yet sufficient to trigger liquefaction. This case possibly represents a nearly borderline "lower-bound" condition for the very low seismic stress which presumably triggered liquefaction. The area where liquefaction occurred is located in the municipality of the Vittorito village, close to the right bank of the Aterno river. The area is utilized for agriculture purposes only and the ground surface is relatively flat. The ground water table is located about at 0.3-0.5 m below the ground surface. The liquefaction phenomena at Vittorito were revealed through a series of sand boils and small sand volcanoes, composed of fine-grained sand, which were detected in cultivated fields in the aftermath of the main shock. The area is geologically characterized by the presence of recent alluvial plain deposits, in particular by Holocene gravelly-sandy deposits including some silty sand. Other formations in the area are Pliocenic-Pleistocenic deposits composed by coarse-grained materials alternating with coarse debris. The area affected by liquefaction was investigated by means of two boreholes to 5 m depth, three seismic dilatometer tests (SDMT) and one cone penetration test (CPT). Details can be found in Monaco et al. (2011). The upper portion of the soil profile, which presumably originated liquefaction, is composed of a topsoil layer of ≈ 1 m thickness, followed by a sandy silt layer of ≈ 2 m thickness and by a gravel layer of ≈ 3 m thickness. The grain size distribution of the soil samples retrieved from the boreholes indicated sandy silt above ≈ 1.8 m depth, and gravelly sand below ≈ 1.8 m depth, both with relatively high uniformity coefficient. Below ≈ 6 m depth the soil is mostly fine-grained (silty clay to clayey silt, with some sand). An analysis of the liquefaction phenomena at Vittorito using simplified methods based on SDMT and CPT results was presented by Monaco et al. (2011). Since no single strong motion recording station of the RAN network was available in the proximity of Vittorito, Monaco et al. (2011) estimated the maximum horizontal acceleration at this site (a_{max} = 0.088 *g*) by comparing the ground motion recordings of the main shock at the closest RAN station (Sulmona) with the ground motion characteristics obtained by interpolating data available in the Italian earthquake database and existing GMPEs, taking into account local stratigraphic amplification.

A re-evaluation of liquefaction at the site of Vittorito based on SDMT results is illustrated in this paper. The motivations for such new analyses are mainly: (1) use of more recent methods for liquefaction assessment based on the horizontal stress index K_D (Tsai et al. 2009, Robertson 2012, Marchetti 2016), in addition to the method (Monaco et al. 2005) considered in Monaco et al. (2011); (2) revised magnitude of the April 6, 2009 main shock (M_w = 6.1 instead of 6.3). The maximum horizontal acceleration used in this study for evaluating *CSR,* estimated using the GMPE by Bindi et al. (2011) as previously discussed, is a_{max} = 0.085 *g,* i.e. very close to the value considered by Monaco et al. (2011). The results of liquefaction analyses at the location of one SDMT sounding, representative for the site conditions in the Vittorito liquefaction area, are summarized in Figure 2, which shows the profiles with depth of: (1) the material index $/_D$, obtained from DMT interpretation (Marchetti 1980), indicating soil type; (2) the SDMT parameter used in each case for evaluating *CRR,* i.e. the overburden stress-corrected shear wave velocity V_{S1} calculated from V_S (Figure 2a), or the horizontal stress index K_D (Figure 2b); (3) *CSR* compared to *CRR*; (4) the liquefaction safety factor FS_{liq}; and (5) the liquefaction potential index *LPI.* Figure 2 shows that:

a. one of the two methods based on V_S (Andrus & Stokoe 2000) indicated occurrence of liquefaction (FS_{liq} < 1) in the upper 2 m, with *LPI* estimated as “low” to “moderate”, while the other (Kayen et al. 2013) did not reveal any liquefaction;
b. all the four methods based on K_D pointed out the occurrence of liquefaction at greater depths (≈ 3 to 6 m), with “low” *LPI.* These results are in agreement with the trend reported by Monaco et al. (2011) as regards the presumed depth of liquefaction, but the estimated *LPI* is much lower.

This inconsistency is mainly due to the fact that in this study very low K_D values (K_D ≈ 0.6-0.8) found in gravel at ≈ 4.5 to 6 m depth were ignored in the analysis, as considered “unreliable”.

The discrepancy between the presumed depth of liquefaction estimated by *V*S and *K*D could be due, at least in part, to the following aspects: (1) K_D is more sensitive than V_S to near-surface overconsolidation (shallow crusts); (2) the parameter K_D is normalized to the vertical effective stress c'vc>; however all current K_D-based methods do not account for any limiting threshold value in the normalization at shallow depths, as σ'_{v0} approaches zero (like e.g. C_N for CPT).

4 L’AQUILA – PONTE RASAROLO SITE

The site of Ponte Rasarolo is located in the urban area of L’Aquila, near the banks of the Aterno river southward of the city center, at only about 1.5 km distance from the epicenter of the April 6, 2009 earthquake. Differently from Vittorito, this site was characterized by a severe acceleration field. The site is located in a narrow area, close to the railway line, mainly composed of uncultivated fields, with few rural constructions and warehouses. The ground surface is nearly flat. The groundwater table is about 3 m below the ground surface. Evidence of liquefaction at Ponte Rasarolo was first detected in post-earthquake field reconnaissance

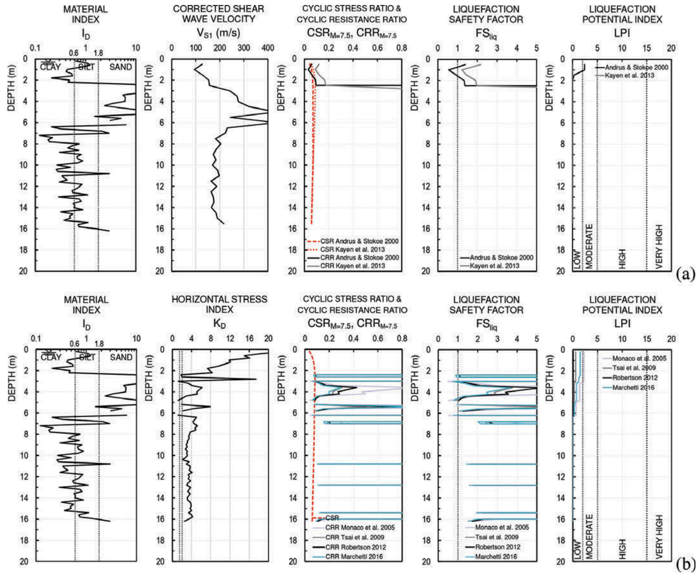

Figure 2. Vittorito – Results of the liquefaction analyses based on (a) the shear wave velocity V_S, and (b) the horizontal stress index K_D.

by Aydan et al. (2009). In this area they observed several sand boils, up to 15 cm thick, at various locations and many NESW trending fractures, parallel to the river banks, that they attributed to liquefaction. The grain size distribution of samples taken from the sand boils was found to fall within the easily-liquefiable bounds according to common classification systems (PHRI 1997). By use of empirical methods Aydan et al. (2009) estimated a thickness of the liquefied sand layer of ≈ 1.5-2 m.

The area is formed by Holocene fluvial and alluvial deposits, about 10 m thick, composed of medium to fine loose sandy gravel beds alternating with medium sands and silty sands. The recent alluvial deposits lay on the top of very thick (≈ 200 m or more), fine- to medium-grained Pleistocene fluvial and lacustrine deposits, mostly composed of sandy silts, sands and clayey silts. The carbonatic bedrock is very deep, below the Pleistocene fluvial-lacustrine deposits.

The site of Ponte Rasarolo was investigated by four SDMTs. Details can be found in Monaco et al. (2015). The soil profile is composed by a ≈ 4-5 m thick layer of loose silty sand and sand (likely liquefied), with some gravel at the bottom (≈ 4.5 to 5.5 m) characterized by very low K_D values (K_D ≈ 0.1-0.7), which were ignored in the liquefaction analyses as considered "unreliable". This shallow layer overlies a very stiff, highly overconsolidated silty clay.

Despite the presence of several strong motion recording stations of the RAN network not far from the site of Ponte Rasarolo, the evaluation of the maximum horizontal acceleration induced by the April 6, 2009 main shock is a critical issue for liquefaction assessment at this site, due to the complex geological setting of the valley. Five strong motion stations (AQG, AQA, AQV, AQM, AQK) located within less than 10 km from the epicenter, none on outcropping bedrock, recorded values of a_{max} between 0.33 *g* (AQK-WE) to 0.66 *g* (AQV-WE), indicating a significant influence of site effects related to different subsoil conditions. In this study *CSR* was calculated assuming a_{max} = 0.379 *g*, as estimated using the GMPE by Bindi et al. (2011).

The results of the liquefaction analyses at the location of one representative SDMT sounding, close to the sand boils, are summarized in Figure 3. It can be noted that:

a. the two methods based on V_S do not point out any liquefaction;
b. all the four methods based on K_D point out possible occurrence of liquefaction in the sand at ≈ 3 to 4.5 m depth, thus confirming the presumed thickness of the liquefied layer (» 1.5 m) estimated by Aydan et al. (2009). The *LPI* estimated from K_D was found "low" to "moderate".

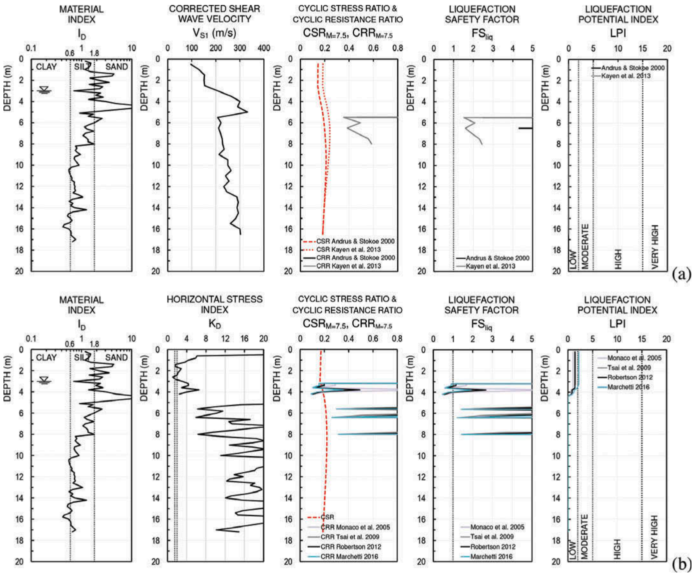

Figure 3. L'Aquila – Ponte Rasarolo – Results of the liquefaction analyses based on (a) the shear wave velocity Vs, and (b) the horizontal stress index K_D.

5 FOSSA SITE

The village of Fossa is located about 10 km far from the epicenter of the April 6, 2009 earthquake, in the Aterno river plain SE of L'Aquila. This alluvial plain, relatively large and flat, is intensely cultivated and hosts several small residential buildings. Besides the Aterno river, several canals and streams are present. The ground water table is about 2-3 m below the ground surface. The area is formed by recent alluvial deposits of variable thickness, mostly composed of fine-grained soils (silty clay to clayey silt) alternating with silty sand layers in the upper portion. Evidence of liquefaction (sand volcanoes) triggered by the April 6, 2009 earthquake in the plain near Fossa were reported by De Martini et al. (2012). These Authors investigated the liquefaction features by means of trenching and coring, as well as sedimentological analyses and dating, aimed at detecting possible paleo-liquefaction events and identifying the relation between potential shallow liquefaction sources and the sand boils at the surface. De Martini et al. (2012) reported a maximum thickness of 10 cm for the sand boils, similar to the values observed at Vittorito and Ponte Rasarolo. This observation fits well with the ≈ 1-1.5 m thickness of the potential liquefaction source found in trenching at depth. Sedimentological analyses highlighted strong similarities between the sand of the boils and the sand found below 4 m of depth, suggesting the latter being the layer that liquefied, but a different source located at depth greater than the 6.3 m reached by trenching could not be excluded.

Subsequently the area of Fossa was investigated by boreholes, piezocone tests (CPTu) and seismic dilatometer tests (SDMT) at different locations where sand boils have been observed. The results are currently under study. Figure 4 illustrates the results of preliminary liquefaction analyses at the location of one representative SDMT sounding. *CSR* was calculated assuming $a_{\max} = 0.379\ g$ (the same value used for LAquila – Ponte Rasarolo), as estimated using the GMPE by Bindi et al. (2011). Figure 4 shows that:

a. the two methods based on V_S provide liquefaction in a very thin layer at ≈ 4-4.5 m depth, with "low" *LPI*;
b. the four methods based on K_D point out possible occurrence of liquefaction at the same depth of ≈ 4-4.5 m depth, but also at greater depths (≈ 9.7-10.3 m). The *LPI* estimated from K_D was found "moderate".

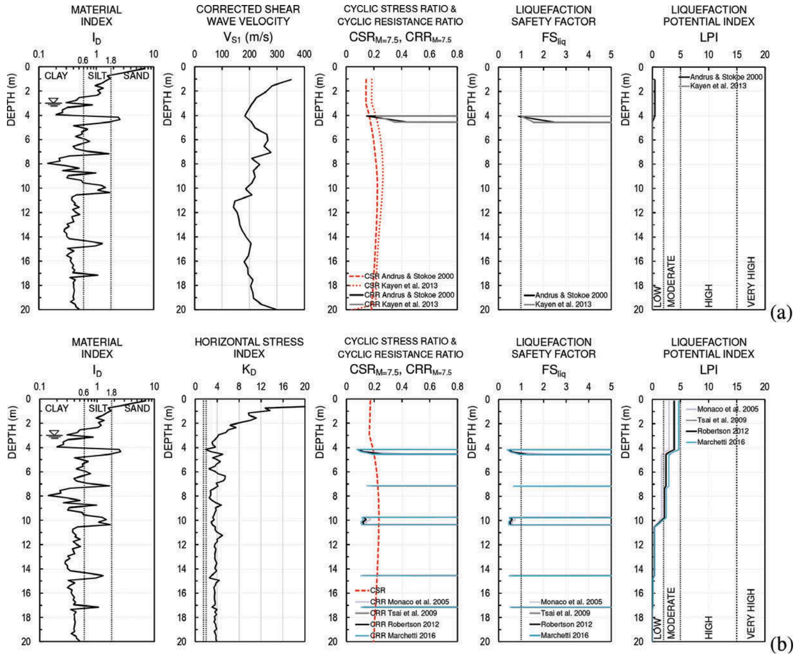

Figure 4. Fossa – Results of the liquefaction analyses based on (a) the shear wave velocity V_S, and (b) the horizontal stress index K_D.

In this case both V_S- and K_D-based methods provide liquefaction at the depth of ≈ 4 m recognized by De Martini et al. (2012) in trenching survey as probable source of liquefaction. Possibly the *LPI* estimated from K_D could be more closely related to the observed sand boil thickness.

6 CONCLUSIONS

The review of the liquefaction phenomena triggered by the 2009 L'Aquila earthquake presented in this paper may possibly contribute to enlarge the knowledge about the liquefaction case-histories in this earthquake-prone region. Despite the considerable distance, the three cases show some similarities as regards the liquefaction evidence at surface (sand boil thickness) and the common alluvial depositional environment, as well as the properties, depth and thickness of the presumed liquefied soil layer. Liquefaction occurrence is confirmed by SDMT-based analyses. In general, the methods based on V_S indicate "low" *LPI,* while the methods based on *Ko* provide "low" to "moderate" *LPI.* Further research is needed to determine more accurately the ground motion characteristics which triggered liquefaction, particularly in the epicentral area.

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