The importance of mini-cone penetration test in thin-layered soils

Claudia Meisina (Primary author)
Department of Earth and Environmental Sciences, University of Pavia, Pavia, Italy
claudia.meisina@unipv.it

Roberta Bonì[1], Massimiliano Bordoni[2]
Department of Earth and Environmental Sciences, University of Pavia, Pavia, Italy,
roberta.boni01@universitadipavia.it[1], *massimiliano.bordoni@unipv.it*[2]

Stefano Stacul[1] (Corresponding author), Diego Lo Presti[2]
Department of Civil and Industrial Engineering, University of Pisa, Pisa, Italy, *stefano.stacul@for.unipi.it*[1], *d.lopresti@ing.unipi.it*[2]

ABSTRACT: Cone Penetration Test (CPT) is one of the most popular in-situ test. Testing procedures and cone geometry are fixed by international well-recognized standards; usually a cone with an apex angle of 60° and a tip cross-section of 10 cm^2 has been recommended. The use of mini-cone is not considered by these standards and its use was recommended by various researchers in order to enhance the capability of identifying thin layers. This paper shows and compares the experimental results obtained by using a standard cone and a mini-piezocone. Tests were carried out at Calendasco (Piacenza-Italy) in a natural soil deposit mainly consisting of clayey – sandy silts. Grain size distribution with depth was also available. Other tests were carried out at Cavezzo (Modena-Italy) where liquefaction-induced phenomena were observed during the 29th May 2012 seismic sequence. The purpose was to investigate capabilities and limitations of mini-piezocone and to explore the possibility of obtaining a better prediction of soil stratigraphy in thin layered deposits.

Keywords: Cone Penetration Test; CPT; Mini CPT; Layered Deposits; thin layer

1. Introduction

Cone penetration test (CPT) provides crucial data for the preparation of the geological/geotechnical model of the shallow subsurface [1, 2]. However, the spatial resolution of cone tip resistance (q_t) and sleeve friction (f_s) measurements is still limited by the physical volume of soil around a cone tip (zone of influence) that influences these measurements. The dimensions of this zone of influence depend on the cone size and the strength of the soils. In particular, Lunne et al. (1997) [3] experimentally observed that the tip resistance senses the presence of an interface at a distance from the interface which increases as the material stiffness raises. Moreover, in the case of stiff layers, the target tip resistance was measured only for a layer thickness of 10-20 cone diameters, while for soft layers a thickness of 1-2 diameters was enough. As a consequence, in case of stiff thin layers the tip resistance could be underestimated. This has implications in some challenging issues of CPT interpretation as transition zones and thin layers identification [4, 5, 6]. CPT interpretation is affected by large uncertainties especially for deposits containing multiple thin layers, as a result of the deposition of sediments related to intermittent flows leading to alternating sand and clay layers quite frequent in alluvial settings, in particular channel and levee facies.

In order to improve CPT capabilities, possible solutions can derive by the application of methodologies for thin layer correction [5]. The use of a mini-cone test (mini-CPT) could also represent a suitable solution.

International standards such as ASTM D5578 [7] and ISO 22476-1 [8] define testing procedures, cone geometry and accuracy/repeatability requirements for testing with electric cone or piezocone. Usually a cone with an apex angle of 60° and a tip cross-section of 10 or 15 cm^2 is recommended. The use of mini-cone is not considered by these standards. In any case, various authors developed and used mini-cones for different purposes [6, 9, 10, 11, 12].

The identification of thin layers is also difficult in boreholes with fluid circulation. The use of water could result in the misinterpretation of thin layer of sand or silt. On the other hand, the use of undisturbed sampling techniques in sandy soils, which would help the recognition of thin layers, is sometimes difficult and very expensive (e.g. gel push and freezing). The CPT tests therefore remain extremely useful for the identification of thin layers.

The purpose of the present study is to compare couples of standard and mini cone tests carried out at some test sites in the po Plain. The capabilities and limitations of the mini-cone have been investigated for a better identification of thin soil layers.

2. Test areas

Two test sites were selected in the Po Plain (Northern Italy) (Fig. 1). The test site A is located at Calendasco (province of Piacenza,) and it is characterized by Holocenic deposits of the Po river consisting of unsaturated silty clay and sandy silts (CL) with intercalated thin layers of sand (thickness 13-35 cm) to a variable depth from

6.6 to 8.6 m. At greater depths a gravelly layer is present. The water table is 9.5 m below the ground surface.

The test site B is located at Cavezzo (Province of Modena) on the right side of the Secchia river (Fig. 1). The shallow lithostratigraphic succession at Cavezzo is characterized by alluvial deposits including interbedded fine silty-clayey sediments with marker layers rich on peat and interbedded sands and silty sands. These shallow deposits (down to 30 m in depth) are due to the sedimentation of the Secchia river. The Cavezzo area, where the tests were carried out, was characterized from the engineering geological point of view through investigations in the framework of the LIQUEFACT Horizon 2020 project [13]. The tests were carried out in silty-sandy soils with thin layers (silty layers in sandy soils and sandy layers in silty soils) corresponding to the recent alluvial plain and to the fluvial channel. The borehole executed in the area shows clay with sand and sand mixtures (silty sand and sandy silt, CL, fine contents = 24-50%, IP = 8) in the upper 5 m and sand and silty sand from 5 to 10 m (fine content FC = 15-28%). The water table depth is 2,10 m (March 2019). The liquefaction-induced ground surface manifestations after the May 29th 2012 earthquake with 5,8 Magnitude [14, 15] are located along a buried abandoned riverbed of the Secchia River that was active during Roman and Medieval times until the 13th century.

Figure 1. Geographical location of the test sites.

3. Equipments

Penetration tests were carried out by using a Penetrometer, standard piezocone (CPTu) and mini-piezocone. All the equipments were provided by Pagani Geotechnical Equipment (Piacenza – Italy). CPTu tests were carried out through a Pagani Penetrometer model TG63-150kN and according to ASTM D5778; the acquisition system/datalogger was TGAS-08. Silicone oil was used for saturation of the filter.

In this study, the mini-cone tip area (base area) was 2 cm^2, (16 mm in diameter) the friction sleeve area was 50 cm^2 and the cone apex angle was 60 degrees. The net area ratio of the miniature cone was 0,8. The mini-cone was pushed into the soil at a relatively constant rate of v = 2 cm/s. This involves a different normalized velocity $V_N = v/(d \cdot c_v)$ between standard and mini piezocone, where d is the cone diameter and c_v the coefficient of primary consolidation [16]. Anyway, the possible effects of such a difference appear negligible. Lower force is required to push the mini-cone into the soil [9] and a smaller and lighter vehicle is necessary compared to the standard CPTu test. This fact provides a greater mobility and site accessibility [17]. The maximum axial load experienced during the mini-cone tests was approximately equal to 0,9 kN. The mini-cone tip resistance and sleeve friction were recorded at depth intervals of 1 cm. Table 1 summarizes the full-scale output of measuring sensors.

Table 1. Full scale output of sensors

Measurement channel	Full scale output	Precision
Tip resistance (q_c):	30 MPa	0.005 MPa
Sleeve friction (f_s)	0.5 MPa	0.04 kPa
Pore Pressure (u_2)	2.5 MPa	0.04 kPa

In the test site A, two test series were performed. The first series consisted of 8 pairs of mini and standard tests that were carried out at the Pagani Geotechnical Equipment test field (Fig. 2). In addition, the penetrometer was used to retrieve Shelby tube samples. Samples were retrieved from three locations (A, B and C in Fig. 2). As for locations A and C, the maximum depth of 2.5 m was reached. At B location, a depth of 3.0 m was reached. The soil was sampled continuously every 0.50 m. Grain size distribution of the sampled soil was carried out at the Geotechnical Laboratory of the University of Pisa. Grain-size curves were usually determined every 0.1 m.

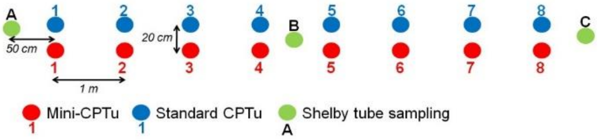


Figure 2. Test design of site A.

In the test site B, three pairs of CPTu and mini-CPTu were performed by Pagani Geotechnical Equipment at Cavezzo. They reach the depth of 10 m for the test 1 and 2 and 5 m for the test number 3 (Fig. 3). In this paper, only the results for the pairs CPTu2 – mini-CPTu2 were analyzed.

Figure 3. Test design of site B.

4. Comparison of results

The tip resistance (q_c) for different pairs of standard CPTu – mini-CPTu performed at Calendasco are compared in Figs. 4-5. It is worth remembering that borehole

A is close to CPTu1 – mini-CPTu1, borehole B is close to CPTu4 – mini-CPTu4 and CPTu5 – mini-CPTu5, while borehole C is close to CPTu8 – mini-CPTu8.

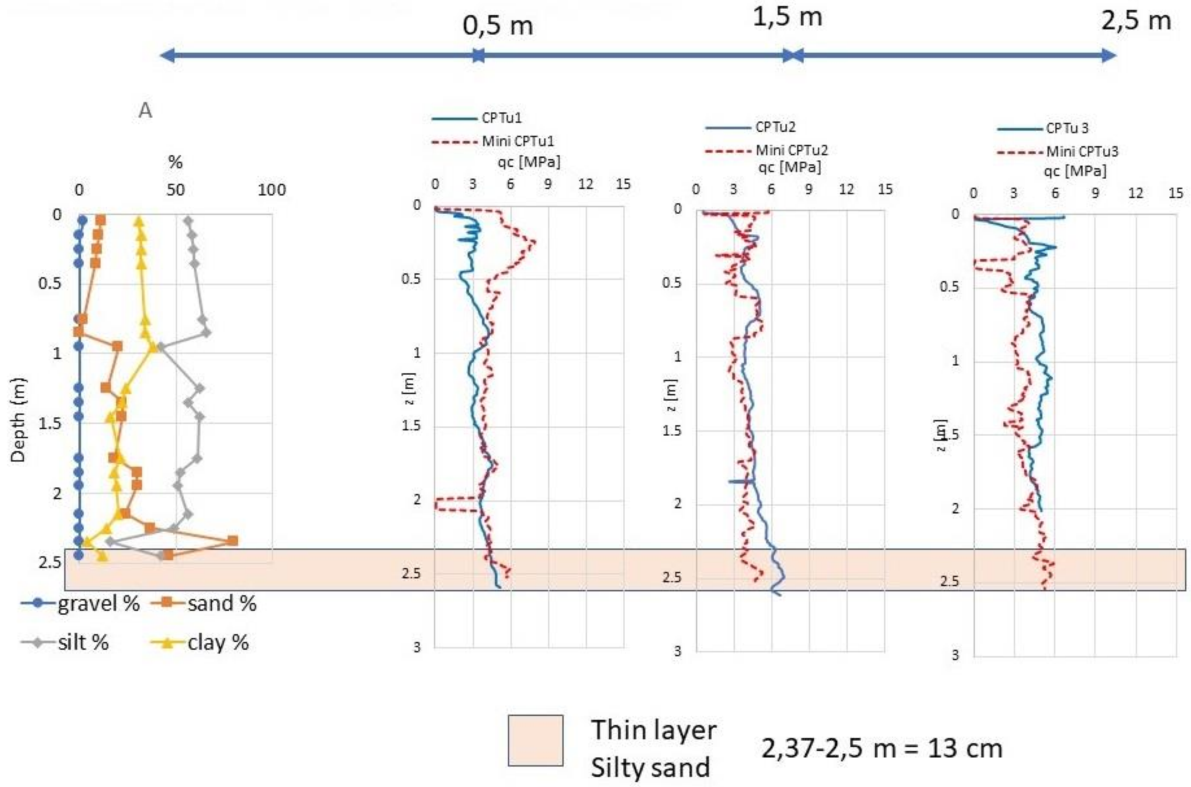


Figure 4. Comparison standard CPT vs mini-CPT in correspondence of the borehole A in the test site A.

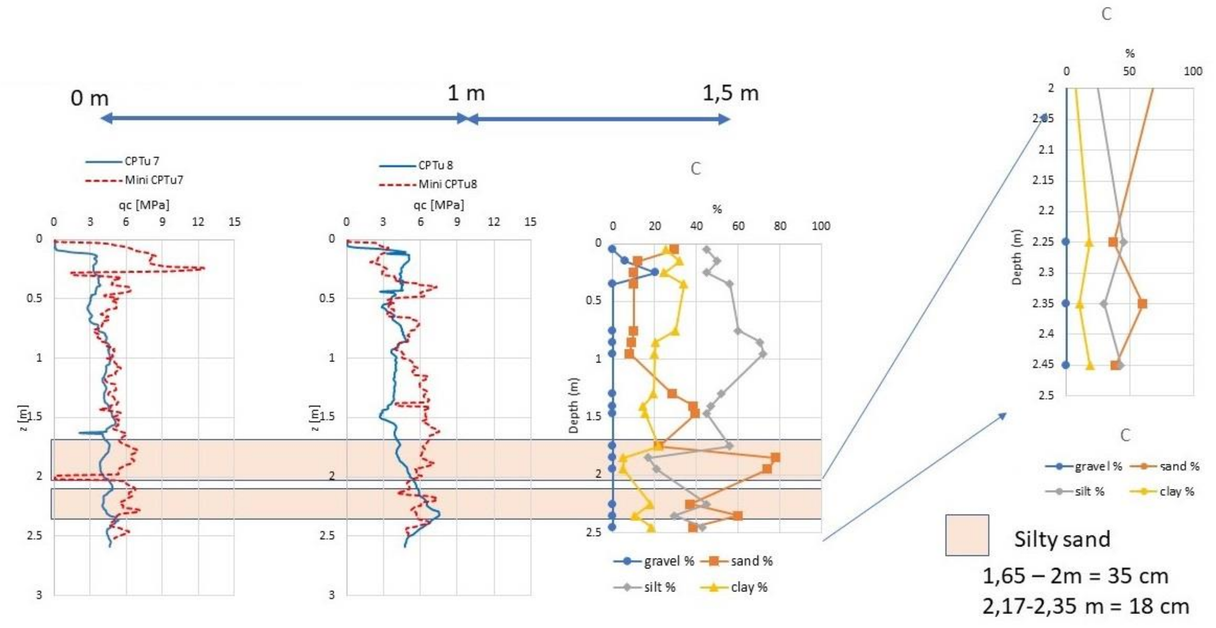


Figure 5. Comparison standard CPT vs mini-CPT in correspondence of the borehole C in the test site A.

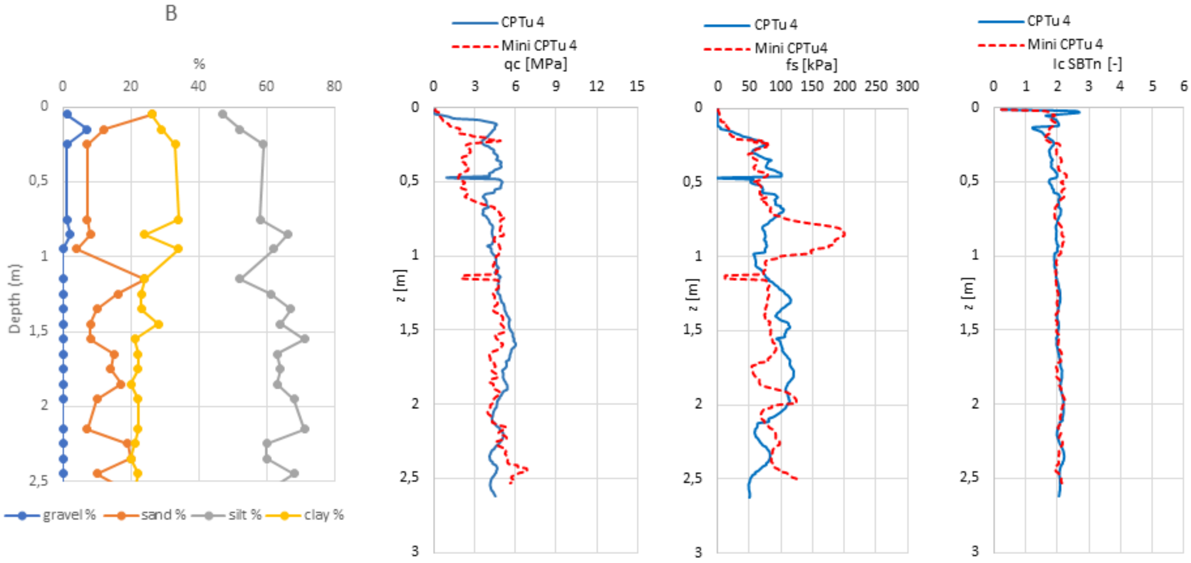


Figure 6. Comparison standard CPT vs mini-CPT in correspondence of the borehole B in the test site A.

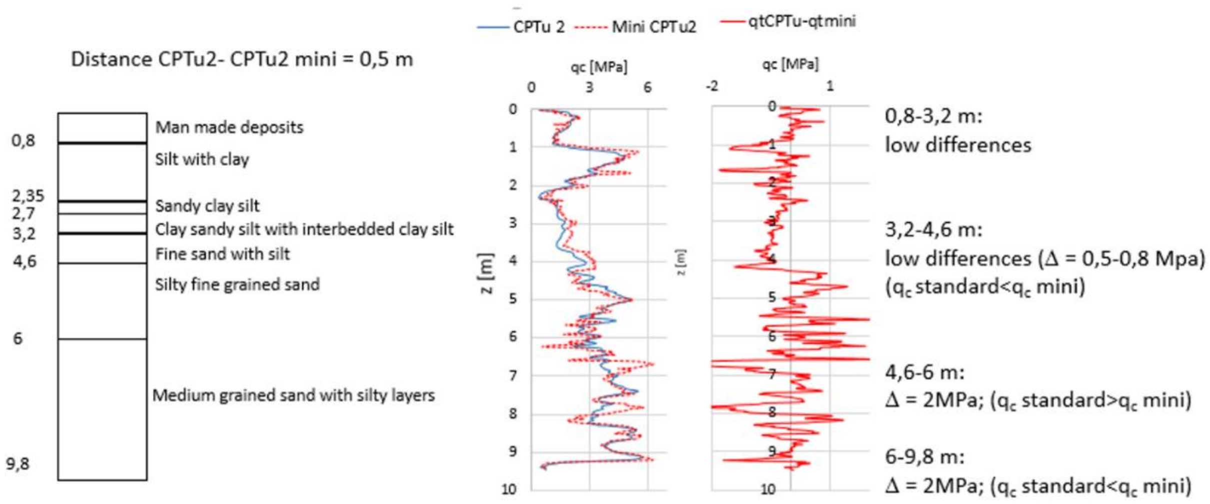


Figure 7. Comparison standard CPT vs mini-CPT in correspondence of the borehole in the test site B.

The soil mainly consists of silt (50 % on average) and clay (30 % on average). In borehole A, a thin layer of silty sand is present between 2,37 and 2,5 m (thickness of 13 cm) (Fig. 4). The largest percentages of granular soil (from fine sand to medium gravel) were observed in borehole C where the granular fraction was from 30 to 70 % (thin layers of silty sand between 1,65 and 2 m – 35 cm- and between 2,17 and 2,33 m – 18 cm) (Fig. 5). No thin layers were observed in borehole B.

Occasionally large discrepancies in terms of q_c or f_s between standard and mini cone can be observed (Figs. 4-5). Anyway, the comparison in terms of q_c (Figs. 4-5) suggests the following observations:

- in some cases, differences are negligible (but they can also reach 1-2 MPa);
- in other cases, these differences may disappear and the q_c profiles from both types of tests may perfectly overlap after a simple vertical translation;
- differences are not systematic;
- differences do not seem linked to the soil grain size;
- generally, q_c(standard) is less than q_c(mini).

The comparison between standard and mini cone test results in terms of f_s suggests the same observations as for q_c (Fig. 6). It is possible to conclude that the spatial variability more than the systematic effect of the tip geometry can be considered responsible of the observed differences. On the other hand, large values of the tip resistance especially in the shallower layers may be a consequence of desiccation phenomena which makes unreliable the use of conventional classification charts [18, 19]. For the test site B, the comparison between standard and mini cone test results in terms of q_c (Fig. 7) suggests the following considerations:

- from 0,8 to 3,2 m: silt with clay, low differences;
- from 3,8 to 4,6 m: (silt with clay, sandy clay silt, clay sandy silt with interbedded clay silt and fine sand with silt) the differences are negligible (q_c(standard) < q_c(mini)), (Δ = 0,5-0,8 MPa);
- from 4,6 m to 6 m: silty fine-grained sand, strong differences between q_c(standard) and q_c(mini) (Δ = 2MPa) and q_c(standard) > q_c(mini);
- from 6 m to 9,8 m: strong differences between q_c(standard) and q_c(mini) (Δ = 2MPa) and q_c(standard) < q_c(mini).

The differences seem to be related to differences in grain size and in particular to the presence of sandy layers. For the test site B, the comparison between standard and mini cone test results in terms of f_s do not evidence any particular correlations. Generally, from 0,8 m to 4,6 m f_s(standard) > f_s(mini) (Δ < 50kPa), whereas from 4,6 m to 9,4 m the differences are smaller and f_s(standard) < f_s(mini). Soil Behaviour Type Index (I_c) represents the radius of concentric circles that define the boundaries of soil type. It is possible to identify the transition from one soil type to another using the rate of change of I_c. When the CPTu is in transition from sand to clay, the I_c will move from low values in the sand to higher values in the clay. Robertson and Wride (1998) [20] suggested that the approximate boundary between sand-like and clay-like behavior is around I_c = 2.60. Hence, when the rate of change of I_c is rapid and is crossing the boundary defined by I_c = 2.60, the cone is likely in transition from a sand-like to clay-like soil or vice versa. Thus, profiles of I_c can provide a simple means to identify these transition zones. The comparison between the I_c values by standard and mini cone (Fig. 8) evidences for the test site A that I_c(mini) = I_c(standard) except for thin layers of sand where I_c(mini) ≤ I_c(standard). The thin layer from 2,17 and 2,35 m is not identified by standard CPTu, which presents two peaks of I_c that do not correspond to the right depth of the thin layer, on the other hand the mini-CPTu recognize the depth of the thin layer. The comparison of I_c(standard) vs I_c(mini) for the test site B highlights different behaviors between the layers as for q_c but with a different meaning. In the first layers till 2,7 m I_c(mini) = I_c(standard); at depth between 2,7 m and 4,6 m the behavior is different and I_c(mini) < I_c(standard); from 4,6 m and 9,8 m I_c(mini) ≥ I_c(standard) (Fig. 9). It seems that the differences in term of I_c are stronger in the layer between 2,7 m and 4,6 m, where the mini-cone is able probably to identify thin layers of sand. After comparing q_c, f_s and I_c of standard and mini CPTu the thin layer correction proposed by Boulanger and De Jong (2018) was applied to all the standard CPTu and mini-CPTu that were performed in the test sites A and B using the software CPeT-IT v.3.

For the test site A, the thin layers of the borehole A (from 2,37 m to 2,5 m) and from boreholes C (from 1,65-2m) are not detected by standard CPTu. The application of the thin layer correction to standard CPT does not improve the identification, except for the thin layer from 2,17 to 2,35m which is identified, but a wrong depth (Fig. 10). Mini-CPTu identify the thin layers except for the thin layer of borehole C between 1,65-2 m. The correction of mini-CPTu doesn't improve the identification (Fig. 10).

For the test site B, the correction of the mini-CPTu improves the identification of thin layers of sand between 2,7 and 4,6 m (Fig. 11). In particular, mini-CPTu recognizes a thin layer of sand between 4 and 4,25 m. From 6 to 9,8 m, mini-cone also evidences sand layer containing silty layers. The correction of standard CPTu improves the identification, but in most cases the depth does not matches that identified from boreholes. Also, in this case the application of the thin layer correction to mini-CPTu does not improve the results.

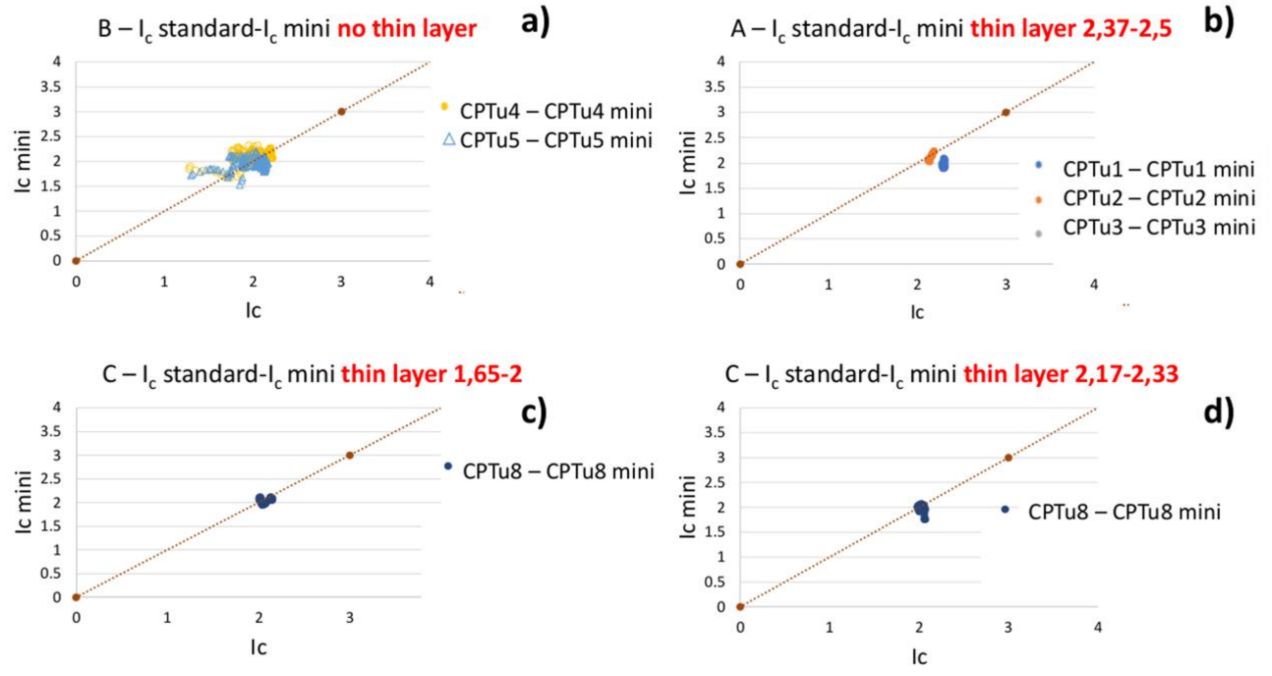
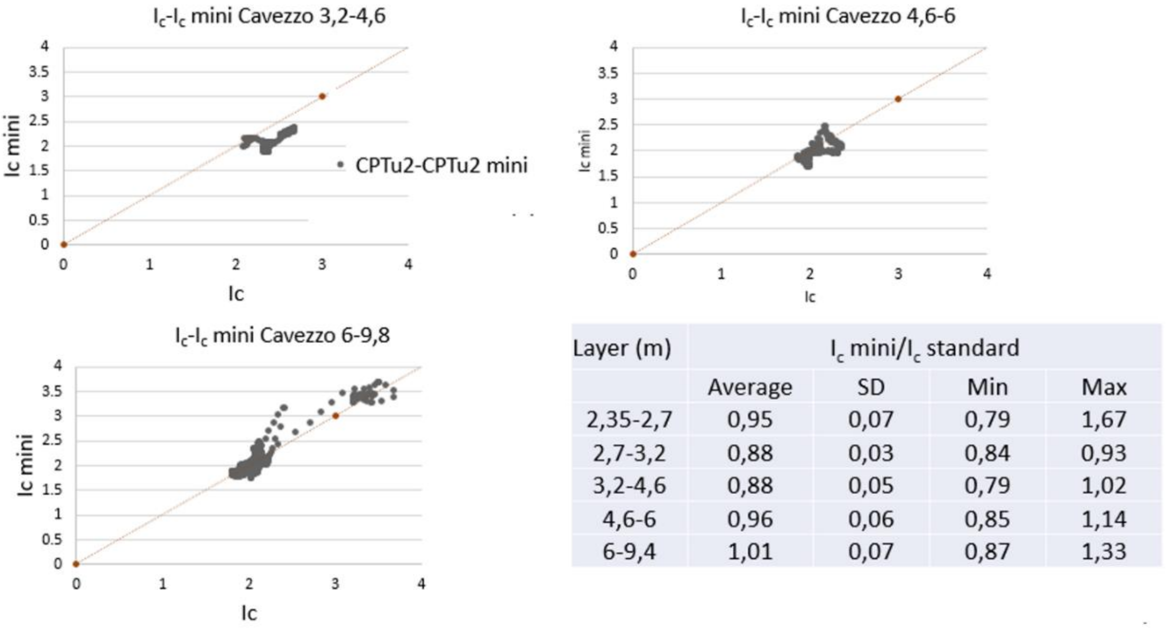


Figure 8. Test site A: I_c standard vs I_c mini.



Layer (m)	I_c mini/I_c standard			
	Average	SD	Min	Max
2,35-2,7	0,95	0,07	0,79	1,67
2,7-3,2	0,88	0,03	0,84	0,93
3,2-4,6	0,88	0,05	0,79	1,02
4,6-6	0,96	0,06	0,85	1,14
6-9,4	1,01	0,07	0,87	1,33

Figure 9. Test site A: I_c standard vs I_c mini.

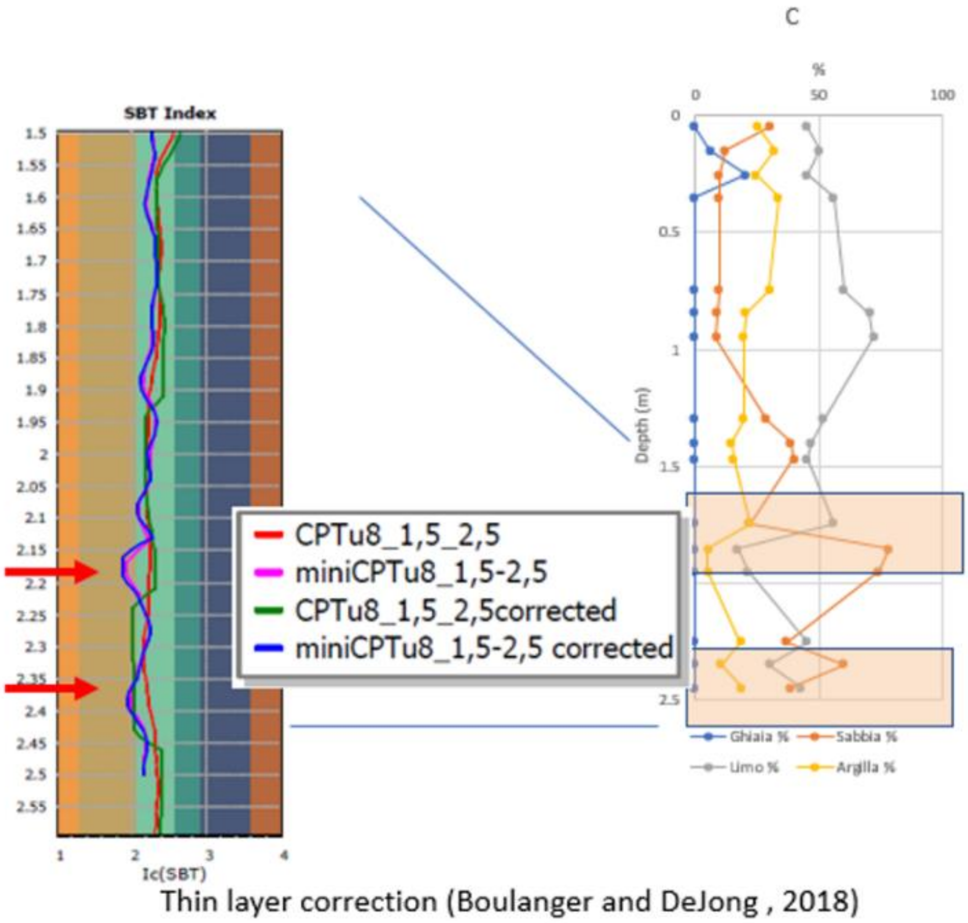


Figure 10. Test site A: thin layer correction applied to standard CPTu8 and mini-CPTu8. Close up of the depth between 1,5- 2,6 m and comparison with the grain size.

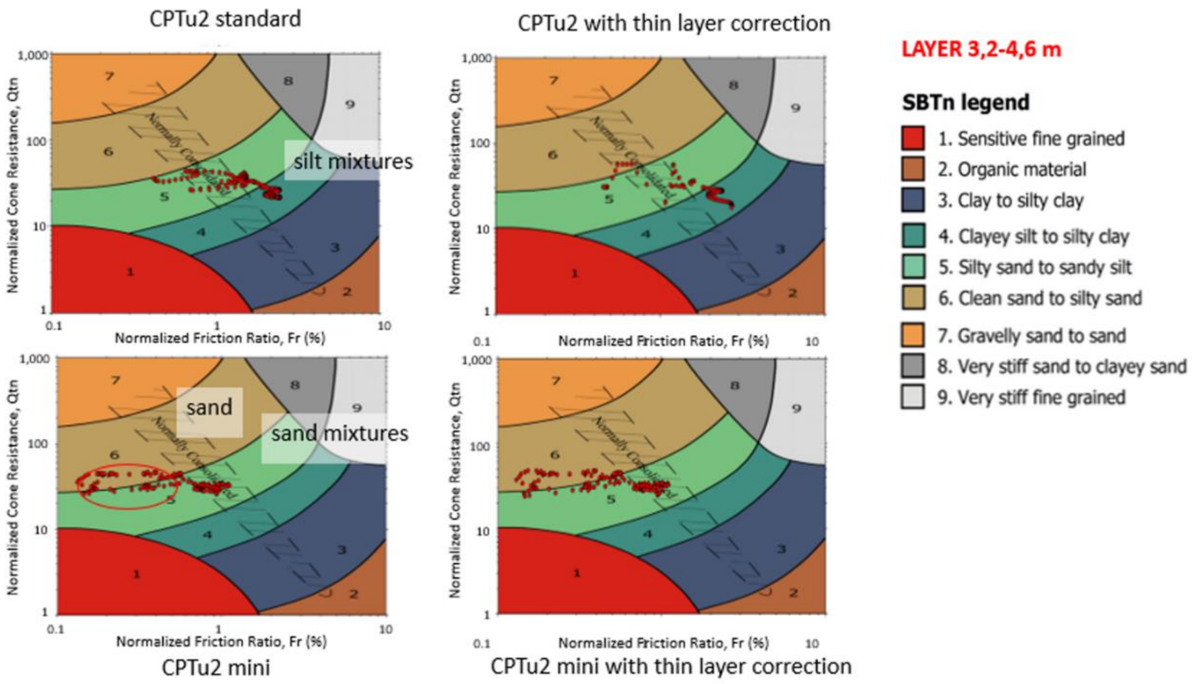


Figure 11. SBTn plot for the test site B: thin layer correction.

5. Conclusions

To overcome the standard CPT test drawbacks in identifying/characterizing thin soil layers, the use of a mini-cone test (mini-CPT) represents a suitable solution. The work investigated the capabilities and limitations of the mini-cone for a better identification of thin soil layers and improvement of liquefaction analysis in layered soil deposits. Two test sites representative of different conditions were selected: site A (Calendasco) is characterized by thin layer of sand in silty clay, in unsaturated conditions; site B (Cavezzo) represents thin layers of silty mixtures in sandy soils and sandy layers in silty soils, the soils are saturated and liquefaction phenomena occurred during the seismic sequence of 2012. The thin layers have thickness from 10 to 35 cm.

The comparison of q_c(standard) – f_s(standard) and q_c(mini) – f_s(mini) highlights that generally not systematic differences exist, even if generally q_c(standard) < q_c(mini). In some cases, differences of q_c are not negligible (1-2 MPa) and are not related to differences in grain size but they depend on the spatial heterogeneity. Similar conclusions can be drawn as far as f_s is considered. In both the test sites thin sandy layers are characterized by I_c(mini) ≤ I_c(standard), with a ratio of the I_c index as low as 0.88. This allows us to conclude that the mini-cone is certainly a valid alternative to the standard in identifying thin sandy layers.

Thin layers are generally not detected by standard CPTu and for the study case, the thin layer correction looks ineffective, as the thin sandy layers are not identified, or their depth/thickness does not match the borehole evidences. On the other hand, in both sites, thin layers are generally detected by mini-CPTu. For obvious intrinsic reasons, the correction doesn’t apply to the mini-cone.

The advantages of the use of mini-CPT can be summarized in the more detailed stratigraphic logging; in the correct thin layers identification. Mini-cone seems to be very promising for shallow investigations in soils with multiple thin layers (shallow landslides, liquefaction in shallow horizons, etc…). Another advantage is the fact that smaller and light vehicle is necessary compared to the standard CPT test.

Acknowledgement

The authors thank Pagani Geotechnical Equipment (Piacenza, Italy), which provided all the equipment. The borehole in the area of Cavezzo were carried out in the frame of the project Horizon 2020 LIQUEFACT (Assessment and mitigation of liquefaction potential across Europe: a holistic approach to protect structures / infrastructures for improved resilience to earthquake-induced liquefaction disasters). The LIQUEFACT project has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement No. 700748. The authors would also thank the Major of the Cavezzo Municipality and the technical staff in particular Ing. Agnese Malagoli and Arch. Antonella Marcantoni for the logistic support during the CPT tests carried out in March 2019. This research was partially funded by University of Pavia in the framework of a research grant award “assegno di tipo A premiale” for research activities at the Dept. of Earth and Environmental Sciences, within the research project entitled “Sustainable groundwater resources management by integrating A-

DInSAR derived monitoring and flow modeling results” assigned to Roberta Bonì in March 2019.

References

[1] Bucci, M. G., Villamor, P., Almond, P., Tuttle, M., Stringer, M., Ries, W., ... & Watson, M. "Associations between sediment architecture and liquefaction susceptibility in fluvial settings: The 2010–2011 Canterbury Earthquake Sequence, New Zealand", Engineering Geology, 237, pp. 181-197, 2018. https://doi.org/10.1016/j.enggeo.2018.01.013

[2] Gallerini, G., De Donatis, M. "3D modeling using geognostic data: The case of the low valley of Foglia river (Italy)", Computers & Geosciences, 35(1), pp. 146-164, 2009. https://doi.org/10.1016/j.cageo.2007.09.012

[3] Lunne, T., Robertson, P., Powell, J. "Cone Penetration Testing in Geotechnical Practice", First edition, Blackie & Professional, London UK., 1997, pp. 352.

[4] Van der Linden, T. I., De Lange, D. A., Korff, M. "Cone penetration testing in thinly inter-layered soils", Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 171(3), 215-231, 2018. https://doi.org/10.1680/jgeen.17.00061

[5] Boulanger, R. W., DeJong, J. T. "Inverse filtering procedure to correct cone penetration data for thin-layer and transition effects", In: Proceedings of the 4th International Symposium on Cone Penetration Testing (CPT 2018), Delft, The Netherlands. CRC Press, June 21-22, 2018, pp. 25-45.

[6] De Lange, D. A., Terwindt, J., Van der Linden, T. I. "CPT in thinly inter-layered soils", In: Proceedings of the 4th International Symposium on Cone Penetration Testing (CPT 2018), Delft, The Netherlands. CRC Press, June 21-22, 2018, p. 383.

[7] ASTM. "Standard test method for performing electronic friction cone and piezocone penetration testing of soils" D 5578-95, Philadelphia, 1995.

[8] ISO. Geotechnical investigation and testing – Field testing – Part 1: Electrical cone and piezocone penetration tests, International Standard ISO 22476-1:2012.

[9] Tumay, M. T., Kurup, P. U., Boggess, R. L. "A continuous intrusion electronic miniature cone penetration test system for site characterization", In: Proceedings, International Conference on Site Characterization, Vol. 98, 1998, pp. 1183-1188.

[10] Tumay, M. T., Titi, H. H., Senneset, K., Sandven, R. "Continuous intrusion miniature piezocone penetration test in quick soil deposits", In: Proceedings of the Fifteenth International Conference on Soil Mechanics and Geotechnical Engineering, Vol. 1-3, Istanbul, Turkey, 2001, pp. 523-526.

[11] Damavandi-Monfared, S., Sadrekarimi, A. "Development of a miniature cone penetrometer for calibration chamber testing", Geotechnical Testing Journal, 38(6), pp. 878-892, 2015. https://doi.org/10.1520/GTJ20150036

[12] Lo Presti, D., Squeglia, N., Cosanti, B. "Evaluating degree of compaction of levees using Cone Penetration Testing", Journal of GeoEngineering, 13(3), pp. 1-14, 2018. http://dx.doi.org/10.6310/jog.201809_13(3).4

[13] Meisina, C., Bonì, R., Bordoni, M., Lai, C. G., Famà, A., Bozzoni, F., Cosentini, R. M., Castaldini, D., Fontana, D., Lugli, S., Ghinoi, A., Martelli, L. Severi, P. "3D Geological model reconstruction for liquefaction hazard assessment in the Po Plain", In: Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions, Silvestri & Moraci (Ed, s), In: 7th International Conference on Earthquake Geotechnical Engineering, 7ICEGE, Rome, Italy, June 17-20, 2019, pp. 3837-3844.

[14] Lo Presti, D., Sassu, M., Luzi, L., Pacor, F., Castaldini, D., Tosatti, G., Meisina, C., Zizioli, D., Zucca, F., Rossi, G., Saccorotti, G., Piccinini, D. "A report on the 2012 seismic sequence in Emilia (Northern Italy) ", In: Seventh International Conference on case Histories in Geotechnical Engineering, Chicago, April 29-May 4, 2013, ISBN 1-887009-17-5.

[15] Emergeo Working Group, "Liquefaction phenomena associated with the Emilia earthquake sequence of May–June 2012 (Northern Italy) ", Natural Hazards and Earth System Sciences, 13, pp. 935-947, 2013. https://doi.org/10.5194/nhess-13-935-2013

[16] Lehane, B. M., O’Loughlın, C.D., Gaudın, C., Randolph M.F. "Rate effects on penetrometer resistance in kaolin", Geotechnique 59 (1), pp. 41–52, 2009. https://doi.org/10.1680/geot.2007.00072

[17] Tufenkjian, M. R., Thompson, D. J. "Shallow penetration resistance of a minicone in sand", In: Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka, Japan, 2005, p .89.

[18] Lo Presti, D.; Stacul, S.; Meisina, C.; Bordoni, M.; Bittelli, M. "Preliminary Validation of a Novel Method for the Assessment of Effective Stress State in Partially Saturated Soils by Cone Penetration Tests", Geosciences, 8, 30, 2018. https://doi.org/10.3390/geosciences8010030

[19] Lo Presti, D.; Giusti, I.; Cosanti, B.; Squeglia, N.; Pagani, E. "Interpretation of CPTu in “unusual” soils", Rivista Italiana di Geotecnica, 50, pp. 23–42, 2016.

[20] Robertson, P., Wride, C. "Evaluating cyclic liquefaction potential using the cone penetration test", Canadian Geotechnical Journal, 35(3), pp. 442-459, 1998. https://doi.org/10.1139/t98-017