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Comparative Study of CPTU and SDMT in Liquefaction-Prone Silty Sands with Ground Improvement

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# 1 **Comparative study of CPTU and SDMT in liquefaction prone silty sands with ground** 2 **improvement**

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4 M. Rollins<sup>6</sup>, Luca Minarelli<sup>7</sup>, Diego Marchetti<sup>8</sup>, Kord J. Wissmann<sup>9</sup>

5 **Abstract:** Following the 2012 Emilia-Romagna seismic sequence, widespread liquefaction of silty  
6 sands was observed, providing the opportunity to enhance our knowledge of the influence of fines  
7 content on seismic hazard and mitigation works. This paper presents the results of a thorough  
8 geotechnical investigation performed in connection with full-scale controlled blast tests in Bondeno,  
9 a small village that suffered liquefaction in 2012. Piezocone (CPTU) and seismic dilatometer  
10 (SDMT) tests were performed in natural and improved soils after Rammed Aggregate Pier<sup>®</sup> (RAP)  
11 treatment to a depth of 9.5 m to provide accurate soil characterization, to evaluate liquefaction, and  
12 to verify the effectiveness of the ground improvement. The combined use of CPTU and DMT data  
13 provided reliable estimates of the overconsolidation ratio and at-rest earth pressure coefficient and  
14 highlighted the soil improvement in silty sands between 4 and 9 m in depth. Shear wave velocity  
15 measurements showed a low sensitivity to RAP installation. The treatment effectiveness was also  
16 confirmed by the use of the simplified procedures for liquefaction assessment, underlining the  
17 important influence of the adopted fines profile, and by the blast-induced liquefaction. CPTU and  
18 DMT parameters remained approximately unchanged between the piers after the detonation.

19 **Keywords:** controlled blasting, in-situ tests, liquefaction assessment, Rammed Aggregate Piers,  
20 silty sands, dense granular columns

## 21 **INTRODUCTION**

22 During the latest decades several “simplified procedures” for liquefaction assessment have been  
23 developed following the earthquakes and related co-seismic effects recorded around the world (e.g.,

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24 Seed and Idriss 1971, Robertson and Wride 1998, Andrus and Stokoe 2000, Youd et al. 2001, Idriss  
25 and Boulanger 2008, Kayen et al. 2013, Boulanger and Idriss 2014, Marchetti 2016, Saye et al.  
26 2021). The use of these assessment approaches based on in-situ tests, such as the Standard  
27 Penetration Test (SPT), Cone Penetration Test (CPT), and shear wave velocity measurements ( $V_s$ )  
28 contemplates the application of a correction factor for the fines content ( $FC$ ) of the soils susceptible  
29 to liquefaction. However, there is considerable uncertainty regarding the influence of non-plastic  
30 fines in relation to liquefaction triggering due to the cutoff value of the soil behavior type index ( $I_c$ )  
31 and the poor performance of  $I_c$ - $FC$  correlations (specifically for CPT). In addition, uncertainty  
32 exists due to the presence of surface cohesive layers and/or interbedded plastic soils, and due to the  
33 assumption that the  $FC$  correction factors generally increase with increasing fines but are essentially  
34 “capped” at  $FC = 35\%$  (e.g., Maurer et al. 2015a, Green et al. 2006, Prakash and Puri 2010, Polito  
35 and Martin 2001, Kokusho et al. 2012). These uncertainties require further study especially when  
36 applied to both natural and treated soils.

37 Several ground improvement solutions are available to mitigate the liquefaction hazard posed by  
38 clean sands, namely, increasing the soil resistance by densification or reducing the earthquake-  
39 induced excess pore pressures through drainage or reducing the shear strains through reinforcement.  
40 Vibratory compaction methods are a common and effective form of densification for cohesionless  
41 soils (Castro 1969), as proven by extensive research (e.g., D’Appolonia 1954, Mitchell 1981, Baez  
42 1995, Adalier and Elgamal 2004, Wissmann et al. 2015, Vautherin et al. 2017 Amoroso et al. 2018).  
43 However, their effectiveness decreases as the fines content and plasticity increase (Mitchell 1981).  
44 Therefore, other ground improvement techniques, such as vibratory replacement, are often preferred  
45 in silty sands or sandy silts to protect the soil against liquefaction by increasing soil density,  
46 providing drainage for excess pore water pressures, and increasing the stiffness and shear resistance  
47 of the soil (Priebe 1998). Examples of this type of reinforcement include Stone Columns (SC), Soil  
48 Mixed Columns (SMC), and Rammed Aggregate Piers (RAP). This last approach appears to be a  
49 promising solution in sandy silts and silty sands to increase not only the density, but also the lateral  
50 stress and shear stiffness, which are often neglected and poorly understood (Smith and Wissmann  
51 2018, Amoroso et al. 2020).

52 The at-rest earth pressure coefficient ( $K_0$ ) is a key soil parameter that should be considered with  
53 reference to liquefaction mitigation works (Schmertmann 1985, Salgado et al. 1997, Harada et al.  
54 2010). In this respect, in-situ tests have an essential role to play in estimating the horizontal stress in  
55 granular soils before and after treatment. As argued by Massarsch et al. (2019), the use of cone  
56 penetration test (CPT) and flat dilatometer test (DMT) results could produce improved estimates of  
57  $K_0$ . Moreover, Baldi et al. (1986) and later Hossain and Andrus (2016) proposed a combined CPT-

58 DMT  $K_0$ -interpretation to take into account both the resistance and stress history of the soil, while  
59 the use of a CPT-only approach would have been overly affected by arching of stresses around the  
60 penetrating sleeve.

61 The coupling of CPT and DMT tests with down-hole geophysics (i.e., seismic piezocone  
62 SCPTU and seismic dilatometer SDMT) provides a more efficient approach to the task of  
63 geotechnical site characterization, offering clear opportunities for the economical and optimal  
64 collection of the data (Mayne et al. 2009). Therefore, direct push technologies are more relevant for  
65 understanding the changes in soil properties following ground improvement (e.g., Schmertmann et  
66 al. 1986, Jendebay 1992, Balachowski and Kurek 2015, Amoroso et al. 2018, Massarsch and  
67 Fellenius 2019), and the time-dependence of the soil properties following artificially induced-  
68 liquefaction, such as controlled blasting (e.g., Solymar 1984, Ashford et al. 2004, Finno et al. 2016,  
69 Amoroso et al. 2017, Passeri et al. 2018).

70 This investigation presents in-situ test results from a thorough geotechnical campaign performed  
71 before and after Rammed Aggregate Pier (RAP) treatment of a silty sand site in Bondeno (Italy).  
72 Bondeno is a small village strongly affected by liquefaction following the 2012 Emilia-Romagna  
73 seismic sequence where blast liquefaction testing was subsequently performed to understand the  
74 behavior of the treated soil relative to the untreated soil. The overall details of the research activities  
75 can be found in Amoroso et al. (2020) while details regarding the performance of the RAP group  
76 are provided by Rollins et al. (2021). This paper is focused on the results of piezocone (CPTU) and  
77 seismic dilatometer (SDMT) tests performed in natural and treated soils characterized by high non-  
78 plastic fines content, before and after blasting. These results provide accurate soil characterization,  
79 evaluate liquefaction potential, and verify the effectiveness of the ground improvement.

## 80 **THE BONDENO TEST SITE (BTS)**

### 81 **Geological and geomorphological setting**

82 The Bondeno Test Site (BTS) is located in the south-eastern portion of the Quaternary alluvial  
83 Po Plain, one of the largest and most populous plains in Europe. The area was affected in 2012 by  
84 an intense seismic activity linked to the tectonic evolution of the fault-fold structures (Fig. 1a) that  
85 form the front of the Apennine chain buried below the plain (e.g., Toscani et al. 2009).

86 The seismic sequence induced widespread site effects, including liquefaction manifestations,  
87 soil fracturing and lateral spreading (Emergeo Working Group 2013). These phenomena occurred  
88 mainly along ancient paleochannels (Fig. 1b) of the Po River and other minor rivers of Apennine  
89 origin (e.g., Civico et al. 2015, Caputo et al. 2016, Stefani et al. 2018), some of which preserve a  
90 strong morphological expression (Fig. 1c). The Quaternary evolution of these river systems led to  
91 the formation, in the subsoil, of a complex twist of elongated sandy deposits or paleochannels,

92 laterally confined by clayey deposits accumulated into interfluvial depression (e.g., Amorosi et al.  
93 2016, Stefani et al. 2018). These continental sediments form the subsoil for a few hundred meters.

94 At BTS the liquefaction hazard is concentrated in a subsurface sandy deposit of a Holocene Po  
95 meander (Figs. 1c and 1d). Fig. 1c shows the higher elevations (brownish zones) indicating fluvial  
96 ridges bounding the lower, relatively flat interfluvial depression (greenish zones). The meandering  
97 course of the paleochannel is built up within the interfluvial depression and supports the  
98 identification of the paleochannel axis together with the location of sand boils. The meander base is  
99 frequently cut into upper Pleistocene coarse sand, accumulated during syn-glacial times. The  
100 meander unit geometry has been reconstructed through the analysis of remote sensing data (satellite  
101 images and LIDAR) and correlation of subsurface geotechnical investigations (Amoroso et al.  
102 2020). This meander sand body is partially buried by finer grained levee sediment of historic age.

### 103 **Site investigations**

104 At the BTS the geotechnical campaign was structured in three phases, as detailed in Table 1 and  
105 Fig. 2, following the activities of the blast experimental research program, as described in general  
106 by Amoroso et al. (2020):

- 107 • Phase I consisted of site investigations performed before the treatment (pre-RAP) and before the  
108 blast (pre-blast). Boreholes with SPTs and disturbed soil sampling, CPTUs, and SDMTs were  
109 executed up to a maximum depth of 20 m in two relatively small circular areas (10 m-diameters  
110 at 20 m-spacing) associated with the blast experiment, one for testing the natural soil (Natural  
111 Panel, NP) and one for testing the improved soil (Improved Panel, IP). The aims were to verify  
112 the subsoil homogeneity, and to provide detailed geotechnical characterization and liquefaction  
113 assessment of the two blast panels;
- 114 • Phase II included site investigations carried out approximately one month after the pier  
115 installation (post-RAP) and before the blast (pre-blast) within the IP. The treatment consisted of  
116 a 4 × 4 quadrangular grid (2 m center-to-center spacing) of RAP columns, each 9.5 m long and  
117 with a final diameter of 0.5 m (area replacement ratio equal to 5%). Details regarding the  
118 construction methodology itself are reported in Saftner et al. (2018). Each CPTU, Medusa DMT  
119 (automated dilatometer test, see Marchetti et al. 2019) and SDMT test was performed up to a  
120 maximum depth of 15 m at the exact center between of four RAPs (see Fig. 2) to verify the  
121 effectiveness of the ground improvement technique especially regarding liquefaction;
- 122 • Phase III comprised three different site campaigns executed soon after the blast-induced  
123 liquefaction (post-blast June), then approximately two and three months after the controlled  
124 blasting (post-blast July and September) within the IP and NP. Details regarding the blast  
125 experiment are summarized in the next section. CPTU, Medusa DMT and SDMT tests were

126 carried out to a maximum depth of 15 m, and for the IP, the in-situ tests were located at the  
127 exact center between four RAPs (see Fig. 2). The goal of this phase was to study the time-  
128 dependence of soil properties following artificially induced-liquefaction both in the natural and  
129 treated soils.

### 130 **Blast test experiment**

131 To provide a direct comparison of ground performance with and without RAP treatment, blast  
132 liquefaction testing (Ashford et al. 2004) was performed at each test panel. A total of 16 explosive  
133 charges (8 of 0.5 kg at 3.5 m and 8 of 2.0 kg charges at 6.5 m in depth) were detonated sequentially  
134 at one second intervals around the periphery of two 10 m-diameter circles at each test panel. This  
135 blasting sequence induced liquefaction (excess pore pressure ratio  $R_u = 100\%$ , where  $R_u$  is the ratio  
136 between the excess pore pressure and the effective vertical stress) to a depth of 11 m in the NP, but  
137 only induced  $R_u$  values of about 75% in the IP (Rollins et al. 2021). Ground surface settlement at  
138 the center of the NP was 10 cm, but only 4 cm in the IP. Based on profilometer measurements,  
139 settlement within the treated zone (0 to 9.5 m) was reduced by 75% in the IP relative to the NP  
140 (Pesci et al. 2022). Several large sand boils developed within the NP after blasting and produced  
141 considerable sand ejecta, while sand boils only developed outside the treated area in the IP  
142 (Amoroso et al. 2020). Thus, based on the metrics of excess pore pressure, settlement, and ejecta,  
143 the RAP group installation improved the site considerably.

## 144 **SITE CHARACTERIZATION**

### 145 **First phase: initial conditions of natural ground**

146 During the pre-RAP and pre-blast phase a borehole (S01), along with six SPTs, was carried out  
147 within the IP and 20 disturbed soil samples were extracted. The borehole log revealed the presence  
148 of a silty clay (CL) crust in the upper 3.5 m with an average plasticity index ( $PI$ ) of 20%, followed  
149 by a non-plastic silty sand with  $FC$  typically in the range 25-35% and therefore classified as SM  
150 (Table 2), according to the Unified Soil Classification System, USCS (ASTM D2487-11 2011,  
151 ASTM D2488-09 2009).

152 A selection of grain size distribution curves determined on the soil samples is provided in Fig.  
153 3a, whereas the SPT blow counts  $N_{SPT}$  recorded in silty sands are plotted in Fig. 3b, together with  
154 values of fines content obtained from sieve analysis. It is worth observing that results from particle  
155 size analysis are in good agreement with the high  $FC$  detected for the non-plastic silty-sandy  
156 deposits previously investigated in the liquefied areas after the 2012 Emilia-Romagna seismic  
157 sequence (e.g., Porcino and Diano 2016, Facciorusso et al. 2016, Fontana et al. 2019). SPT blow  
158 counts ( $N_{SPT}$ ) turned out to be quite low between 3.5 and 6.0 m in depth, while increasing at greater  
159 depth. This preliminary information suggests a higher susceptibility to liquefaction in the upper part

160 of the SM layer.

161 Fig. 4a shows the profiles of the corrected cone resistance,  $q_t$ , sleeve friction,  $f_s$ , and pore  
162 pressure,  $u$ , obtained from two representative piezocone tests, namely CPTU11 and CPTU01, both  
163 carried out in the pre-RAP phase and located in the natural panel and in that to be treated,  
164 respectively. As detailed in the following, classification results and CPTU-based estimates of  
165 several relevant geotechnical parameters are also shown in Fig. 4a.

166 The comparative analysis of the  $q_t$ ,  $f_s$  and  $u$  profiles reveals substantial agreement between the  
167 piezocone measurements collected in the two panels, thus indicating negligible horizontal spatial  
168 variability in the stratigraphic conditions of the whole test site. In particular, the interpretation of  
169 piezocone data in terms of the well-known classification framework by Robertson (2009),  
170 expressed as soil behavior type index ( $I_c$ ), shows that most of the soils between 1.5 and 3.3 m in  
171 depth belong to the domains of silty clay/clayey silts. Compared to the natural panel, a slightly  
172 higher occurrence of silty sediments is observed in the panel selected for treatment. The underlying  
173 sediments, from 3.3 to 20 m, can be classified in both panels as predominantly silty sands. The  $I_c$   
174 profiles computed from CPTU01 and CPTU11 are almost identical and generally oscillate about an  
175 average value equal to  $1.75 \pm 0.10$  and  $1.77 \pm 0.12$ , respectively. However, the analysis of the pore  
176 pressure profile in the NP seems to suggest the presence of an interbedded layer of dilative silts at  
177 approximately 12.5-13.5 m in depth, not identified by the  $I_c$ . The latter is actually based only on the  
178 stress-normalized cone resistance  $Q_t$  and friction ratio  $F_r$ .

179 It is also worth observing that the application of a number of well-known CPTU-based  
180 empirical correlations (Robertson and Wride 1998, Suzuki et al. 1998, Boulanger and Idriss 2014),  
181 all dependent in different ways on the  $I_c$ , typically results in significant underestimation of the fines  
182 content, compared to the values obtained from grain size analysis. Indeed, as shown in Fig. 4a, good  
183 agreement with the average profile of laboratory  $FC$  is observed for the Boulanger and Idriss (2014)  
184 correlation for cohesive layer only.

185 Sands detected from 3.3 to 20 m in depth turn out to be in a medium-dense state. Most of the  
186 computed values of the relative density  $D_R$ , obtained by applying the correlation of Jamiolkowski et  
187 al. (2001) to the CPTU data, oscillate in the range of 50 to 60%. This outcome is also confirmed by  
188 discrete SPT-based predictions (Skempton 1986), which have been superimposed on the CPTU-  
189 based  $D_R$  profiles reported in Fig. 4a. According to the correlation developed by Robertson (2010),  
190 the corresponding state parameter  $\psi$  (as defined by Been and Jefferies 1985) has been found to be  
191 negative, on average close to -0.1 (thus theoretically suggesting dilative behavior at large strains),  
192 with minor differences over the whole thickness of the sandy layer. However, it is well-known that  
193 the determination of the in-situ soil state from cone penetration measurements actually involves

194 solving an inverse problem based on various independent geotechnical variables (Jefferies and Been  
195 2006), hence the estimates of  $\psi$  provided by simplified relationships, such as those reported in Fig.  
196 4a, must be seen as an approximation of the actual in-situ soil state and should therefore be  
197 considered relatively uncertain.

198 The profile of the one-dimensional constrained modulus  $M$ , obtained by applying the empirical  
199 correlation developed by Robertson (2009) in the framework of a so-called unified approach, shows  
200 minor variations in the shallow silty clays and then increases with depth (approximately linearly) in  
201 the underlying sands. These estimates cannot be compared for validation with any oedometer test  
202 result, nor with compressibility parameters back-calculated from 1D field settlements. However, as  
203 will be discussed subsequently, the  $M$  profile plotted in Fig. 4a turns out to be in a rather good  
204 agreement with that computed from SDMT measurements. At the same time, it should be  
205 mentioned that the application of other well-known CPTU-based correlations, either devised for  
206 sands (e.g., Lunne and Christophersen 1983) or for silty sediments (e.g., Senneset et al. 1988),  
207 resulted in predictions of  $M$  equal to about half the values provided by Robertson's unified  
208 approach.

209 With regards to the soil shear strength of the sands, predictions of the effective peak friction  
210 angle  $\phi'$  provided by the Kulhawy and Mayne (1990) correlation appear to be in good agreement  
211 with those computed from SPT blow counts. The profile exhibits minor variability from 3.3 to 20 m  
212 in depth, with  $\phi'$  estimates being on average equal to  $37.7^\circ \pm 1.0^\circ$  in the natural panel and  $38.0^\circ \pm 0.9^\circ$   
213 in the panel to be treated.

214 Fig. 4b summarizes the results obtained from SDMT in natural soils, in terms of profiles with  
215 depth both of measured parameters, namely, the corrected DMT pressure readings  $p_0$ ,  $p_1$ ,  $p_2$  and the  
216 shear wave velocity  $V_s$ , along with parameters obtained from the usual DMT interpretation  
217 (Marchetti 1980, Marchetti et al. 2001), namely, the material index  $I_D$  (indicating soil type), the  
218 pore pressure index  $U_D$  (related to soil permeability), the horizontal stress index  $K_D$  (related to stress  
219 history), the constrained modulus  $M$ , the friction angle  $\phi'$  in sand, as well as the small strain shear  
220 modulus  $G_0$  obtained as  $G_0 = \rho V_s^2$  (where  $\rho$  is the soil density, derived from the unit weight  $\gamma$   
221 estimated from DMT).

222 The values of  $p_0$  and  $p_1$  measured in the NP and IP (pre-RAP), as well as the derived  
223 parameters, are generally similar or slightly variable, reflecting a general consistency of the soil  
224 properties across the test area, as also observed from CPTU measurements. Below a depth of about  
225 3.4 m,  $p_2$  closely approximates the in-situ equilibrium pore pressure  $u_0$  and accordingly  $U_D \approx 0$ ,  
226 indicating fully drained response, while in the upper soil layer  $p_2 > u_0$  and  $U_D > 0$ , indicating  
227 undrained response and excess pore pressure induced by blade penetration (Marchetti et al. 2001).

228 The interpretation of SDMT results, in particular  $I_D$  and  $U_D$ , are consistent with CPTU and borehole  
229 data, and identify an upper silty clay to clayey silt unit extending to a depth of about 3.4 m from the  
230 ground surface, underlain by silty sand down to a depth of about 12.6 m, followed by sandy silt at  
231 depths between about 12.6 and 13.4 m, and then silty sand down to the maximum investigated  
232 depth of 15 m.

233 Below a shallow “crust” (more pronounced in the IP), the different  $K_D$  values in the sandy units  
234 (paleochannel of the Po River from 3.4 to 12.6 m, glacial braided Po River deposits below 13.4 m)  
235 may be related to their different geologic depositional environment. In contrast, the  $V_S$  increases  
236 consistently with the effective vertical stress in all soil units.

237 The values of  $\phi'$  estimated from SDMT in sand (Marchetti 1997) are broadly in agreement with  
238 the values obtained from the CPTU. The values of  $M$  estimated from the SDMT (Marchetti 1980),  
239 similar to those derived from the CPTU (Robertson 2009, Fig. 4a), indicate higher compressibility  
240 of the upper cohesive unit, while the sands below 3.4 m in depth are significantly less compressible.  
241 While  $M$  refers to stiffness at “working strain” level (Marchetti et al. 2008),  $G_0$ , corresponding to  
242 stiffness at very small strains, increases gradually with depth, without sharp contrasts between  
243 different soil units.

244 Fig. 5 shows the stratigraphic arrangement of the subsoil beneath the test site area along a  
245 North-South cross-section, as deduced by the combined interpretation of borehole logs, SPT,  
246 CPTU, Medusa DMT and SDMT described above, all carried out before the RAP installation. Apart  
247 from a 0.8 m thick topsoil layer (CH, according to USCS), the following well-defined stratigraphic  
248 units, also reflecting their sedimentological framework, could be identified:

- 249 • a layer of silty clays (CL, according to USCS), from 0.8 to about 3.3-3.5 m in depth;
- 250 • a predominantly silty sand unit, approximately 9 m thick, attributable to Holocene alluvial  
251 deposits of the Po River paleochannel. Samples recovered from this unit can be generally  
252 classified as SM, having a  $FC$  typically in the range 25-35% (see Table 2). Thin layers of  
253 coarser sediments have been occasionally found;
- 254 • a thin layer of sandy silt (ML), from 11.8-12.6 to 13.0-13.4 m in depth (interfluvial deposits);
- 255 • sands-silty sands (SP-SM) of the late Pleistocene epoch (namely, glacial braided Po River  
256 deposits), detected below 13.0-13.4 m in depth.

257 In this stratigraphic section, the groundwater table (GWT) is located at approximately 0.5 m  
258 from the ground surface, being governed by the water level in a nearby channel.

259 As evident from Fig. 5, the whole set of site investigations did not provide any significant  
260 evidence of horizontal spatial variability in the stratigraphic arrangement of the entire study area.  
261 Accordingly, the subsoil of the two panels appears to be fully comparable, and thus perfectly

262 suitable for analyzing the different responses of treated and untreated soils both during the blast test  
263 and some months after the liquefaction experiment.

#### 264 **Second phase: post-RAP treatment**

265 Fig. 6 provides a comparison between field soil properties before and after RAP installation in  
266 the IP, in terms of both CPTU and SDMT profiles.

267 As regards the piezocone profiles, the increase in the  $q_t$  values after column construction  
268 appears to be particularly noticeable ( $q_t = 13.10 \pm 1.76$  MPa versus  $9.54 \pm 1.37$  MPa before  
269 installation) from 6 to 8.5 m in depth, and relatively moderate from 4 to 6 m. Negligible changes in  
270 the  $q_t$  profile can be observed in the silty sands below the base of the piers. Obviously, these  
271 changes in  $q_t$  affect the computed estimates of the geotechnical parameters reported in Fig. 6,  
272 namely  $M$ ,  $\psi$ ,  $D_R$  and  $\phi'$ , as discussed below. The RAP treatment did not produce any improvement  
273 in the cohesive upper 4 m of the profile. This is consistent with experience in cohesive soils using  
274 other vibratory ground improvement techniques (Mitchell 1981).

275 The effect of RAP installation is evidently reflected by the increase in  $K_D$  (on average 48-53%),  
276 and even more in  $M$  from SDMT (80-87%), at depths between 4 and 9 m (Fig. 6, Table 3). The  
277 corresponding average increase in  $q_t$  is 30-35%. These results point to a significant increase in  
278 horizontal stress and stiffness resulting from pier installation, in agreement with previous  
279 observations (Saftner et al. 2018). In fact, the horizontal stress strongly influences both  $K_D$  and  $M$   
280 estimated from the DMT using the Marchetti (1980) correlation, which incorporates  $K_D$ . The  
281 increase in  $M$  estimated from the CPTU is less pronounced, thus suggesting a lower sensitivity of  $q_t$   
282 to an increase in horizontal stress. Between 6 and 8.5 m in depth, the pier installation increased  $D_R$   
283 by an average of 10%, corresponding to a variation in the state parameter  $\psi$  of approximately -0.05  
284 (more dilative), as deduced from CPTU measurements. Despite the uncertainties surrounding the  
285 computation of  $\psi$ , already mentioned, the computed trend is consistent with the increased density of  
286 the sand induced by RAP installation. As in the case of the CPTU, the SDMT did not any show  
287 significant improvement between 0 and 4 m in depth.

288 The observed results are in line with previous comparisons of pre- vs. post- CPTs and DMTs  
289 executed for monitoring ground improvement (e.g., Schmertmann et al. 1986, Jendebay 1992), since  
290 the RAP installation produced an average increase in  $M$  from DMT after treatment approximately  
291 2.5 times the corresponding increase in cone penetration resistance  $q_c$ .

292 The decrease in  $K_D$  observed in the upper crust may be due in part to the construction of an  
293 overlying working platform, but also to the RAP installation under low confining stress and to  
294 seasonal variations in water content caused by the fluctuation of the GWT from 1.5 m (February  
295 2018) to 0.5 m (March 2018), as reported in Table 1. No improvement was detected in the silty

296 sands below the toe of piers, unlike RAP case histories in clean sands studied in New Zealand (e.g.,  
297 Wissmann et al. 2015, Vautherin et al. 2017).

298 To investigate further the variation of  $M$  before and after treatment in relation to data sources  
299 and computation methods, Fig. 7 shows a comparison between profiles of  $M$  computed by applying  
300 different empirical correlations (Robertson 2009, Lunne and Christophersen 1983, Senneset et al.  
301 1988) to CPTU measurements, and estimates of  $M$  obtained from the SDMT (Marchetti 1980), in  
302 both natural and treated soils (IP pre- and post-RAP). For useful comparison, Fig. 7 also includes a  
303 few approximate values of  $M$  inferred from the SDMT-based small strain shear modulus  $G_0$ ,  
304 assuming a conventional decay of  $G/G_0$  at “working strain” level, namely  $G/G_0 = 0.4$  (Gajo and  
305 Muir Wood 1999), together with a Poisson’s ratio  $\nu = 0.2$ . In natural soils,  $M$  from the DMT is  
306 similar to  $M$  estimated from the CPTU when the Robertson (2009) correlation is adopted, while the  
307  $M$  values provided by the alternative approaches (Lunne and Christophersen 1983, Senneset et al.  
308 1988) turn out to be significantly lower. In treated soils, as mentioned,  $M$  values from the DMT  
309 show a more significant increment with respect to CPTU, thus confirming that the DMT is more  
310 sensitive to stiffness variations as a reasonable consequence of the increase of horizontal stress -  
311 and therefore of mean stress - produced by pier installation.

312 The combined interpretation of CPTU and DMT data provided information on the stress history  
313 and the state parameter in sand, in both the natural and treated soils as shown in Fig. 8. Filtering the  
314 data for  $I_D \geq 1.8$  and  $I_c \leq 2.6$ , in the sandy layers the ratio  $M/q_t$  (with  $M$  estimated from DMT) is  
315 shown in Fig. 8. The average values of  $M/q_t$  are about 7-10 in natural soil and 13-14 in treated soil  
316 (Table 3). These values are in line with the available experience from field observations before and  
317 after compaction of sand fills, reported by Marchetti et al. (2001) and Marchetti and Monaco  
318 (2018), which show an increase in the ratio  $M$  from DMT to  $q_c$  from CPTU of between 5-10 before  
319 compaction to between 12-24 after compaction. The finding that compaction increases both  $M$  from  
320 DMT and  $q_c$ , but  $M$  at a faster rate, suggested the potential use of the ratio  $M$  from DMT/ $q_c$ , as a  
321 broad indicator of “equivalent”  $OCR$  in sands.

322 The in-situ earth pressure coefficient  $K_0$  was estimated using correlations proposed by Baldi et  
323 al. (1986), based on both DMT and CPT data, and by Hossain and Andrus (2016), which require as  
324 an additional input also  $OCR$  (in this case evaluated according to Monaco et al. 2014). In the upper  
325 silty clay layer  $OCR$  and  $K_0$  were estimated from the DMT (Marchetti 1980).

326 The  $OCR$ s of about 1-2 estimated in the natural soil, excluding the shallow “crust”, indicate that  
327 the deposit is normally consolidated or slightly overconsolidated, with  $K_0 \approx 0.5-0.7$ . As an effect of  
328 the RAP installation, the “equivalent”  $OCR$  increased to about 3-3.5 and  $K_0$  to about 0.9-1. The  
329 values of  $K_0$  estimated according to Hossain and Andrus (2016) are lower than those estimated

330 according to Baldi et al. (1986). The increase of  $M/q_t$ ,  $OCR$  and  $K_0$  after treatment was more  
331 pronounced at depths between 7 and 9 m (Table 3).

332 An approximate estimate of the in-situ state parameter  $\psi$  in sand from DMT was obtained  
333 according to Yu (2004), with  $K_0$  determined by both Baldi et al. (1986) and Hossain and Andrus  
334 (2016) methods. Fig. 8 shows that the input  $K_0$  has a large influence on the calculated values of  $\psi$ ,  
335 with an apparent contradiction versus the expected trend. In fact, the higher  $K_0$  (i.e., higher  $OCR$ )  
336 estimated according to Baldi et al. (1986) should involve lower negative values of  $\psi$  compared to  
337 those obtained using  $K_0$  from Hossain and Andrus (2016), while the opposite is observed in Fig. 8.  
338 On the other hand, the reduction of  $\psi$  after treatment found using both  $K_0$  methods is consistent  
339 with the corresponding increase of  $OCR$  and  $K_0$  before and after treatment. However, the computed  
340 values turn out to be significantly different from those obtained from CPTU data interpretation.

### 341 **Third phase: post-blast conditions**

342 Fig. 9 summarizes the results obtained from CPTU and SDMT pre- and post-blast. In the NP  
343 (Fig. 9a) the pre-blast data refer to natural soil, while in the IP (Fig. 9b) both to natural and treated  
344 soils. In both panels the post-blast data were collected immediately after the blast (June 2018),  
345 about one month later (July 2018), and about three months later (September 2018).

346 With regards to the piezocone tests in the NP, comparison between the pre-blast test (CPTU11)  
347 and that performed a few days after blasting (CPTU11ter) does not reveal any significant changes in  
348 soil response, in terms of  $q_t$  and the relevant parameters  $M$ ,  $\psi$ ,  $D_R$ ,  $\phi'$ . In addition, in spite of a  
349 somewhat horizontal spatial variability detected in tests conducted some months after the  
350 experiment (CPTU11quater and CPTU11quintus), only a slight increase in  $q_t$  can be observed from  
351 approximately 6.7 to 8.8 m. Consequently, little variation in  $M$ ,  $\psi$ ,  $D_R$  and  $\phi'$  can be noticed within  
352 this depth interval. With respect to the CPTU tests in the IP, field measurements collected soon after  
353 and some months after the blast experiment show properties very similar to those observed in the  
354 post-RAP test (CPTU01bis). As a result, relevant changes in the predicted soil parameters cannot be  
355 clearly recognized from tests during the third-phase.

356 In natural soil (NP) the parameters  $K_D$  and  $M$  from DMT show an increase greater than 100%  
357 soon after the blast at depths between about 6 and 9 m, that can be related to the blast-induced  
358 settlements measured by the profilometer in the same depth interval (Rollins et al. 2021). However,  
359 these parameters remain unchanged at greater depths. An increase in these properties is also  
360 observed in the upper silty clay layer. In the following three months of observation,  $K_D$  and  $M$  from  
361 DMT do not exhibit any significant time-dependent gain or reduction overall, apart from local  
362 variations. In the treated soil (IP), the variation of  $K_D$  and  $M$  from DMT before and after the blast is  
363 much lower, possibly as a consequence of the effectiveness of the piers.

364 In both natural and treated soils  $V_S$  does not show changes before and after blasting, as  
365 previously found by Passeri et al. (2018) in another controlled blasting test performed in the natural  
366 silty sand of Emilia-Romagna.

### 367 LIQUEFACTION ASSESSMENT

368 Liquefaction assessment was performed in pre-blast natural (NS) and treated (TS) soils to verify  
369 the effectiveness of the RAP piers. The simplified procedure by Seed and Idriss (1971) has been  
370 applied to SPT, CPTU, DMT and  $V_S$  data, giving emphasis to the use of different in-situ test  
371 methods to provide a more reliable estimation as recommended by many authors (e.g., Robertson  
372 and Wride 1998, Youd and Idriss 2001, Idriss and Boulanger 2004). In particular, the cyclic  
373 resistance ratio at  $M_w = 7.5$  ( $CRR_{7.5}$ ) was evaluated by:

- 374 • the corrected SPT blow count  $(N_1)_{60}$  obtained from Youd et al. (2001), Idriss and Boulanger  
375 (2008) and Boulanger and Idriss (2014) SPT-approaches and based on measured hammer  
376 energy;
- 377 • the normalized overburden corrected cone tip resistance  $q_{cIN}$  calculated from Robertson and  
378 Wride (1998), Idriss and Boulanger (2008) and Boulanger and Idriss (2014) CPTU-methods;
- 379 • the horizontal stress index  $K_D$  estimated from Monaco et al. (2005), Tsai et al. (2009),  
380 Robertson (2013) and Marchetti (2016) DMT-methods;
- 381 • the combination of  $q_{cIN}$  and  $K_D$  parameters into Marchetti (2016) CPTU-DMT correlation;
- 382 • the overburden stress corrected shear wave velocity  $V_{SI}$  in the Andrus and Stokoe (2000) and  
383 Kayen et al. (2013)  $V_S$ -based procedures.

384 To screen out “clay-like” soils, a threshold was set at  $I_c \leq 2.6$  for CPT data and at  $I_D \geq 1.0$  for  
385 DMT and  $V_S$  measurements, considering the non-plastic behavior of the silty sands, as provided by  
386 the Atterberg limits (Table 2). Due to the nature of the analyzed soil deposits, the application of a  
387 correction factor for the fines content was also contemplated for the liquefaction susceptibility: for  
388 SPT, CPTU and  $V_S$  methods the  $FC$  profile obtained from laboratory tests (namely “ $FC_{Lab}$ ”) was  
389 used (see Fig. 4a), while for DMT approaches, no  $FC$  corrections are available yet. Moreover, only  
390 for CPTU, liquefaction assessment was carried out also referring to the  $FC$  estimation of their own  
391 methods (see Fig. 4a; please note that the average curve from Suzuki et al. 1998 is the  $FC$   
392 correlation used for the method by Idriss and Boulanger 2008 and that the fitting parameter  $C_{FC}$  was  
393 assumed equal to the default and average value,  $C_{FC} = 0.0$ , for Boulanger and Idriss 2014).

394 The cyclic stress ratio at  $M_w = 7.5$  ( $CSR_{7.5}$ ) was evaluated using two different seismic inputs:

- 395 • 2012 Emilia-Romagna earthquake: the epicenter of the main shock occurred on the 20<sup>th</sup> May  
396 2012 was the closer at BTS, generating liquefaction evidences (Pizzi and Scisciani 2012) and  
397 recording a moment magnitude  $M_w = 5.9$  (<http://terremoti.ingv.it/en>) and a peak ground

398 acceleration  $a_{max} = 0.29g$  (<http://shakemap.rm.ingv.it/shake/index.html>). The ShakeMaps were  
399 produced by the Istituto Nazionale di Geofisica e Vulcanologia and were previously used for  
400 liquefaction studies in the Emilia-Romagna area (Facciorusso et al. 2015, Santucci de Magistris  
401 et al. 2014);

402 • design earthquake: according to the ongoing seismic microzonation study of the Bondeno  
403 municipality and to the Italian Building Code (2018), the ground motion for a return period of  
404 475 years corresponds to  $M_w = 6.14$  and  $a_{max} = 0.22g$ .

405 Moreover, for SPT, CPTU and  $V_S$  methods the magnitude scaling factor ( $MSF$ ) and the shear  
406 stress reduction coefficient ( $r_d$ ) were evaluated according to the respective formulas provided by  
407 each method, while DMT approaches referred to the correlations by Idriss and Boulanger (2008).  
408 Finally, the GWT was assumed equal to 0.5 m, considering the most safe value estimated by CPTU  
409 and SDMT during the site investigations (Table 1).

410 Figs. 10 and 11 provide the results of the liquefaction analysis for natural (NS) and treated (TS)  
411 soils, respectively, using the 2012 Emilia-Romagna earthquake: the profiles of the liquefaction  
412 safety factor ( $FS_{liq}$ ) and liquefaction potential index ( $LPI$ ) according to Iwasaki et al. (1982) are  
413 shown for all the in-situ test methods, while the liquefaction induced vertical settlements ( $S$ ) are  
414 plotted only for CPTU using Zhang et al. (2002). The main findings are listed below:

- 415 • the main liquefiable layer was confined approximately between 3.4 and 5.6 m according to most  
416 of the SPT and CPT methods (Figs. 10a and 10b), while it was limited on average from 3 to 4 m  
417 for DMT and  $V_S$  data due to the high values of  $K_D$  and  $V_S$  at greater depths (Figs. 10c and 10d);
- 418 • for the natural soil the  $LPI$  was generally  $\leq 5$  identifying a low liquefaction risk (Fig. 10),  
419 although the 2012 earthquake generated sand boils covering an area of about 4 to 6 meters  
420 length and 1.5 meters width. The lowest  $LPI$  values were obtained from (1) all the DMT and  
421 CPTU-DMT procedures, probably due to the smaller thickness detected for the liquefiable layer,  
422 (2) the SPT-approaches by Youd et al. (2001) and Idriss and Boulanger (2008) and (3) the  
423 CPTU-correlation by Idriss and Boulanger (2008) applying the laboratory  $FC$  profile. On the  
424 contrary, Boulanger and Idriss (2014) provided high and very high liquefaction risk for CPTU-  
425 based methods (assuming  $C_{FC} = 0.0$ ), respectively;
- 426 • pre-RAP CPTU liquefaction analyses results were very sensitive to the non-plastic fines  
427 contents (Fig. 10b), confirming evidences already available in the international literature (e.g.,  
428 Maurer et al. 2015a, Green et al. 2006, Prakash and Puri 2010, Polito and Martin 2001,  
429 Kokusho et al. 2012): the use of the  $FC$  profile from lab testing dramatically reduced ( $\approx 70$ -  
430 80%)  $LPI$  and  $S$  estimated using a “blind”  $FC$  profile (i.e., the  $FC$  profile suggested by the  
431 various empirical methods – applied without the availability of soil sampling). Consequently,

432 the use of these laboratory data produced an underestimated result for Idriss and Boulanger  
433 (2008) and a more realistic liquefaction evaluation for Boulanger and Idriss (2014);

434 • for the post-RAP susceptibility assessment, the CPTU highlighted the effectiveness of the  
435 liquefaction mitigation treatment, showing a reduction of the  $LPI$  and  $S$  from 40 to 60% (Fig.  
436 11a). In contrast, the decrease was not evident for DMT data (Fig. 11b), where, despite the  
437 consistent increase of the  $K_D$  and  $M$  values and of the CPTU-DMT combined parameters due to  
438 the piers (Figs. 6, 7 and 8, Table 3), the thin liquefiable layer between 3 and 4 m maintained a  
439 similar potential before and after treatment. The  $V_S$  measurements also did not provide a  $LPI$   
440 decrease (Fig. 11c) that can be attributed to the absence of a significant increase in the shear  
441 wave velocity along the RAP length (Fig. 6, Table 3).

442 Following the above considerations, Table 4 shows liquefaction severity indices obtained for  
443 both the seismic inputs referring only to the CPTU data: beside the  $LPI$  and  $S$  already introduced,  
444 the Ishihara inspired liquefaction potential index ( $LPI_{ish}$ ) according to Maurer et al. (2015b), and the  
445 liquefaction severity number ( $LSN$ ) according to van Ballegooy et al. (2014) are reported. For the  
446 calculation of the  $LPI_{ish}$  the non-liquefiable crust was assumed to have a thickness of approximately  
447 3.4 m, as provided by the CPTU profiles. All the indices evidenced a marked reduction comparing  
448 pre-RAP and post-RAP results, and an important influence of the adopted  $FC$  profile, as already  
449 emphasized. However, the  $LPI_{ish}$  and  $LSN$  values strongly underestimated the 2012 liquefaction  
450 evidences, while the  $LPI$  and  $S$  appeared to be closer to predicting what actually happened in  
451 Emilia-Romagna although still a little low. The design earthquake results underlined a similar trend  
452 when compared with the liquefaction indices obtained using the 2012 seismic input, even though  
453 the absolute values were smaller.

## 454 CONCLUSIONS

455 At the BTS a comprehensive comparative study based on CPTU and SDMT testing was carried  
456 out at a liquefaction-prone silty sand site improved by Rammed Aggregate Piers and subjected to  
457 controlled blasting. The main outcomes are summarized, as follows:

458 • CPTU and SDMT tests revealed a good agreement in the geotechnical characterization of the  
459 site, detecting homogenous soil properties in both the natural and improved panels. The use of  
460 both CPTU and DMT provided better estimates of soil properties in sandy layers (e.g.  $OCR$ ,  
461  $K_0$ ), that are usually not determinable by the use of a single type of in-situ test;

462 • the comparison of the in-situ tests performed pre-blast in natural and treated soils highlighted  
463 the effectiveness of the RAP treatment between 4 and 9 m in depth within silty sands. The  
464 increases in the DMT parameters following treatment were more pronounced relative to those  
465 obtained from the CPTU data (e.g.,  $K_D$  increased  $\approx 48$ -53%,  $M$  increased  $\approx 80$ -87%,  $q_t$  increased

466  $\approx 30\text{-}35\%$ ), thus suggesting a higher sensitivity of DMT to the increase in horizontal stress. On  
467 the contrary, the  $V_S$  measurements showed a very low sensitivity to the ground improvement.  
468 Moreover, the combined use of CPTU and DMT tests showed a significant increase of  $M/q_t$  and  
469  $K_0$  after treatment, supporting the use of the piers to increase the lateral soil stress and mitigate  
470 liquefaction;

- 471 • the controlled blasting induced, soon after the detonation, an increase greater than 100% for  $K_D$   
472 and  $M$  in the deeper silty sand layer (6-9 m in depth) of the natural panel, that remained constant  
473 with time. No time-dependency was observed in the improved panel, where CPTU and DMT  
474 parameters maintained the same pre-blast values confirming the effectiveness of the piers  
475 relative to liquefaction. Lastly in this case, the  $V_S$  measurements did not indicate any significant  
476 change between pre- and post-blast results in either the natural or treated soils;
- 477 • the liquefaction assessments by different geotechnical and geophysical tests provided broad  
478 agreement in detecting the 2012 liquefied layer, although DMT- and  $V_S$ -based methods  
479 suggested a low liquefaction risk for the natural soil. Comparing pre-RAP and post-RAP results,  
480 all the liquefaction severity indices evidenced a marked reduction as a result of RAP treatment  
481 and an important influence of the adopted  $FC$  profile. However, the  $LPI_{ish}$  and  $LSN$  values  
482 strongly underestimated the 2012 liquefaction evidences, while the  $LPI$  and  $S$  appeared to  
483 provide a better prediction - although still a little low - of what actually happened in Emilia-  
484 Romagna;
- 485 • further studies are required to investigate the mechanisms that reduced liquefaction-induced  
486 settlements around the piers by using both advanced laboratory tests and numerical modeling.

487

## 488 **DATA AVAILABILITY STATEMENT**

489 Some or all data, models, or code that support the findings of this study are available from the  
490 corresponding author upon reasonable request. These data include in-situ and laboratory test results.

491

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509

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## Tables

**Table 1.** List of the in-situ tests associated with the different phases of the BTS experimental program: phase I is pre-RAP and pre-blast; phase II is post-RAP and pre-blast; phase III is post-blast. Ground water table (GWT) from each test is indicated.

<i>Phase</i>	<i>Period</i>	<i>Location</i>	<i>Borehole</i>	<i>CPTU test</i>	<i>DMT-SDMT test</i>	<i>GWT from CPTU test (m)</i>	<i>GWT from DMT test (m)</i>
I	February 2018	IP	S01	CPTU01	SDMT01	1.50	1.50
I	February 2018	NP	S11	CPTU11	-	1.50	-
I	March 2018	IP	-	CPTU02	MEDUSA DMT01	0.50	0.50
I	April 2018	NP	-	CPTU12	SDMT11	0.80	0.80
I	April 2018	Between IP-NP	-	-	MEDUSA DMT11	-	0.80
II	April 2018	IP	-	-	MEDUSA DMT01bis	-	0.80
II	April 2018	IP	-	CPTU01bis	SDMT01bis	0.85	0.80
III	June 2018	IP	-	CPTU01ter	SDMT01ter	0.70	0.70
III	June 2018	NP	-	CPTU11ter	SDMT11ter	0.80	0.70
III	July 2018	IP	-	CPTU01quater	SDMT01quater	0.60	0.80
III	July 2018	NP	-	CPTU11quater	SDMT11quater	0.64	0.80
III	September 2018	IP	-	CPTU01quintus	SDMT01quintus	0.90	0.43
III	September 2018	NP	-	CPTU11quintus	MEDUSA DMT11quintus	0.90	2.00
III	September 2018	NP	-	-	SDMT11quintus	-	-

**Table 2.** Index properties of the analyzed samples related to USCS soil classification.

<i>Panel</i>	<i>Depth (m)</i>	<i>FC (%)</i>	<i>PI (%)</i>	<i>C<sub>U</sub> (-)</i>	<i>C<sub>c</sub> (-)</i>	<i>USCS classification</i>
natural panel (NP)	3.30-3.50	88.24	17.6	-	-	Silty clay (CL)*
natural panel (NP)	3.60-3.80	22.64	non-plastic	-	-	Silty sand (SM)*
natural panel (NP)	4.30-4.50	40.79	non-plastic	-	-	Silty sand (SM)*
natural panel (NP)	5.50-5.70	22.44	non-plastic	-	-	Silty sand (SM)*
natural panel (NP)	6.80-7.00	26.02	non-plastic	-	-	Silty sand (SM)*
natural panel (NP)	7.00-7.10	30.81	non-plastic	-	-	Silty sand (SM)*
improved panel (IP)	2.15-2.30	82.02	22.1	-	-	Silty clay (CL)*
improved panel (IP)	2.80-3.00	92.63	21.6	-	-	Silty clay (CL)*
improved panel (IP)	3.30-3.50	75.25	-	-	-	Silty clay (CL)*
improved panel (IP)	4.35-4.50	28.24	non-plastic	-	-	Silty sand (SM)*
improved panel (IP)	4.50-4.95	20.50	non-plastic	-	-	Silty sand (SM)*
improved panel (IP)	5.45-5.60	20.45	non-plastic	17.23	4.11	Silty sand (SM)
improved panel (IP)	5.60-6.05	35.71	non-plastic	-	-	Silty sand (SM)*
improved panel (IP)	6.25-6.45	31.38	non-plastic	39.30	1.09	Silty sand (SM)
improved panel (IP)	7.40-7.50	37.70	non-plastic	57.04	1.04	Silty sand (SM)
improved panel (IP)	8.85-9.00	26.03	non-plastic	20.92	1.46	Silty sand (SM)
improved panel (IP)	9.80-10.00	4.77	non-plastic	2.56	1.32	Poorly graded sand (SP)
improved panel (IP)	10.35-10.55	40.94	non-plastic	-	-	Silty sand (SM)*
improved panel (IP)	11.80-12.00	28.38	non-plastic	-	-	Silty sand (SM)*
improved panel (IP)	12.40-12.60	1.40	non-plastic	2.27	1.15	Poorly graded sand (SP)

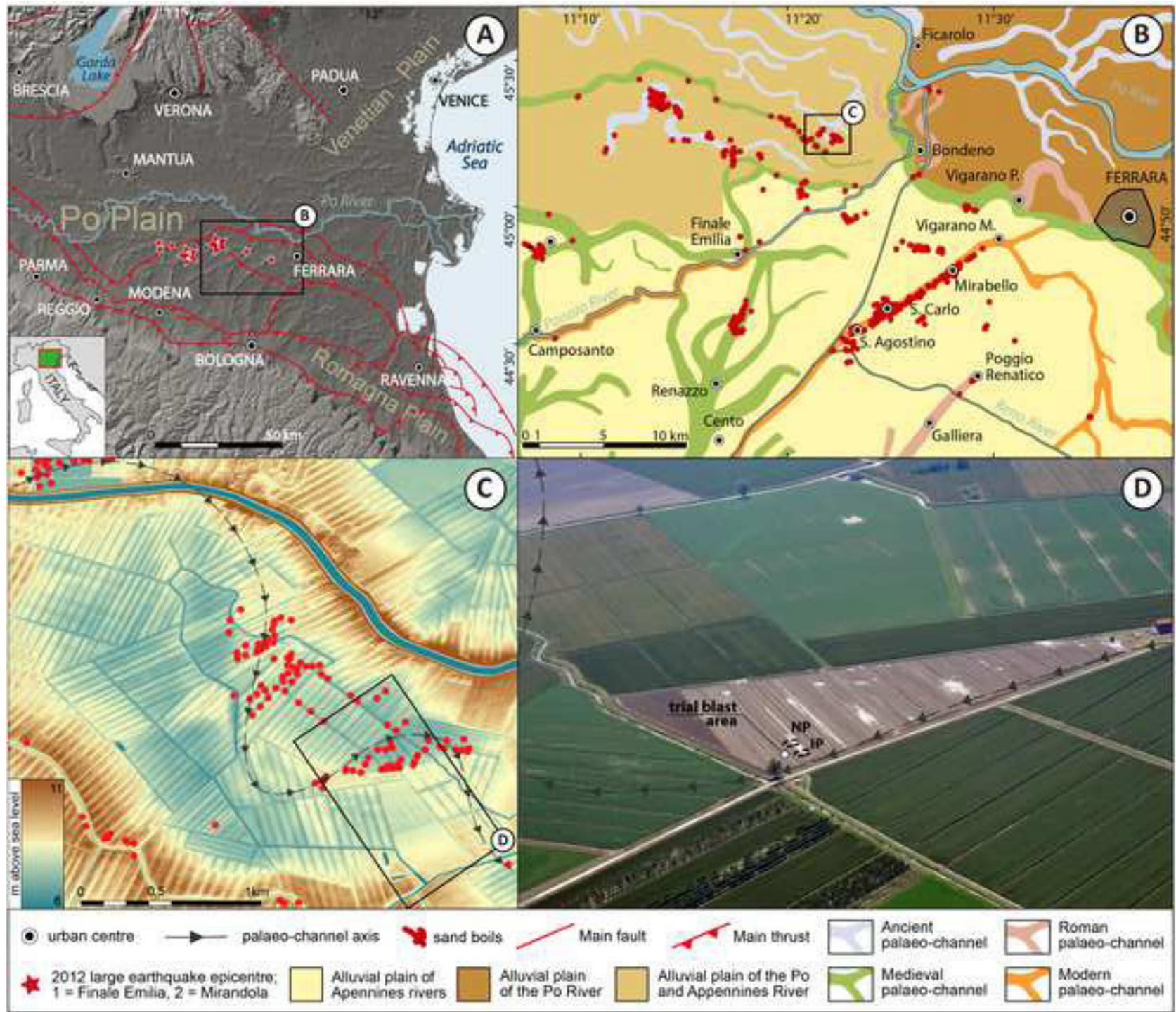
Notes: FC is the fines content; PI is the plasticity index; C<sub>U</sub> is the coefficient of uniformity; C<sub>c</sub> is the coefficient of gradation; \* refers to USCS visual manual procedure.

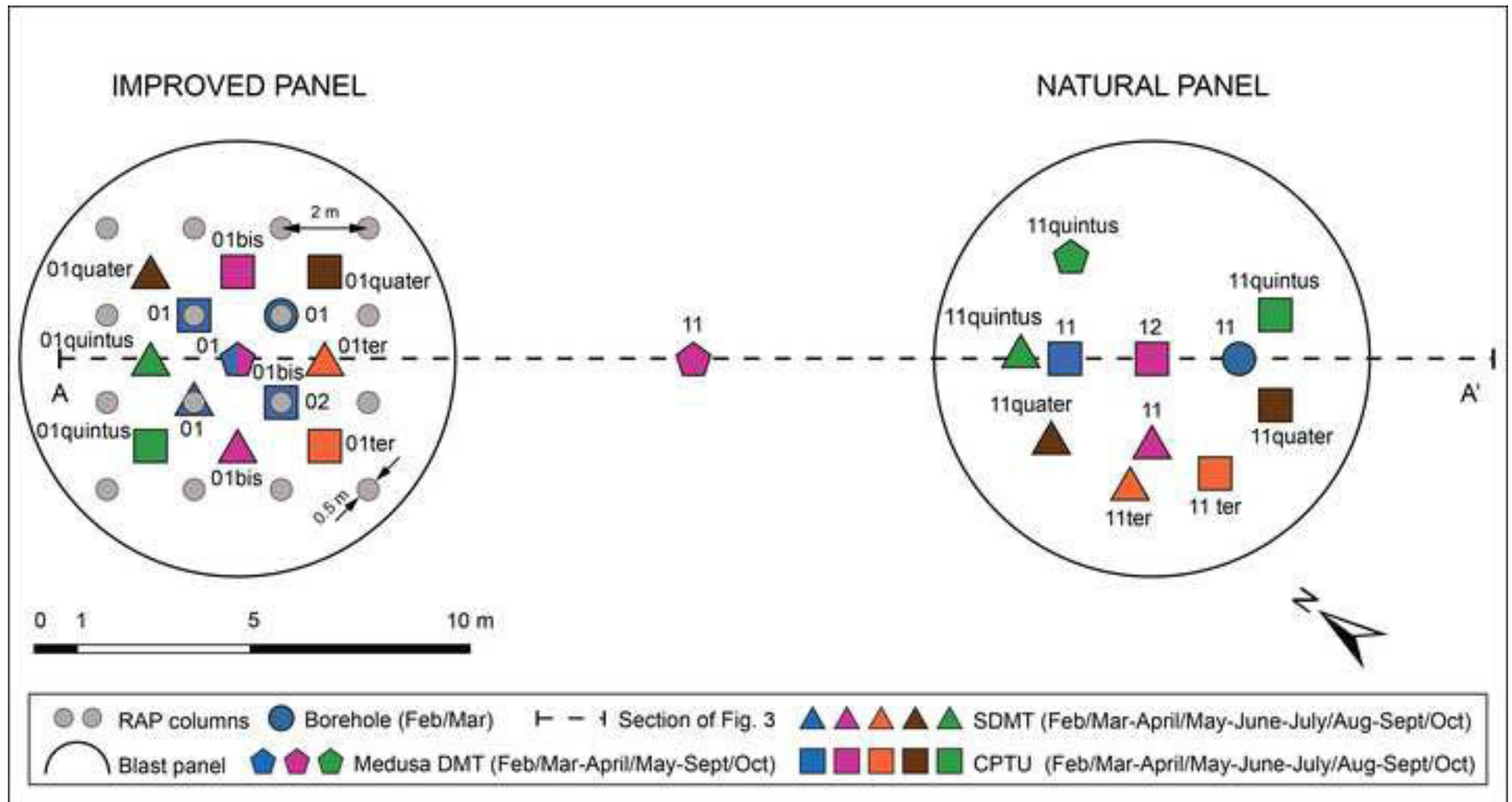
**Table 3.** Average geotechnical parameters estimated by CPTU and SDMT in natural (NS) and treated (TS) soils. The percentage in brackets represents the increase of the average parameters that was due to the improvement and is equal to the difference between the TS and NS parameters divided by the NS parameter multiplied by 100%.

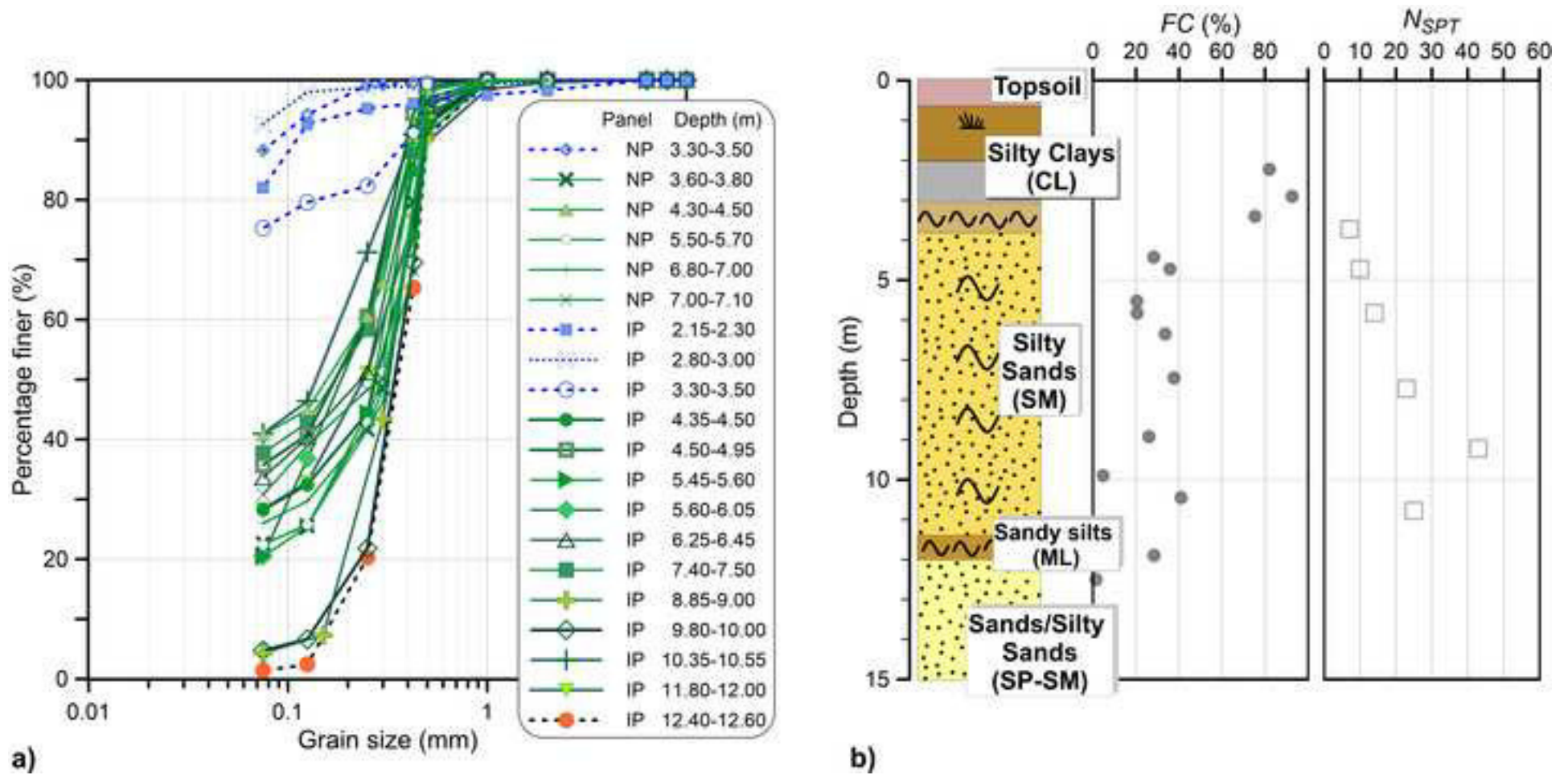
$z$ (m)	Soil	CPTU		DMT		CPTU-DMT			SDMT
		$q_t$ (MPa)	$D_R$ (%)	$K_D$ (-)	$M$ (MPa)	$M/q_t$ (-)	$OCR$ (-)	$K_0$ (-)	$V_s$ (m/s)
4.0-7.0	NS	7.10	53.91	8.45	70.96	10.39	2.11	0.70	154
	TS	9.21 (30%)	60.87 (13%)	12.49 (48%)	128.31 (80%)	13.43 (29%)	3.18 (51%)	0.91 (29%)	179 (16%)
7.0-9.0	NS	9.96	58.36	8.48	94.91	7.42	1.11	0.51	181
	TS	13.44 (35%)	66.28 (14%)	12.98 (53%)	177.16 (87%)	14.37 (94%)	3.53 (218%)	0.99 (93%)	178 (-2%)

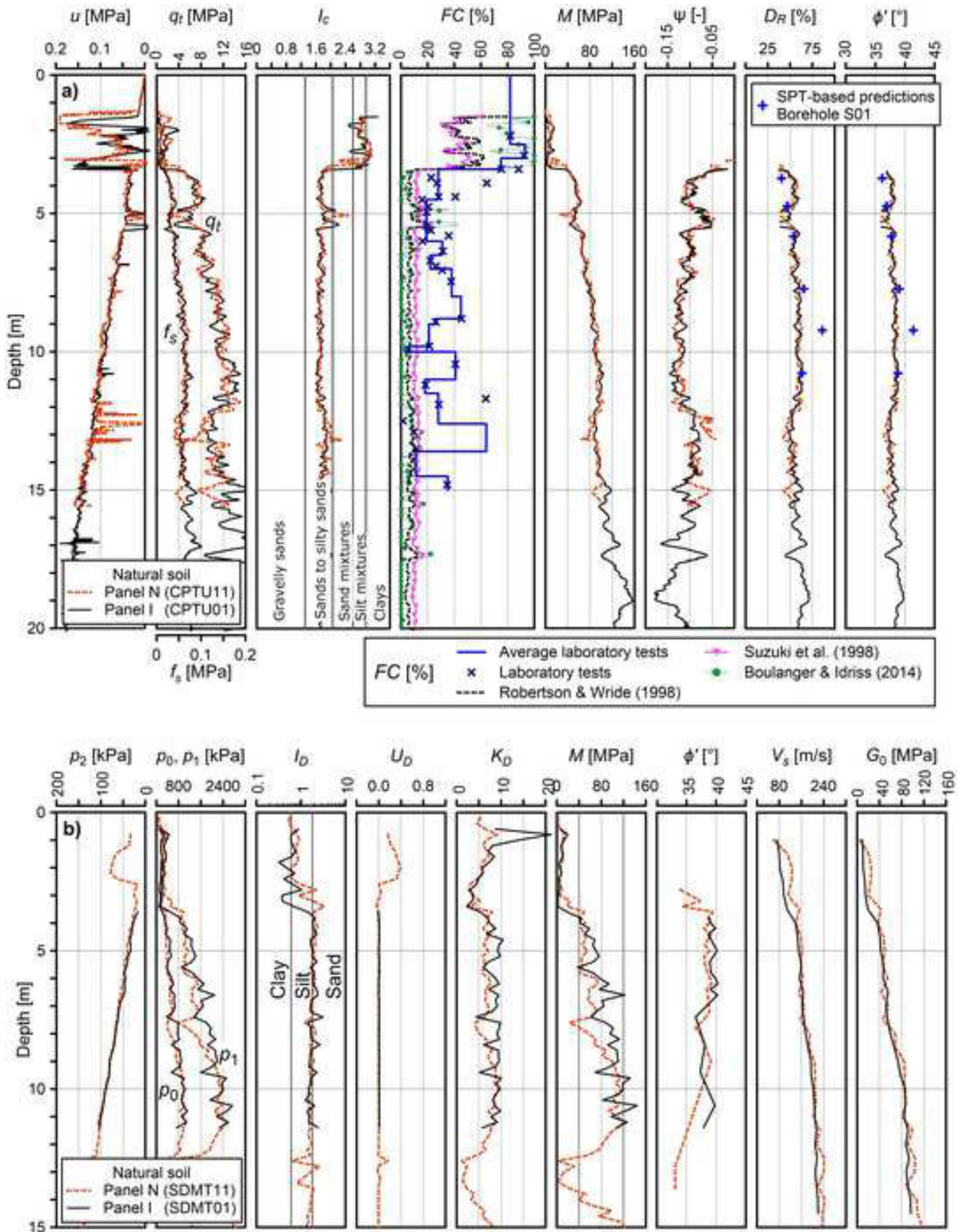
**Table 4.** Comparison of liquefaction severity indices obtained from CPTU in pre-blast natural (NS) and treated (TS) soils for both the ground motions. The percentage in brackets represents the variation of the average parameters that was due to the improvement and is equal to the difference between the TS and NS parameters divided by the NS parameter multiplied by 100%.

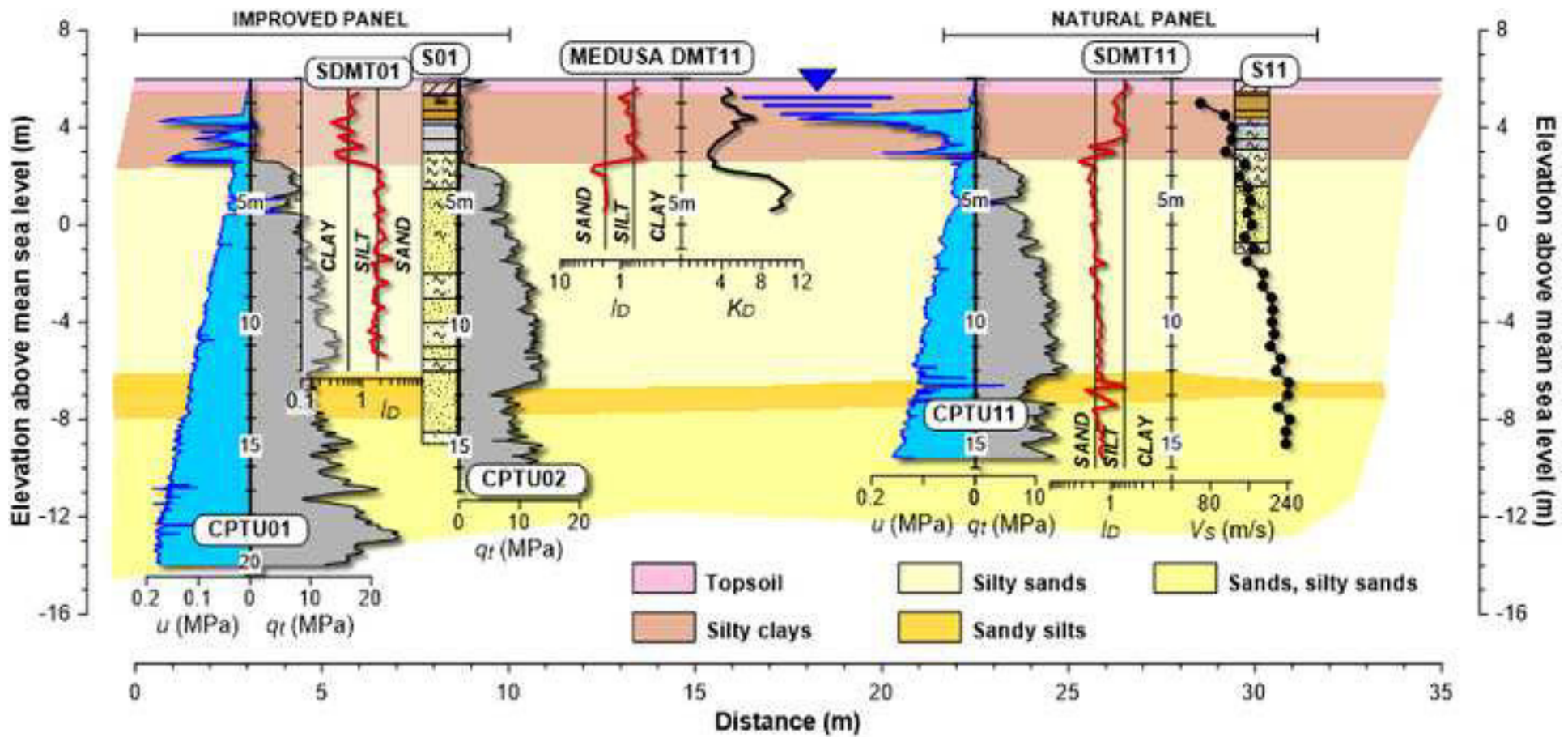
Method	Soil	$M_w = 5.9, PGA = 0.29g$				$M_w = 6.14, PGA = 0.22g$			
		LPI	LPI <sub>ish</sub>	LSN	S (cm)	LPI	LPI <sub>ish</sub>	LSN	S (cm)
Robertson and Wride (1998)	NS	4.020	1.416	13.027	6.485	1.695	0.106	8.352	3.977
	TS	1.573 (-61%)	0.401 (-72%)	5.711 (-56%)	2.284 (-65%)	0.903 (-47%)	0.026 (-75%)	4.207 (-50%)	1.591 (-60%)
Idriss and Boulanger (2008)	NS	4.616	0.802	11.653	6.133	1.145	0.178	6.101	3.086
	TS	1.925 (-58%)	0.408 (-49%)	6.464 (-45%)	2.910 (-53%)	0.737 (-36%)	0.000 (-100%)	3.321 (-46%)	1.404 (-55%)
Idriss and Boulanger (2008) with FC <sub>Lab</sub>	NS	1.411	0.668	3.480	1.678	0.701	0.262	2.224	1.077
	TS	0.925 (-34%)	0.243 (-64%)	2.245 (-35%)	0.995 (-41%)	0.399 (-43%)	0.000 (-100%)	1.335 (-40%)	0.626 (-42%)
Boulanger and Idriss (2014)	NS	18.700	11.664	24.034	13.809	12.570	6.289	22.166	12.446
	TS	10.668 (-43%)	5.088 (-56%)	16.440 (-32%)	8.388 (-39%)	5.637 (-55%)	1.726 (-72%)	12.756 (-42%)	6.213 (-50%)
Boulanger and Idriss (2014) with FC <sub>Lab</sub>	NS	4.295	2.299	7.694	3.750	2.439	1.030	5.417	2.631
	TS	2.434 (-43%)	0.939 (-58%)	4.560 (-41%)	2.083 (-44%)	1.103 (-55%)	0.482 (-53%)	2.965 (-45%)	1.367 (-48%)

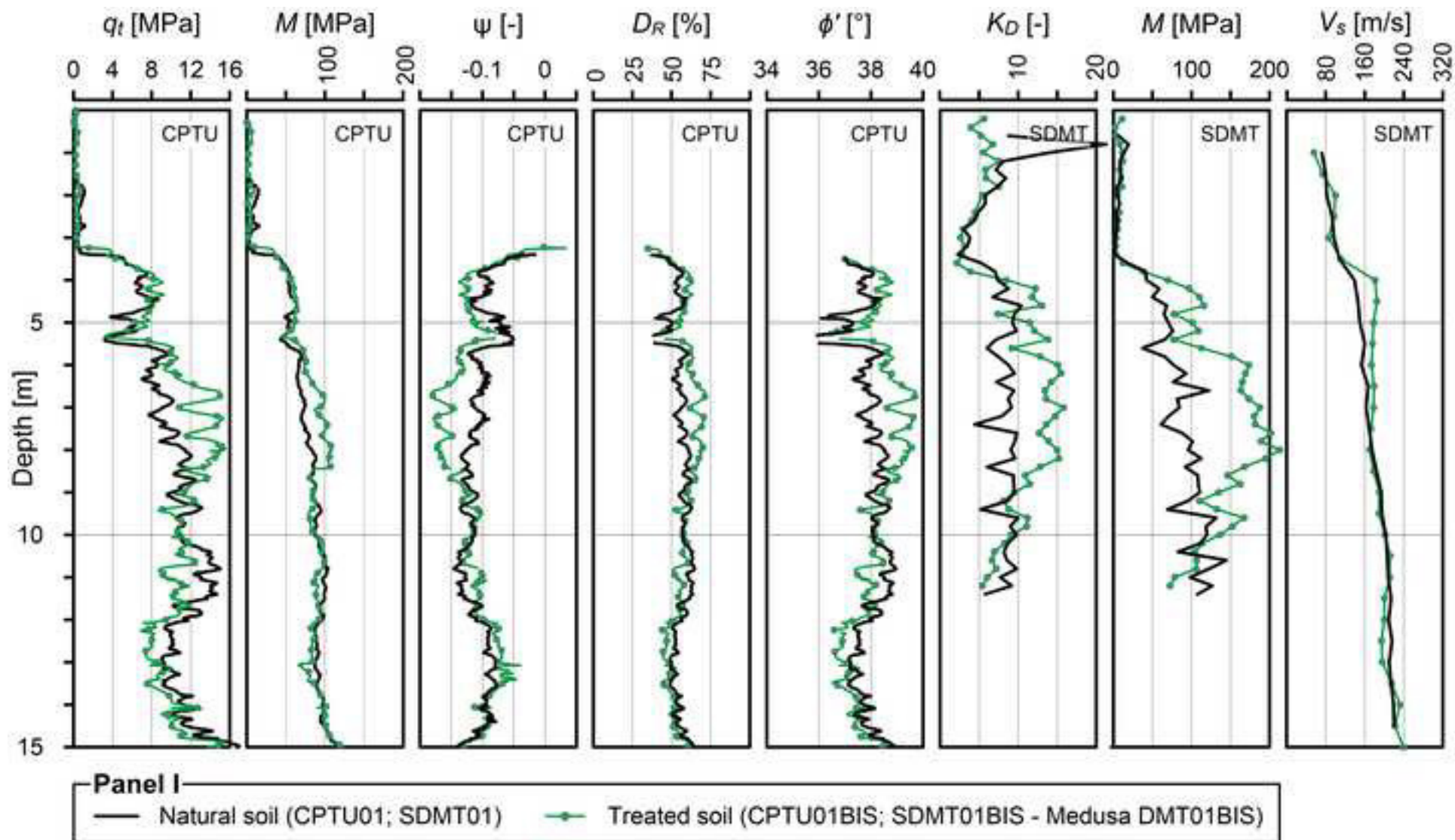


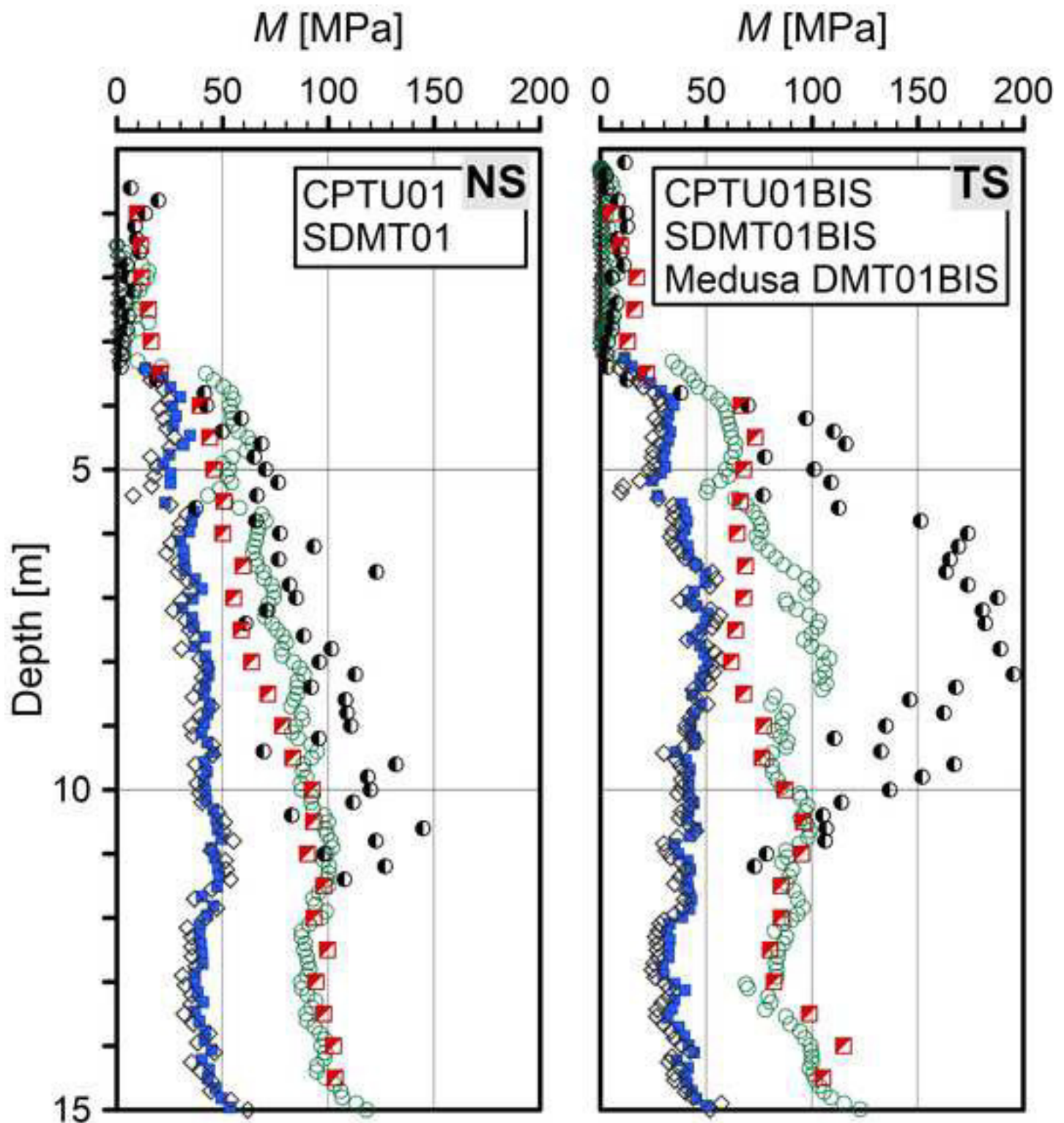




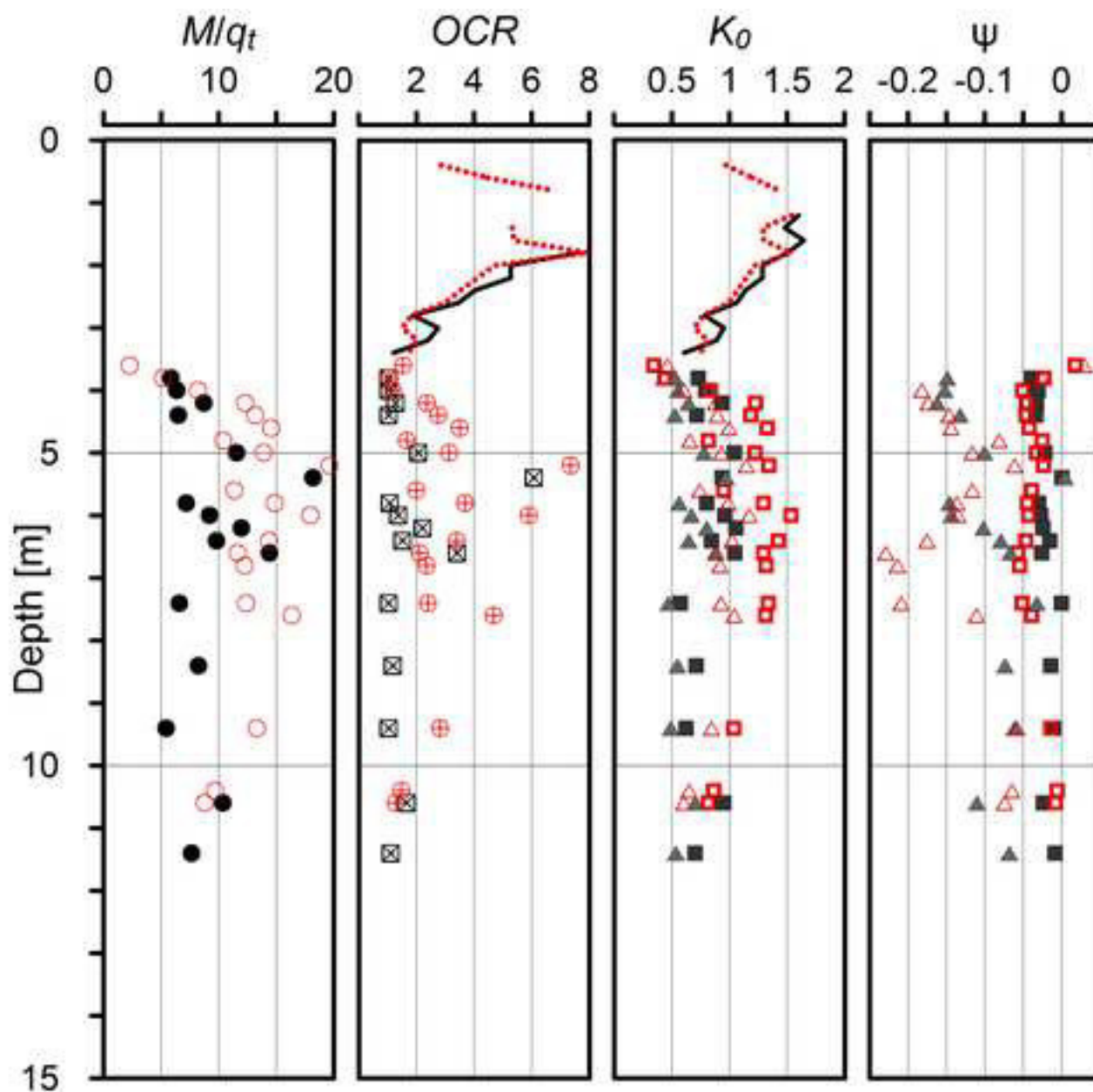






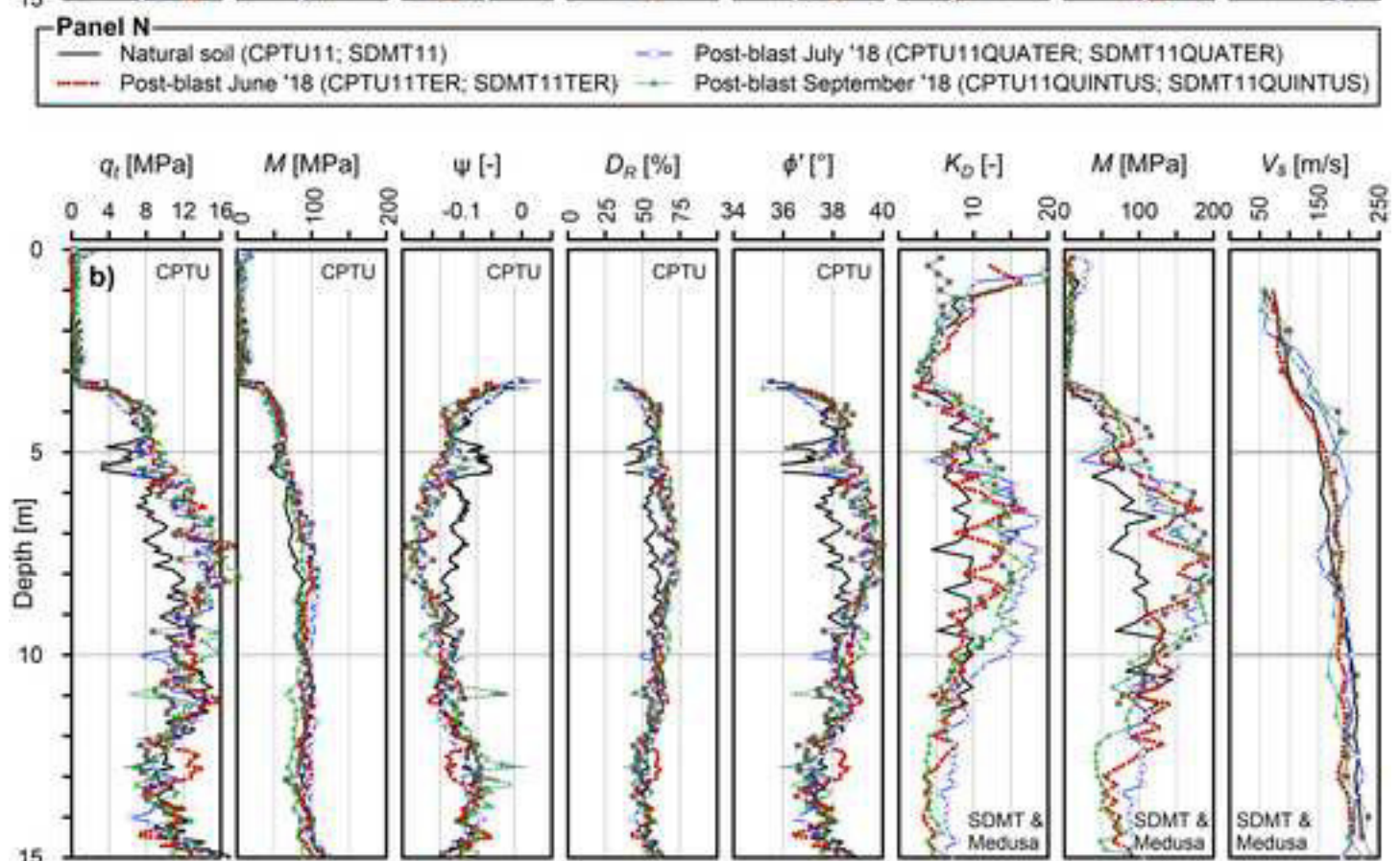
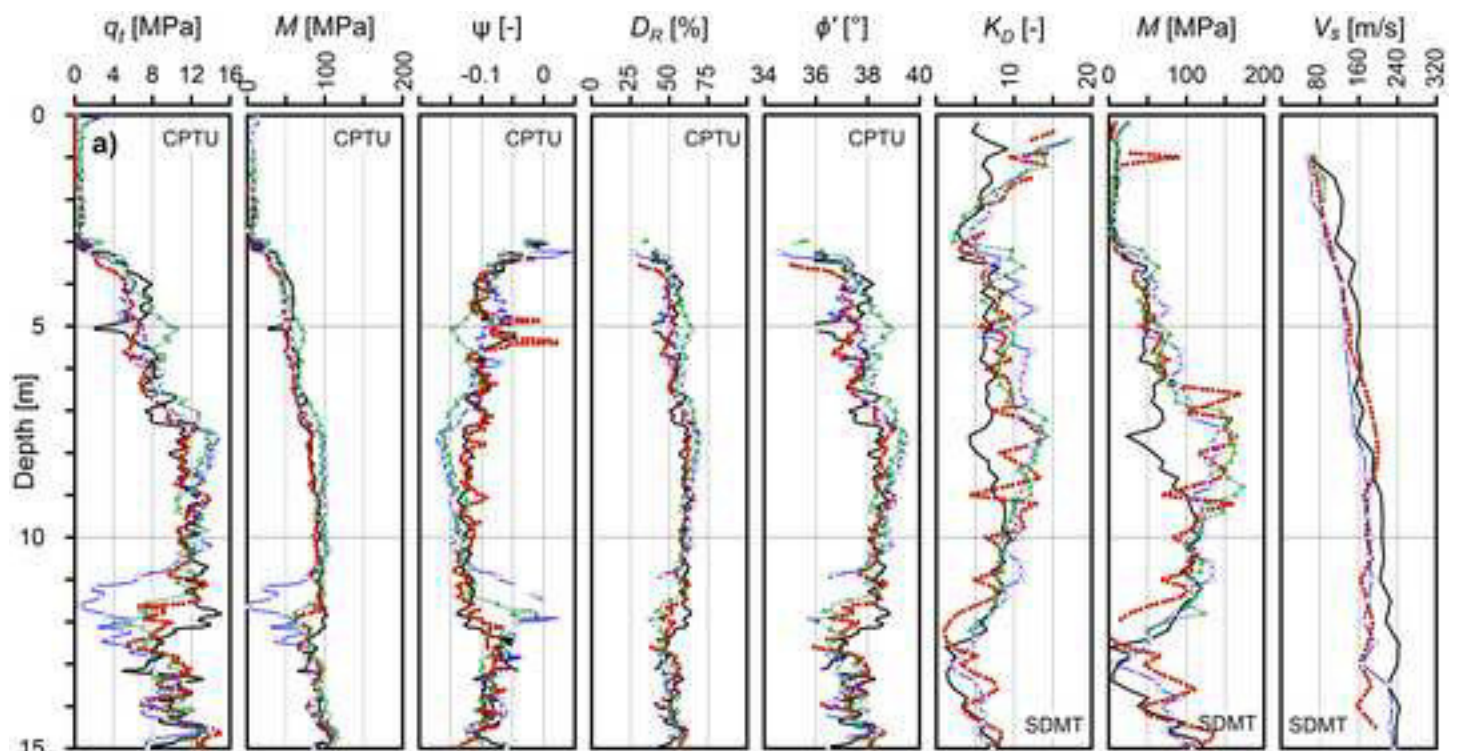
**Panel I**

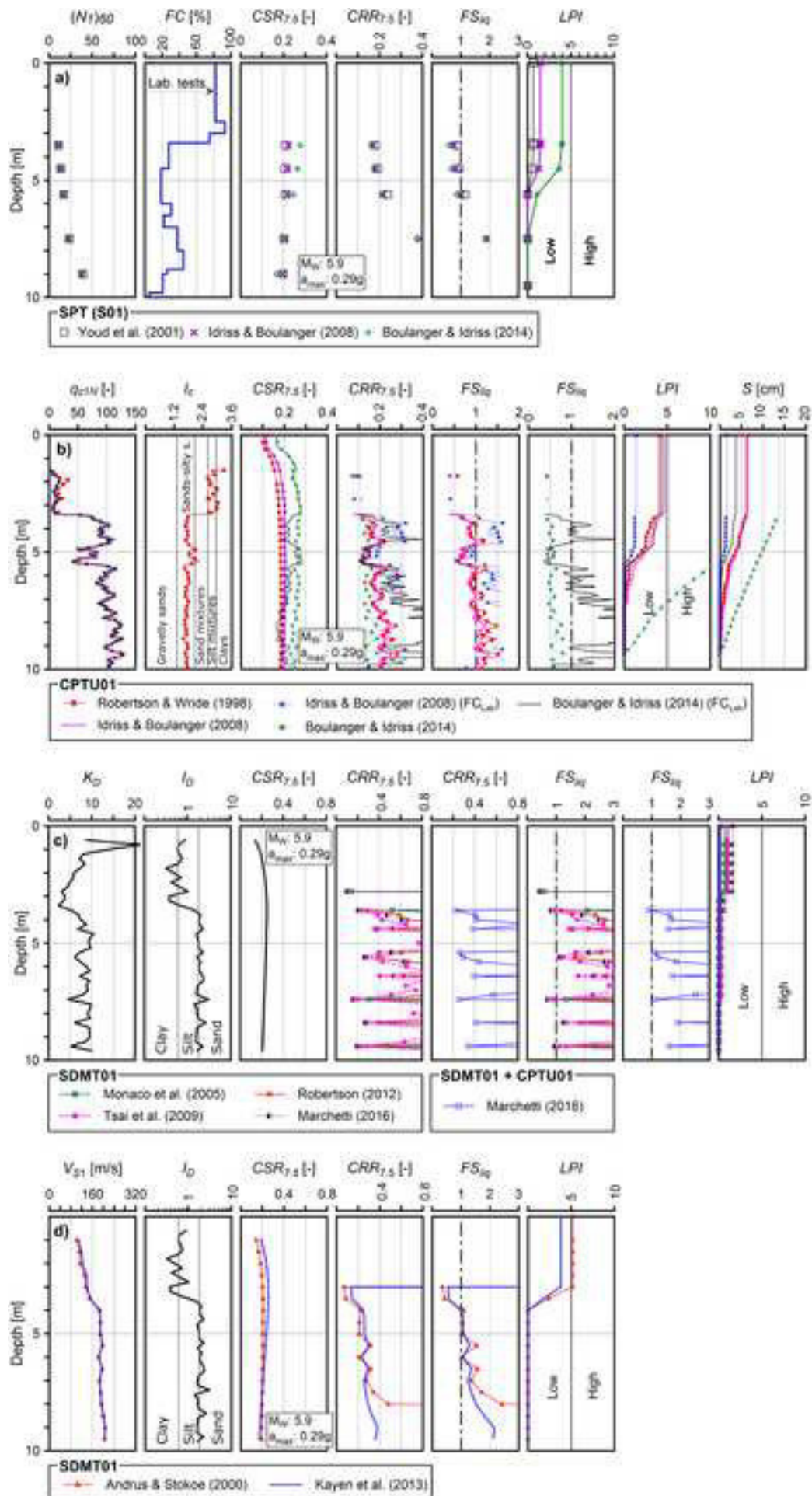
- CPTU - Lunne & Christophersen (1983)
- ◇ CPTU - Senneset et al. (1988)
- CPTU - Robertson & Cabal (2012)
- SDMT & Medusa DMT
- $M$  from  $G/G_0 = 0.4$

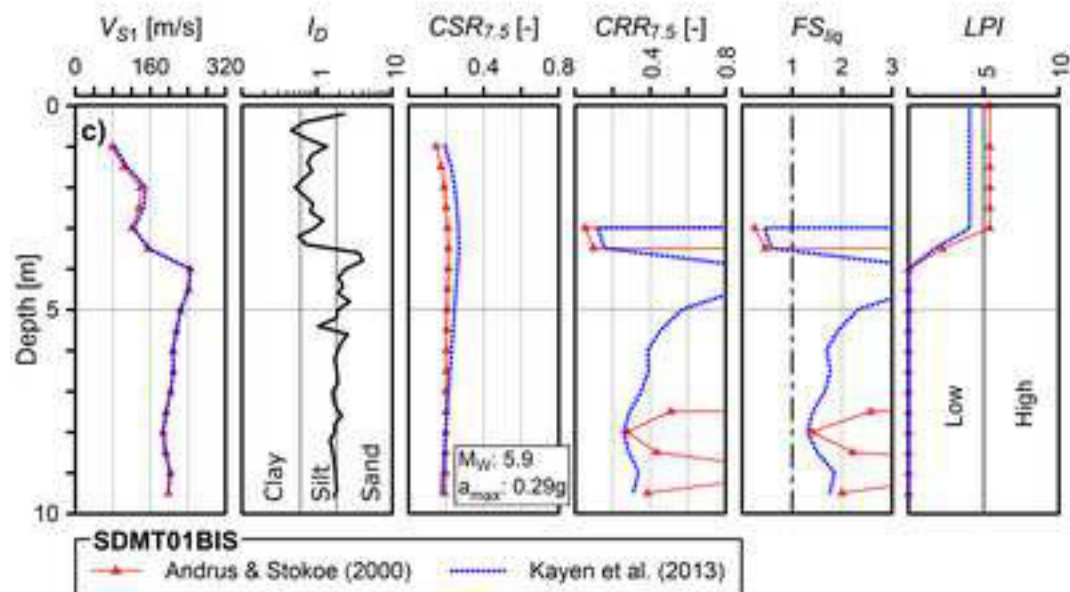
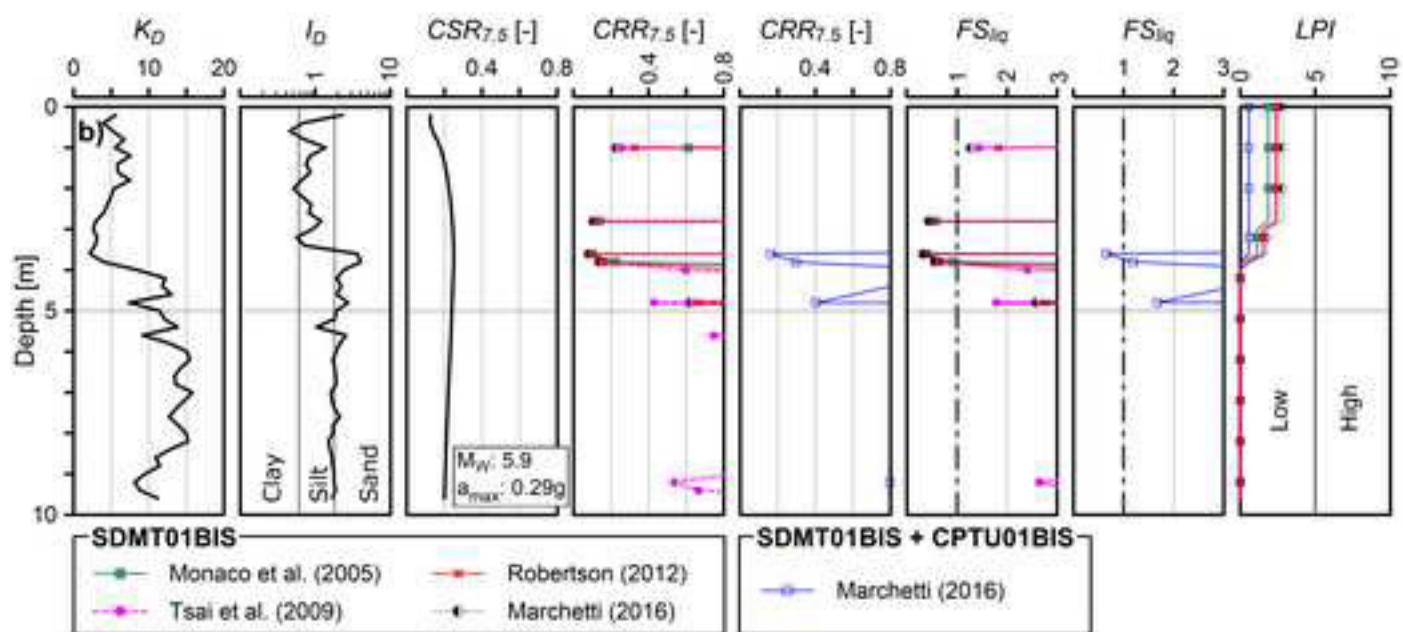
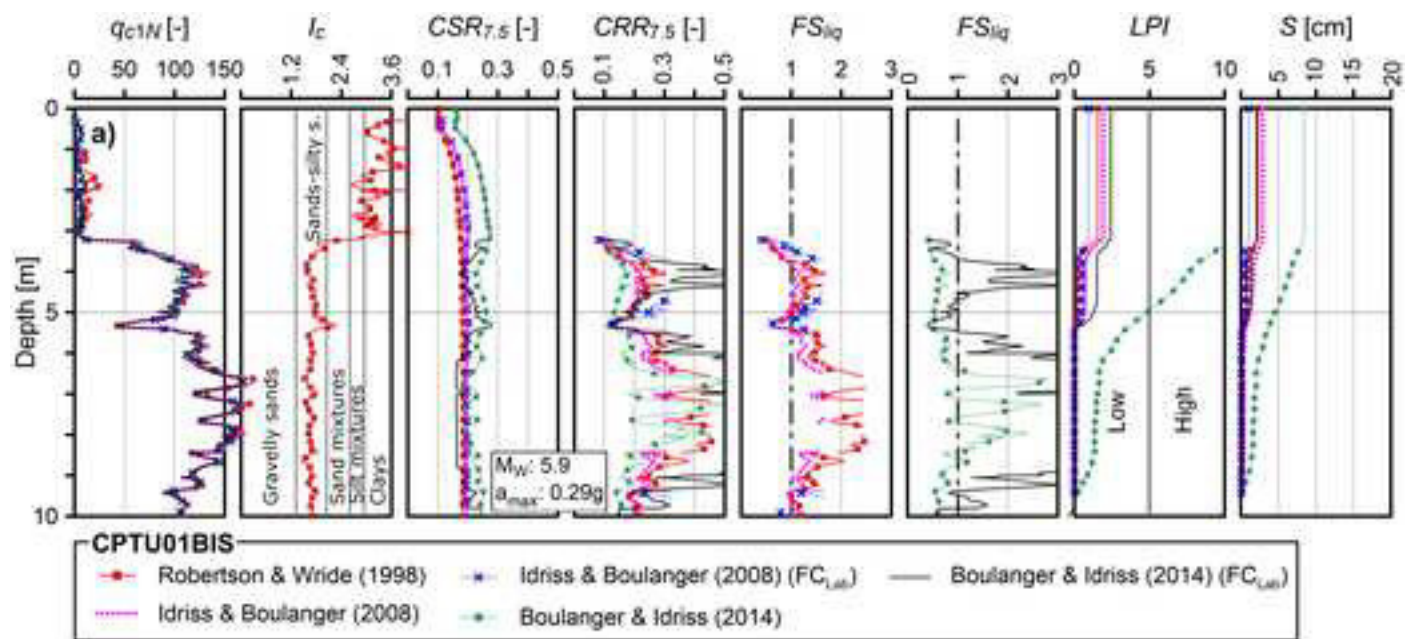


### Panel I

- |                           |   |  |
|---------------------------|---|--|
| <b><math>M/q_t</math></b> | ● | Natural (N): SDMT01 & CPTU01                         |
|                           | ○ | Treated (T): SDMT01BIS + Medusa DMT01BIS & CPTU01BIS |
| <b>OCR</b>                | — | N  |
|                           | ⊠ | N  |
| <b><math>K_0</math></b>   | — | N  |
|                           | ▲ | N  |
| <b><math>\psi</math></b>  | ■ | N  |
|                           | ▲ | N  |
|                           | ⋯ | T Marchetti (1980)                                   |
|                           | ⊕ | T Monaco et al. (2014)                               |
|                           | ⋯ | T Marchetti (1980)                                   |
|                           | ■ | T Baldi et al. (1986)                                |
|                           | ▲ | T Hossain & Andrus (2016)                            |
|                           | ■ | T Baldi et al. (1986); Yu (2004)                     |
|                           | ▲ | T Hossain & Andrus (2016); Yu (2004)                 |







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**Fig. 1.** (a) Location of the Bondeno Test Site (BTS) and of 2012 main shocks; (b) map of the paleochannel bodies (modified after Stefani et al. 2018), of the surface manifestations of liquefaction following the 2012 Emilia-Romagna earthquake (Emergeo Working Group 2013) and of the location of the blast area; (c) geomorphological features from LIDAR map (modified after Amoroso et al. 2020): greenish color indicates lower elevation above the sea level, while brownish color refers to higher elevation; (d) aerial photo with liquefaction evidences (modified after EMERGEO Working Group 2013).

**Fig. 2.** Map of the in-situ tests carried out at the BTS pre-blast (February–March 2018), post-RAP (April 2018) and post-blast (June, July–August and September 2018).

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**Fig. 5.** North-South cross-section of the BTS with “first-phase” CPTU and SDMT log profiles and boreholes.

**Fig. 6.** CPTU and SDMT interpreted results in natural (NS) and treated (TS) soils:  $q_t$ ,  $M$ ,  $\psi$ ,  $D_R$ ,  $\varphi'$  from CPTU;  $K_D$ ,  $M$ ,  $V_S$  from SDMT.

**Fig. 7.** Comparison of the constrained modulus profiles in natural (NS) and treated (TS) soils obtained from CPTU and SDMT (IP pre- and post-RAP).

**Fig. 8.** CPTU-DMT combined interpreted results in natural (NS) and treated (TS) soils:  $M/q_t$ ,  $OCR$ ,  $K_0$ ,  $\psi$ .

**Fig. 9.** CPTU and SDMT interpreted results in (a) natural soil pre- and post-blast (NP) and (b) treated soil pre and post-blast (IP):  $Q_t$ ,  $M$ ,  $D_R$ ,  $\varphi'$  from CPTU;  $K_D$ ,  $M$ ,  $V_S$  from SDMT.

**Fig. 10.** Liquefaction assessment in natural soil (NS) pre-blast by (a) SPT, (b) CPTU, (c) DMT and combined CPTU-DMT, (d)  $V_S$  test results.

**Fig. 11.** Liquefaction assessment in treated soil (TS) pre-blast by (a) CPTU, (b) DMT and combined CPTU-DMT, (c)  $V_S$  test results.