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# A case study on energy-based evaluation of deep vibro compaction method

## Une étude de cas sur l'évaluation basée sur l'énergie de la méthode de compactage par vibration profonde

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**ABSTRACT**: This case history describes a well-documented and recently completed project in the Caribbean consisting of densification of hydraulic fills by vibro compaction method. The results of compaction are discussed based on energy criteria. The project site covers approximately 13,500 $m^2$ with an average depth of 9.5 m are densified to a minimum relative density of 65% against liquefaction. Soil classification for initial state of the hydraulic fills is investigated based on CPTU tests. Before the commencement of the works, vibro compaction parameter tests were carried out in 3 different test areas. The physical properties of the hydraulic fill and the details of the densification applications are presented. A comprehensive quality control program was pursued in the project. The successful execution of works illustrates the effectiveness of the selected method. In this study, the total amount of compaction energy transferred per unit volume of loose hydraulic fill, corresponding increase in cone resistance ($\Delta q_c$), the grid spacing, the vibro compaction production time are presented for each type of soil and results are presented.

**RÉSUMÉ**: Cette étude de cas décrit un projet bien documenté et récemment achevé dans les Caraïbes, qui consiste à densifier des remblais hydrauliques par la méthode du vibrocompactage. Les résultats du compactage sont discutés sur la base de critères énergétiques. Le site du projet couvre une superficie d'environ 13,500 $m^2$ et le sol y est densifié jusqu'à une profondeur moyenne de 9.5 m et une densité relative minimale de 65% contre la liquéfaction. La classification du sol pour l'état initial des remblais hydrauliques est étudiée sur la base des résultats de l'essai de pénétration au piézocône (Piezocone Penetration Test CPTu). Avant le début des travaux, des essais sur les paramètres de vibrocompactage ont été effectués dans 3 différentes zones d'essai. Les propriétés physiques des remblais hydrauliques et les détails des travaux de densification sont présentés. Un programme compréhensif de contrôle de la qualité a été mis en place dans le cadre du projet. L'exécution satisfaisante des travaux illustre l'efficacité de la méthode choisie. Dans cette étude, la quantité totale d'énergie de compactage transférée par unité de volume de remblai hydraulique meuble, l'augmentation correspondante de la résistance du cône, ($\Delta q_c$), l'espacement des grilles, le temps de production du vibrocompactage sont présentés pour chaque type de sol et les résultats pertinents sont indiqués.

**Keywords:** Hydraulic fill; compaction energy; vibro compaction; liquefaction; cone Penetration Test (CPT).

## 1 INTRODUCTION

The proposed port in the Caribbean has been under operation since 1929. Due to the development of the maritime transport methods and port facilities in the recent years, a development plan was implemented for future port layout design to meet traffic demand through 2020.

The project involves the redevelopment of the existing port. The project will enhance the passenger experience and provide additional business opportunities for the local population. The project will also include the construction of a new terminal building; the creation of an event and entertainment area; investments in retail facilities; and the design and construction of new food and beverage facilities. The project consists of expansion of the existing cruise pier, combi-wall driving works on existing wharf, construction of two new marinas for tour boats, dredging, densification of dredged hydraulic fill by vibro compaction method, expanding the port area by reclaiming and renovating & refurbishing of existing piers, arrival building, museum, signature restaurant, amphitheatre, 3 pier buildings, canopies, town square, market place, landscape works and all relevant construction, mechanical, electrical and architectural activities.

With the completion of all construction activities, the renovated port is expected to welcome over 4 million passengers annually. The location and general layout of the project site are shown in Figure 1.

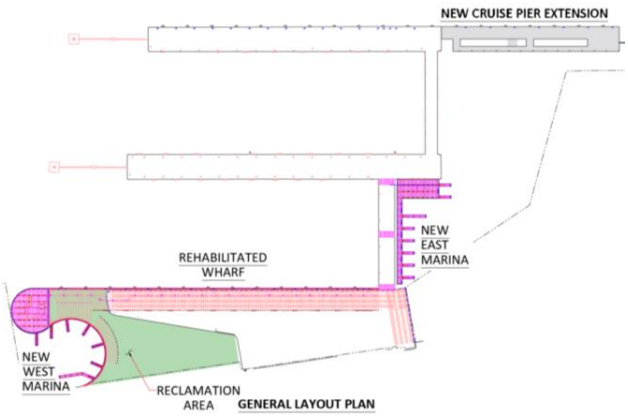



*Figure 1. General layout of project site.*

## 2 SUBSOIL CONDITION AND DREDGING WORKS

A total of five boreholes were carried out within the scope of preliminary soil investigations in the project area. Among these boreholes, B-5 and B-7 were carried out on the land side, and B-4, B-6, and B-9 boreholes were carried out on the sea side. Samples from soil and rock layers were taken by the Standard Penetration Test (SPT) and NQ rock coring. Borehole layout plan given in Figure 2.




*Figure 2. Borehole layout plan.*

The idealized soil profile of the proposed project site and BIM model of seabed are shown in Figure 3. For onshore boreholes, the groundwater elevations are typically the same as the sea level in the adjacent port area.

The project consists of a construction of a 250-meter-long pier extension to the east of the northernmost existing cruise ship pier and the reclamation of the quay area at the south end of the port, between the pier structure and the coastline, by filling with hydraulic fill sand. A new combi-wall consisting of steel pipe piles and sheet piles was constructed in front of the existing combi-wall system to renovate the existing system. Behind the combi-wall, dredged loose granular hydraulic fill material covering an area of approximately 13,500 m$^2$ with an average depth of 9.5 m was placed. Then the hydraulic fill was compacted by vibroflotation method to achieve a minimum relative density of 65%.

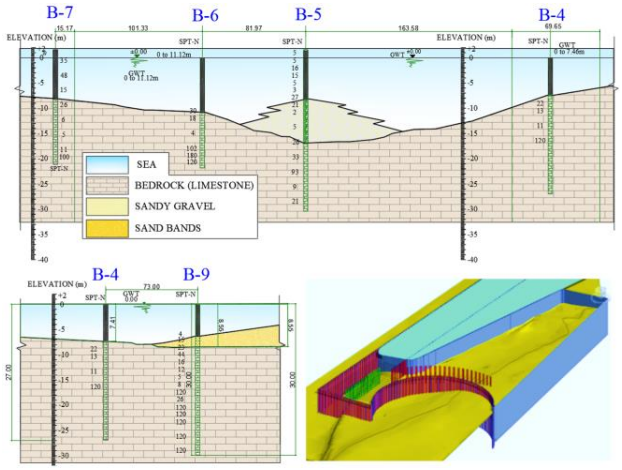



*Figure 3. Idealized soil profile and BIM model of seabed.*

In total, approximately 127,530 m$^3$ of loose granular fill material was dredged from the seabed and transported to the reclamation area by pipelines. Double rows of silt curtains are installed on the outside of the combi-wall to reduce and limit turbidity.

### 2.1 Evaluation of Fill Material Quality

Two methods were used to evaluate the quality of fill material. In the first evaluation method, with the help of the relation developed by Brown (1977), the suitability of the fill material for vibro compaction method was determined according to the soil grain size:

$$SN = 1.7\sqrt{\frac{3}{D_{50}{}^2} + \frac{1}{D_{20}{}^2} + \frac{1}{D_{10}{}^2}} \qquad (1)$$

where D50 is the diameter of the grain through which 50% of the soil passes, D20: It is the diameter of the grain through which 20% of the soil passes. D10: It is the diameter of the grain through which 10% of the soil passes. The suitability numbers method is an accepted and widely used method used to decide on the improvement of the fill material by the vibro compaction method. It is stated that vibro compaction is suitable for fill materials where the suitability numbers are in the range of 1 to 30.

The preliminary evaluation of the samples taken from the hydraulic fill from the project site area shows that suitability of the hydraulic fill is good to excellent. The results of the sieve analysis and suitability numbers (SN) performed on 13 samples taken from the filling area are summarized in Figure 5.

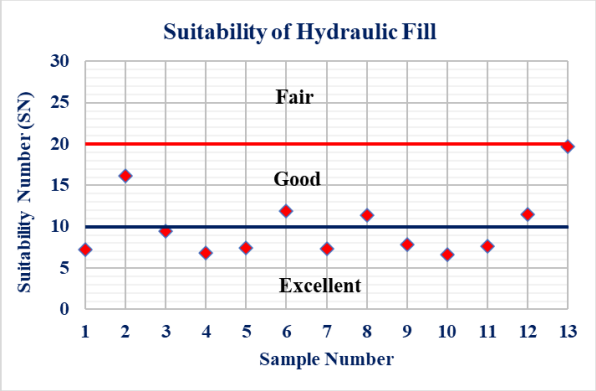



*Figure 4. Suitability number of hydraulic fills.*

In the second method, the results of the two pre-CPT tests performed in the center of the reclamation area were evaluated for compactability of the hydraulic fill by using the method proposed by Massarsch (1991). The results show that the hydraulic fill is marginally compactible to compactible as shown in the Figure 5.

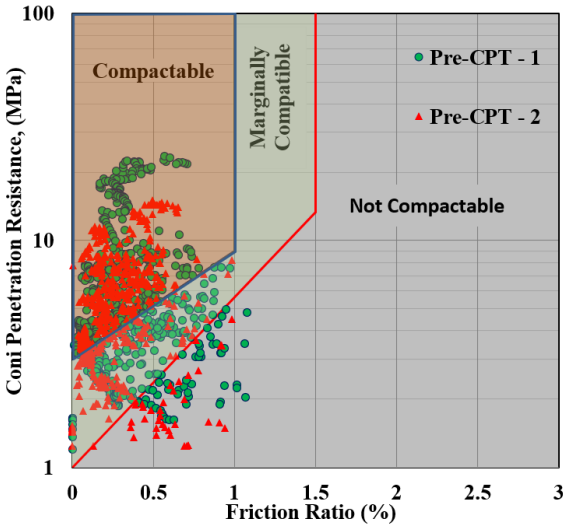



*Figure 5. Compatibility assessment of hydraulic fill.*

## 3 FULL-SCALE FIELD TESTS

To verify the installation parameters of vibro compaction works, preliminary tests were performed at a designated test area before the commencement of the works. In the test area, different grids of vibro compaction were tested with an equilateral triangular grid of 3.25x3.25m, 3.50x3.50m and 3.75x3.75m. These grid configurations were chosen to assess the performance of the vibro compaction method under different grid spacing. Before the tests, pre-CPT (Cone Penetration Test) were performed at the center of the test area for evaluating the initial state of the hydraulic fill.

Post CPT tests were performed ten days after the completion of the vibro compaction application. The layout plan for full scale preliminary tests is shown in Figure 6.

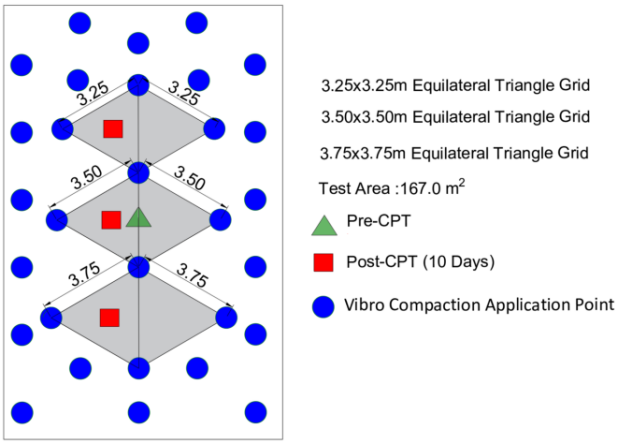



*Figure 6. Layout plan for full scale preliminary tests.*

Since the hydraulic fill is marginally compactible a double pass application method was introduced and tested. The double pass method consists of two passes over the same location by using vibroflot as shown in Figure 7. This approach is commonly employed to achieve a higher degree of compaction compared with single pass method.

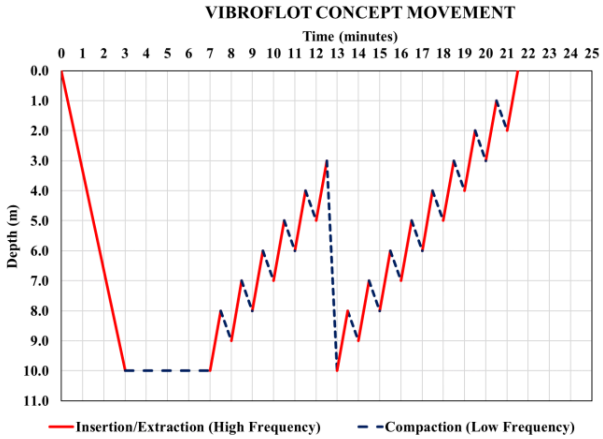



*Figure 7. Vibro compaction with double pass method.*

CPTs performed before and after the densification by vibroflotation method and the energy applied to the soil in the vicinity of CPT test location (TA-7) are shown in Figure 8.

In order to measure and evaluate the effectiveness of vibro compaction application, production parameters were recorded with the help of a full-time electronic data collection unit. Using the obtained data, compaction energy was calculated precisely along the depth. The correlation developed by Baldi et al. (1986) was used to convert the targeted relative density value

into the equivalent cone end resistance with overburden pressure correction.

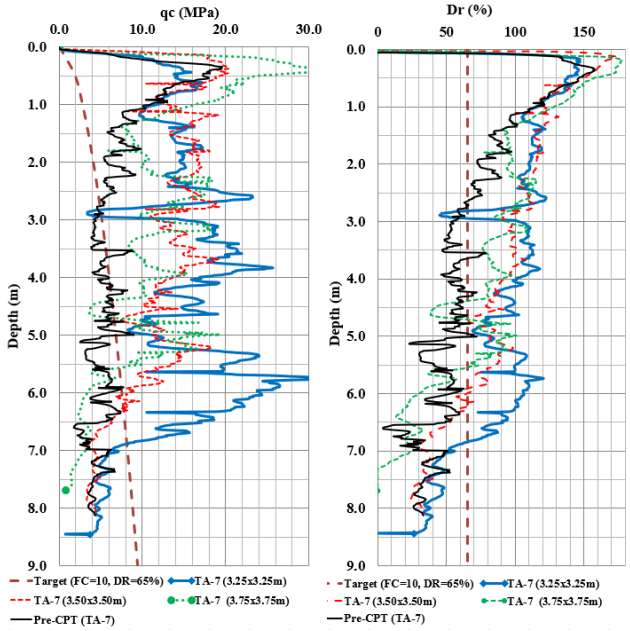



*Figure 8. Cone penetration test results of TA-7.*

Vibro compaction application with double passes and CPTs were performed using different grid spacing. According to the post-CPT results, all applications using the double pass method fulfils the target cone tip resistance and average relative density criteria (65%), and an average increase in cone tip resistance was obtained between 65% and 124%. The results of the full-scale field experiment using different grid spacings are summarized in Table 1.

*Table 1. Full-scale field tests results.*

| Grid Spacing (m) | Avg. Depth (m) | Average Compaction Energy (kJ/m$^3$) | Δqc (Mpa) | Δqc (%) |
|---|---|---|---|---|
| **3.25** | 8.80 | 2201.85 | 7.67 | **124%** |
| **3.50** | 8.50 | 1843.09 | 5.67 | **91%** |
| **3.75** | 8.00 | 1737.38 | 4.01 | **65%** |

In vibro compaction works, an optimization is required for production parameters in order to optimize production time and grid spacing. After determining the targeted improvement rate, the compaction energy that needs to be transferred to the fill material can be calculated with the help of the relationship given below. Since compaction energy is calculated using vibro compaction application parameters, this relationship can be used to evaluate whether the parameters are chosen correctly. As a result of the preliminary tests carried out in three different areas within the proposed site, a 93.8% linear correlation was obtained between the increase in cone tip resistance (Δqc) and compaction energy. The relationship between compaction energy and increase in cone tip resistance (Δqc) is given in Figure 9 and equation 2.

$$\Delta qc = 0.0073 x E_c - 8.27 \qquad (2)$$

where Δqc is the increase in tip resistance (Mpa) and Ec is the vibro compaction energy (kJ/m$^3$).

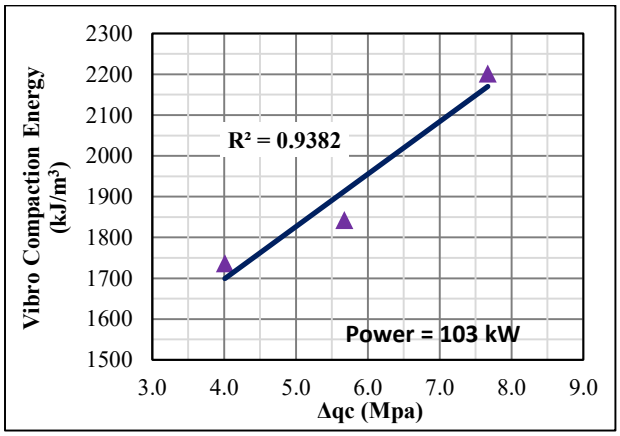



*Figure 9. Relationship between vibro compaction energy and Δqc.*

## 3.1 Evaluation of time-dependent improvement rate

An additional in-situ preliminary field test was conducted in Test Area-4 to evaulate time-dependent improvement behaviour after completion of vibro compaction works. The general layout plan of the test area is shown in Figure 10.

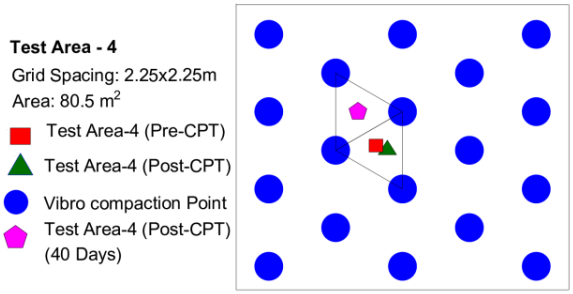



*Figure 10. Layout of test area-4.*

The time dependent behaviour is shown in Figure 11 by comparing pre-CPT, 2-day, 10-day, and 40-day Post-CPT cone tip resistance with depth.

According to the 40-day post Cone Penetration Test (CPT) results, in vibro compaction applications using a high-pressure water jet, the water jet initially increases the pore water pressure in the soil. After the completion of the compaction process, the pore water

pressure starts to decrease over time, and soil particles come closer together. As the excess pore water pressure in the soil diminishes over time, the cone tip resistance is observed to increase gradually because the soil particles transit to a denser arrangement pattern. The rate and magnitude of time-dependent improvement varies depending on various factors, such as the soil permeability, coefficient and drainage conditions.

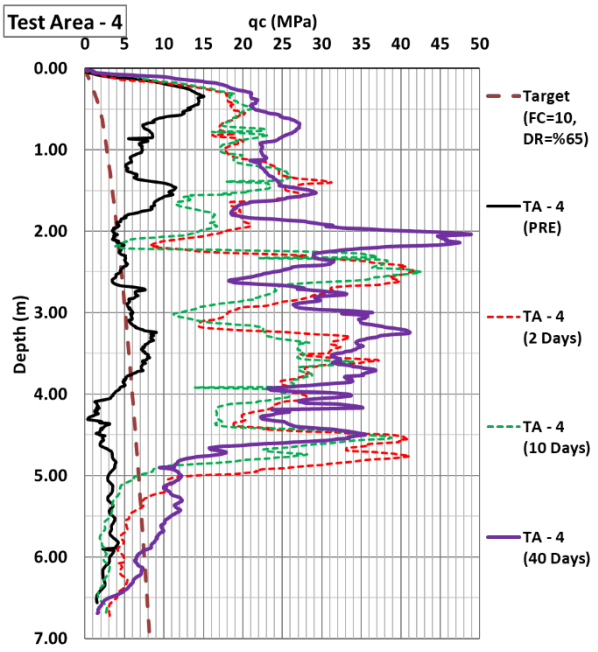



*Figure 11. Cone penetration test results of TA-4.*

It was determined that there was an increase in average cone tip resistance along the depth in the Cone Penetration Test conducted 40 days after the vibro compaction application. Thus, results support and confirm other studies conducted in this context in the literature.

## 4 CONCLUSION

This study emphasized the importance of selecting correct relationship between improvement rate and energy consumption per unit soil volume in vibro compaction applications. This would enhance the efficiency of quality control and design processes, while also offering advantages in terms of cost, quality control and work schedule in large-scale soil improvement projects.

Within the scope of this study, the initial engineering properties of the filling material acquired by dredging from the seabed and placed hydraulically in the reclamation area, the details of the seabed dredging application, the details of the vibro compaction application, the details of the full-scale field experiment carried out from the reclamation area, and the results obtained are explained.

In the double-pass vibro compaction application, in which three different grid spacings are realized with equilateral triangle grid spacing, it has been observed that the cone tip resistance decreases with the increase in the grid spacing.

The study investigated the correlation between the energy applied during vibro compaction, the resulting CPT tip resistance values, and the actual improvement rate of the soil. This analysis aimed to assess the effectiveness of the vibro compaction method in achieving the desired improvement rate in soil engineering properties.

The correct handling of the relationship between the improvement rate and the energy consumed per unit soil volume in vibro compaction applications is believed to enhance the efficiency of the quality control and design processes. By optimizing this relationship, it is possible to achieve desired improvements in soil properties.

The results obtained from the study are expected to significantly contribute to the design and quality control processes in large-scale soil improvement projects. These findings likely provide insights into the relationship between energy consumption, improvement rates, and soil performance, allowing for more efficient and effective planning and execution of vibro compaction projects.

Overall, the study emphasizes the importance of proper handling of energy consumption and improvement rates in vibro compaction applications. By ensuring the correct balance and understanding of this relationship, advantages can be gained in terms of cost-effectiveness, quality control, and adherence to work schedules in large-scale soil improvement projects.

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