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

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17 **Abstract:** This paper shows and compares the experimental results obtained by using a standard cone
18 (10 cm²) and a minipiezocone (2 cm²). Tests were carried out at Calendasco (Piacenza-Italy) in a

19 natural soil deposit mainly consisting of clayey – sandy silts. Grain size distribution with depth was
20 also available. Other tests were carried out at Cavezzo (Modena-Italy) where liquefaction-induced
21 phenomena were observed during the 29th May 2012 seismic sequence. The purpose was to
22 investigate capabilities and limitations of minipiezococone and to explore the possibility of obtaining a
23 better prediction of soil stratigraphy in thin layered deposits. Systematic differences in terms of tip
24 resistance and sleeve friction were not observed, even though, generally, $q_c \text{ standard} < q_c \text{ mini}$. The
25 spatial heterogeneity was considered responsible of the higher observed differences. In both the test
26 sites thin sandy layers are characterized by $I_c \text{ mini} \leq I_c \text{ standard}$, with a ratio of the I_c index as low as
27 0.88. This allows us to conclude that the mini-cone could be a valid alternative to the standard in
28 identifying thin sandy layers.

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

30 **Introduction**

31 Since the early works of Treadwell (1976) and Lunne et al. (1997) it is well recognized that the tip
32 resistance is influenced by the soil properties both ahead and behind the tip. In particular, Lunne et
33 al. (1997) experimentally observed that the tip resistance senses the presence of an interface at a
34 distance from the interface which increases as the material stiffness raises. Moreover, in the case of
35 stiff layers, the target tip resistance was measured only for a layer thickness of 10-20 cone diameters,
36 while for soft layers a thickness of 1-2 diameters was sufficient. As a consequence, in case of stiff
37 thin layers the tip resistance could be underestimated. In practice, it has been concluded that it is
38 easier to detect thin soft layers than stiff ones. Later researches confirmed these observations, in
39 particular the contribution by Walker and Yu (2006, 2010) that performed a numerical analysis of
40 undrained penetration within a layered clay model (FEM with adaptive mesh).

41 The fact that the target tip resistance of stiff layers may be measured only when the layer thickness is
42 greater than 10-20 diameters could be explained, from a qualitative point of view, by the following
43 hypotheses (Lo Presti et al. 2009): indeed, the tip resistance can be considered as the ultimate bearing

44 capacity of a deep foundation. When the tip is moving from a stiff sand layer towards a soft layer it
45 is possible to assume a local/punching failure mechanism. On the other hand, in the opposite case a
46 general failure mechanism could be considered. This has implications in some challenging issues of
47 CPTu interpretation as transition zones and thin layers identification (Van der Linden, 2018,
48 Boulanger and De Jong, 2018; De Lange, 2018).

49 CPTu interpretation is affected by large uncertainties especially for deposits containing multiple thin
50 layers, as a result of the deposition of sediments related to intermittent flows leading to alternating
51 sand and clay layers quite frequent in alluvial settings, in particular in channel and levee facies. In
52 order to improve CPTu capabilities, possible solutions can derive by the application of methodologies
53 for thin layer correction or the use of a cone of smaller size (mini-cone). Many researchers attempted
54 to model the cone penetration in layered soils by using different approaches (Vreugdenhil et al. 1994,
55 Yue and Yin (1999), Ahmadi and Robertson (2005), Tehrani et al. (2017), Xu and Lehane (2008),
56 Mo et al. (2015, 2017). These studies were aimed at modelling the cone penetration in layered soils,
57 validating the proposed model by means of available experiments (not numerous) and suggesting a
58 correction procedure. When the cone is approaching an interface, the distance at which the tip
59 resistance is influenced by such an interface is called “sensing distance” (Tehrani et al. 2017). After
60 the cone passes the interface, the “development distance” is that at which the tip resistance is no more
61 affected by such interface. The correction procedures were mainly developed to correct the
62 experimental results in case of stiff layers sandwiched between soft layers. In practice the objective
63 was to find the real thickness of the stiff layers and the corrected tip resistance. Such a correction
64 procedure is extremely important in liquefaction analyses of layered sand deposits. According to
65 Boulanger et al. (2016) the use of simplified liquefaction vulnerability indices can overestimate the
66 liquefaction potential. This is confirmed especially in the case of moderate earthquake (Lo Presti et
67 al. 2013). Boulanger and DeJong (2018) provided an almost complete literature review concerning
68 such a topic and suggested a correction methodology (inverse filtering procedure) based on previous

69 researches. They also applied the procedure for re-analysing some real cases. A simple correction can
70 be done by the use of the following method (Ahmadi and Robertson 2005):

$$71 \quad q_c^* = K_H \cdot q_{cA}$$

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

74 On the whole, the available correction procedures never consider the sleeve friction (f_s) or dynamic
75 pore pressure (u_2), nonetheless the sleeve friction seems to be more sensitive to layering (Boulanger
76 and DeJong 2018). In fact, it could be possible to model the soil layers beneath the tip as a series of
77 springs, while the soil in contact with the sleeve could be represented as parallel springs. With this
78 respect the sleeve friction is a “local measurement” (Lo Presti et al 2009).

79 To overcome the standard CPTu test drawbacks in identifying/characterizing thin soil layers, the use
80 of a mini–cone test (mini-CPTu) could also represent a suitable solution. International standards such
81 as ASTM D5578 (2012) and ISO 22476-1 (2012) define testing procedures, cone geometry and
82 accuracy/repeatability requirements for testing with electric cone or piezocone. Usually a cone with
83 an apex angle of 60° and a tip cross-section of 10 or 15 cm² is recommended. The use of mini-cone
84 is not considered by these standards. In any case, various authors developed and used mini-cones for
85 different purposes. Tumay et al. (1998, 2001) developed a mini cone with an apex angle of 60° ,
86 projected cone area of 2 cm² and a friction sleeve area of 40 cm², for application in the field of
87 “Transportation Geotechnics”. Power and Geise (1995) and Tufenkjian and Thompson (2005)
88 developed and used a similar mini-cone for the seafloor exploration. Mini-cones were also used for
89 testing in small Calibration Chambers CC (De Linna 1990; Kurup et al. 1994, Abedin 1995; Franzen
90 2006; Kumar and Raju 2008; Löfroth 2008; Kokusho et al. 2012; Pournaghiazar et al. 2012,
91 Damavandi-Monfared and Sadrekarimi 2015, Lo Presti et al. 2018a). Lo Presti et al. (2018a)
92 performed penetration tests in compacted, fine grained, partially saturated samples in a small CC by

93 using a mini-cone with a projected cone area of 0.5 cm^2 . Kurup et al. (1994) and Abu-Farsakh et al.
94 (1998) performed and analysed penetration tests in a CC on fully saturated cohesive soils by using a
95 mini-cone. In particular, they focused on pore pressure generation and dissipation. More recently, De
96 Lange et al. (2018) investigated the interpretation of CPTu in laminated soils based on experimental
97 laboratory CPTu tests performed in artificially built up layered soil. While all the above-mentioned
98 studies employed mini-cones in 1 g conditions, other mini-cones were also developed for centrifuge
99 testing (e.g., Bolton et al. 1999). A summary of miniature cones for Calibration Chamber (CC)
100 Testing is given by Damavandi-Monfared and Sadrekarimi (2015). Only few of these mini-cones
101 provide simultaneous measurements of cone tip resistance, sleeve friction and dynamic pore water
102 pressure. In conclusion, the use in common practice of mini-cones is mainly restricted to shallow
103 exploration and enhancement of the capability of CPTu in identifying thin layers.

104 A direct comparison of the measured tip resistance has been done by various researchers, reaching
105 different conclusions. The different ratio between cone diameter d_c and the mean grain size d_{50} ,
106 could be the reason for such differences. In the case of the analysed test sites, the soil size effects are
107 null because the ratio d_c/d_{50} values are higher than 28 (Bolton et al., 1999).

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

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

127 **Equipment and testing procedures**

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

133 **Mini Piezocone**

134 In this study, the mini-cone tip area (base area) was 2 cm², (16 mm in diameter) the friction sleeve
135 area was 50 cm² and the cone apex angle was 60 degrees. The net area ratio of the miniature cone
136 was 0.8. The mini-cone was pushed into the soil at a relatively constant rate of $v = 2$ cm/sec. This
137 involves a different normalized velocity between standard and mini piezocone ($VN = v/(d \cdot Cv)$) where
138 d is the cone diameter and Cv the coefficient of primary consolidation (Lehane et al. 2009). Anyway,
139 the possible effects of such a difference appear negligible. Lower force is required to push the mini-
140 cone into the soil (Tumay et al., 1998) and a smaller and lighter vehicle is necessary compared to the
141 standard CPTu test. This fact provides a greater mobility and site accessibility (Tufenkjian and

142 Thompson, 2005). The maximum axial load experienced during the mini-cone tests was
143 approximately equal to 0.9 kN. The mini-cone tip resistance and sleeve friction were recorded at
144 depth intervals of 1 cm. Penetration tests were carried out by using a Penetrometer, standard
145 piezocone (CPTu) and mini piezocone. All the equipment was provided by Pagani Geotechnical
146 Equipment (Piacenza, Italy). CPTu tests were carried out through a Pagani Penetrometer model
147 TG63-150kN and according to ASTM D5778; the acquisition system/datalogger was TGAS-08. As
148 for the standard cone, silicone oil was used for saturation of the filter.

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

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

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

162 **The Test Sites**

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

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

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

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

176 The test site B is located at Cavezzo (Cavezzo municipality, Province of Modena) on the right side
177 of the Secchia river (Fig.1). The territory is quite flat, has elevations gently decreasing from 34 m
178 a.s.l. approx. in the south to approximately 16 m a.s.l. approx. in the north. The site is located about
179 3 km far from the epicentre of the May 29th 2012 earthquake ($M_w= 5.8$; Rovida et al., 2016). The
180 shallow lithostratigrafic succession at Cavezzo is characterized by alluvial deposits including
181 interbedded fine silty-clayey sediments with marker layers rich on peat and interbedded sands and
182 silty sands. These shallow deposits (down to 30 m in depth) are due to the sedimentation of the
183 Secchia river, whereas the deeper sands are probably referable to the sedimentation of soils from the
184 Po river (Castaldini, 1989). The lithostratigraphy of the first 30 meters of the alluvial successions
185 shows that the deposition in the study area was characterised by significant variations, both vertically
186 and horizontally, due to frequent changes in the fluvial drainage framework and regime. Channel-
187 levee units consisting of sand layers (channels) that alternate to fine sand-silt- bodies (levees and
188 proximal crevasse splays) pass to distal levee and alluvial plain silts and silty clays. The contact
189 among these layers are variable, from discrete interfaces to gradual-transitional passages at a
190 centimetric to decimetric scale, both fining and coarsening upward, depending on the fluvial

191 dynamics. A reference conceptual model based on the data obtained in the investigated site was
192 elaborated and adopted to interpret the engineering proprieties of soils (Meisina et al, 2019). In
193 particular, five stratigraphic units were identified:

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

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

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

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

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

201 The units investigated in this paper correspond to Units A and B. The water table depth in the test site
202 B is 2.10 m (March 2019). The liquefaction-induced ground surface manifestations known as co-
203 seismic effects at Cavezzo after the May 29th 2012 earthquake with 5.8 Magnitude (Lo Presti et al.
204 2013, Emergeo Working Group, 2013) are located along a buried abandoned riverbed of the Secchia
205 River that was active during Roman and Medieval times until the 13th century. The observed co-
206 seismic effects consisted of liquefaction, fractures, water level rise and liquefaction (liquefaction
207 means sand transportation at the ground level). The Cavezzo area, where the tests were carried out,
208 was characterized from the engineering geological and geotechnical point of view through
209 investigations in the framework of the LIQUEFACT Horizon 2020 project. The data belong to
210 different databases listed as follow (Fig.8):

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

214 • Collection and digitization of Post-2012 earthquakes geognostic investigations (MUDE
215 database), (borehole SP877_R and CPT U857_R);

216 • Investigation campaigns funded by Comune di Cavezzo and RER performed by Tecnoin
217 Geosolution and Elletipi (Laboratory tests) in December 2017 and January 2018 (borehole
218 SL999_COM and CPT SU909_LIQ1).

219 Silty sands and sandy silts are present between 2.3 and 10 m from ground level, which are overlapped
220 by a clayey soil of about 2.3 m in thickness. The borehole SP919 LIQ1 shows clay with sand and
221 sand mixtures (silty sand and sandy silt, CL, fine contents = 24-50%, IP = 8) in the upper 5 m and
222 sand and silty sand from 5 to 10 m (fine content FC = 15-28%) (Fig.3 and Table 2).

223 Regarding the samples used for the classification tests, the material extracted from the boreholes
224 SP919_LIQ1 and SL999_COM and the samples of the Cavezzo sand boils were analysed at the
225 geotechnical and sedimentological laboratories of the University of Pavia, Modena and Reggio Emilia
226 (Fig.4). Textural analyses were performed both on sand blows and in sandy layers in the subsurface
227 at different depths. Grain-size analyses were performed using standard techniques: mechanical
228 sieving for the sandy fraction and hydrometer analysis for fine-grained sediments. Sand samples
229 consisting of a few hundreds of grams were washed with dilute H₂O₂ to remove organic matter. Grain-
230 size analyses are reported as the granulometric curve in Figure 5. Sand blows are slightly more
231 selected than the sand from the source layers as a result of the ejection mechanism (Fontana et al.,
232 2015, 2019). The petrographic composition (quartz+feldspar, carbonate, lithic content) of the sand of
233 boreholes and the sand blows was compared (Fig. 6). Modal analyses were carried out on the 0.125–
234 0.250 mm fraction, by point counting (300 points) under transmitted-light microscopy. The
235 composition of sand blows overlaps the composition of shallow sand layers from both boreholes
236 down to the depth of 4.5 m, thus suggesting these layers as the source for liquefied sands.

237 **The Tests**

238 In the test site A, two test series were performed. The first series consisted of 8 pairs of mini and
239 standard tests that were carried out at the Pagani Geotechnical Equipment test field (Fig. 7). In
240 addition, the penetrometer was used to retrieve Shelby tube samples. Samples were retrieved from
241 three locations (A, B and C in Fig. 7). As for locations A and C, the maximum depth of 2.5 m was
242 reached. At B location, a depth of 3.0 m was reached. The soil was sampled continuously every 0.50
243 m. Grain size distribution of the sampled soil was carried out at the Geotechnical Laboratory of the
244 University of Pisa. Grain-size curves were usually determined every 0.1 m.

245 In the test site B, three pairs of CPTu and mini CPTu were performed by Pagani Geotechnical
246 Equipment at Cavezzo. They reach the depth of 10 m for the test 1 and 2 and 5 m for the test number
247 3 (Fig. 8). In this paper, only the results for the pairs CPTu2-mini CPTu2 were analysed. The area is
248 characterized by a strong lateral and vertical heterogeneity, as demonstrated by the Soil Behaviour
249 Type Index (I_c), with an increase of the sandy layers from North to South where sand boils occurred
250 (Fig.9). In relation with their location the tests were compared with the borehole SP 919 LIQ1
251 performed in the frame of the project Horizon 2020 LIQUEFACT.

252 **Analyses and Results**

253 The tip resistance (q_c) for different pairs of standard CPTu-mini CPTu performed at Calendasco are
254 compared in Figures 10-11. It is worth remembering that borehole A is close to CPTu1-mini CPTu1,
255 borehole B is close to CPTu4-mini CPTu4 and CPTu5-mini CPTu5, while borehole C is close to
256 CPTu8-mini CPTu8.

257 The soil mainly consists of silt (50 % on average) and clay (30 % on average). In borehole A, a thin
258 layer of silty sand is present between 2.37 and 2.5 m (thickness of 13 cm) (Fig.10). The largest
259 percentages of granular soil (from fine sand to medium gravel) were observed in borehole C where
260 the granular fraction was from 30 to 70 % (thin layers of silty sand between 1.65 and 2 m – 35 cm-
261 and between 2.17 and 2.33 m – 18 cm) (Fig.11).

262 Occasionally large discrepancies in terms of q_c or f_s between standard and mini-cone can be observed
263 (Figures 10 and 11). Anyway, the comparison in terms of q_c (Figures 10 and 11) suggests the
264 following observations:

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

271 The comparison between standard and mini-cone test results in terms of f_s suggests the same
272 observations as for q_c (Figures 10 and 11).

273 It is possible to conclude that the spatial variability more than the systematic effect of the tip diameter
274 can be considered responsible of the observed differences. On the other hand, large values of the tip
275 resistance especially in the shallower layers may be a consequence of desiccation phenomena which
276 makes unreliable the use of conventional classification charts.

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

- 279 - from 0.8 to 3.2 m: silt with clay, small differences;
- 280 - from 3.8 to 4.6 m: (silt with clay, sandy clay silt, clay sandy silt with interbedded clay silt and
281 fine sand with silt) the differences are negligible (q_c standard $< q_c$ mini), ($\Delta = 0.5-0.8$ MPa);
- 282 - from 4.6 m to 6 m: silty fine-grained sand, strong differences between q_c standard and mini ($\Delta =$
283 2MPa) and q_c standard $> q_c$ mini;

284 - from 6 m to 9.8 m: strong differences between q_c standard and mini ($\Delta = 2\text{MPa}$) and q_c standard $< q_c$
285 mini.

286 The differences seem to be related to differences in grain size and in particular to the presence of
287 sandy layers.

288 For the test site B, the comparison between standard and mini-cone test results in terms of f_s do not
289 evidence any particular correlations. Generally, from 0.8 m to 4.6 m f_s standard $> f_s$ mini ($\Delta < 50\text{kPa}$),
290 whereas from 4.6 m to 9.4 m the differences are smaller and f_s standard $< f_s$ mini (Fig. 12). Soil
291 Behaviour Type Index (I_c) represents the radius of concentric circles that define the boundaries of
292 soil type and it estimated using the following equation (Robertson et al., 1990):

$$293 I_c = \sqrt{(3.47 - \log Q_{tn})^2 + (\log(F_r) + 1.22)^2}$$

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

$$295 Q_{tn} = \left(\frac{q_t - \sigma_{v0}}{p_a} \right) \left(\frac{p_a}{\sigma'_{v0}} \right)^n$$

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

$$298 F_r = \left[\left(\frac{f_s}{(q_t - \sigma_{v0})} \right) \right] 100\%$$

299 It is possible to identify the transition from one soil type to another using the rate of change of I_c .
300 When the CPTu is in transition from sand to clay, the SBTn I_c will move from low values in the sand
301 to higher values in the clay. Robertson and Wride (1998) suggested that the approximate boundary
302 between sand-like and clay-like behaviour is around $I_c = 2.60$. Hence, when the rate of change of I_c
303 is rapid and is crossing the boundary defined by $I_c = 2.60$, the cone is likely in transition from a sand-
304 like to clay-like soil or vice versa. Thus, profiles of I_c can provide a simple means to identify these
305 transition zones. The results of the comparison between the I_c values standard and mini are
306 represented in figures 13 and 14, for the test sites A and B, respectively. The comparison between the
307 I_c values by standard and mini-cone (Fig.13) evidences for the test site A that I_c mini = I_c standard

308 except for thin layers of sand where $I_c \text{ mini} \leq I_c \text{ standard}$ (Fig.13). The thin layer from 2.17 and 2.33
309 m is not identified by standard CPTu, which presents two peaks of I_c that do not correspond to the
310 right depth of the thin layer, on the other hand the mini CPTu recognize the depth of the thin layer
311 (Fig.15). The comparison of $I_c \text{ standard}$ vs $I_c \text{ mini}$ for the test site B highlights different behaviours
312 between the layers as for q_c but with a different meaning. In the first layers till 2.7 m $I_c \text{ mini} = I_c$
313 standard; at depth between 2.7 m and 4.6 m the behaviour is different and $I_c \text{ mini} < I_c \text{ standard}$; from
314 4.6 m and 9.8 m $I_c \text{ mini} \geq I_c \text{ standard}$ (Fig.14). It seems that the differences in term of I_c are stronger in
315 the layer between 2.7 m and 4.6 m, where the mini-cone is able probably to identify thin layers of
316 sand. After comparing q_c , f_s and I_c of standard and mini CPTu the thin layer correction proposed by
317 Boulanger and De Jong (2018) was applied to all the standard CPTu and mini CPTu that were
318 performed in the test sites A and B using the software CPeT-IT v.3.

319 For the test site A, the thin layers of the borehole A (from 2.37 m to 2.5 m) and from boreholes C
320 (from 1.65-2m) are not detected by standard CPTu. The application of the thin layer correction to
321 standard CPTu does not improve the identification, except for the thin layer from 2.17 to 2.35 m
322 which is identified, but a wrong depth (Fig.15). Mini CPTu identify the thin layers except for the thin
323 layer of borehole C between 1.65-2 m. The correction of mini CPTu doesn't improve the
324 identification (Fig.15). In terms of stratigraphic interpretation, the Fig. 16 illustrates the I_c profile
325 along the 8 tests (standard CPTu, corrected standard CPTu and mini CPTu). It is evident in all cases
326 the overestimation of the grain size (all the soils have an I_c index less than 2.6 exhibiting a sand-like
327 behavior) due to unsaturated conditions. Nevertheless, the sand ($I_c < 1.8$) are identified only by mini
328 CPTu.

329 For the test site B, the correction of the mini CPTu improves the identification of thin layers of sand
330 between 2.7 and 4.6 m (Fig.17). In particular mini CPTu recognises a thin layer of sand between 4
331 and 4.25 m. From 6 to 9.8 m, mini cone also evidences sand layer containing silty layers. The
332 correction of standard CPTu improves the identification, but in most cases the depth does not matches

333 that identified from boreholes. Also in this case the application of the thin layer correction to mini
334 CPTu does not improve the results.

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

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

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

$$345 \quad FS = \frac{CRR}{CSR} = 1$$

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

$$348 \quad LPI = \int_0^{20} F_1 W(z) dz$$

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

$$351 \quad W(z) = 10 - 0.5z$$

352 whereas F_1 is computed using the following equations:

$$353 \quad \text{if } FS \leq 1 \quad F_1 = 1 - FS$$

$$354 \quad \text{if } FS > 1 \quad F_1 = 0$$

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

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

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

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

374 **Conclusions**

375 To overcome the standard CPTu test drawbacks in identifying/characterizing thin soil layers, the use
376 of a mini-cone test (mini-CPTu) represents a suitable solution. The work investigated the capabilities
377 and limitations of the mini-cone for a better identification of thin soil layers and improvement of
378 liquefaction analysis in layered soil deposits. Two test sites representative of different conditions
379 were selected: site A (Calendasco) is characterized by thin layer of sand in silty clay, in unsaturated
380 conditions; site B (Cavezzo) represents thin layers of silty mixtures in sandy soils and sandy layers

381 in silty soils, the soils are saturated and liquefaction phenomena occurred during the seismic sequence
382 of 2012. The thin layers have thickness from 10 to 35 cm.

383 The comparison of q_c standard – f_s standard and q_c mini – f_s mini highlights that generally not
384 systematic differences exist, even if generally q_c standard < q_c mini. In some cases, differences of q_c
385 are not negligible (1-2 MPa) and are not related to differences in grain size and are not evident
386 systematic effect of the tip geometry but they depend on the spatial heterogeneity. Similar conclusions
387 can be drawn as far as f_s is considered. In both the test sites thin sandy layers are characterized by I_c
388 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-
389 cone is certainly a valid alternative to the standard in identifying thin sandy layers.

390 Thin layers are generally not detected by standard CPTu and for the study case, the thin layer
391 correction looks ineffective, as the thin sandy layers are not identified or their depth/thickness does
392 not match the borehole evidences. On the other hand, in both sites, thin layers are generally detected
393 by mini CPTu and the thin layer correction will be significantly smaller for the smaller diameter mini-
394 cone.

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

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

402 Differences between the I_c values inferred from standard and mini-cone affect the liquefaction
403 potential assessment. For site B, in the layer between 3.2 and 4.6 m (fine sand with silt) the differences
404 between FS standard and FS mini are relevant and are related to the identification through mini-CPTu

405 of thin layers of sands, not evident through standard CPTu. These results are in good agreement with
406 the results of the petrographic and sedimentological studies, which evidences that the composition of
407 sand blows overlaps the composition of shallow sand layers down to the depth of 4.6 m, thus
408 suggesting these layers as the source for liquefied sands.

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

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

419 **Data Availability**

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

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565

566 **Tables**

567

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

568

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

570

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

571

572 **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.

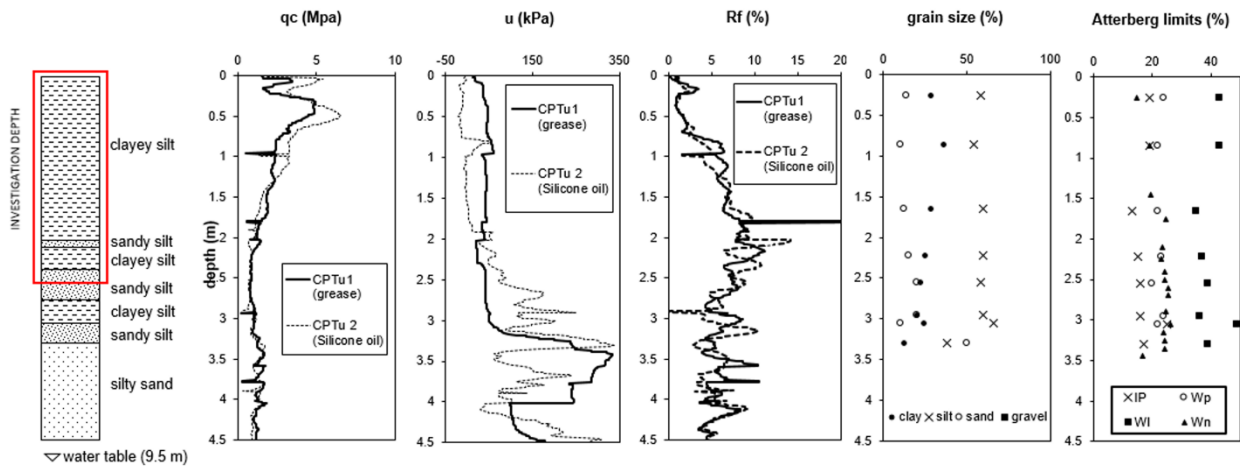


Fig. 2. Test site A: Soil profile and geotechnical characteristics. qc: cone resistance; u_0 : in-situ pore pressure; u_2 : pore pressure measure dat cone base; fs: sleeve friction; Rf: friction ratio ($fs/qc \cdot 100$) IP: plastic index;

Wp: plastic limit; WI: liquid limit, wn: natural water content.

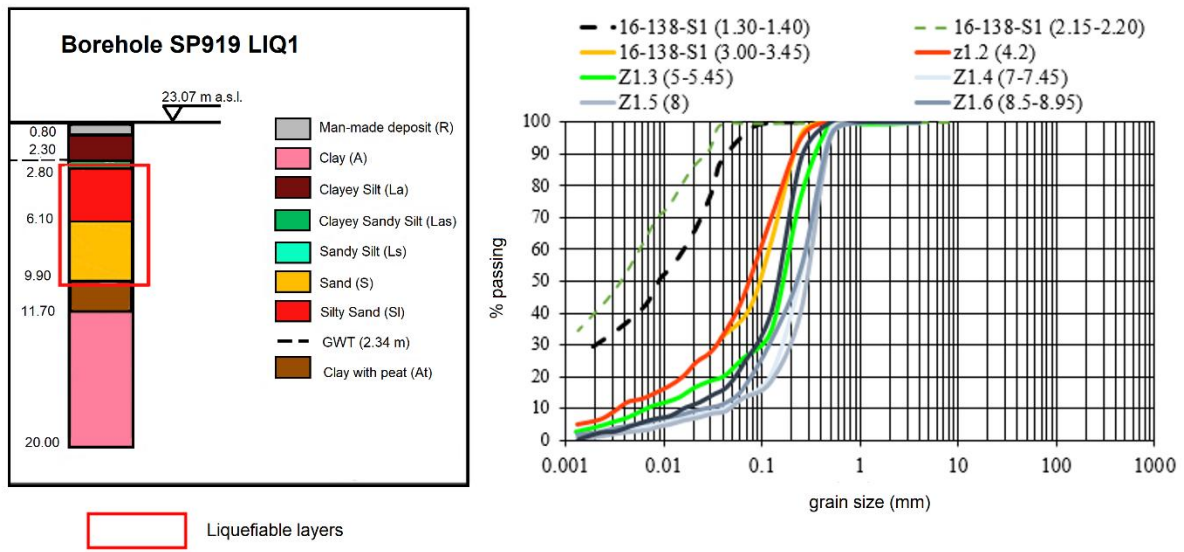


Fig. 3. Test site B: simplified borehole and grain size curves.



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

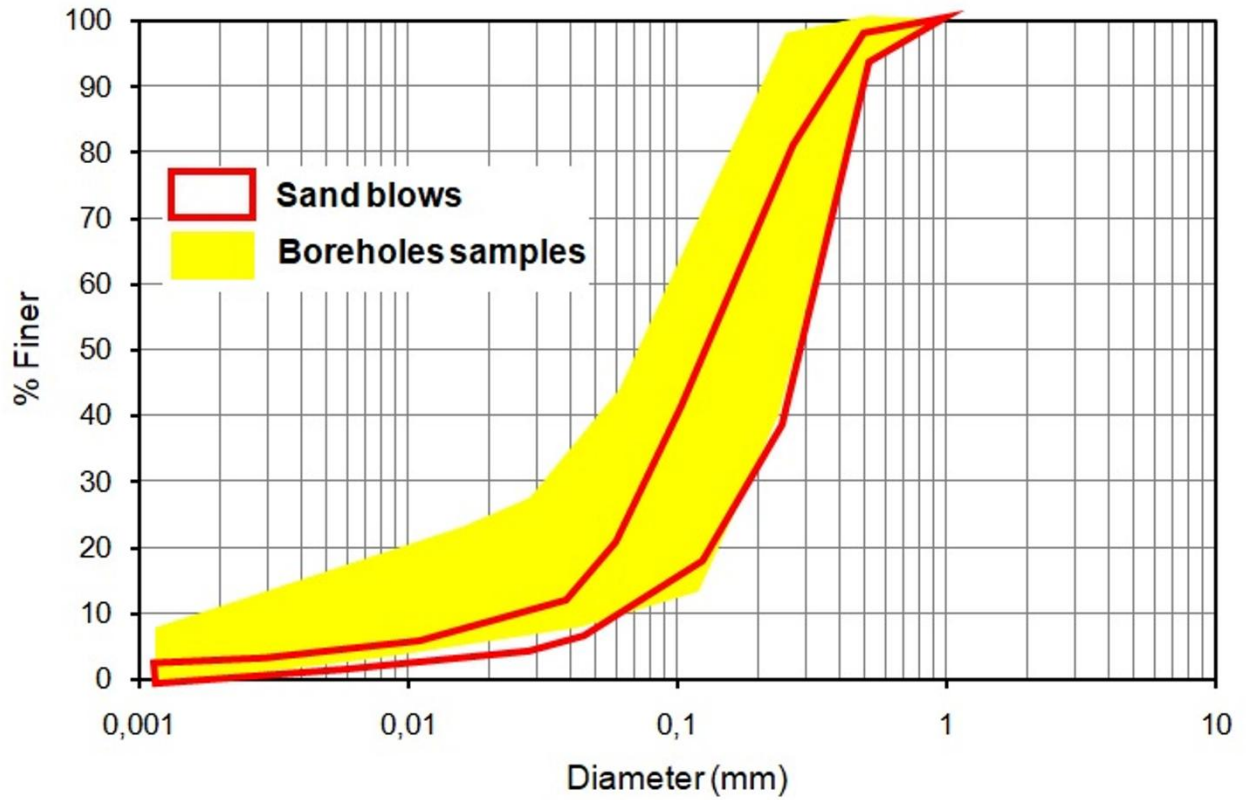


Fig. 5. Grain size curves of sand boils and the sands collected from boreholes.

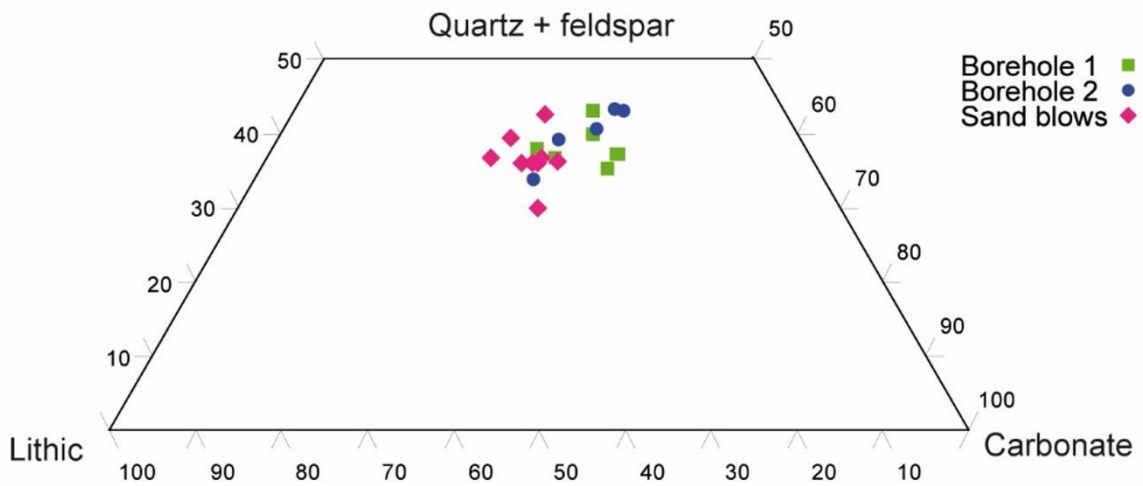


Fig. 6. Composition of liquefiable sand.

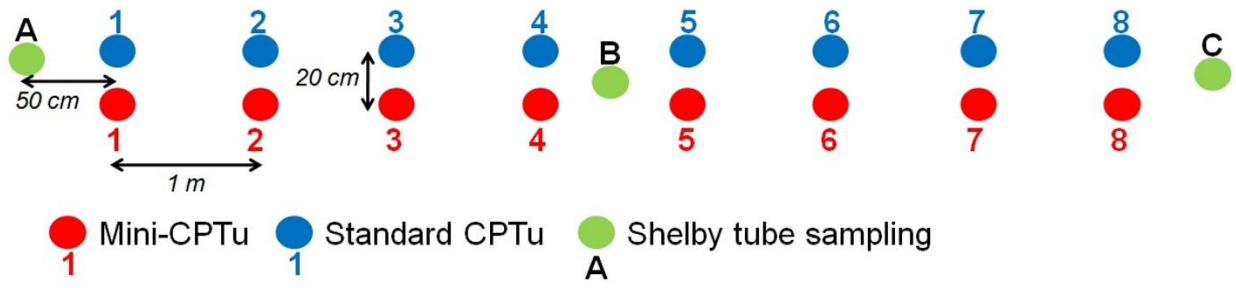


Fig. 7. Test site A: Test design.

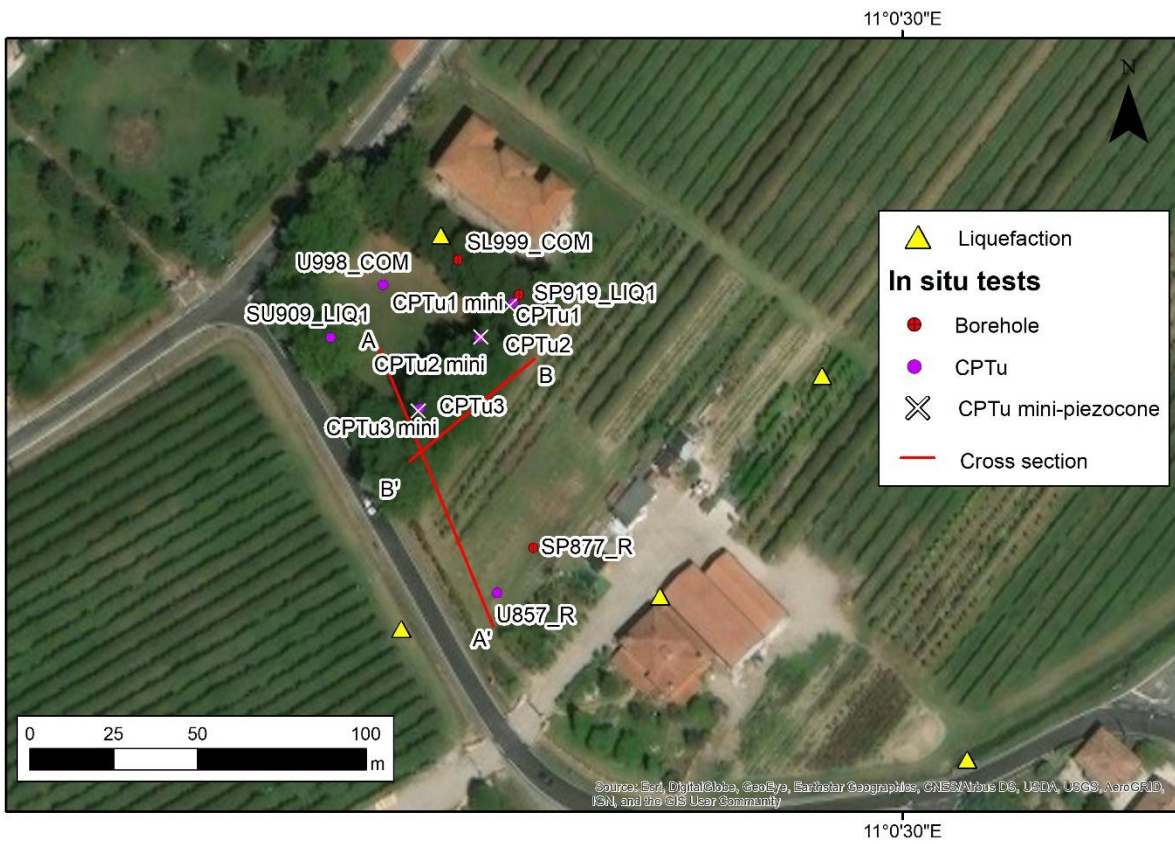


Fig. 8. Test site B: Test design.

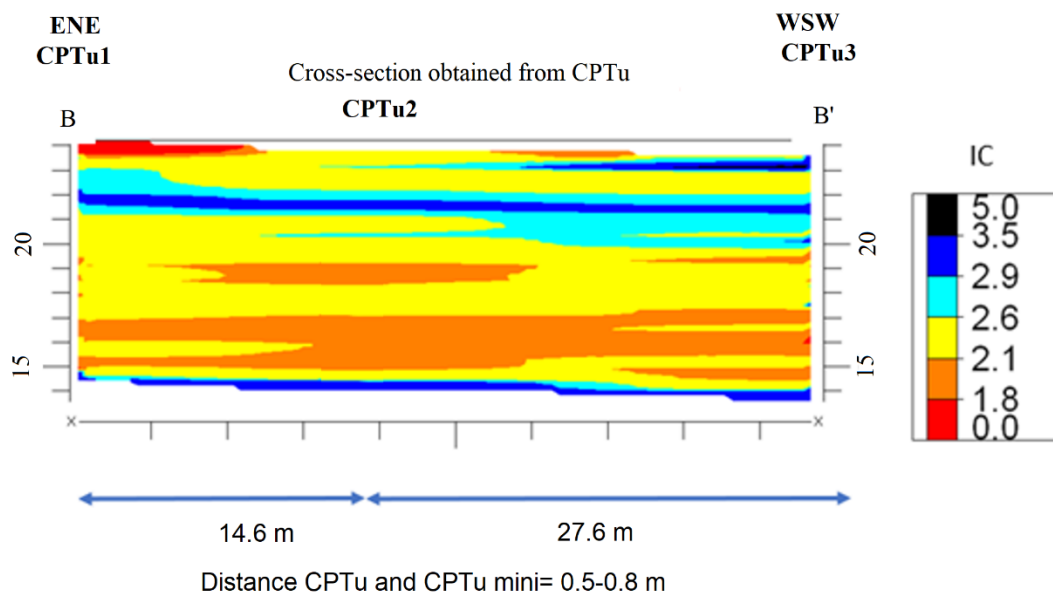
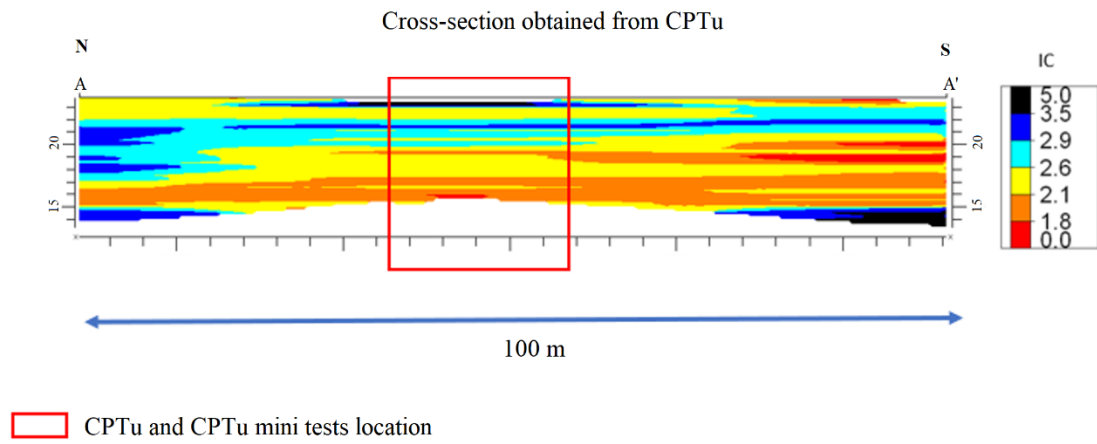


Fig. 9. Test site B: Ic profile section A-A' and B-B'.

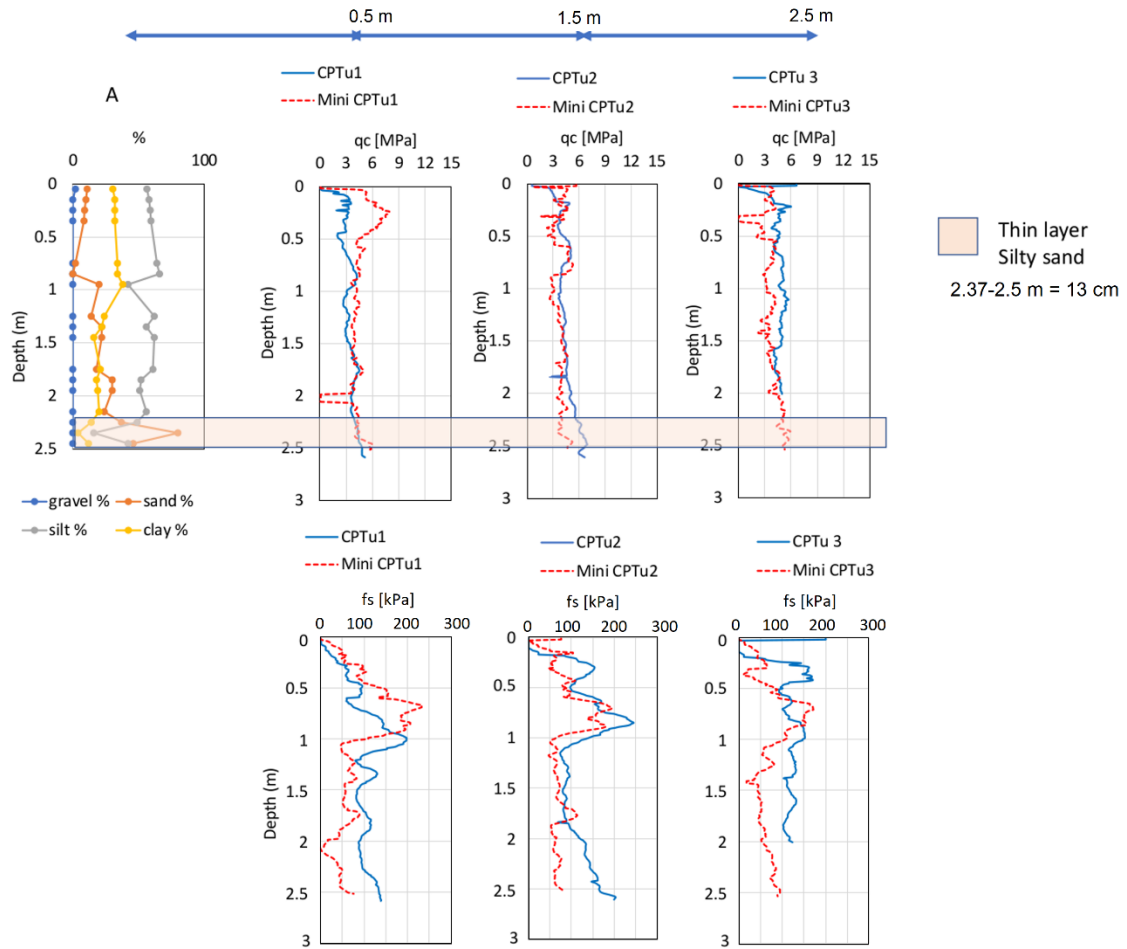


Fig. 10. Test site A: comparison standard CPT vs mini CPT in correspondence of the borehole A.

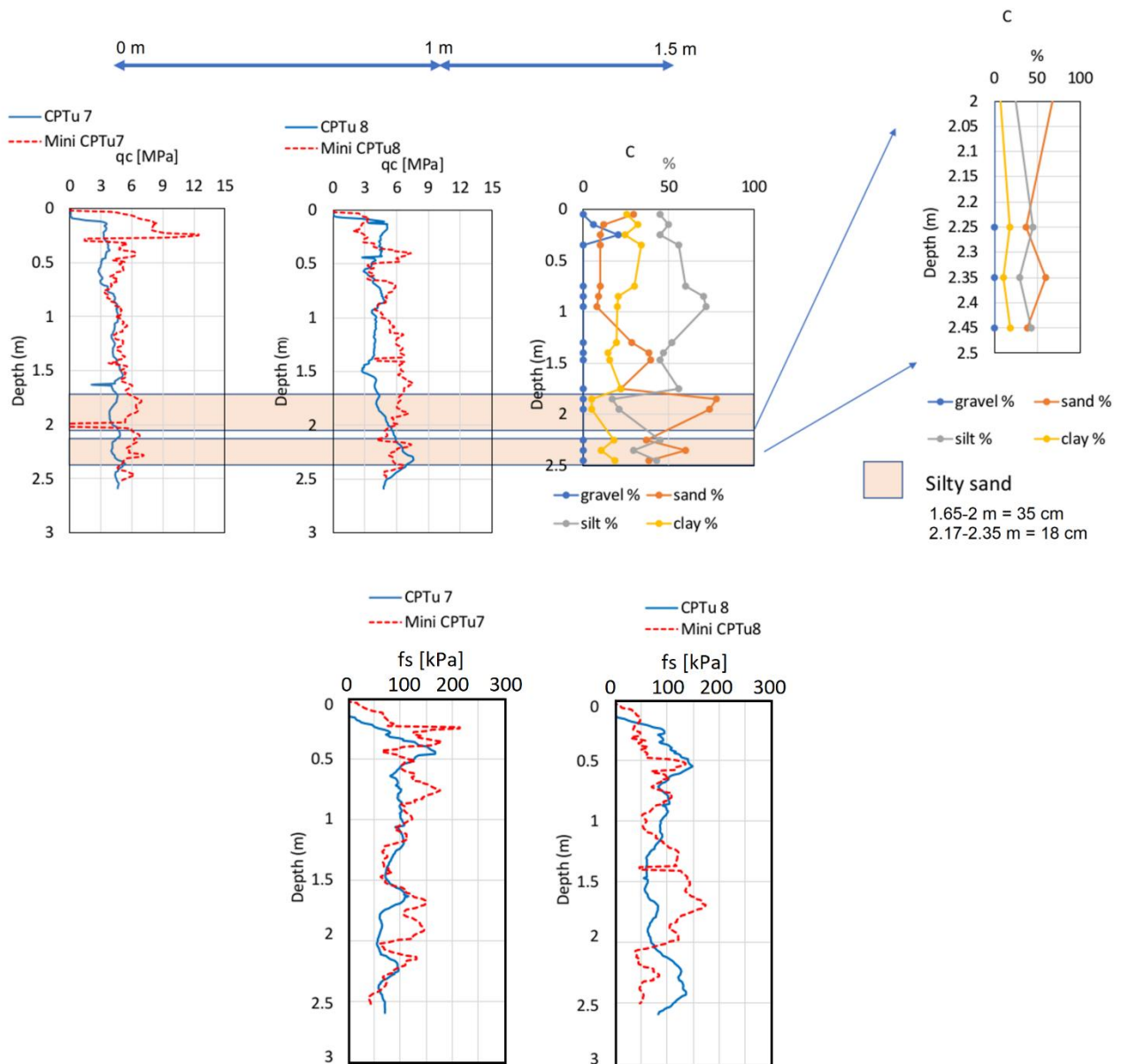


Fig. 11. Test site A: comparison standard CPT vs mini CPT in correspondence of the borehole C.

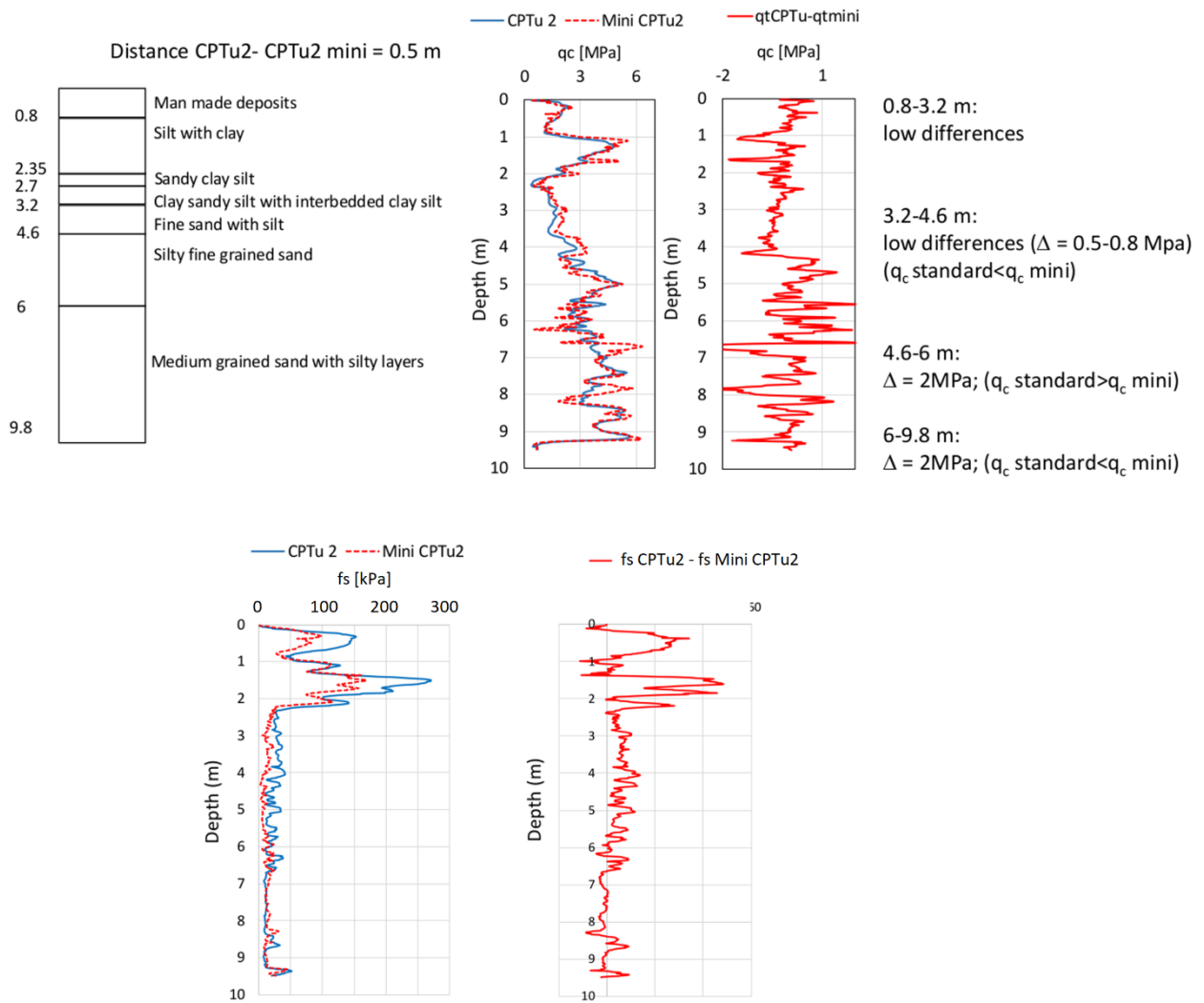


Fig. 12. Test site B: comparison standard CPTu2 vs CPTu2 mini.

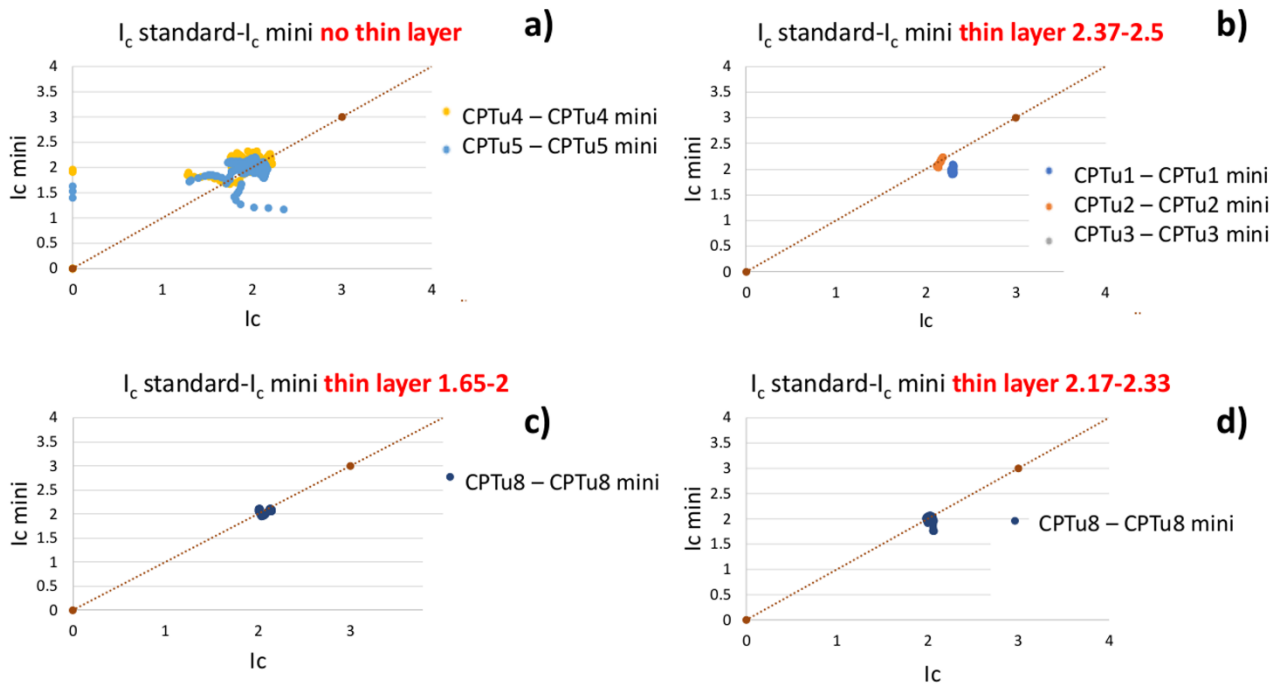


Fig. 13. Test site A: I_c standard vs I_c mini.

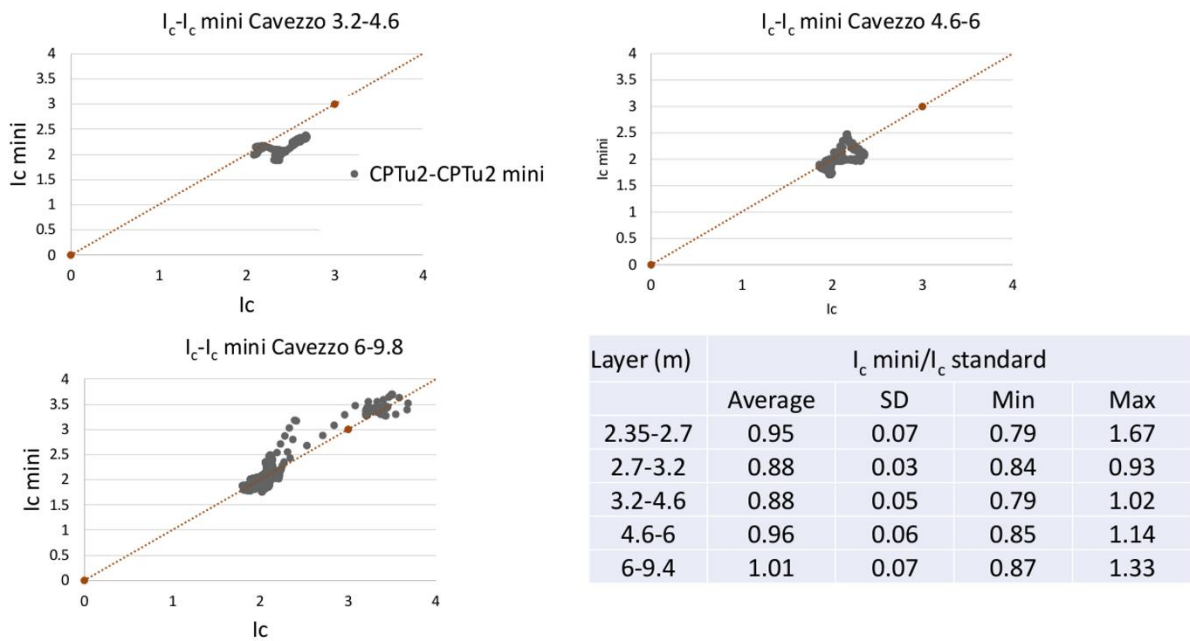


Fig. 14. Test site B: I_c standard vs I_c mini.

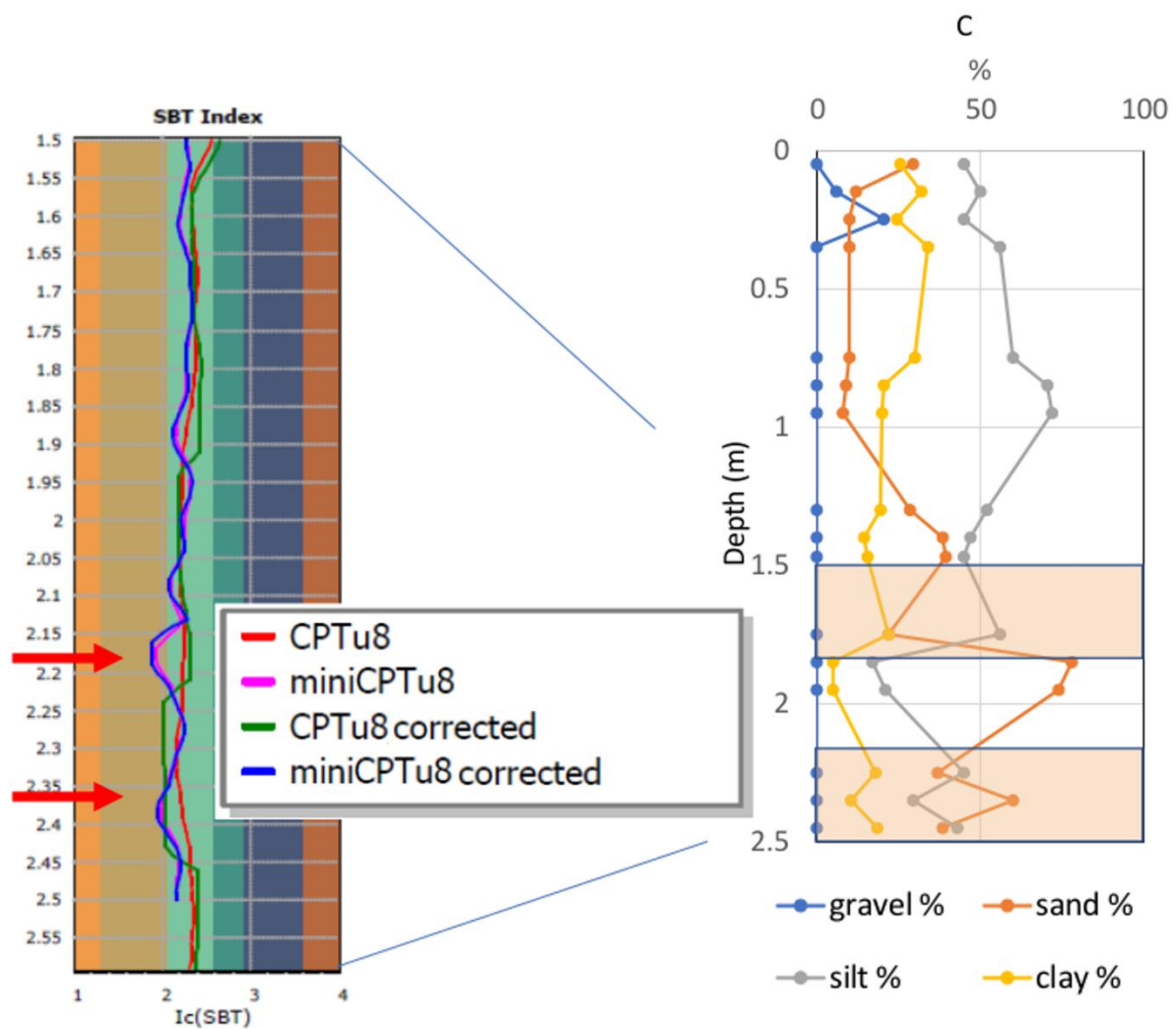


Fig. 15. Test site A: thin layer correction applied to standard CPTu8 and mini CPTu8. Close up of the depth between 1.5- 2.6 m and comparison with the grain size.

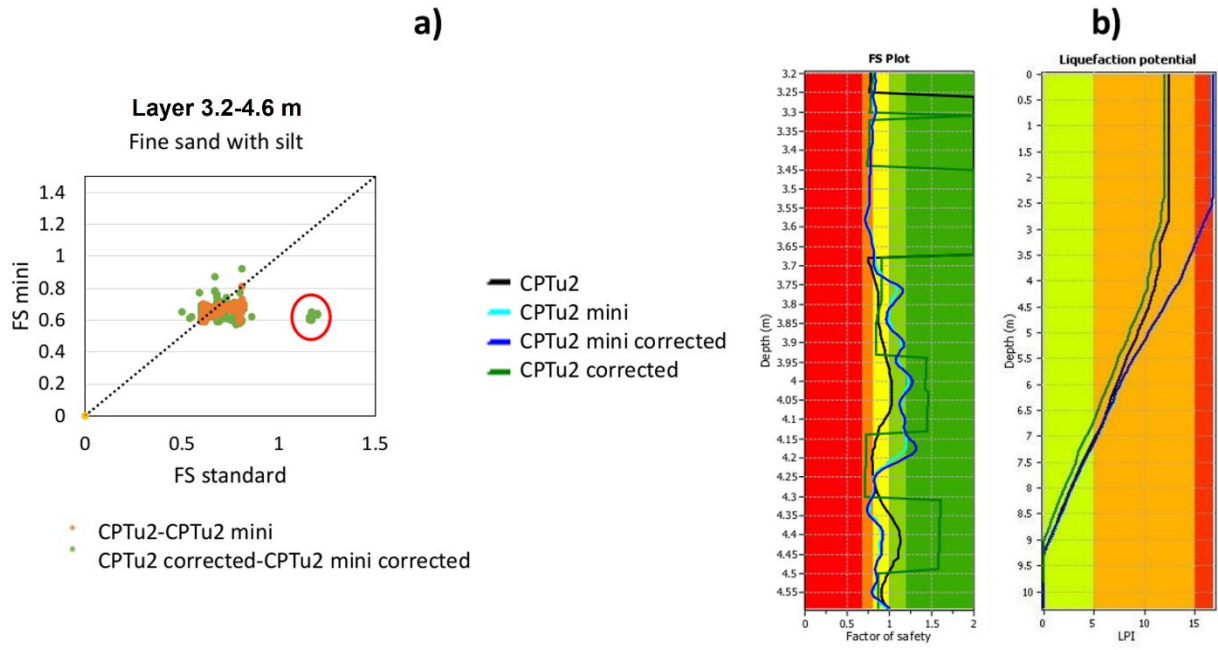


Fig. 18. Test site B – a) Liquefaction Factor of Safety (FS) of the layer between 3.2 and 4.6 m. b) Liquefaction potential assessment and FS for the test site B.