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Monitoring ground improvement by Rammed Aggregate Piers using a combined CPTU and SDMT approach at a silty sand liquefaction-prone site in Emilia-Romagna

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ABSTRACT: Following the 2012 Emilia-Romagna earthquake, widespread liquefaction of silty sands was observed, providing the opportunity to gain a better understanding of the influence of fines content on liquefaction hazard and mitigation works. This paper presents the results of a thorough geotechnical investigation performed as part of a full-scale liquefaction experiment involving controlled blast tests in Bondeno, a small village that suffered liquefaction in 2012. Piezocone (CPTU) and seismic dilatometer (SDMT) tests were performed in natural and improved soils after Rammed Aggregate Pier® (RAP) treatment to provide accurate soil characterization and to evaluate the effectiveness of liquefaction mitigation. CPTU and SDMT results revealed a good agreement in the geotechnical characterization of the site, detecting homogenous soil properties in both the natural and treated soils and estimating CPTU-DMT coupled parameters in sandy layers (e.g. overconsolidation ratio, at-rest earth pressure coefficient), that are usually not determinable by the use of a single type of in situ test. In particular, the combined use of CPTU-DMT data provided verification of the increase in the lateral stress produced by the RAP installation. Data analyses revealed that the RAPs were an effective ground improvement technique despite the high percent of fines (≈ 25-35%).

1 INTRODUCTION

Several ground improvement solutions are available to mitigate the liquefaction hazard posed by clean sands; namely, increasing the soil resistance by densification or reducing the earthquake-induced excess pore pressures through drainage or reducing the shear strains through reinforcement. Vibratory compaction methods are a common and effective form of densification for cohesionless soils (Castro 1969), as proven by extensive research (e.g. Mitchell 1981, Vautherin et al. 2017, Amoroso et al. 2018). However, their effectiveness decreases as the fines content and plasticity increase (Mitchell 1981). Therefore, other ground improvement techniques, such as vibratory replacement, are often preferred in silty sands or sandy silts to protect the soil against liquefaction by increasing soil density, providing drainage for excess pore water pressures, and increasing the stiffness and shear resistance of the soil (Priebe 1998).

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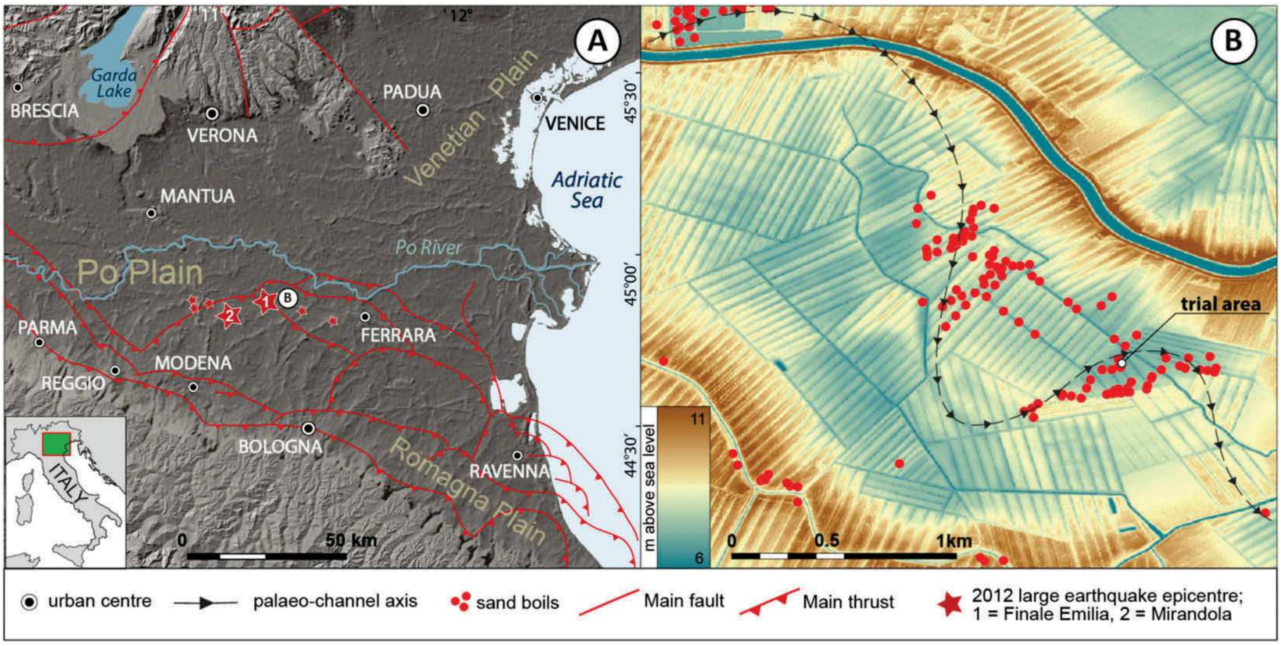

Figure 1. (a) Location of the Bondeno Test Site and of 2012 main shocks; (b) geomorphological features from LIDAR map (modified after Amoroso et al. 2020): greenish color indicates lower elevation above the sea level, while brownish color refers to higher elevation.

Examples of this type of reinforcement include Stone Columns (SC), Soil Mixed Columns (SMC), and Rammed Aggregate Piers (RAP). This last approach appears to be a promising solution in sandy silts and silty sands to increase not only the density, but also the lateral stress and shear stiffness, which is often neglected and poorly understood (Smith & Wissmann 2018, Amoroso et al. 2020).

The at-rest earth pressure coefficient (K_0) is a key parameter that should be considered with reference to liquefaction mitigation works (Schmertmann 1985, Salgado et al. 1997, Harada et al. 2010).

In this respect, in situ tests have an essential role to play in estimating the horizontal stress in granular soils before and after treatment. As argued by Massarsch et al. (2019), using cone penetration test (CPT) and flat dilatometer test (DMT) results could produce improved estimates of K_0. Moreover, Baldi et al. (1986) and later Hossain & Andrus (2016) proposed a combined CPT-DMT K_0-interpretation to take into account both the resistance and stress history of the soil, while the use of a CPT-only approach would have been overly affected by arching of stresses around the penetrating sleeve.

The coupling of CPT and DMT tests with downhole geophysics (i.e. seismic piezocone SCPTU and seismic dilatometer SDMT) provides a more efficient approach to the task of geotechnical site characterization, offering clear opportunities for the economical and optimal collection of the data (Mayne et al. 2009). Therefore, direct push technologies are more relevant for understanding the changes in soil properties following ground improvement (e.g. Jendeby 1992, Amoroso et al. 2018).

This investigation presents in situ test results from a thorough geotechnical campaign performed before and after Rammed Aggregate Pier (RAP) treatment of a silty sand site in Bondeno (Italy), a small village strongly affected by liquefaction following the 2012 Emilia-Romagna earthquake. The overall details of the research activities can be found in Amoroso et al. (2020) while details regarding the performance of the RAP group following a blast test are provided by Rollins et al. (2021) and regarding the liquefaction assessment and ground improvement are listed in Amoroso et al. (2022).

2 THE BONDENO TEST SITE (BTS)

2.1 *Geological and geomorphological setting*

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

The earthquake sequence induced widespread site effects, including liquefaction manifestations, soil fracturing and lateral spreading (Emergeo Working Group 2013). At BTS the liquefaction hazard is concentrated in a subsurface sand deposit of a Holocene Po meander (Figure 1b). Figure 1b shows the higher elevations (brownish zones) indicating fluvial ridges bounding the lower, relatively flat interfluvial depression (greenish zones). The meandering course of the paleochannel is built up within the interfluvial depression and supports the identification of the paleochannel axis together with the location of sand boils. The

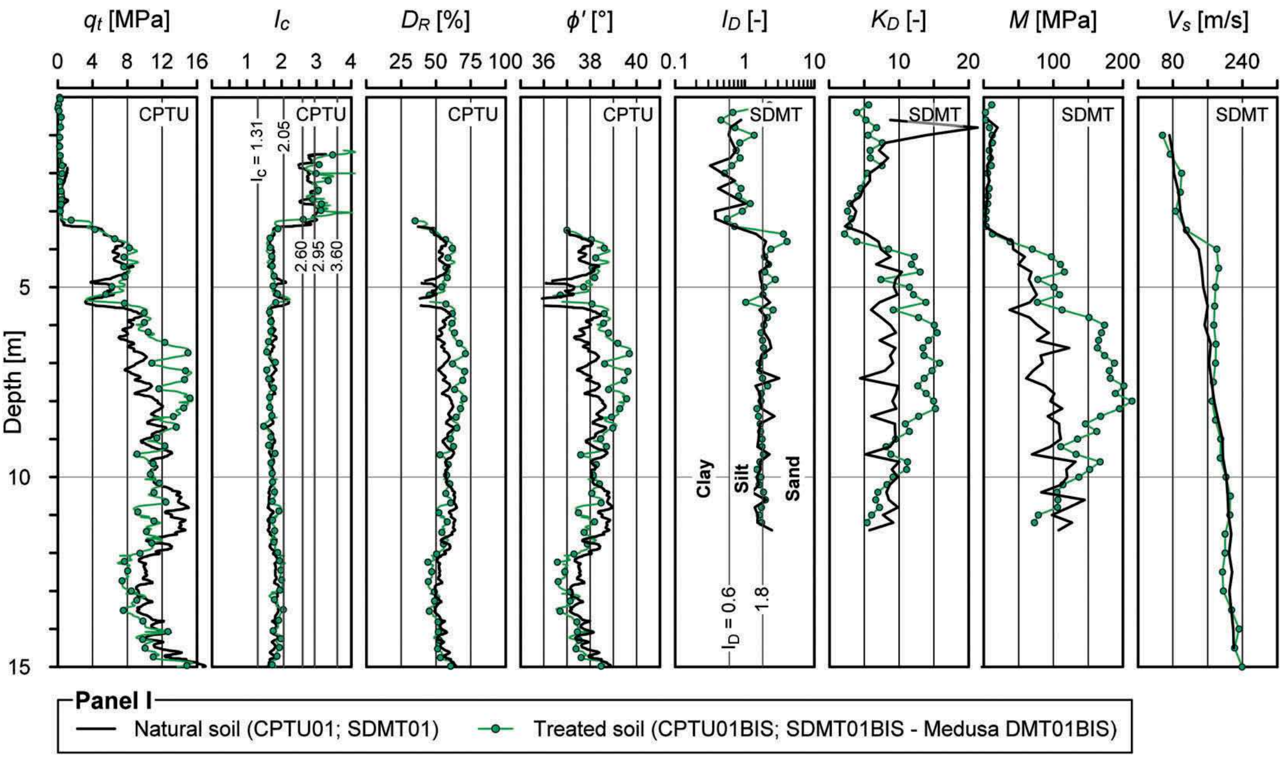

Figure 2. CPTU and SDMT interpreted results in natural (NS) and treated (TS) soils: (a) q_t, I_c, D_R, φ' from CPTU; (b) I_D, K_D, M, V_S from SDMT (modified after Amoroso et al. 2022).

meander base is frequently cut into upper Pleistocene coarse sand, accumulated during syn-glacial times. The meander unit geometry has been reconstructed through the analysis of remote sensing data (satellite images and LIDAR) and correlation of underground geotechnical investigations (Amoroso et al. 2020). This meander sand body is partially buried by finer grained levee sediment of historic age.

2.2 *Site investigations*

To assess the effectiveness of the RAP treatment at the BTS, in situ tests were performed before and after pier installations, according to the phases reported below:

- Phase I consisted of site investigations performed before the treatment (pre-RAP) and before the blast (pre-blast). Boreholes with SPTs and disturbed soil sampling, CPTUs, and SDMTs were executed up to a maximum depth of 20 m in two relatively small circular areas (10 m-diameter and 20 m-spacing) associated with the blast experiment, one for testing the natural soil (Natural Panel, NP) and one for testing the improved soil (Improved Panel, IP). This paper includes only CPTUs and SDMTs performed in the IP;
- Phase II included site investigations carried out approximately one month after the pier installation (post-RAP) and before the blast (pre-blast) within the IP. The treatment consisted of a 4 × 4 quadrangular grid (2 m center-to-center spacing) of RAP columns, each 9.5 m long and with a final diameter of 0.5 m (area replacement ratio equal to 5%). Details on the construction methodology are reported in Saftner et al. (2018). Each CPTU, Medusa DMT (automated dilatometer test, Marchetti et al. 2019) and SDMT test was performed up to a maximum depth of 15 m at the exact center of four RAPs.

Further details on the site investigations performed within the full-scale liquefaction experiment through controlled blast tests are reported in Amoroso et al. (2022).

3 SITE CHARACTERIZATION

3.1 *Natural soil*

The stratigraphic arrangement of the subsoil beneath the test site area was deduced by the combined interpretation of borehole logs, SPTs, CPTUs, Medusa DMTs and SDMTs carried out before the RAP installation, as reported by Amoroso et al. (2020). Apart from a 0.8 m thick topsoil layer (CH, according to Unified Soil Classification System, USCS ASTM D2487-11 2011), the following well-defined stratigraphic units, also reflecting their sedimentological framework, could be identified:

- a layer of clays and silts (CL), from 0.8 to approximately 3.3-3.4 m in depth;
- a predominantly silty sand unit, approximately 9 m thick, attributable to Holocene alluvial deposits of a Po river paleochannel. Samples

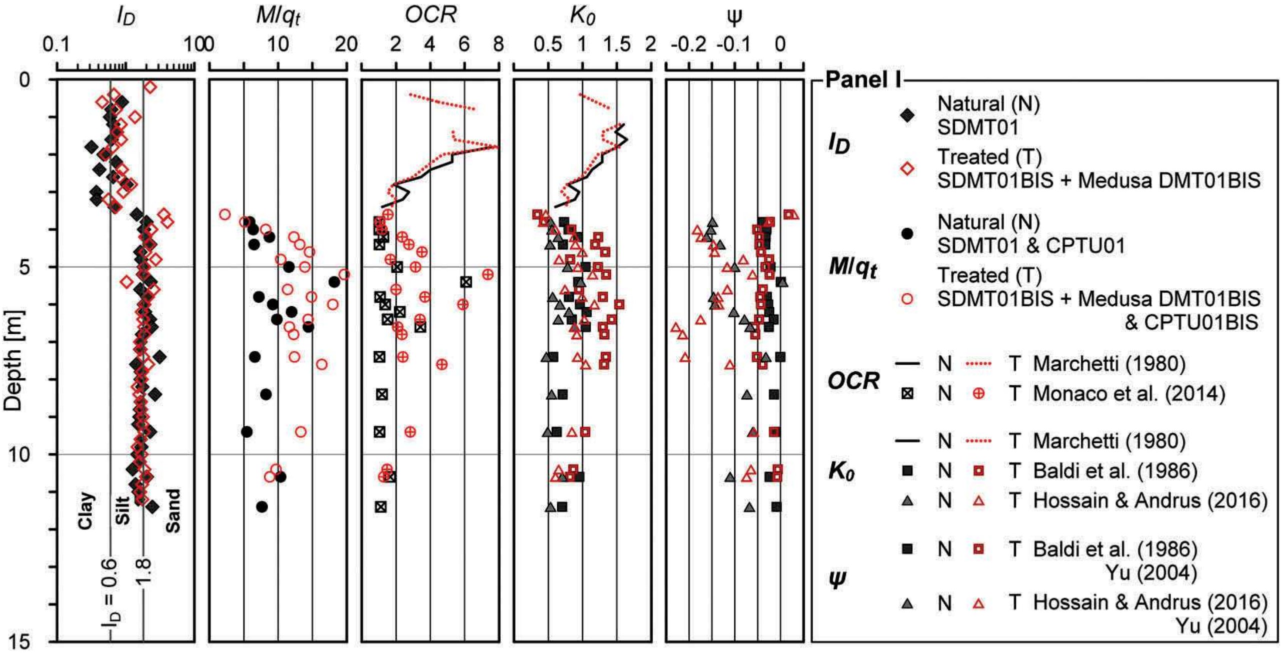

Figure 3. CPTU-DMT combined interpreted results in natural (NS) and treated (TS) soils: I_D, M/q_t, OCR, K_0, ψ (modified after Amoroso et al. 2022).

recovered from this unit can generally be classified as SM, having a *FC* typically in the range of 25-35%. Thin layers of coarser sediments have been occasionally found;

- a thin layer of sandy silt (ML), from 11.8-12.6 to 13.0-13.4 m in depth (interfluvial deposits);
- sands-silty sands (SP-SM) of the late Pleistocene epoch (namely, glacial braided Po River deposits), detected below 13.0-13.4 m in depth.

Figure 2 provides plots of representative piezocone and seismic dilatometer profiles carried out in the pre-RAP phase and located in the treated panel, respectively CPTU01 and SDMT01 (black lines). In particular, the CPTU profiles are shown in terms of the corrected cone resistance (q_t), soil behavior type index (I_c, Robertson 2009), relative density (D_R, Jamilokowski et al. 2001), and friction angle (φ', Kulhawy & Mayne 1990), while the SDMT results are reported in terms of the soil material index (I_D), horizontal stress index (K_D), constrained modulus (M), and shear wave velocity V_S), according to Marchetti (1980) and Marchetti et al. (2001) correlations.

The comparative analysis of the CPTU and SDMT parameters reveals a substantial agreement between the measurements collected in the IP, thus indicating negligible horizontal spatial variability in the stratigraphic conditions of the test site.

3.2 *Improved soil*

Figure 2 also provides a comparison between field soil properties before and after RAP installation in the IP, in terms of both CPTU and SDMT profiles (green lines).

With regard to the piezocone profiles (Figure 2), the increase in the q_t values after column construction appears to be particularly noticeable (q_t = 13.10 ± 1.76 MPa versus 9.54 ± 1.37 MPa before installation) from 6 to 8.5 m in depth, but relatively moderate from 3.5 to 6 m. Negligible changes in the q_t profile can be observed in the silty sands below the base of the piers. Obviously, these changes in q_t affect the computed estimates of the geotechnical parameters reported in Figure 2, i.e. D_R and ϕ'.

The effect of RAP installation is evidently reflected by the increase in K_D (on average 48-53%), and even more in the higher M from SDMT (80-87%), at depths between 4 and 9 m (Figure 2b). The corresponding average increase in q_t is 30-35% (and in D_R is approximately 10% and is limited to a depth between 6 and 8.5 m). These results point to a significant increase in horizontal stress and stiffness resulting from pier installation, in agreement with previous observations (Saftner et al. 2018). In fact, the horizontal stress strongly influences both K_D and M estimated from DMT using the Marchetti (1980) correlation, which incorporates K_D.

The observed results are in line with previous comparisons of pre- vs. post- CPTs and DMTs executed for monitoring ground improvement (e.g. Jendeby 1992), since the RAP installation produced an average increase in M from DMT after treatment approximately 2.5 times the corresponding increase in cone penetration resistance q_c. The decrease in K_D observed in the upper crust may be due in part to the construction of an overlying working platform, but also to RAP installation under low confining stress and to seasonal variations in water content caused by fluctuation of the GWT from 1.5 m (February 2018) to 0.5 m (March 2018). No improvement was detected in the silty sands below the toe of piers, unlike RAP case histories in clean sands studied in New Zealand (e.g. Vautherin et al. 2017).

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

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

The *OCR*s of about 1-2 estimated in the natural soil, excluding the shallow "crust", indicate that the deposit is normally consolidated or slightly overconsolidated, with $K_0 \approx 0.5$-0.7. As a result of the RAP installation, the "equivalent" *OCR* increased to about 3-3.5 and K_0 to about 0.9-1. The values of K_0 estimated according to Hossain & Andrus (2016) are lower than those estimated according to Baldi et al. (1986). The increase of M/q_t, *OCR* and K_0 after treatment was more pronounced at depths between 7 and 9 m.

An approximate estimate of the in situ state parameter ψ in sand from DMT was obtained according to Yu (2004), with K_0 determined by both Baldi et al. (1986) and Hossain and Andrus (2016) methods. Figure 3 shows that the input K_0 has a large influence on the calculated values of ψ, with an apparent contradiction versus the expected trend. In fact, the higher K_0 (i.e. higher *OCR*) estimated according to Baldi et al. (1986) should involve lower negative values of ψ compared to those obtained using K_0 from Hossain & Andrus (2016), while the opposite is observed in Figure 3. On the other hand, the reduction of ψ after treatment found using both K_0 methods is consistent with the corresponding increase of *OCR* and K_0 before and after treatment.

A more complete overview on the ground improvement effectiveness at BTS using in situ tests is reported in Amoroso et al. (2022).

4 CONCLUSIONS

At BTS a comprehensive comparative study based on CPTU and SDMT testing was carried out in a liquefaction-prone silty sand site improved by a group of Rammed Aggregate Piers and subjected to controlled blasting.

CPTU and SDMT tests revealed good agreement in the geotechnical characterization of the site, detecting homogenous soil properties in both the natural and improved panels. Use of both CPTU and DMT provided better estimates of soil properties in sandy layers (e.g. *OCR*, K_0), that are usually not determinable using a single type of in situ tests.

The comparison of the in situ tests performed preblast in natural and treated soils highlighted the effectiveness of the RAP treatment between 4 and 9 m depth in silty sands. The increase in the DMT parameters following treatment were more pronounced relative to those obtained from CPTU data (i.e. K_D increase ≈ 48-53%, M increase ≈ 80-87%, q_t increase ≈ 30-35%), thus suggesting a higher sensitivity of DMT to the increase of horizontal stress. On the contrary, V_S measurements showed a very low sensitivity to the ground improvement Moreover, the combined use of CPTU and DMT tests showed a significant increase of M/q_t and K_0 after treatment, supporting the use of the piers to increase the lateral soil stress and to mitigate liquefaction.

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