INVESTIGATIONS AND LIQUEFACTION ASSESSMENT AT THE PAGLIARE DI SASSA SITE (L'AQUILA, CENTRAL ITALY)

A. Chiaradonna[1], P. Monaco[2] & M. Tallini[2]

[1] University of L'Aquila, L'Aquila, Italy, anna.chiaradonna1@univaq.it

[2] University of L'Aquila, L'Aquila, Italy

Abstract: *This paper illustrates the results of site investigations and liquefaction analyses at the Pagliare di Sassa site (PSS), carried out as part of a 3rd level Seismic Microzonation study of the western portion of L'Aquila Municipality territory (central Italy). The PSS was investigated by boreholes, geotechnical in-situ tests and geophysical surveys. The subsoil model of the PSS, defined based on the available geological and geotechnical data, is characterized by features potentially predisposing to liquefaction, such as shallow sand levels and groundwater table close to the ground surface. The liquefaction potential has been investigated using simplified methods based on different in-situ test results (CPTU, DMT, V_S). The Pagliare di Sassa pilot study has provided a useful contribution in the evaluation of the liquefaction potential of soils within the area involved by the Seismic Microzonation study, aiming to correctly plan the use of the territory with respect to the seismic risk.*

1. Introduction

The Seismic Microzonation studies consist of the identification of microzones characterized by homogeneous response to seismic ground shaking which are classified as stable zones, vulnerable zones prone to local seismic amplification effects, and unstable zones. For the latter zones, the prevailing effects are due to permanent deformations, mainly surface faulting, landslides, and soil liquefaction.

L'Aquila Municipality territory (central Italy) is characterized by (i) medium-high seismicity, by (ii) near-source events as represented by the 2009 L'Aquila earthquake ($M_w = 6.1$), and by (iii) medium-field historical events with considerable magnitudes (M_w = 6.7-7.0). Moreover, liquefaction evidence observed during the 2009 L'Aquila earthquake (Monaco and Amoroso 2019), or paleoliquefaction features found in Holocene deposits, were recognized at various sites. One paleoliquefaction site is located close to the Pagliare di Sassa site (PSS), which is included in a recent 3rd level Seismic Microzonation study of the western portion of L'Aquila Municipality territory (Tallini et al. 2023, 2024).

Geological information and geotechnical data available from previous investigations have indicated that the PSS is characterized by features potentially predisposing to liquefaction, such as shallow sand levels and water table close to the ground surface. For this reason, the PSS was selected as a representative site for a pilot study aiming to evaluate the liquefaction potential of soils within the area involved by the Seismic Microzonation study, with the objective to safely plan the use of the territory and to support decision-making strategies for the reduction of the seismic risk at large scale.

The PSS was recently investigated by boreholes, geotechnical in-situ tests and geophysical surveys, as illustrated in the paper after a general description of the geological setting of the area. The results of liquefaction analyses carried out using simplified methods based on different in-situ tests are illustrated and commented in the following.

2. Geological setting

The geological framework of central Italy is caused by the overlap of two main stages: the Neogene contractional orogenic stage during which the Apennine chain was built up and the subsequent Pliocene-Quaternary post-orogenic stage. During this second stage, SW- and S-dipping extensional faults generated complex graben or semi-graben corresponding geomorphologically to the intermontane basins scattered in central Italy. They were filled up by coarse- and fine-grained detrital deposits, such as conglomerates, breccia, sand and pelite, sedimented chiefly in lacustrine, slope and alluvial environments (Carminati et al. 2010, Cavinato and De Celles 1999, Cosentino et al. 2017). Furthermore, many of these extensional faults are seismogenic and responsible for the present-day and historical seismicity even producing earthquakes with maximum expected magnitudes up to 6.5-7 (Boncio et al. 2004, Galadini and Galli 2000).

The study area is placed within L'Aquila-Scoppito basin (BAS) which is representative of the aforementioned intermontane basins (Nocentini et al. 2017, Figure 1). It is characterized by a notable seismic hazard, as showed by the recent near-source April 6, 2009 M_w = 6.1 L'Aquila earthquake. BAS is an E-W trending asymmetrical graben, bordered to the North by the S-dipping normal Mt. Pettino Fault, that is the master and active fault of BAS, and to the South by the antithetic Sassa Fault (SF) (Figure 1) (Durante et al. 2017).

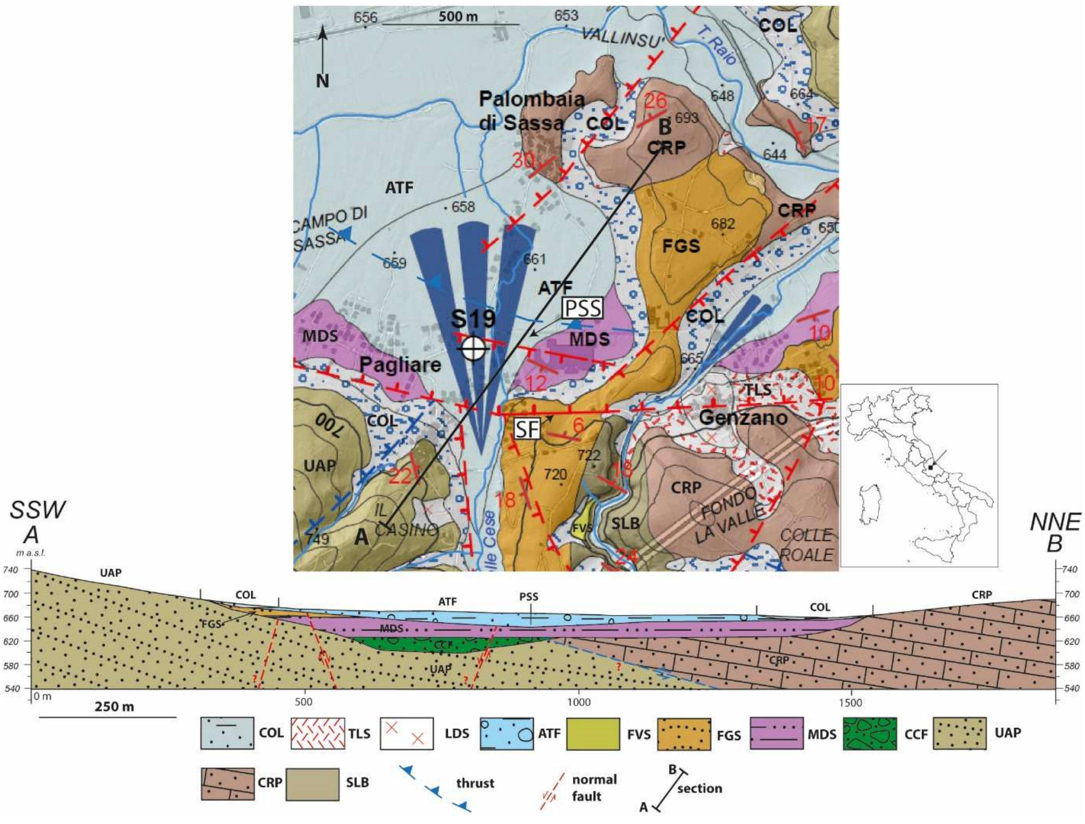

Figure 1. Local geological map by Nocentini et al. (2017) (top) and representative section (bottom) of Pagliare di Sassa (PSS) study site area. COL: colluvial deposit; TLS: slope deposit; LDS: landslide deposit; ATF: alluvial deposit; COL, TLS, LDS and ATF belong to the Aterno R. Synthem (Holocene); FVS: alluvial terraced deposit, Fosso Vetoio Synthem (Upper Pleistocene); FGS: braided fluvial and alluvial fan deposit, Fosso Genzano Synthem (Middle Pleistocene); MDS: floodplain alluvial deposit, Madonna della Strada Synthem (Calabrian); CCF: alluvial fan & debris flow deposit, Colle Cantaro-Cave Formation (Gelasian-upper Piacenzian); UAP: synorogenic terrigenous unit (sandstone & claystone) (Upper Miocene); CRP: detrital limestone (Middle-Lower Miocene); SLB: Meso-Cenozoic slope to basin carbonate units; SF: Pagliare di Sassa Fault.

Starting from the upper Pliocene, BAS was filled up by mainly alluvial, slope and colluvial deposits laying through an erosion surface onto the Upper Miocene sandstone and claystone and Meso-Cenozoic carbonate rocks. The most recent BAS deposits (ATF Synthem) are represented by slope and colluvial deposits bordering the base of the surrounding reliefs and by the recent alluvial deposits of the Aterno River and its tributaries.

It is noteworthy that, even if the recent April 6, 2009 $M_w = 6.1$ L'Aquila earthquake did not trigger liquefaction phenomena in BAS, the seismological, geological, and hydrogeological elements lead to believe that their formation could be possible.

3. The Pagliare di Sassa site (PSS)

3.1. Site description

The Pagliare di Sassa site (PSS) is located in the western portion of the L'Aquila Municipality territory. After the April 6, 2009 L'Aquila earthquake, the PSS was one of the 19 sites selected for the construction of new seismically isolated buildings for temporary housing of homeless people (C.A.S.E. Project).

The PSS falls within the alluvial deposit of the Aterno R. plain (ATF Synthem in Figure 1) consisting of medium- to fine-grained, well-sorted, sub- to well-rounded, loose sandy gravel beds, alternating with levee medium sand and silty sand layers, passing to overbank clayey silts with sometimes a remarkable organic content.

As part of the Microzonation Study, the PSS was considered eligible for more in-depth investigation, due to the presence of conditions potentially predisposing to liquefaction (i.e., presence of sand levels, relatively shallow groundwater table). However, as already mentioned, no evidence of liquefaction was reported at the PSS during the 2009 L'Aquila earthquake.

3.2. Site investigations

A site investigation campaign at the PSS was specifically planned and carried out in September 2020, aiming to obtain data for liquefaction assessment. This campaign (Figure 2) included one continuous core borehole (PSS-BH) to a depth of 20 m b.g.l., one piezocone penetration test (PSS-CPTU) to 10.70 m depth b.g.l., and one seismic dilatometer test (PSS-SDMT) to 9.80 m depth with measurements of the shear wave velocity V_S every 0.50 m. Both the CPTU and the SDMT soundings were stopped at depths where the maximum push capacity of the penetrometer rig was reached.

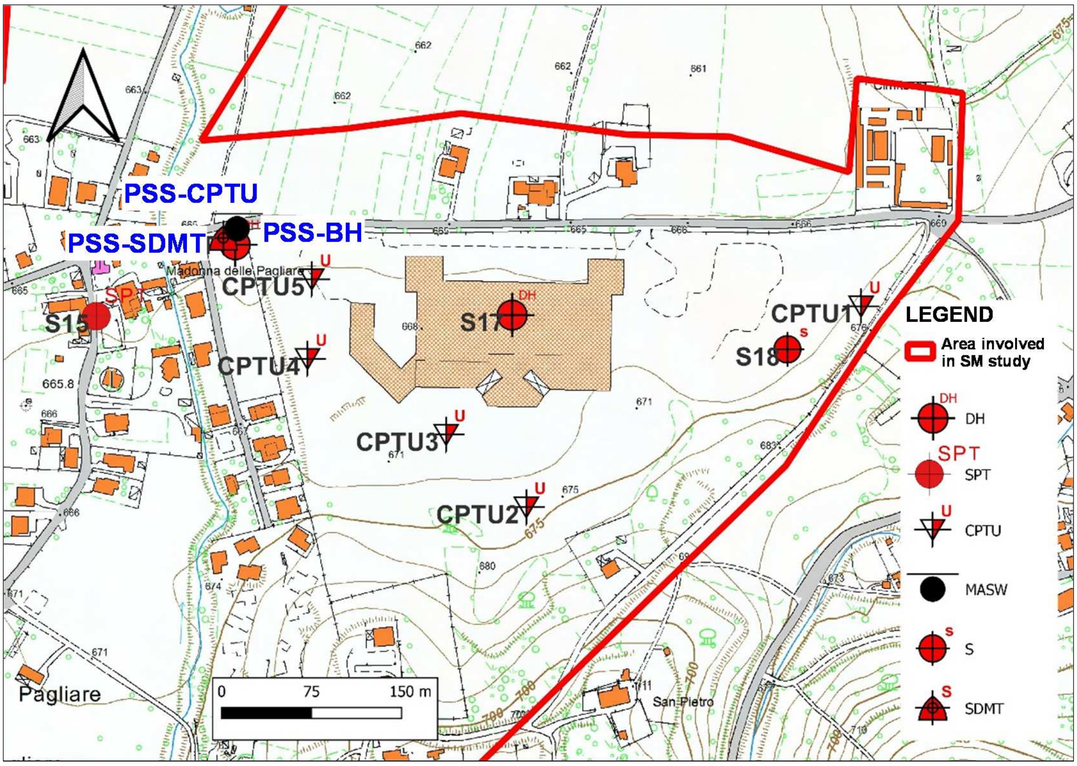

Figure 2. Location of recent and previous investigations carried out at the PSS and its surroundings.

Results were also available from previous investigations carried out in the area surrounding the PSS in the aftermath of the 2009 L'Aquila earthquake, as part of first-emergency surveys promoted by the Italian Department of Civil Protection for the selection and characterization of the C.A.S.E. Project sites (MS–AQ Working Group 2010). These investigations included one borehole (S17) to a depth of 30 m b.g.l. with standard penetration tests (SPT) and retrieval of two undisturbed samples subsequently subjected to laboratory tests, one Down-Hole test to 30 m depth in the same borehole, and five CPTU soundings (CPTU1 – CPTU5) to depths ranging between 10.60 m and 14 m b.g.l.. Additional borehole data from independent investigations carried out in the area (S15, S18) were also available. The location of the recent and previous investigations carried out at the PSS and its surroundings is shown in Figure 2.

The stratigraphic log of the borehole PSS-BH (Figure 3a) shows an alternation of predominantly sandy layers and clayey to clayey-sandy layers with some intercalation of gravel in clayey matrix, down to the maximum investigated depth of 20 m. These lithologies refer to the Holocene alluvial deposit of the ATF Synthem. The alluvial deposit of the borehole PSS-BH presumably lays upon the sand and pelite deposit of the MDS Synthem, which in turn lays upon the calcareous conglomerate and breccia of CCF formation and the Upper Miocene sandstone and claystone, the last two corresponding to the seismic bedrock (Nocentini et al. 2017, Figure 1). Standard penetration tests (SPT) were performed in the borehole PSS-BH at depths of 5.60 m, 9.00 m and 13.50 m. The SPT blowcounts are shown in Figure 3a, along with pocket penetrometer measurements. Two undisturbed samples were taken at depths of 5.00-5.60 m and 8.50-9.00 m, respectively. Figures 3b and 3c show the corresponding soil type description inferred from CPTU and DMT interpretation in the upper 10-11 m, as represented by the depth profiles of the Soil Behavior Type Index I_c obtained from PSS-CPTU and of the material index I_D (according to Marchetti 1980) obtained from PSS-SDMT, respectively.

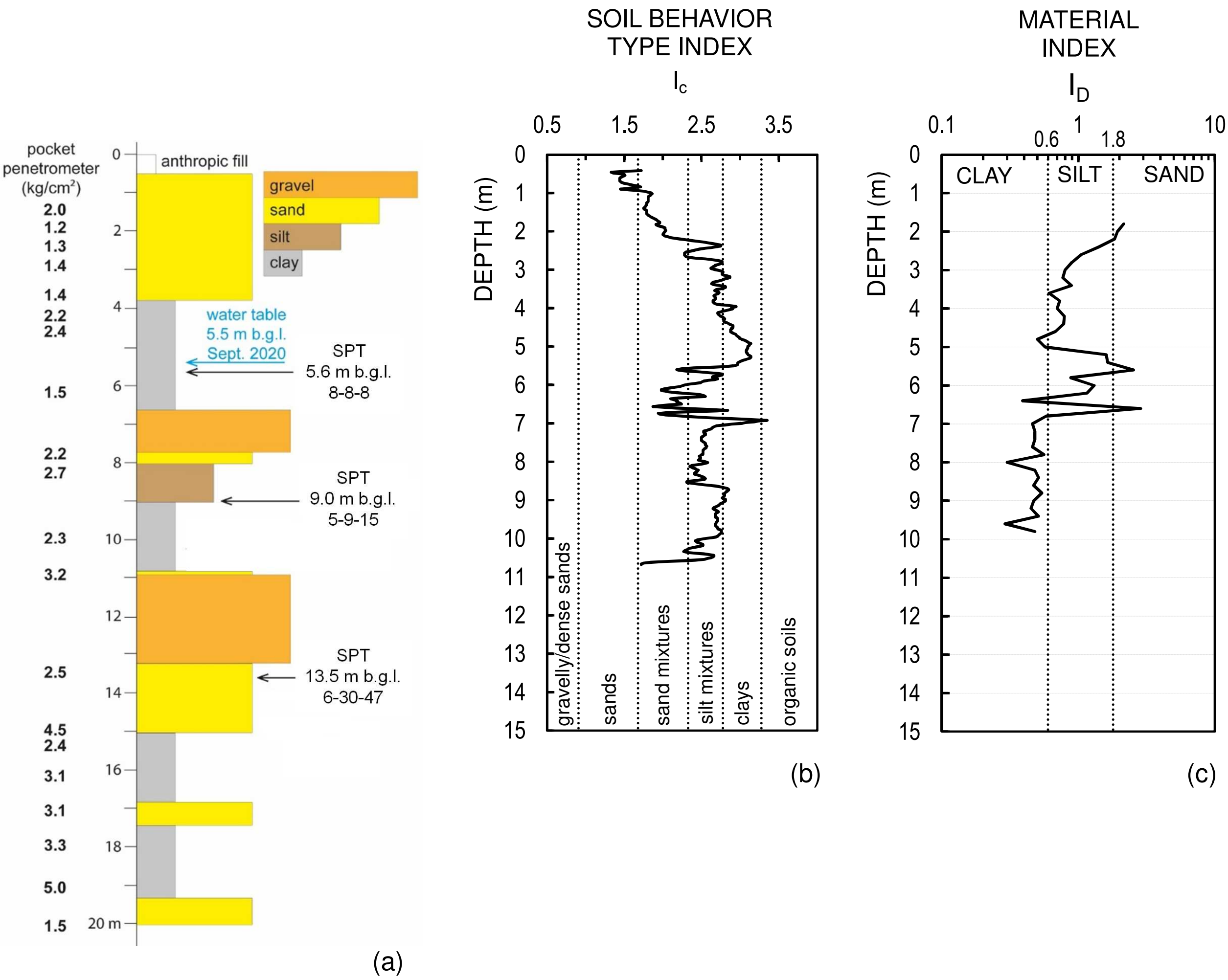

Figure 3. Stratigraphic log of borehole PSS-BH (a) and depth profiles of Soil Behavior Type Index I_c from PSS-CPTU (b) and material index I_D from PSS-SDMT (c).

During the site investigation (September 2020) the groundwater table was found at a depth of about 5.50 m from the ground surface, as measured in an open standpipe piezometer installed in the borehole PSS-BH.

4. Liquefaction assessment by simplified methods

4.1. Procedure

Liquefaction analyses at the PSS were carried out by use of methods developed in the framework of the “simplified procedure” introduced by Seed and Idriss (1971). This procedure is based on the comparison, at any 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 in free field conditions at each depth was calculated as:

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

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 I_L (Iwasaki et al. 1982), defined as:

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

where z is the depth below the ground surface (in m), $w(z)$ = 10 – 0.5 z is a depth weighting factor, and the function $F(z)$ depends on the safety factor F_L calculated at each depth ($F = 1 - F_L$ if $F_L \leq 1$, $F = 0$ if $F_L > 1$).

At the PSS the in-situ tests (CPTU and SDMT) used to evaluate *CRR* and F_L did not reach the depth of 20 m, required to calculate I_L according to Eq. (2). Therefore I_L was calculated down to the maximum investigated depth of about 10 m assuming that below this depth, where the probe penetration stopped, the soils could be reasonably considered as “non liquefiable”, as confirmed by the PSS-BH borehole log (Figure 3a).

4.2. Scenario earthquake and evaluation of the cyclic stress ratio

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. The moment magnitude (M_w) of the earthquake is also needed to calculate the magnitude scaling factor (*MSF*). The criteria adopted for selecting the scenario earthquake and estimating the related parameters for liquefaction assessment are consistent with the scope of the Seismic Microzonation study including the PSS area.

The maximum horizontal acceleration (a_{max}) at the surface was evaluated based on the indications provided by the Italian building code (NTC 2018). The basic seismic hazard parameters are also available from the MPS04-S1 seismic hazard model platform (http://esse1-gis.mi.ingv.it). For the liquefaction analyses, a scenario earthquake with a return period T_R = 475 years was considered, representative of the life-safety limit state (SLV) for ordinary structures and associated with a 10% probability of exceedance in 50 years. Assuming this scenario earthquake, the maximum horizontal acceleration (a_g) on outcropping rock (soil type A: $V_S > 800$ m/s) for flat or gently sloping ground (topographic category T1) was estimated as a_g = 0.261 g. The peak ground acceleration (a_{max}) was then evaluated by multiplying a_g by the amplification coefficient $S = S_S \cdot S_T$ calculated for the PSS in accordance with NTC (2018). The stratigraphic amplification coefficient S_S was evaluated assuming ground type C (equivalent shear wave velocity $V_{S,eq}$ ranging from 180 m/s to 360 m/s), based on the V_S measured at the PSS. The topographic amplification coefficient S_T was assumed equal to 1, considering that the ground surface at the PSS is gently sloping. Based on the above assumptions, the peak ground acceleration was assumed equal to a_{max} = 0.347 g.

The moment magnitude (M_w) was evaluated as the maximum magnitude (M_{wmax}) associated to the seismogenic zone including the study area, in accordance with one of the criteria provided by current national guidelines for liquefaction assessment in Seismic Microzonation studies (LQ 2018). Therefore M_w was assumed equal to M_{wmax} = 7.06, i.e., the maximum magnitude associated to the seismogenic zone including L'Aquila Municipality.

The groundwater table was assumed at a depth of 5.50 m b.g.l., as indicated by piezometer measurements carried out in September 2020.

4.3. Evaluation of the cyclic resistance ratio

The cyclic resistance ratio (*CRR*) was estimated by use of empirical methods based on soil parameters obtained from different in-situ tests, in particular:

- based on CPTU results, according to Boulanger and Idriss (2014), using as an index parameter the corrected cone resistance (q_{c1Ncs});
- based on SPT results, according to Boulanger and Idriss (2014), using as an index parameter the corrected blowcount ($(N_1)_{60cs}$);
- based on V_S measurements, according to Andrus and Stokoe (2000) and Kayen et al. (2013), using as an index parameter the overburden-stress corrected shear wave velocity V_{S1};
- based on DMT results, according to Robertson (2012), Marchetti (2016) and Chiaradonna and Monaco (2022), using as an index parameter the horizontal stress index K_D defined by Marchetti (1980);
- based on the combined use of DMT (K_D) and CPT (q_{c1Ncs}) results, according to Marchetti (2016).

In the CPT-, SPT- and V_S-based methods, the magnitude scaling factors *MSF* were evaluated according to the specific formulations proposed by the authors of each method. In the DMT-based methods, *CSR* at each depth and *MSF* were calculated according to Idriss and Boulanger (2008).

Differently from methods based on other tests, which include correction factors to take into account the effect of the fines content (*FC*), the DMT-based methods currently available are valid only for clean sands (at present the *FC* correction for the *CRR*-K_D correlation is under study).

4.4. Results and comments

Figure 4 summarizes the results of the liquefaction analyses based on the CPTU and SDMT data obtained from the 2020 site investigation. In particular, Figure 4 shows the depth profiles of: (1) the parameter indicative of soil type, i.e., the Soil Behavior Type Index I_c obtained from CPTU (Figure 4a) or the material index I_D obtained from DMT (Figures 4b and 4c); (2) the parameter used in each case for evaluating *CRR*, i.e., the corrected cone resistance q_{c1Ncs} obtained from CPTU (Figure 4a), the overburden stress-corrected shear wave velocity V_{S1} calculated from V_S (Figure 4b) or the horizontal stress index K_D (Figure 4c) obtained from SDMT; (3) *CSR* compared to *CRR*; 4) the liquefaction safety factor F_L; (5) the liquefaction potential index I_L.

The analysis based on CPTU data (Figure 4a) shows that liquefaction ($F_L < 1$) may occur in predominantly sandy layers at depths between about 5.50 m to 10.50 m. The corresponding value of the liquefaction potential index I_L is equal to 6.5, denoting a "high risk" condition. On the other hand, the analyses based on SDMT data, both V_S-based (Figure 4b) and K_D-based (Figure 4c) methods, in substantial agreement with each other, show possible occurrence of liquefaction ($F_L < 1$) in layers of limited thickness at depths between about 5.50 m and 6.60 m. The corresponding values of the liquefaction potential index I_L calculated with the different methods based on V_S and K_D do not exceed 1.3 and 1.8, respectively, denoting a "low risk" condition.

It is noted in Figure 4 that simplified methods for liquefaction assessment based on different in-situ tests provided different estimates of the liquefaction risk, ranging from "low" to "high". The highest I_L was obtained using the method based on CPTU data (Boulanger and Idriss 2014), while the lowest I_L was provided by the methods based on V_S (Andrus and Stokoe 2000, Kayen et al. 2013). The methods based on DMT (Robertson 2012, Marchetti 2016, Chiaradonna and Monaco 2022) and on the combined use of DMT and CPT (Marchetti 2016) provided very similar I_L values, slightly higher than those obtained by the V_S-based methods.

The method based on SPT data (Boulanger and Idriss 2014) also indicated liquefaction occurrence ($F_L < 1$) at the depths of 5.60 m and 9 m (blowcounts in Figure 3a). However for the SPT-based analysis the liquefaction index I_L was not calculated as considered not to be representative over the entire borehole depth, due to the limited amount of SPT data at isolated test depths.

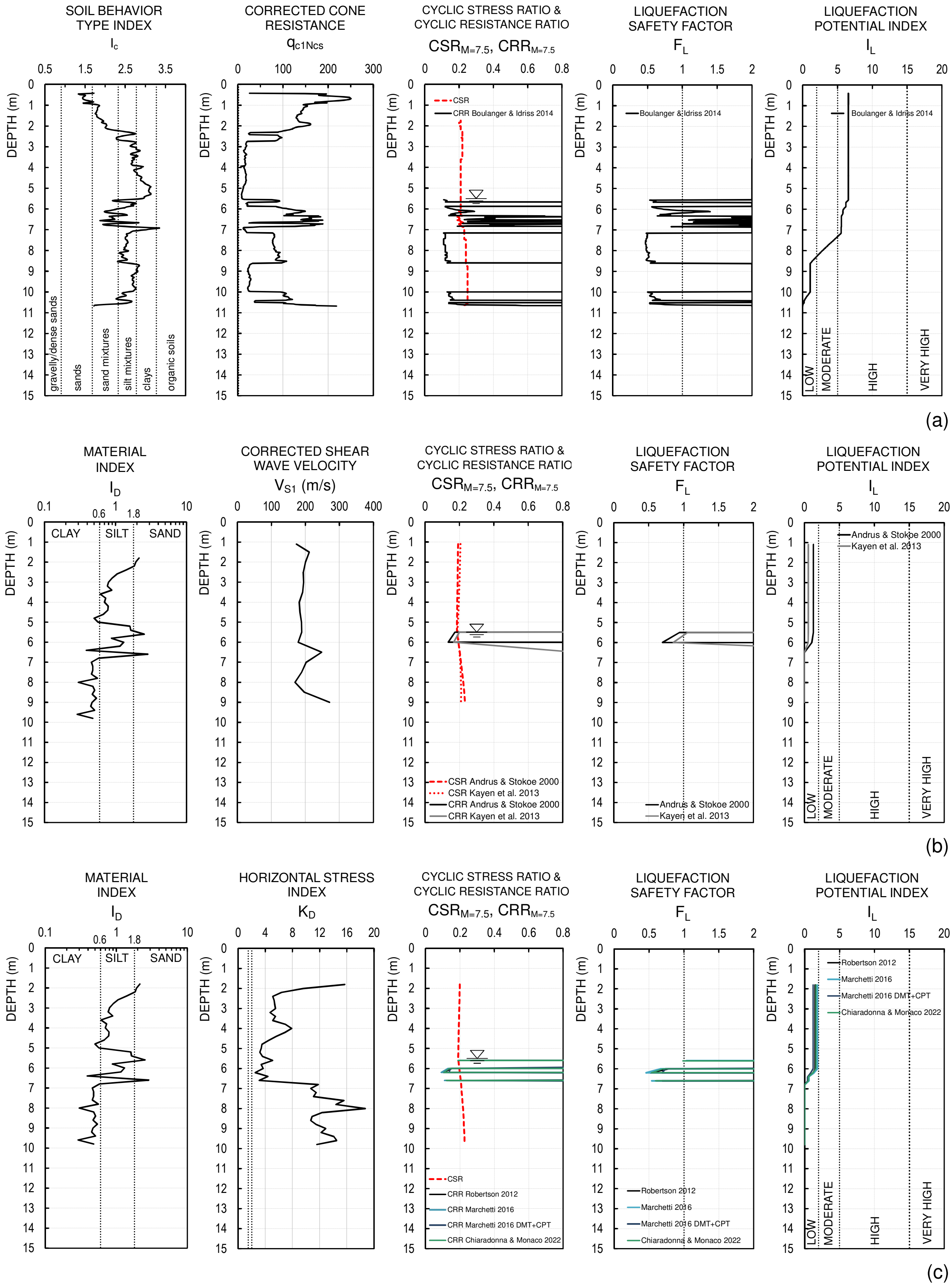

Figure 4. Results of liquefaction analyses based on (a) corrected cone resistance q_{c1Ncs} from PSS-CPTU, (b) corrected shear wave velocity V_{S1} from PSS-SDMT, and (c) horizontal stress index K_D from PSS-SDMT.

The discrepancy in liquefaction risk predictions provided by different test methods has been previously observed in cases where both CPTU, DMT and V_S data were available (e.g., Monaco et al. 2016). However, the use of "redundant" correlations for a more reliable estimate of the liquefaction risk using simplified methods is generally recommended. Among others, Robertson and Wride (1998) recommended to estimate *CRR* by more than one method for medium- to high-risk projects, while *CRR* from CPT-only (preferred to SPT) may be adequate for low-risk, small-scale projects. Youd et al. (2001) recommended that, whenever possible, two or more tests should be used. Idriss and Boulanger (2004) warned that using a number of in-situ tests should be the basis for standard practice, and the allure of relying on a single approach (e.g., CPT-only) should be avoided.

One possible source of unconsistency of results could be related to the different way in which the influence of the fines content (*FC*) is taken into account in the various methods. At the PSS, in the CPTU-based analysis (Boulanger and Idriss 2014) the *FC* effect was estimated from CPTU data and incorporated in the calculation. In the V_S-based analysis (Andrus and Stokoe 2000, Kayen et al. 2013), in absence of specific information from laboratory tests, *FC* was cautelatively estimated based on the borehole log. On the other hand, the DMT-based methods (Robertson 2012, Marchetti 2016, Chiaradonna and Monaco 2022) are valid for clean sand, without any correction for *FC*, hence the estimated values of I_L are presumably realistic in clean sands, but could be overestimated in silty sands and sandy silts.

The results obtained based on data from the 2020 site investigation have been substantially confirmed by additional analyses based on data from the previous CPTUs carried out in the area (CPTU1 – CPTU 5 in Figure 2) using the method by Boulanger and Idriss (2014). The liquefaction potential index I_L was found to range from values as low as 0.7 (CPTU2) and 1.2 (CPTU3) associated to "low" liquefaction risk, up to a maximum value of 7.7 (CPTU5) denoting "high" risk, with intermediate values of 2.6 (CPTU4) and 4.1 (CPTU1) related to a "moderate" risk condition. These results suggest that the liquefaction risk assessment in the PSS area is also possibly affected by local variability of soil conditions.

5. Conclusions

The Pagliare di Sassa (PSS) case study has provided a useful contribution for the assessment of the liquefaction risk within the area involved by the 3rd level Seismic Microzonation study in the western portion of L'Aquila Municipality, aiming to safely plan the use of the territory and to support decision-making strategies for the reduction of the seismic risk at large scale.

Liquefaction analyses carried out at the PSS by simplified methods based on different in-situ testing techniques (CPTU, DMT, V_S), even though with some discrepancy in the results, have pointed out that the liquefaction risk in this area cannot be ignored. These results confirm earlier predictions based on the available geological information and previous geotechnical investigation data, which had identified at the PSS soil conditions potentially predisposing to liquefaction (shallow sand layers, water table close to ground surface), thus addressing the selection of the PSS as a representative pilot site for liquefaction assessment in the area involved by the Seismic Microzonation study.

Further research, based on numerical analyses according to the equivalent linear and nonlinear approaches, is ongoing to investigate in-depth the liquefaction potential of the site.

6. Acknowledgements

This study is part of the 3rd level Seismic Microzonation project activities carried out on pilot areas located in the L'Aquila Municipality area. We would like to thank warmly (i) the Abruzzo Region (Department of Government of the Territory and Environmental Policies – Risk Prevention Service of Civil Protection, and (ii) L'Aquila Municipality for funding the aforementioned project and the in-situ investigations (borehole, CPTU, SDMT) at the Pagliare di Sassa site, respectively.

This work has also been supported by the Research Project ReLUIS-DPC 2022-2024 funded by the Italian Civil Protection Department (WP16 – Task 1 'Site response analysis and liquefaction').

7. References

Andrus R.D., Stokoe K.H. II (2000). Liquefaction resistance of soils from shear-wave velocity, *Journal of Geotechnical and Geoenvironmental Engineering*, 126(11): 1015-1025.

Boncio P., Amoroso S., Galadini F., Galderisi A., Iezzi G., Liberi F. (2020). Earthquake-induced liquefaction features in a late Quaternary fine-grained lacustrine succession (Fucino Lake, Italy): Implications for microzonation studies, *Engineering Geology*, 272: 105621.

Boulanger R.W., Idriss I.M. (2014). *CPT and SPT liquefaction triggering procedures*, Report No. UCD/GCM-14/01, University of California at Davis.

Carminati E., Lustrino M., Cuffaro M., Doglioni C. (2010). Tectonics, magmatism and geodynamics of Italy: What we know and what we imagine, *Journal of the Virtual Explorer*, 36: 9, doi:10.3809/jvirtex.2010.00226

Cavinato G.P., De Celles P.G. (1999). Extensional basins in the tectonically bimodal central Apennines fold-thrust belt, Italy: response to corner flow above a subducting slab in retrograde motion, *Geology*, 27: 955-958.

Chiaradonna A., Monaco P. (2022). Assessment of liquefaction triggering by seismic dilatometer tests: comparison between semi-empirical approaches and non-linear dynamic analyses, *Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE 2022)*, Sydney, Australia.

Cosentino D., Asti R., Nocentini M., Gliozzi E., Kotsakis T., Mattei M., Esu D., Spadi M., Tallini M., Cifelli F., Pennacchioni M., Cavuoto G., Di Fiore V. (2017). New insights into the onset and evolution of the central Apennine extensional intermontane basins based on the tectonically active L'Aquila Basin (central Italy), *Bulletin of the Geological Society of America*, 129: 1314-1336.

Durante F., Di Giulio G., Tallini M., Milana G., Macerola L. (2017). A multidisciplinary approach to the seismic characterization of a mountain top (Monteluco, central Italy), *Physics and Chemistry of the Earth, Parts A/B/C*, 98: 119-135.

Galadini F., Galli P. (2000). Active tectonics in the central Apennines (Italy) – Input data for seismic hazard assessment, *Natural Hazards*, 22: 225-268.

Idriss I.M., Boulanger R.W. (2004). Semi-empirical procedures for evaluating liquefaction potential during earthquakes, *Proceedings of the 11th International Conference on Soil Dynamics and Earthquake Engineering and the 33rd International Conference on Earthquake Geotechnical Engineering*, Berkeley, CA, US.

Idriss I.M., Boulanger R.W. (2008). *Soil liquefaction during earthquakes*, EERI Publication No. MNO-12, Earthquake Engineering Research Institute, Oakland, CA, US.

Iwasaki T., Tokida K., Tatsuoka F., Yasuda S., Sato H. (1982). Microzonation for soil liquefaction potential using simplified methods, *Proceedings of the 3rd International Conference on Microzonation*, Seattle, WA, US.

Kayen R., Moss R.E.S., Thompson E.M., Seed R.B., Cetin K.O., Der Kiureghian A., Tanaka Y., Tokimatsu K. (2013). Shear-Wave Velocity-Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential, *Journal of Geotechnical and Geoenvironmental Engineering*, 139(3): 407-419.

LQ (2018). *Linee guida per la gestione del territorio in aree interessate da liquefazioni*, versione 1.0, Commissione tecnica per la microzonazione sismica, Roma, https://www.centromicrozonazionesismica.it/it/strumenti/linee-guida-ms

Marchetti S. (1980). In Situ Tests by Flat Dilatometer, *Journal of the Geotechnical Engineering Division*, 106(3): 299-321.

Marchetti S. (2016). Incorporating the Stress History Parameter K_D of DMT into the Liquefaction Correlations in Clean Uncemented Sands, *Journal of Geotechnical and Geoenvironmental Engineering*, 142: 04015072.

Monaco P., Amoroso S. (2019). Review of the liquefaction cases triggered by the 2009 L'Aquila earthquake (Italy), *Proceedings of the 7th International Conference on Earthquake Geotechnical Engineering (VII ICEGE)*, Rome, Italy.

Monaco P., Tonni L., Gottardi G., Marchi M., Martelli L., Amoroso S., Simeoni L. (2016). Combined use of SDMT-CPTU results for site characterization and liquefaction analysis of canal levees, *Proceedings of the 5th International Conference on Geotechnical and Geophysical Site Characterisation ISC'5*, Gold Coast, Australia.

MS–AQ Working Group (2010). *Microzonazione sismica per la ricostruzione dell'area aquilana*, Regione Abruzzo – Dipartimento della Protezione Civile, L'Aquila, 3 vol. and Cd-rom (in Italian).

Nocentini M., Asti R., Cosentino D., Durante F., Gliozzi E., Macerola L., Tallini M. (2017). Plio-Quaternary geology of L'Aquila-Scoppito Basin (Central Italy), *Journal of Maps*, 13(2): 563-574.

NTC (2018). Ministero delle Infrastrutture e dei Trasporti. D.M. 17.01.2018 – Aggiornamento delle "Norme Tecniche per le Costruzioni".

Robertson P.K. (2012). The James K. Mitchell Lecture: Interpretation of in-situ tests – some insights, *Proceedings of the 4th International Conference on Geotechnical and Geophysical Site Characterization (ISC'4)*, Porto de Galinhas, Brazil.

Robertson P.K., Wride C.E. (1998). Evaluating cyclic liquefaction potential using the cone penetration test, *Canadian Geotechnical Journal*, 35(3): 442-459.

Seed H.B., Idriss I.M. (1971). Simplified procedure for evaluating soil liquefaction potential, *Journal of the Soil Mechanics and Foundations Division*, 97(9): 1249-1273.

Tallini M., Morana E., Guerriero V., Spadi M. (2024). Seismic microzonation studies by using the equivalent linear approach (L'Aquila, central Italy). *Proceedings of the 18th World Conference on Earthquake Engineering (WCEE2024)*, Milan, Italy.

Tallini M., Spadi M., Morana E., Chiaradonna A., Monaco P., Compagnoni M., Pergalani F., Di Giulio G., Milana G., Vassallo M., Cattani C., Montaldi C., Zullo F., Sciortino A., Basi M. (2023). In-depth third level Seismic Microzonation studies in pilot areas of L'Aquila Municipality (Central Italy). *Proceedings of the 41st National Conference of the GNGTS (GNGTS 2023)*, Bologna, Italy.

Youd T.L., Idriss I.M., Andrus R.D. et al. (2001). Liquefaction resistance of soils: Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils, Journal of Geotechnical and Geoenvironmental Engineering, 127(10): 817-833.