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Monitoring ground improvement using in situ tests in Guayaquil, Ecuador

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ABSTRACT: The present work describes the use of the seismic dilatometer test (SDMT) and the piezocone test (CPTu), to assess the effects of ground improvement at a wastewater treatment plant in Guayaquil, Ecuador. The ground improvement consisted of 15 m-long, 0.55 m-diameter and 2 m-spacing stone columns built with vibro-replacement technique. The tests were carried out both in natural and in treated soils to compare the variation of the geotechnical parameters in the analyzed deposits. The results show specific sensitivity of the DMT over the CPTu tests to the ground improvement into the layer composed of sands and sandy silts, while VS values show a limited increase in the treated area.

1 INTRODUCTION

Ground improvement involves different techniques to modify soil response under different conditions. Ground modification performance is based on assessing problematic soils, liquefaction potential, soil instability, insufficient bearing capacity and excessive settlement, seepage. U.S. Army Corps of Engineers (1999).

Mitchell (2008) discussed the applications and limitations of these densification methods, and the author noted that the degree of improvement given by the deep dynamic compaction, vibro-compaction and blasting is greater in clean sands since it decreases as the fines content (FC) increases. Nevertheless, several studies have documented mitigation works using various FC values (including rather high percentages), highlighting an improvement given by the vibro-replacement stone columns, Mackiewicz & Camp (2007) used an improvement index (I_i), given by the ratio between the cone resistance (q_c) after and before the treatment minus one, to provide an improvement of $0.3 < I_i < 2.8$ for FC < 5%, and of $0 < I_i < 1.6$ for 15% < FC < 40%. (Luehring et al. 2001) showed an increase of 95% for the corrected SPT blow count $(N_1)_{60}$, and 180% for the normalized corrected cone resistance q_{c1N}, using vibro-replacement stone columns in combination with vertical drains in deposits with FC < 65%. Mitchell & Wentz (1991) showed a 100% increase for the corrected cone resistance for overburden stress, (q_{c1}), and a 45% increase for the SPT corrected penetration resistance, $(N_1)_{60}$, when comparing pre and post-treatment results in soil layers with FC < 55%. Vibro-replacement stone columns installation may have the double beneficial effect to cause densification of the surrounding soil during installation and facilitate the dissipation of the excess of pore water pressure developed during an earthquake, by providing a shorter path of drainage, Adalier & Elgamal (2004).

Therefore, the effectiveness verification of the improvement using in situ tests becomes relevant since these investigations allow a quick assessment, which compares selected geotechnical parameters obtained before and after the treatment. Numerous authors (Schmertmann 1986, Mackiewicz & Camp 2007, Mitchell 2008, Monaco et al. 2014, Bałachowski & Kurek 2015, Wotherspoon et al. 2015, Massarsch & Fellenius 2019, Massarsch et al. 2020) evaluate the change of the soil characteristics using different in situ tests and their parameters: SPT blow count N_{SPT} in the standard penetration test (SPT),

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horizontal stress index K_D and constrained modulus M in the flat dilatometer test (DMT), corrected cone resistance q_t in the piezocone penetrometer test (CPTu). Other studies (e.g., Wotherspoon et al. 2015, Hwang et al. 2017, Comina et al. 2021) have applied shear wave velocity V_S in the geophysical measurements provided by invasive or non-invasive tests (e.g., seismic piezocone SCPTu, seismic dilatometer SDMT, down-hole DH, cross-hole CH, multichannel analysis of surface waves MASW). Moreover, several research discusses the change in the at-rest lateral earth pressure coefficient K_0, the overconsolidation ratio OCR and the ratio M/q_t when monitoring the densification effectiveness and the lateral stress increase. A combination of CPT and DMT tests is performed to estimate the parameters mentioned above, as suggested in previous studies (e.g., Baldi et al. 1986, Marchetti et al. 2001, Amoroso et al. 2018, 2020, Massarsch et al. 2020)

The present study describes the effects of ground improvement using SDMT and CPTu tests. In this regard, CPTu and SDMT tests and V_S measurements were executed in natural and treated soils, to compare the geotechnical parameters, to assess liquefaction before and after treatment.

2 COMBINATION OF SDMT AND CPTU FOR MONITORING GROUND IMPROVEMENT

Single-parameters derived from SDMT and CPTu tests can detect the modification in soil characteristics due to improvement works. As stated by various authors (e.g. Schmertmann 1986, Bałachowski & Kurek 2015, Amoroso et al. 2018, 2020, Massarsch & Fellenius 2019, Massarsch et al. 2020), these parameters can be identified in the horizontal stress index K_D and the constrained modulus M from DMT, the corrected cone resistance q_t (or the cone resistance q_c) and the relative density D_R from CPT. K_D is directly derived from the corrected DMT membrane lift-off pressure reading and contains information about the stress history of the soil. Concurrently M is a function of the three DMT intermediate parameters (horizontal stress index K_D, dilatometer modulus E_D and material index I_D). q_t (or q_c) is a direct measurement from CPT, while D_R is usually based on correlations as a function of the cone resistance and effective stress, Juang et al. (1996). According to previous ground improvement studies related to densification techniques (e.g. Massarsch & Fellenius 2002, 2019, Massarsch et al. 2019), the horizontal stress also increases after compaction, making K_D (and therefore M) more sensitive than q_t (and consequently D_R) to detect the modifications induced by the treatment.

Moreover, the coupled CPT-DMT parameters, such as K_0, OCR, can help identify the treatment effectiveness in sandy soils. The present research estimated K_0 using the more recent relationship proposed by Hossain & Andrus (2016):

$$K_0 = 0.72 + 0.456 \log OCR + 0.035 K_D - 0.194 \log^{q_c/\sigma'_{v0}} \quad (1)$$

where σ'_{v0} is the vertical effective stress.

To estimate OCR in sands the approximation by Monaco et al. (2014) was used:

$$OCR = 0.0344(M/q_t)^2 - 0.4174(M/q_t) + 2.2914 \quad (2)$$

3 IN SITU TESTS

The results presented in this study belong to a trial site located within a wastewater treatment plant (WTP) in Guayaquil, Ecuador. Figure 1, shows the location where CPTu and SDMT tests were performed before the stone columns (SC) installation, natural soil (NS), and after SC installation, treated soil (TS), up to 16-20 m depth. NS soil testing is identified as CPTu1_NS and SDMT1_NS, while surveys after SC installation are detected as CPTu2_TS and SDMT2_TS. The SC were in a staggered arrangement with 2 m spacing. Additional information regarding the NS condition was obtained from the borehole, SPTs (SPTP3_NS) and CPTu tests (CPTu14_NS) performed during the WTP construction.

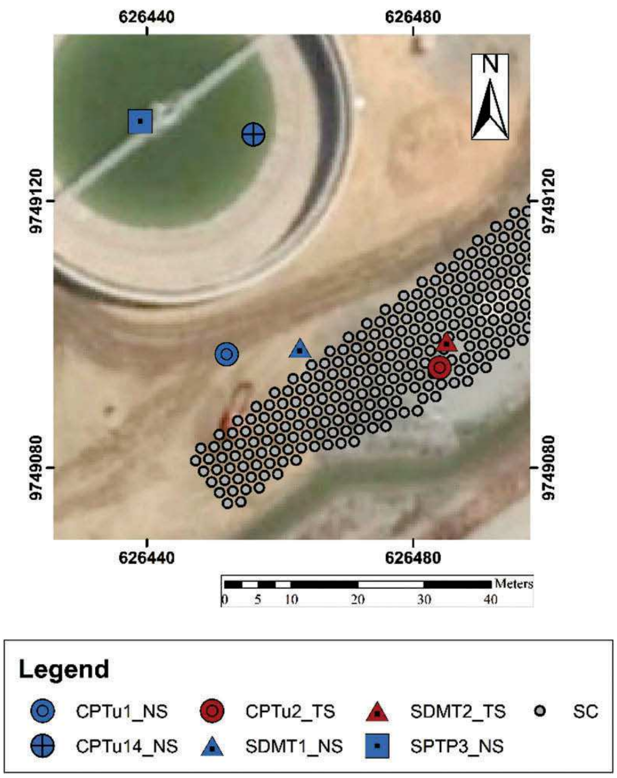

Figure 1. Location of the water treatment plant at "Las Esclusas", in-situ tests and stone columns.

For the execution of CPTus and SDMTs, the shallow compacted fill layer (≈ 0.6-0.8 m thick) was removed, to prevent damage to the geotechnical equipment. Table 1 summarizes the basic information of the in-situ tests used for verifying the ground improvement effectiveness. The ground-water table (GWT) fluctuations, at the trial site, were strongly influenced by the Guayas river tide, following the Navy Oceanographic and Antarctic Institute measurements, INOCAR (2021).

Table 1. Summary information of the in situ tests at the trial site.

Field test	Depth (m)	GWT depth* (m)
SPTP3_NS	19.0	2.0
CPTu14_NS	20.8	2.7
SDMT1_NS	20.4	3.4
SDMT2_TS	20.6	3.4
CPTu1_NS	17.6	3.8
CPTu2_TS	19.0	3.8

* Note: Measured from the ground surface post filling.

3.1 *Geotechnical description*

Figure 2 summarize the soil profile in both soil conditions using CPTu and SDMT tests at the Guayaquil trial site. Beneath the shallow fill, the soil is variable, but four clearly defined layers can be observed. The first layer is approximately 2 m thick and varies from silt to clay, as described by: the soil behavior index (I_c) profile that intercalates between 2.6 and 3.4, the material index (I_D) values which are between 0.2 and 1.1. Underlying this layer, loose to medium dense sand mixtures (2MPa < q_t < 8 MPa; 2 < K_D < 9) are present with a maximum depth of ≈ 10 m. These non-plastic sands and silty sands are mainly characterized by I_c < 2.6 and I_D > 1.2. A lens of variable thickness, comprised of silt mixtures (2.6 < I_c < 3.0, 0.6 < I_D < 1.1) is present within the sandy layer between ≈ 7 and 10 m depth. Finally, below 10-11 m depth, normally to moderately overconsolidated clays are encountered, according to OCR approximation by Marchetti et al. (2001). This finding associates the following DMT and CPTu parameters: 2.2 < K_D < 3.3, with 3.1 < I_c < 3.9, 0.2 < q_t < 2.0 and 0.2 < I_D < 0.6.

4 GROUND IMPROVEMENT

Figures 2 and 3 show the variation of the CPTu, DMT and combined (CPTu and SDMT) parameters in natural soil (NS) and treated soil (TS), estimated according to Robertson & Cabal (2015). The relative density (D_R) estimation is based on the correlations proposed by Kulhawy & Mayne (1990). I_c profiles present a very slight variability of the soil before and after treatment, which makes quite comparable the data within the depth of the SC improvement where the silty sand to sandy silt layer (I_c < 2.6) is located. However, for some depth intervals between 4 and 10 m, q_t (≈ 4.2-6 m, 8-9 m, 9.6-10.4 m depth), and D_R (≈ 4.5-6 m, 8-9 m depth) values in the NS are somewhat higher than in TS. This rise is observed when the I_c increases in the TS, and it behaves more like fine-grained soil. Figure 3 also compares the CPTu-D_R values with the ones evaluated from SPT, Skempton (1986). The D_R SPT-based values in the NS are in good agreement with the related CPTu ones from ≈ 6 to 8 m depth, while between 8 and 11 m depth, the SPT-based method overpredicts the relative density. The SPT-based overestimations of D_R can be attributed to the lens of silt mixtures detected only by CPTu and SDMT.

The DMT parameters, were calculated using the Marchetti et al. (2001) formulae. The equilibrium pore pressure, u_0, obtained from the third DMT pressure reading (p_2) into the sandy layers, well determined the GWT location. The effectiveness of the treatment is noticeable from ≈ 2 to 6 m depth, by looking at K_D and M and profiles (Figures 2, 3); in this depth range, I_D > 0.6 predominate in both soil conditions. The increase in K_D profile is clearly defined in this depth interval and a 52% increment is observed after the treatment. The shear wave velocity V_S (Figure 3) also provides some increase after improvement, but limited between 4 and 6 m. A specific lateral soil heterogeneity is distinguishable in the NS and TS, I_D profiles between ≈ 6 to 8 m depth: the TS exhibits a fine-grained soil behavior, considering the lower I_D values (0.3 < I_D < 1.2 corresponding to silty clay to silt), while the NS of the same layer results mostly silty-sandy (1.2 < I_D < 2.3). This response helps to understand why for the same depth interval, the horizontal stress index K_D and the constrained modulus M are much lower despite the SC installation. The analysis of CPTu and DMT combined parameters is displayed in Figure 3 to monitor ground improvement effectiveness. The OCR and K_0 estimations were performed both in fine-grained and incoherent soils. Specifically, for I_D < 1.2, OCR and K_0 were estimated by DMT using Marchetti et al. (2001) formulae, while for sandy layers (I_c < 2.6 and I_D > 1.2) the combined CPT-DMT approach was used according to Equation 2 from Monaco et al. (2014) for OCR and to Equation 1 from Hossain & Andrus (2016) for K_0. The OCR and K_0 profiles detect the effectiveness of the SC treatment between ≈ 2.6 and 6.6 m depth. Below 6.6 m, the NS and TS trend remains unchanged despite the SC installation.

Table 2 summarizes the average test results of the single and combined parameters in the layer where the increase was better noticed for I_c < 2.6 and I_D > 1.2, approximately between 3.2 and 6.6 m depth. The improvement was calculated by relating the difference between TS and NS to NS results, expressed as a percentage. The CPTu conventional indicators of improvement show an increment of 6% for q_t and 7% for D_R, while for

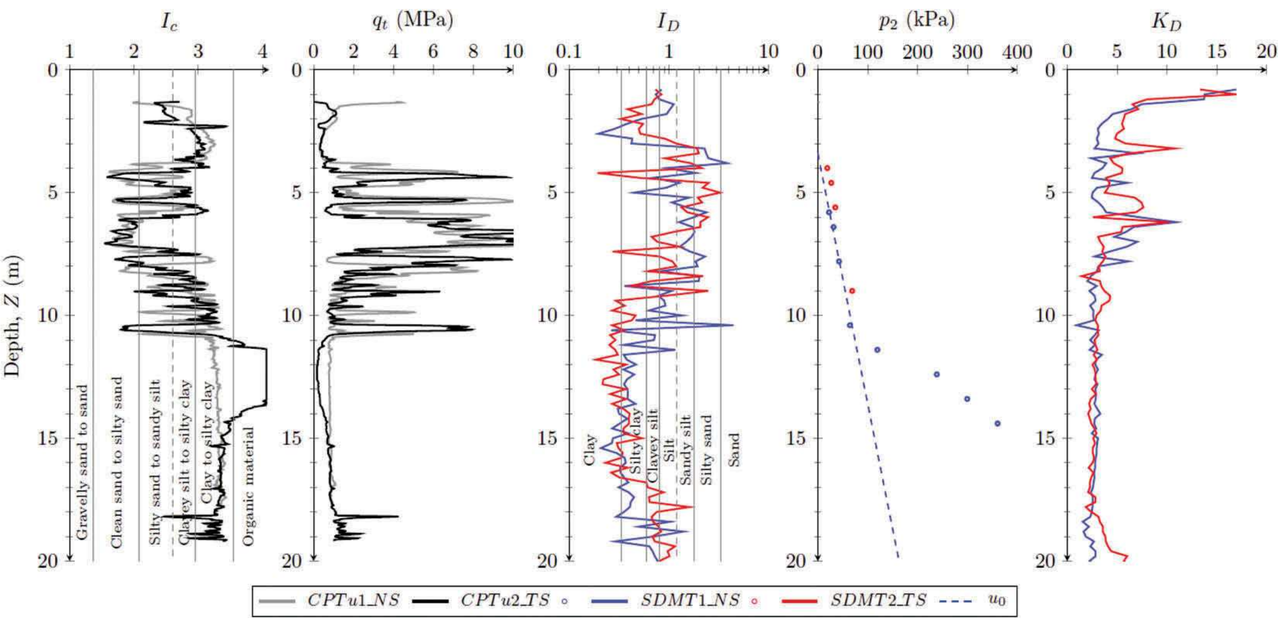

Figure 2. CPTu and SDMT basic parameters in both soil conditions (natural and treated soil) at the Guayaquil trial site.

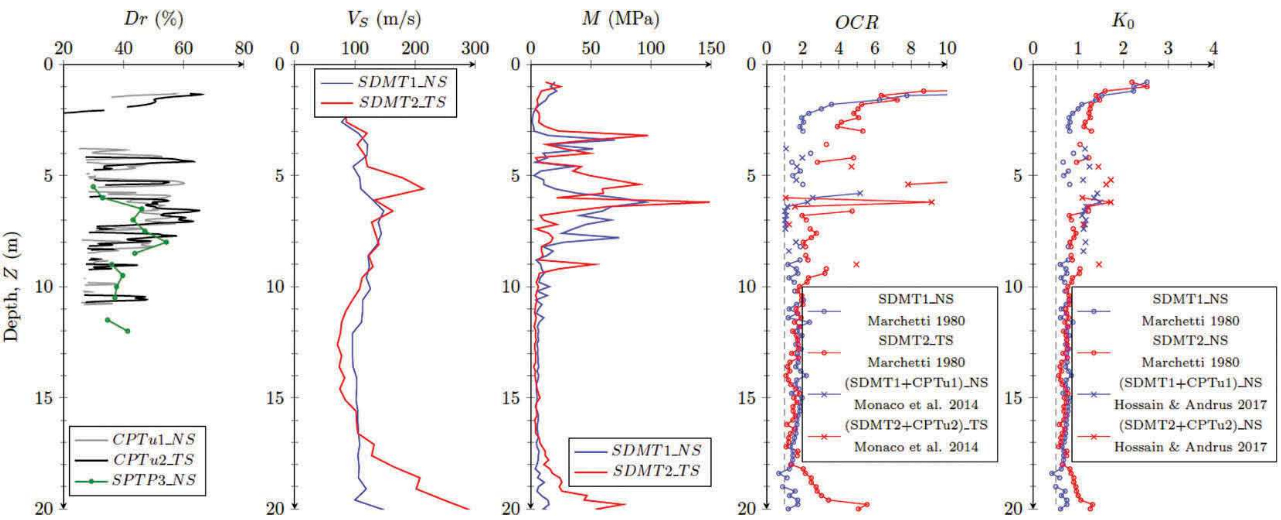

Figure 3. CPTu and SDMT estimated parameters in terms of D_R, V_S, M, OCR and K_0 at the Guayaquil trial site.

Table 2. Summary of average parameters (pre and post treatment) between 3.2 and 6.6 m depth: q_t, D_R, K_D, M, V_S, OCR, K_0.

	q_t (MPa)	D_R (%)	K_D	M (Mpa)	V_S (m/s)	OCR	K_0
NS	5.0	42.5	5.0	43.6	121.2	3.1	1.3
TS	5.3	45.7	6.2	61.9	152.8	6.1	1.5
Inc. (%)	6.0	7.6	22.4	42.0	26.1	98.4	15.8

the SDMT parameters, K_D increased 22%, M 42% and V_S 26%. For the combined CPTu and SDMT parameters, K_0 increased just 16%, while OCR increased 98%

5 CONCLUSIONS

Despite the length of the SCs, the effectiveness of the treatment resulted noticeable only between 3.2 to 6.6 m depth, where the sand mixtures where detected by in situ tests. Below this layer a lens of silt mixtures, with higher FC (up to 46%) approximately between 7 to 10 m depth, and of a cohesive soil layer, from 10-11 m depth, were identified.

The evaluation of the soil improvement between 3.2 to 6.6 m depth was mainly detected by using the combined CPTu and SDMT parameters, with a 98 % increment in OCR and 15% increment in K_0. The relatively low increment in K_0 can be attributed to the high initial K_0 condition in NS ($K_0 \approx 1.27$), as already noticed by Schmertmann (1985). In the CPTu based effectiveness assessment, q_t and D_R

have a similar increase (6% and 7.5% respectively), although the NS and TS were related to quite homogeneous subsoil, as detectable looking at I_c. Furthermore, SDMT single parameters, K_D, M, V_S, provided a more evident SC improvement, even still limited, 22%, 42% and 26% respectively. Therefore, at the Guayaquil trial site the densification provided by the SCs resulted merely perceived by the CPTu tests probably also due to the lateral soil variability.

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