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*Full Length Research Paper*

# Effective improvement depth for ground treated with rapid impact compaction

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**Ground improvement has been used on many construction sites to densify granular material, in other word, to improve soil properties and reduce potential settlement. This paper evaluates the efficiency of rapid impact compaction (RIC), which is an improvement on the process of deep dynamic compaction, in ground improvement. In this technique, ground improvement is achieved by impacting the ground with a 7 tone weight, 35 times/min, and drop height of 0.8 m at 2.5 m C/C square grid spacing. Method evaluation is made by comparing the tip resistance of pre-treatment and post treatment cone penetrometer test (CPT) soundings. However, the effective improvement depths and the factors affecting the depth are discussed, and a formula for calculating the effective depth is presented. Vibration monitoring was conducted to check the effect of the vibrations born by RIC machine on the adjacent structures to assess how much the process is considered environmentally friendly and accordingly the challenging locations it can reach especially in the urban areas. It was found that the RIC succeeded in achieving the required degree of improvement, improvement depth depends on soil properties and energy applied; and the effective improvement depth formula presented by this study is true when the soil is granular and homogeneous with depth. Vibrations by RIC machine were within allowable limits and with controlled effect on the adjacent structures.**

**Key words:** Rapid impact compaction, granular soils, ground improvement, *in-situ* testing, soil compaction, RIC vibrations, improvement depth, cone penetration test, machine vibrations, urban areas.

## INTRODUCTION

Due to the extensive presence of weak and compressible soil in this part of the world, construction work often requires the use of soil improvement works to eliminate significant short and long term settlements. Where the major deficiency of the ground is related to its loose state, *in situ* compaction may be the most appropriate type of treatment. Soil compaction can be used to improve the geotechnical properties of natural or man-made soil deposits, consisting primarily of granular materials.

The project site is part of the large tin mining area in and around Ipoh-Perak, Malaysia, primarily in the river valleys where tin has been mined since the beginning of the last century. The tin bearing sediments can be 50 m thick or more. Close to the ground surface, the sediments are often peaty or clayey. They become coarser with depth.

The bedrock below the alluvium is comprised of granite or of sedimentary rocks, shale, schist and limestone, which have been folded and metamorphosed. The surface of the granite, shale and schist is generally relatively smooth, while that of lime stone can be extremely rough with numerous deep crevices, overhangs and of high pinnacles (Tan and Bachelor, 1981), which makes pile driving extremely difficult. Sinkholes are common in this area. Soil improvement by Rapid Impact Compaction (RIC) was recommended for this site.

Rapid Impact Compaction, which is the core of this paper, was developed in early 1990's by British Sheet piling in Conjunction with British Army as an improvement on the process of Deep Dynamic Compaction. RIC is rapid, cost effective and can reach challenging locations (Charels and Watts, 2002; Kristiansen and Davies, 2004).

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**Table 1.** Soil behavior type (Lunne et al., 1997).

| SBT zones | SBTn** zones |
|---|---|
| 1 Sensitive fine grained | 1 Sensitive fine grained |
| 2 Organic soil | 2 Organic soil |
| 3 Clay | 3 Clay |
| 4 Clay and silty clay | 4 Clay and silty clay |
| 5 Clay and silty clay | 5 Silty sand and sandy silt |
| 6 Sandy silt and clayey silt | 6 Sand and silty sand |
| 7 Silty sand and sandy silt | 7 Sand |
| 8 Sand and silty sand | 8 Very dense/stiff soil* |
| 9 Sand | 9 Very dense/stiff soil* |
| 10 Sand | |
| 11 Very dense/stiff soil* | |
| 12 Very dense/stiff soil* | |

*Heavily over consolidated and/or cemented. **Soil behavior type (Normalized), SBT (Lunne et al., 1997). SBTn Index, $I_c$: $I_c = ((3.47 - \log Q_{t1})^2 + (\log F_r + 1.22)^2)^{0.5}$; Where: Normalized cone resistance, $Q_{t1}$: $Q_{t1} = (q_t - \sigma_{vo}) / \sigma'_{vo}$, Total cone resistance, $q_t$ (MPa): $q_t = q_c + u\,(1\text{-}a)$; Normalized friction ratio, $F_r$ (%): $F_r = f_s / (q_t - \sigma_{vo}) \times 100\%$; Friction Ratio, $R_f$ (%): $R_f = (f_s/q_t) \times 100\%$.

The objective of this study was to assess the performance of RIC in ground improvement using *in situ* testing. The most important tool for deciding, which soils can be improved by dynamic methods is the cone penetration test (NCHRP, 2007). Pre treatment and Post treatment penetration testing was conducted to assess the depth and degree of improvement achieved. Effective improvement depth and factors affecting that depth were discussed. A formula for calculating the effective depth is presented based on the formula for dynamic compaction, in which the energy applied is the main parameter. An interpretation software (CPeT-IT) based on Lunne, (1997) was used in this study for data analyses. Data from Vibration monitoring was collected in terms of peak particle velocity to examine the effect of the RIC machine vibrations on the existing railway track at the treated sites and to assess whether the vibrations are within the limitations stated by the standards in their effect on existing structures.

It was found that with the compaction energy chosen for this site, the method achieved the required improvement to a 5.0 m depth in granular soils where the soil condition was uniform with depth. Vibration monitoring proved that the method is environmentally friendly based on the measurement of peak particle velocity (mm/s) of vibrations caused by RIC machine, which proved to be less than vibrations caused by crossing train and less than standard limits for vibrations effect on adjacent structures.

## Soil and groundwater conditions

In general, the soil at the subject site comprised mainly of sand and silty sand, based on the normalized soil behavior type classification (SBTn) (Table 1) (Lunne et al., 1997), through the investigated depth, which extended to 10 m. Figures 1 and 2 shows the geotechnical section at project site and test area, respectively and also indicates the existence of soft layers with different thickness within the center of the project site, which affected the depth of improvement. Groundwater was at depth of 0.5 m from the ground surface.

## METHODOLOGY

Based on soil condition, Rapid Impact Compaction (RIC) was adopted to treat the loose granular soils at the subject site by compacting the ground with 7 ton ram, 35 blows/min and drop height of 0.8 m. The soil improvement was assessed by comparing the cone tip resistance of pre treatment and post treatment CPT soundings. An interpretation of soil properties from CPT was made using interpretation software (CPeT-IT) based on Lunne et al. (1997) to assess the degree and depth of improvement achieved. Pre treatment and post treatment cone tip resistance were obtained according to the plan as follows:

1. The construction site was divided into (10.00 × 10.00 m) area to carry out the soil compaction by RIC.
2. Pretreatment CPT is to be conducted at the center of each area. The results of the pre-treatment tests shall be used as the basis to determine the degree of improvement achieved.
3. To carry out the RIC work as specified and all parameters should be recorded including, energy applied, spacing and grid of the compaction points, number of passes required to achieve the specified improvement and average enforced settlement. Three Test areas where treated with application of different energy to assess the degree of improvement achieved.
4. To carry out post treatment field testing at the center of the treated area to establish the range of improvement achieved.
5. Based on the pre treatment and post treatment CPT soundings, the proper parameters of the energy applied to achieve the required improvement in terms of number of blows and drop height are decided based on the ground response to compaction and degree of improvement in soil properties.
6. Vibration monitoring was conducted to establish the range of

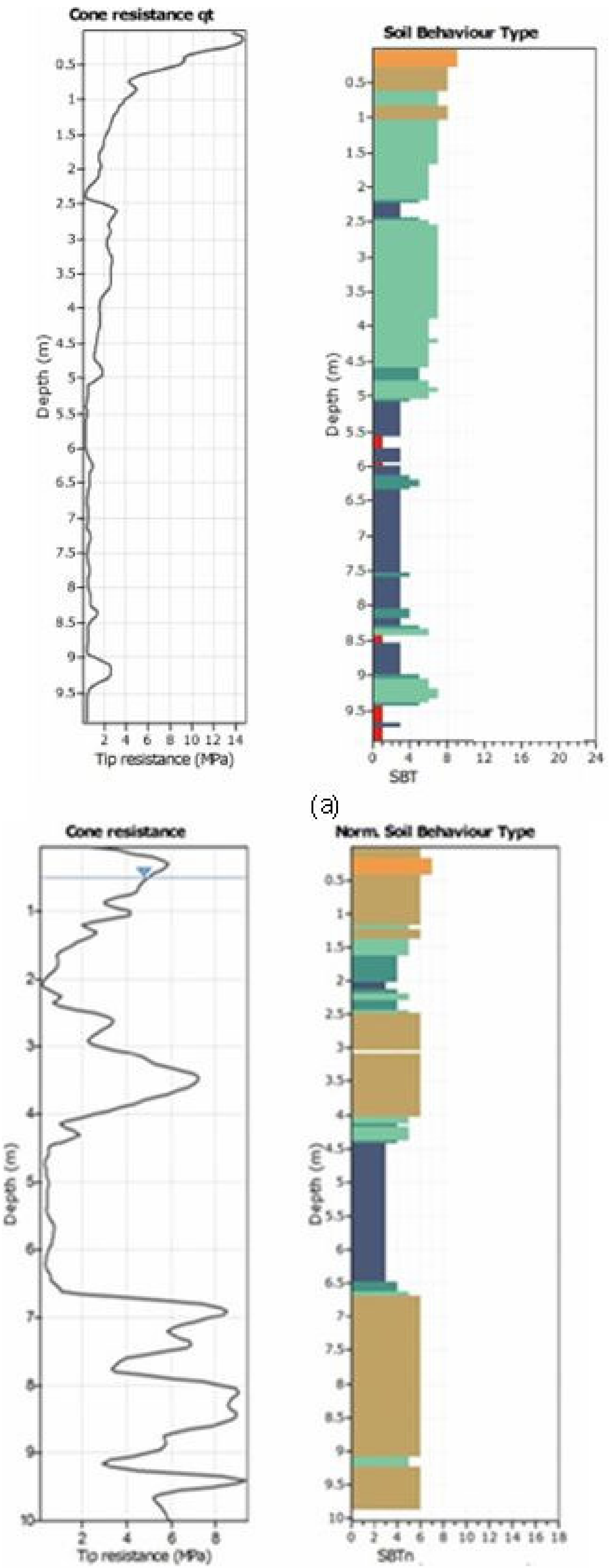



**Figure 1.** Pre-Treatment CPT Results and Soil profile at the project site. (a) soil profile at CPT 29 & 30A, (b) soil profile at CPT 54.

vibrations created by the equipment and their effect on the adjacent structures. Ground vibrations from RIC machine and Train crossing were monitored on the ground surface at various distances from the railway track in terms of peak particle velocities (PPV) to compare the effect of the RIC machine vibrations on the existing railway track at the treated site.

Measurements made before and after treatment provides an indication of the effectiveness of the treatment in improving properties and the depth to which improvement has been achieved. CPT measurements are correlated with density index and hence used to characterize how much improvement is attained by the soil in terms of shear strength, compressibility and settlement.

## RESULTS

Figures 2 and 3 shows how much improvement was attained by the soil with depth in terms of the increase of total cone resistance. The improvement achieved is based on soil uniformity with depth, and energy applied, which is a function of ram weight (kept constant to 7 ton), drop height and number of blows per minute.

### Effective improvement depth

The improvement depths achieved at nine locations within the project area are listed in Table 3, values presented in the table were obtained from the comparison of pre treatment and post treatment soil properties with depth, as the increase of cone tip resistance (Figure 3), led to an improvement of soil properties estimated from data interpretations (Table 2). A minimum increase of 30% in soil properties is considered the minimum accepted improvement. At the test area, Improvement depth was 5.8 and 7.2 m for areas treated with 40 blows, drop height of 1.0 and 50 blows, drop height of 1.2 m, respectively (Figure 2).

### Improvement depth formula

The improvement depths from field observations based on CPT were compared with the results obtained from Equation (1). The formula in Equation (1) is derived from the equation used in calculating the depth of improvement for ground treated with dynamic compaction (Robert, 1995) and number of blows ($N_b$) been added to the original equation, as it is an important parameter of the energy applied to the soil during compaction process:

$$D = n\,(W.H.N_b)^{0.5} \qquad (1)$$

Where:

$D$ = depth of improvement in meters.
$W$ = mass of tamper in tone
$H$ = drop height in meters.
$n$ = empirical coefficient that is less than 1.0
$N_b$= number of blows.

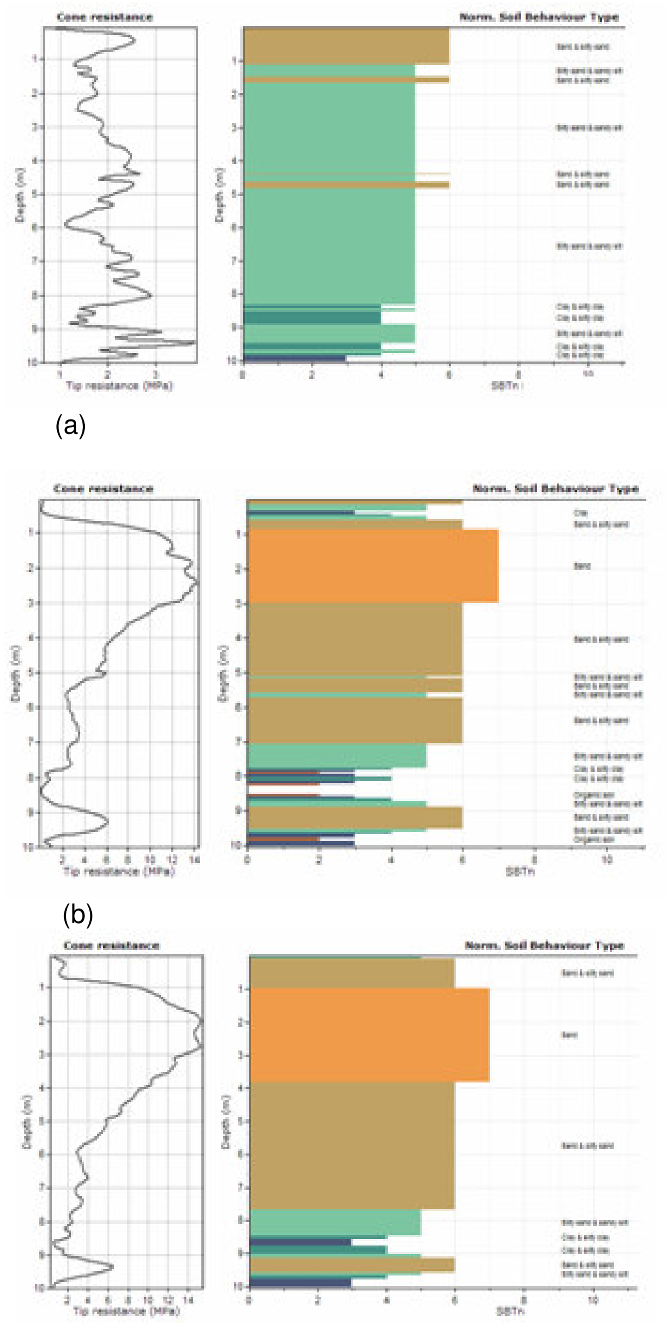



**Figure 2.** (a) Pre- Treatment CPT and Soil profile at Test Area. (b) Post-Treatment CPT Results for area treated with 40 blows and 1.0 m drop height. (c) Post Treatment CPT Results for area Treated with 50 blows and 1.2m drop height.

### The presence of hard or soft layers effect on the depth of Improvement

At some locations, the Presence of hard or soft layers would affect the improvement depth. If there is an energy absorbing layer such as weak saturated clay within the soil mass (Figure 3b), the depth of improvement will be reduced to an extent that is dependent upon the thickness of the layer and the position within the soil deposit as shown in Table 4.

A hard layer at ground surface could restrict the amount of energy transferred to the deeper layers. At certain part of the project site where thick crust of densified material is present (an old road exists), it was necessary to loosen the surface layer to allow the energy to be transmitted to greater depths. This was done by the RIC machine itself as shown in Figure 4.

### Vibrations

Vibrations monitoring at CPT 54 near the railway track in term of peak particle velocity (PPV) were recorded, measurement locations, distance to source of vibration, action caused by vibrations and values, are listed in Table 5. The values obtained will be used first to assess the effect of the RIC on adjacent structures compared to train crossing and whether the vibration are within the limits of available standards on implementing the technique in urban areas.

## DISCUSSION

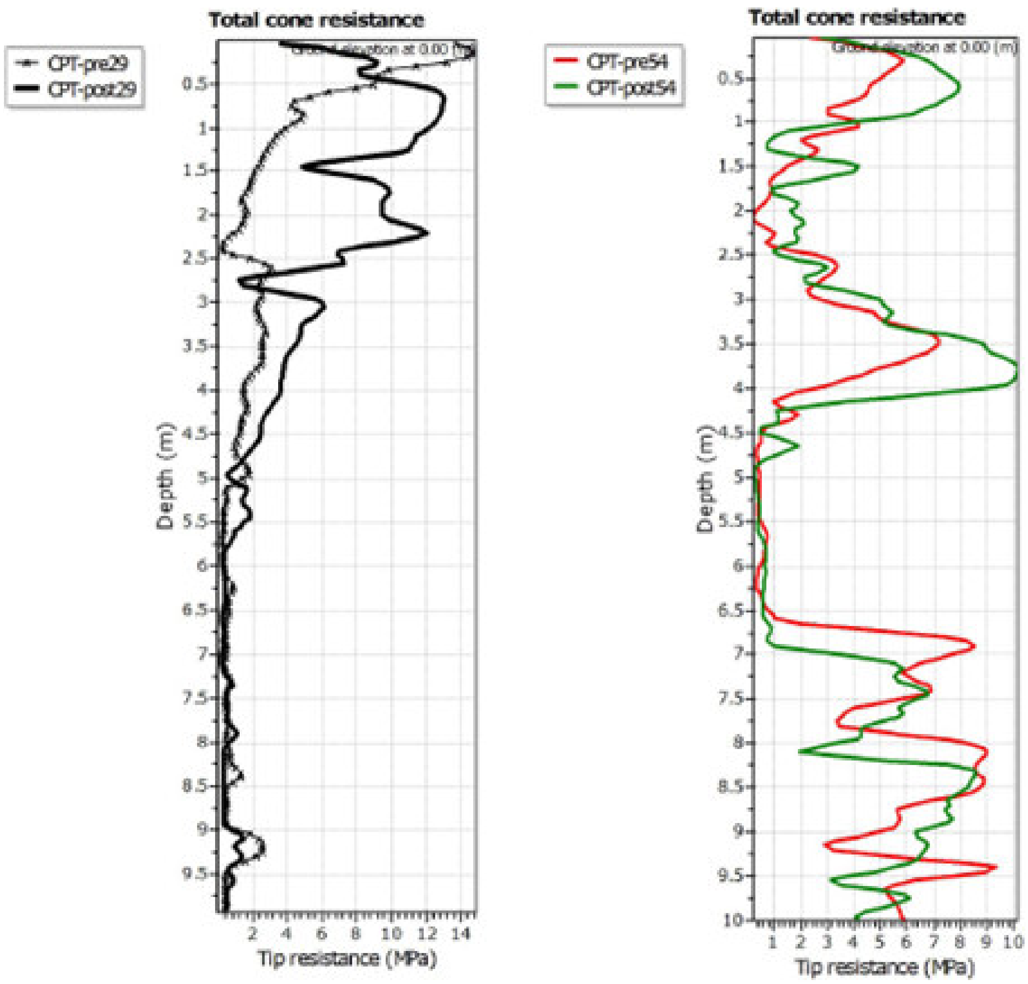
### Improvement in soil properties

Following treatment with RIC, confirmatory testing was conducted using CPT. The increased in the post-treatment tip cone resistance relative to the pre-treatment tip resistance showed that treatment with RIC resulted in a significant improvement in soil properties, that is, a minimum increase of 30% soil properties was obtained (Table 2), to at least 5.0 m depth (Figure 3a), unless affected by the existence of energy absorbing layer such as weak saturated clay within the soil mass, which reduces the improvement depth (Figure 3b). Improvement extended to about 6.0 and 7.0 m for areas treated with 40 and 50 blows, respectively as shown in Figure 2.

### Improvement depth

RIC succeeded to improve the soil properties at the project site with the energy applied, but the depth of improvement differed from one location to another depending on the following conditions:

1. Clayey layers with thickness ranging from 2.00 - 4.00 m exist at different locations within the depth. The existence of such soil layer acts as an energy absorbing layer, which influenced the effective improvement depth at certain locations (Table 4).
2. Improvement depth for the area treated with 35 blows and drop height of 0.8 m from Equation (1) is 4.90 m, for areas treated with 40 blows and drop height 1.0 m is 5.8 m, and 50 blows with drop height of 1.2 m is 7.2 m.




**(a)** **(b)**

**Figure 3.** Overlay Drawing of Pre treatment and post treatment cone resistance at project site. (a) At CPT 29 & 30A; (b) at CPT 54.

Results obtained showed the applicability of the formula at locations where the soil stratums are uniform, homogeneous, and mainly of granular nature at CPT29, CPT30A and for the test areas Figure 2.
3. Clayey layers with shallow depths of about 0.5 m and below did not affect the results, while thick layers within the depth make this formula to be invalid for calculating the improvement depth.
4. If the energy absorbing layer is relatively thick (more than 2.0 m) and located within the center of the loose deposit, the depth of improvement will not extend below the depth of the weak layer (Table 4). If the weak layer is close to the surface of the deposit and is not very thick, it is possible that the tamper will penetrate through the layer and deliver the energy to the underlying loose deposits.
5. A hard layer on the ground surface could restrict the amount of energy transferred to the deeper layers and it is necessary to loosen the surface layer to allow the energy to be transmitted to greater depths (Figure 4).

### Vibration monitoring

Peak particle velocity was measured from the center of the 1.5 m diameter RIC foot on the ground surface. Results showed that vibrations caused by RIC machine are considerably lower than train crossings (Table 5). In addition, values obtained showed that the peak particle velocity is within the limits of BS 7385: Part 2:1993, which was considered for the evaluation of vibrations at this project. A further evaluation was made in this paper with other standards available for the Vibration criteria of compaction projects like that of Siskind et al. (1980) and New (1986) who put forward representative vibration criteria from different countries, standards, structures or object type with the location of measurements,

**Table 2.** Pre Treatment and Post treatment soil properties.

| CPT | Pre – treatment total cone resistance-MPA | Post treatment total cone resistance-MPA | Pre – treatment sleeve friction-kPa | Post -treatment sleeve friction-kPa | Pre – treatment N60-blows | Post treatment N60-blows |
|---|---|---|---|---|---|---|
| 29 | 3.25 | 6.6 | 24.48 | 32.88 | 6.2 | 11.49 |
| 30A | 2.66 | 7.08 | 14.46 | 38.78 | 5.01 | 11.92 |
| 39A | 6.36 | 11.28 | 30.71 | 81.73 | 10.86 | 19.21 |
| 40 | 5.49 | 9.93 | 18.93 | 45.91 | 9.46 | 16.50 |
| 45 | 4.78 | 13.52 | 12.63 | 52.85 | 8.11 | 21.56 |
| 46 | 9.28 | 12.43 | 66.63 | 55.53 | 15.86 | 20.34 |
| 54 | 3.31 | 4.67 | 13.97 | 28.96 | 6.06 | 8.45 |
| 58 | 2.02 | 5.72 | 8.01 | 26.18 | 3.84 | 9.87 |
| 64 | 3.14 | 4.31 | 15 | 27.82 | 5.7 | 7.89 |

| CPT | Pre - treatment Dr% | Post -treatment Dr% | Pre – treatment friction angle-degree | Post treatment friction angle-degree |
|---|---|---|---|---|
| 29 | 45.66 | 64.64 | 40.80 | 44.46 |
| 30A | 44 | 57.74 | 40.55 | 43.70 |
| 39A | 63.64 | 81.12 | 44.57 | 47.93 |
| 40 | 61.24 | 80.04 | 45.38 | 47.94 |
| 45 | 59.84 | 87.78 | 43.80 | 48.41 |
| 46 | 71.80 | 86.27 | 46 | 48.02 |
| 54 | 52.17 | 58.43 | 43.58 | 44.25 |
| 58 | 38.52 | 63.91 | 39.79 | 44.81 |
| 64 | 54.28 | 60.46 | 43.06 | 45.14 |

**Table 3.** Effective improvement depth from at site confirmed by CPT test.

| CPT location | 29 | 30A | 39A | 40 | 45 | 46 | 54 | 58 | 64 |
|---|---|---|---|---|---|---|---|---|---|
| Estimated Improvement Depth(m) | 5.0 | 5.0 | 4.0 | 3.5 | 3.5 | 4.0 | 4.0 | 3.5 | 3.5 |

**Table 4.** Thickness and Location of the weak saturated clay layer within the treated area.

| CPT location | Improvement depth (m) achieved based on CPT | Thickness of weak saturated clay (m)* | Location of the weak saturated clay, depth (m) |
|---|---|---|---|
| 39A | 4.00 | 4.00 | 4.0 - 8.0 |
| 40 | 3.50 | 3.00 | 3.0 - 6.5 |
| 45 | 3.50 | 2.50 | 3.5 - 6.0 |
| 46 | 4.00 | 2.00 | 4.0 - 6.0 |
| 54 | 4.00 | 3.00 | 4.0 - 7.0 |
| 58 | 3.50 | 3.00 | 3.5 - 6.5 |

Eliminating the improvement from extending to greater depth.

frequencies, and the peak particle velocity (mm/sec). The values obtained at site for the vibrations caused by the Rapid Impact Compaction machine were lower than the lower limit accepted by all the aforementioned standards even for sensitive structures. Compared to Dynamic Compaction, the vibrations caused by RIC machine clearly show the advantage of maintaining the RIC foot in contact with the ground to optimize the transfer of energy during the compaction process.

## Conclusion

The results show significant increase of cone tip

**Figure 4.** Hard layer at the surface of the treated area.

**Table 5.** Sample of vibrations monitoring details at project area.

| Monitoring location, date and time | Vibration source | PPV (mm/s) | Action |
|---|---|---|---|
| CPT 54 (No.1); 17/05/2007 10:14:08am - 10:34::57am | At 5 m from the center of railway track | 2.43 | During piling machine compaction |
| CPT 54 (No.2); 17/05/2007 10:36:51am - 10:54:32am | At 5m from the center of railway track | 2.75 | During piling machine compaction |
| CPT 54 (No.3); 25/05/2007 22:19:16 pm - 22:21:15 pm | Besides railway track | 15.15 | During logistic train crossing |
| CPT 54 (No.3); 25/05/2007 22:47:42 pm - 22:50:50 pm | Besides railway track | 10.67 | During logistic train crossing |
| CPT 54 (No.4); 26/05/2007 00:22:26 am - 00:26:37 am | Besides railway track | 27.18 | During passenger train crossing |

resistance which demonstrates decrease of compressibility:

1. Effective improvement depth

a) The technique was successful to improve soil properties as depths reaches up to 7.0 m depending on energy applied and where the soil layers were mainly of uniform homogenous granular nature at test area.
b) The formula presented by this study: {D = n $(W.H.N_b)^{0}$.5} to calculate the improvement depth proved to be applicable and correct for granular soils that were uniform with depth. It is also found that the formula will be invalid when thick clayey layers exist within the center of the treated area.
c) Clayey layers with thickness equal to or less than 0.5 m did not affect the improvement depth and the results obtained from the formula.
d) Clayey layers with thickness greater than 2.00 m and located within the center of the loose deposit, cause the depth of improvement not to extend below the depth of the weak layer.
e) The presence of a hard layer at the ground surface, limit the amount of energy transferred to deeper layers. Such layers should be removed before starting the treatment process.

2. Rapid Impact Compaction proved to be environmentally friendly and have very limited effect on adjacent structures, which allows the use of this improvement technique at urban areas. Vibrations caused by the RIC machine were measured in terms of peak particle velocity

(PPV) and found to be 2.43 mm/s at 5 m from the railway track, which is less than those measured for train crossings and also lies within the safe and allowable limits of vibration stated in the standards.

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