Evaluation the Effectiveness of Rapid Impact Compaction (RIC) as a Ground Improvement Technique

Bashar Tarawneh, Ph.D, P.E
Assistant Professor
Civil Engineering Department
The University of Jordan
Amman, Jordan

Mounir Matraji
Operation Manager
Menard Vibro Middle East
Dubai, UAE

Abstract

In recent years, Rapid Impact Compaction (RIC) has gained popularity as a ground improvement technique. RIC is an innovative dynamic compaction technique mainly used to compact sandy soils, where silt and clay contents are low. The RIC system uses "controlled impact compaction" of the ground using a 9-ton hammer dropped from height between 0.3 m to 1.2 m onto a 1.5 m diameter steel patent foot delivering about 26,487 to 105,948 Joules of energy per drop. To evaluate the effectiveness of this technique, RIC is used to improve an area of approximately 35,000 m^2 in a project site near Dubai, UAE. Cone Penetration Tests were carried out before and after improvement. The results showed improvement of the soil down to 5.0 meters below the ground level. CPT results showed a significant improvement in soil tip resistance (q_c) when the friction ratio (R_f %) is less than 1% and a slight improvement when R_f is above 1%. Calculations showed enhancement in the soil bearing capacity and reduction in the expected settlements.

I. INTRODUCTION

Rapid Impact Compaction (RIC) is an innovative dynamic compaction device mainly used to compact sandy soils, where silt and clay contents are low. RIC closes the gap between the surface compaction methods (e.g. roller compaction) and the deep compaction methods (e.g. deep dynamic compaction) and permitting a middle-deep improvement of the ground. RIC has been used to treat a range of fills of a generally granular nature [1] and some natural sandy and silty soils [2].

The RIC system uses "controlled impact compaction" of the ground using a 9-ton hammer dropped from height between 0.3 m to 1.2 m onto a 1.5 m diameter steel patent foot delivering about 26,487 to 105,948 Joules of energy per drop. RIC can be used to densify loose soils down to a depth of about 4 m to 6m. RIC consists of an excavator-mounted hydraulic pile-driving hammer striking a circular plate (patent foot) that rests on the ground. The tamper typically strikes the plate at a rate of 40 to 60 blows per minute. Figure 1 shows rapid impact compactor and impact foot with driving cap.

Figure1. Rapid Impact Compactor (left), Impact Foot with Driving Cap (right)

RIC can be used to improve bearing capacity and reduce liquefaction potential of loose soils. The compaction sequence is designed to work from the outside in, so that compaction of the lower zone soils occurs first followed by compaction of the upper zone. Data monitoring during the compaction process and the online display in the operator's cab enables compaction control, an economic application of the compaction tool, and a work integrated quality control. The total impact depth of the impact foot, the number of blows, and the final settlement of the impact foot after a blow define the stopping criteria.

The way in which RIC improves the ground is a "top-down" process, compared to Dynamic Compaction (DC) which is a "bottom-up" process. The first few blows in rapid impact compaction create a dense plug of soil immediately beneath the compaction foot. Further blows advance this plug deeper, which compacts soil in a deeper layer. This process progresses until little further penetration of the compaction foot can be achieved with increasing blows [3].

Falkner et al. [4], presented theoretical investigations, on RIC, comprise numerical computer simulations of the impulse-type compaction effect, the energy transfer into the soil and the wave propagation. Experimental tests on different soil conditions provide the verification of theoretical analyses and the basis for the optimized and economic application of the compaction method in practice. Case studies of different construction projects demonstrate the successful application the RIC for middle-deep improvement and compaction of the ground.

Simpsons [5] presented a case study on using RIC in a reclaimed site (1.21-square-kilometer) in California, USA. Pre and post treatment CPTs results were presented. Also a comparison of before and after liquefaction potential were presented. In addition, the results of vibration monitoring performed during RIC were discussed. It's concluded that RIC is a viable and economical method of ground improvement and liquefaction mitigation.

In this paper, RIC is used as a soil improvement technique in a project site near Dubai, UAE to improve the soil bearing capacity and reduce settlements. The objectives of this paper are to:

- Evaluate the effect of this technique on the soil bearing capacity and settlements.
- Determine the depth of improvement giving the existing soil conditions.

II. PROJECT DESCRIPTION

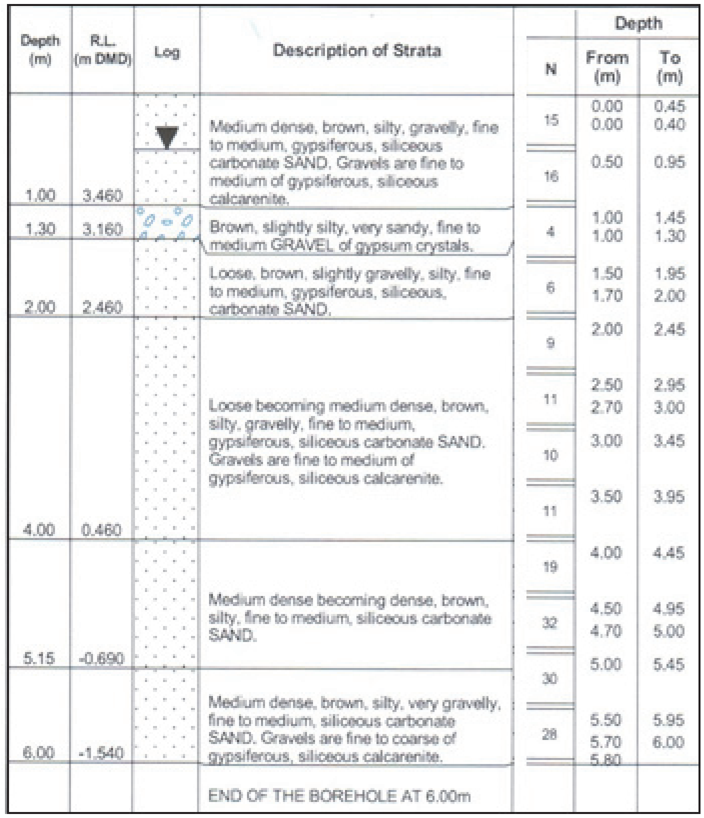
As part of the Jumeirah Park development project, one hundred thirty four villas (134) are proposed to be constructed. The project site is located off Sheik Mohammed Bin Zayed Road, Dubai, UAE.

In some areas of the project site, a loose to very loose fine to medium sand layer is encountered at a depth ranging from 1.0m to 4.0m below the ground level. Figure 2 shows one of the drilled boreholes at the project site. Cohesive soil was not encountered in the project area. Water table was encountered at a depth of 0.5m to 2.0m below the ground level.

A. FOUNDATION DESIGN CRITERIA

The designer proposed the bottom of footings (B.O.F) to be constructed at 1.0m below the ground level. The design criteria, for the foundation, are to use square footing (2.5m by 2.5 m), 200 kPa bearing pressure, and settlement shall not to exceed 25mm in order to minimize differential settlement.

It's proposed to use Schmertmann method to carry out the settlement calculations. The bearing capacity and settlement criteria could not be met based on the existing soil conditions for 58 Villas. Therefore, a ground improvement is needed to meet the project criteria.



Depth (m)	R.L. (m DMD)	Log	Description of Strata
1.00	3.460		Medium dense, brown, silty, gravelly, fine to medium, gypsiferous, siliceous carbonate SAND. Gravels are fine to medium of gypsiferous, siliceous calcarenite.
1.30	3.160		Brown, slightly silty, very sandy, fine to medium GRAVEL of gypsum crystals.
2.00	2.460		Loose, brown, slightly gravelly, silty, fine to medium, gypsiferous, siliceous, carbonate SAND.
4.00	0.460		Loose becoming medium dense, brown, silty, gravelly, fine to medium, gypsiferous, siliceous carbonate SAND. Gravels are fine to medium of gypsiferous, siliceous calcarenite.
5.15	-0.690		Medium dense becoming dense, brown, silty, fine to medium, siliceous carbonate SAND.
6.00	-1.540		Medium dense, brown, silty, very gravelly, fine to medium, siliceous carbonate SAND. Gravels are fine to coarse of gypsiferous, siliceous calcarenite.
			END OF THE BOREHOLE AT 6.00m

N	Depth From (m)	Depth To (m)
15	0.00 0.00	0.45 0.40
16	0.50	0.95
4	1.00 1.00	1.45 1.30
6	1.50 1.70	1.95 2.00
9	2.00	2.45
11	2.50 2.70	2.95 3.00
10	3.00	3.45
11	3.50	3.95
19	4.00	4.45
32	4.50 4.70	4.95 5.00
30	5.00	5.45
28	5.50 5.70 5.80	5.95 6.00

Figure 2. SPT Representing the Soil Profile

III. SELECTION OF SUITABLE GROUND IMPROVEMENT TECHNIQUE

Considering the soil profile of loose to very loose fine to medium sand, three soil improvement techniques were considered namely: Vibrocompaction, Dynamic Compaction, and Rapid Impact Compaction. Those methods were considered because they are suitable for granular soil and available in the local market.

Vibro-Compaction is effective in improving the relative density of granular soils with suitable gradations and limited fines contents (not more than 5%). A vibroflot is penetrated to the required design depth, assisted by water jetting from the nose cone. Upon reaching design depth water jetting is reduced before the vibroflot is slowly extracted, with pauses at regular intervals to ensure satisfactory levels of compaction are achieved at each depth. The vibroflot is withdrawn back to the surface where a zone of compacted ground is formed around the insertion point. In this method, the soil particles are forced into a denser configuration by the generation of radial vibrations, resulting in a soil matrix with greater density and increased mechanical properties (shear strength, stiffness, and bearing capacity).

DC was first popularized by Menard [6] and has become a well-known ground improvement technique due to its simplicity, cost-effectiveness, and the considerable depth it affects. With this technique, the ground can be repeatedly impacted by a large pounder weighing typically 6 to 40 tons, which is dropped onto predetermined grid points on the ground surface in free fall from a height varying from 10 to 40 m to increase the degree of compaction and bearing capacity and decrease collapsibility of loess within a specified depth of improvement [7].

Table 1 summarizes the limitations of vibrocompaction and dynamic compaction when compared to rapid impact compaction. The vibrocompaction is not suitable because the fine content of the existing soil is more than 5%. The dynamic compaction is not suitable for this project due to nearby existing structures which may be damaged due to vibrations. Also, the RIC is more productive and cost effective when compared to the other two methods. It should be noted that the given productivity and the cost are estimated for this project and may vary for other projects depending on the soil profile and depth of improvement.

TABLE 1. LIMITATIONS OF VIBROCOMPACTION AND DYNAMIC COMPACTION

Technique	**Technique Limitation for this Project**	**Productivity (m^2 per shift per machine)**	**Cost (Dollars/m^2)**
Vibrocompaction (VC)	Fine content shall not be more than 5%	700	40
Dynamic Compaction (DC)	Damage to nearby existing structures and utilities due high impact energy.	1,000	30
Rapid Impact Compaction (RIC)	No limitations	2,500	15

IV. SOIL IMPROVEMENT USING RIC

Considering the cost and the schedule, it was concluded that performing RIC using the proposed design criteria is the optimum alternative. Among the evaluated soil improvement techniques, RIC was selected because it reduced the cost and time when compared to Vibro compaction, and DC. The RIC work was finished within three weeks for whole project area which is about (35,000 m^2).

One Cone Penetration Test (CPT) was carried out at each villa location before the commencement of the compaction to evaluate the soil conditions and to determine the needed degree of compaction to meet the design criteria.

A. RIC TRIAL AREA

Preliminary trials are crucial to any extensive RIC works to provide the designer with the necessary information to allow refinement of the compaction procedure. Two villas were used as a trial area to establish a compaction design criteria. Moreover, as the main RIC works are proceeding, ongoing monitoring and testing is necessary to ensure that the appropriate amount of energy is being transferred to the soil and that performance requirements are being met. The compaction trial is important for the evaluation of ground response. The optimal number of blows per pass is typically taken as the value beyond which continued blows produce negligible further penetration of the compaction foot.

The process of compaction started by using a 6m grid then compacting a 3m grid in order to allow for deep improvement. Figure 3 shows the sequence of the compaction. Compaction was delivered at each point until one of the following criteria was satisfied:

A. Maximum number of blows = 60
B. Maximum foot travel = 800 mm
C. Minimum foot settlement = 8 mm

Compaction of the 6m and 3m grid is considered one pass (sequence 1 and 2). One CPT test per villas was carried out after each pass. The project design criteria (settlement and bearing pressure) were met after the third pass. After completing the trial area, It’s concluded that three passes are required using the above mentioned compaction criteria.

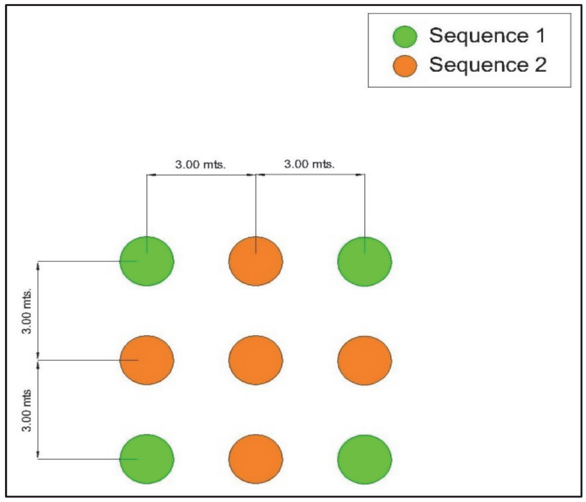


Figure 3. Compaction Points Layout

The sequence of the RIC works involved the following:

- *Step 1* - Excavation to foundation level.
- *Step 2* - Pre-treatment CPT testing.
- *Step 3* - First pass of RIC, leveling.
- *Step 4* - Second pass of RIC, leveling.
- *Step 5* - Third pass of RIC, leveling.
- *Step 7* - Level survey, post treatment testing.

Table 2 shows a typical output of the RIC monitoring system. The RIC monitor data out provides point ID, coordinates, date and time of compaction, total number of blows, final foot settlement, final foot travel depth, average fall height, and total energy.

Figure 4 shows the tip resistance for the pre-improvement, post 1st, 2nd, and 3rd Pass. It can be noted that the first pass energy was consumed to break the existing hard layer (crust) at the top while the 1st and 2nd passes improved the soil.

TABLE 2. RIC MONITOR DATA OUTPUT

Design Data			RIC Monitor Data						
Point ID	Design Coordinates		Date	Time	Total blows	Final set	Final depth	Ave fall	Total energy
	Easting	Northing				mm	m	mm	Tm
01	483460	2770184	23-10-13	14:31:43	17	8	0.533	1130	172.86
02	483456	2770179	23-10-13	14:32:42	21	8	0.207	1176	222.35
03	483452	2770174	23-10-13	14:33:34	13	8	0.118	1164	136.21
04	483448	2770170	23-10-13	14:34:30	19	8	0.186	1175	200.85
05	483445	2770165	23-10-13	14:35:24	18	8	0.182	1155	187.08
06	483441	2770160	23-10-13	14:36:24	18	8	0.196	1147	185.82
07	483437	2770156	23-10-13	14:37:19	20	8	0.213	1159	208.61
08	483433	2770151	23-10-13	14:38:19	23	7	0.258	1143	236.62
09	483429	2770147	23-10-13	14:39:41	21	8	0.205	1147	216.85
10	483425	2770150	23-10-13	14:41:02	15	7	0.147	1110	149.91
11	483429	2770155	23-10-13	14:41:50	16	7	0.199	1132	163.01

B. POST IMPROVEMENT TESTING PROGRAM

Testing is necessary to assure that appropriate amount of energy is being transferred to the soil and that performance requirements are being met. The degree of compaction is evaluated by comparing the pre and post CPTs and calculating the expected settlements.

Following the RIC work, one CPT per villa was carried out to provide post-treatment evaluation. The post-treatment CPTs were advanced, near to pre-treatment CPTs, to depths of about 6 meters approximately two days after the RIC treatment to allow for dissipation of pore water pressure. The corresponding post-treatment CPTs indicate an increase in the tip resistance within these same depths.

Figure 5 compare the results of the pre- and post-treatment CPTs. The pre-improvement CPTs showed a loose layer approximately between the depths of 1.5m to 3.5m. The goal is to improve the loose layer and meet the project design criteria. It's clear that the tip resistance values were significantly increased approximately between the depths of 1.0m to 5.0m below the ground. As shown in the figures, a significant improvement was achieved when the friction ratio (R_f %) is less than 1%. A slight improvement was achieved when R_f is more than 1%.

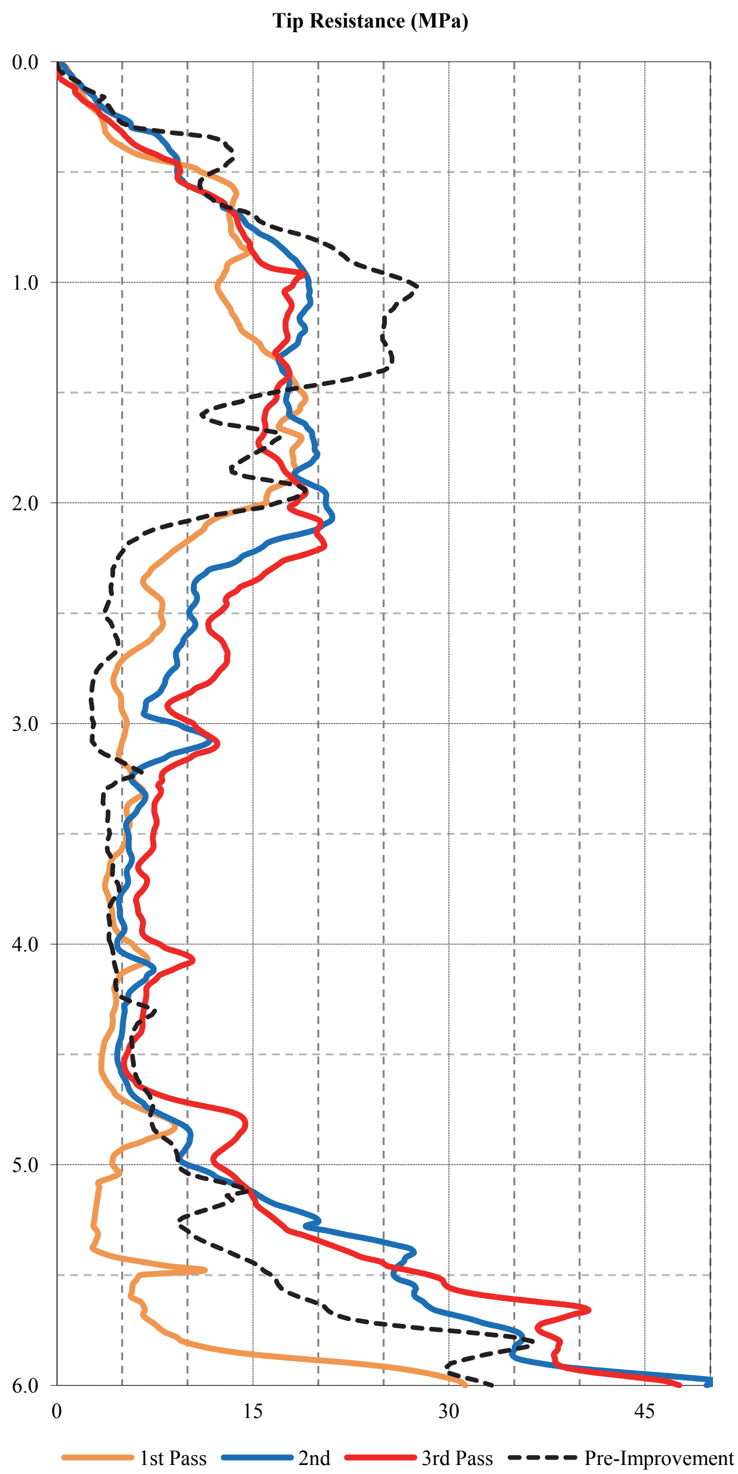


Figure 4. Tip Resistance for the Pre-Improvement, Post 1st, 2nd, and 3rd Pass

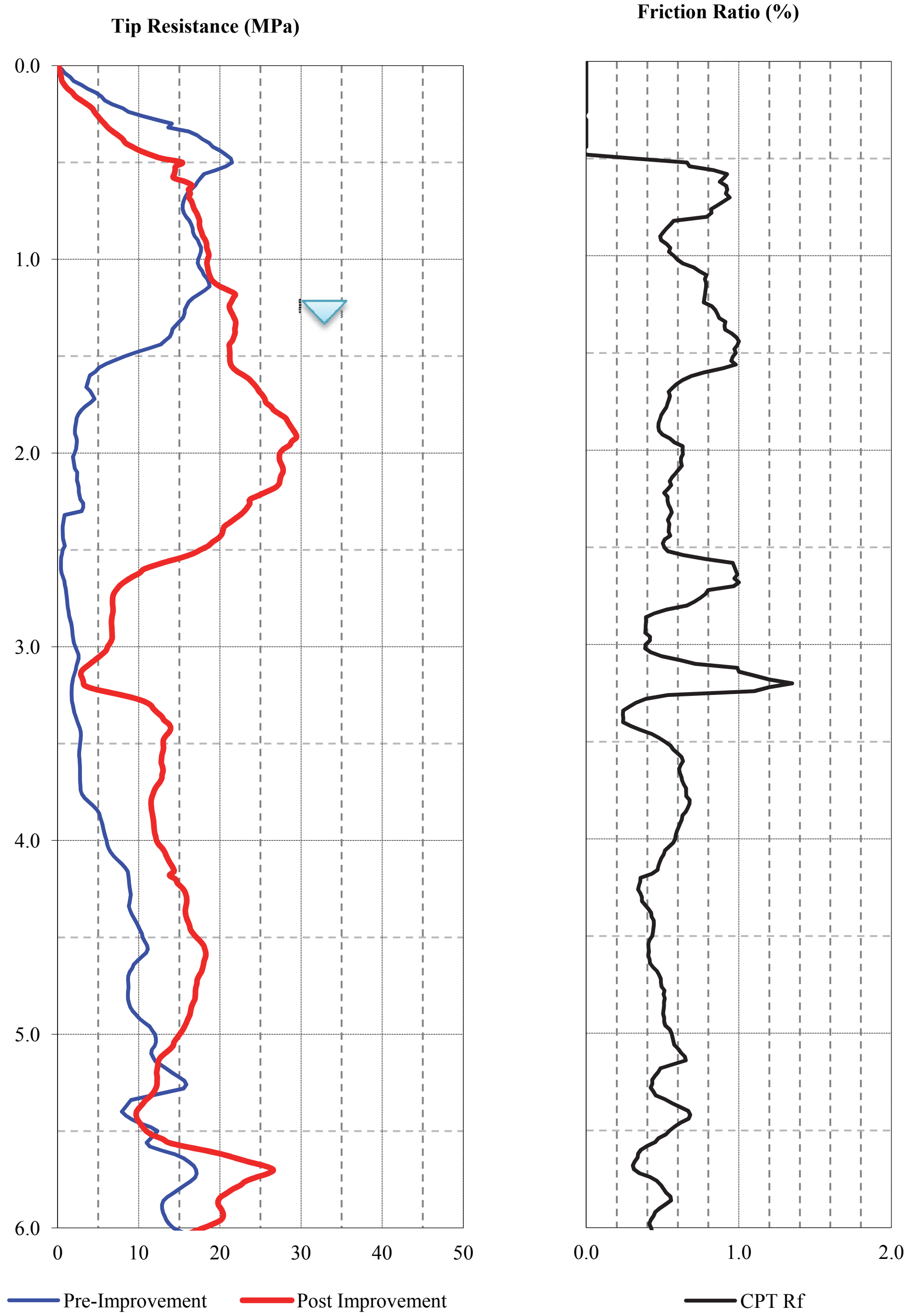


Figure 5. Pre and Post Improvement Tip Resistance

C. SETTLEMENT CALCULATIONS

Schmertmann [8] studied the distribution of vertical strain within a linear elastic half-space under a uniform pressure. His then developed a procedure for estimating footing settlement formula using cone penetration test (CPT) data, as:

$$S_e = C_1 C_2 q \sum_0^{Z_z} \left(\frac{I_z}{E_s} \right) \Delta z$$

where S_e = immediate settlement (inches); C_1 = depth correction factor; C_2 = soil creep factor; q = applied pressure (200 kPa); ΔZ= q_c measurement spacing (0.02m); I_z = strain influence factor; and E_s = modulus of elasticity. The depth correction factor and the soil creep factor can be determined by Equations 1 and 2, respectively. For the creep factor, the value for time elapsed (t) should be at least 0.1 years.

$$C_1 = 1 - 0.5 \left(\frac{\gamma D_f}{q} \right) \quad (1)$$

$$C_2 = 1 + 0.2 \log \left(\frac{t}{0.1} \right) \quad (2)$$

The granular soil strata to a depth of 2B below the footing is subdivided into several layers using the

CPT plot of the tip resistance (q_c) vs. depth. Within each layer the tip resistance stress (q_c) value should be approximately the same. For a footing with its L/B ratio between 1 and 10, the two curves must be interpolated to produce a strain distribution profile curve suitable for the desired L/B value. Once the layers are set up and the profile drawn, the I_z value at the mid-point of each layer can be determined.

For axisymmetric footings (L/B = 1.0), Equation 3 is used to determine E_s from q_c. However for footings with L/B > 10.0, or plane strain footings, E_s can be determined from Equation 4.

$$E_s = 2.5 q_c \quad (3)$$

$$E_s = 3.5 q_c \quad (4)$$

Settlement calculations were carried out for the compacted 58 Villas using the pre and post improvement CPTs. Schmertmann method was used to calculate the settlements for a bearing pressure of 200kpa and footing size of (2.5m by 2.5m).

Figure 6 shows a comparison between the pre and post expected settlements for the 58 villas. It's obvious that the RIC reduces the expected settlements, by an average of 45%, for all villas to meet the design criteria (25mm).

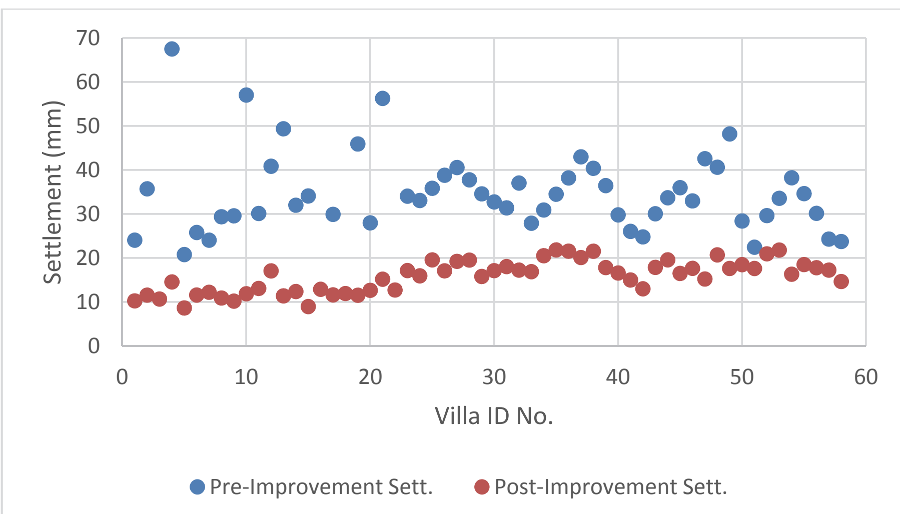


Figure 6. Settlement Values based on the Pre and Post Improvement CPTs

V. CONCLUSIONS

RIC is a cost-effective technique of ground improvement. The project presented herein benefited from its use, essentially by meeting the design criteria with a reduction in the foundation costs and construction time. The cost and time to perform RIC provided a savings to the project versus the cost of the foundation system without it. Results of the field pre and post improvement testing indicate improvement of soil to depths of up to 5.0 meters below the ground level.

Settlements calculations showed that the RIC method reduced the expected settlement by an average of 45% which is significant. A significant improvement was achieved when the friction ratio (R_f %) is less than 1%. A slight improvement was achieved when R_f is more than 1%.

RIC is considered to have less cost and more productivity when compared to other ground improvement techniques such as Dynamic Compaction and Vibrocompaction. It also, has less vibration effect when compared to dynamic compaction. No known damage to nearby utilities has occurred at the time RIC was performed.

REFERENCES

[1] Watts, K.S. and Charles, J.A., 1993. Initial Assessment of a New Rapid Impact Ground Compactor. Proceedings of the Conference on Engineered Fills, pp 399-412. London, Thomas Telford.

[2] Braithwaite, E.J. and Du Preez, R.W., 1997. Rapid impact compaction in southern Africa. Proceedings of the Conference on Geology for Engineering, Urban Planning and the Environment. South African Institute of Engineering Geologists, 13-14 November 1997.

[3] Serridge, C.J. and Synac, O., 2006. Application of the Rapid Impact Compaction (RIC) Technique for Risk Mitigation in Problematic Soils, IAEG 2006 Paper No.294

[4] Falkner F.J., Adam C., Paulmich I., Adam D., and Fürpass J., 2010. Rapid impact compaction for middle-deep improvement of the ground – numerical and experimental investigation. The 14th Danube-European Conference on Geotechnical Engineering "From Research to Design in European Practice", June 2-4, 2010, Bratislava, Slovakia, CD-ROM paper, 10 pp.

[5] Simpson, L., Jang, S., Ronan, C., and Splitter, L. (2008) Liquefaction Potential Mitigation Using Rapid Impact Compaction. Geotechnical Earthquake Engineering and Soil Dynamics IV: pp. 1-10.

[6] Menard, L., and Broise, Y. (1975). "Theoretical and practical aspects of dynamic consolidation." *Geotechnique*, 25 (1), 3–18.

[7] Lutenegger, A. J. (1986). "Dynamic compaction in friable loess." *J. Geotech. Eng.*, 112(6), 663–667.

[8] Schmertmann, J. H., Hartman, J. P., and Brown, P. R., 1978. "Improved Strain Influence Factor Diagrams." American Society of Civil Engineers, Journal of the Geotechnical Engineering Division, 104 (No. GT8), 1131-1135.