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DYNAMIC COMPACTION IN LOOSE GRANULAR DEPOSITS; A COMPARISON BETWEEN RESULTS FROM CONVENTIONAL AND RECENT IMPROVEMENT METHODS

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ABSTRACT

This study presents the results of dynamic compaction in loose, saturated granular deposits. The dynamic compaction operations were conducted by (a) the conventional method of Falling Weight Treatment (a.k.a. Deep Dynamic Compaction - DDC) and (b) the more recent Rapid Impact Compaction (RIC) method. The results of either soil improvement method are being presented, normalized and compared side by side in regards to the resulting soil improvement characteristics as well as the degree of efficiency with varying depth and location. Last, but not least, the improved mean soil compressibility parameters are validated through an embankment surcharge test.

INTRODUCTION

Dymanic compaction operations were conducted in a coastal area of the Arabic Peninsula as part of a major soil improvement plan; this would provide foundation support for single- and multiple-story buildings for residential, commercial, retail, administrative and other uses. These proposed buildings are coupled by a complete infrastructure scheme, which includes roads, parking lots, parks, recreation areas, utilities, waste-water treatment plant, etc. The surface soil conditions are characterized as poor (predominantly aeolian sands and dune sands), while site seismicity is graded as low to medium ($a_{,max}$ = 0.22 g). The governing soil improvement requirement that dictated the soil treatment program goals was to keep the total and differential settlement under acceptable limits.

GEOLOGIC / GEOTECHNICAL CONDITIONS

Geology and Seismotectonics

The generalized project area is characterized by recent alluvial deposits (wadi deposits), which originate from the foothills. They then expand downstream into thicker alluvial fan deposits to form the costal plain where the project lies. Site soil stratigraphy near the surface includes aeolian sand and beach/dune sands, underlain by alternating layers of sabkha saline clay and silt. Dense sand and hard clays are encountered at greater depths.

From a geotectonic standpoint, the separation and splitting of the Arabian Plate from the African Plate along the Red Sea and the Gulf of Aden axes followed by a drift of the Arabian Plate to the north and northeast at a rate of 3 to 4 cm per year, lead ultimately to a collision with the Eurasian Plate which resulted in the formation of the Zagros fold-belt and thrust belt. Zagros fold-belt is the major source of earthquakes in the eastern border of the Arabic Plate. However, low- to moderate-magnitude earthquakes have been generated by local sources too, originated within the Arabic Peninsula (Abdalla and Al-Homoud, 2004). These two distinct earthquake groups were considered towards the selection of the design ground motion.

Local Soil Conditions

Based on the soil exploration, the soil stratigraphy is characterized by a layer of loose to medium dense, poorly-graded sand with silt (SPT blowcounts on the order of 5 to 15, predominantly fine- to medium-grained, fines content on the order of 5 to 15 %). The thickness of this stratum ranges between four and eight meters, the thickest appearing closest to the coast side. In certain locations, this layer was overlain by a thin silty/clayey, up to a meter-thick cap.

The top granular layer is underlain by a low to medium plasticity, medium stiff to stiff, two to three meter-thick layer of silt and clay. At greater depths the soil exploration encountered very dense sand and hard clay layers.

Due to the proximity to the Arabic sea and the relatively low grade elevations (on the order of +1 to +2 meters above mean sea level), the groundwater depth was encountered at depths ranging between 0.5 and 1.5 m).

SOIL IMPROVEMENT TECHNIQUES UTILIZED IN THE PROJECT

Provided the granular nature of the surface soil layer and the project extent, it was decided to proceed with dynamic compaction as a means of ground improvement. Soil improvement was deemed necessary in order to (a) provide bearing capacity under static and pseudo-static loading conditions through building shallow foundation, (b) keep the anticipated total and differential settlement under tolerable values, and (c) mitigate the liquefaction potential generated by a low-to-medium seismic event. Out of these three conditions, the governing one was (b), namely the requirement to maintain the total and differential settlement under acceptable limits; these ought to be compatible with the demands of the superstructures, which are expected to gain support on a shallow foundation system. In order to conduct a cost-efficient soil improvement program on a timely manner, two dynamic compaction methods became available at the site, as follows: in areas where the improvement target zone thickness was about eight meters, dynamic compaction proceeded via the conventional Falling Weight Treatment, also known as Deep Dynamic Compaction (DDC); in areas where the target zone thickness varied between four and six meters, the more recent Rapid Impact Compaction (RIC) method was utilized. These two methods exhibit significant differences pertinent to their application, as well as their effectiveness and cost-efficiency.

Falling Weight Treatment Method (a.k.a. "Deep Dynamic Compaction", DDC)

This method has been commonly used within the last decades predominantly for granular soil improvement. The concept is pretty simple; a relatively large weight repetitively free-falls from a pre-determined height. The impact-induced energy triggers a soil-grain relative location re-arrangement, therefore a void volume reduction, which translates to a higher post-improvement soil density (Photo 1). Usually the transmitted energy is on the order of 300 – 500 ton-m per blow. The impact points are pre-determined; additional points may be added during the process in between by reducing their spacing, depending on the progress of the operation. The following formula has been widely used, first by Menard (1975), then by others (Tan et al., 2007, Chu et al., 2009) in order to estimate the soil improvement influence depth, D:

$$D = n \times \sqrt{W \times h} \quad (1)$$

Where W is the falling weight in metric tons, h is the drop height in meters and n is an empirical factor that varies between 0.3-0.8; based on other researchers it may as well vary between 0.5-1.0, or approach a value of 0.5 for cohesionless soils (Tan et al., 2007).

Photo 1. Typical configuration for Falling Weight Treatment, also known as Deep Dynamic Compaction - DDC.

Rapid Impact Compaction Method (RIC)

The main principle of this method is the application of compactive energy in the form of repetitive blows by a cylindrical-shaped weight to a 1.5 m-diameter steel articulated foot which is in direct contact with the soil. The drop height is 1.20 m and drop frequency is about 30 blows per minute. This equipment may be assembled onto a conventional rig on tracks, via a boom (Photo 2). As a result, the granular material

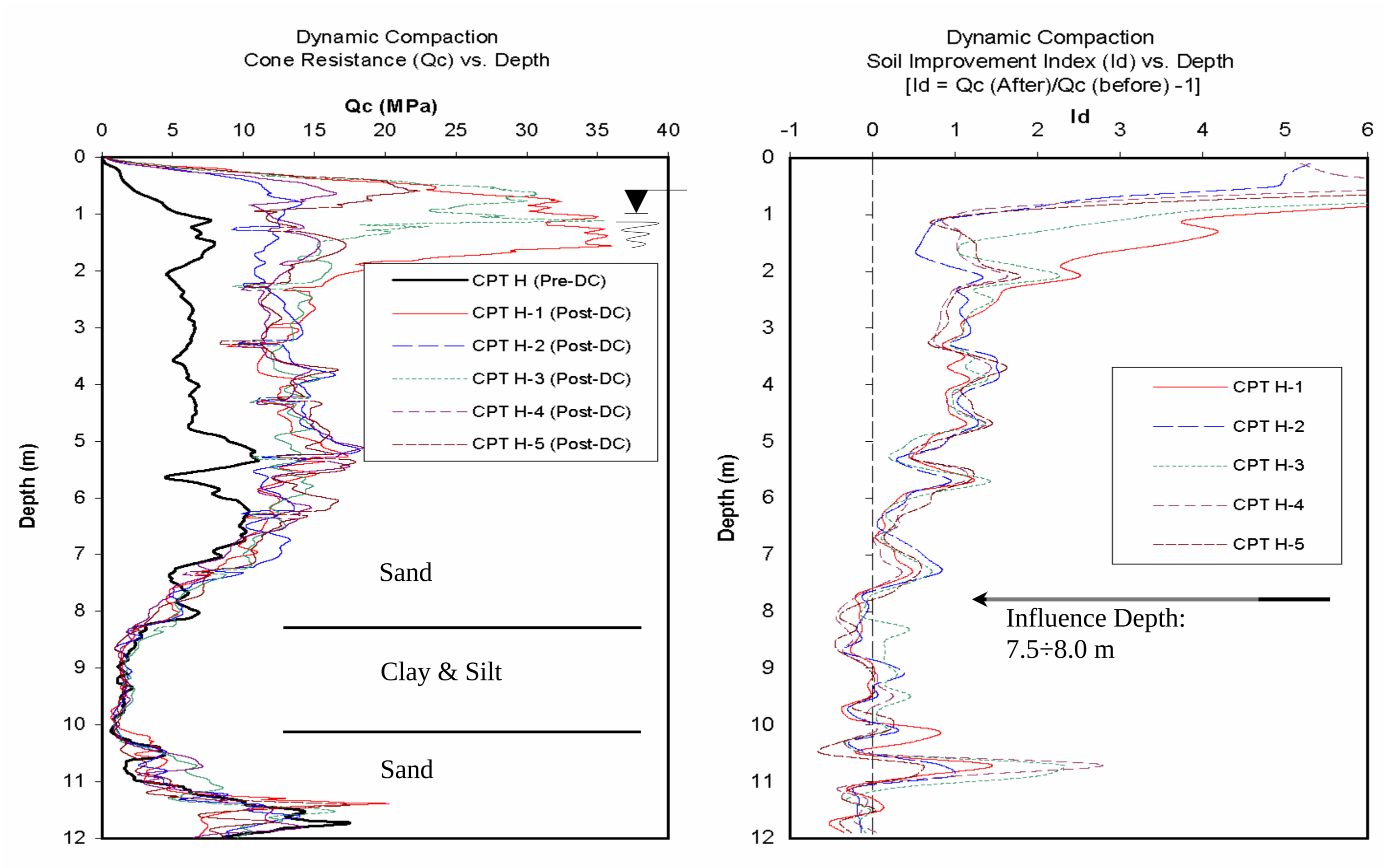

Fig. 1. (a) Comparison of cone resistance (CPT) before and after dynamic compaction via DDC; (b) corresponding soil improvement index in neighboring locations.

is displaced into the underlying ground forming imaginary stone columns. The compaction points are pre-determined and form a pattern. The entire operation takes place in a number of subsequent stages, which is a function of the soil improvement goals, the nature and initial condition of the soil,

Photo 2. Soil Improvement Operations via Rapid Impact Compaction (RIC).

the presence of groundwater, etc. The influence depth in this project reached almost seven meters, depending on the induced energy.

DISCUSSION ON SOIL IMPROVEMENT RESULTS

Falling Weight Treatment Method (DDC)

Soil improvement operations were conducted through falling weight treatment in an area of the project where the requirements called for an eight meter-thick target zone. The falling weight utilized was 20 metric tons and drop height was 23 meters. The total compacting energy was on the order of 350-400 ton-m per square meter.

The soil improvement quality control was carried out via (a) Cone Penetration Testing (CPT) before and after the implementation of the improvement program, (b) Menard-type Pressuremeter Testing (PMT) before and after soil improvement, and (c) back-analysis of recorded settlement data induced by a full-scale embankment loading test, which was used to confirm the soil improvement goals in terms of the post-improvement modulus of elasticity values (Es).

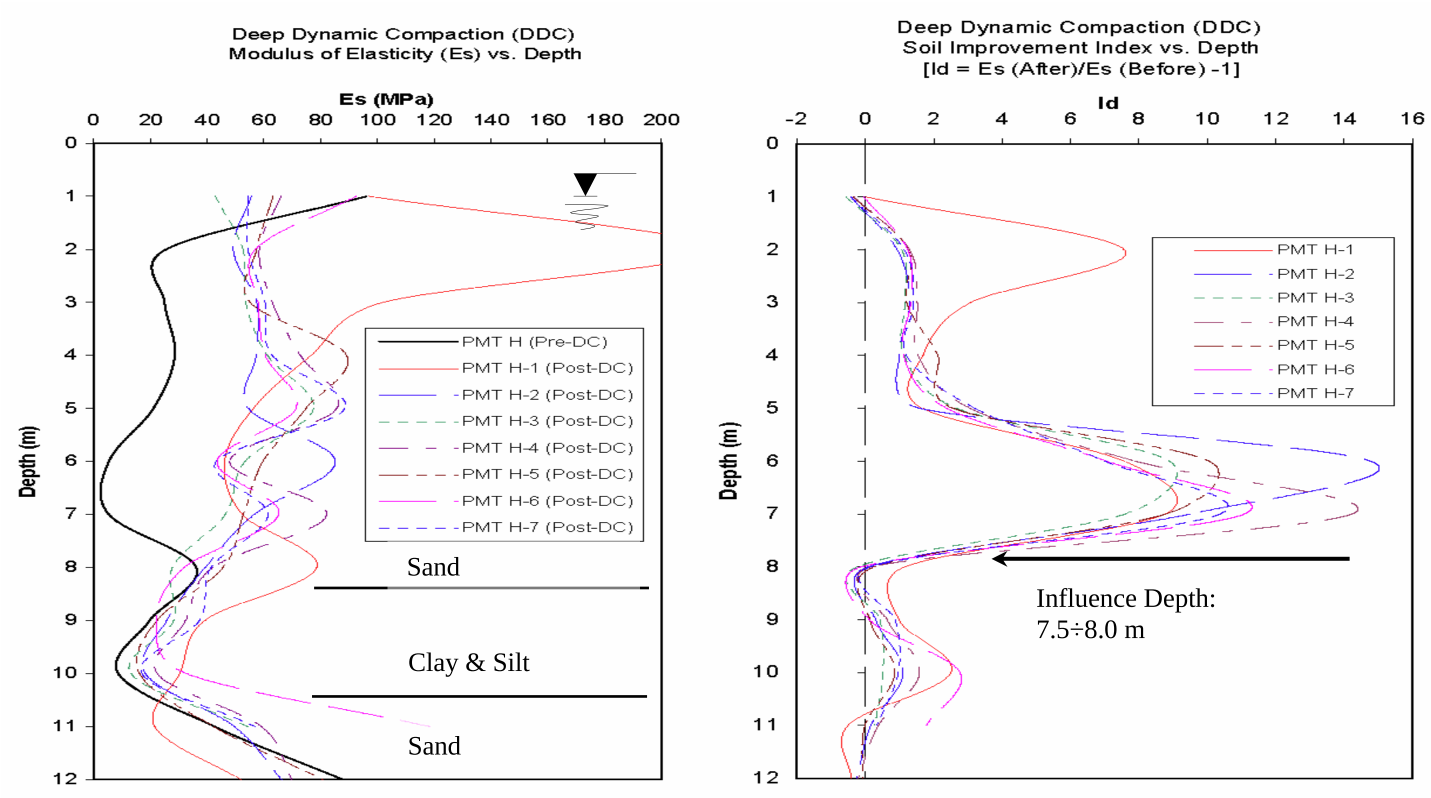

Fig. 2. (a) Comparison of Pressuremeter Testing results (PMT) before and after dynamic compaction via DDC; (b) resulting soil improvement index in neighboring locations

Dove et al. (2000) introduced the concept of **Soil Improvement Index** (Id) as a soil improvement criterion based on cone tip resistance (Qc) values of the Cone Penetration Test (CPT) before and after the soil improvement operations:

$$I_d = \frac{Qc, after}{Qc, before} - 1 \tag{2}$$

Post-improvement increase of the cone resistance value (Qc, after) at a certain depth leads to positive Id values (Id>0), which indicates soil improvement; therefore, a plot of the Soil Improvement Index versus depth provides information regarding the method's depth of influence. The above formula may be utilized to provide an indirect soil improvement measurement related to the Modulus of Elasticity, Es:

$$I_d = \frac{Es, after}{Es, before} - 1 \tag{3}$$

Figure 1(a) illustrates typical CPT results versus depth in neighboring locations, before and after the soil improvement operations through falling weight treatment (DDC). Figure 1(b) exhibits the corresponding Soil Improvement Index values (Id) versus depth for the exact same locations. Based on the graph the influence depth at this particular location was estimated to be around 7.5 to 8 meters; this translates to the entire sand layer undergone improvement, which was the original target zone. The influence depth along the entire area where DDC was applied varied between 7 and 8.5 meters. Consequently, the resulting "n" empirical factor from equation (1) is between 0.33 and 0.40, which seems to be rather on the low side of the acceptable margin of values. Based on Fig. 1(b) the mean Soil Improvement Index (Id) within the influence depth is 1.11, while it ranges between 0.57 and 1.11 along the entire area that underwent DDC treatment. The post-improvement Qc values within the influence depth average 13.5 MPa. It should be noted that values of Qc of the CPT within the upper 0.3 to 0.5 m are considered non-valid due to soil disturbance, therefore corresponding values of Id should be ignored.

Similarly, Fig. 2(a) provides a cross-comparison between modulus of elasticity (Es) values versus depth, before and after DDC treatment. These values were collected through Menard-type Pressuremeter Tests (PMT) conducted in neighboring locations. Figure 2(b) presents the corresponding Id values versus depth for the same locations, as defined by equation (3). According to these data, the influence depth is about eight meters. Factor n, as defined by equation (1) varied

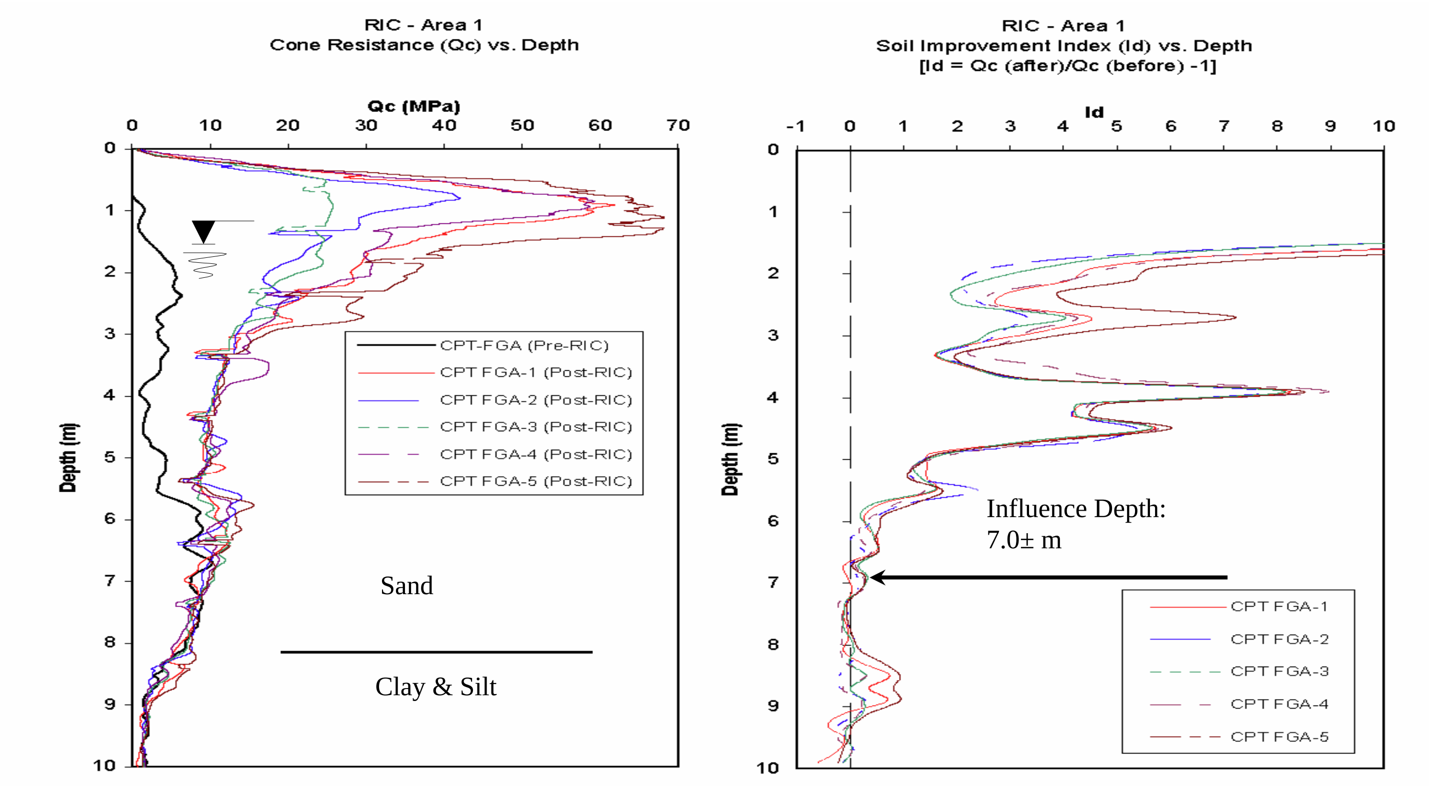

Fig. 3. (a) Comparison of cone resistance results (CPT) before and after dynamic compaction via RIC; (b) resulting soil improvement index in neighboring locations (Area 1)

between 0.37-0.40, for the entire DDC application area. The mean Id value expressed in terms of Es within the influence zone is 0.96, based on Fig. 2(b); values of Id varied between 0.91 and 1.06 for the entire DDC application area. Last, but not least, the average values of Es within the influence zone came out to be on the order of 56 to 60 MPa.

Based on the previous discussion, the overall DDC quality control through CPT and PMT data presented comparable results pertinent to (a) the soil improvement influence depth, which means factor "n" too, as defined in equation (1), and (b) soil improvement index Id. In addition, average values of cone resistance (Qc) and modulus of elasticity (Es) within the soil improvement influence zone may now be correlated through locally-gained experience as follows:

$$E_s = (4 \sim 4.5) \times Qc \tag{4}$$

This correlation seems to be rather on the upper boundary of the one introduced by Lunne and Christophersen (1983):

$$E_s = 2 \times Qc + 20(MPa),\ for 10MPa \leq Qc \leq 50MPa \tag{5}$$

Last, but not least, a full-scale embankment loading test was implemented in order to validate the modulus of elasticity design values and yield a correlation with recorded settlement data. The embankment was seven meter-high, 10 by 10 m in plan-view at crest-height, inclined at 1:2 (Vertical:Horizontal) slope, and constructed on DDC-improved soil.

Table 1. Cross-comparison of settlement calculation results triggered by the embankment loading test with and without dynamic compaction through DDC

Layer	**Thickness (m)**	**Soil Elasticity Modulus, Es (MPa)**			**Settlement Estimate (cm)**		
		(a) Pre-DDC, in-situ value	(b) Post-DDC, design values	(c) Post-DDC, back-calculated values from PMT	(a) Using in-situ value/ Pre-DDC	(b) Using post-DDC design values	(c) Using Post-DDC, back-calculated values from PMT
1 SM	5	5	50	60	9.1	0.91	0.75
2 SM	2	25	40	50	0.7	0.44	0.35
3 SM	1	10	30	40	0.84	0.40	0.20
4 through 7: SM & CL	32 m (total)	varies	varies	varies	3.1	3.1	3.1
		Sum:			**13.7**	**4.9**	**4.4**
Total observed settlement: 4.3 cm							

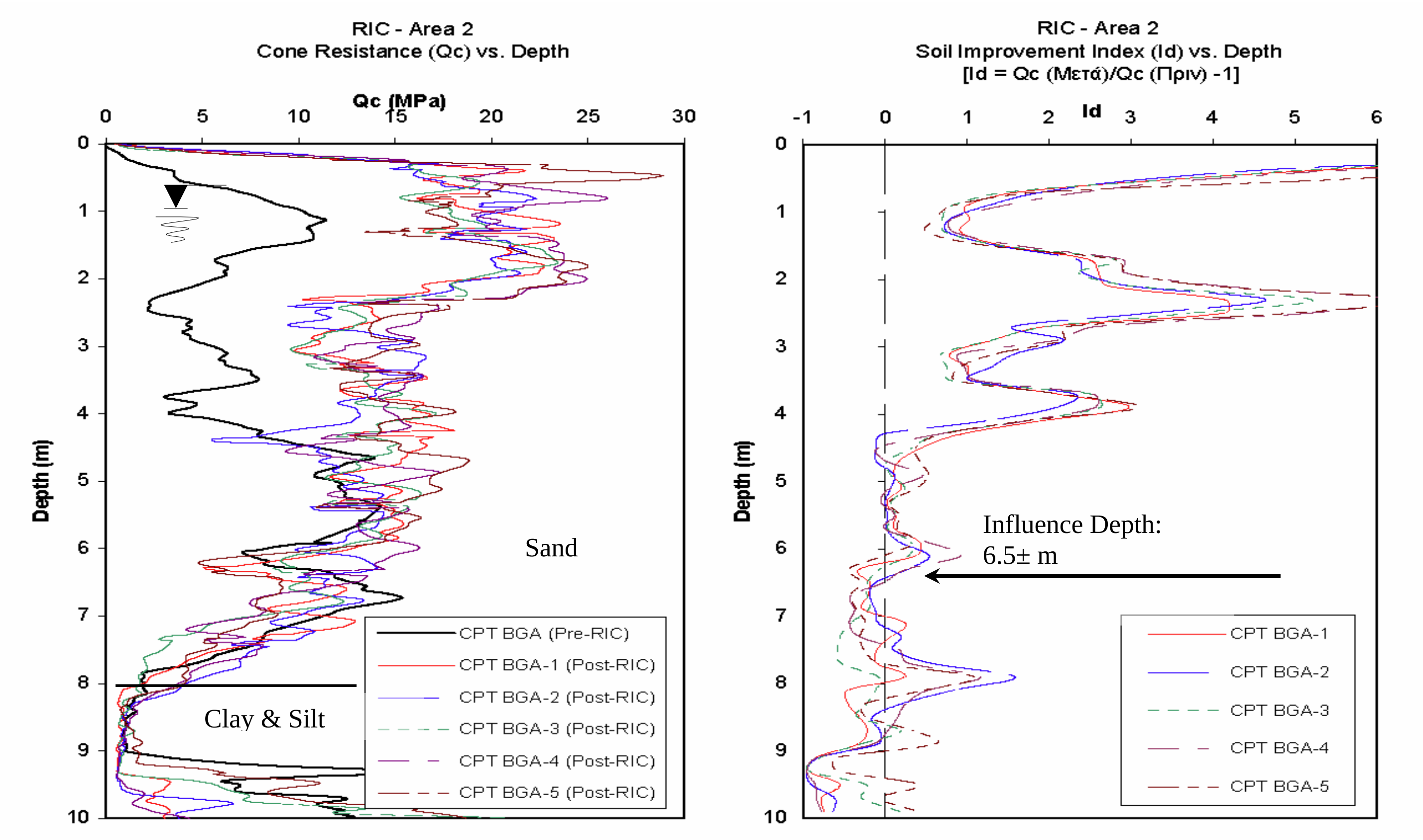

Fig. 4. (a) Comparison of cone resistance results (CPT) before and after dynamic compaction via RIC; (b) resulting soil improvement index in neighboring locations (Area 2)

Table 1 compares estimated settlement values triggered by the embankment load, by using appropriate compressibility parameters (Es) that represent the following conditions: (a) No DDC soil improvement takes place, therefore in-situ Es values are adopted, (b) soil improvement via DDC occurs, so pre-selected target Es values are utilized as design values that are expected to keep anticipated building settlement under tolerable limits and (c) soil improvement via DDC occurs and back-calculated Es values through PMT are utilized. Estimated settlement through condition (a) is obviously excessive and unacceptable. It is also inferred through Table 1 that the DDC post-improvement deformation parameters (Es) adopted during the design stage were on the conservative side (condition (b)); this explains why the settlement was overestimated by about ten percent compared with case (c), which uses post-improvement back-calculated, therefore more realistic Es values. It should be also noted that the maximum observed settlement value was 4.3 cm. This value matches the estimated settlement by condition (c).

<u>Rapid Impact Compaction Method (RIC)</u>

Three distinct cases undergone soil improvement via the RIC procedure are herein presented; these exhibited significant differences in regards to the stratigraphy and the pre-improvement in-situ state. The soil improvement expressed through CPT tests, as well as the improvement index Id for these three areas are depicted in Figs. 3, 4 and 5. Figures 3 and 4, representing Areas 1 and 2 respectively, show that in cases with similar stratigraphy but different in-situ density, the amount of energy required to accomplish the soil improvement goals is disproportional; the energy required to achieve the soil improvement target of Qc = 12 MPa came out to be between 400 and 570 $ton-m/m^2$ in Area 1 (lower pre-improvement cone resistance, Qc), whereas in Area 2 (greater pre-improvement cone resistance, Qc) the target value was reached by using only 70 to 250 $ton-m/m^2$. In the case of higher pre-improvement stage (Area 2, Fig, 4) the soil improvement Id ranged between 0.65 and 1.2, versus Area 1 where it varied between 2 and 4.7. In addition, post-improvement cone resistance values Qc in Area 2 were between 15 and 18 MPa, while corresponding values in Area 1 varied between 16 and 20 MPa.

In regards to Area 3, illustrated in Fig. 5, the soil improvement influence depth was limited to four meters due to the presence of an underlying clayey / silty layer between the depths of four and six meters below grade. The soil improvement index Id in this case ranged between 0.55 and 1.1. The required

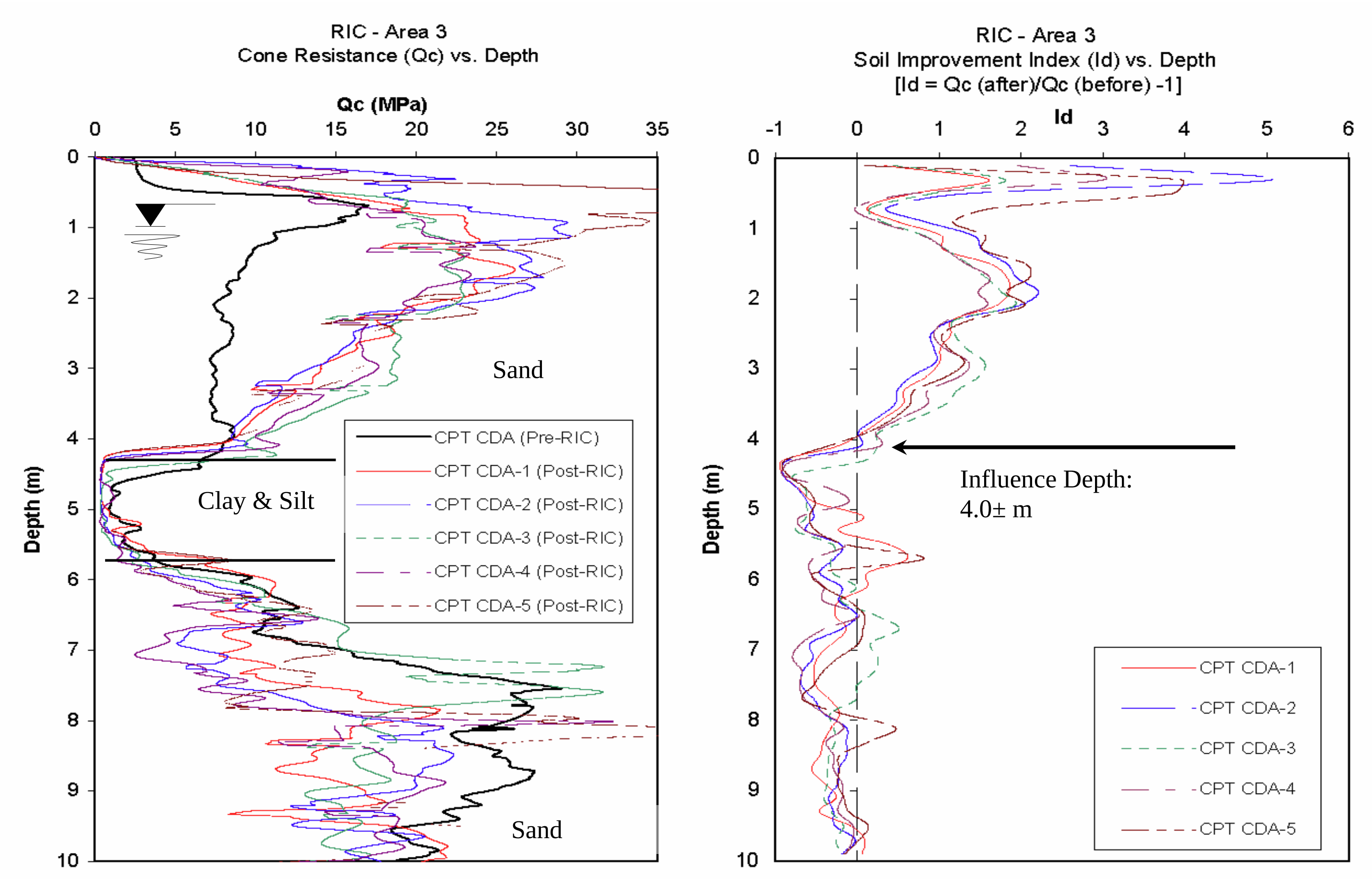

Fig. 5. (a) Comparison of cone resistance results (CPT) before and after dynamic compaction via RIC; (b) resulting soil improvement index in neighboring locations (Area 3)

compacting energy varied from 150 to 300 $ton - m/m^2$.

Last, but not least, the highest mean post-improvement Qc values occurred in Area 3, ranging between 17 and 26 MPa; this may be attributed to potential reflection of the compactive energy at the interface with the fine-grained layer at the depth of four meters.

Formula (1) was utilized in order to back-calculate the values for the empirical factor "n", based on the data collected during the soil improvement; the energy term is recorded during the soil improvement procedure ("W x h" term), whereas the influence depth (D) was estimated by the relative graphs as described above. Therefore, "n" factor values ranged between 0.3 and 0.4 for the poorer pre-improvement soil conditions (Area 1), whereas corresponding "n" values for the case of the better pre-improvement stage (Area 2) ranged between 0.4 and 0.7. Regarding Area 3, it was deemed that this formula has no applicability due to the presence of the clay-silt layer within the theoretical reach of the RIC method, i.e. at depths between four and six meters.

CONCLUSIONS

The most important conclusions of this study, which are pertinent to the particular soil formations encountered in the project location are as follows:

1. Both soil improvement approaches (DDC and RIC) yielded satisfactory results in terms of soil improvement on loose, granular deposits. All three requirement of the soil improvement strategy have been achieved, namely bearing capacity, acceptable settlement within tolerable limits and mitigation of liquefaction potential. The results are in general accordance with data that have been published in the literature.
2. It appears that Falling Weight Treatment (DDC) may be more effective in cases where the soil improvement program calls for either a relatively thick target zone (on the order of six to eight meters), or in cases where the pre-improvement soil conditions are relatively poor.
3. It seems that the recently-developed Rapid Impact

Compaction (RIC) method may be preferable in areas where the soil improvement goals in terms of influence depth are on the order of up to five-six meters.

4. Soil improvement cost, measured per unit area proved to be lower via the RIC method; it came out to be on the order of 60% of the corresponding DDC cost. In certain cases, depending on the equipment available onsite and the soil improvement target zone, RIC procedure may be faster as well.
5. In the case of Falling Weight Treatment (DDC), evaluation of soil improvement was conducted through both Cone Penetration Testing (CPT) and Menard-type Pressuremeter Testing (PMT). Both approaches provided reasonable and comparable results, therefore they both remain valid.
6. Resulting values of the "n" factor ranged between 0.37-0.4 for the DDC method, while for the RIC case it varied between 0.3-0.4 for Area 1 and 0.4-0.7 for Area 2.
7. In the event where a cohesive layer is encountered within the theoretical influence zone of the dynamic compaction method, it seems that the compactive energy may be reflected at the interface, therefore the actual influence zone is limited by the interface of the two strata.
8. In RIC-treated Area 1, characterized by poor pre-improvement soil conditions, soil improvement within the upper part of the target zone (between the depths of zero and two meters below grade) proved to be much greater in proportion to the remainder of the target zone (located between two and six meters below grade); this phenomenon may be attributed to the soil particle re-arrangement, triggered by the particular mechanism with which the compactive energy is imposed against the ground surface.

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