

SDMT-based Analysis of the Liquefaction Phenomena Induced by the April 6, 2009 Earthquake at Ponte Rasarolo, L'Aquila (Italy)

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ABSTRACT: This paper analyzes the liquefaction phenomena induced by the April 6, 2009 L'Aquila earthquake (Italy) at the site of Ponte Rasarolo, L'Aquila, located in the epicentral area. The site was investigated by seismic dilatometer tests (SDMT). The SDMT results were used to perform liquefaction analyses by simplified methods which derive the cyclic resistance ratio CRR from the shear wave velocity V_S (Andrus & Stokoe 2000, Kayen et al. 2013) and from the horizontal stress index K_D (Monaco et al. 2005, Tsai et al. 2009, Robertson 2012). The cyclic stress ratio CSR was estimated based on data from strong motion recordings in the area. The results of the liquefaction analyses, both based on V_S and on K_D , confirmed the occurrence of liquefaction in a loose sand layer at about 3 to 4.5 m depth.

1 INTRODUCTION

The April 6, 2009, magnitude $M_w = 6.3$ L'Aquila earthquake (central Italy) caused 309 victims, about 1,600 injured, 40,000 homeless and huge economic losses. The earthquake produced a heavy damage in the city of L'Aquila (MCS Intensity $I = VIII-IX$) and in several near villages (maximum MCS Intensity $I = IX-X$ at Onna and Castelnuovo). The main geotechnical aspects of the L'Aquila earthquake have been investigated by several researchers (see e.g. Monaco et al. 2012). A few cases of liquefaction triggered by the April 6, 2009 main shock have been reported. The most documented is the case of Vittorito, located about 45 km far from the epicentre, known as a nearly borderline "lower-bound" condition for the very low seismic stress which presumably triggered liquefaction. An analysis of the liquefaction phenomena at Vittorito based on the results of seismic dilatometer tests (SDMT) was presented by Monaco et al. (2011). Evidences of liquefaction and paleo-liquefaction near Fossa, about 10 km far from the epicentre, were reported by De Martini et al. (2012). The liquefaction phenomena analyzed in this paper occurred at the site of Ponte Rasarolo, L'Aquila, located only about 1.5 km far from the epicentre.

2 EVIDENCE OF LIQUEFACTION FROM FIELD RECONNAISSANCE

Liquefaction and lateral spreading phenomena at the site of Ponte Rasarolo were first detected by Aydan et al. (2009). During post-earthquake field reconnaissance, from April 19 to 23, 2009, in this area (called "Martini district") they observed several sand boils, up to 15 cm thick, at various locations and many NE-SE trending fractures, parallel to the river banks, attributed to liquefaction (Fig. 1). The grain size distribution of soil samples taken from the sand boils (Fig. 2) was found to fall within the easily-liquefiable bounds according to the Japan Port and Harbour Research Institute classification (PHRI 1997). By use of empirical methods, Aydan et al. (2009) estimated a thickness of the liquefied sand layer between 1.5 and 2 m.

3 BASIC GEOLOGICAL SETTING

The liquefaction site under study is located South of the hill on which the old city centre of L'Aquila was built, very close to the banks of the Aterno river, at an elevation of ≈ 614 m a.s.l.. This area is formed by Holocene gravelly-sandy alluvial deposits originated



Fig. 1. Evidence of liquefaction (sand boils, ground fractures) observed at Ponte Rasarolo in post-earthquake (April 2009) field reconnaissance (Aydan et al. 2009).

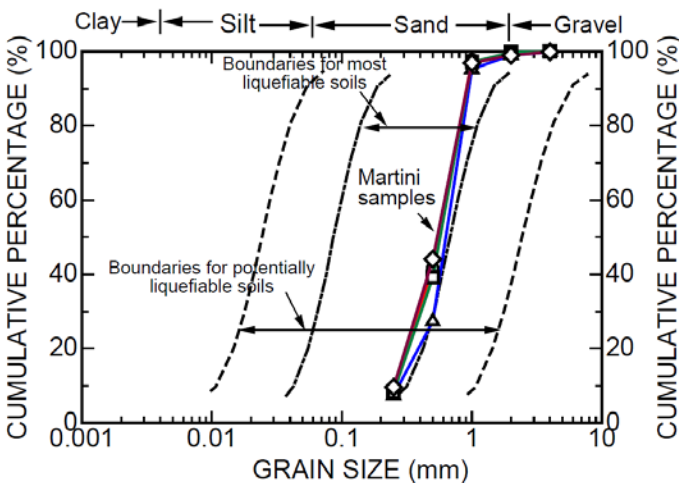


Fig. 2. Grain size distribution of boiled sand compared to easily-liquefiable bounds according to the PHRI (1997) classification (Aydan et al. 2009).

by the Aterno river, placed on the top of very thick (≈ 190 m), fine- to medium-grained, predominantly silty Pleistocene lacustrine deposits. Based on gravimetric investigations (MS–AQ Working Group 2010), confirmed directly by deep boreholes (Amoroso et al. 2010), the top surface of the bedrock (limestone) is found at an elevation of ≈ 425 m a.s.l., at the bottom of the lacustrine deposits. Further details can be found e.g. in MS–AQ Working Group (2010) and Monaco et al. (2012).

4 SDMT INVESTIGATIONS

In January 2010 the site was investigated by four seismic dilatometer tests. Despite the several months

elapsed after the earthquake, evidences of liquefaction were still clearly visible at the site (Fig. 3a). Three SDMT soundings (SDMT 1, SDMT 2 and SDMT 3) were executed just in correspondence of sand boils, and one sounding (SDMT 4) within a short distance outside the sand boils area, where apparent effects of liquefaction had not been detected. The location of the SDMT soundings is shown in Fig. 3b.

The ground surface at the site is nearly flat. The groundwater table is located at a depth of ≈ 3 m below the ground surface.

The SDMT results are shown in Fig. 4, in the form of superimposed profiles with depth of four basic parameters obtained by usual DMT interpretation (Marchetti 1980, Marchetti et al. 2001), namely the material index I_D (indicating soil type), the constrained modulus M , the undrained shear strength c_u (in clay) and the horizontal stress index K_D (related to stress history), as well as the profile of the measured shear wave velocity V_S .

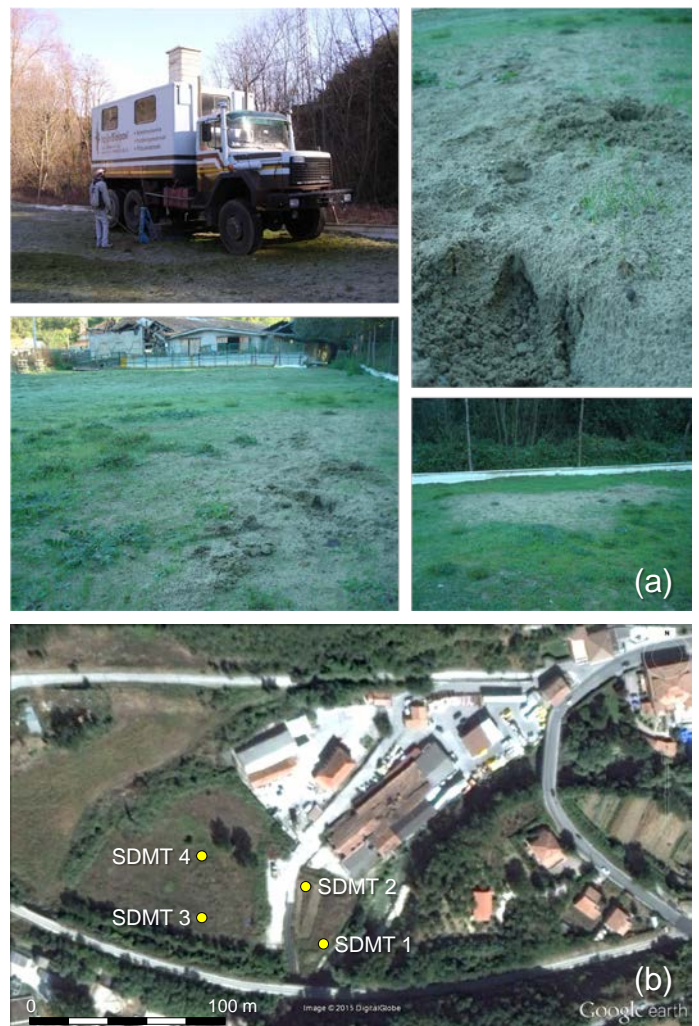


Fig. 3. SDMT investigations (January 2010). (a) Residual evidence of liquefaction. (b) Location of SDMT soundings.

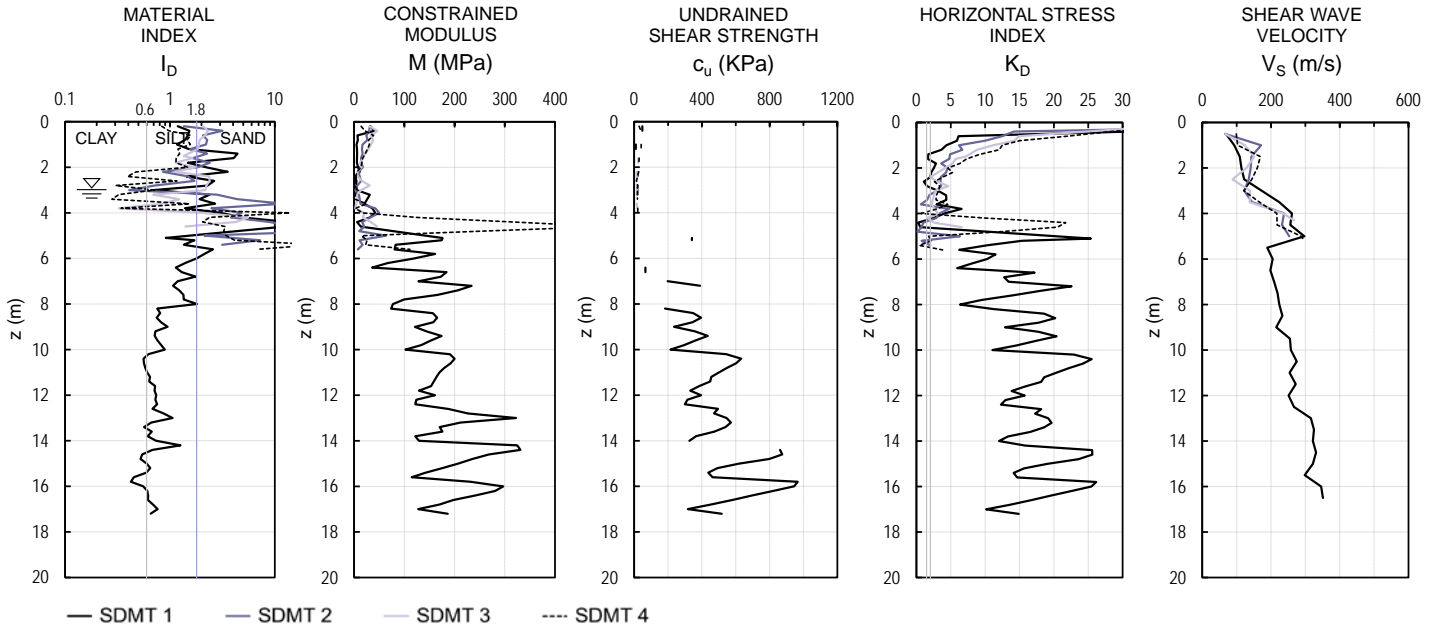


Fig. 4. SDMT results.

The SDMT results in Fig. 4 indicate that the soil profile is composed by a shallow, 4-5 m thick loose sand layer (alluvial deposits), presumed origin of the observed liquefaction, overlying a very stiff, highly overconsolidated silty clay (lacustrine deposits).

Due to the presence of gravel at the bottom of the sand layer, only one sounding (SDMT 1) could penetrate into the stiff clay layer. However in this case the maximum test depth, limited by the push capacity of the rig, was 17.20 m below the ground surface. The other three SDMT soundings only reached a depth of 4.60-5.60 m.

5 SDMT-BASED LIQUEFACTION ANALYSIS

5.1 Methods of analysis

The SDMT results were used to perform liquefaction analyses by use of empirical methods based on the shear wave velocity V_s and on the horizontal stress index K_D . Such methods were developed in the framework of the "simplified procedure" (Seed & Idriss 1971), based on the comparison, at any given depth, of the seismic demand on a soil layer generated by the earthquake (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 F_L at each depth was calculated as:

$$F_L = \frac{CRR}{CSR} = \frac{CRR_{M=7.5} \cdot MSF}{CSR} \quad (1)$$

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, introduced to account for a different earthquake magnitude.

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

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

where $w(z)$ is a depth weighting factor and the function $F(z)$ depends on the safety factor, according to Sonmez (2003).

The evaluation of I_L according to Eq. (2) requires the calculation of the liquefaction safety factor down to a depth of 20 m, which in this case was not reached by the SDMT soundings. However in this case, in order to obtain an approximate estimate of I_L , it was assumed that the stiff silty clay below the upper alluvial deposits, found in SDMT 1 at ≈ 8 m depth, could be reasonably considered as "non liquefiable".

5.2 Evaluation of the cyclic stress ratio CSR

The 2009 L'Aquila earthquake was the first well-documented earthquake instrumentally recorded in a near-fault area in Italy. The ground motion recordings provided by several stations of the Italian strong motion network (RAN, Rete Accelerometrica Nazionale), managed by the Italian Department of Civil Protection, are available on the web site of the Italian accelerometric archive ITACA 2.0 (2011) (see also Luzi et al. 2008, Pacor et al. 2011).

Five strong motion stations (AQG, AQA, AQV, AQM, AQK) are located within less than 10 km from the epicentre. All these five stations recorded values of the horizontal peak ground acceleration (*PGA*) higher than 0.35 *g* during the main shock (see e.g. Masi et al. 2011). The *PGA* recorded by the different stations varied in a wide range, from 0.33 *g* (AQK-WE) to 0.66 *g* (AQV-WE), indicating a significant influence of site effects related to different subsoil conditions (none of these stations is placed on outcropping bedrock). The closest station (AQK) is located at a distance of only ≈ 700 m from the site of Ponte Rasarolo. However at the AQK site the elevation of the ground surface is about 670 m a.s.l., i.e. ≈ 60 m higher, and the subsoil conditions are quite different, since a thick stiff layer of calcareous breccias is present above the silty lacustrine deposits. It appears then questionable to extrapolate the strong motion data recorded at AQK to the site of Ponte Rasarolo.

Hence, despite the large amount of accelerometric data, the evaluation of the seismic action induced by the main shock at the examined site is affected by significant uncertainty.

For a preliminary assessment of liquefaction occurrence, the cyclic stress ratio *CSR* at each depth was calculated as recommended by Idriss & Boulanger (2004). The horizontal peak ground acceleration (*PGA*) was estimated as:

$$PGA = S \cdot a_g = 1.33 \cdot 0.35 = 0.465g \quad (3)$$

where *S* is the soil factor, which takes into account local amplification effects, and *a_g* is the horizontal peak acceleration on outcropping bedrock.

At the site of Ponte Rasarolo site the soil factor (*S* = 1.33) was calculated according to the Italian building code (NTC 2008) for "ground type C", assuming *V_{S,30}* ("equivalent" shear wave velocity in the upper 30 m) between 180 m/s and 360 m/s, as inferred from SDMT 1. The horizontal peak acceleration on outcropping bedrock (*a_g* = 0.35 *g*) was estimated as an average of the values obtained by deconvolution of the strong motion recorded at the station AQG (a few km West) in the two horizontal directions AQG-NS and AQG-WE (Masci 2011). The same *PGA* = 0.465 *g* was obtained as mean value of the horizontal ground motion components recorded at all the five stations located in the epicentral area.

The ground water table was assumed at a depth of 3 m below the ground surface, as observed during SDMT investigations.

The values of the soil unit weight γ used in vertical stress calculation were estimated by DMT interpretation (Marchetti & Crapps 1981).

5.3 Evaluation of the cyclic resistance ratio *CRR*

The cyclic resistance ratio $CRR_{M=7.5}$ was estimated from the overburden stress-corrected shear wave velocity (*V_{SI}*) using the correlations proposed by Andrus & Stokoe (2000) and Kayen et al. (2013) for different values of the fines content (*FC*). In absence of specific data, no corrections for *FC* were applied, assuming that the "parent" sand layer has the same grain size distribution of the observed sand boils at the surface (Fig. 2), i.e. it can be considered as a "clean sand".

$CRR_{M=7.5}$ was estimated from the horizontal stress index *K_D* using the correlations proposed by Monaco et al. (2005), Tsai et al. (2009) and Robertson (2012), valid for clean sands (at present the *FC* correction for the *CRR-K_D* correlation is still under study). Very low *K_D* values (*K_D* \approx 0.1-0.7) found in gravel at \approx 4.5 to 5.5 m depth, at the base of the sand layer, were ignored in the analysis.

The magnitude scaling factors *MSF* were calculated for a moment magnitude *M_w* = 6.3, i.e. assuming the April 6, 2009 main shock as the seismic event which triggered liquefaction.

5.4 Results and comments

The results of the liquefaction analyses at the location of each SDMT sounding are summarized in Figs 5 to 8, which show, for each location, the profiles with depth of: (1) the material index *I_D*; (2) the parameter used in each case for evaluating *CRR*, *V_{SI}* (a) or *K_D* (b); (3) *CSR* compared to *CRR*; (4) the liquefaction safety factor *F_L*; and (5) the liquefaction potential index *I_L*.

The three methods based on *K_D* considered in this study provided similar results. At the locations of SDMT 1, SDMT 2 and SDMT 3, executed just in correspondence of sand boils, all the three methods signaled possible occurrence of liquefaction (*F_L* < 1) in the sand layer at \approx 3 to 4.5 m depth, thus confirming the presumed thickness of the liquefied sand layer of \approx 1.5 m estimated by Aydan et al. (2009). The same sand layer was indentified as the presumed origin of liquefaction by the methods based on *V_S*.

The liquefaction potential index *I_L* estimated from *K_D* by different methods was generally found "moderate", ranging from *I_L* \approx 2-3 (SDMT 1, SDMT 2) to *I_L* \approx 4-5 (SDMT 3). The analyses based on *V_S* provided "low" to "moderate" *I_L* values, ranging from *I_L* \approx 1-2 (SDMT 1, SDMT 2) to *I_L* \approx 3-4 (SDMT 3).

At the location of SDMT 4, where apparent surface evidence of liquefaction had not been detected, the methods based on *K_D* indicated

marginal liquefaction in a thin sand layer at ≈ 5 m depth (possibly too thin/deep to originate sand boils at the ground surface), while no liquefaction was detected by V_S .

The $CSR-K_D$ data pairs obtained at Ponte Rasarolo from SDMT 1, SDMT 2 and SDMT 3, as average of the CSR and K_D values in the presumably liquefied sand layer, are plotted in Fig. 9, compared to the $CRR-K_D$ boundary curves (Monaco et al. 2005, Tsai et al. 2009, Robertson 2012) which separate "liquefaction" and "no liquefaction". Since such boundary curves refer to a magnitude $M_w = 7.5$, the CSR values were divided by the magnitude scaling factor MSF for a consistent comparison. Fig. 9 shows that all the data points plot above the $CRR-K_D$ curves, in agreement with field performance.

6 CONCLUSIONS

The SDMT permits to obtain two parallel independent estimates of CRR , one from the shear wave velocity V_S (measured) and the other from the horizontal stress index K_D (obtained from usual DMT interpretation), by use of empirical methods developed in the framework of the "simplified procedure".

The results of SDMT investigations carried out at the site of Ponte Rasarolo (L'Aquila), presented in this paper, were used to tentatively back-analyze the liquefaction phenomena observed at this site after the April 6, 2009 earthquake. The liquefaction analyses carried out using simplified methods based on both V_S and K_D confirmed that moderate liquefaction phenomena may have been plausibly

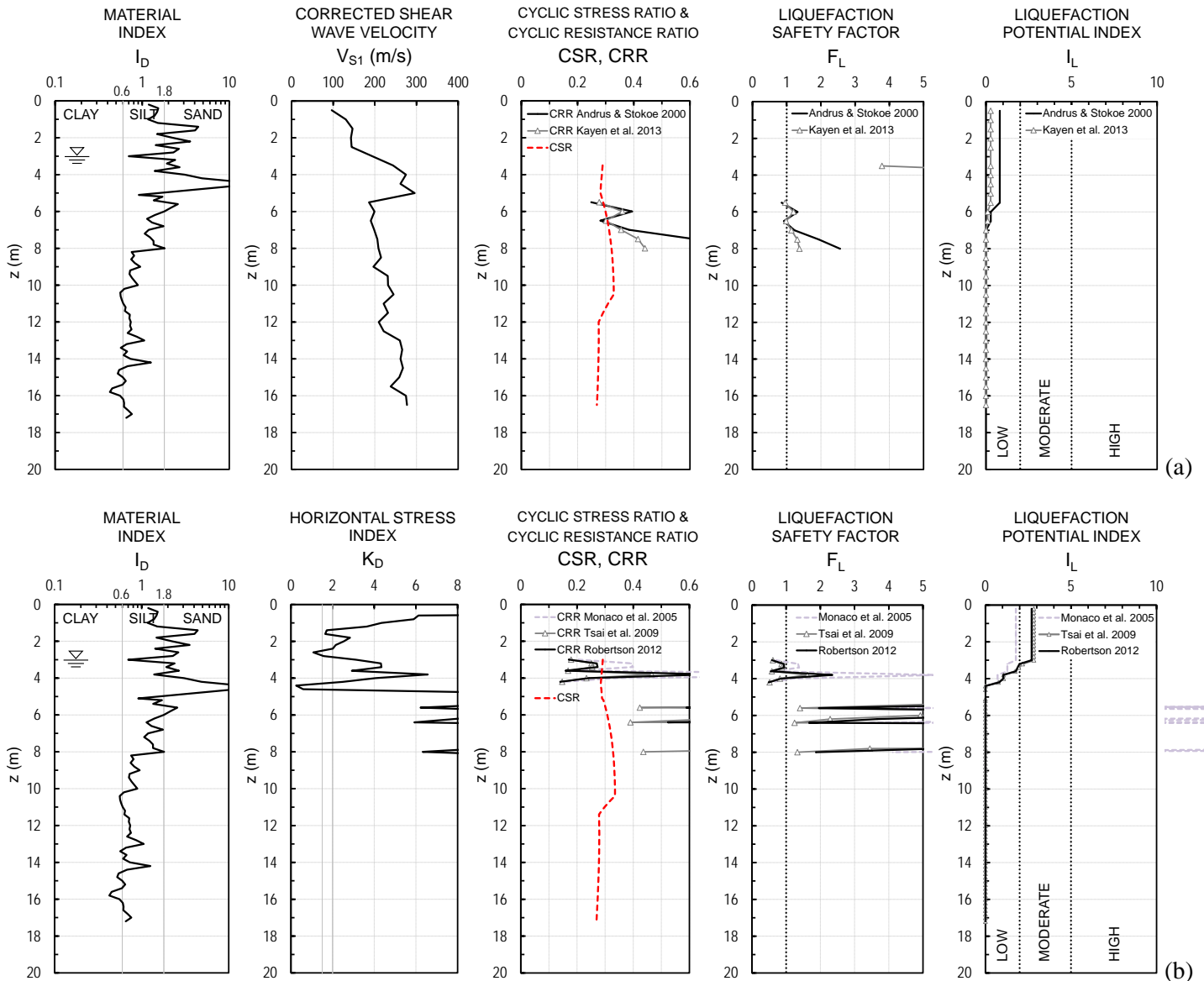


Fig. 5. SDMT 1. Results of the liquefaction analyses based on (a) the shear wave velocity V_S , and (b) the horizontal stress index K_D .

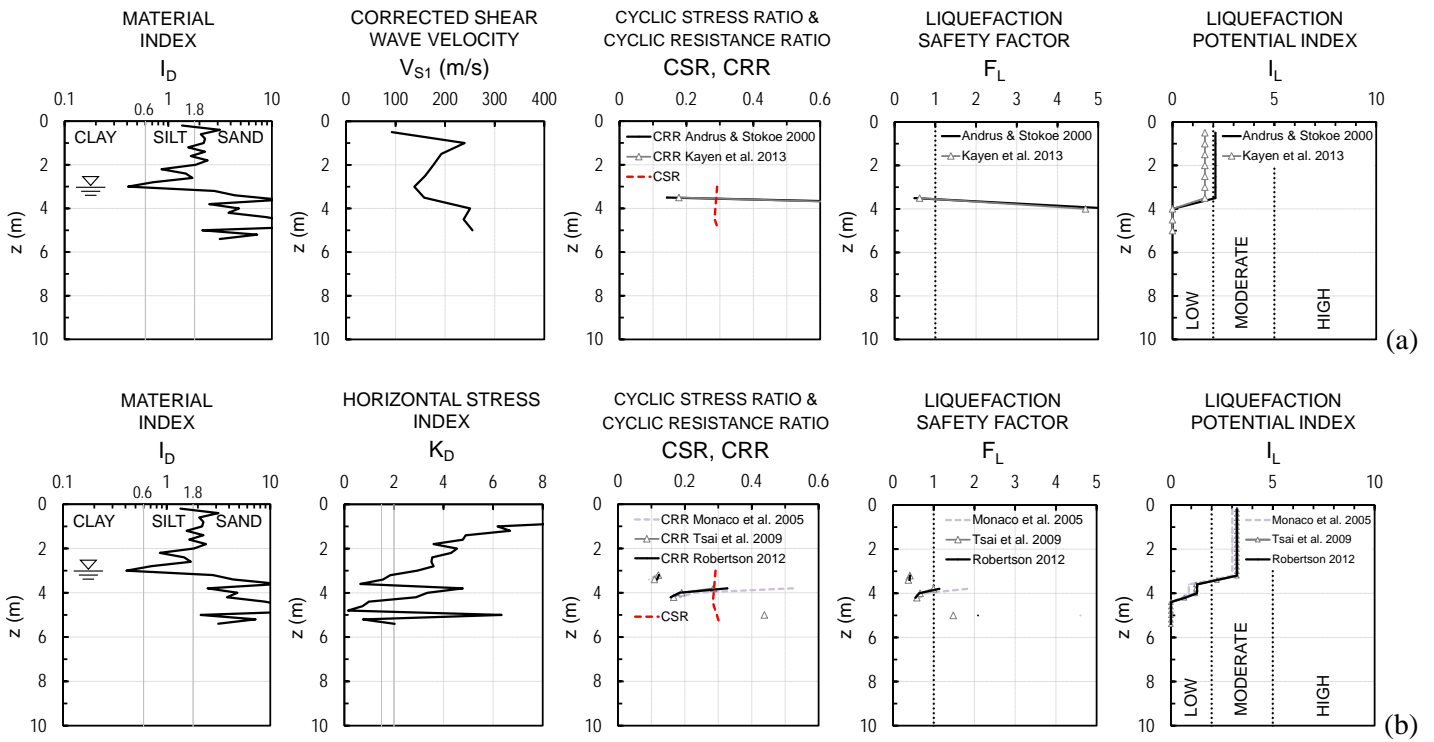


Fig. 6. SDMT 2. Results of the liquefaction analyses based on (a) the shear wave velocity V_S , and (b) the horizontal stress index K_D .

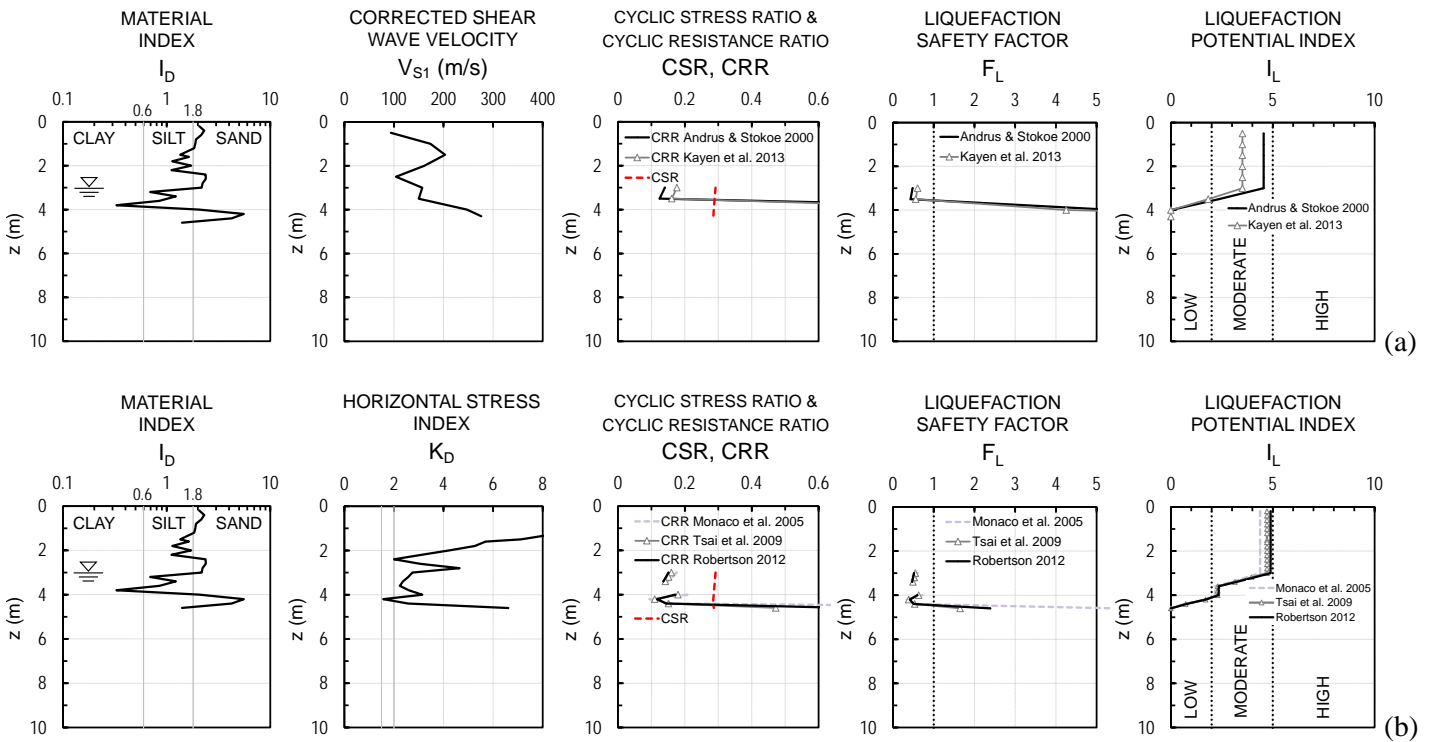


Fig. 7. SDMT 3. Results of the liquefaction analyses based on (a) the shear wave velocity V_S , and (b) the horizontal stress index K_D .

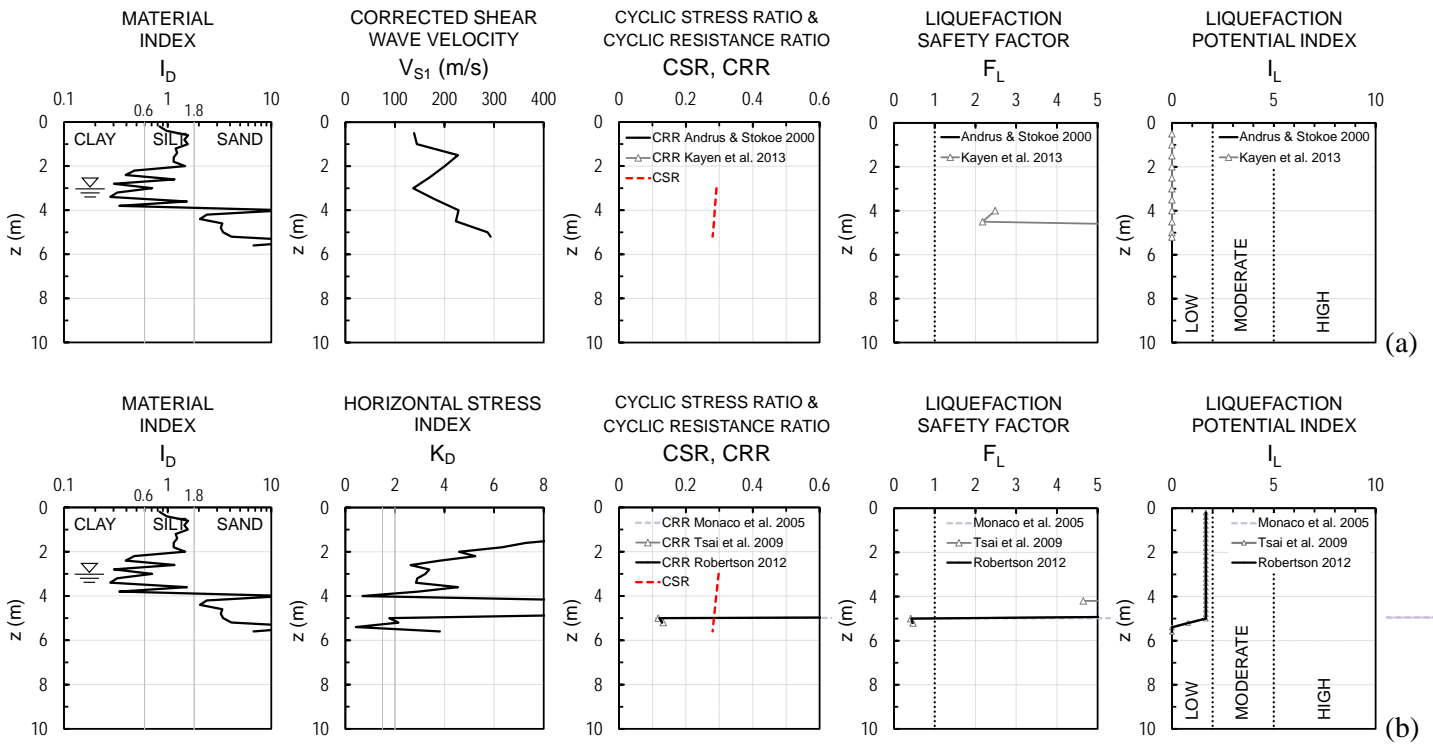


Fig. 8. SDMT 4. Results of the liquefaction analyses based on (a) the shear wave velocity V_S , and (b) the horizontal stress index K_D .

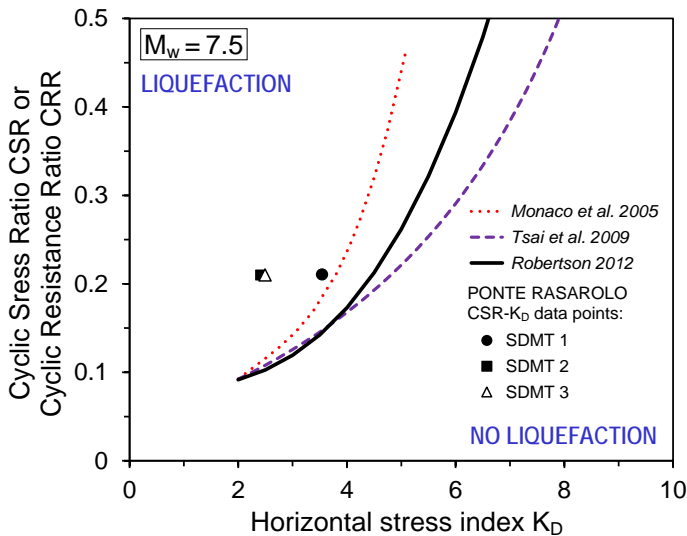


Fig. 9. Comparison of CSR/MSF vs. K_D values in the presumably liquefied sand layer and $CRR_{M=7.5}$ vs. K_D curves for clean sand proposed by Monaco et al. (2005), Tsai et al. (2009) and Robertson (2012).

induced by the April 6, 2009 main shock in a loose sand layer at about 3 to 4.5 m depth.

At the site of Ponte Rasarolo the methods based on V_S and K_D provided similar results, differently from many other cases (see e.g. Maugeri & Monaco 2006) where the CRR evaluated from V_S and from K_D were found substantially different.

As well known, the database for assessing liquefaction from the DMT horizontal stress index K_D is relatively small and additional results from

field test sites are necessary to improve the reliability of the procedure.

The additional field performance data obtained at Ponte Rasarolo, summarized in Fig. 9, could possibly be added to the database for liquefaction assessment using the DMT- K_D (for clean sands). It should be reminded, however, that these data rely on a preliminary simplified assessment of the seismic action (cyclic stress ratio CSR) which triggered liquefaction during the April 6, 2009 earthquake. Further ongoing research, including additional site investigations and numerical site seismic response analyses based on an accurate definition of the subsoil model, the dynamic soil properties and the input earthquake data, will provide a more sound estimate of CSR .

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