

Fines content determination through geotechnical and geophysical tests for liquefaction assessment in the Emilia alluvial plain (Ferrara, Italy)

Original

Fines content determination through geotechnical and geophysical tests for liquefaction assessment in the Emilia alluvial plain (Ferrara, Italy) / Di Buccio, F., Comina, C., Fontana, D., Minarelli, L., Vagnon, F., Amoroso, S.. - In: SOIL DYNAMICS AND EARTHQUAKE ENGINEERING. - ISSN 0267-7261. - 173:(2023), p. 108057. [10.1016/j.soildyn.2023.108057]

Availability:

This version is available at: 11583/2981333 since: 2023-10-31T14:29:46Z

Publisher:

ELSEVIER SCI LTD

Published

DOI:10.1016/j.soildyn.2023.108057

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<http://dx.doi.org/10.1016/j.soildyn.2023.108057>

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1 **Fines content determination through geotechnical and geophysical**
2 **tests for liquefaction assessment in the Emilia alluvial plain (Ferrara,**
3 **Italy)**
4

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18 **Highlights**

- 19
- Fines content importance for liquefaction assessment
 - New fines content correlations from flat dilatometer and geophysical tests
 - Calibration of existing cone penetration test correlations for fines content
 - Proposed fines content correlations for the Emilia plain (Ferrara, Italy)
 - Integration of punctual and linear investigations for liquefaction assessment
- 24

25 **ABSTRACT**

26 The influence of the fines content on the cyclic resistance has been widely studied and the importance
27 of the determination of this parameter from different geotechnical tests has been underlined for
28 liquefaction assessments. Geotechnical evidences from local investigations may however not
29 completely reflect the lateral subsoil variability, which is important for the identification of localized
30 potential liquefaction phenomena. Geophysical tests can be useful in the imaging of these lateral
31 variations and related fines content variability. In this study calibration of existing fines content
32 correlations with piezocone tests are accomplished and new specific correlations are proposed to
33 assess the fines content both from flat dilatometer and geophysical tests in two liquefied research sites
34 of the Emilia alluvial plain (Italy), following the 2012 earthquakes. The proposed correlations are
35 tested in a third site showing the usefulness of the fines content determination for liquefaction
36 assessment, and its imaging in 1D and 2D profiles.
37

38 Keywords: fines content, liquefaction assessment, geophysical tests, cone penetration test, flat
39 dilatometer test

40

41 **1. Introduction**

42 During the latest decades several procedures for liquefaction assessment have been developed (e.g.,
43 [1], [2], [3], [4], [5], [7], [8], [9], [10]). These procedures are based on geotechnical and geophysical
44 in-situ tests, such as Standard Penetration Test (SPT), Cone Penetration Test (CPT), Flat Dilatometer
45 test (DMT), Chinese Dynamic Cone Penetration Test (DPT) and shear wave velocity measurements
46 (V_s). SPT, CPT and V_s procedures already foresee the application of a correction factor for the fines
47 content (FC) of the soils susceptible to liquefaction. However, as observed ([11]), the fines content
48 correction applied to the normalized in-situ test parameters using a “blind” FC estimate or a
49 laboratory-calibrated FC relationship provides high differences into the susceptibility evaluation (e.g.
50 thickness and depth of the liquefied layer, classification of the site according to the available severity
51 liquefaction indexes, agreement between liquefaction prediction and liquefaction observations).
52 Therefore, accurate liquefaction analyses require site-specific FC estimates representative of the
53 regional geological framework which influences the soil properties of a specific area.

54 The FC determination on site is usually non trivial, since it can be performed following detailed
55 sampling and granulometric analyses, even though this approach does not provide continuous FC
56 profiles and is significantly expensive and time consuming. Alternatively, the FC can be estimated
57 by means of empirical correlations with resistance parameters from geotechnical tests. The soil
58 behaviour type index (I_c), obtainable from CPT tip resistance (q_c) and sleeve friction (f_s), can be for
59 example used. The I_c parameter is somehow correlated with FC and commonly used in liquefaction
60 assessments (e.g. [12], [7]). However, there is considerable scatter in the data on which the FC- I_c
61 correlations are based (e.g. [13],[14], [15]). Boulanger and Idriss [7] attributed the large scatter
62 observed within each dataset to three main factors; (1) lateral and vertical geologic variability
63 occurring over very short distances; (2) fundamental limitations in the I_c parameter when attempting
64 to categorise a wide group of soil types and (3) uncertainty associated with the influence of soil
65 plasticity. As the I_c parameter is based on correlations with the mechanical behaviour of soils, and
66 due to inherent soil variability, it is crucial to develop site-specific correlations and fitting parameters,
67 which can be adjusted to calibrate the empirical FC- I_c equations to peculiar site conditions (based on
68 laboratory testing).

69 Similar shortcomings can be associated to other in-situ tests, such as the flat dilatometer test (DMT),
70 for which it is possible to estimate soil types using the material index (I_D) according to Marchetti et
71 al. [16]. As for the I_c , the I_D is not a grain size distribution index, but it reflects the mechanical

72 response of the soil deposits (e.g. [17]) supplementing also to discern free-draining from non-free-
73 draining layers ([18]). However, no specific FC-DMT correlations are yet available in the
74 international literature. Geotechnical evidences from the abovementioned punctual investigations
75 may not identify the lateral subsoil variability, which is important for the identification of localized
76 potential liquefaction phenomena (e.g. [19]). In this respect, geophysical tests could be crucial for
77 imaging the lateral variations and for a more comprehensive view of the geological variability at the
78 study site. Recent studies (e.g. [20], [21], [22]) suggested the use of combined geophysical
79 measurements of electrical resistivity (R) and shear wave velocity (V_s) for a direct FC determination
80 through appropriate mixture theories. Goff et al. [23] proposed a new relationship between soil type,
81 R and V_s . Hayashi et al. [24] developed a second order multivariable polynomial equation from a
82 least square regression fit of cross-plotted R and V_s data to distinguish clays, sands, and gravels.
83 Recently Takahashi et al [22] proposed a method for profiling the clay content from a R and V_s data
84 by implementing the unconsolidated sand model and the Glover's model ([25]). A similar approach
85 has been adopted by Vagnon et al. [26] and Vagnon et al [27] for obtaining 2D FC sections from
86 combined R and V_s measurements along river embankments and earth dams.

87 In this paper both geotechnical (CPT and DMT) and geophysical tests (based on R and V_s) in the
88 Emilia plain (Ferrara province, Italy) are studied in the aim of developing reliable FC determinations
89 of the specific study area, strongly affected by liquefaction phenomena following the 2012 seismic
90 sequence ([28]). Specific correlations at two trial test sites are compared with laboratory evidences
91 from borehole samples. Particularly, a new devoted correlation is proposed to derive FC from DMT
92 and analysis of existing approaches to determine FC from geophysical data are evaluated. The
93 established correlations are then used to image the FC variability in a third test site both along 1D
94 profiles and 2D sections. In developing the proposed procedure this study took advantage of the rich
95 dataset and accurate geological, geotechnical and geophysical knowledge available in the Emilia plain
96 ([15]). The combined geotechnical and geophysical approach may be particularly effective in
97 reconstructing the subsoil configuration of alluvial settings, characterized by high lateral and vertical
98 variability in sediment type and grain-size. In particular, the FC imaging may allow to identify the
99 upper non-liquefiable high FC crust covering the lower FC liquefiable layers, representing a pivotal
100 contribution in reliable liquefaction assessment.

101

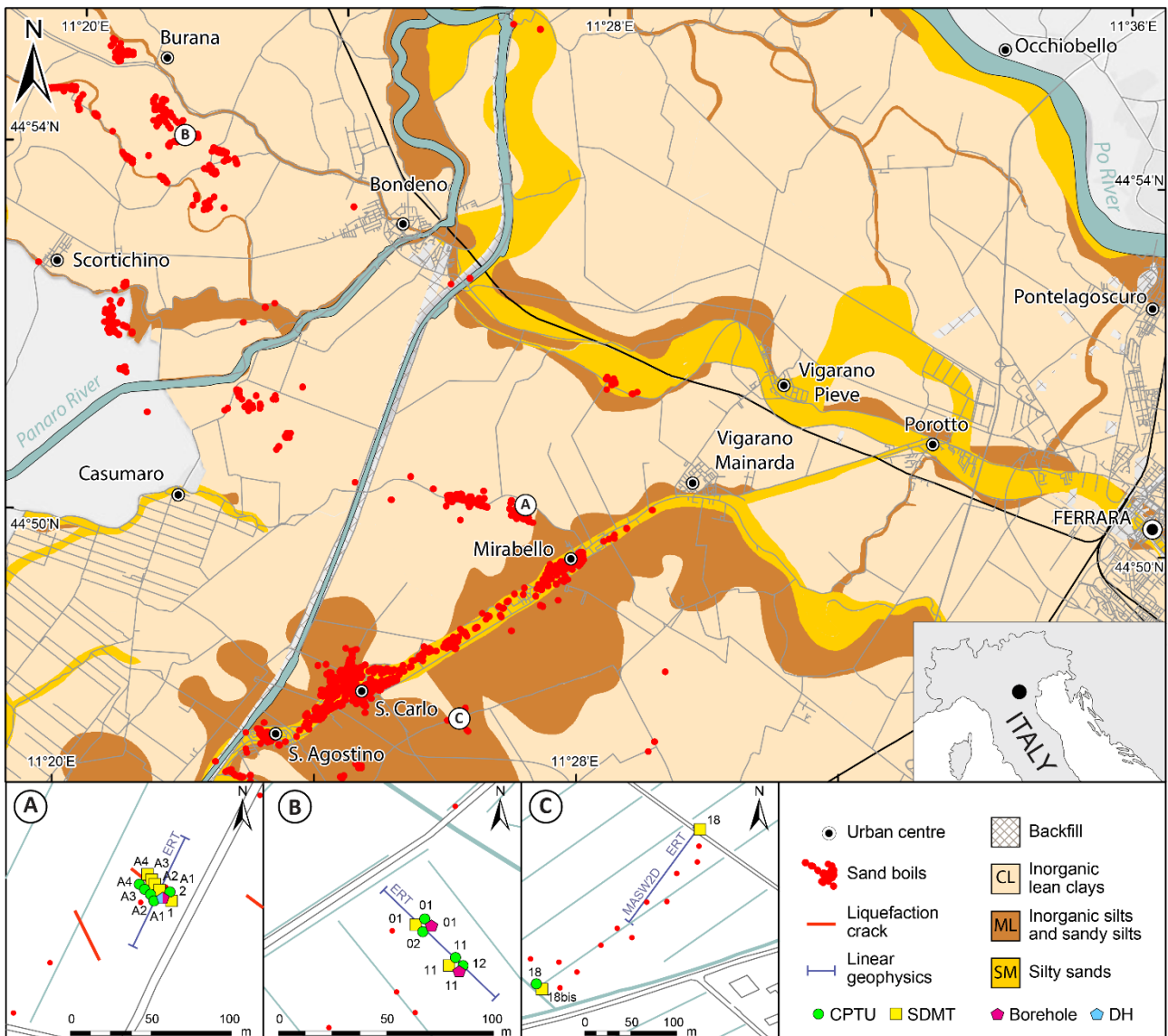
102 **2. Geological setting**

103 The study area is part of the Po plain basin, the syntectonic sedimentary wedge filling the Pliocene–
104 Pleistocene Apennine foredeep. The structural setting of the Po basin originated in response to the
105 collision between the Adria microplate and Eurasia during the Cenozoic. High subsidence rates due

106 to the tectonic loading, associated with strong sediment input, generated a thick Pliocene-Quaternary
107 succession ([29]). The basin infill is up to 4 km-thick, and the Quaternary deposits reach a thickness
108 of 1.5 km.

109 The study area within the Ferrara plain (Fig. 1) corresponds to the buried frontal portion of the
110 compressive ramp, and the associated active faults are responsible of the well documented seismic
111 activity ([30]) which in several cases has induced critical liquefaction phenomena (red dots in Fig.
112 1), as for the Emilia seismic sequence in 2012 ([28]).

113



114
115 **Fig. 1** Engineering geological map of the outcropping alluvial deposits of the studied area within the
116 Emilia plain in the Ferrara province (Italy) with evidence of the liquefaction phenomena referable to
117 the Emilia seismic sequence in 2012 (red dots); in A, B and C details of the studied sites (Mirabello,
118 Bondeno and San Carlo, respectively) and executed geotechnical and geophysical tests are reported.

119

120 The main drainage, the Po River, interacts with a dense network of transverse tributaries. The river
121 network continuously shifted laterally as a consequence of climate changes and local tectonic events
122 ([31]). The late evolution of the alluvial system has been traced following the physical evidence of
123 paleochannels on the alluvial plain surface ([32]), and the provenance composition of buried channel
124 sands compared with present day rivers ([33], [34]).

125 The engineering geological map (Fig. 1) was derived from the critical synthesis of the available
126 seismic microzonation studies, using the geological-technical units defined by SM Working Group
127 (2015) in agreement with Unified Soil Classification System USCS [35]. This map describes the
128 surface distribution of the fluvial sediments deposited by the Po and by some Apennine rivers, such
129 as Reno and Panaro. The study sediments largely consist of mostly inorganic lean clays (CL,
130 according to the USCS [35]), deposited into moist inter-river depressions. The argillaceous units are
131 crisscrossed by sinuous silty sandy bodies (SM, according to USCS classification), deposited into
132 fluvial channels, and potentially subjected to liquefaction phenomena. The Po sandy bodies are
133 generally coarser and less silty than the Apennine bodies ([15]). The channel bodies are often flanked
134 by levee deposits, by fluvial crevasse splays, or by the granular infilling of minor river channels (silts
135 and sandy silts, ML, according to USCS classification).

136 All the studied sites are characterized by an argillaceous crust, cohesive and not liquefiable, with a
137 variable thickness ranging from 3 m in the northern site of Bondeno (B in Fig. 1) to 6 m in Mirabello
138 (A in Fig. 1) and up to 9 m in the southernmost site of San Carlo (C in Fig. 1) ([36], [37]). The
139 argillaceous crust overlies liquefiable buried silty sands and sandy silts (SM, ML) organized in
140 vertically stacked channel-belt bodies referable to the Po River (Bondeno, Mirabello) or as thin,
141 relatively narrow lens-shaped bodies of silty sands and sandy silts with an Apennine signature,
142 deposited by the Reno River (San Carlo site).

143 Within this geological context, the geotechnical and geophysical characterization is mainly focused:
144 1) to provide an estimate of the thickness of the shallower high FC portion of the subsoil, which
145 corresponds to the non-liquefiable crust (increased thickness of the crust will result in reduced
146 liquefaction hazard) and 2) to estimate the FC in the underlying sandy silt and silty sand layers to
147 evidence zones more prone to liquefaction (increased FC in these layer will result in reduced
148 liquefaction hazard).

149

150 **3. Methodologies for the fines content estimation**

151 **3.1. FC estimates from geotechnical in-situ tests**

152 Site-specific calibrations using laboratory tests are required to provide reliable FC estimations
153 through correlations with resistance parameters from geotechnical tests, otherwise parametric

154 analyses are recommended to evaluate the sensitivity to FC estimates (e.g. [7]). In this study, the
155 equations proposed by Suzuki et al. [38] (Eq. 1) and Boulanger and Idriss [7] (Eq. 2) as a function of
156 the soil behaviour type index (I_c) from CPT:

$$FC = x_c \cdot (2.8 \cdot I_c^{2.6}) \quad (1)$$

$$FC = 80 \cdot (I_c + C_{FC}) - 137 \quad (2)$$

157 were applied and calibrated using available direct geotechnical investigations (granulometric analyses
158 on borehole samples).

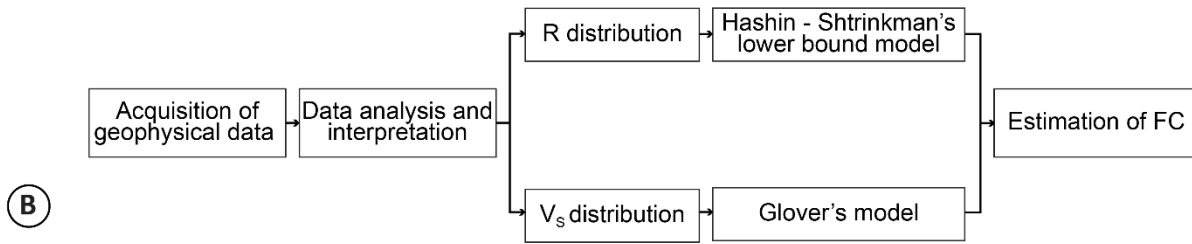
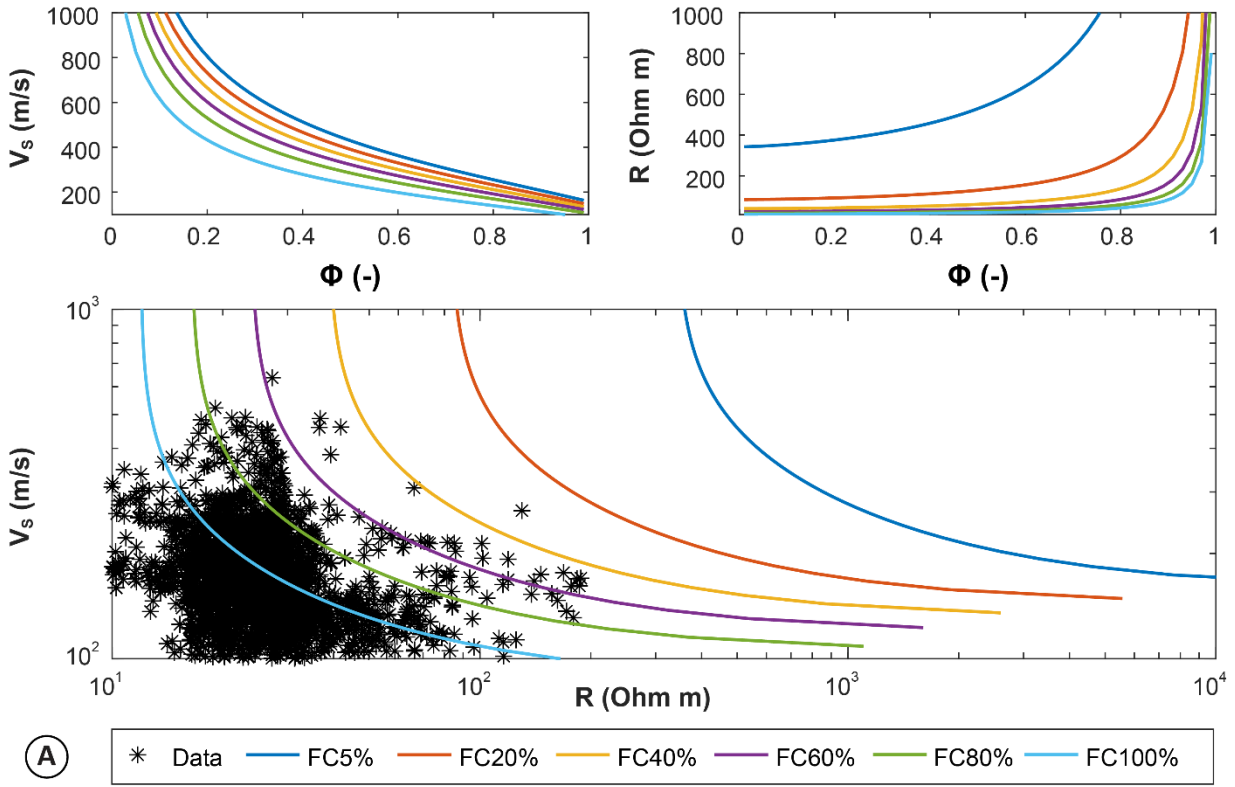
159 Both the equations include a correlation coefficient, x_c for Suzuki et al. [38] and C_{FC} for Boulanger
160 and Idriss [7], which takes into account the variability of the datasets used by the authors. The range
161 of variability of these coefficients is quite wide and, as suggested by the authors, is site-specific. In
162 particular, x_c ranges between 0.5 to 2, while C_{FC} varies from a minimum value of -0.29 to a maximum
163 of 0.29. The variability of these coefficients has been therefore analysed for two test sites (A and B
164 in Fig. 1) within the 2012 Emilia earthquake epicentral area and calibrated to obtain site-specific FC-
165 correlations with CPT. Moreover, the first fines content correlation starting from DMT results has
166 been proposed. The proposed FC-DMT equation involves, similarly to CPT, the parameter I_D and a
167 calibration coefficient to consider the variability of the dataset, which has been obtained from a linear
168 regression using flat dilatometer and laboratory data of the studied sites.

169

170 **3.2. FC estimates from geophysical tests**

171 The conceptual workflow adopted for the evaluation of FC from geophysical tests is reported in Fig.
172 2. The workflow is based on the construction of theoretical R and V_s curves as a function of FC to
173 which associate the observed experimental data.

174



175

176 **Fig. 2 (a)** Theoretical V_s - ϕ , R - ϕ and V_s - R relationship as a function of theoretical FC for a given
 177 depth and superimposed example distribution of field data. **(b)** Workflow for estimating FC using
 178 multiple geophysical data (modified from Vagnon et al. [27])

179

180 In detail:

- 181 a) the Glover's equation ([25]) is adopted to exploit the relationship between soil porosity (ϕ)
 182 and resistivity (R) considering also the degree of saturation as in the following:

$$\frac{1}{R} = \frac{1}{R_g} \cdot (1 - \phi)^{\frac{\log(1-\phi^m)}{\log(1-\phi)}} + \frac{1}{R_f} \cdot \phi^m \cdot S_w^q \quad (3)$$

183 where R is the overall resistivity of the soil, R_g and R_f are respectively the soil grain and fluid
 184 resistivities, m is the cementation factor, q is the saturation index and S_w is the saturation
 185 degree;

- 186 b) the Hashin-Shtrikman upper bound model ([39]) is adopted to express R_g as a function of the
 187 constituting grains (mixture of sand and silt/clay):

$$\frac{1}{R_g} = \frac{1}{R_{clay}} \cdot \left[1 - \frac{3 \cdot (1-FC) \cdot \Delta R}{R_{clay} - FC \cdot \Delta R} \right] \quad (4)$$

188 where FC is the fines content, R_{clay} is the clay resistivity and ΔR is defined as:

$$\Delta R = \frac{1}{R_{clay}} - \frac{1}{R_{sand}} \quad (5)$$

189 where R_{sand} is the resistivity of non-clay particles.

190 c) Hashin-Shtrikman lower bound ([39]) and the Voigt-Reuss-Hill model ([40]) are adopted to
 191 infer the relationship between soil porosity (ϕ) and shear wave velocity (V_s), using the
 192 following equations:

$$V_s = \sqrt{\frac{\left(\left(\frac{\phi}{\phi_0} + \frac{1 - \phi}{\phi_0} \right)^{-1} - Z \right)}{\rho}} \quad (6)$$

193 with:

$$Z = \frac{G_{HM}}{6} \cdot \frac{9 \cdot K_{HM} + 8 \cdot G_{HM}}{K_{HM} + 2 \cdot G_{HM}} \quad (7)$$

$$K_{HM} = \left[\frac{n^2 \cdot (1 - \phi)^2 \cdot G_g^2}{18 \cdot \pi^2 \cdot (1 - \nu)^2} P \right]^{\frac{1}{3}} \quad (8)$$

$$G_{HM} = \left[\frac{5 - 4 \cdot \nu}{5 \cdot (2 - \nu)} \right] \cdot \left[\frac{3n^2 \cdot (1 - \phi)^2 \cdot G_g^2}{2\pi^2 \cdot (1 - \nu)^2} \cdot P \right]^{\frac{1}{3}} \quad (9)$$

$$G_g = \frac{\left[(1-FC) \cdot G_{sand} + C \cdot G_{clay} + \left(\frac{1-FC}{G_{sand}} + \frac{FC}{G_{clay}} \right)^{-1} \right]}{2} \quad (10)$$

194 where ρ is the bulk density of the soil, G_{HM} and K_{HM} are respectively the shear and bulk moduli of
 195 the soil at the critical porosity, ϕ_0 , n is the coordination number, P is the confining pressure, ν is the
 196 Poisson's ratio of the soil, G_{sand} and G_{clay} are respectively the shear moduli of sand and silt/clay
 197 components, and G_g is the shear modulus of the soil grains.

198 All the constitutive parameters of the above equations can be obtained by in-situ geological and
 199 geotechnical information or assumed based on the wide scientific literature on this topic (such as R_{clay}
 200 and R_{sand}). Further details about the choice of the constitutive parameters and on the sensitivity
 201 analysis of the above equations can be found in Vagnon et al [27].

202 By superimposing the measured R and V_s values at a given depth to the theoretical constant FC
 203 curves, it is then possible to obtain the soil FC associating the experimental data to the nearest FC
 204 curve. Specific calibrations are also possible if direct FC estimations are available at a particular site
 205 to compare the results. This approach has been attempted in this study changing the constitutive

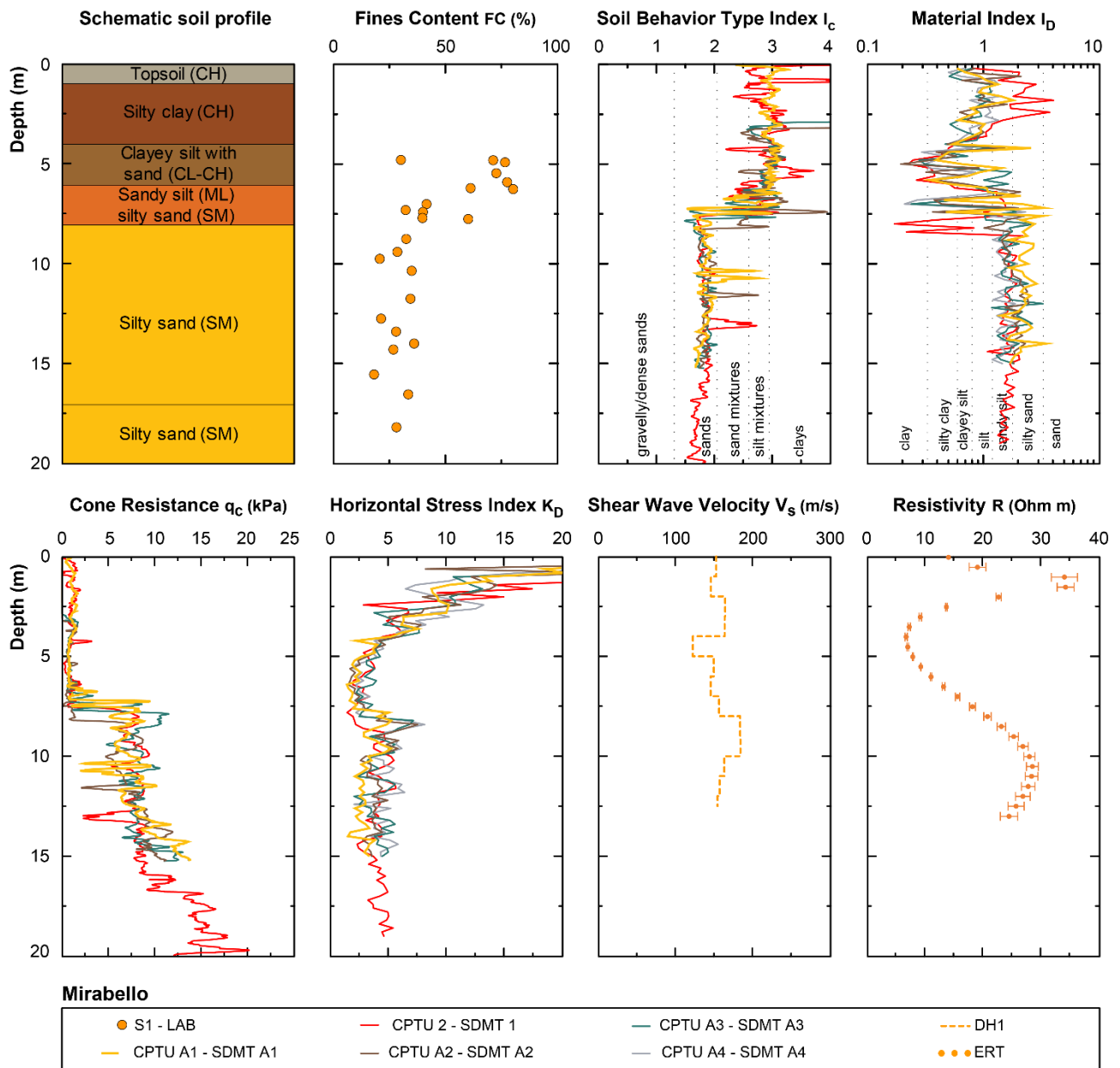
206 parameters to allow the better possible match with available direct geotechnical investigations at the
207 two calibration sites (A and B in Fig. 1).

208

209 **4. Geotechnical and geophysical characterization at the calibration sites and site-specific** 210 **FC estimates**

211 The sites adopted for the calibration of the proposed procedure refer to Mirabello (Site A in Fig. 1)
212 and Bondeno (Site B in Fig. 1), two villages located in the province of Ferrara (Italy), strongly
213 affected by liquefaction phenomena following the 2012 Emilia seismic sequence. These sites have
214 been studied through numerous research activities, including full-scale blast-induced liquefaction
215 experiments, to which the data used in this work refer. In particular, the Mirabello test site (Site A in
216 Fig. 1) was the site of the first Italian blast-induced liquefaction test performed in silty sands. Its
217 main goal was to study the variation of soil properties before and after the execution of the blast test
218 sequence ([36], [19]), by performing piezocone (CPTU), seismic dilatometer (SDMT), down-hole
219 tests (DH) in boreholes, and electrical resistivity tomographies (ERT). On the contrary, the Bondeno
220 test site (Site B in Fig. 1) was realized to study the effectiveness of rammed aggregate piers towards
221 liquefaction mitigation in silty sands using explosives, and geotechnical and geophysical tests
222 (boreholes, CPTU, SDMT, ERT) were performed before and after treatment, and after the blast at
223 different times ([37], [11], [9]).

224 The subsoil model of the Mirabello test site can be identified using the available borehole log and
225 related laboratory tests and the DH and ERT surveys, five CPTUs and five SDMTs performed along
226 a 2012 liquefaction crack (see Fig. 1). The schematic soil profile with the USCS classification is
227 reported in the first line of Fig. 3 together with the FC data obtained from laboratory tests ([34]) and
228 the in-situ soil type indicators, the I_c from CPTU and the I_D from DMT. Direct measurements from
229 the site investigations are also reported in the second line of Fig. 3 in terms of the corrected cone
230 resistance (q_t) from CPTU, the horizontal stress index (K_D) from DMT, the shear wave velocity (V_s)
231 from DH, and the resistivity (R) from ERT.



232

233 **Fig. 3** Soil profiles at the Mirabello test site. First line: schematic soil profile with USCS
 234 classification, fines content (FC) from laboratory tests, soil behaviour type index (I_c) from CPTU,
 235 material index (I_D) from DMT; second line: corrected cone resistance (q_t) from CPTU, horizontal
 236 stress index (K_D) from DMT, shear wave velocity (V_s) from DH, resistivity (R) from ERT.

237

238 The measurements highlight a thick non-liquefiable crust in the upper 6 m, characterized by silts and
 239 clays, CH-CL according to USCS classification, with fine content $FC \approx 70-100\%$ and plasticity index
 240 $PI \approx 23-54\%$. The underlying layers are mainly composed by low plastic-non plastic sandy silts and
 241 silty sands of Apennine (Reno River) provenance, litharenitic in composition, (ML-SM with $FC \approx$
 242 $25-75\%$, $PI \approx 5-9\%$ between 6 and 8 m depth) and quartz-feldspar-rich Alpine (Po River) provenances
 243 (SM with $FC \approx 20-35\%$, $PI \approx 0\%$, below 8 m depth). Fontana et al. (2019) [34] identified the

244 litharenitic silty sands with Apennine provenance as the source layer that liquefied in 2012, by
245 comparing compositional and granulometric analyses on the borehole samples and the sand boils.
246 This assessment matches well with the CPT and DMT profiles: q_t values are limited approximately
247 between 0.8 and 2 MPa and K_D data varies from about 1.5 to 3 in the Apennine-derived layer, while
248 both the parameters have a considerable increase in the deeper Alpine-derived sand layers ($q_t \approx 6-18$
249 MPa, $K_D \approx 3-6$).

250 Coherently with the above results the DH test identifies a first silty clay layer (V_s of about 150 m/s)
251 3 m thick. Below this layer, a velocity inversion is observed in the clayey silty layer from 4 to 6 m
252 (V_s of about 120 m/s). Thereafter, a progressive increase in V_s in the Apennine sandy silts and silty
253 sands and in the underlying Po sandy loams is observed. DH data were obtained at the site by means
254 of a seismic chain of 8 triaxial (10 Hz) geophones with 1 m spacing, connected to a Geonics - Geode
255 seismograph. The seismic chain was lowered into the hole with a 2 geophones superposition for
256 consecutive lowerings. For the acquisitions a 5 kg sledge-hammer striking laterally on a 1.5 m steel
257 bar was adopted. Source polarity inversion was also used. Data were processed, after first break
258 picking, both with the interpolation method and with the true interval method following the ASTM
259 D7400-14 [41] standards and in ISSMGE guidelines ([42]). Good quality data were obtained in most
260 acquisitions (for more details see [19]) allowing a very reliable soil profile reconstruction.

261 The V_s results are confirmed by the ERT results. A shallow resistive (resistivity of about 30 Ohm·m)
262 layer (topsoil and silty clays) 4 m-thick is observed. This layer corresponds to the high-velocity layer
263 identified by the DH test and is related to the presence of a dry crust at the time of execution of the
264 tests, due to an arid winter season. A less resistive (resistivity of about 7 Ohm·m) layer is observed
265 from 4 to 6 m, related to the presence of saturated clayey silts. A noticeable increase in resistivity is
266 observed between 6 and 8 m in the fluvial Apennine deposits, while the resistivity results
267 approximately constant in the Po River silty sands. ERT data were acquired with a Syscal – Pro
268 georesistivitymeter and 72 electrodes at 1 m spacing. A Wenner-Schlumberger acquisition sequence
269 was adopted with 1287 potential measurements. This sequence allowed a dense spatial distribution
270 of measuring points combining both lateral and vertical resolution (for more details see [19]).
271 Experimental data were inverted with Res2DInv ([43]) after filtering of anomalous measurements
272 (with standard deviations higher than 5%). A very good convergence of the results was obtained from
273 the inverted resistivity model with a global root mean square error below 2%. The resistivity profile
274 reported in Fig. 3 was then obtained from the inverted resistivity model by considering the average
275 resistivity with depth in the zone (within a 1 m radius) where the other geotechnical data were
276 available (see Fig. 1A). Variability from the average resistivity value span from 7 %, near the surface

277 to 1 – 2 % at depth, averaging 3.35%. The relatively higher variability near surface reflects the more
278 laterally heterogeneous top soil.

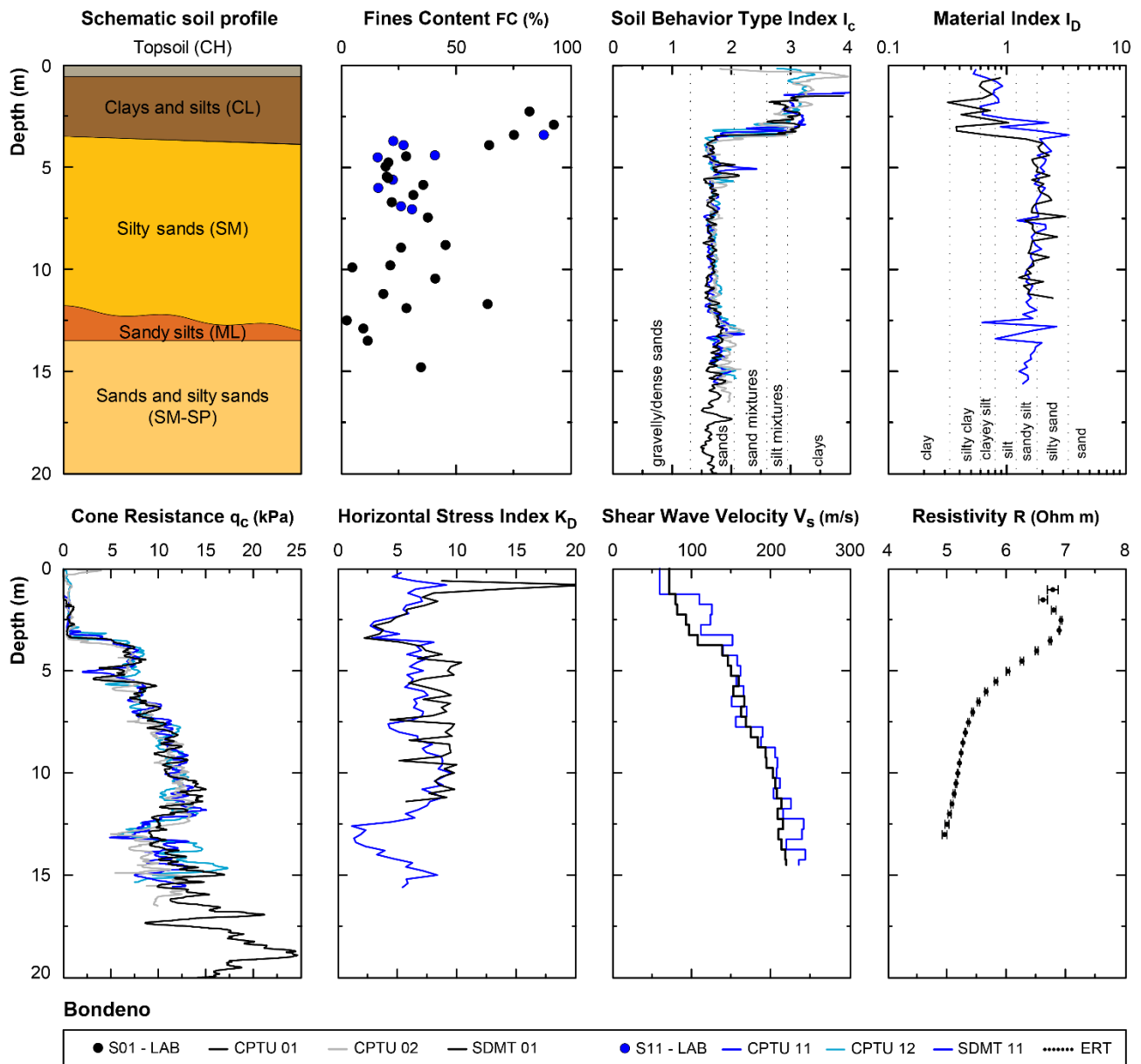
279 At the Bondeno test site the geotechnical model was reconstructed using the two available borehole
280 logs and the related laboratory tests, four CPTUs, two SDMTs and the ERT. The location of the
281 surveys is reported in Fig. 1 and covers a wide area, extended about 70 m and largely affected by the
282 2012 sand ejecta. The summary of the geotechnical and geophysical characterization is reported in
283 Fig. 4. The reconstructed stratigraphic column is composed by a thin silty-clayey non-liquefiable
284 crust in the upper 3.5 m depth, namely CL for USCS classification, with $FC > 65\%$ and $PI \approx 18-22\%$,
285 followed by a non-plastic thick sandy and silty-sandy layer with considerable values of $FC \approx 25-35\%$
286 (SM-SP). According to the liquefaction assessment presented by Amoroso et al. [11] using the
287 “simplified method” ([1]), the 2012 liquefied deposits can be detected into the upper layer of Po River
288 silty sands (depth approximately between 3.5 and 12 m), characterized by lower values of resistance
289 and stiffness. However, as highlighted already by the authors, the fines content correction applied to
290 the CPT procedure using a “blind” FC estimate or a laboratory-calibrated FC relationship provides
291 high differences into the susceptibility evaluation, resulting important to provide a site-specific FC
292 estimate for the 2012 Emilia epicentral area.

293 Geophysical evidences are in good agreement with geotechnical tests. Results of the SDMT test
294 identify a first silty-clayey layer (V_s around 100 m/s) about 3 to 4 m thick. Below this layer, a
295 progressive velocity increase is observed in the thick sandy and silty-sandy layer (V_s from 150 to 250
296 m/s). SDMT data were obtained at the site with two horizontal geophones (frequency of 28 Hz and
297 sensitivity of 0.600 V/ips), spaced 0.5 m, for measuring V_s each 0.5 m (Amoroso et al., 2020). A
298 biaxial inclinometer is also located at the midpoint of the seismic probe to monitor the tilt during the
299 penetration and to eventually correct V_s measurements. A manual hammer hitting horizontally an
300 appropriate base is used to generate S-waves at the ground surface. The S-wave source, 10 kg heavy,
301 is oriented parallel to the receiver axis to increase the sensitivity to the generated shear waves. The
302 S-wave source, connected to a different external trigger, is usually located at a distance of less than 1
303 m from the DMT penetrating rods to have the S-waves travel nearly vertical. The seismic signal,
304 acquired by the geophones, is amplified and digitized at depth. The recording system consists of one
305 channel for each geophone, having identical phase characteristics and adjustable gain control. Usual
306 sampling interval of 200 μs is used for S-waves. A similar processing approach than for the DH data
307 was adopted allowing good quality data and a very reliable soil profile reconstruction.

308 Generally, very low resistivities were measured at the test site due to anomalous very high electrical
309 conductivity of the saturating water (above 1300 $\mu S/cm$). These high conductivity values strongly
310 influenced the imaged resistivity data towards lower resistivity values, partially compromising the

311 ability of the surveys in detecting stratigraphic changes. Nevertheless, a clear transition is evidenced
312 in the resistivity profile from the silty-clayey layer in the upper 3.5 m depth (resistivity of about 7
313 Ohm·m) to the following sandy and silty-sandy layers (resistivity of about 5 Ohm·m). ERT data were
314 acquired with a Syscal – Pro georesistivitymeter and 64 electrodes at 1 m spacing. A similar Wenner-
315 Schlumberger acquisition sequence than in the Miralbello site was adopted with 990 potential
316 measurements, reduced with respect to Mirabello due to the reduced array length. Data were inverted
317 with the same approach than in the Mirabello site with an even increased convergence (global root
318 mean square error below 1%). As before the resistivity profile reported in Fig. 4 was then obtained
319 from the inverted resistivity model considering the average resistivity with depth in the zone (within
320 a 1 m radius) where the other geotechnical data were available (see Fig. 1B). Variability from the
321 average resistivity value span in this case from 1.3 %, near the surface to about 0.05 % at depth,
322 averaging 0.45%. The relatively low variability, reduced with respect to the Mirabello site, reflect the
323 high fluid conductivity that tend to homogenize the whole resistivity section.

324



325

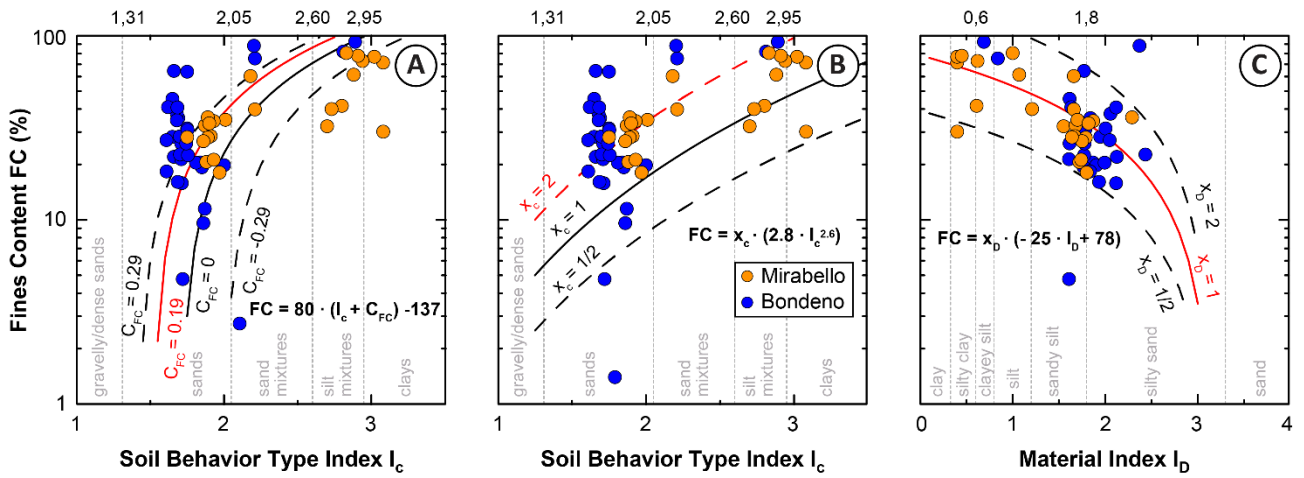
326 **Fig. 4** Soil profiles at the Bondeno test site. First line: schematic soil profile with USCS classification,
 327 fines content (FC) from laboratory tests, soil behaviour type index (I_c) from CPTU, material index
 328 (I_D) from DMT; second line: corrected cone resistance (q_c) from CPTU, horizontal stress index (K_D)
 329 from DMT, shear wave velocity (V_s) from SDMT, resistivity (R) from ERT.

330

331 4.1. Calibration of FC estimates

332 The x_c (Eq. 1, [38]) and C_{FC} (Eq. 2, [7]) coefficients have been calibrated using the FC values obtained
 333 by laboratory tests and the available CPTU data at the Mirabello and Bondeno test sites. In order to
 334 obtain a single I_c value to associate to the laboratory FC, I_c was averaged at ± 0.1 m with respect to
 335 the depth of the analysed sample. The plot of the entire I_c -FC dataset shows a high variability of the
 336 C_{FC} values mostly in the 0.00 to 0.40 range and in the 1 to 4 range for the x_c coefficient, as reported

337 in Figs. 5a and 5b. The best fitting of the C_{FC} and x_c values (red curves in Figs. 5a and 5b) reports a
 338 positive value of $C_{FC} = 0.19$ for [7] and the upper bound of the [38] formulation equal to $x_c = 2$.



339 **Fig. 5** FC estimates using in-situ tests at the Mirabello and Bondeno test sites: (a) calibration of the
 340 I_c -FC chart by [7]; (b) calibration of the I_c -FC chart by [38]; (c) I_D -FC chart proposed in this study
 341 based on DMT data.
 342

343
 344 The availability of flat dilatometer data have allowed to propose the first correlation between the
 345 material index (I_D) and the fines content. During the DMT soundings, the measurements were
 346 collected every 0.2 m, therefore the I_D was averaged at ± 0.2 m with respect to the sample depth. The
 347 coupling of the DMT and laboratory data has provided the following linear regression (red line in
 348 Fig. 5c):

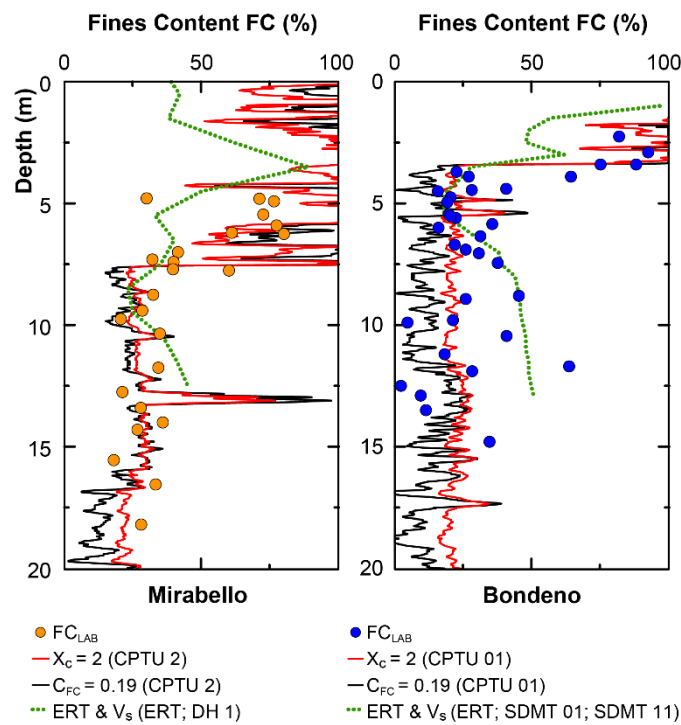
$$FC = x_D \cdot (-31 \cdot I_D + 91) \quad (11)$$

349 Upper and lower bounds in the correlation can be detected using a coefficient named x_D that varies
 350 from 0.5 to 2 (dashed lines in Fig. 5c). Furthermore, in all the plots of Fig. 5, dot vertical lines have
 351 been added according to the soil type thresholds identified by I_c and I_D , which may be useful in
 352 additional refinements of calibration for indirect FC estimates obtained in further investigations in
 353 these areas.

354 The application of the calibrated coefficients to single CPTU and DMT at the research sites allowed
 355 to compare the site-specific FC predictions with the FC laboratory measurements. Analogously to
 356 geotechnical tests, the procedure described in Section 3.2 was used for forecasting FC from
 357 geophysical surveys.

358 Fig. 6 plots the FC estimates by CPTU and DMT for the Mirabello and Bondeno test sites, together
 359 with the FC estimates from the geophysical tests and available laboratory data. The indirect FC
 360 estimates (from geotechnical and geophysical tests) are reasonably in good agreement with the
 361 laboratory FC data points. For both the sites the sharp vertical variations between clays/silts and silty
 362 sands, at about 6 m at the Mirabello site and 3 m at the Bondeno site, are satisfactorily reproduced by

363 all the adopted indirect methodologies. Results based on the geophysical tests at the Mirabello test
 364 site appear to show a shallower thickness of the clay layer apparently in accordance with some
 365 laboratory FC estimates. Both the DMT and geophysical estimates appear to show a reduced FC in
 366 the upper portion of the cohesive crust where laboratory data are limited. Within the underlying sandy
 367 silt/silty sand layers, the proposed correlations show a greater variability which is also displayed in
 368 the laboratory FC estimates. Particularly at the Bondeno site results based on the geophysical tests
 369 seem to diverge from the ones from the geotechnical tests below about 6 m depth. This behaviour can
 370 be related to the higher subsoil variability (laboratory FC varying between 10 to 50 % below 5 m
 371 depth) and therefore to the more localized nature of geotechnical testing with respect to the
 372 geophysical ones. Indeed, also the different estimates from geotechnical testing are less in agreement
 373 in this test site. However, this effect can be also partially related to the high fluid conductivity at the
 374 Bondeno test site which can partially drive the geophysical estimates to higher FC.
 375



376
 377 **Fig. 6** Comparison between FC profiles at the Mirabello and Bondeno test sites: laboratory data (FC
 378 LAB), estimates using CPT relationships with $x_c = 2$ ([38]) and $C_{FC} = 0.19$ ([7]), new FC predictions
 379 by DMT and geophysical surveys (ERT and V_s from DH or SDMT).
 380
 381 Regarding CPT predictions, the assumed Sukuki et al. [38] coefficient ($x_c = 2$) provides a FC profile
 382 that fits better to the laboratory data than using the site-specific Boulanger and Idriss [7] coefficient
 383 ($C_{FC} = 0.19$). This is also confirmed by comparing the overall standard deviation (SD) of the FC
 384 predictions with respect to the laboratory measurements:

$$SD = \frac{\sqrt{\sum (FC_{CPT} - FC_{LAB})^2}}{N} \quad (12)$$

385 Where FC_{CPT} is the FC prediction obtained by CPT correlations, FC_{LAB} is the FC value measured in
 386 the laboratory and N the total number of measurements. At both the test sites, the SD based the Suzuki
 387 et al. [38] estimate (25% in Mirabello and 17% in Bondeno) is lower than that the one obtained using
 388 the Boulanger and Idriss [7] equation (31% in Mirabello and 21% in Bondeno) allowing an overall
 389 better agreement with the laboratory data.

390 The comparison between the FC measurements and predictions from the newly proposed DMT
 391 correlation (Fig. 5) seems to perform better in the silty sandy layer, where the number of laboratory
 392 samples is considerably higher, compared to the upper cohesive crusts (few available samples). The
 393 average SD for the DMT correlation is 23% in Mirabello and 24% in Bondeno, therefore of the same
 394 order of the CPT correlations.

395 The FC profile estimated from geophysical surveys is also in reasonably good agreement with
 396 laboratory measurements, highlighting the potentialities of the proposed methodology for a
 397 preliminary screening of the potentially liquefiable soil and upper cohesive crust. The average SD for
 398 the geophysical correlation at both the sites is 32% in Mirabello and 22% in Bondeno.

399

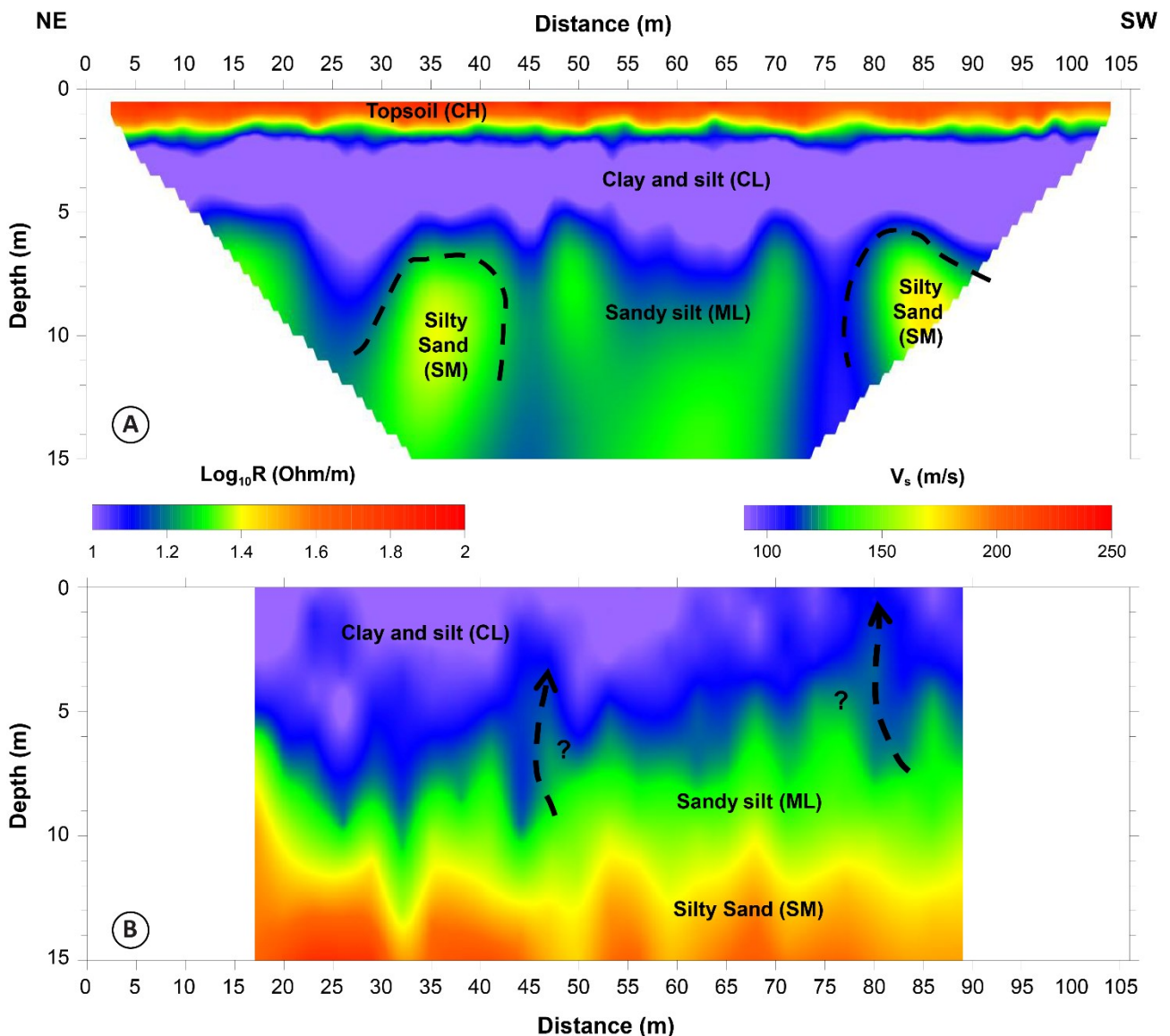
400 **5. Application of the calibrated correlations at the San Carlo test site.**

401 The correlations described in the previous sections have been used to forecast the FC variability in
 402 the third site of San Carlo (Site C, Fig. 1) both along 1D profiles (geotechnical correlations) and 2D
 403 sections (geophysical correlation). As shown in Fig. 1, both ERT and MASW2D surveys were
 404 performed along the direction where the 2012 sand boils occurred at the site, while two SDMTs and
 405 one CPTU were carried at the border of the same alignment.

406 Both the geophysical surveys have the same length (106.5 m) and acquisition spacing (electrodes and
 407 geophones 1.5 m-spaced) to guarantee a perfect overlap of the results and good compromise between
 408 the depth of investigation (DOI) and the data coverage. ERT data at this site were obtained following
 409 similar approaches than in the calibration sites. Particularly the same approach adopted at the
 410 Mirabello site was used for data acquisition (Syscal – Pro georesistivitymeter and 72 electrodes at 1
 411 m spacing with same Wenner-Schlumberger acquisition sequence with 1287 quadrupole). Also data
 412 processing and inversion was similar with a very good convergence (global root mean square error
 413 below 1%). As already mentioned this sequence allowed a dense spatial distribution of measuring
 414 points combining both lateral and vertical resolution with a resulting resolution of about 0.5 m both
 415 in the vertical and horizontal direction.

416 The seismic data were instead analysed with a specific procedure for the analysis of Rayleigh wave
 417 fundamental mode dispersion curves ([45], [46]) to allow the reconstruction of a 2D V_s section. This

418 approach is based on the use of a direct Wavelength-Depth transform of experimental dispersion
 419 curves and does not require a formal solution of the inverse problem. This transform has been
 420 obtained considering the similitude between the weighted average V_s profile and the dispersion curve
 421 and represents the surface waves skin depth for increasing wavelengths. Further detail on the way in
 422 which this transform was obtained and can be applied for “D V_s section reconstruction can be found
 423 in Anjom et al. [47]. In this same paper a study on the uncertainty analysis of this approach was also
 424 reported showing that minor and uniform uncertainties (less than 10 per cent in most regions) can be
 425 obtained.
 426



427
 428 **Fig. 7** Geophysical tests executed at the San Carlo test site (Site C, Fig. 1) with superimposed
 429 stratigraphic interpretation: a) ERT and b) MASW2D.
 430 Using the calibrated methodologies described in sections 3 and 4, the 2D imaging of FC for the San
 431 Carlo test site has been evaluated from the geophysical data and the 1D FC profiles obtained from

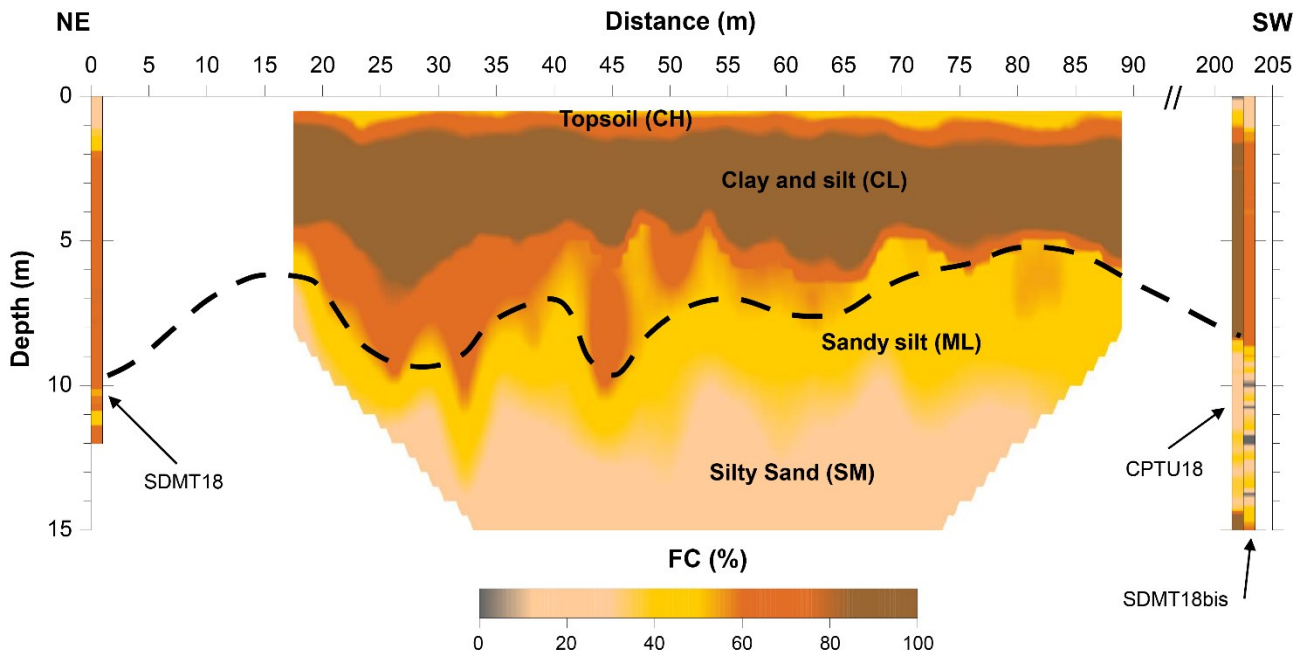
432 available geotechnical tests (Fig. 8). The colour scale adopted for the FC representation is similar to
433 the one used for the stratigraphic profiles of the calibration sites (see Figs. 3 and 4) to allow a direct
434 comparison.

435

436 ERT results (Fig. 7a) are in good agreement with the attended stratigraphic scheme in the area
437 reporting: a shallow layer of topsoil with quite high resistivity (ranging between 60 and 100 Ohm·m)
438 which can be related to the extremely arid conditions during the measurements, till the depth of 2 m;
439 below a more conductive layer (resistivity lower than 10 Ohm·m) of clays and silts, with a variable
440 thickness of 4-7 m and a resistive layer (ranging between 20 and 30 Ohm·m) of sandy silts. Within
441 this last layer local increases in resistivity are imaged reflecting the local presence of silty sands. The
442 interface between the clayey and sandy silty/silty sandy deposits is not horizontal but exhibits
443 elongated resistivity anomalies, which might be correlated with liquefaction effects occurred during
444 the 2012 earthquake. It must be however considered that due to the presence of the low resistivity
445 clay layer a reduction in sensitivity is observed in the final inverted model below about 7 m depth.
446 This effect still allows to consider very reliable the imaging of the interface between the clayey and
447 sandy silty/silty sandy deposits but less certain the resistivity values below this interface.

448 A similar setting emerges from the seismic tests at the site (Fig. 7b). Below a shallow low-velocity
449 (V_s lower than 100 m/s) layer of clays and silts, a progressive increase in V_s is observed, due to the
450 passage to sandy silts and silty sands. This last transition is better evidenced in the seismic data with
451 respect to the resistivity data which conversely have higher resolution in the identification of the
452 shallow topsoil. Similarly to the ERT section the transition from clayey and sandy silty/silty sandy
453 deposits is not horizontal but exhibits localized anomalies in which portions of soil with V_s values up
454 to 120 m/s are mixed (particularly at 45 and 80 m progressives) in a more homogeneous clayey layer
455 with average V_s lower than 100 m/s. In particular, at 80 m progressive, it is clearly visible the material
456 uplift up to the surface potentially correlated to the observed liquefaction phenomena in the same
457 portion of the profile (see Fig. 1).

458



459
 460 **Fig. 8.** Imaging of the FC from geotechnical and geophysical data at the San Carlo test site (Site C,
 461 Fig. 2).

462
 463 From these results it can be observed that, even if the punctual 1D tests are not in the same position
 464 of the 2D section for logistic constrain, a similar site setting emerges from all the surveys. The
 465 argillaceous cohesive and not liquefiable crust (CL, CH) can be estimated to be about 8 to 10 m thick
 466 from geotechnical tests and about 5 to 8 m thick from geophysical tests. These last tests evidence also
 467 a significant lateral variability of the crust thickness (higher in the NE portion of the 2D profile) with
 468 also relevant oscillations within the profile. In general, the proposed FC screening from the
 469 geophysical data appear to be satisfactory, with the great advantage with respect to the punctual
 470 geotechnical information of estimating the parameter variations along a wider portion of the site and
 471 therefore providing relevant information for the estimation of susceptibility to liquefaction. With
 472 respect to the geotechnical tests, the geophysical estimates report a less thick portion of the subsoil
 473 with $FC > 80\%$ and a less marked interface with the underlying sandy silt and silty sand with a FC
 474 transition and lateral variability. The geological setting emerging from the geophysical data appears
 475 to be coherent with respect to the presence at the site of widespread liquefaction phenomena. The
 476 combination of the geotechnical and geophysical tests has permitted to reconstruct the geometry and
 477 thickness of the fluvial channel sandy body that originated the liquefaction in 2012. This body appears
 478 oriented perpendicularly with respect to the 2012 liquefaction alignment and to the geophysical tests.
 479 The maximum thickness of the sandy body appears to be comprised between the 55 and 90
 480 progressives, with a sharp lateral closure north-eastward in correspondence of the SDMT18 test (Fig.
 481 6).

482

483 **6. Conclusions**

484 Specific fines content (FC) procedures, based on geotechnical and geophysical data, have been
485 proposed for more proper liquefaction hazard estimations in the alluvial Emilia plain (Italy) affected
486 by the 2012 seismic sequence. These methodologies are based on CPT or DMT or electrical resistivity
487 and shear wave velocity measurements.

488 Specifically, a new and firstly proposed correlation between FC and DMT data has been developed
489 and calibrated, increasing the potentiality of the DMT tests and its applicability in the study area. The
490 paper shows the potentiality of the CPT and DMT cost-effective procedures in the definition of the
491 FC vertical profile (1D imaging), supported by independent laboratory FC estimates at the calibration
492 sites.

493 The linear geophysical surveys allowed to obtain 2D imaging of the fines content, able to distinguish
494 the upper non-liquefiable high FC crust and the underlying lower FC sandy silty/silty sandy layers.
495 Moreover these techniques provided a reasonable subsoil reconstruction of alluvial succession,
496 highlighting geometrical variability and grain-size. This approach, calibrated at the study sites, has
497 provided relevant information for the estimation of liquefaction susceptibility along 2D profiles, and
498 significant advantage with respect to the punctual estimation carried out by the geotechnical tests.
499 The integration of punctual and linear investigations has also supported the reconstruction of the
500 geometry and thickness of the 2012 liquefied deposits.

501

502 **Acknowledgements**

503 Special thanks to Studio Prof. Marchetti to freely provide the seismic dilatometer equipment for the
504 field investigations, to Prof. Marco Stefani for the review of the manuscript and to Giacomo Maci to
505 support the data collection. This work is partly funded by Search for Excellence – Uda 2019
506 (University of Chieti-Pescara), Evaluation and Improvement of Methods to Consider Influence of
507 Surface Clay Layers on Liquefaction-Induced Settlement (CLIQUEST). However, the opinions,
508 conclusions, and recommendations in this paper do not necessarily represent those of the sponsors.

509

510 **Funding**

511 This work is partly funded by Search for Excellence – Uda 2019 (University of Chieti-Pescara),
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513 Liquefaction-Induced Settlement (CLIQUEST). However, the opinions, conclusions, and
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515

516 **Declaration of competing interest**

517 The authors declare no competing interests.

518

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