Ground improvement using rapid impact compaction: case study in Dubai

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Professional paper

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In recent years, the Rapid Impact Compaction has gained popularity as a ground improvement technique. To evaluate the usefulness of this technique in the Arabian Gulf Region, the RIC is used to improve an area of 29,000 m² on a project site near Dubai, UAE, where the groundwater level is shallow. Cone Penetration Tests and settlement calculations were carried out before and after soil improvement. Test results show improvement in the soil bearing capacity and reduction in expected settlements.

Stručni rad

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Poboljšanje tla pomoću brzog udarnog zbijanja: studija slučaja u Dubaiju

Tijekom nekoliko proteklih godina brzo udarno zbijanje postalo je popularna metoda za poboljšanje tla. Da bi se procijenila korisnost te metode na području Perzijskog zaljeva, brzo udarno zbijanje primjenjeno je za poboljšanje tla površine 29.000 m² na gradilištu u blizini Dubaija, gdje je zabilježena visoka razina podzemne vode. Statički penetracijski pokus i proračuni slijeganja provedeni su prije i nakon poboljšanja tla. Ispitivanja su pokazala poboljšanje nosivosti tla i smanjenje očekivanih slijeganja.

Fachbericht

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Bodenverbesserung durch schnelle Schlagverdichtung: Fallstudie in Dubai

In den letzten Jahren ist die schnelle Schlagverdichtung eine beliebte Methode zur Bodenverbesserung. Um die Anwendungsfähigkeit dieses Verfahrens im Persischen Golf zu erfragen, ist die schnelle Schlagverdichtung zur Verbesserung von 29.000 m² Baugrund in der Nähe von Dubai angewandt worden, wo sich ein hoher Grundwasserstand zeigte. Statische Penetrationsversuche und die Berechnung von Setzungen sind vor und nach der Bodenverbesserung durchgeführt worden. Des Weiteren haben die Versuche eine erhöhte Tragfähigkeit des Bodens und eine Verminderung der erwarteten Setzungen vorgezeigt.

1. Introduction

The Rapid Impact Compaction (RIC) is an innovative dynamic compaction method mainly used to compact sandy soils, where silt and clay contents are low. The RIC closes the gap between surface compaction methods (e.g. roller compaction), and deep compaction methods (e.g. deep dynamic compaction), and enables a middle-deep improvement of the ground. The 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 the "controlled impact compaction" of the ground using a 9-ton hammer that is dropped from the height of between 0.3 m and 1.2 m onto a 1.5 m diameter steel patent foot delivering about 26,487 to 105,948 Joules of energy per drop. The RIC can be used to densify loose soils down to the depth of about 4 m to 6m. The RIC device 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 the rate of 40 to 60 blows per minute. The rapid impact compactor and impact foot with driving cap is shown in Figure 1.

The RIC can be used to improve the bearing capacity and reduce the 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, and is 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 economical 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 the 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 the 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 of the RIC, which comprise numerical computer simulations of the impulse-type compaction effect, the energy transfer into the soil, and the wave propagation. Experimental tests in different soil conditions provide verification of theoretical analyses and the basis for an optimized and economical application of the compaction method in practice. Case studies of different construction projects demonstrate the successful application of the RIC for middle-deep improvement and compaction of the ground.

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

In this paper, the RIC is used as a soil improvement technique at 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;
- define a procedure on how to use this technique in case of a shallow groundwater level; and
- evaluate the vibration effect of the RIC.

2. Project description

One hundred and thirty-four villas (134) are proposed to be constructed In the scope of the Jumeirah Park development project. The project site is located off Sheik Mohammed Bin Zayed Road, Dubai, UAE, as shown in Figure 2.

In some areas of the project site, a loose to very loose fine to medium-grained sand layer is encountered at the depth ranging from approximately1.0 m to 4.5 m below the ground level. These

Figure 1. a) rapid impact compactor; b) impact foot with driving cap

Figure 2. Google map of the site location in Dubai, UAE
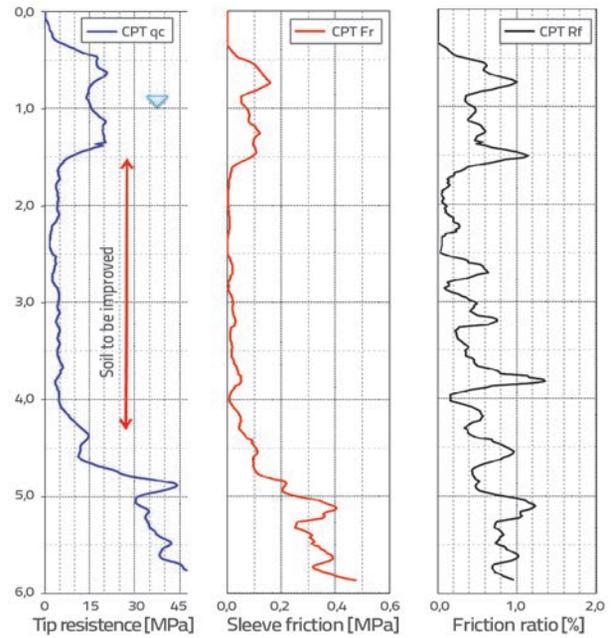
Figure 3. CPT representing soil profile

Table 1. SPT representing the soil profile

Depth [m]	R.L. [m DMD]	Log	Description of strata	N	Depth from [m]	Depth to [m]
		▼	Medium dense, brown, silty, gravelly, fine to medium, gypsiferous, siliceous carbonate SAND. Gravels are fine to medium of gypsiferous, siliceous calcarenite.	15	0,00 0,00	0,45 0,40
1,00	3,460			16	0,50	0,95
1,30	3,160		Brown, sligthly silty, very sandy, fine to medium GRAVEL of gypsum crystals.	4	1,00 1,00	1,45 1,30
2,00	2,460		Loose, brown, slightly gravelly, silty, fine to medium, gypsiferous, siliceous carbonate SAND.	6	1,50 1,70	1,95 2,00
			Loose becoming medium dense, brown, silty, gravelly, fine to medium, gypsiferous, siliceous carbonate SAND. Gravels are fine to medium of gypsiferous, siliceous calcarenite.	9	2,00	2,45
				11	2,50 2,70	2,95 3,00
				10	3,00	3,45
4,00	0,690			11	3,50	3,95
			Medium dense becoming dense, brown, silty, fine to medium, siliceous carbonate SAND.	19	4,00	4,45
5,15	-0,690			32	4,50 4,70	4,95 5,00
			Medium dense, brown, silty, very gravelly, fine to medium, siliceous, carbonate SAND. Gravels are fine to coarse of gypsiferous, siliceous calcarenite.	30	5,00	5.45
6,00	-1,540			28	5,50 5,70 5,80	5,95 6,00
			Snd of the borehole at 6,00 m			
R.L. - Reduced level; DMD - Dubai Municipality Datum; N - number of blows						

soil conditions can be represented by the Standard Penetration Test (SPT) and Cone Penetration Test (CPT), as shown in Figure 3 and Table 1, respectively. Cohesive soil was not encountered in the project area. Water table was encountered at the depth of 0.5 m to 2.0 m below the ground level.

2.1. Regional geology

The general geology of the UAE has been substantially influenced by the marine deposits associated with the continuous sea level changes during the relatively recent geological time. Moreover, with the existing mountainous geology across the UAE, the country is considered to be a relatively low-lying area. Geological conditions in Dubai essentially are marked by a linear coastline dissected by creeks. Superficial deposits consist of beach dune sands with marine sands and silts. Furthermore, the erosion, capillary rise phenomena, and evaporation, have led to extensive silt deposits in some areas, especially near the creeks. These superficial deposits are underlined by alternating layers of calcarenite, carbonate sandstone, sands, and cemented sand layers.

2.2. Foundation design criteria

The designer proposed that the bottom of footings (B.O.F) be constructed at 1.0 m below the existing ground level. It should be noted that the B.O.F is at zero CPT level. The design criteria for the foundation call for the use of the square footing (2.5 m by 2.5 m), with the 200 kPa bearing pressure, while settlement should not exceed 25 mm so as to minimize differential settlements. The Schmertmann method was proposed to carry out the settlement calculations. The bearing capacity and settlement criteria for 58 villas could not be met based on the existing soil conditions. This project is a design-build project and so the contractor had to explore several alternatives to overcome the existing soil conditions. The following alternatives were evaluated based on their cost and time, because completing the foundation was on the critical path of the project schedule:

1. Use deep foundations such as piles instead of shallow foundations.
2. Increase the footing size to reduce the bearing pressure.
3. Improve soil using one of the ground improvement techniques for granular material, such as the Vibro Compaction (VC), Dynamic Compaction (DC), and Rapid Impact Compactions (RIC).

3. Limitations of other soil improvement techniques

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

3.1. Vibrocompaction

Vibrocompaction and its practical applications are extensively described in geotechnical literature, e.g. by Massarsch and Fellenius [6], and Massarsch [7, 8]. The 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 brought down to the required design depth, and the process is assisted by water jetting from the nose cone. Upon reaching the design depth, the water jetting is reduced and the vibroflot is slowly extracted, with pauses at regular intervals to ensure that satisfactory levels of compaction are achieved at each depth. The vibroflot is withdrawn to the surface where a zone of compacted ground is formed around the insertion point. In this method, soil particles are forced into a denser configuration by the generation of radial vibrations, resulting in a soil matrix with greater density and improved mechanical properties (shear strength, stiffness, and bearing capacity).

3.2. Dynamic compaction (DC)

The DC was first popularized by Menard [9] and has become a well-known ground improvement technique due to its simplicity, cost-effectiveness, and the considerable depth it can cover. With this technique, the ground can be repeatedly impacted by a large pounder typically weighing 6 to 40 tons, which is dropped onto predetermined grid points on the ground surface in free fall from the height varying from 10 to 40 m, so as to increase the degree of compaction and bearing capacity and decrease the collapsibility of loess within a specified depth of improvement [10].

The limitations of vibrocompaction and dynamic compaction, when compared to rapid impact compaction, are summarized in Table 2. The vibrocompaction is not suitable because the fines content of the existing soil exceeds 5 %. The dynamic compaction is not suitable for this project because the nearby existing

Table 2. Limitations of vibrocompaction and dynamic compaction

Technique	Technique limitation for this project	Productivity [m² / shift / machine]	Cost [Dollars / m²]
Vibrocompaction (VC)	Fines content shall not exceed 5 %	700	40
Dynamic Compaction (DC)	Damage to nearby existing structures and utilities due to high impact energy	1,000	30
Rapid Impact Compaction (RIC)	No limitations	2,500	15

structures might 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 cost are estimated specifically for this project, and may vary for other projects depending on the soil profile and depth of improvement.

4. Soil improvement using RIC

Considering the cost and schedule, the contractor concluded that realisation of the RIC using the proposed design criteria is an optimum alternative. The RIC method was selected among the evaluated soil improvement techniques because it reduced the cost and time when compared to vibro compaction and the DC. The RIC work was finished within three weeks on the entire project area of about 29,000 m^2.

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

4.1. Groundwater effect

Groundwater level is a significant factor for estimating suitability of the RIC method. Shallow groundwater level can act as a hydraulic barrier reducing the effective transfer of energy to the soil. Based on the CPT results, the ground water level is close to the ground surface (0.5 m to 2.0 m below ground). Therefore, the compaction energy may not propagate deep enough to improve the soil due to the build-up of pore water pressure during compaction.
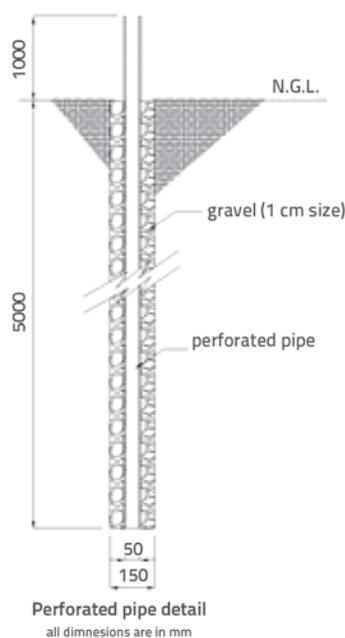
Figure 4. Well point pipe details (N.G.L - Natural Ground Level)

To reduce the build-up of pore water pressure during compaction, four well point pipes were installed in the vicinity of each villa. 5 cm diameter polyvinyl chloride (PVC) perforated pipes were used. 15 cm holes were drilled and jetted to the depth of 5 m below the ground. Figure 4 shows details of the well point pipes. Those pipes release the pore water pressure so that the compaction energy can propagate deeper.

4.2. RIC trial phase

Preliminary trials are crucial to any extensive RIC works as they provide the designer with the information that is needed to further refine the compaction procedure. Two villas were used as a trial area to establish the compaction design criteria. Moreover, as the main RIC works were proceeding, the ongoing monitoring and testing was necessary to ensure that an appropriate amount of energy is being transferred to the soil, and that performance requirements were being met. The compaction trial is important for the evaluation of ground response. An 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 trial area compaction process started by using a 6m grid, and was continued by compacting a 3m grid in order to allow for deep improvement. The compaction sequence is shown in Figure 5.
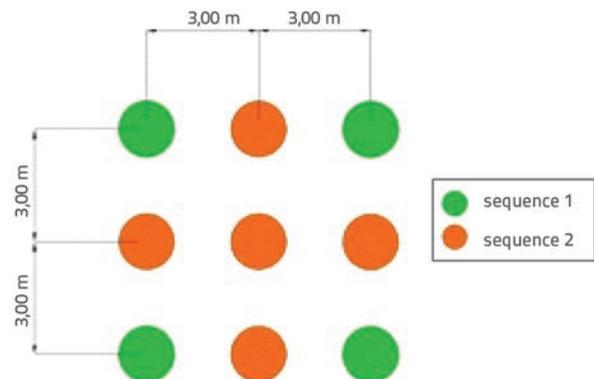
Figure 5. Compaction points layout

The compaction was made at each point until one of the following criteria was satisfied:
- Maximum number of blows: 60
- Maximum foot travel: 800 mm
- Minimum foot settlement: 8 mm.

It should be noted that the maximum number of blows is limited to 60 due to the limited readout capability of the data acquisition system. The maximum foot travel is limited to 800 mm because of the limit depth allowed by the boom on the RIC machine. The minimum foot settlement is limited to 8 mm because it was achievable after the third pass where the settlement criterion was met. It can also be noted that more compaction energy is provided if the settlement is reduced to 7 or 6 mm, which is not

Table 3. Sample of RIC monitor data output

Point	Coordinates		Date	Time	Total blows	Final set [mm]	Final depth [m]	Ave fall [mm]	Total energy [kNm]
	East	North							
1	483460	2770184	23.10.2013.	14:31:43	17	8	0,553	1130	1728,6
2	483456	2770179	23.10.2013.	14:32:42	21	8	0,207	1176	2223,5
3	483452	2770174	23.10.2013.	14:33:34	13	8	0,118	1164	1362,1
4	483448	2770170	23.10.2013.	14:34:30	19	8	0,186	1175	2008,5
5	483445	2770165	23.10.2013.	14:35:24	18	8	0,182	1155	1870,8
6	483441	2770160	23.10.2013.	14:36:24	18	8	0,196	1147	1858,2
7	483437	2770156	23.10.2013.	14:37:19	20	8	0,213	1159	2086,1
8	483433	2770151	23.10.2013.	14:38:19	23	8	0,258	1143	2366,2
9	483429	2770147	23.10.2013.	14:39:41	21	8	0,205	1147	2168,5
10	483425	2770150	23.10.2013.	14:41:02	15	8	0,147	1110	1499,1
11	483429	2770155	23.10.2013.	14:41:50	16		0,199	1132	1630,1

needed because the criteria were already met. Therefore, the 8 mm was adopted as an optimum foot settlement.

Table 2 shows a typical output of the RIC monitoring system. The RIC monitor data provides the 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.

The 6 m and 3 m compaction grid is considered to be one pass (sequences 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 was concluded that three passes are required using the above mentioned compaction criteria. 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.

Figure 6.a shows the tip resistance for the pre-improvement, and after the 1st, 2nd, and 3rd passes for the trial area. It can be noted that the first pass energy was consumed to break the existing hard layer (crust) at the top while the 2nd and 3rd passes improved the soil.

Figure 6.a shows a drop in tip resistance, at the depth of 5-6 m, after the first pass. This drop is due to the fact that the soil profile was pushed down after the loose soil was compacted. However, the soil was improved after the 2nd and 3rd passes at that depth. Figure 6.b shows the post and pre improvement ratio q_c which provides a direct insight into the percentage of improvement after each pass. It can be noted that the 3rd pass has the highest ratios of improvement when compared to the 1st and 2nd passes.

It was concluded that the foundation design criteria (settlement and bearing pressure) were met after the third pass. Therefore, three passes were performed to meet design criteria in the project area.
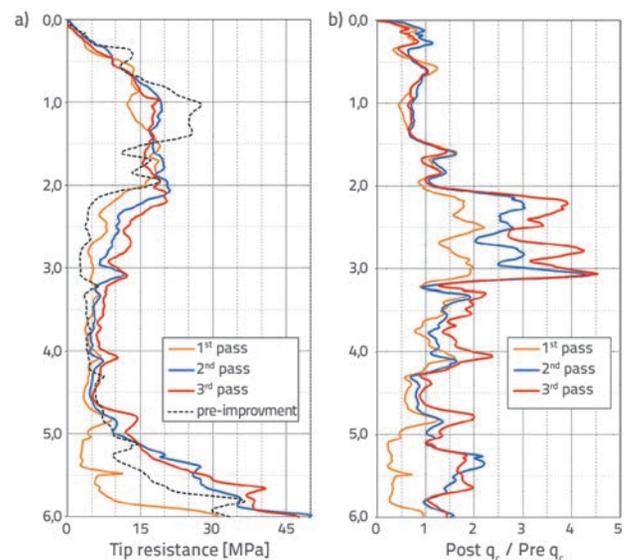
Figure 6. a) tip resistance for the pre-improvement, post 1st, 2nd, and 3rd pass; b) post and pre improvement ratio q_c

4.3. Production phase and post improvement testing program

After completion of the trial area, the compaction work was carried out on the project site using the compaction criteria given in section 4.2 and the point layout as shown in Figure 5. The testing is necessary to ensure that an appropriate amount of energy is being transferred to the soil, and that performance requirements are
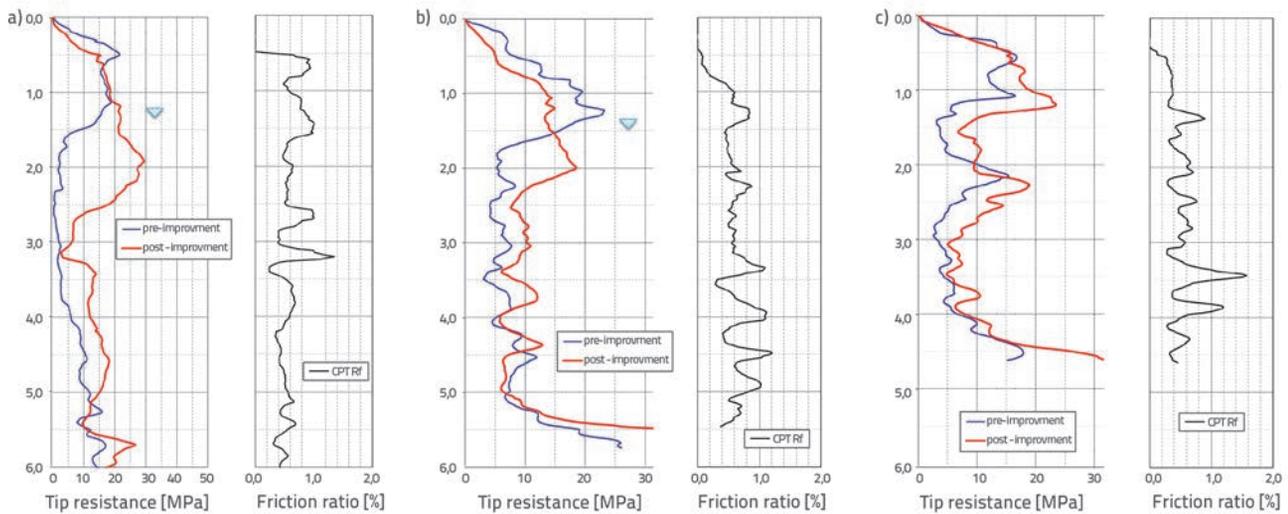
Figure 7. Pre and post improvement tip resistance

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 the post-treatment evaluation. The post-treatment CPTs were advanced, near pre-treatment CPTs, to depths of about 6 meters approximately two days after the RIC treatment to allow for the dissipation of pore water pressure. The corresponding post-treatment CPTs indicate an increase in the tip resistance within these depths.

Pre- and post-treatment CPT results are compared in Figures 7.a through 7.c. The pre-improvement CPTs showed a loose layer approximately between the depths of 1.5 m and 3.5 m. The goal is to improve the loose layer and meet the project design criteria. It's clear that the tip resistance values were significantly higher approximately between the depths of 1.0 m and 5.0 m below the ground. As shown in the figures, a significant improvement was achieved when the friction ratio (R_f %) was less than 1 %. A slight improvement was achieved when R_f was between 1 % and 2 %.

4.4. Vibration monitoring

Vibrations of the trial area were monitored during the compaction so as to evaluate the potential for damage to nearby roads, structures, and utilities. Seismographs were placed at 8.5 m away from compaction point to measure the peak particle velocity (PPV), which is the parameter that is most commonly used to evaluate the effects of vibrations on structures. The maximum PPV during compaction amounted to 20 mm/s. The Building Research Establishment [11] specifies that the PPV of 50 mm/s causes damage to reinforced or framed structures.

The recorded PPVs and frequencies are below the thresholds as specified by the U.S. Bureau of Mines (USBM) Office of Surface Mining (OSM) Research Investigation (RI) 8507 [12], as shown in Figure 8. Throughout the project site, vibrations due to compaction did not cause any damage to the surrounding structures, roads, and other services.
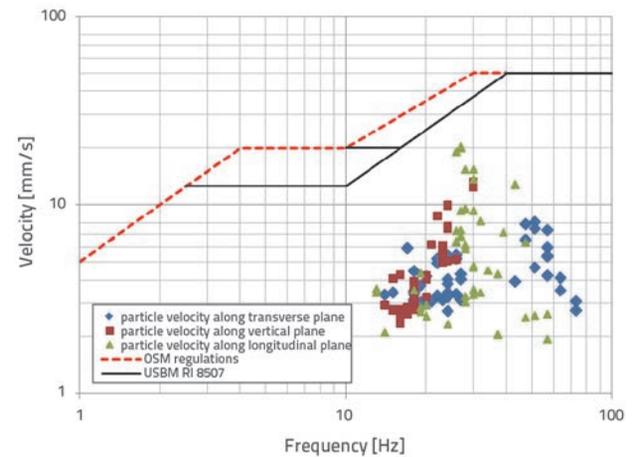
Figure 8. Vibration monitoring compared to the USBM RI8507 standards

4.5. Settlement calculations

Schmertmann [13, 14] studied the distribution of vertical strain within a linear elastic half-space under uniform pressure. He then developed a procedure for estimating the footing settlement formula using the cone penetration test (CPT) data, as shown in Equation 1:

$$S_e = C_1 C_2 q \sum_0^{z_z} \left(\frac{I_z}{E_s} \right) \Delta z \tag{1}$$

where S_e - immediate settlement (meters); C_1 - depth correction factor; C_2 - soil creep factor; q - applied pressure (200 kPa); Δz - q_c measurement spacing (0.02 m); I_z - strain influence factor; and E_s - modulus of elasticity. Equation 2 provides a correction factor for the foundation depth. Equation 3 provides a correction factor to account for the creep in soil. The elapsed time (t) of 10 years is used in the settlement calculations. This is based on client recommendations because there is no available information about the soil creep in the project area.

$$C_1 = 1 - 0.5\left(\frac{\gamma D_f}{q}\right) \tag{2}$$

$$C_2 = 1 + 0.2\log\left(\frac{t}{0.1}\right) \tag{3}$$

The granular soil strata to the depth of 2B below the footing are subdivided into several layers using the CPT plot of the tip resistance (q_c) vs. depth. Within each layer, the tip resistance stress value (q_c) should be approximately the same. The key strain influence factor values were provided for L/B ratio of 1 as shown in Table 4 (L is length and B is width of footing). 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 4 is used to determine E_s from q_c.

$$E_s = 2,5\ q_c \tag{4}$$

Table 4. Reference values of strain influence factor I_z

(L/B) ratio	I_z value	Depth z
1	0,1	0
	0,5	0,5 B
	0,0	2 B

Figure 9. Settlement values based on the pre and post improvement CPTs

It should be noted that Equation 4 is used to calculate E_s using an electrical CPT cone to measure tip resistance values. 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 the bearing pressure of 200kpa and the footing size of (2.5 m by 2.5 m). Figure 9 shows a comparison between the pre and post expected settlements for the 58 villas. It is obvious that the RIC reduces the expected settlements by an average of 45 %, for all villas to meet the design criteria (25 mm).

5. Conclusions

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

Settlement calculations showed that the RIC method reduced the expected settlement by an average of 45 %, which is quite significant. A significant improvement was achieved when the friction ratio (R_f %) was less than 1 %. A slight improvement was achieved when R_f was between 1 % and 2 %.

The RIC is considered to be less costly and more productive when compared to other ground improvement techniques such as the dynamic compaction and vibrocompaction. It also has lower vibration effects when compared to dynamic compaction. No known damage to nearby utilities was noted at the time the RIC was used. The groundwater level is a significant factor when considering suitability of the RIC method. A shallow groundwater level can act as a hydraulic barrier and reduce an effective transfer of energy to the soil. The installation of well point pipes improved propagation of the compaction energy to deeper zones by releasing the build-up pore water pressure.

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