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Development and use of a minicone for liquefaction risk evaluation in layered soil deposits

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Abstract: This paper shows and compares the experimental results obtained by using a standard cone (10 cm^2) and a minipiezocone (2 cm^2). 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 minipiezocone and to explore the possibility of obtaining a better prediction of soil stratigraphy in thin layered deposits. Systematic differences in terms of tip resistance and sleeve friction were not observed, even though, generally, q_c standard$<q_c$ mini. The spatial heterogeneity was considered responsible of the higher observed differences. In both the test sites thin sandy layers are characterized by I_c mini$\leq$ 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 could be a valid alternative to the standard in identifying thin sandy layers.

Keywords: Cone Penetration Test CPTu, Mini CPTu, Layered Deposits, Liquefaction risk

Introduction

Since the early works of Treadwell (1976) and Lunne et al. (1997) it is well recognized that the tip resistance is influenced by the soil properties both ahead and behind the tip. In particular, Lunne et al. (1997) 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 sufficient. As a consequence, in case of stiff thin layers the tip resistance could be underestimated. In practice, it has been concluded that it is easier to detect thin soft layers than stiff ones. Later researches confirmed these observations, in particular the contribution by Walker and Yu (2006, 2010) that performed a numerical analysis of undrained penetration within a layered clay model (FEM with adaptive mesh).

The fact that the target tip resistance of stiff layers may be measured only when the layer thickness is greater than 10-20 diameters could be explained, from a qualitative point of view, by the following hypotheses (Lo Presti et al. 2009): indeed, the tip resistance can be considered as the ultimate bearing capacity of a deep foundation. When the tip is moving from a stiff sand layer towards a soft layer it is possible to assume a local/punching failure mechanism. On the other hand, in the opposite case a general failure mechanism could be considered. This has implications in some challenging issues of CPTu interpretation as transition zones and thin layers identification (Van der Linden, 2018, Boulanger and De Jong, 2018; De Lange, 2018).

CPTu 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 in channel and levee facies. In order to improve CPTu capabilities, possible solutions can derive by the application of methodologies for thin layer correction or the use of a cone of smaller size (mini-cone). Many researchers attempted to model the cone penetration in layered soils by using different approaches (Vreugdenhil et al. 1994, Yue and Yin (1999), Ahmadi and Robertson (2005), Tehrani et al. (2017), Xu and Lehane (2008), Mo et al. (2015, 2017). These studies were aimed at modelling the cone penetration in layered soils, validating the proposed model by means of available experiments (not numerous) and suggesting a correction procedure. When the cone is approaching an interface, the distance at which the tip resistance is influenced by such an interface is called “sensing distance” (Tehrani et al. 2017). After the cone passes the interface, the “development distance” is that at which the tip resistance is no more affected by such interface. The correction procedures were mainly developed to correct the experimental results in case of stiff layers sandwiched between soft layers. In practice the objective was to find the real thickness of the stiff layers and the corrected tip resistance. Such a correction procedure is extremely important in liquefaction analyses of layered sand deposits. According to Boulanger et al. (2016) the use of simplified liquefaction vulnerability indices can overestimate the liquefaction potential. This is confirmed especially in the case of moderate earthquake (Lo Presti et al. 2013). Boulanger and DeJong (2018) provided an almost complete literature review concerning such a topic and suggested a correction methodology (inverse filtering procedure) based on previous researches. They also applied the procedure for re-analysing some real cases. A simple correction can be done by the use of the following method (Ahmadi and Robertson 2005):

$$q_c^* = K_H \cdot q_{cA}$$

Where: $\mathbf{q_c^*} =$ correct tip resistance of layer A; $\mathbf{K_H} =$ correction factor; $\mathbf{q_{cA}}$ = measured tip resistance of layer A.

On the whole, the available correction procedures never consider the sleeve friction (fs) or dynamic pore pressure (u2), nonetheless the sleeve friction seems to be more sensitive to layering (Boulanger and DeJong 2018). In fact, it could be possible to model the soil layers beneath the tip as a series of springs, while the soil in contact with the sleeve could be represented as parallel springs. With this respect the sleeve friction is a “local measurement” (Lo Presti et al 2009).

To overcome the standard CPTu test drawbacks in identifying/characterizing thin soil layers, the use of a mini–cone test (mini-CPTu) could also represent a suitable solution. International standards such as ASTM D5578 (2012) and ISO 22476-1 (2012) 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. Tumay et al. (1998, 2001) developed a mini cone with an apex angle of 60°, projected cone area of 2 cm^2 and a friction sleeve area of 40 cm^2, for application in the field of “Transportation Geotechnics”. Power and Geise (1995) and Tufenkjian and Thompson (2005) developed and used a similar mini-cone for the seafloor exploration. Mini-cones were also used for testing in small Calibration Chambers CC (De Linna 1990; Kurup et al. 1994, Abedin 1995; Franzen 2006; Kumar and Raju 2008; Löfroth 2008; Kokusho et al. 2012; Pournaghiazar et al. 2012, Damavandi-Monfared and Sadrekarimi 2015, Lo Presti et al. 2018a). Lo Presti et al. (2018a) performed penetration tests in compacted, fine grained, partially saturated samples in a small CC by using a mini-cone with a projected cone area of 0.5 cm^2. Kurup et al. (1994) and Abu-Farsakh et al. (1998) performed and analysed penetration tests in a CC on fully saturated cohesive soils by using a mini-cone. In particular, they focused on pore pressure generation and dissipation. More recently, De Lange et al. (2018) investigated the interpretation of CPTu in laminated soils based on experimental laboratory CPTu tests performed in artificially built up layered soil. While all the above-mentioned studies employed mini-cones in 1 g conditions, other mini-cones were also developed for centrifuge testing (e.g., Bolton et al. 1999). A summary of miniature cones for Calibration Chamber (CC) Testing is given by Damavandi-Monfared and Sadrekarimi (2015). Only few of these mini-cones provide simultaneous measurements of cone tip resistance, sleeve friction and dynamic pore water pressure. In conclusion, the use in common practice of mini-cones is mainly restricted to shallow exploration and enhancement of the capability of CPTu in identifying thin layers.

A direct comparison of the measured tip resistance has been done by various researchers, reaching different conclusions. The different ratio between cone diameter dc and the mean grain size d50, could be the reason for such differences. In the case of the analysed test sites, the soil size effects are null because the ratio dc/d50 values are higher than 28 (Bolton et al.,1999).

Considering the difficulties in thin layer identification during conventional boreholes as well costs and difficulties when using advanced methods (e.g. gel push and/or freezing), the CPTu tests remain extremely useful for the identification of thin layers. The purpose of the present study was to compare pairs of standard and mini-cone tests carried out at Calendasco (Piacenza, Northern Italy) at the Pagani Geotechnical Equipment test field in a natural soil deposit consisting of clayey-sandy silts. Another test series were carried out at Cavezzo (Modena, Northern Italy). In the latter site liquefaction-evidences were observed during the 2012 seismic sequence. The capabilities and limitations of the mini-cone have been investigated for a better identification of thin soil layers and improvement of liquefaction analysis in layered soil deposits. More specifically, the comparison involved the following activities:

- comparing the measured tip resistance of pairs of standard and mini-cone tests;
- comparing the measured sleeve friction of pairs of standard and mini-cone tests;
- comparing the inferred Behaviour Type Index (Ic);
- considering the grain size distribution variation with depth;
- evidencing differences in soil layering as inferred from standard and mini-cone tests;
- applying the thin – layer correction to both standard and mini-cone, according to the Boulanger and De Jong (2018) procedure;
- investigating the capabilities and limitations of mini-cone for the improvement of liquefaction analysis.

Equipment and testing procedures

Penetration tests were carried out by using a Penetrometer, standard piezocone (CPTu) and mini – piezocone. All the equipment was 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.

Mini Piezocone

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/sec. This involves a different normalized velocity between standard and mini piezocone (VN = v/(d*Cv) where d is the cone diameter and Cv the coefficient of primary consolidation (Lehane et al. 2009). Anyway, the possible effects of such a difference appear negligible. Lower force is required to push the mini-cone into the soil (Tumay et al., 1998) and a smaller and lighter vehicle is necessary compared to the standard CPTu test. This fact provides a greater mobility and site accessibility (Tufenkjian and

Thompson, 2005). 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. Penetration tests were carried out by using a Penetrometer, standard piezocone (CPTu) and mini piezocone. All the equipment was 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. As for the standard cone, silicone oil was used for saturation of the filter.

Furthermore, the mini piezocone was used to measure the effect of penetration rate on pore pressure (U2) as well as on tip resistance and sleeve friction (Giusti 2017). The mini piezocone has already been used for evaluating the effect of penetration rate on pore pressure (U2) as well as on tip resistance and sleeve friction (Giusti 2017). Table 1 summarizes some characteristics of the sensors in the case of the mini-piezocone.

Giusti (2017) performed a series of tests in the Calibration Chamber (CC) of Pagani Geotechnical Equipment Company. In particular, the pore water pressure was measured using silicone grease (very fluid, NLGI 149 00) as the slot filter saturation fluid. The use of grease as a saturation fluid was first proposed by Elmgrem (1995) and Larsson (1995), and various comparisons have testified its reliability.

Unfortunately, the pore pressures measurements with mini-cone in the test sites, did not give reasonable values of the dynamic pore pressure during penetration. Therefore, these data were not included in the work and further studies will be performed to address this issue.

The Test Sites

Two test sites are located in the Po Plain (Northern Italy) (Fig.1):

- Test site A Calendasco: silty clay soils, thin layers of sand (thickness 13-35 cm) in silty clay, unsaturated conditions, no liquefaction.

- Test site B Cavezzo: silty-sandy soils, thin layers (silty layers in sandy soils and sandy layers in silty soils), saturated conditions, liquefaction.

The test site A is located at Calendasco (province of Piacenza, Italy) and it is characterized by Holocenic deposits of the Po river consisting of clayey silts and sandy silts (CL) with sandy intercalations down to a variable depth from 6.6 to 8.6 m (Fig.2). At greater depths a gravelly layer is present. The water table is 9.5 m below the ground surface. For this study, standard and mini CPTu supplied measurements of cone tip resistance (q_c) and sleeve friction (f_s). The pore pressure measurements resulted useless because the soil was almost dry. Indeed, tests were performed during a very dry season (end of August 2018). As the tip resistance is affected by the soil moisture (Lo Presti et al. 2016, 2018a, 2018b), all the test - pairs were carried out at the same time.

The test site B is located at Cavezzo (Cavezzo municipality, Province of Modena) on the right side of the Secchia river (Fig.1). The territory is quite flat, has elevations gently decreasing from 34 m a.s.l. approx. in the south to approximately 16 m a.s.l. approx. in the north. The site is located about 3 km far from the epicentre of the May 29th 2012 earthquake (Mw= 5.8; Rovida et al., 2016). The shallow lithostratigrafic 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, whereas the deeper sands are probably referable to the sedimentation of soils from the Po river (Castaldini, 1989). The lithostratigraphy of the first 30 meters of the alluvial successions shows that the deposition in the study area was characterised by significant variations, both vertically and horizontally, due to frequent changes in the fluvial drainage framework and regime. Channel–levee units consisting of sand layers (channels) that alternate to fine sand-silt- bodies (levees and proximal crevasse splays) pass to distal levee and alluvial plain silts and silty clays. The contact among these layers are variable, from discrete interfaces to gradual-transitional passages at a centimetric to decimetric scale, both fining and coarsening upward, depending on the fluvial dynamics. A reference conceptual model based on the data obtained in the investigated site was elaborated and adopted to interpret the engineering proprieties of soils (Meisina et al, 2019). In particular, five stratigraphic units were identified:

-Unit A; heterogeneous deposits, lithological classes clayey silt and clayey sandy silt (La, Las), with interbedded thin silty sand (Sl) layers corresponding to the recent alluvial plain.

- Unit B; lithological classes sand (S), silty sand (Sl) and sandy silt (Ls) corresponding to the fluvial channel.

- Unit C; clay (A) and clay with peat (At) corresponding to the lacustrine depositional environment.

- Unit D; clay (A) of the ancient alluvial plain.

- Unit E; dense sands of the ancient fluvial channel.

The units investigated in this paper correspond to Units A and B. The water table depth in the test site B is 2.10 m (March 2019). The liquefaction-induced ground surface manifestations known as co-seismic effects at Cavezzo after the May 29th 2012 earthquake with 5.8 Magnitude (Lo Presti et al. 2013, Emergeo Working Group, 2013) are located along a buried abandoned riverbed of the Secchia River that was active during Roman and Medieval times until the 13th century. The observed co-seismic effects consisted of liquefaction, fractures, water level rise and liquefaction (liquefaction means sand transportation at the ground level). The Cavezzo area, where the tests were carried out, was characterized from the engineering geological and geotechnical point of view through investigations in the framework of the LIQUEFACT Horizon 2020 project. The data belong to different databases listed as follow (Fig.8):

• LIQUEFACT investigation campaigns performed by Geostudi Astier in December 2016, by Geotecnica Veneta and UNIPV- DSTA (Laboratory of Engineering Geology and Geotechnics) in January 2017 (borehole SP919_LIQ1 and CPT U998_COM);

- Collection and digitization of Post-2012 earthquakes geognostic investigations (MUDE database), (borehole SP877_R and CPT U857_R);
- Investigation campaigns funded by Comune di Cavezzo and RER performed by Tecnoin Geosolution and Elletipi (Laboratory tests) in December 2017 and January 2018 (borehole SL999_COM and CPT SU909_LIQ1).

Silty sands and sandy silts are present between 2.3 and 10 m from ground level, which are overlapped by a clayey soil of about 2.3 m in thickness. The borehole SP919 LIQ1 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%) (Fig.3 and Table 2).

Regarding the samples used for the classification tests, the material extracted from the boreholes SP919_LIQ1 and SL999_COM and the samples of the Cavezzo sand boils were analysed at the geotechnical and sedimentological laboratories of the University of Pavia, Modena and Reggio Emilia (Fig.4). Textural analyses were performed both on sand blows and in sandy layers in the subsurface at different depths. Grain-size analyses were performed using standard techniques: mechanical sieving for the sandy fraction and hydrometer analysis for fine-grained sediments. Sand samples consisting of a few hundreds of grams were washed with dilute H_2O_2 to remove organic matter. Grain-size analyses are reported as the granulometric curve in Figure 5. Sand blows are slightly more selected that the sand from the source layers as a result of the ejection mechanism (Fontana et al., 2015, 2019). The petrographic composition (quartz+feldspar, carbonate, lithic content) of the sand of boreholes and the sand blows was compared (Fig. 6). Modal analyses were carried out on the 0.125–0.250 mm fraction, by point counting (300 points) under transmitted-light microscopy. The composition of sand blows overlaps the composition of shallow sand layers from both boreholes down to the depth of 4.5 m, thus suggesting these layers as the source for liquefied sands.

The Tests

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. 7). In addition, the penetrometer was used to retrieve Shelby tube samples. Samples were retrieved from three locations (A, B and C in Fig. 7). 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.

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. 8). In this paper, only the results for the pairs CPTu2-mini CPTu2 were analysed. The area is characterized by a strong lateral and vertical heterogeneity, as demonstrated by the Soil Behaviour Type Index (I_c), with an increase of the sandy layers from North to South where sand boils occurred (Fig.9). In relation with their location the tests were compared with the borehole SP 919 LIQ1 performed in the frame of the project Horizon 2020 LIQUEFACT.

Analyses and Results

The tip resistance (q_c) for different pairs of standard CPTu-mini CPTu performed at Calendasco are compared in Figures 10-11. 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.

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.10). 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.11).

Occasionally large discrepancies in terms of q_c or fs between standard and mini-cone can be observed (Figures 10 and 11). Anyway, the comparison in terms of q_c (Figures 10 and 11) 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 (Figures 10 and 11).

It is possible to conclude that the spatial variability more than the systematic effect of the tip diameter 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.

No thin layers were observed in borehole B (Fig.12). For the test site B, the comparison between standard and mini-cone test results in terms of q_c (Fig.12) suggests the following considerations:

- from 0.8 to 3.2 m: silt with clay, small 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 mini (Δ = 2MPa) and q_c standard$>q_c$ mini;

- from 6 m to 9.8 m: strong differences between q_c standard and 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$>$$f_s$ mini ($\Delta<50$kPa), whereas from 4.6 m to 9.4 m the differences are smaller and f_s standard$<$$f_s$ mini (Fig. 12). Soil Behaviour Type Index (I_c) represents the radius of concentric circles that define the boundaries of soil type and it estimated using the following equation (Robertson et al., 1990):

$$I_c = \sqrt{(3.47 - \log Q_{tn})^2 + (\log(F_r) + 1.22)^2}$$

where Q_{tn} and F are computed using the following equations:

$$Q_{tn} = \left(\frac{q_t - \sigma_{v0}}{p_a}\right)\left(\frac{p_a}{\sigma'_{v0}}\right)^n$$

q_t, p_a, and n stand for the total tip resistance, the atmospheric pressure and the stress exponent (Robertson et al. 1990). σ_{v0} and σ'_{v0} stand for the *in situ* total and effective vertical stress, respectively.

$$F_r = \left[\left({f_s}/{(q_t - \sigma_{v0})}\right)\right] 100\%$$

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 SBTn I_c will move from low values in the sand to higher values in the clay. Robertson and Wride (1998) suggested that the approximate boundary between sand-like and clay-like behaviour 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 results of the comparison between the I_c values standard and mini are represented in figures 13 and 14, for the test sites A and B, respectively. The comparison between the I_c values by standard and mini-cone (Fig.13) 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 (Fig.13). The thin layer from 2.17 and 2.33 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 (Fig.15). The comparison of I_c standard vs I_c mini for the test site B highlights different behaviours 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 behaviour is different and I_c mini$<I_c$ standard; from 4.6 m and 9.8 m I_c mini$\geq I_c$ standard (Fig.14). 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 CPTu does not improve the identification, except for the thin layer from 2.17 to 2.35 m which is identified, but a wrong depth (Fig.15). 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.15). In terms of stratigraphic interpretation, the Fig. 16 illustrates the I_c profile along the 8 tests (standard CPTu, corrected standard CPTu and mini CPTu). It is evident in all cases the overestimation of the grain size (all the soils have an I_c index less than 2.6 exhibiting a sand-like behavior) due to unsaturated conditions. Nevertheless, the sand ($I_c<1.8$) are identified only by mini CPTu.

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.17). In particular mini CPTu recognises 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.

The ratio between the q_c in the stronger versus the weaker layers has been estimated for both sites. The results give insight that the ratio is 1.2 and 1.3 for the test site A and B, respectively. Considering that the ratio is lower than 3 and the common literature values (Boulanger and DeJong, 2018), probably the mini cone and corrections did not have a large effect on q_c values of the analysed test sites.

Furthermore, factors of safety against liquefaction (FS) and Liquefaction Potential Index (LPI) were computed according to the procedures proposed by Boulanger and Idriss (2014, 2015).

The safety factor (FS) is estimated using simplified procedure based on the estimation of the earthquake induced cyclic stress ratio (CSR) and the cyclic resistance ratio (CRR) at various depths and it is assumed that the liquefaction occurs at a given depth in the following case:

$$FS = \frac{CRR}{CSR} = 1$$

The liquefaction potential index (LPI) is estimated for at least the first 20 m from g.l. using the approach proposed by Iwasaki (1978):

$$LPI = \int_0^{20} F_1 \, W(z) dz$$

where z is the depth expressed in meters below the ground level and W(z) is a depth weighting function computed as follow:

$$W(z) = 10 - 0.5z$$

whereas F_1 is computed using the following equations:

if FS ≤ 1 $\quad F_1 = 1 - FS$

if FS > 1 $\quad F_1 = 0$

For the assessment of FS and LPI, additional data were required: soil unit weight; water table depth; PGA (peak ground horizontal acceleration); Mw (moment magnitude).

An estimate of the unit weight (γ) was obtained from laboratory tests on specimens. In particular, the following estimate was adopted for computations: γ =19.0 kN/m^3.

The analyses were performed using the minimum value of the ground water table depth (GWT) obtained from monitored freatimeters available for the test site and observed measurements from post-earthquake evidences, by using a value of 0.5 and 2.1 m below ground level, respectively (Table 3). Furthermore, a sensitivity analysis of the I_c cut-off was performed. In particular, a range of I_c cut-off in between 2.5 and 2.8 was considered. The results show that the I_c cut-off effects on LPI were moderate and almost null for the minicone.

The CSR was inferred from an estimate of PGA (Peak Ground acceleration) (0.17) and moment magnitude Mw = 5.8 (May 29th event) was used to compute the FS in the study area. The LPI inferred from mini-cone is higher than that obtained from standard cone (depths in between 10 and 15 m) (Fig.18a). The LPI inferred from standard CPTu does not change after the thin layer correction in the layer 3.2 and 4.6 m (fine sand with silt). Differences between FS standard and FS mini are observed only in the layer between 3.2 and 4.6 m (fine sand with silt) (Fig.18b). The thin layer correction doesn't affect FS determination. These results are in good agreement with the identification of thin layer of sands by the mini-cone in the layer from 3.2 to 4.6 m and with the results of the petrographic and sedimentological studies.

Conclusions

To overcome the standard CPTu test drawbacks in identifying/characterizing thin soil layers, the use of a mini–cone test (mini-CPTu) 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 and are not evident systematic effect of the tip geometry but they depend on the spatial heterogeneity. Similar conclusions can be drawn as far as fs is considered. In both the test sites thin sandy layers are characterized by I_c mini$\leq I_c$ 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 and the thin layer correction will be significantly smaller for the smaller diameter mini-cone.

The mini piezocone was used for determining the effect of penetration rate on pore pressure (U2) as well as on tip resistance and sleeve friction (Giusti 2017). These tests were performed in the Calibration Chamber (CC) of Pagani Geotechnical Equipment Company. Compacted and saturated silt mixtures were successfully tested.

Unfortunately, in situ tests with minicone that were carried out for this paper, could not give reasonable measurement of dynamic pore pressure during penetration. Actually, the reasons for this unsuccessful behaviour are unclear and require further studies.

Differences between the I_c values inferred from standard and mini-cone affect the liquefaction potential assessment. For site B, in the layer between 3.2 and 4.6 m (fine sand with silt) the differences between FS standard and FS mini are relevant and are related to the identification through mini-CPTu of thin layers of sands, not evident through standard CPTu. These results are in good agreement with the results of the petrographic and sedimentological studies, which evidences that the composition of sand blows overlaps the composition of shallow sand layers down to the depth of 4.6 m, thus suggesting these layers as the source for liquefied sands.

The LPI obtained from mini-cone results is higher than that from standard (LPI increases from 10 to 15). The LPI calculated with standard CPTu does not change with the thin layer correction in the layer 3.2 and 4.6 m (fine sand with silt). These results are unexpected and require additional research before drawing definitive conclusions. More precisely, the adopted correction procedure was developed to overcome the liquefaction risk overprediction when using simplified methods.

The advantages of the use of mini CPTu 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 CPTu test.

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Acknowledgement

The authors thank Pagani Geotechnical Equipment (Piacenza, Italy), which provided all the equipment. The authors are thankful to Prof. Paul W. Mayne and Dr. Barry Christopher for pointing out to Pagani about the necessity of a commercial mini-CPTu. Some boreholes and CPTu used to build the geological cross sections 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: 1) Prof C. Lai, Ing. F. Bozzoni, Prof R. Cosentini and Ing. A Famà for the help in the interpretation of the boreholes and CPTu carried out during the LIQUEFACT project; 2) Dott Martelli of Emilia Romagna Region for some boreholes and CPTu data; 3) 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 CPTu 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.

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Tables

Table 1. Characteristics of the sensors for the mini-piezocone.

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

Table 2. Details of the test site B. FC: materials passing a number 200 sieve ASTM; Wl: liquid limit; IP: plasticity index.

Layer (m)	USCS	FC (%)	Wl (%)	IP
La (0.8-3.2)	CL	90-98	38-41	19-23
Sl (3.2-4.6)	CL	35	25	8
Sl (4.6-6.0)	SM	20-38	-	-
S (6-9.9)	S	10-20	-	-
A (>9.9)	CH	94-99	58-66	41-45

Table 3. Results of the sensitivity analysis of the LPI obtained using different values of the I_c cut-off.

		LPI			
		I_c=2.5	**I_c =2.6**	**I_c =2.7**	**I_c =2.8**
CPTu2	GWT in situ (m): 2.10	5	5	5	5

	GWT min. (m): 0.5	12	12.5	12.5	13
CPTu2 mini	GWT in situ (m): 2.10	7.5	7.5	7.5	7.5
	GWT min. (m): 0.5	17	17	17	17

Fig. 1. Geographical location of the test sites. Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

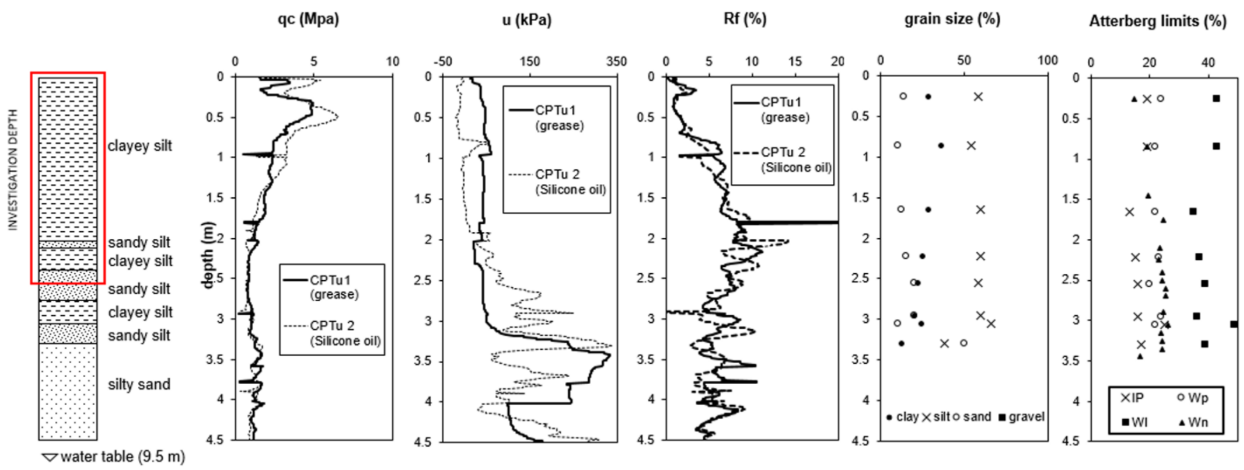


Fig. 2. Test site A: Soil profile and geotechnical characteristics. qc: cone resistance; u0: in-situ pore pressure; u2: pore pressure measure dat cone base; fs: sleeve friction; Rf: friction ratio (fs/qc*100) IP: plastic index; Wp: plastic limit; Wl: liquid limit, wn: natural water content.

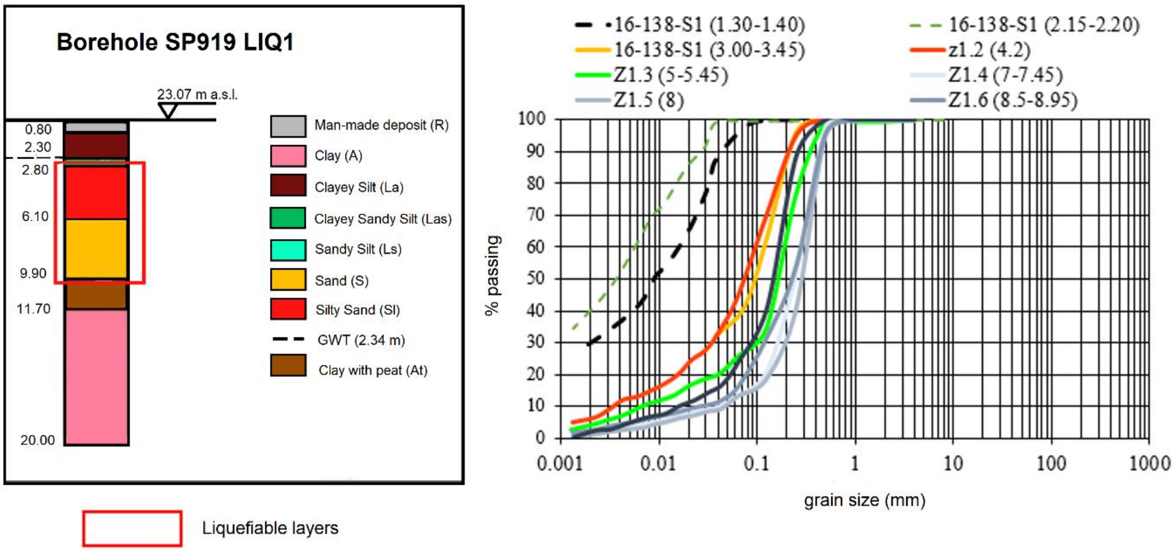


Fig. 3. Test site B: simplified borehole and grain size curves.

Fig.4. Example of liquefaction-induced ground surface effects observed in Cavezzo after the 29th May 2012 earthquake with 5.8 magnitude.

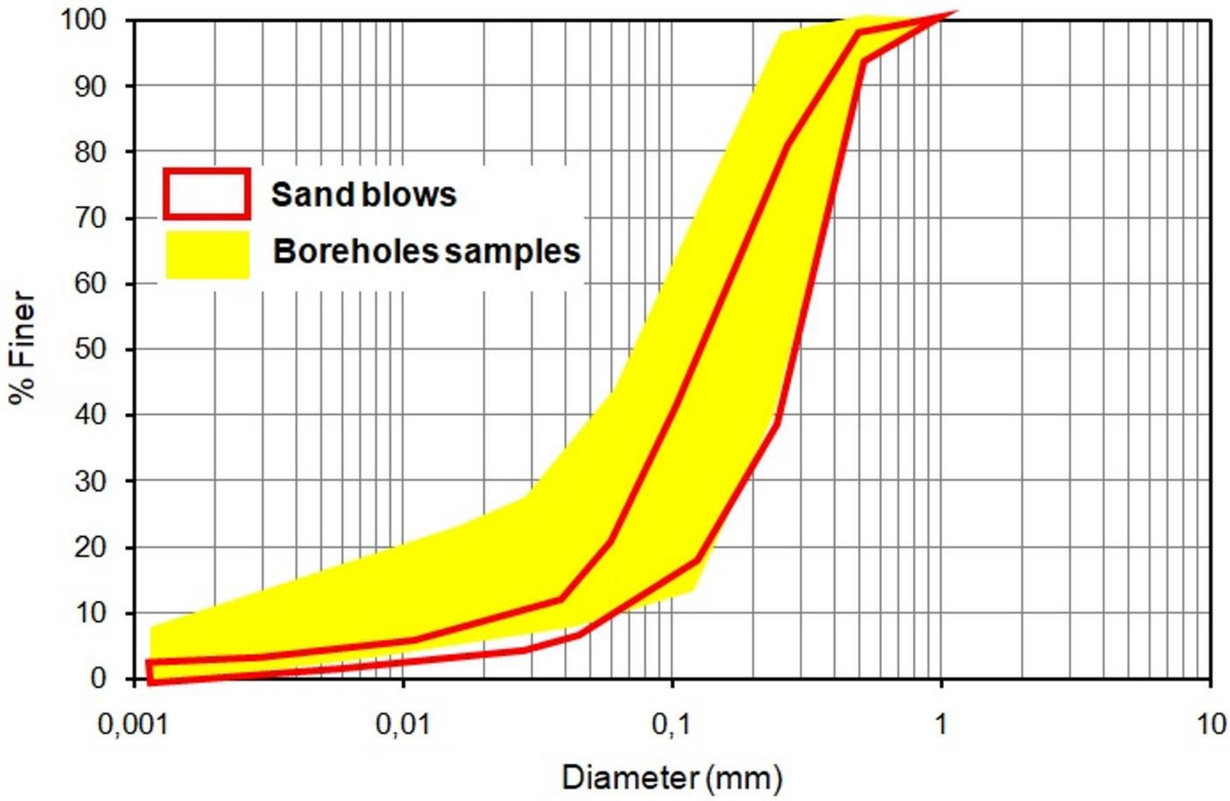


Fig. 5. Grain size curves of sand boils and the sands collected from boreholes.

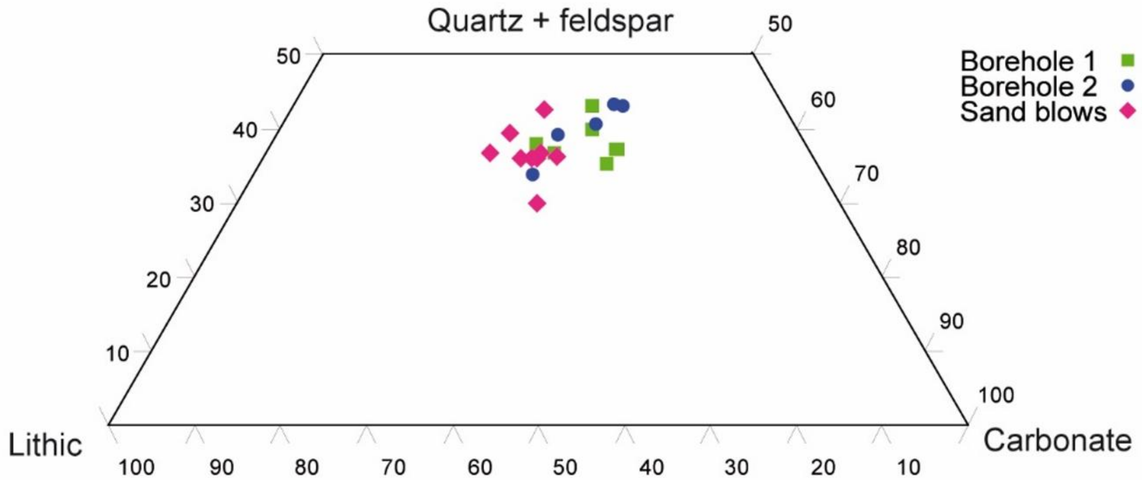


Fig. 6. Composition of liquefiable sand.

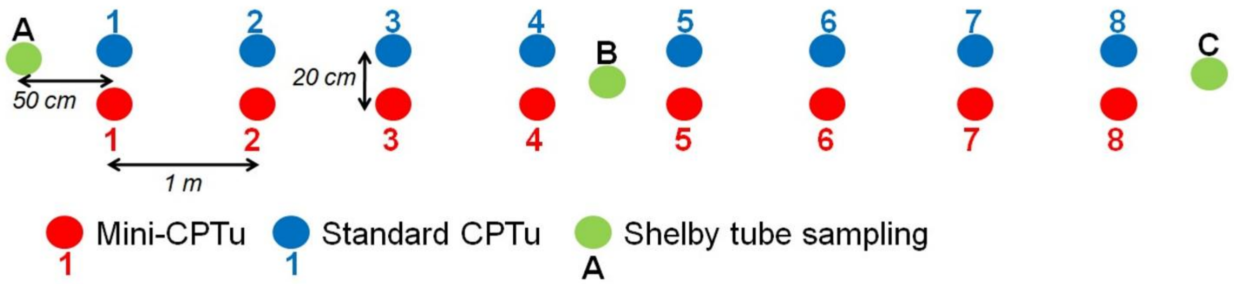


Fig. 7. Test site A: Test design.

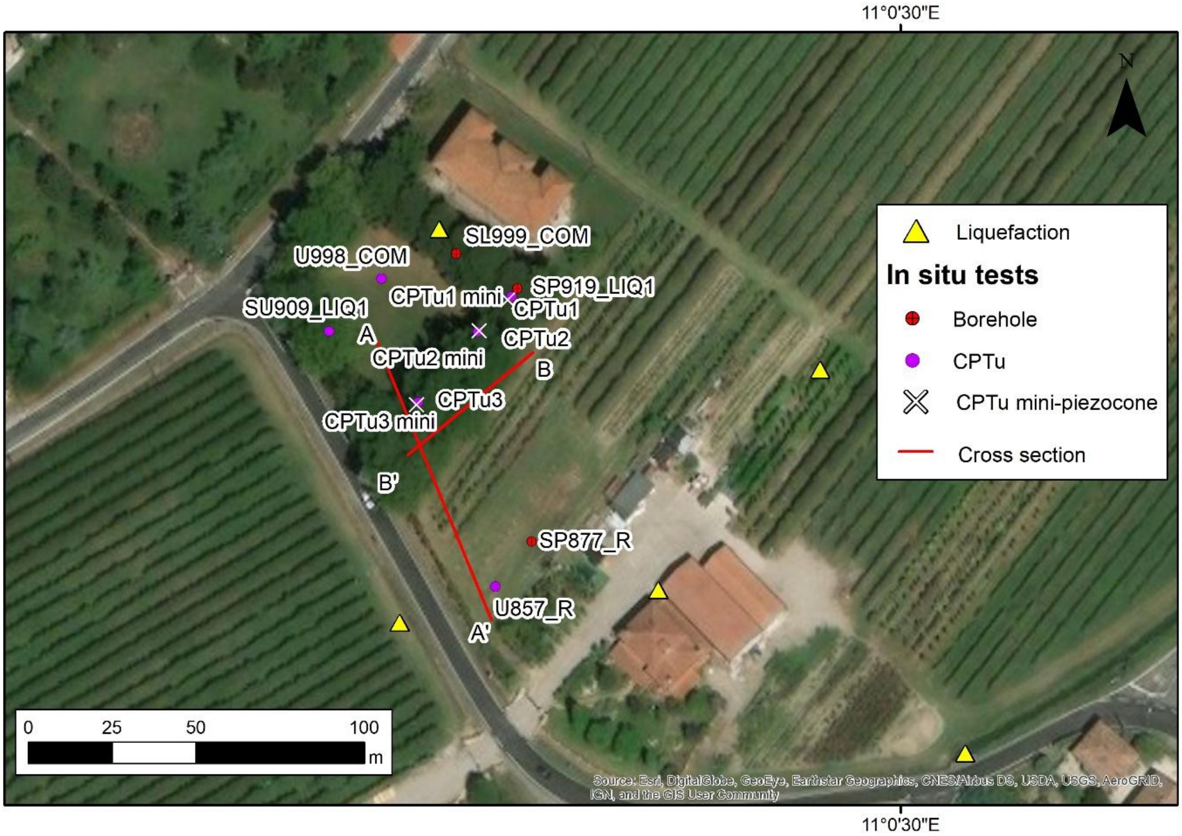


Fig. 8. Test site B: Test design.

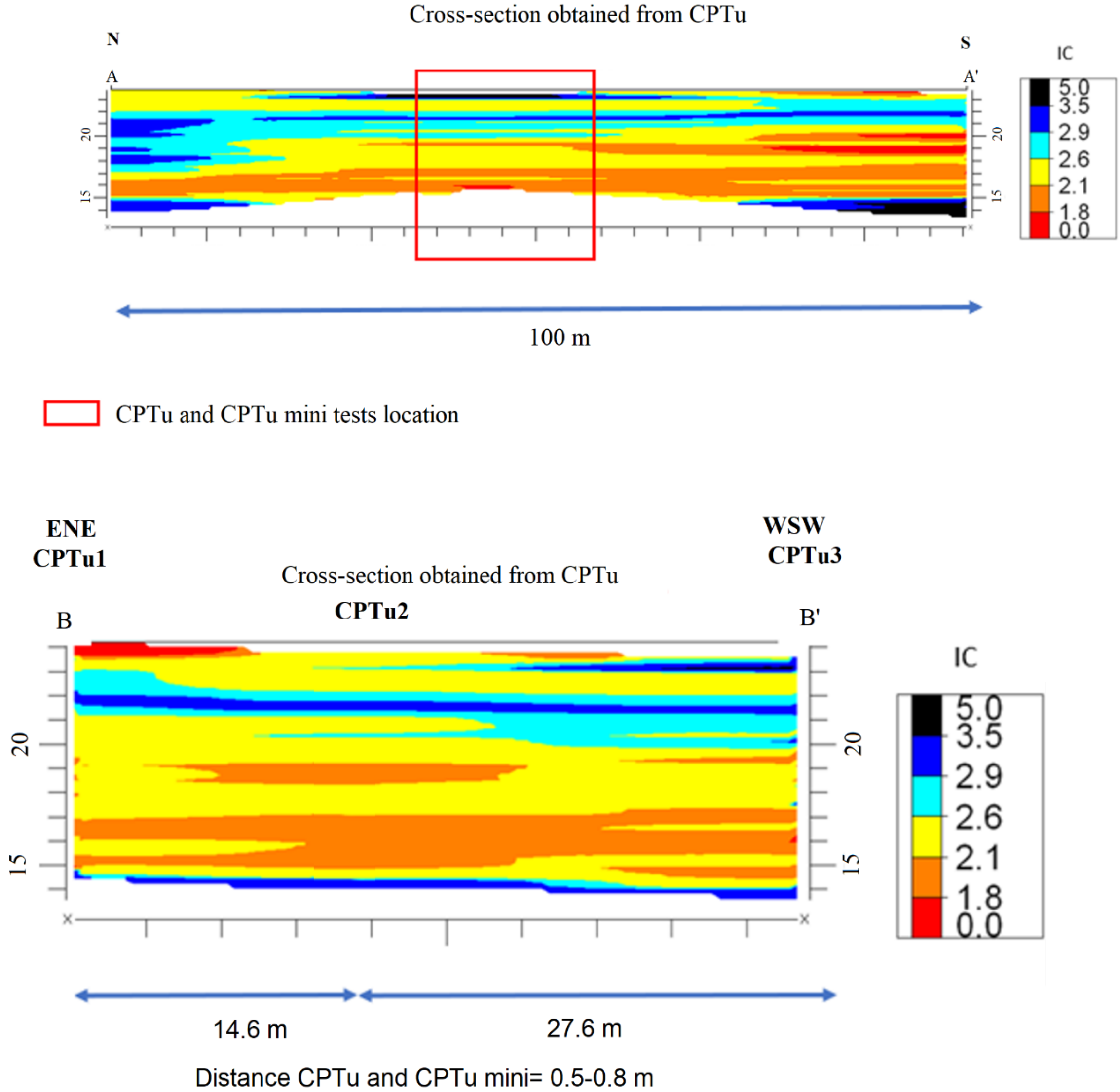


Fig. 9. Test site B: Ic profile section A-A' and B-B'.

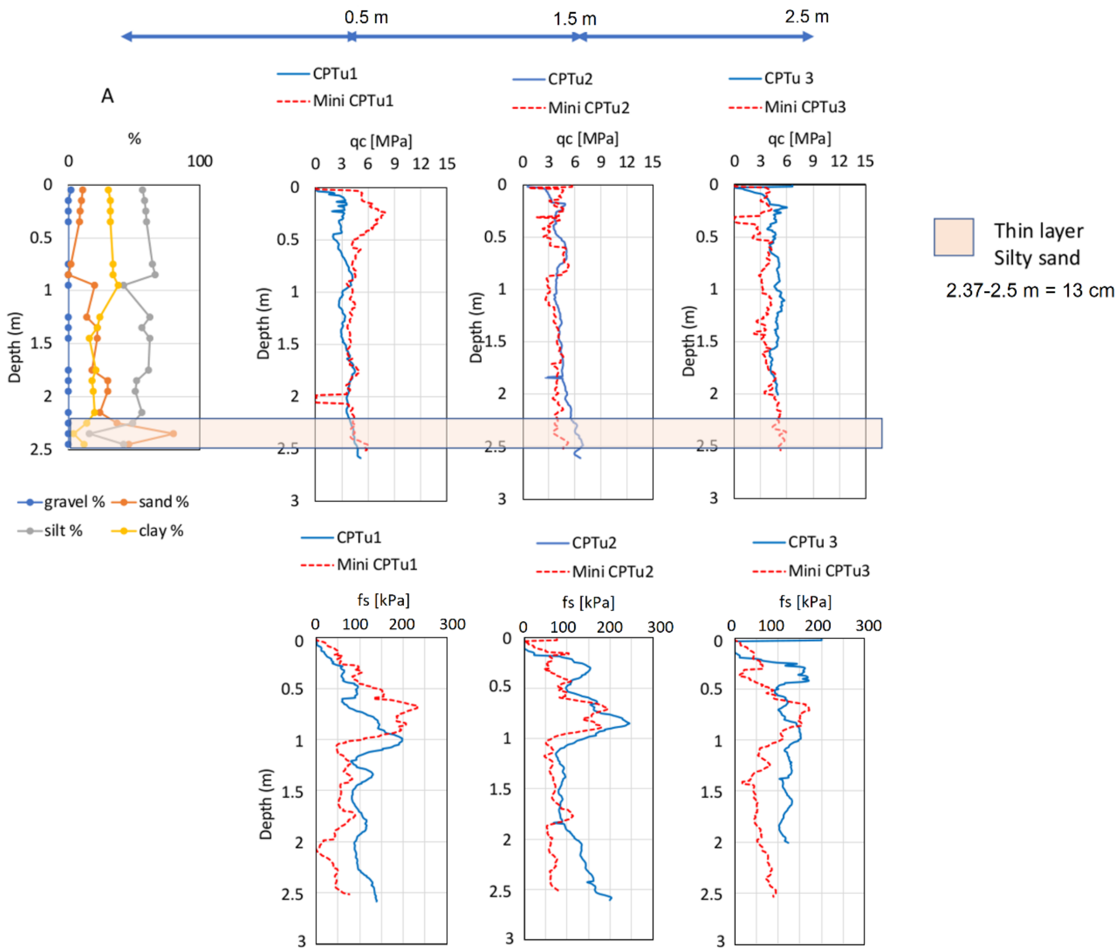


Fig. 10. Test site A: comparison standard CPT vs mini CPT in correspondence of the borehole A.

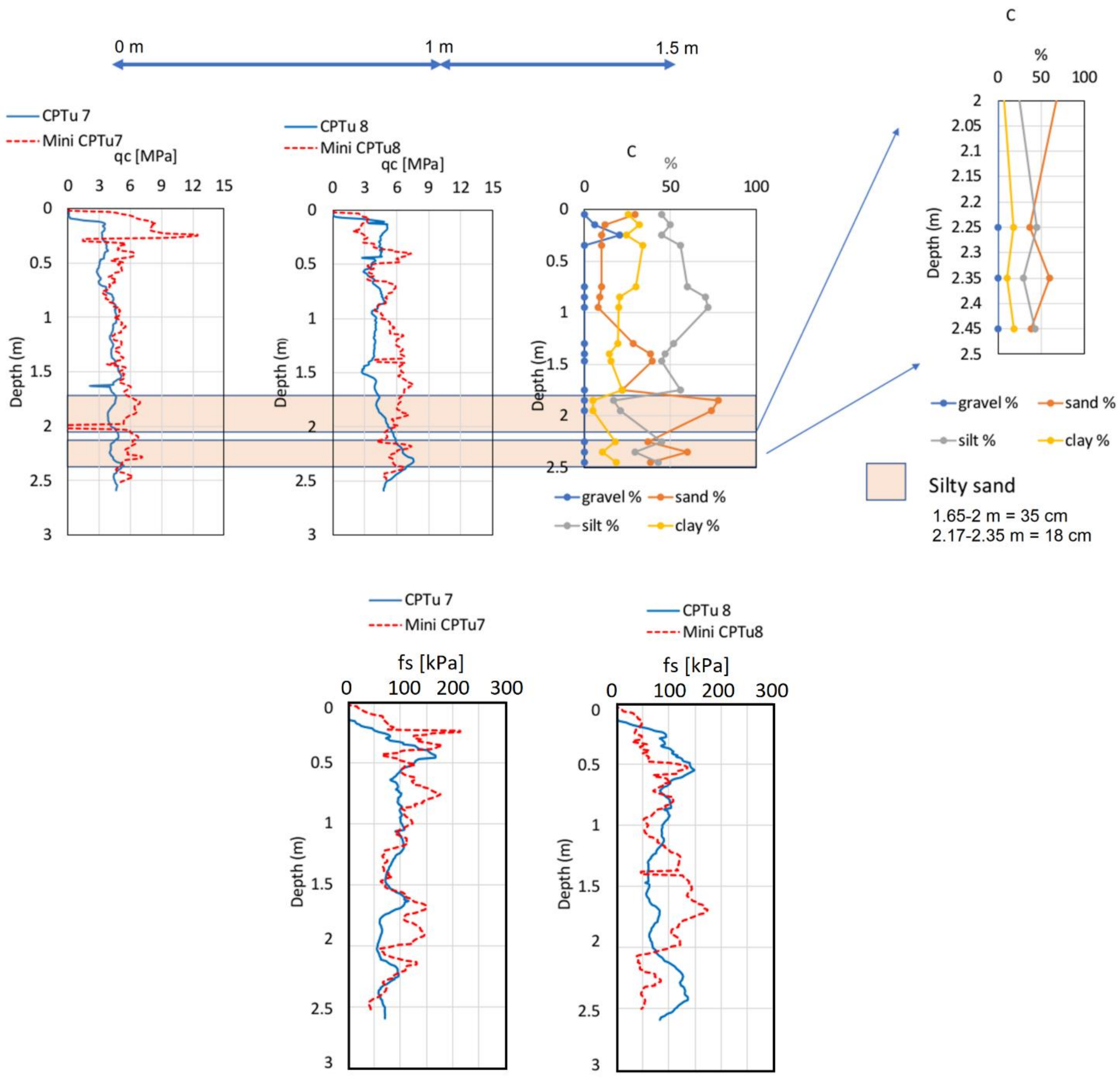


Fig. 11. Test site A: comparison standard CPT vs mini CPT in correspondence of the borehole C.

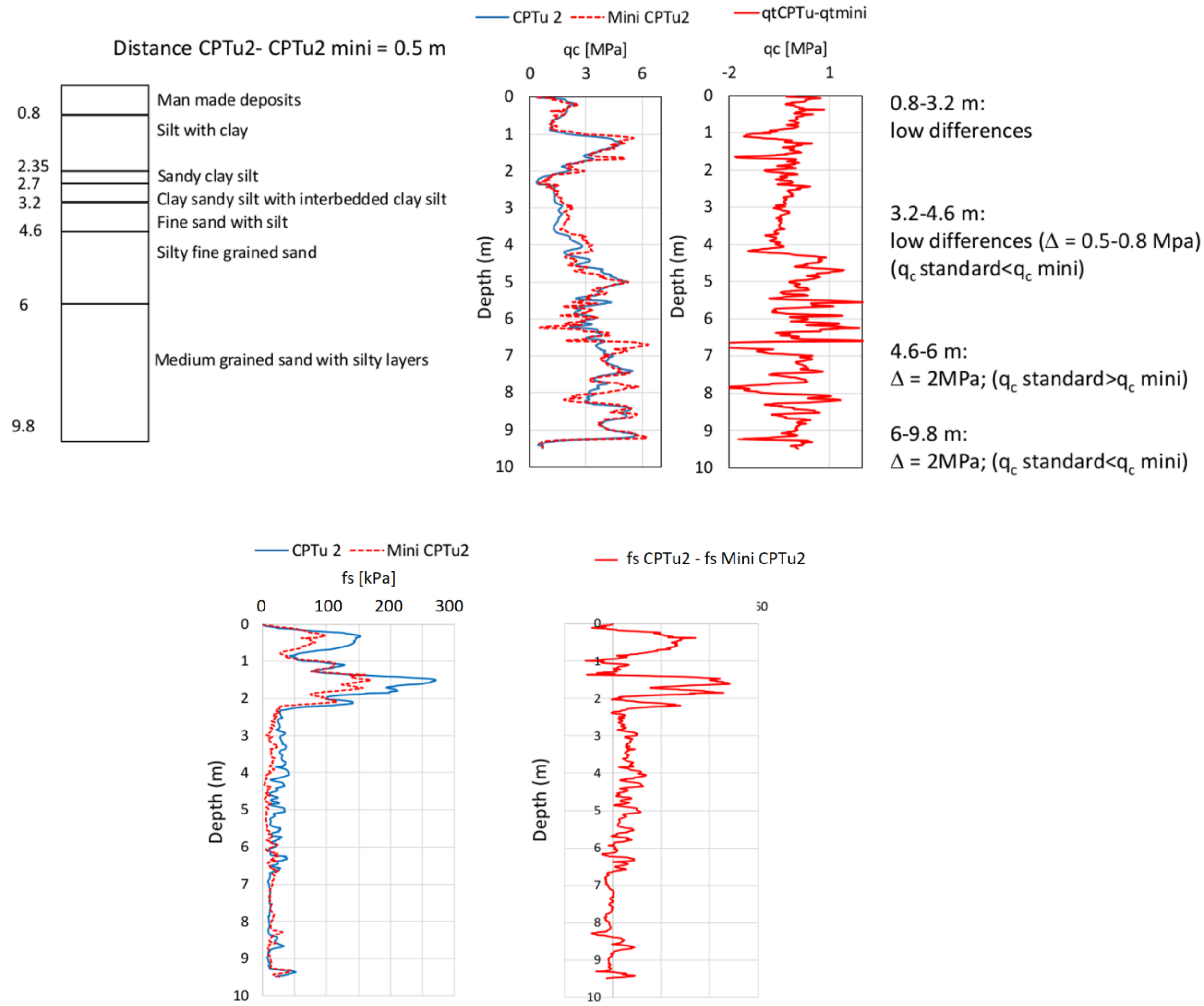


Fig. 12. Test site B: comparison standard CPTu2 vs CPTu2 mini.

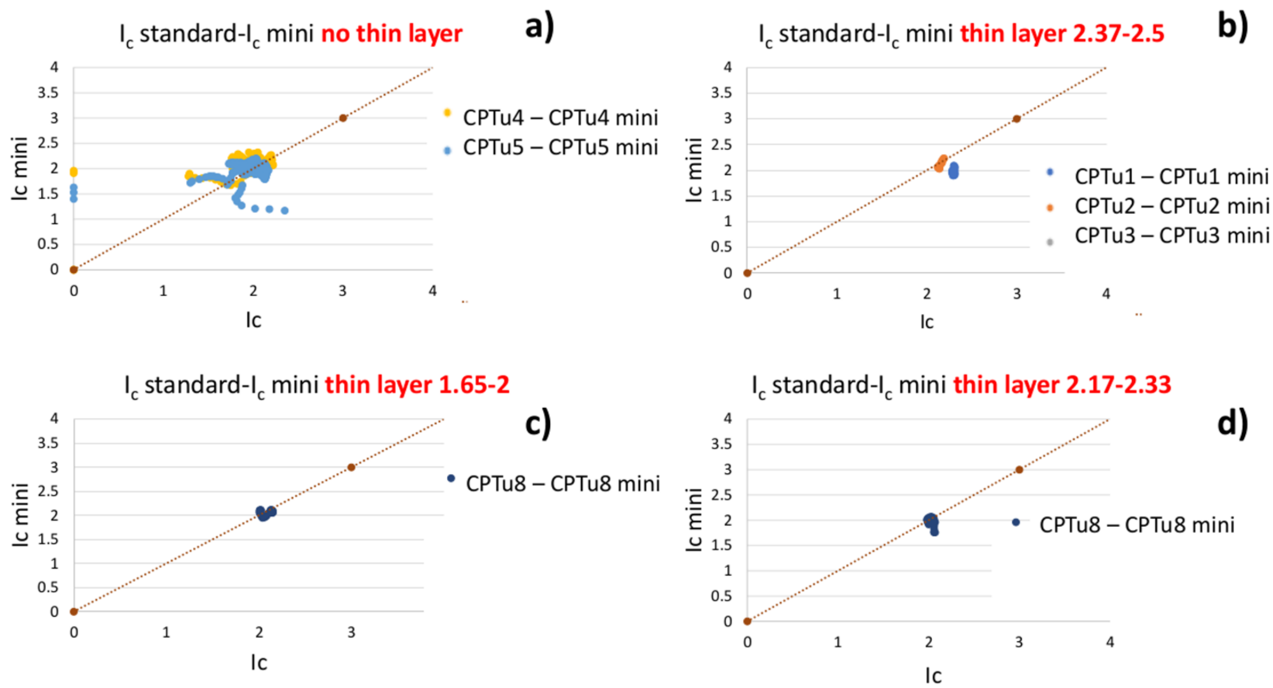
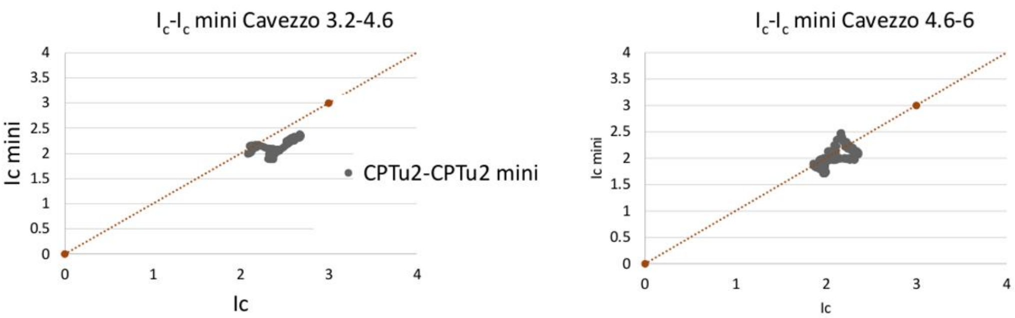
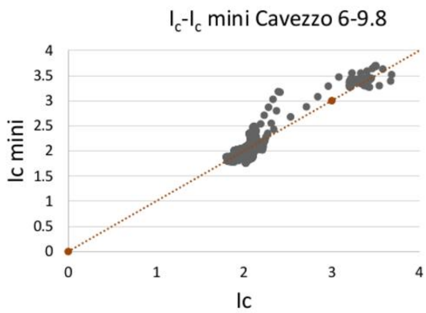


Fig. 13. Test site A: Ic standard vs Ic mini.





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

Fig. 14. Test site B: Ic standard vs Ic mini.

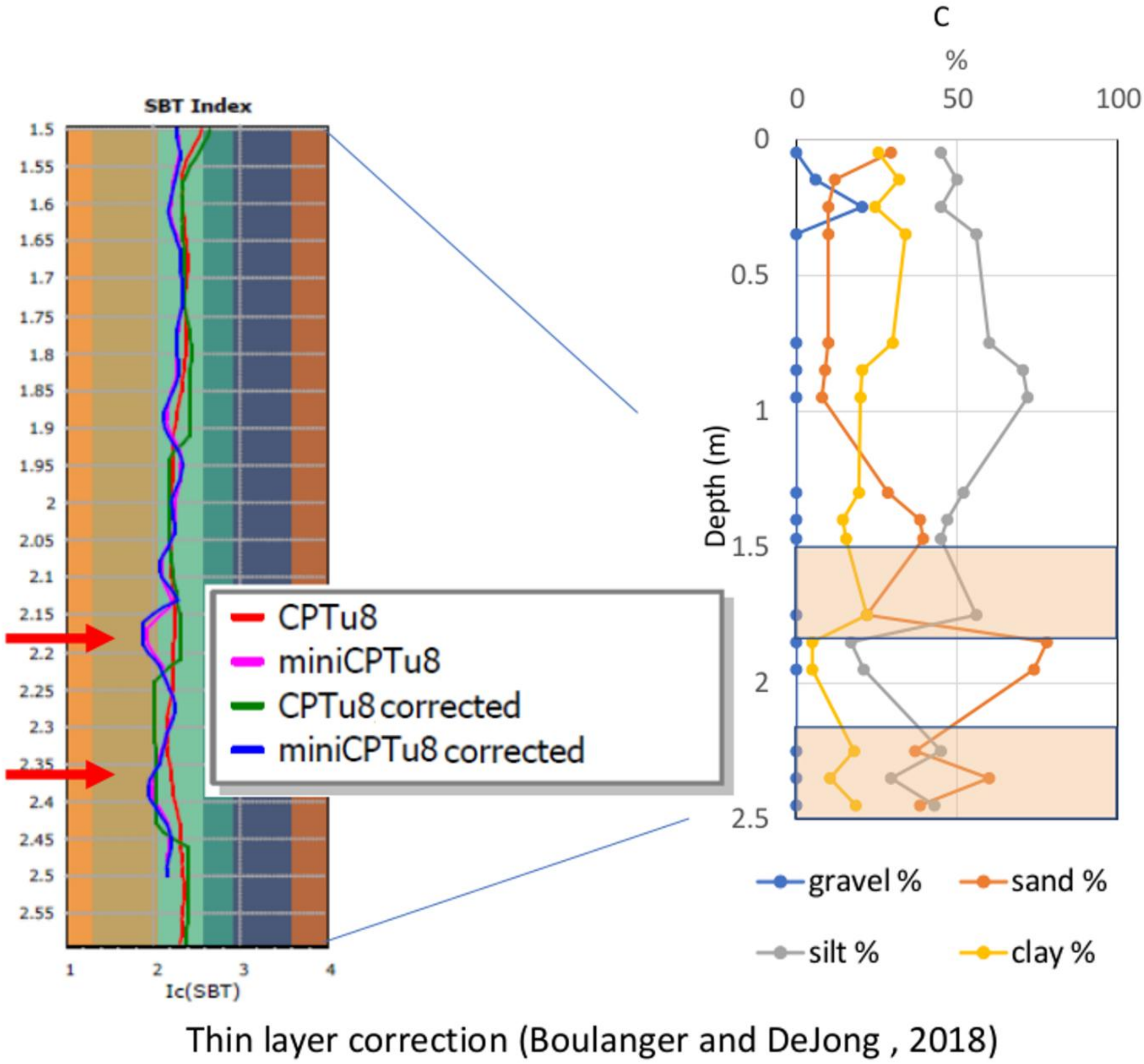


Fig. 15. Test site A: thin layer correction applied to standard CPTu8 and mini CPTu8. Close up of the depth between 1.5- 2.6 m and comparaison with the grain size.

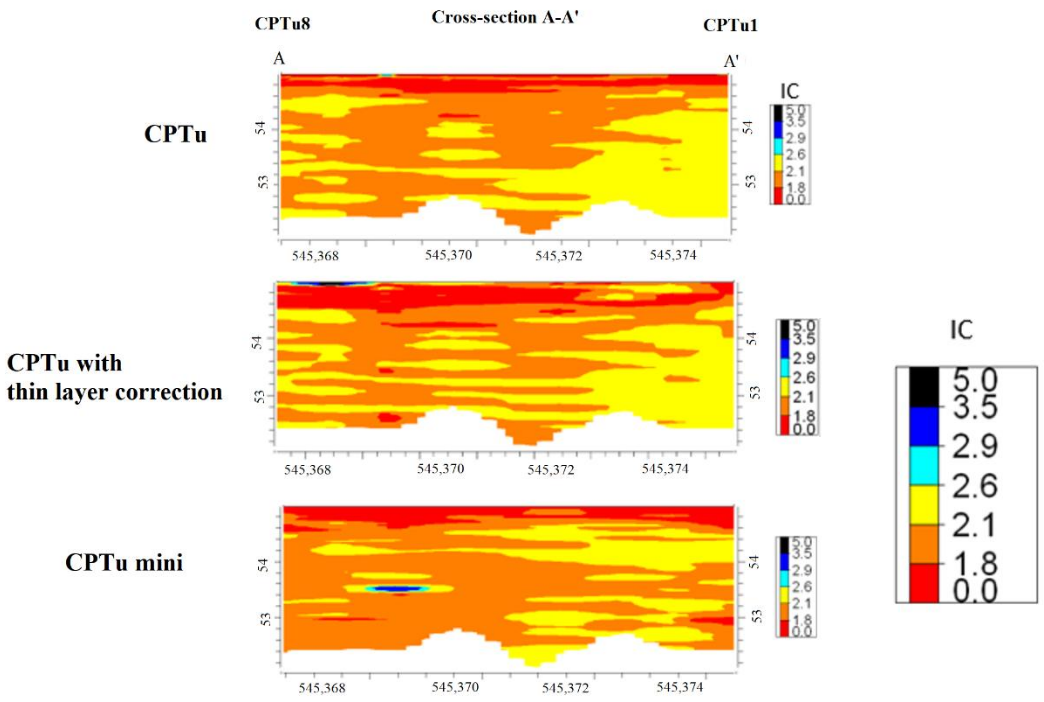


Fig. 16. Test site A: IC profile along the standard CPTu, corrected CPTu and mini CPTu.

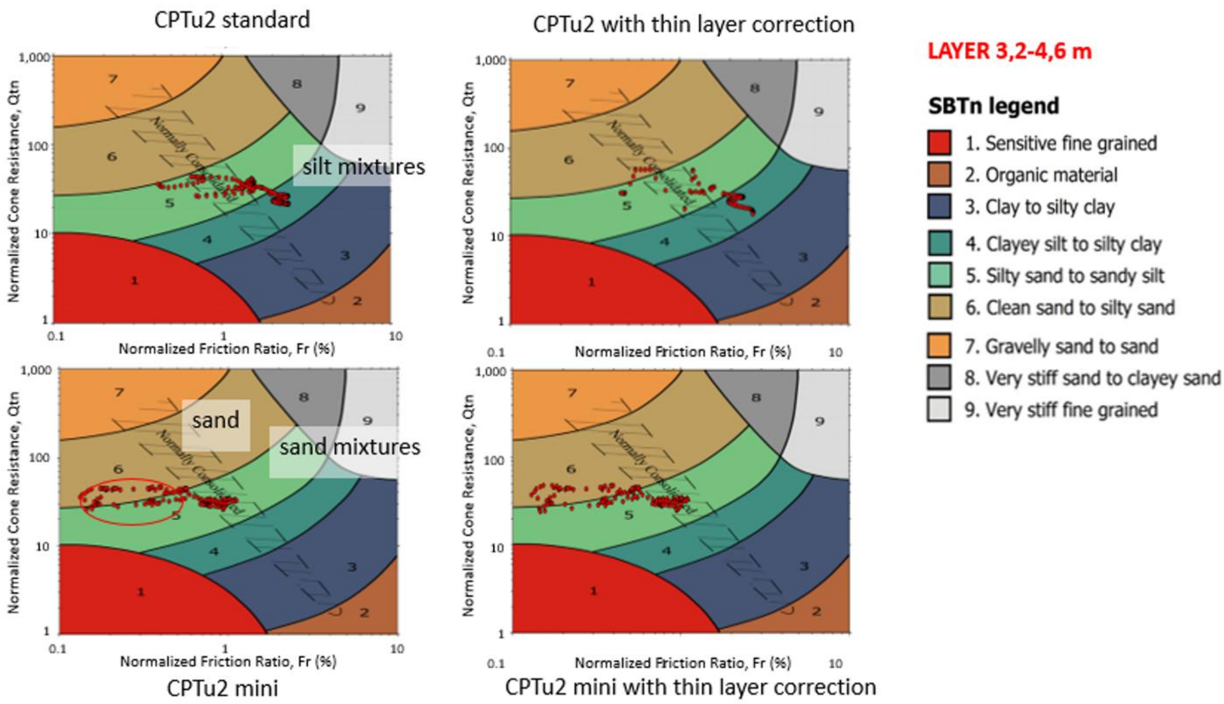


Fig. 17. SBTn plot for the test site B: thin layer correction.

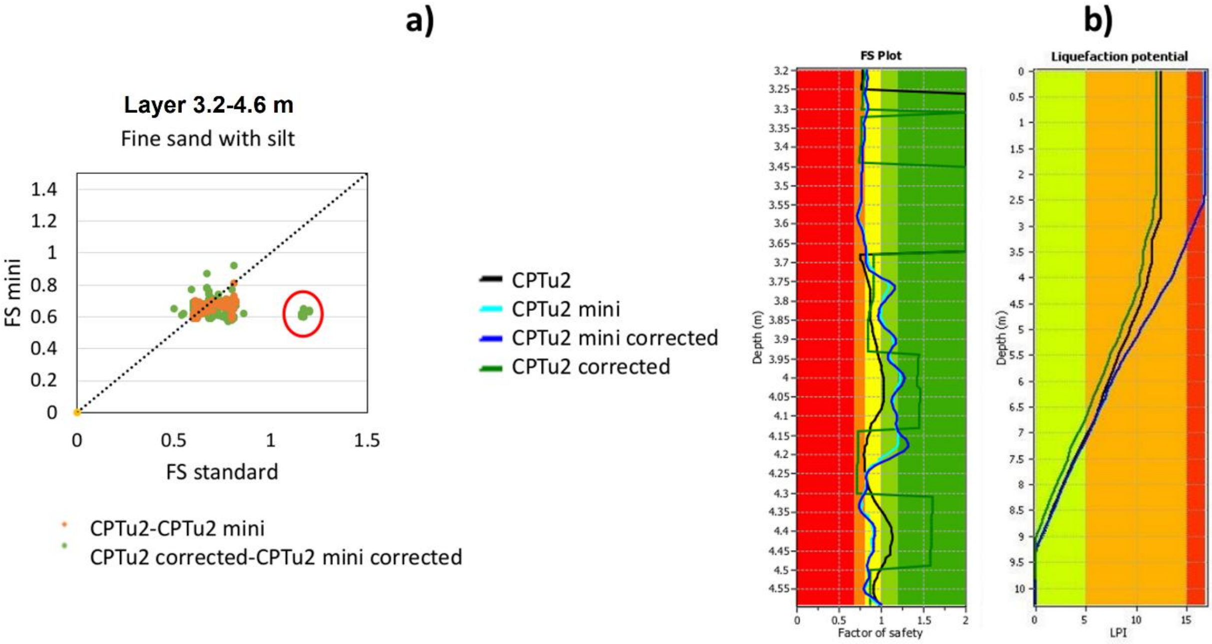


Fig. 18. Test site B – a) Liquefaction Factor of Safety (FS) of the layer between 3.2 and 4.6 m. b) Liquefaction potential assessment and FS for the test site B.