

Blast-induced liquefaction in silty sands for full-scale testing of ground improvement methods: Insights from a multidisciplinary study

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2 methods: insights from a multidisciplinary study

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36

## 37 HIGHLIGHTS

38 Blast tests produced liquefaction and sand boils at a silty sand site in northern Italy

39 Blast tests produced volumetric strain similar to that expected in an earthquake

40 Aggregate piers as a liquefaction hazard mitigation strategy improved soil performance

41 Geophysical and geotechnical site investigations were carried out before and after blasting

42 Field responses of treated and non-treated soils during blasting were compared

43

## 44 ABSTRACT

45 In the engineering geology field increased attention has been posed in recent years to potential  
46 liquefaction mitigation interventions in susceptible sand formations. In silty sands this is a major  
47 challenge because, as the fines content increases, vibratory methods for densification become  
48 progressively less effective. An alternative mitigation technique can be the installation of Rammed  
49 Aggregate Pier® (RAP) columns that can increase the resistance of the soil, accounting for its  
50 lateral stress increase and for the stiffness increase from soil and RAP composite response. To  
51 investigate the influence of these factors on liquefaction resistance, full-scale blast tests were  
52 performed at a silty sand site in Bondeno (Ferrara, Italy) where liquefaction was observed after the  
53 2012 Emilia-Romagna earthquake. A multidisciplinary team of forty researchers carried out  
54 devoted experimental activities aimed at better understanding the liquefaction process at the field  
55 scale and the effectiveness of the treatment using inter-related methods. Both natural and improved

56 areas were investigated by in-situ tests and later subjected to controlled blasting. The blast tests  
57 were monitored with geotechnical and geophysical instrumentation, topographical surveying and  
58 geological analyses on the sand boils. Results showed the RAP effectiveness due to the  
59 improvement of soil properties within the liquefiable layer and a consequent reduction of the blast-  
60 induced liquefaction settlements, likely due to soil densification and increased lateral stress. The  
61 applied multidisciplinary approach adopted for the study allowed better understanding of the  
62 mechanism involved in the liquefaction mitigation intervention and provided a better overall  
63 evaluation of mitigation effectiveness.

64

65 *Keywords:* liquefaction, blast test, rammed aggregate piers, ground improvement, silty sands,  
66 Emilia-Romagna earthquake

67

## 68 **1. Introduction**

69 The identification of an effective soil improvement technique for the mitigation of liquefaction  
70 hazard in silty sand deposits is undoubtedly a major challenge for engineers, geologists, building  
71 owners, developers, and specialty contractors. Indeed, as the fines content increases, the normally  
72 adopted vibratory methods for densification become progressively less effective and therefore more  
73 expensive approaches, such as soil mixing or deep foundations, are often required. Most of these  
74 alternative techniques are based on the installation of stiffer elements within the soil aimed at  
75 increasing both strength and soil density: typical examples are the Rammed Aggregate Piers®  
76 (RAP), Stone Columns (SC), Low Mobility Grout (LMG) or Timber Displacement Pile (TDP). In  
77 recent years, the Resonant Compaction Method (RCM) has also been investigated as a ground  
78 improvement solution in liquefaction-prone silts-silty sands (e.g. Li et al., 2018).

79 Over the last decades, a large amount of research has been carried out on liquefaction mitigation in  
80 clean sands, especially with reference to ground improvement techniques by densification. In recent  
81 years research interest has been also extended to liquefaction-prone deposits of silts and silty sands.

82 It is worth mentioning here the valuable outcomes from the extensive investigations carried out in  
83 Christchurch (New Zealand), following the widespread liquefaction and lateral spreading evidences  
84 due to the 2010-2011 Canterbury earthquake sequence (Giona Bucci et al., 2018). Wissmann et al.  
85 (2015), Vautherin et al. (2017), and Amoroso et al. (2018) examined the performance of RAP  
86 installation, showing that densification can be obtained and reliably quantified by means of  
87 piezocone (CPTU) and flat dilatometer (DMT) measurements in granular soil deposits having a soil  
88 behaviour type index  $I_c < 1.8$  or a material index  $I_D > 1.8$ , also at depths exceeding the design  
89 treatment depth. Wotherspoon et al. (2015) and Hwang et al. (2017) assessed the effectiveness of  
90 soil stiffening caused by the installation of SC, RAP and LMG using cross-hole tests. RAP  
91 appeared to produce stiffer discrete inclusions than SC, while LMG column installation actually  
92 compromised the liquefaction resistance. Finally, Alexander et al. (2017) examined the performance  
93 of a SC foundation system subjected to the Canterbury earthquake, showing that SC can cause  
94 contamination of gravel with silty fines and prevent drainage during shaking, thus resulting in loss  
95 of performance.

96 After the 1991 Loma Prieta earthquake, mitigation strategies against liquefaction in silty sands were  
97 also analyzed by Mitchell and Wentz (1991), who compared the performance of sites reinforced by  
98 SC with that of adjacent untreated areas. Minor or negligible damage was observed in the improved  
99 soils, whereas cracks and/or settlements, primarily due to liquefaction, occurred in untreated soil  
100 deposits. However, as the non-plastic fines content increased, the SC technique appeared to be more  
101 successful in combination with pre-installed wick drains (Adalier et al., 2003). Gianella and  
102 Stuedlein (2017) studied the behavior of sands and silty sands treated by TDP in South Carolina,  
103 proposing this technique as a suitable and potentially sustainable ground improvement alternative.  
104 Significant increases in cone resistance were observed after installation, though followed by a  
105 reduction in the long term. Finally, Li et al. (2018) reported a series of in-situ tests and full-scale  
106 field tests to investigate the RCM compaction effects on laterally loaded piles in silts and silty sands

107 in eastern China, showing that this approach results in increase lateral resistance of the piles as well  
108 as in a reduction in soil liquefaction potential.

109 The increase in penetration resistance due to the installation of the ground improvement techniques  
110 described previously is generally attributed to the increase in soil density alone, erroneously  
111 neglecting the influence of lateral stress. Nonetheless, it has been observed (Harada et al., 2010;  
112 Salgado et al., 1997) that the potential increment of lateral pressure can go well above the normally-  
113 consolidated state, thus contributing to the increase of the liquefaction resistance within the  
114 improved soils. In addition, it is still uncertain how to accurately account for the composite action  
115 of discrete elements and soil. Soil-cement columns or grids constructed by cement deep soil mixing,  
116 jet grouting, or other methods (e.g. SC) are considered effective for mitigating liquefaction in silty  
117 sands by shear reinforcement mechanism (e.g. Mitchell, 2008; Adalier and Elgamal, 2004).  
118 However, recent numerical studies by Rayamajhi et al. (2014, 2016) and Green et al. (2008)  
119 demonstrated that discrete columns may deform in both flexure and shear, being less effective in  
120 reducing shear stresses than what shear stress compatibility implies. Investigations based on  
121 vibroseis “T-Rex” and/or cross-hole tests in New Zealand and Ecuador (Wissmann et al., 2015;  
122 Smith and Wissmann, 2018) provided evidence that RAP reinforced ground is significantly stiffer  
123 than the untreated natural soil.

124 The level of shear stress reduction in the surrounding soil due to the in-situ installation of discrete  
125 columns has still not been demonstrated by field data. Therefore, full-scale liquefaction tests in the  
126 field, under controlled conditions, are important for a proper quantification of lateral stress and  
127 shear stiffening phenomena. These tests will improve understanding of the behavior of the soil and  
128 column composite response under conditions similar to those induced by earthquakes.

129 Previous experiences in the United States and New Zealand (e.g. Ashford et al., 2004; Wentz et al.,  
130 2015; Saftner et al., 2015; Gianella and Stuedlein, 2017) show that liquefaction can be induced and  
131 monitored in clean sands with controlled blasting. Some efforts have also recently focused on  
132 studying the behavior of siltier deposits during blast-liquefaction tests in Italy (Amoroso et al.,

133 2017; Fontana et al., 2019; Passeri et al., 2018; Pesci et al., 2018). Furthermore, little research is  
134 available to demonstrate RAP effectiveness in mitigating liquefaction in sandy silts and silty sands,  
135 using blast-induced liquefaction. Nevertheless, preliminary results from a silty sandy case history in  
136 Ecuador suggest that RAP ground improvement elements installed beneath a 700 m-long bridge  
137 embankment prevented lateral spreading and settlement during the 2016,  $M_w$  7.8 Muisne earthquake  
138 (Smith and Wissmann, 2018).

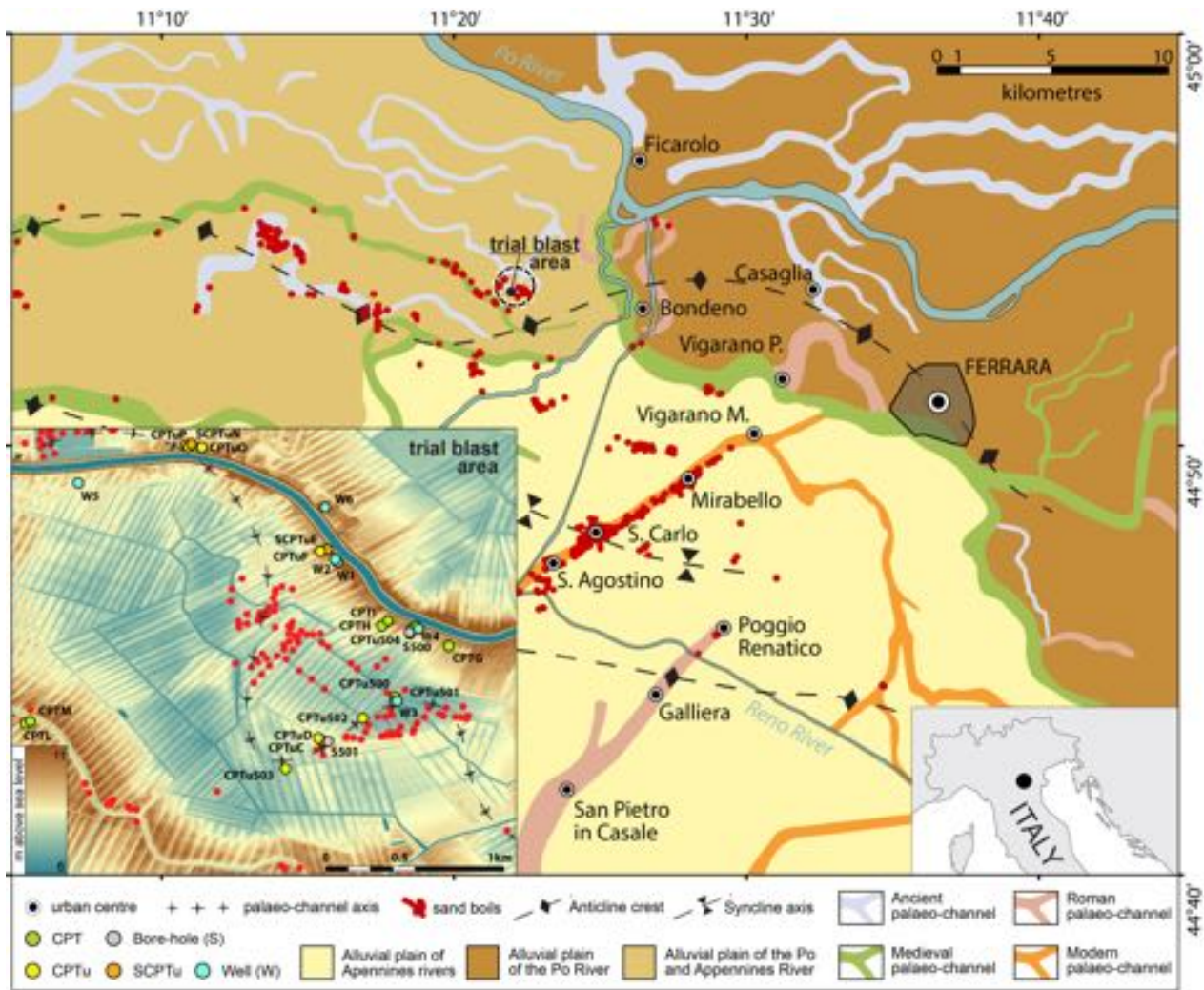
139 In this context, full-scale blast tests were performed at a silty sand site in Bondeno (Ferrara, Italy)  
140 where liquefaction was observed after the 2012 Emilia-Romagna earthquake (Emergeo Working  
141 Group, 2013), as preliminarily presented by Amoroso et al. (2019). Compared to previous blast  
142 experiences, the present study is based on a multidisciplinary approach, involving a team of forty  
143 researchers with expertise in the fields of geology, geophysics, geotechnical engineering and site  
144 surveying, in order to gain a comprehensive understanding of the mechanisms governing the  
145 selected engineering solution for liquefaction mitigation. Geotechnical testing, surface seismic and  
146 geoelectrical surveys were performed before and after RAP installation, as well as after blasting, to  
147 verify the effectiveness of the treatment. An array of explosive charges was detonated sequentially  
148 on improved and unimproved test areas to evaluate relative liquefaction resistance after RAP  
149 installation, monitoring excess pore pressures, settlements and accelerations. Also, four small  
150 exploratory trenches were dug to identify deformational features related to the blast tests and to  
151 characterize the fractures/conduits used by the liquefied sands during blast tests and in the 2012  
152 earthquake. Samples of ejecta and in-situ sand were collected to characterize the soil deposits with  
153 geotechnical and/or petrographic laboratory tests. This combination of geological and geotechnical  
154 methods appears to be vital for a proper interpretation of the liquefaction process and for verifying  
155 the seismic origin of dykes (Obermeier, 1998). The paper describes the testing program and  
156 presents insights from this multidisciplinary study.

157

## 158 **2. Geology, geomorphology, and seismotectonic framework of the study area**

159        **2.1. Geological setting**

160    The blast test site area is located in the south-eastern portion of the Quaternary alluvial plain which  
161    extends between the southern Alps and the northern Apennines. This plain is one of the deepest  
162    alluvial plain in Europe, though the exact depth of the seismic bedrock and the relevant seismic-  
163    wave properties are still a matter of debate among researchers (Molinari et al., 2015). The test site  
164    lies on the buried external portions of the Apennine chain, consisting of seismically active fault-fold  
165    structures (Toscani et al., 2009). The sedimentary units involved in the experiment accumulated  
166    during the late Pleistocene and Holocene periods, and show significant lateral variability in  
167    thickness (Minarelli et al., 2016). The latest Pleistocene unit is part of a depositional cycle typically  
168    referred to as Villa Verrucchio Subsynthem (AES7), whereas the Holocene sediments pertain to the  
169    Ravenna Subsynthem (AES8). Several generations of fluvial channel deposits were fed from the  
170    south by the Apennine streams and from the west by the Po River (Fig. 1).



171

172 Fig. 1. Map of the paleochannel bodies (modified after Stefani et al., 2018), of the surface  
 173 manifestations of liquefaction following the 2012 Emilia-Romagna earthquake (Emergeo Working  
 174 Group, 2013) and of the location of the blast area. The traces of the main anticline crest and  
 175 syncline axis of the buried tectonic belt are also depicted. The lower-left corner shows the  
 176 geomorphological features from LIDAR map together with the available investigations and the  
 177 2012 sand boils.

178

## 179 2.2. Seismic activity and effects

180 The area has a seismic history of low- to moderate-magnitude events. The most relevant past event  
 181 is the VIII MCS (moment magnitude  $M_w$  5.5) 1570 earthquake that struck the area of Ferrara,  
 182 causing liquefaction phenomena, open fractures and changes in channel water flows (Caputo et al.,

183 2016). In May 2012, a seismic sequence affected the area with two main shocks (Pondrelli et al.,  
184 2012). The first occurred on May 20<sup>th</sup> ( $M_w$  6.1), with an epicenter at about 15 km to the south-west  
185 of the test site, followed by aftershocks up to  $M_w$  5.1. The second main seismic event took place on  
186 May 29<sup>th</sup> ( $M_w$  5.9), with an epicenter located at about 24 km to the south-west of the test site. The  
187 highest peak ground accelerations (*PGA*) recorded at nearby strong-motion stations located in the  
188 epicentral area turned out to be approximately 0.3g and 0.9g, for the horizontal and vertical  
189 components, respectively (Luzi et al., 2013). Both main shocks induced important secondary effects  
190 at the surface, such as widespread liquefaction, sand boils (Fig. 1) and ground failures, together  
191 with lateral spreading and differential settlements. Sand boils and liquefaction manifestations  
192 occurred mainly along paleochannel deposits (Fig. 1).

193

### 194 **2.3. Geomorphological framework**

195 A strong link between the geographic distribution of the fluvial sand deposits and the location of  
196 liquefaction events was observed for the 2012 seismic crisis (e.g. Papathanassiou et al., 2015;  
197 Caputo et al., 2016) using satellite images and high-resolution LIDAR topographic models (Civico  
198 et al., 2015). The detected geomorphological features were also documented by the comprehensive  
199 database of subsurface investigations collected for the ongoing seismic microzonation (Fig. 1) and  
200 by other studies (Amoroso et al., 2020; Tonni et al., 2015).

201 The selected test site, which experienced the occurrence of a large number of sand boils (Fig. 1)  
202 during the 2012 seismic sequence (Emergeo Working Group, 2013), is located above a meander  
203 point bar structure. This meander morphology is partially confined by younger higher fluvial ridges  
204 bordering the test area in the south and the north (Fig. 1) and forming an interfluvial depression.

205

### 206 **2.4. Stratigraphic organization**

207 The fluvial sediments at the test site belong to three superimposed units, related to different  
208 depositional environments and chronological intervals (Figs. 1 and 4):

209 (a) the lower unit consists of fluvial medium-grained sands and silty sands, deposited during the late  
 210 glacial maximum (Pleistocene) into a braided river channel system (upper portion of AES7 unit).  
 211 This unit is about 20 m-thick topped by a regional paleosoil surface, overlain floodplain fine-  
 212 grained sediments. At the test site, the top of this unit corresponds to the erosive base of a Holocene  
 213 fluvial channel sand body;

214 (b) the middle unit is formed by fluvial sandy silts, laterally grading into argillaceous sediments.  
 215 This unit is approximately 9 m-thick (AES8 unit, Holocene). The interpretation of satellite images  
 216 and topographic data, coupled with information obtained from subsurface logs, suggests that the  
 217 sand accumulated into a meandering channel of the Po River. At the test site, this unit is buried at a  
 218 shallow depth. The liquefaction induced by the blast test largely took place within this unit;

219 (c) the upper unit comprises fluvial clays and silts (3 m-thick) forming the uppermost part of the  
 220 AES8 unit, deposited during the final infilling of the fluvial channel, probably recording influxes  
 221 from Apennine-derived rivers.

222

### 223 3. Description of the field activities

224 The blast tests activities were conducted over a period of one year (November 2017-October 2018),  
 225 as listed in Table 1.

226 Table 1. Activities associated with blast tests at Bondeno site.

Phase	Activity	Period
I	Preliminary investigations for site selection	November 2017-January 2018
II	Geotechnical and geophysical tests for characterization of the test site	February-March 2018
III	RAP column installation	March-April 2018
IV	Geotechnical and geophysical tests one month after RAP installation	April-May 2018
V	Installation of blast holes, profilometers, accelerometers, pore pressure transducers	May 2018
VI	Blast tests	4 June 2018
VII	Geotechnical and geophysical tests soon after blast tests	June 2018
VIII	Geotechnical and geophysical tests one month and a half to two months after blast tests	July-August 2018
IX	Geological, geotechnical and geophysical tests three to four months after blast tests	September-October 2018

227

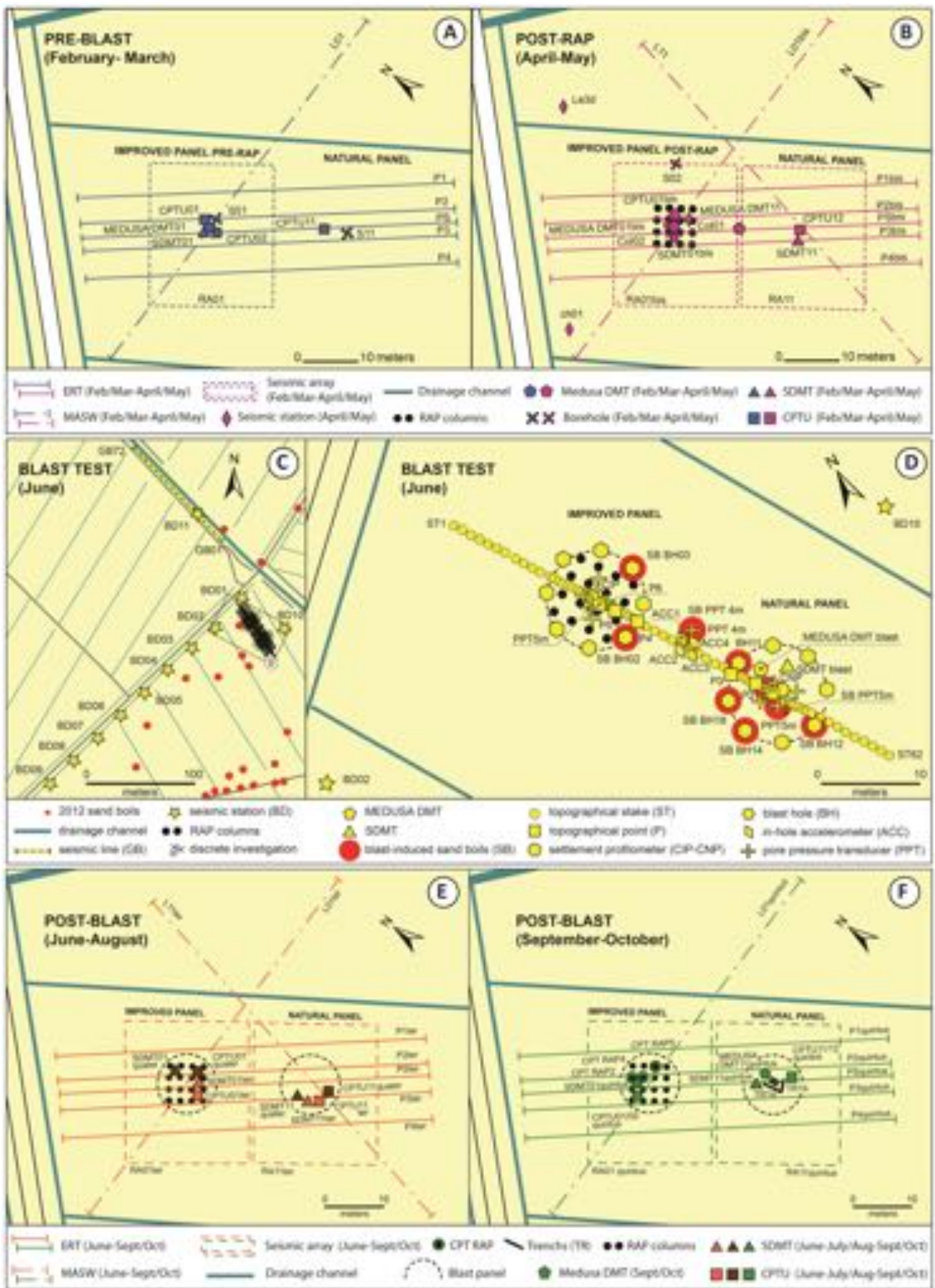
228 From November 2017 to January 2018, preliminary investigations were aimed at identifying the  
229 most suitable test site. This choice was guided by the need to select a shallow liquefiable layer of  
230 silty sands, also taking into account the previously mentioned geomorphological considerations and  
231 2012 liquefaction evidences. Furthermore, the site was located at a distance from buildings and  
232 human activities of this area in order to minimize the effect of vibrations generated by the  
233 detonation.

234

### 235 **3.1. Pre-blast activities**

#### 236 **3.1.1. Pre-RAP investigations**

237 From February to March 2018 an intensive geotechnical and geophysical campaign was carried out  
238 in order to achieve a detailed characterization of the upper 20 m of the subsoil, also useful for the  
239 design of the RAP columns and the blast tests. These surveys allowed identifying a relatively  
240 homogeneous area (60 m x 40 m), where two blast panels - one for testing the natural soil (Natural  
241 Panel, NP) and one for the improved soil (Improved Panel, IP) - were eventually placed (Figs. 2a  
242 and 2b). Later investigations were all concentrated in these two relatively small circular areas  
243 spaced 20 m apart, each having a diameter of 10 m. The geotechnical investigations, pushed to  
244 approximately 15 to 20 m in depth, consisted of: (i) two boreholes, one in the IP and one in the NP,  
245 along with standard penetration testing (SPT) and disturbed soil sampling for grain size distribution  
246 analyses, determination of Atterberg limits, petrographic analyses and radiocarbon dating; (ii) two  
247 piezocone (CPTU) tests, one in the IP and one in the NP; (iii) one seismic dilatometer (SDMT) test  
248 in the IP. The geophysical surveys consisted of: (i) five electrical resistivity tomography (ERT)  
249 alignments, spaced at 2 to 5 m and 63 m long (64 electrodes for each line), crossing the IP and the  
250 NP; (ii) one active P-wave and S-wave tomography, 71 m long, performed using firstly 72 vertical  
251 geophones and secondly 72 horizontal geophones along the same line; and (iii) one passive 2D-  
252 rectangular array (24 m x 21 m) using 72 P-wave geophones spaced at 3 m, and centered in the IP.



254 Fig. 2. Map of the investigations at the test site carried out pre-blast in February-March 2018 (a),  
255 post-RAP in April-May 2018 (b), during blast at small (c) and large (d) scale, post-blast in June-  
256 July-August 2018 (e) and in September-October 2018 (f).

257

258 Grain size analyses were carried out using a Mastersizer 3000 particle size. Compositional analyses  
259 under transmitted light microscopy were performed on the 0.125–0.250 mm fraction, according to  
260 the Gazzi-Dickinson method, designed to minimize the dependence of the analysis on the grain-size  
261 (Fontana et al., 2015).

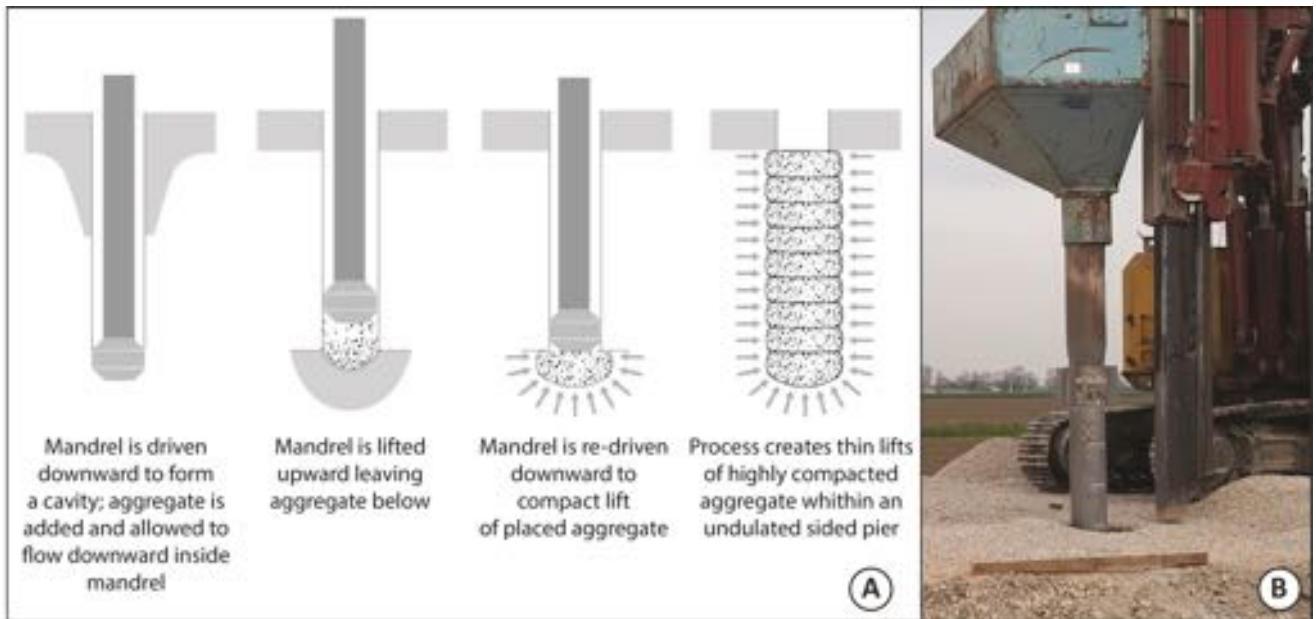
262 Prior to RAP installation, a 0.5 m-thick, geosynthetic-reinforced, gravel platform was set up to  
263 allow the access of the RAP installation equipment machinery. Moreover, an additional CPTU was  
264 performed to check the IP homogeneity, and a SDMT was also performed within the NP.

265

### 266 **3.1.2. RAP installation**

267 Between the end of March and the beginning of April 2018, a 4x4 quadrangular grid (2 m center-to-  
268 center spacing) of RAP columns, each 9.5 m long, was built (Fig. 2). The final diameter of each pier  
269 was 0.5 m with an associated area replacement ratio, defined as the ratio of the pier area to the  
270 tributary soil area surrounding the pier, equal to 5%. Because of construction issues, the last column  
271 of the third line was limited to only 5.5 m depth. For quality control of the ground improvement  
272 work, ten RAPs were subjected to aggregate flow rate tests and crowd stabilization tests in order to  
273 evaluate the pier gravel volume and to measure the column stiffness, respectively. These tests  
274 revealed a reduced effectiveness of the construction procedure for the upper-left piers.

275 The RAP elements were constructed using a displacement technique with an excavator mounted  
276 mobile ram base machine fitted with a high frequency (30 to 40 Hz) vertically oscillating hammer  
277 as illustrated in Fig. 3.



278  
 279 Fig. 3. (a) RAP column installation scheme with vibratory hammer and hopper/mandrel for gravel  
 280 installation (Wissmann et al., 2015); (b) RAP installation at Bondeno test site.

281  
 282 The base machine drives a 300 mm outside diameter open-ended pipe mandrel fitted with a unique  
 283 specially-designed 360 mm diameter tamper foot into the ground. Proprietary internal restrictor  
 284 elements prevent soil from entering the mandrel during driving and serve as an internal compaction  
 285 surface during tamping. After driving to the designed depth, the hollow mandrel serves as a conduit  
 286 for aggregate placement. Placed inside, the aggregate flows to the bottom of the mandrel. The  
 287 tamper foot and mandrel are then raised approximately 0.9 m and then driven back down 0.6 m,  
 288 forming a 0.3 m-thick compacted lift. Compaction is achieved through static down force and  
 289 dynamic vertical ramming from the hammer combined with the confinement of the tamper's  
 290 restrictor elements. The process densifies aggregate vertically and the beveled tamper foot forces  
 291 aggregate laterally into cavity sidewalls. Crushed gravel (typically graded at 10 to 40 mm in particle  
 292 size) is fed through the mandrel from a top mounted hopper and compacted in the displaced cavities  
 293 to create approximately a 0.5 m-diameter, dense, stiff, aggregate pier element. The construction  
 294 methodology has been described in detail by Saftner et al. (2018).

296 **3.1.3. Post-RAP investigations**

297 At the end of April 2018 supplementary geotechnical tests were carried out in the middle of four  
298 piers (Fig. 2b) and pushed to a maximum depth of 15 m, in order to evaluate the RAP effect on soil  
299 response one month after construction. DMT soundings were performed using a new device, the  
300 Medusa DMT, that is a combination of the flat dilatometer with hydraulic automation and a  
301 measuring system for autonomously performing DMT tests (Marchetti et al., 2019).

302 At the beginning of May 2018, the temporary gravel platform was removed to allow additional  
303 geophysical surveys with the same configuration as the original investigation (Fig. 2b): (i) five ERT  
304 alignments; (ii) two active P-wave and S-wave tomographies, one in the IP and one in the NP; (iii)  
305 two passive 2D-rectangular arrays, one centered in the IP and one centered in the NP; and (iv) four  
306 surface seismic stations, equipped with three-components Lennartz-5s velocimeter, two in the  
307 treated area and two in the natural soil.

308

309 **3.2. Blast activities**

310 In May 2018, blast holes, profilometers, accelerometers, pore pressure transducers, seismic DMT  
311 and Medusa DMT equipment were installed in the ground. Topographical reference points, seismic  
312 stations and geophones were placed on the surface in preparation for the blast tests that took place  
313 on June 4<sup>th</sup>, 2018 (Figs. 2c and 2d). Locations of the instrumentation relative to the blast holes for  
314 each panel are shown in Fig. 2d.

315 Eight blast holes (BH), 7 m deep and equally distributed along a 5 m-radius ring, were drilled in  
316 each panel. Charges were located in each BH at 3.5 m (0.5 kg) and 6.5 m (2.0 kg) within the  
317 potentially liquefiable layer. This soil layer was detected between 3 and 8 m depth according to a  
318 preliminary assessment of liquefaction susceptibility, that considered a design earthquake for a 475  
319 years return period ( $M_w = 6.14$  and  $PGA = 0.22g$ , Amoroso et al., 2019).

320 At the center of each panel, a profilometer (CNP for the natural panel and CIP for the improved  
321 panel) was anchored at 15 m depth to record the settlement vs. depth profile. In fact, previous

322 experiences worldwide (e.g. Amoroso et al., 2017; Gianella and Stuedlein, 2017; Finno et al., 2016)  
323 provided evidence of a bowl shaped displacement surface following blasting. Furthermore, from the  
324 previous blast experiment carried out in a site of the Po River valley, it was observed that  
325 settlements in the circular blasting area were similar to liquefaction-induced vertical displacements  
326 predicted for a  $M_w$  7.5 earthquake in the same depth interval (Amoroso et al., 2017).

327 To estimate blast-induced shear strains and shear stresses, four in-hole 200g triaxial  
328 microelectromechanical (MEMS) accelerometers (ACC) were located at approximately midway  
329 between the two panels (i.e. about 10 m from CNP and CIP), using a 1 m-squared configuration  
330 between 3.5 and 4.5 m deep and recorded at a sampling rate of 1000 Hz. Pore pressure transducers  
331 (PPT) were installed from 4 to 9 m at each meter of depth, within the liquefiable layer (1 or 2 m  
332 distance from the center of each panel) to measure the generation and subsequent dissipation of the  
333 excess pore pressures induced by the blasts in the silty sand deposits of both panels, at a sampling  
334 rate of 100 Hz. An additional PPT was set up at an average depth of 4 m in the middle of the  
335 accelerometer array to study the non-linear soil response induced by the blast-liquefaction, coupling  
336 the shear strains with the excess pore pressures. A SDMT and a Medusa DMT were finally installed  
337 at 6.1 m deep in the natural panel to monitor the variation of shear wave velocity with excess pore  
338 pressure following the blasts.

339 Six survey rods (P) were located within the NP and the IP and an alignment of sixty-two survey  
340 stakes (ST) crossing both panels was set up to record the vertical ground surface settlements over  
341 time after the blasts and to integrate with the profilometer data, Terrestrial Laser Scanning (TLS),  
342 and Structure from Motion (SfM) aerial photogrammetry. A line of seventy-two P-wave geophones  
343 (GB, 4.5 Hz) was installed at an average distance of 100 m from the blast area, while eleven surface  
344 seismic stations (BD), each of them composed of a velocimeter (Lennartz-5s) and an accelerometer  
345 (Episensor-1s), were located along a Y-shaped configuration, having the closest and the farthest  
346 stations at 25 and 250 m, respectively (Fig. 2c), to record the particle motion with distance and to  
347 verify the level of vibration generated by the detonation.

348 Explosives were detonated on June 4<sup>th</sup>, with a microdelay of 1 second between subsequent charges  
349 and starting the detonation from the bottom (6.5 m deep) to the upper level (3.5 m deep). The blasts  
350 of the two panels were designed separately (i.e. blast #1 for the NP and blast #2 for the IP) to limit  
351 effects of superposition and consequently to study the effect of the blast-induced liquefaction on the  
352 IP and the NP separately.

353 Surface movements induced by underground explosions and liquefaction effects were observed by  
354 means of TLS and SfM surveys performed before and after each blast test providing and comparing  
355 multi-temporal Digital Terrain Models (DTMs). Unmanned Aerial Systems (UAS) equipped with  
356 DJI FC6310 and DJI FC350 cameras and a Teledyne Polaris scanner were used. The results from  
357 TLS dense point clouds, characterized by a mean 5 mm sampling step, provide a complete  
358 description of subsidence rates in the area following liquefaction and pore pressure dissipation.

359

### 360 **3.3. Post-blast activities**

361 Three post-blast investigations were performed in June, July-August and September-October 2018  
362 (Figs. 2e and 2f), with the aim of comparing the variation with time of the geotechnical and  
363 geophysical parameters before and after the blast tests in both panels.

364 Two piezocone and two seismic dilatometer tests were carried out up to 15 m deep, in the IP and the  
365 NP soon after the blast tests. Moreover, in June 2018 ERT surveys and active and passive  
366 geophysical surveys were performed using the same configuration of the previous investigations  
367 shown in Fig. 2e.

368 One month and a half to two months after the blast tests, an additional in-situ testing campaign was  
369 repeated: two CPTUs and two SDMTs were performed, up to 15 m deep, between piers and within  
370 the untreated area, as shown in Fig. 2e.

371 Finally, three to four months after blasting, the last geotechnical and geophysical tests were carried  
372 out, as reported in Fig. 2f. As for the previous investigations, CPTUs, SDMTs and Medusa DMTs  
373 were performed in the IP and the NP, pushing tests to a maximum depth of 15 m. Moreover, three

374 mechanical cone penetration tests were performed at the center of RAP piers (CPT RAP) to a depth  
375 of approximately 11 m. In September-October 2018 ERT, active and passive geophysical surveys  
376 were repeated again using the same configuration of the previous investigations.

377 At the conclusion of the experimental activities, four small exploratory trenches were dug across the  
378 liquefaction-induced sand boils within the natural panel (Fig. 2f). The excavations were performed  
379 to better understand the blast-induced liquefaction mechanism but also to identify and characterize  
380 the fractures/conduits used by the liquefied sands in the 2012 earthquake (Amoroso et al., 2017) and  
381 possibly during older events (De Martini et al., 2012; Caputo et al., 2016). Moreover, sand samples  
382 were collected from the fractures as well as from the surface (sand boils) in order to study the  
383 variability in grain size potentially related to the liquefaction process and to the liquefied sand paths  
384 (Fontana et al., 2019).

385

#### 386 **4. Main geotechnical features from the pre-blast investigations**

387 The interpretation of all the geotechnical and geophysical investigations performed in both panels  
388 (IP, NP) prior to improvement was used to define a representative stratigraphic model of the natural  
389 subsoil (Fig. 4a). The identified soil units are listed below and classified in terms of the Unified Soil  
390 Classification System (USCS), according to ASTM D2487-11 (2011):

391 (i) top soil (CH) from the ground surface to 0.8 m;

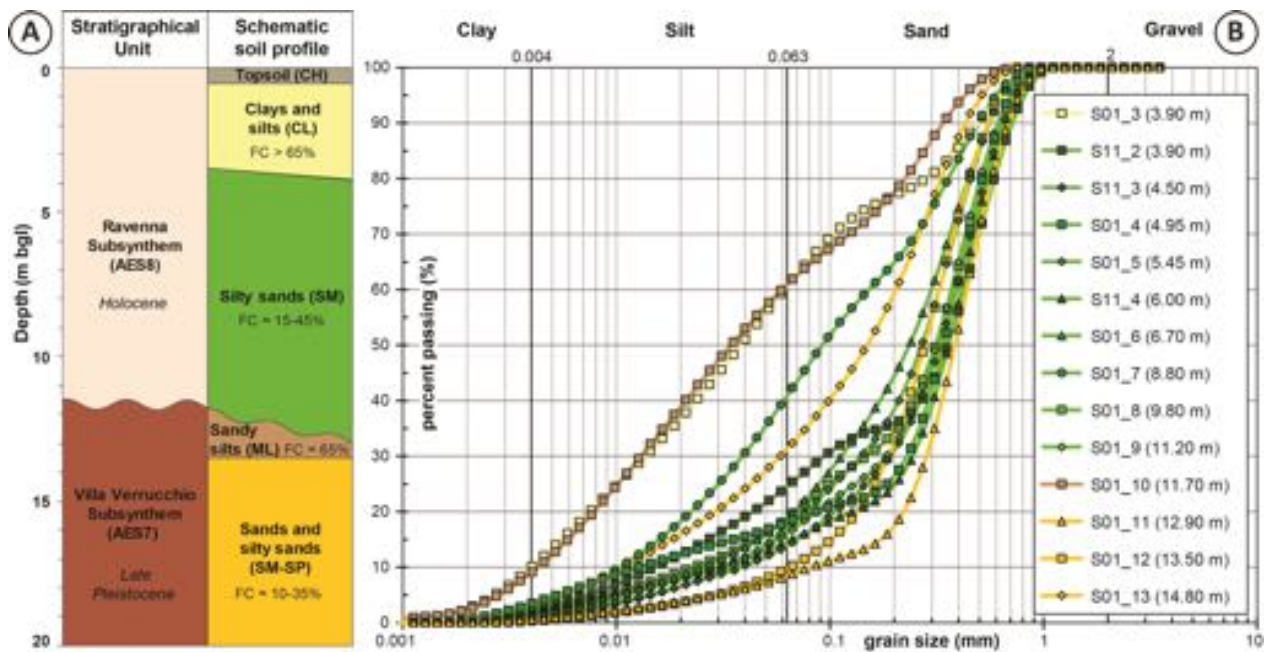
392 (ii) clays and silts (CL) from 0.8 to 3.4 m;

393 (iii) silty sands (SM) from 3.4 to 12.6 m (paleochannel of the Po River);

394 (iv) sandy silts (ML) from 12.6 to 13.4 m (well-drained interfluvial deposits);

395 (v) sands and silty sands (SM-SP) from 13.4 to 15.6 m (glacial braided Po River deposits).

396 The silty sands (SM) and sandy silts (ML) have laterally a variable thickness due to their channel-  
397 filling nature. In this respect, the ML layer can vary in depth between 11.70 and 13.40 m, and have  
398 a minimum thickness of approximately 0.5 m.



399

400 Fig. 4. Average subsoil profile at the test site and stratigraphic units (a) and grain size analyses (b).

401

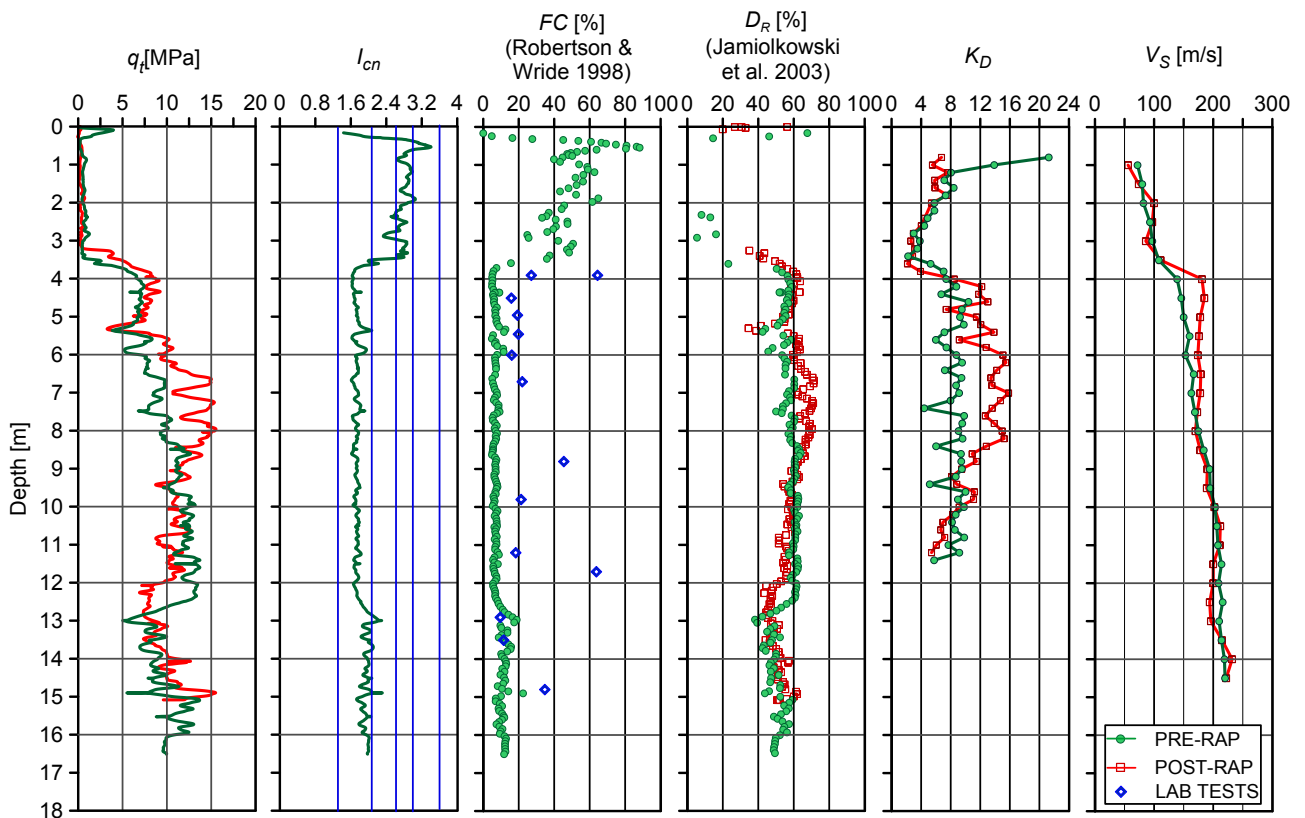
402 Fig. 4b shows the results of the grain size analyses performed on the disturbed samples from S01  
 403 and S11 boreholes. The analyzed samples range from silty sands to silts with a variable amount of  
 404 sand and clay. The majority of samples fits in a relatively narrow range, predominantly made up of  
 405 fine sands; the content of silt is on average less than 25% and clay is < 5%. A higher percentage of  
 406 fine sediments can be found in the shallowest sands (3.9 m depth) or in thin lenses detected at 8.8,  
 407 11.7 and 14.8 m depth. In particular, Fig. 4 shows that the SM layer has a fine content  $FC \approx 15-$   
 408 45%, while  $FC \approx 65\%$  for the ML layer and  $FC \approx 10-35\%$  for the SM-SP layer.

409 Sands from cores S01 and S11 have a quartz-feldspar rich composition and are made up of quartz,  
 410 feldspars and subordinate lithic fragments. Siliciclastic lithics include low-grade metamorphic  
 411 rocks, shales and spillite and carbonate lithic. Crystals of muscovite, chlorite and biotite are also  
 412 present as well as heavy minerals. The composition of the sands show a clear affinity with sands  
 413 from the Po River.

414 With reference to the defined stratigraphic model, Fig. 5 shows the soil response prior to RAP  
 415 installation in terms of corrected cone resistance ( $q_t$ ) from CPTU test, horizontal stress index ( $K_D$ )  
 416 and shear wave velocity ( $V_S$ ) from the SDMT test. The variation of  $q_t$  and  $K_D$  profiles with depth

417 looks related to the geologic depositional environment. Below the fine-grained units detected in the  
 418 upper 3.4 m, the paleochannel of the Po River (from 3.4 to 12 m) is characterized by different  $q_t$  and  
 419  $K_D$  values when compared with glacial braided Po River deposits (below 13.4 m). In contrast, the  $V_S$   
 420 increases consistently with the effective vertical stress.

421 Fig. 5 also provides interpretations of CPTU measurements in terms of the soil behavior type index  
 422 ( $I_{cn}$ ), fines content ( $FC$ ) according to Robertson and Wride (1998), and relative density ( $D_R$ )  
 423 computed with the correlation proposed by Jamiolkowski et al. (2003). The computed  $FC$  values  
 424 appear to be generally underestimated in comparison with those obtained from laboratory tests (blue  
 425 dots in Fig. 5). However, at the test site the dataset is currently too small to develop a site-specific  
 426 correlation that would take into account the uncertainties related to  $FC-I_{cn}$  relationship (e.g.  
 427 plasticity and mineralogy).



428  
 429 Fig. 5. CPTU and SDMT profiles pre/post RAP installation.

430

431 **5. Main outcomes from the experimental activities**

## 432 **5.1. Post-RAP investigations**

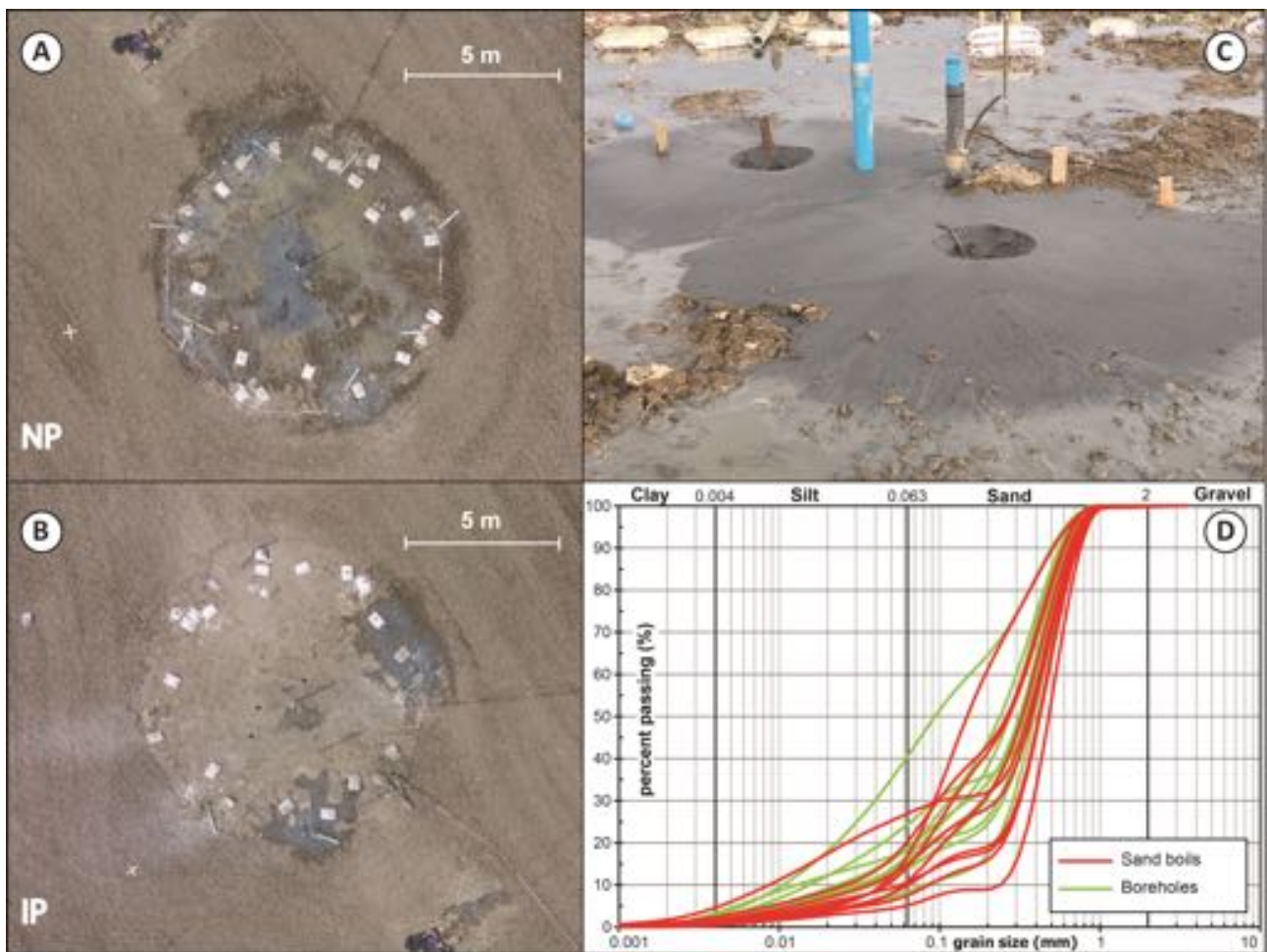
433 The site investigation performed one month after RAP column installation was helpful to  
434 understand the effectiveness of the ground improvement technique. Fig. 5 provides a comparison  
435 between field soil responses before and after treatment, in terms of both CPTU and SDMT profiles.  
436 A decrease of soil properties in the upper crust, partly due to the construction of the platform, but  
437 also to the low confinement induced by RAP installation and the seasonal variations in water  
438 content caused by fluctuation of the GWT from 1.5 m (February 2018) to 0.8 m (April 2018), is  
439 observed. Conversely, the layer between 3.4 and 9.5 m shows an increase in resistance and stiffness  
440 due to the installation of the piers. Unlike clean sands studied in New Zealand (e.g. Wissmann et al.,  
441 2015, Vautherin et al., 2017), in this case no improvement was detected in the silty sands below the  
442 toe of piers (Fig. 5). Looking in detail at the in-situ test data between 3.5 and 5.5 m depths,  $q_t$  and  
443  $K_D$  increase on average from 7 to 8 MPa, and from 7-9 to 12, respectively. This trend is further  
444 confirmed in the underlying layer, between 5.5 and 9.5 m, where the natural soil is characterized by  
445  $q_t \approx 8-10$  MPa and  $K_D \approx 7-9$ , and the treated soil assumes values of  $q_t \approx 10-14$  kPa and  $K_D \approx 13-15$ .  
446 Moreover, from 3.5 to 5.5 m in depth, the CPTU-based estimates of  $D_R$  shows a minor increase  
447 after pier installation, whereas a more significant increase is observed at 5.5-9.5 m (i.e. from  
448 approximately 60 to 70%). In contrast,  $V_S$  measurements show a limited improvement between 4  
449 and 7 m depth, from 140-165 to 175-185 m/s, and remain constant below 7 m (Fig. 5). This  
450 tendency may be related to the decrease in vertical effective stress with some disturbance to the soil  
451 structure (e.g. Mitchell and Solimar, 1984), for RAP installation.

452

## 453 **5.2. Blast test effects**

454 Figs. 6a and 6b show the results of the aerial SfM survey after both blasts. It can be easily observed  
455 that liquefaction was induced in the NP, as clearly indicated by the widespread sand boil evidence  
456 in this location (see also Fig. 2d). In contrast, only minor liquefaction traces are observed within the

457 IP, mainly near the edge of the blast ring. These limited sand boils are, however, outside the limits  
458 of the RAP group and likely developed in unimproved soils in this area.



459  
460 Fig. 6. SfM point cloud of surveyed area showing liquefaction-induced sand boils after blast #1 in  
461 the NP (a) and blast #2 in the IP (b). Detail of the sand boils in the NP (c); grain size distributions of  
462 the sand boils (in red) compared with sands from the boreholes (in green) (d).

463  
464 Fig. 6c documents the sand boils induced by the blast in the NP after blast #1. Grain size  
465 distribution analyses on soil samples collected from the sand boils (green curves in Fig. 6d) detected  
466 medium-grained sands with a fines content varying between 6 and 28%. Compared to grain size  
467 characteristics of the source beds (i.e. SM layer, red curves in Fig. 6d), a selective loss of fines can  
468 be appreciated in the ejected sediments forming the sand boils, thus indicating that the liquefaction

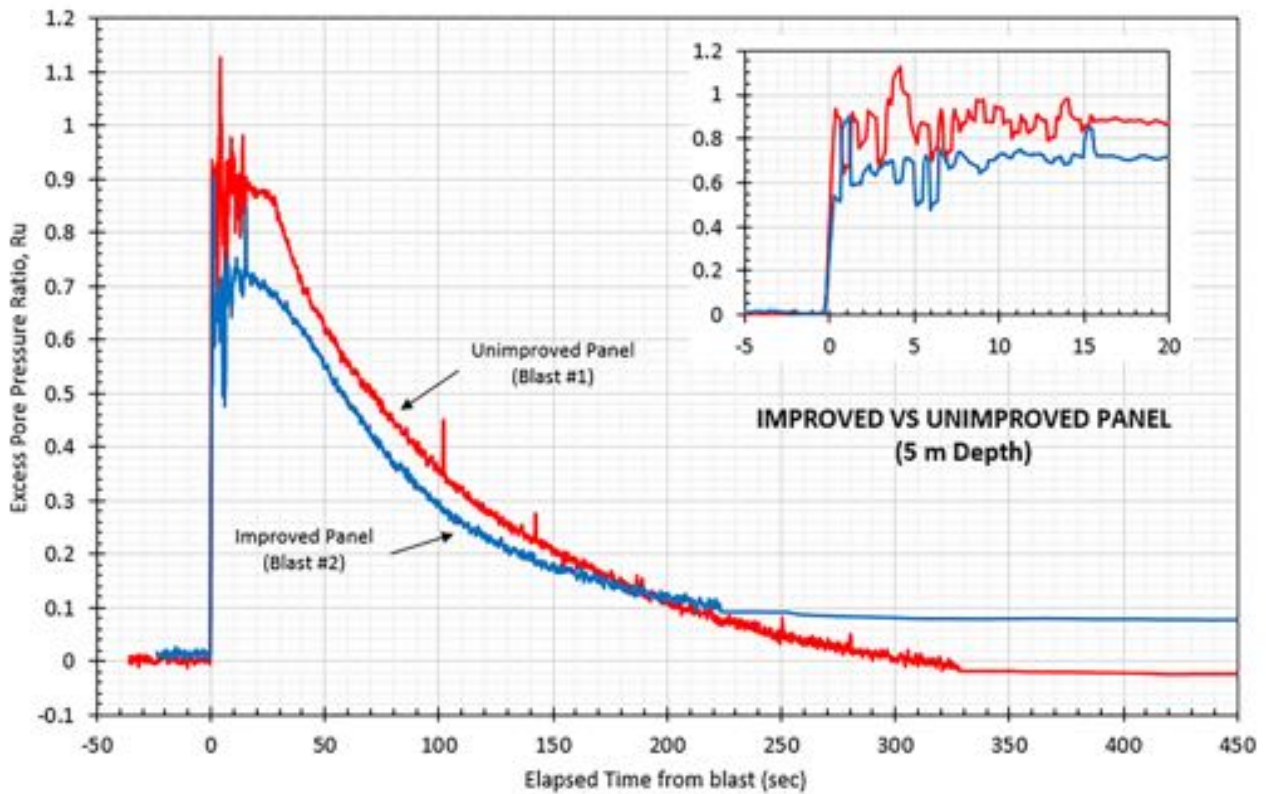
469 process appears to preferentially select the grain diameters, as previously found by Fontana et al.  
470 (2019), Maurer et al. (2019) and Cubrinovski et al. (2018).

471 Pore pressures measured by the PPT were used to compute excess pore pressure ratios ( $R_u =$   
472  $\Delta u / \sigma'_{v0}$ ) in the NP and the IP, where  $\Delta u$  is the measured excess pore pressure and  $\sigma'_{v0}$  is the initial  
473 vertical effective stress prior to the blasts. Soil unit weights were interpreted from the SDMT tests.

474 In the NP,  $R_u$  values reached 1.0, indicating liquefaction, from a depth of 4 to 9 m. Plots of  $R_u$   
475 versus time after blasts are presented in Fig. 7 for transducers at a depth of 5 m in the IP and the NP.

476 In the NP, the blast sequence produced  $R_u$  values near 1.0 which persisted for 15 to 30 seconds (see  
477 the zoom in Fig. 7) and then dissipated to near static levels in about 4 minutes. In the IP, peak  $R_u$   
478 values were somewhat lower ( $R_u = 0.75$ ) than in the NP, but dissipated at a similar rate.

479 Settlement profilometers indicated that liquefaction, and subsequent reconsolidation, occurred  
480 within a zone from about 3 to 11 m below the ground surface which is generally consistent with the  
481 expected zone of liquefiable sediments. In the NP, volumetric strains were consistent with what  
482 would be predicted by Zhang et al. (2002) if a  $M_w$  7.5 earthquake had produced liquefaction from 3  
483 to 11 m with a factor of safety of about 0.9. Volumetric strains in the same depth interval for the IP  
484 were about 20% of those measured for the NP, despite excess pore water pressure values that  
485 resulted in  $R_u$  values of 0.7 to 0.9.



486

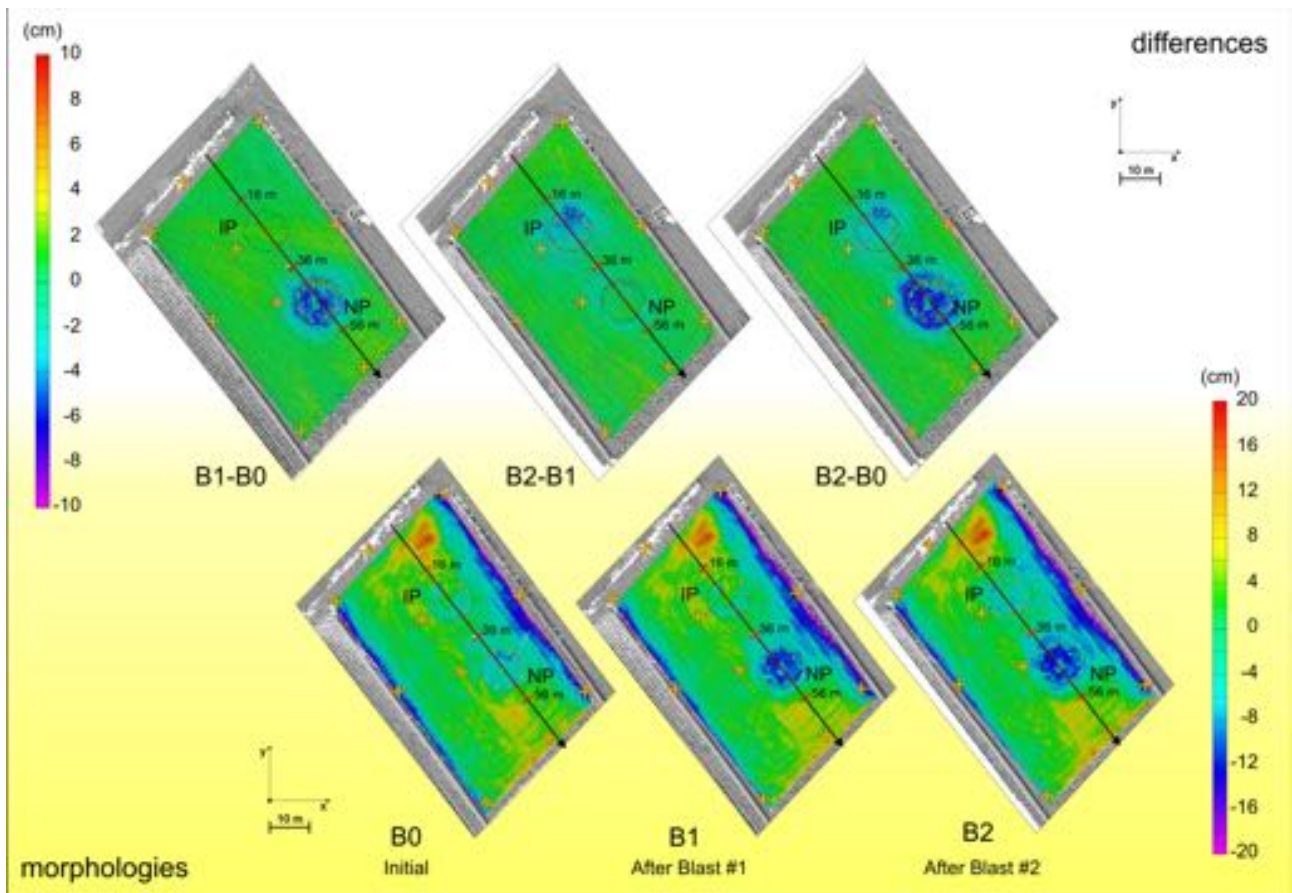
487 Fig. 7. Comparison of measured excess pore pressure vs. time curves for the IP and the NP at a  
 488 depth of 5 m below the ground surface. For both panels the PPTs recorded at a sampling rate of 100  
 489 Hz and the  $R_u$  values were smoothed using a 100 point running average. This was done so that the  
 490 residual excess pore pressure would not be obscured by the transient pressure spikes.

491

492 Fig. 8 shows color settlement contour maps obtained by comparing the TLS-based multi-temporal  
 493 models with the terrain morphology maps. In the NP, after blast #1 there is clear subsidence of the  
 494 area within the explosive charges, with a widely distributed settlement of about 6-8 cm. In contrast,  
 495 after blast #2 only a few small sectors of the IP experienced settlement with an average of 2 cm  
 496 (locally maximum 4-5 cm). For both blast tests, settlements were mainly delimited within about 10  
 497 m from the centers of the blast areas.

498 All topographical surveys indicate that settlements within the NP were on average between 7 and 10  
 499 cm, after both blasts. In contrast, settlements within the IP were between 2 and 5 cm. Liquefaction  
 500 induced settlements in the NP would likely be excessive for many structures, whereas the reduced

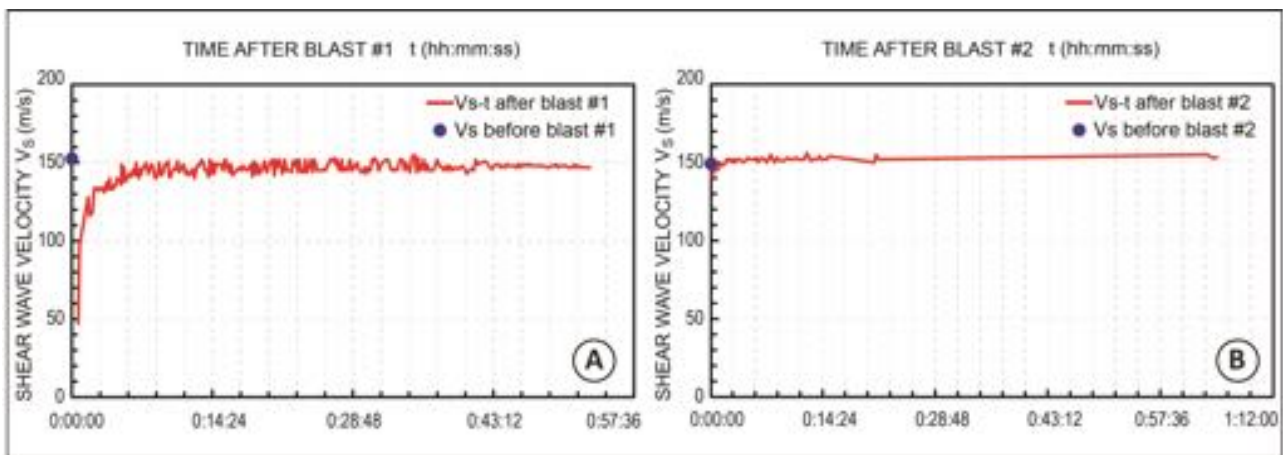
501 settlements in the IP would likely be tolerable. The mechanisms responsible for the reduced  
 502 settlement in the panel treated with RAP columns may be related to soil densification and increased  
 503 lateral stress, but soil-pier interactions may also play a role. Due to the whole test setup the bearing  
 504 capacity was not evaluated, even though it is another important issue within liquefaction evaluation  
 505 criteria.



506  
 507 Fig. 8. Difference maps between TLS-based point clouds (upper panels), where BN-BM means N-  
 508 th point cloud compared with respect to the M-th one, and morphological maps (lower panels).

509  
 510 Fig. 9 shows the SDMT results recorded in the NP during both blasts. Soon after the blast #1, the  
 511 SDMT data show a shear wave velocity decrease to about 30% of its pre-blast value ( $V_S \approx 49$  m/s  
 512 versus  $V_S \approx 152$  m/s), while it took a few minutes to recover to approximately its initial value. For  
 513 blast #2, since the SDMT modulus was still installed in the NP, a smaller decrease of shear wave  
 514 velocity is observed, equal to approximately 5% of its pre-blast value ( $V_S \approx 141$  m/s in place of  $V_S \approx$

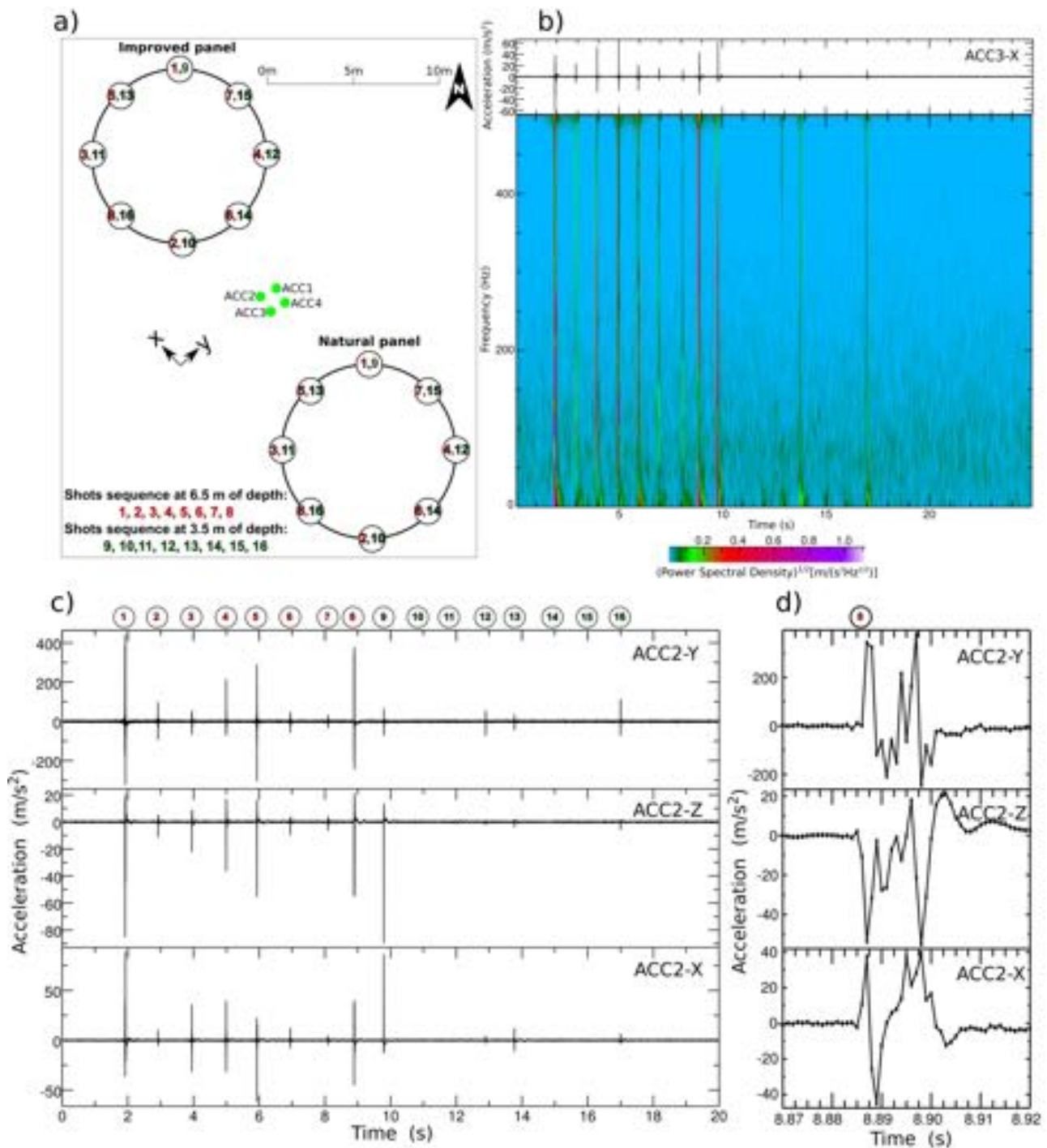
515 149 m/s), associated with a much faster recovery to its initial value. These results are consistent  
516 with other previous experiences (e.g. Rollins et al., 2004; Mahvelati et al., 2016). Blast-induced  
517 liquefaction reduces indeed the vertical effective stress and alters the soil fabric, thus causing initial  
518 losses in soil stiffness (Mitchell and Solymar, 1984). However, the dissipation of the excess pore  
519 pressure allows the soil to reconsolidate into a denser and more stable configuration (Narin van  
520 Court and Mitchell, 1994) characterized by a higher soil stiffness, as confirmed also at the Bondeno  
521 trial site by  $R_u$  and  $V_S$  data (Figs. 7 and 9).



522  
523 Fig. 9. Shear wave velocity data from seismic dilatometer during blasting: (a) blast #1; (b) blast #2.

524  
525 All the seismic instruments installed prior to the blast tests (Figs. 2c and 2d) recorded the signals  
526 produced by both detonations. Particularly, Fig. 10 shows some examples of time-series recorded  
527 by the in-hole accelerometers. The detonations performed at 6.5 m depth produced very energetic  
528 signals that are clearly recognizable in both the time and frequency domains (Fig. 10b). Instead, the  
529 signals recorded at 3.5 m depth have generally lower amplitude, compared to the deeper ones, and,  
530 in some cases, they are difficult to detect in the recorded time-series. The seismic data produced  
531 during each blast are characterized by a very impulsive signal of short duration (about 0.02 s) and  
532 high amplitude followed by a coda having a lower amplitude and a frequency content below 25 Hz  
533 (Fig. 10b). For each detonation, the duration of the entire recorded signal does not exceed 0.4 s  
534 (Figs. 10b and 10d). The maximum peak acceleration recorded by the in-hole sensors was of about

535 45g (ACC2-Y in Fig. 10c) and 52g during blast #1 (NP) and blast #2 (IP), respectively. In both  
536 cases, the maximum acceleration was recorded by the Y-component of ACC2 sensor (Figs. 10a and  
537 10d). From the spectrogram (Fig. 10b), the spectral content of the signals associated to explosions  
538 reach the maximum resolvable frequency (Nyquist frequency at 500 Hz) with the adopted sampling  
539 rate. Nevertheless, for each shot the maximum of signal was observed during the first impulse (Fig.  
540 10c) with a duration of about 0.003 s, corresponding to frequency of about 300 Hz, a value lower  
541 than the Nyquist frequency.



542

543 Fig. 10. Schematic diagram illustrating the locations (and the sequences) of charges detonated in the  
 544 NP and the IP with respect to the positions of the four installed accelerometers (ACC1, ACC2,  
 545 ACC3, ACC4) (a); seismic traces and related spectrogram recorded during blast #1 by the X-  
 546 component of ACC3 in-hole accelerometer (b); time histories of accelerations recorded during blast  
 547 #1 by the three different components of ACC2 accelerometer (c); zoom of signals recorded during

548 blast #1 by the different components of ACC2 during the shot number 8. The circles on the top of  
549 Figs. 10c and 10d show the number of explosions associated with the recorded signals (d).

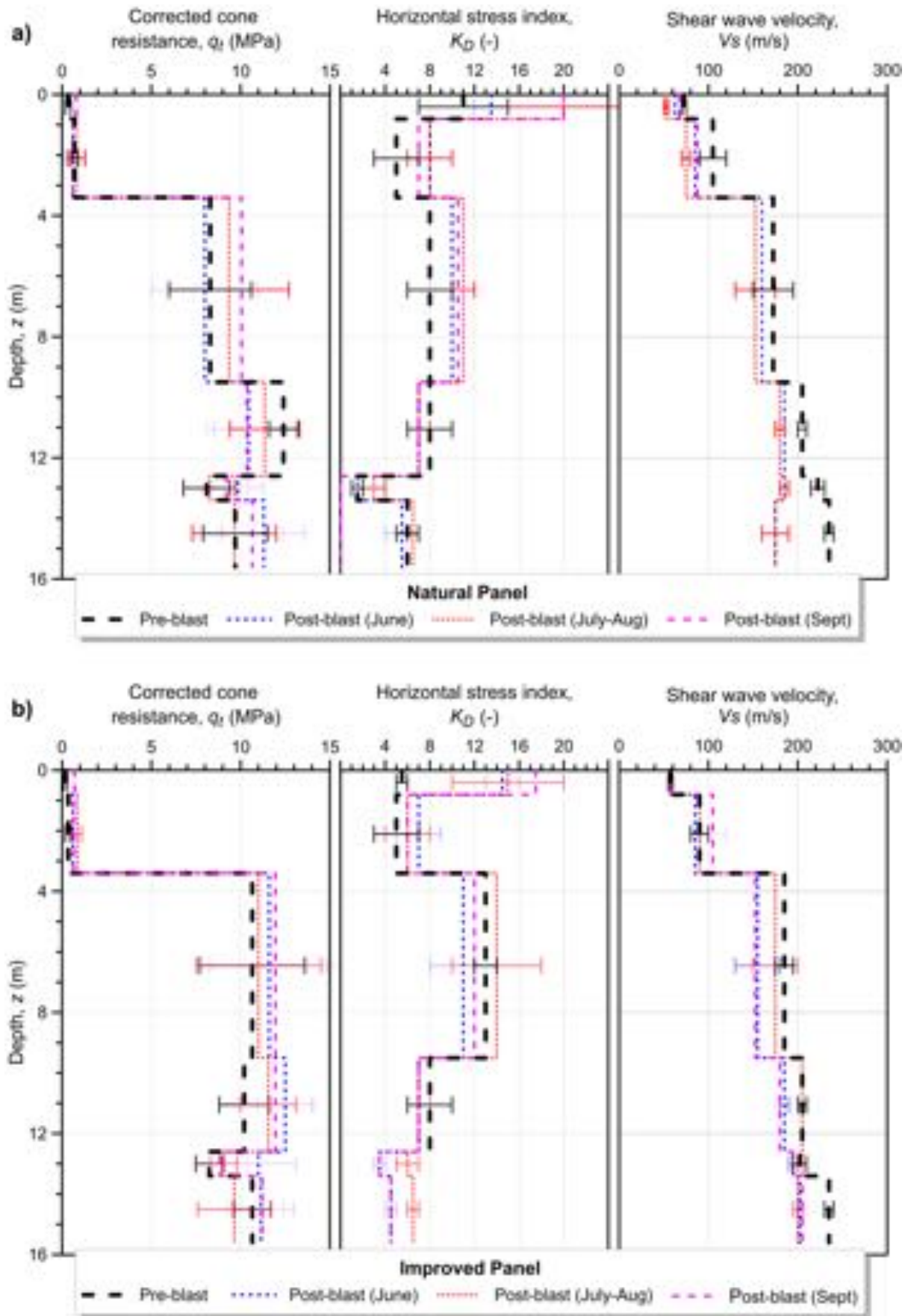
550

551 The seismic stations and the geophones permitted an estimate of the peak ground acceleration  
552 (*PGA*) and peak ground velocity (*PGV*) values generated by both the blasts at distances between 20  
553 and 250 m from the centers of the two panels. For blast #1, the maximum horizontal and vertical  
554 *PGA* were equal to 1.2g and 1.3g, while for blast #2 the values were 0.8g and 3.6g, respectively. In  
555 both cases, the blast-induced ground motion attenuated rapidly with distance and reached values  
556 smaller than 0.01g at about 180 m distance. The *PGV* values provide an exponentially decreasing  
557 trend with distance, consistent with other field test evidences (e.g. Gianella and Stuedlein, 2017;  
558 Amoroso et al., 2017), recording ranges from 0.14 to 0.0007 m/s at 20 and 250 m distance from the  
559 blast centers, respectively.

560

### 561 **5.3. Post-blast investigations and comparison to all previous data**

562 Fig. 11 shows the comparisons between the average profiles of  $q_t$ ,  $K_D$  and  $V_S$  acquired in the pre-  
563 and post-blast investigation campaigns, for both panels. Error bars are displayed in order to take  
564 into account the variability of measurements within the different soil units.



565

566 Fig. 11. Variation of the geotechnical and geophysical parameters before and after the blast test,

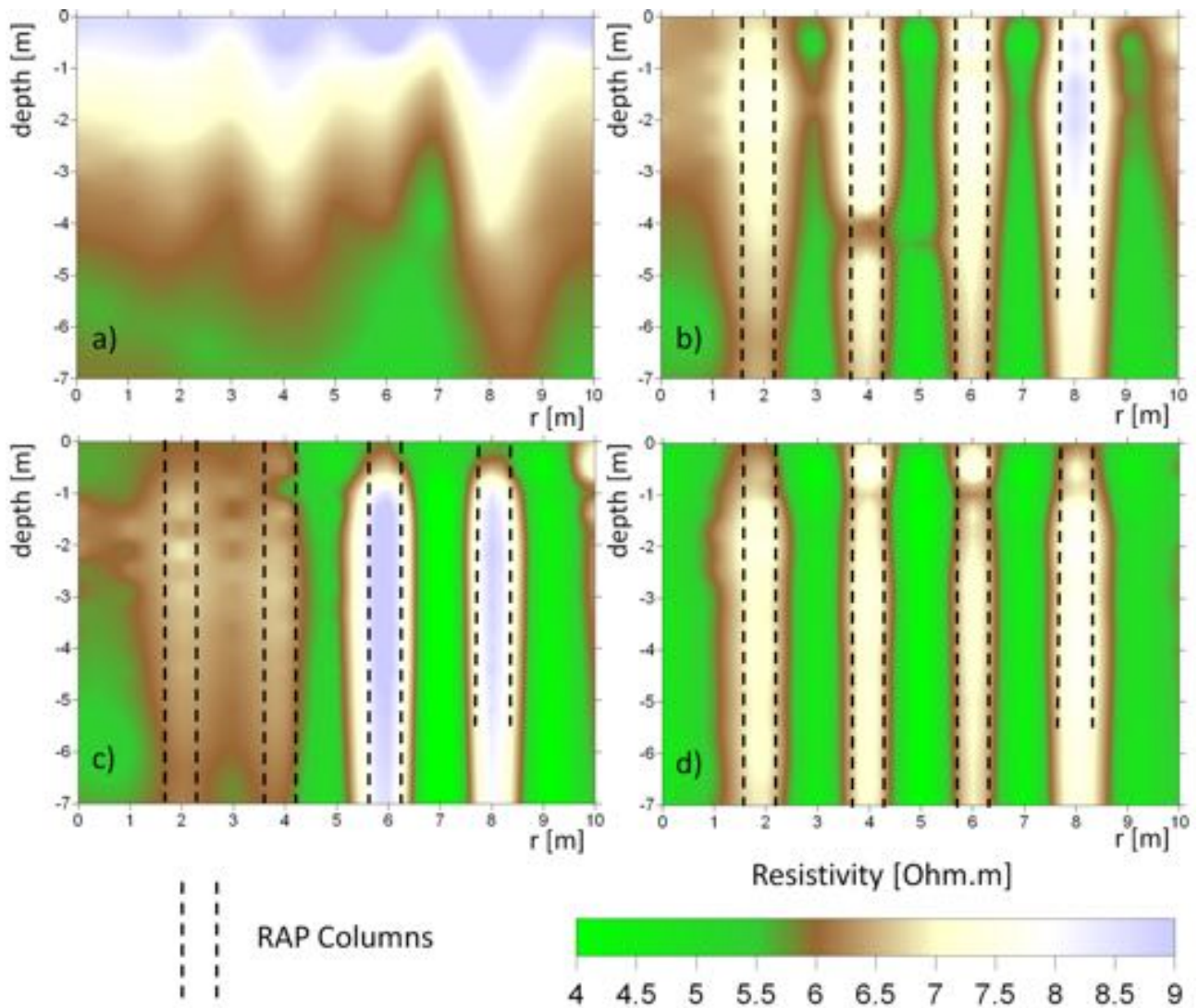
567 obtained from CPTU and SDMT in the NP (a) and the IP (b).

568 With reference to the IP after blasting, the comparison of the piezocone results reveals a general  
569 slight increase of the corrected cone resistance in the silty sands (SM), although the ranges reported  
570 in Fig. 11b do not appear to differ significantly. Negligible changes in the  $q_t$  profiles can be  
571 appreciated within the lower sands/silty sands. Similarly, the cone resistance profiles in the  
572 liquefied layer (3.4-9.5 m) of the NP (Fig. 11a) slightly increase with time (from June to July-  
573 August to September-October), whilst the underlying layers do not show any significant change,  
574 probably as a consequence of the charge locations. It is worth observing that the horizontal spatial  
575 variability of the subsoil complicates at time the direct comparison of the different CPTU  
576 soundings.

577 Based on the DMT results, a few days after blasting, the horizontal stress index turned out to  
578 maintain approximately its average value within the liquefiable layer of the IP (Fig. 11b),  
579 confirming the effectiveness of the piers in silty sand deposits. On the other hand, a small increase  
580 is detectable for the same unit in NP (Fig. 11a), consistently with CPTU measurements, probably  
581 due to some densification induced by the blast-liquefaction settlements. The bottom layers do not  
582 show any substantial increase. In later investigation campaigns, i.e. both in July-August and in  
583 September-October,  $K_D$  values stabilized in both the blast areas, showing on average a significant  
584 increase only within the liquefiable layer in the IP.

585 Finally, post-blasting time-dependent stiffness changes cannot be clearly identified in the IP (Fig.  
586 11b), while an overall small  $V_S$  decrease is observed in the NP (Fig. 11a). This last finding agrees,  
587 for example, with the results obtained by Mahvelati et al. (2016) in Pleistocene-aged sandy  
588 deposits, whereas differs from the observations made by Passeri et al. (2018) in Holocene-aged silty  
589 sands of Mirabello trial site (Emilia-Romagna, Italy). However, the Mirabello deposits are  
590 relatively new Holocene sands in comparison to the deposits of the present study area. Therefore,  
591 differences in geologic age and soil fabric may explain the differences in the rate and magnitude of  
592 stiffness changes.

593 In Fig. 12, the main results of the geoelectric surveys executed in the different time intervals in  
594 correspondence of the IP along the profile PS (see Figs. 2a, 2b, 2e, and 2f) are reported to a reliable  
595 investigation depth of 7 m. The measured resistivity data generally depict a very low resistivity  
596 environment (on average within 4 to 9 Ohm.m, Fig. 12a), even after the RAP construction (Fig.  
597 12b). This is related both to the clayey and silty sand formations at the site and to the relevant  
598 saturating water conductivity. Indeed, water samples collected in wells located in the area (Fig. 1)  
599 revealed anomalously high electrical conductivity values (more than 1200  $\mu\text{S}/\text{cm}$ ). This condition,  
600 together with the low confining pressures due to pier installation near the ground surface, has  
601 influenced the imaged resistivity data, partially compromising the ability of the surveys in detecting  
602 resistivity changes related to the blast effects. Particularly, inverted resistivity data were not always  
603 able to image significant resistivity variations in the subsurface, particularly in the NP, contrary to  
604 previous literature examples (e.g. Passeri et al., 2018). For this reason, raw apparent resistivity data  
605 are presented only in the IP, since these data better reflect the local resistivity variations,  
606 particularly in correspondence with the RAP columns.



607

608 Fig. 12. Apparent resistivity data imaged along the profile PS in correspondence of the IP in the  
 609 different time windows of the surveys: natural soil (a); treated soil before blast (b); treated soil after  
 610 blast – June (c); treated soil after blast – September (d).

611

612 Indeed in the IP the comparison of resistivity distribution imaged before and after the RAP  
 613 installation (Figs. 12a and 12b) satisfactorily defines the subsoil modifications related to the  
 614 installation of the gravel columns (black dashed lines in Figs. 12b, 12c and 12d). The four RAPs  
 615 intercepted by the survey line are indeed well depicted in the resistivity section showing a relatively  
 616 higher resistivity with respect to the natural soil. The last column of the section is known to be  
 617 driven only to 5.5 m depth. Nevertheless, apparent resistivity data also show a partial increase in  
 618 resistivity at greater depths probably due to compaction of the subsoil following tamping. The first

619 two piers along the section appear instead to be less homogeneous, as independently confirmed by  
620 quality control tests performed during their construction (Fig. 12b). After the blast testing the same  
621 first two piers along the section show a more significant resistivity reduction (Fig. 12c), which  
622 makes them less evident with respect to the surrounding soil. This effect could be related to  
623 increased water pressure in this zone of the IP and to partial column modifications after the blast  
624 which could have compromised RAP column resistance, given also their initial reduced stiffness. In  
625 this same zone of the IP, increased settlements after the blast have been depicted (Fig. 8)  
626 corroborating the geophysical evidence. Nevertheless, the apparent RAP column modifications do  
627 not appear to be permanent because the columns are again correctly imaged in the resistivity section  
628 acquired four months after the blast (Fig. 12d). Notwithstanding the difficult environment in terms  
629 of resistivity distribution, the geophysical surveys proved effective in imaging the variations  
630 induced by the blast tests within the RAP columns and can be suggested as a potential monitoring  
631 system.

632 Three trenches were excavated in the N350°-N355° direction (TR1a-c-d in Fig. 13a) and one in the  
633 transverse N65° direction (TR1b in Fig. 13a). The geometrical arrangement of the trenches made it  
634 possible to obtain detailed information on the sand boil genesis and on the previous  
635 fractures/conduits used by the liquefied sands in the 2012 earthquake. Particularly, the main sand  
636 boils developed during the blast tests shown in Fig. 6c reached the surface through the pore pressure  
637 transducer hole (PPT5, Figs. 13b and 13c). Evidence of liquefied sand ejected toward the surface  
638 was also found along the external part of the profilometer (CNP, Fig. 13d). This sand was also  
639 observed filling a sub-horizontal fracture marking a stratigraphic contact (yellow flags in Fig. 13b)  
640 between a silty clay, with sparse pebbles and a few charcoals (stratigraphic level 1 in Fig. 13b), and  
641 an oxidized silty clay (stratigraphic level 2 in Figs. 13b and 13c). Evidence from the 2012  
642 liquefaction (Figs. 13e and 13f) was also found in a 8 cm thick sand layer with a sharp basal contact  
643 on the vegetated surface at the time of the earthquake (Figs. 13e and 13f). The 2012 liquefied sand  
644 utilized an almost vertical thin fracture, visible to a depth of 1.5 m to reach the surface (Fig. 13g). A

645 light grey clayey silt layer at the bottom of the trench (stratigraphic level 3 in Fig. 13c) was also  
 646 observed, and provisionally recognized as one of the impermeable deposits over the liquefiable  
 647 sand. The ejection of sand during the blast test largely utilized pre-existing artificial paths (PPT5  
 648 and CNP) and the weak stratigraphic contact between level 1 and 2.



649  
 650 Fig. 13. Geometrical arrangement of the trenches (a); details of the most significant features  
 651 exposed in the walls. Sand boils from the blast test (b) were generated by sand moving upward  
 652 using the PPT5 pore pressure transducer, colored flags in (c), and the external part of the CNP  
 653 profilometer (d) as conduits. Sand from CNP moved sub-horizontally, as shown by yellow flags, in  
 654 (b). The white dashed circle in (f) indicates the remnants of the vegetation at the ground surface,  
 655 covered by the 2012 sand blow (bottom of the blow marked by colored flags in e, f). Details of the  
 656 2012 vertical path (colored flags) developed along a thin fracture in (g).

657

658 **6. Conclusions**

659 Full-scale blast-induced liquefaction tests (Bondeno, Italy) made it possible to evaluate the  
660 effectiveness of Rammed Aggregate Pier® (RAP) treatment in mitigating liquefaction hazards in  
661 silty sands. A multidisciplinary approach was used to increase the understanding obtained from the  
662 inter-related methods used to document blast-induced liquefaction behavior. The tests were  
663 performed on treated and untreated panels at a test site where sand boils indicated liquefaction  
664 during the 2012  $M_w$  6.1 Emilia-Romagna earthquake.

665 The controlled blasting experiment induced liquefaction in the natural panel (NP) consisting of  
666 untreated silty sands ( $FC \approx 15-45\%$ ) and produced surface settlements of 7 to 10 cm. Numerous  
667 sand boils were induced and volumetric strains within the liquefied layers were similar to those that  
668 would be expected from earthquake-induced liquefaction, in agreement with previous blast  
669 experiments. Grain size distribution curves of the induced sand boils confirmed a selective loss of  
670 fines relative to the source beds in-situ (paleochannel of the Po River), in agreement with previous  
671 blast experiments and earthquake events. In-hole accelerometers were able to record maximum  
672 peak accelerations equal to 45g and 52g, and further analysis will be performed to estimate the  
673 blast-induced shear stress and shear strain.

674 Within the improved panel (IP), excess pore pressure ratios were lower than in the untreated panel,  
675 but still greater than 75%. Despite these relatively high  $R_u$  values, the measured settlements (20 to  
676 50 mm) were significantly lower than in the untreated natural panel, as confirmed by topographical  
677 surveys and geotechnical monitoring. In addition, sand boil formation was strongly reduced.  
678 Therefore, RAP treatment resulted in reducing liquefaction-induced settlements to acceptable levels  
679 for many structures in comparison with the untreated natural soil. The site investigations performed  
680 after blasting also confirmed that the treated soil maintains approximately its pre-blast geotechnical  
681 properties, while the natural untreated soil developed lower values that later recovered with time.  
682 After blasting, some temporary RAP modifications were also detected by the electrical resistivity  
683 profiles and topographical surveys in correspondence with the piers that showed lower stiffness  
684 during the construction procedure.

685 Further in-depth data analysis is necessary to understand the fundamental mechanisms leading to  
686 the reduction in settlement within the treated panel that may be related to soil densification,  
687 increased lateral stress, and composite soil-column behavior during reconsolidation.

688

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716

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