Preliminary Liquefaction Studies for Seismic Microzonation of Avezzano, Italy

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ABSTRACT: An extensive geological, geotechnical and geophysical investigation was undertaken for the seismic microzonation of Avezzano, the main town of Fucino plain (L'Aquila province, Italy). Here, during the 1915 Fucino earthquake evidences of liquefaction were detected. The present study focuses on the liquefaction hazard assessment based on in-situ tests like piezocone (CPTu), dynamic penetration (standard SPT and super heavy DPSH tests), and seismic dilatomer SDMT tests. Results at the test site of Pozzone area have been reported and discussed hereafter. Preliminary results of liquefaction analyses carried out using simplified methods are illustrated, compared and discussed throughout the paper. According to these first outcomes, the SDMT and CPTu investigation methods show similar values of liquefaction susceptibility.

1 INTRODUCTION

The 2012 Emilia Romagna earthquake evidenced the liquefaction susceptibility of those silty and sandy soils that commonly characterize not only the Po river plain but also many alluvial basins spread out along the Italian Peninsula that were formed by extensional tectonics or fluvial erosion. One of these basins is the Fucino plain where an extensive geological, geotechnical and geophysical investigation was committed for the seismic microzonation of Avezzano, the main town of Fucino plain located in central Italy. In particular, areas, where evidence of liquefaction were recorded during the 1915 Fucino earthquake (Galli 2000, Prestininzi & Romeo 2000), were detected to proceed with liquefaction potential evaluation.

In this respect, this paper analyses and compares the results from tests carried out in the Pozzone area by using different geotechnical and geophysical methods: seismic dilatometer (SDMT), piezocone (CPTu), dynamic super heavy penetration (DPSH) tests and seismic noise measurements. The shear wave velocity V_S was acquired by SDMT measurements, considering two symmetrical positions of the shear wave source at the surface in order to confirm the reliability of the "true interval" test configuration.

Preliminary evaluations of the safety factor against liquefaction and the liquefaction potential based on SDMT, CPTu and DPSH are illustrated, compared and discussed throughout the paper.

2 GEOLOGICAL SETTING

The Pozzone site is located in the northern side of the Fucino lacustrine basin. The basin was formed during the Quaternary, due to the activity of two important systems of normal faults. The main fault system dips to the SW and borders the basin to the East. The second fault system dips to the SSE and borders the basin to the North (Cavinato et al. 2002).

The main SW-dipping normal fault system is presently active and was activated by the large (M 7.0) January 13, 1915 earthquake. The Pozzone site is located close to the northern fault system. Four main geo-lithological domains can be identified within the Fucino basin:

1. Meso-Cenozoic calcareous or siliciclastic bedrocks, cropping out at the margins of the basin and buried below a thick cover of continental Quaternary deposits within the basin;
2. Lower-to-Middle Pleistocene slope-derived breccia, fluvial and marginal lacustrine deposits cropping out mostly along the northern slopes;
3. Upper Pleistocene alluvial fans interfingering with coeval lacustrine deposits at the rims of the basin;
4. open lacustrine deposits in the most central part of the basin, which hosted an old lake until its complete drainage at the end of 19^{th} century.

In particular, the Pozzone site is located in the 4^{th} domain, close to the transition to the 3^{rd} domain. The outcropping sediments are lacustrine deposits of latest Pleistocene-Holocene age (Lac3 in Fig. 1). Typically, the Lac3 unit is formed by grey-blue clayey silt passing upwards to light coloured silt and sandy silt, with interstratified sand and peat. The Lac3 unit overlies a thick pile of fine-grained sediments which, according to borehole and seismic reflection data, are up to 200-250 m thick (Boncio et al. 2014, Cavinato et al. 2002). The detailed shallow subsurface stratigraphy of the Pozzone site is poorly known. Only very synthetic logs of wells drilled during the ‘50s for hydrogeological exploration/exploitation are available (Fig. 1).

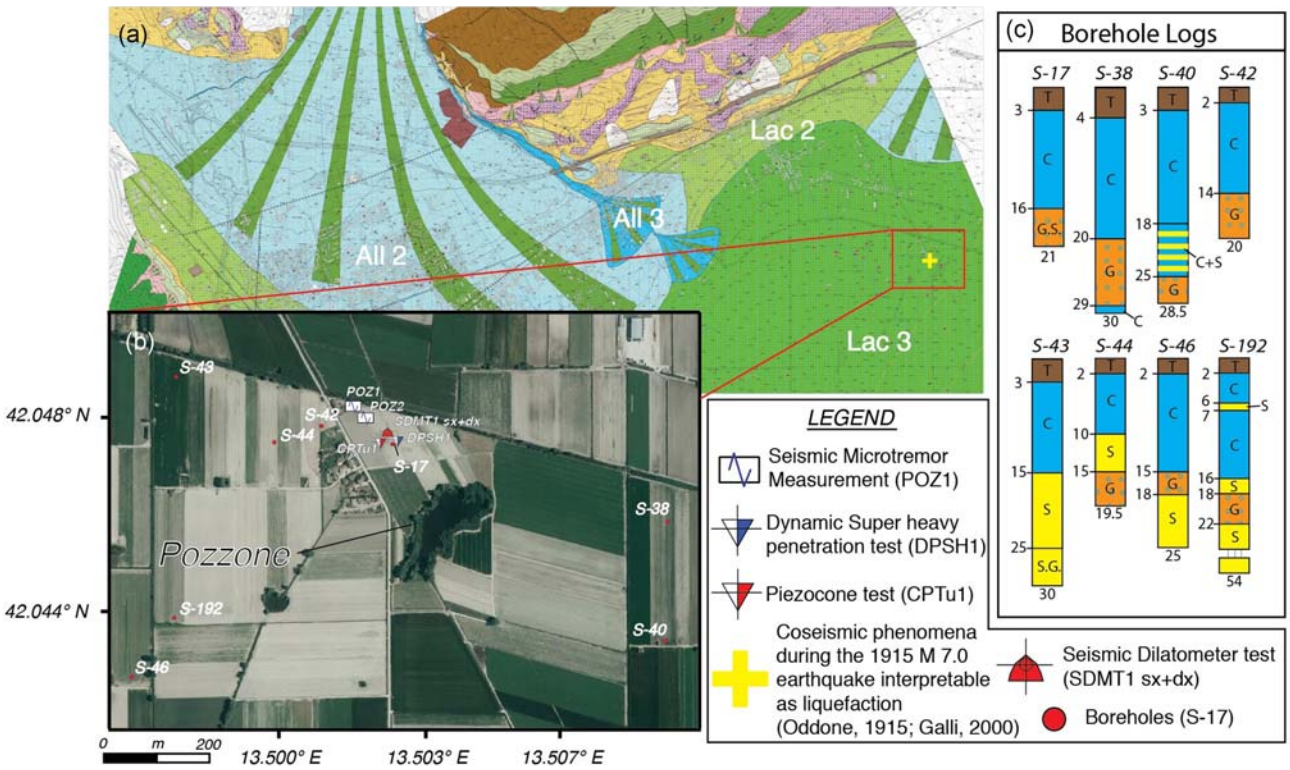


Fig. 1. (a) Geological map of the Pozzone area (Boncio et al. 2014): All2, All3= alluvial and fluvio-glacial deposits (Late Pleistocene-Holocene), Lac2 e Lac3=lacustrine deposits (Late Pleistocene-Holocene); (b) location of the geotechnical and geophysical investigations; (c) boreholes logs: T = topsoil, C = clay, S = sand, G = gravel in confined aquifer , C+S = clay with levels of sand, S.G. = sand and gravel, G.S. = gravel and sand in confined aquifer.

The top 10-15 m depths are dominated by pelitic sediments (prevailing clay, according to borehole logs). Below 10-15 m depths, there are bodies of coarse-grained sediments the lateral continuity of which is difficult to establish (sand, sand and clay, sand and gravel or gravel). The site is characterized by the presence of small permanent lakes interpreted as sinkholes (Nisio et al. 2007). After the 1915 earthquake, Oddone (1915) documented a number of phenomena, such as: a) ground fracturing; b) the disappearance of a small island within the largest of the Pozzone lakes; c) variations of the water level within the lakes; d) a long-lasting turbidity; and e) the tilting of a building, accompanied by the appearance of loose soil, in a site located ~1.3 km SE of Pozzone. All these phenomena collectively suggest the occurrence of liquefaction processes.

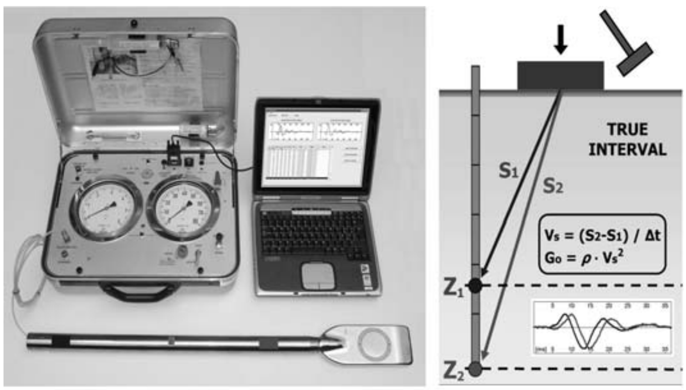
3 GEOTECHNICAL AND GEOPHYSICAL INVESTIGATIONS

At Pozzone several boreholes, 20-54 m depth, were available from the seismic microzonation of Avezzano (Boncio et al. 2014), the closest city to the studied area (Fig. 1), while other site investigation were not detected. In this respect, the geotechnical and geophysical characterization was completed performing a seismic dilatometer test (SDMT1 sx+dx), a piezocone test (CPTu1), a dynamic super heavy penetration test (DPSH1), and seismic noise measurements (POZ1, POZ2), as shown in Fig. 1. A 20 ton light penetrometer was used to push SDMT, CPTu, and DPSH equipment.

3.1 *Seismic dilatometer test (SDMT)*

The SDMT is the combination of the flat dilatometer (Marchetti 1980, Marchetti et al. 2001) with an add-on seismic module for the measurement of the shear wave velocity (Marchetti et al. 2008).

The seismic module (Fig. 2) is a cylindrical element placed above the DMT blade, equipped with two receivers located at 0.5 m distance. When a shear wave is generated at surface, it reaches first the upper receiver, then, after a delay, the lower receiver. The seismograms acquired by the two receivers, amplified and digitized at depth, are transmitted to a PC at the surface, that determines the delay. *Vs* is obtained (Fig. 2b) as the ratio between the difference in distance between the source and the two receivers (S2 - S1) and the delay from the first to the second receiver (*Δt*). The true-interval test configuration with two receivers avoids possible inaccuracy in the determination of the "zero time" at the hammer impact, sometimes observed in the pseudo-interval one-receiver configuration.



(a) (b)

Fig. 2. SDMT test: (a) Equipment; (b) Schematic layout.

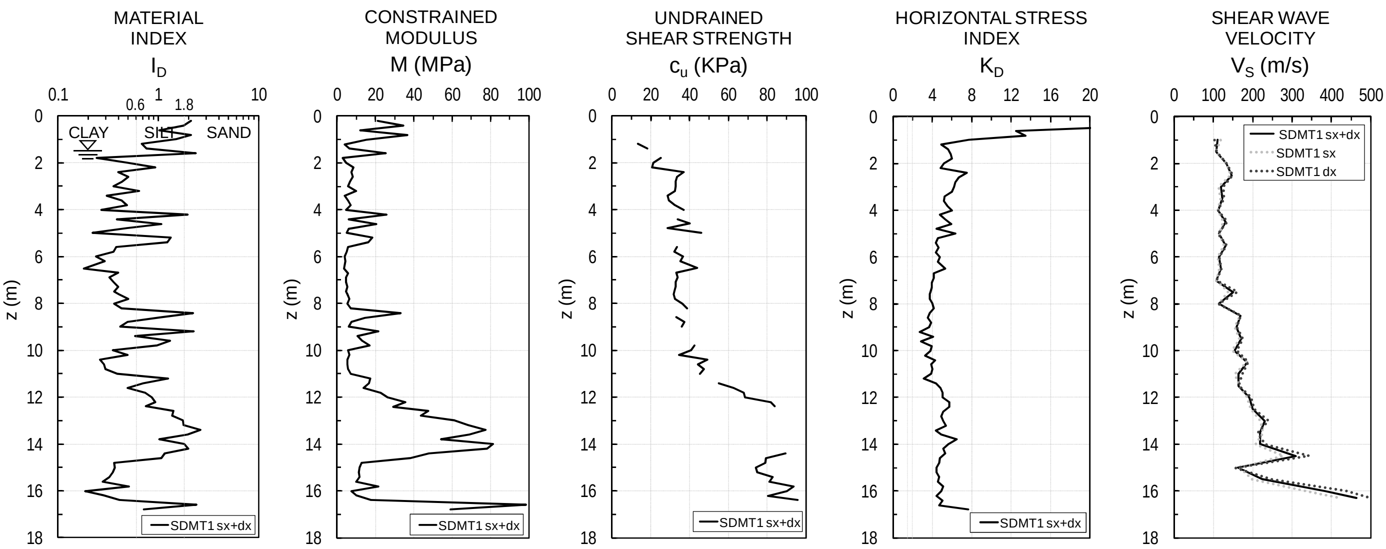


Fig. 3. SDMT results at Pozzone test site.

Moreover, the couple of seismograms recorded by the two receivers at a given test depth corresponds to the same hammer blow. The repeatability of the V_S measurements is remarkable (observed V_S repeatability ≈ 1 %, i.e. a few m/s).

At the Pozzone test site two shear wave sources in a symmetrical configuration (hammer blows strucking the anvil on two opposite sides) were used in order to produce two SH seismic wave trains with opposite polarities (SDMT1 sx and SDMT1 dx). Fig. 3 summarizes the profiles with depth of the SDMT parameters, in terms of material index I_D (indicating soil type), constrained modulus M, undrained shear strenght c_u, and horizontal stress index K_D (related to stress history/OCR), obtained using common DMT interpretation formulae (Marchetti 1980, Marchetti et al. 2001), as well as shear wave velocity V_S. SDMT1 sx+dx test reached 16.80 m depth, where the test was stopped due to the presence of a gravelly layer. The ground water level was detected at 1.70 m depth by means of the C-readings (see Marchetti et al. 2001), additional DMT measurements which were acquired only in sandy layers (8.4 m, 13.4 m, and 16.6 m depth). According to the lithological classification performed by use of the DMT material index I_D, the Pozzone site is characterized by the succession of silty clays with a consistent lens of silty sand (i.e. $I_D > 1.2$) at 12.60-14.40 m depth. These lithologies are also confirmed by CPTu1 and DPSH1 tests, and approximately by the previous boreholes (i.e. S-17 in Fig. 1).

The V_S profiles obtained strucking the beam only at the left end (SDMT1 sx), at the right end (SDMT1 dx) and from the average of the two seismic wave trains (SDMT1 sx+dx) are nearly coincident (Fig. 3). The average relative error estimated comparing SDMT1 sx or SDMT1 dx with SDMT1 sx+dx is roughly 4 %. Such low uncertainty supports the use of a "true interval" configuration, strucking the shear beam only at one end, in current practice.

3.2 *Piezocone test (CPTu) and Dynamic super heavy penetration test (DPSH)*

At the Pozzone test site a CPTu and a DPSH were executed to calculate the liquefaction safety factor (F_L) and the liquefaction potential index (I_L) (Fig. 1). As shown in Fig. 4, both profiles evidence the increase in mechanical resistance and deformability of the soil succession. This is especially true starting from about 12 m depth according to M, c_u and V_S obtained by SDMT (Fig. 3). In order to derive liquefaction parameters from CPTu, the CSR/CRR vs the normalised tip resistance q_{c1n} plot by Robertson & Wride (1997) was used. For lithological classification Robertson (1990) was introduced. In the case of dynamic super heavy penetration tests F_L cannot be evaluated directly, but through converting the blow count number for a 20 cm penetration N into the standard penetration one N_{SPT} (blows/30 cm). The theoretical energy conversion coefficient β_t between the DPSH and the SPT is in this case equal to 1.49, calculated as the ratio of the energy of two equipments. It was at first applied throughout the Fucino area failing the correspondence with N_{SPT} direct measures. Unfortunately, at Pozzone test site, no SPT tests were performed. Hence, site specific energy conversion factors have been calculated at Fucino basin for different lithologies and for the two cases of saturated and non saturated soils (Tables 1, 2).

Table 1. Energy conversion coefficient for converting the blow count number from DPSH to SPT for saturated soils.

Saturated soil	*N (blows/20 cm)*	*N_{SPT} (blows/30 cm)*	β_t
Gravel	> 28	> 46	1.6
Sand	$5 < N < 6$	$28 < N_{SPT} < 29$	5.2
Silt	13	33	2.5
Clay	< 5	< 22	4.4

Table 2. Energy conversion coefficient for converting the blow count number from DPSH to SPT for unsaturated soils.

Unsaturated soil	*N (blows/20 cm)*	*N_{SPT} (blows/30 cm)*	β_t
Gravel	> 30	$44 < N_{SPT} < 54$	1.6
Sand	$6 < N < 9$	$23 < N_{SPT} < 30$	3.6
Silt	13	38	1.6
Clay	< 5	< 22	4.4

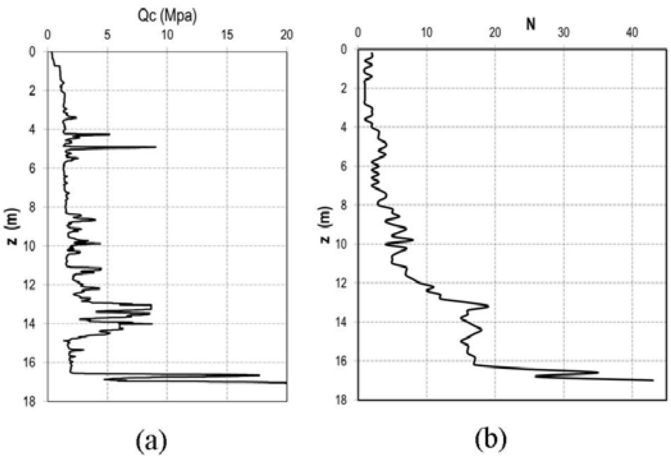


Fig. 4. Pozzone test site: (a) tip resistance profile Q_c from CPTu1; (b) blow count number N (blows/20 cm) profile from DPSH1.

3.3 *Noise measurements*

Seismic noise measurements can provide useful information concerning the seismic response of an area. In particular, single station noise measurement may be used to compute the horizontal-to-vertical spectral ratio (HVNSR). The peak of HVNSR function identifies the fundamental resonance frequency (f_0) of the subsoil that is, in turn, related to the thickness of the soft sediment overlaying the bedrock and the shear-wave velocity structure of the investigated site. Therefore, the results of these investigations allow the detection of possible impedance contrasts in the subsoil, which could be associated, in a 1D assumption, to the overlapping of two or more geologic strata with different geotechnical behavior. To verify this hypothesis, in the test site two seismic stations (POZ1, POZ2, see Fig. 1) have been installed within a range of 50 m along the direction of the supposed lateral variation of soil properties (Boncio et al. 2014). These seismic stations were equipped with MarsLite digitizer and Lennartz 3d/5s velocimeter, with timing warranted by GPS devices.

Synchronous seismic signals of 1 hour time length have been processed with an antitrigger algorithm (Sesame Project) to remove windows containing disturbs and transient signals with high energy. The Fourier spectra were smoothed with a Konno and Ohmachi (1998) algorithm, and HVNSR were calculated as the geometrical mean of the Fourier spectra of horizontal components.

The HVNSR functions obtained at the two stations show the same results in terms of resonance frequency peak, f_0 = 2.6 Hz and amplitude levels of 3.2 (Fig. 5a), therefore the mono-dimensional hypothesis seems to be verified. Hereinafter, for further analysis, data with better quality and longer duration has been considered.

An additional contribution to the analysis can be provided by the inversion of the ellipticity curve obtained as the result of the seismic noise analysis by using the tool dinver provided by Geopsy package. The important assumption of this technique is that the analyzed wavefield is mainly characterized by Rayleigh waves. In this analysis the portion of the HVNSR curve between the main peak and the trough is considered as the expression of the fundamental mode Rayleigh waves ellipticity.

As starting model of the inversion it was considered the V_S profile obtained from the SDMT test. As constrain for the deep subsoil structure, it was considered the general stratigraphy of the site inferred from the borehole data available in the area (Fig. 1). A good fit was obtained between experimental and computed ellipticity curves (Fig. 5b). The obtained V_S profiles show a main impedance contrast between 40 and 45 m and the presence of an intermediate layer between 16 and 40 m with constant V_S of 380 m/s. This result suggests that the impedance contrast between the silty clay and the gravel layers found at the bottom (16.80 meters below the ground level) of the SDMT test (see Section 3.1) seems not to be responsible for the resonance peak obtained from the geophysical measurements.

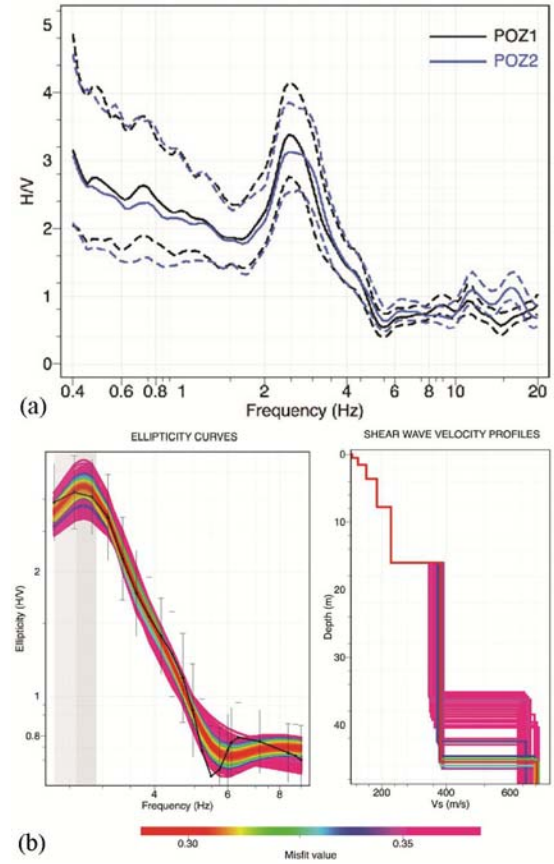


Fig.5. Pozzone site: (a) HVNSR curves for the two measurements POZ1 and POZ2; (b) results of the ellipticity inversion: on the left ellipticity curves (multi-coloured curve) plotted with the HVNSR curve (black line), on the right V_S profiles obtained as result of the inversion process.

4 LIQUEFACTION ANALYSIS

The liquefaction analysis was carried out according to the "simplified procedure" introduced by Seed & Idriss (1971), based on the comparison 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*). Indeed, the liquefaction safety factor F_L was defined as the ratio between *CRR* and *CSR*.

In addition, according to Iwasaki et al. (1982) the liquefaction potential index I_L was introduced to estimate the liquefaction sucebptibility for the whole soil profile.

4.1 *Evaluation of the cyclic stress ratio (CSR)*

The cyclic stress ratio CSR was estimated by Seed & Idriss (1971) formulation, evaluating the Magnitude

Scaling Factor *MSF* and the shear stress reduction coefficient r_d according to Idriss (1999).

For a preliminary assessment, the value of the peak ground acceleration *PGA* at the ground surface was assumed equal to 0.341 g. This value was obtained by the product of the design peak ground acceleration a_g for stiff ground (type "A") and a soil factor *S*, which depends on the subsoil stiffness, namely the stratigraphic amplification factor S_S, and on the topography, defined by the topographic amplification factor S_T, according to the Italian Building Code (NTC 2008).

At Pozzone test site a_g was assumed equal to 0.255 g; this value corresponds to a design earthquake for a return period T_R = 475 years, as reported by the Italian Seismic Hazard Maps (Meletti & Montaldo 2007). S_S was estimated equal to 1.339 considering ground type "C", as indicated by the V_S profile (Fig. 3), and S_T was evaluated equal to 1 identifying Pozzone in a flat area. A magnitude scaling factor *MSF* = 1.14 was applied for the magnitude M_w = 7.06, introduced considering the 923 seismogenetic zone, valid for Fucino plain according to Gruppo di Lavoro MPS (2004) .

4.2 *Evaluation of the cyclic resistance ratio (CRR)*

4.2.1 *SDMT simplified method*

The cyclic resistance ratio *CRR* by SDMT results was evaluated considering two parallel independent estimates, at each depth, from the shear wave velocity V_S (measured) and from the horizontal stress index K_D (provided by current DMT interpretation).

CRR was evaluated from V_S using the correlation proposed by Andrus & Stokoe (2000).

Various *CRR*-K_D correlations have been developed in the last two decades, stimulated by the recognized sensitivity of K_D to a number of factors which are known to increase liquefaction resistance, such as stress history, prestraining/aging, cementation, structure, and by its correlation with relative density and state parameter (see e.g. Monaco et al. 2005). Three recent *CRR*-K_D correlations (Monaco et al. 2005, Tsai et al. 2009, Robertson 2012) were used in this study. All three correlations were derived by translating current methods based on CPT (and SPT), supported by extensive case history databases, but using different approaches, e.g. using relative density as an intermediate parameter (Monaco et al. 2005) or direct correlations q_c -K_D established between the results of adjacent CPT-DMT tests (Tsai et al. 2009, Robertson 2012).

For SDMT1 sx+dx Figs 6 and 7 show the profiles with depth of: the DMT material index I_D, the parameter used for evaluating *CRR* (shear wave velocity V_S, Fig. 6, or horizontal stress index K_D, Fig. 7), the cyclic stress ratio *CSR* (divided by the magnitude scaling factor *MSF*) compared to the cyclic resistance ratio *CRR*, the liquefaction safety factor F_L, and the liquefaction potential index I_L.

The most evident feature emerging from the comparison of the profiles of F_L and I_L obtained by different methods is that *CRR*-V_S and *CRR*-K_D correlations provide different results. In particular, *CRR*-K_D methods detect the consistent lens of silty sand (12.60-14.40 m depth) as marginally liquefiable, in agreement with CPTu results (see 4.2.2 paragraph), while the *CRR*-V_S method indicates liquefiability only of the shallower layers.

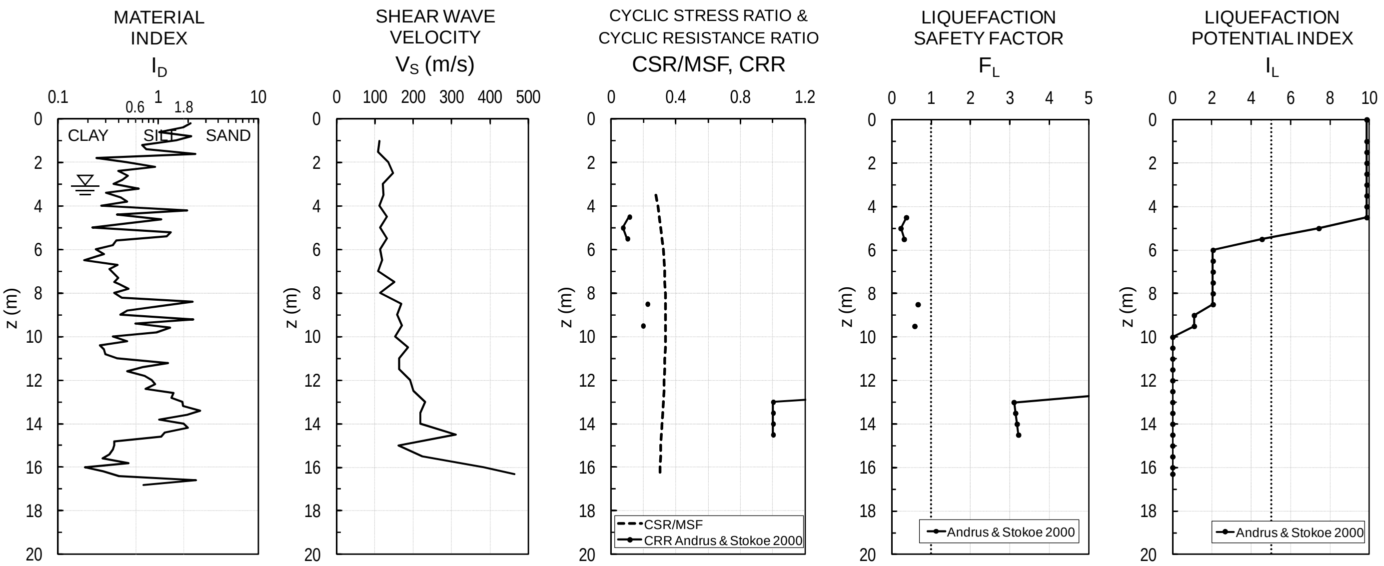


Fig. 6. Results of liquefaction analysis based on the shear wave velocity V_S at Pozzone test site.

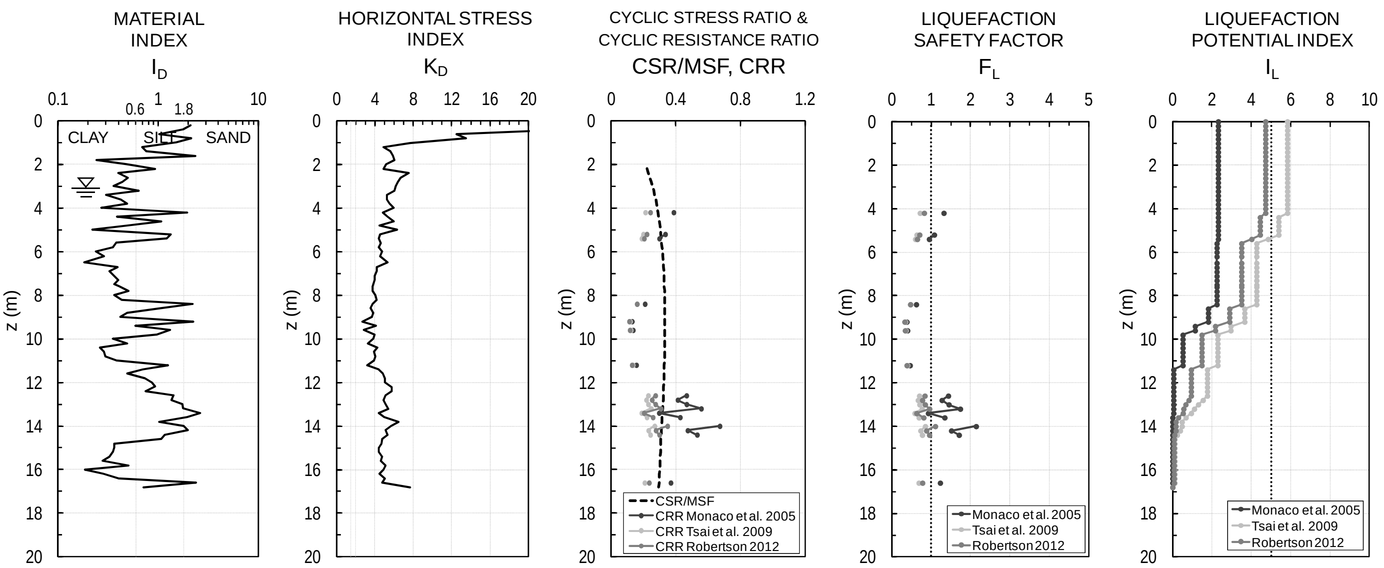


Fig. 7. Results of liquefaction analysis based on the DMT horizontal stress index K_D at Pozzone test site.

This aspect could be due to the fact that K_D is more sensitive than V_S to stress history, prestraining/aging, cementation, structure, relative density and state parameter. However, a similar discrepancy between *CRR* predicted by V_S and by K_D has been observed in several other cases investigated by SDMT (see e.g. Maugeri & Monaco 2006, Monaco & Marchetti 2007).

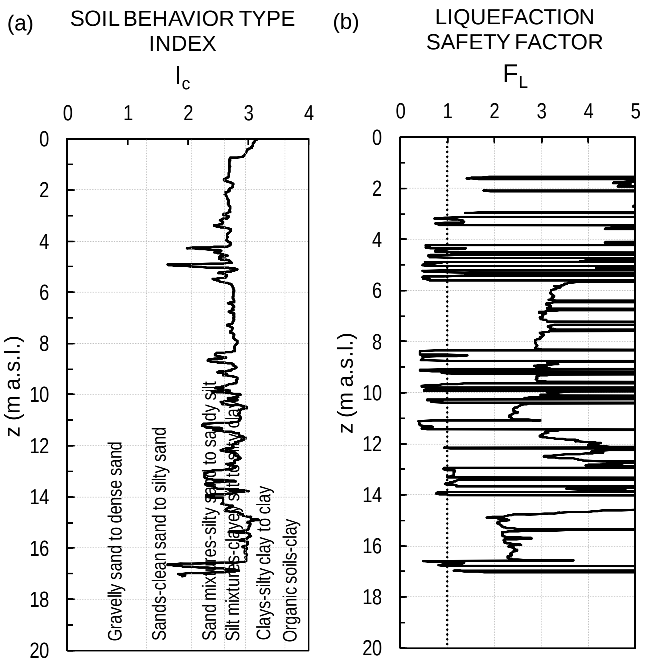


Fig. 8. Soil characterization at Pozzone site drawn from CPTu profile: (a) Soil classification; (b) Safety factor against liquefaction.

4.2.2 *CPTu and N_{SPT} simplified method*

Liquefaction potential index has been calculated for liquefaction hazard assessment along the investigated profile at Pozzone test site. As shown in Figs. 8 and 9, the mixture of silty deposits with sand show to be liquefiable. The high percentage of clay fractions reduces the liquefaction potential index from 5 to 0 from 3.5 m to about 11 m under the surface.

This is confirmed by the profiles in Fig. 4 that show a relevant increase in soil resistance and stiffness at about 12 m. The same results are calculated by DPSH measurements using Seed et al. (1985) but liquefaction potential value is 4 from 3.5 to 9 m, then it rapidly reduces to 0 up to 12 m depth.

5 CONCLUSIONS

The large amount of data provided by the seismic microzonation of Avezzano (Italy), supplied a useful tool for a preliminary liquefaction assessment of Pozzone test site.

CPTu- and DMT-based analyses provide similar results in terms of liquefaction potential index, while the DPSH-based method seems to be less consistent due to the introduction of a energy convertion coefficient, and the V_S-based method indicates higher liquefiability of the shallower layers.

The shear wave velocity V_S acquired by SDMT measurements, considering two different position of the shear wave source at the surface, confirmed the reliability of the "true interval" test configuration.

Further investigations and analyses will be performed to increase the knowledge on liquefaction of the Fucino plain soils.

6 ACKWNOLEDGEMENTS

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7 REFERENCES

Andrus, R.D. and Stokoe, K.H., II. (2000). "Liquefaction resistance of soils from shear-wave velocity." *J. Geotech. Geoenviron. Eng.*, ASCE, 126(11), 1015-1025.

Boncio, P., Milana, G., Cara, F., Di Giulio, G., Di Naccio, D., Famiani, D., Francescone, M., Galadini, F., Mancini, T., Nardone, M., Rosatelli, G. and Vassallo, M. (2014). "Microzonazione Sismica di Livello 1 del Comune di Avezzano." *Unpublished Report with 1:5000 maps and sections*. Regione Abruzzo, 2014, in Italian.

Cavinato, G., Carusi, C., Dall'Asta, M., Miccadei, E. and Piacentini, T. (2002). "Sedimentary and tectonic evolution of Plio-Pleistocene alluvial and lacustrine deposits of Fucino Basin (central Italy)." *Sediment. Geol.* 148, 29–59.

Galli, P. (2000). "New empirical relationships between magnitude and distance for liquefaction." *Tectonophysics*, 324, 169-187.

Gruppo di Lavoro MPS (2004). "Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM 3274 del 20 marzo 2003." *Rapporto Conclusivo per il Dipartimento della Protezione Civile*, INGV, Milano-Roma, aprile 2004, 65 pp. + 5 appendici. http://zonesismiche.mi.ingv.it/, in Italian.

Idriss, I.M. (1999). "An update to the Seed-Idriss simplified procedure for evaluating liquefaction potential". *Proc. TRB Workshop on New Approaches to Liquefaction*, Publ. No. FHWA-RD-99-165, Federal Highway Administration.

Iwasaki, T., Tokida, K., Tatsuoka, F., Watanabe, S., Yasuda, S. and Sato, H. (1982). "Microzonation for soil liquefaction potential using simplified methods." *Proc. of 3rd Int. Conf. on Microzonation*, Seattle, 3, 1319–1330.

Konno, K. and Ohmachi, T. (1998). "Ground motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremors." *Bull. seism. Soc. Am.*, 88-1, 228-241.

Marchetti, S. (1980). "In Situ Tests by Flat Dilatometer." *J. Geotech. Engrg. Div., ASCE*, 106, No.GT3, 299-321.

Marchetti, S., Monaco, P., Totani, G. and Calabrese, M. (2001). "The Flat Dilatometer Test (DMT) in Soil Investigations – A Report by the ISSMGE Committee TC16." *Proc. Int. Conf. on Insitu Measurement of Soil Properties and Case Histories, Bali, 2001, official version reprinted in Flat Dilatometer Testing, Proc. 2nd Int. Conf. on the Flat Dilatometer, Washington D.C., April 2-5, 2006*, 7-48, R.A.Failmezger, J.B.Anderson (eds).

Marchetti, S., Monaco, P., Totani, G. and Marchetti, D. (2008). "In Situ Tests by Seismic Dilatometer (SDMT)." *From Research to Practice in Geotechnical Engineering, ASCE, Geotechnical Special Publication*, 180, 292-311, J.E.Laier, D.K.Crapps, M.H.Hussein (eds).

Maugeri, M. and Monaco, P. (2006). "Liquefaction Potential Evaluation by SDMT." *Proc. 2nd Int. Conf. on the Flat Dilatometer*, Washington, D.C., 295-305.

Meletti, C. and Montaldo V. (2007). "Stime di pericolosità sismica per diverse probabilità di superamento in 50 anni: valori di ag." Progetto DPC-INGV S1, Deliverable D2, http://esse1.mi.ingv.it/d2.html, in Italian.

Monaco, P. and Marchetti, S. (2007). "Evaluating liquefaction potential by seismic dilatometer (SDMT) accounting for aging/stress history." *Proc. 4th Int. Conf. on Earthquake Geotechnical Engineering*, Thessaloniki, Greece, Paper 1626.

Monaco, P., Marchetti, S., Totani, G. and Calabrese, M. (2005). "Sand liquefiability assessment by Flat Dilatometer Test (DMT)." *Proc. XVI ICSMGE*, Osaka, 4, 2693-2697.

Nisio, S., Caramanna, G. and Ciotoli, G. (2007). "Sinkholes in Italy: first results on the inventory and analysis." *Geological Society*, London, Special Publications 2007; v. 279; p. 23-45 doi: 10.1144/SP279.4

NTC (2008). "Approvazione delle nuove norme tecniche per le costruzioni." *Gazzetta Ufficiale della Repubblica Italiana*, n. 29 del 4 febbraio 2008-Suppl. Ordinario n. 30, in Italian.

Oddone, E. (1915). "Gli elementi fisici del grande terremoto Marsicano-Fucense del 13 gennaio 1915." *Bollettino della Società Sismologica Italiana*, 19, 71-217, in Italian.

Prestininzi, A. and Romeo, R.W. (2000). "Earthquake-Induced Ground Failures in Italy." *Engineering Geology*, 58(3-4), 387-397.

Robertson, P. K. (1990). "Soil classification using the CPT." *Can. Geotech. J.*, 27(1), 151–158.

Robertson, P. K., and Wride, C. E. (1997). "Cyclic liquefaction and its evaluation based on the SPT and CPT." *Proc. NCEER Workshop on Evaluation of Liquefaction Resistance of Soil*, 41–87.

Robertson, P.K. (2012). "The James K. Mitchell Lecture: Interpretation of in-situ tests – some insights." *Proc. 4th Int. Conf. on Geotechnical and Geophysical Site Characterization – ISC'4*, Porto de Galinhas, Brazil, 1, 3-24.

Seed, H.B. and Idriss, I.M. (1971). "Simplified procedure for evaluating soil liquefaction potential." *J. Geotech. Engrg. Div.*, ASCE, 97(9), 1249–1273.

Seed, H.B., Tokimatsu, K., Harder, L. F., and Chung, R. M. (1985). "The influence of SPT procedures in soil liquefaction resistance evaluations." J. Geotech. Engrg., ASCE, 111(12), 1425–1445.

Tsai, P., Lee, D., Kung, G.T. and Juang, C.H. (2009). "Simplified DMT-based methods for evaluating liquefaction resistance of soils." *Engineering Geology*, 103(2009), 13-22.