Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-1521

Densification of hydraulic fills by vibroflotation technique

Compactage des remblais hydrauliques par la tecnique de vibroflotation

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ABSTRACT

This case history describes the densification of hydraulic fills by vibroflotation method. A total of 1,034,000 m^3 of hydraulic fills covering an area of 181,000 m^2 are densified to a minimum relative density of 70%. Soil classification for initial state of the hydraulic fills is investigated based on CPTU test results. The physical properties of the hydraulic fills and the details of the densification works are presented and the results of the quality control tests are discussed. Compaction energy and corresponding increase in cone resistance, Δq_c are examined for different type of soil and results are presented.

RÉSUMÉ

L´étude a pour objet le compactage des remlais hydrauliques. L´objectif à atteindre était le compactage à une compacité de 70% d´un remlai de 1.034.000 m^3 de volume réalisé sur une superficie de 181,000 m^2 . La classification initiale des sols est basée sur les resultats des essays CPTU. L´étude montre les caractéristiques, les remblais hydrauliques, les détails du procédé de compactage, ainsi que les aspects du contrôle de qualité des travaux. On y trouvment l´analyse de la relation entre l´augmentation de la résistance en pointe ($\Delta q_{c)}$ pour chacum de type de sol examiné.

1 INTRODUCTION

This case study presents the densification of hydraulic fills placed behind quay walls by vibroflotation method. A development plan was imposed for the port, which has been under operation in Mediterranean Sea so as to meet the planned future traffic demands.

The development works consist of the extension of the main breakwater by 1,150 m, 1,700 m long new general cargo and container quays for the handling of containers, a development of the port's hinder land and vibroflotation works.

2 CHARACTERISTICS OF THE HYDRAULIC FILL

A comprehensive soil investigation programme consists of 13 cone penetration tests (CPTs), 65 borings in the range of 28 m to 100 m with standard penetration tests (SPT) and 20 vibrocore tests with sampling of underwater soil was performed at the proposed site so as to obtain information about the physical properties of material to be dredged and the upper soil layers. Based on the results of the soil investigation programme, the dredged sandy material was approved to be used as hydraulic fill material. The characteristics of the hydraulic fill are as follows :

- Percent by weight passing ASTM sieve no.200 : Max 10%,
- Percent by weight passing 5"-opening ASTM sieve: 100%,
- D_{50} : 0.13 - 0.50 mm

A cutter suction dredger was selected as the most suitable equipment for the execution of the dredging works since the dredged material was dumped into the reclamation areas. The dredged materials were pumped throughout floating and land based pipelines to the reclamation areas. Pipelines and water outlets were installed in several points of the fill areas to provide the adequate settlement of sand and permit silty and clayey material to run off the reclamation areas. A trailing suction hopper dredger was also employed for dredging unsuitable and surplus material and disposal into the open sea.

2.1 *AASHTO Method of Modified Density Tests*

A number of AASHTO method of maximum modified density tests were carried out on samples taken from the hydraulic fill. The observed maximum modified density values vary between the first heading 1860 to 1700 kg/m^3 whereas percentage passing ASTM Sieve No.:200 vary between 5 to 10%.

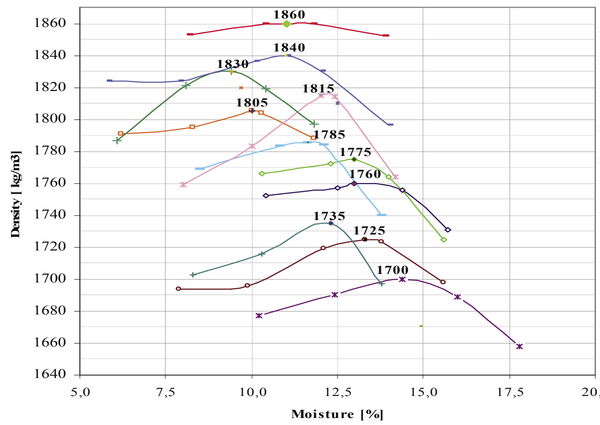


Figure 1. Results of Modified Density on fill samples taken from the hydraulic fill

2.2 *Sieve Analysis Tests*

Sieve analysis tests according to the ASTM E-11 were performed on selected samples, five samples for every 20,000 m^3 of hydraulic fill. The results of sieve analysis show that the fill is Poorly Graded Sand (SP). Average coefficient of uniformity, C_u and coefficient of curvature, Cz of the fill material vary from 2.70 to 4.30 and 0.52 to 1.20 respectively.

The suitability number (S_N) was calculated using the formula suggested by Brown (1977). The suitability number (S_N) calculated ranges from 11.7 to 23.8, with an average of 19.5 which means that the hydraulic fill material is Good to Fair.

3 IN SITU DENSITY OF HYDRAULIC FILL BEFORE DENSIFICATION BY VIBROFLOTATION METHOD

The initial in situ density of hydraulic fills ranges depending on the implemented dredging and placement methods. Static cone penetration test with pore pressure measurement (CPTU) is selected for assessing the initial in-situ density of the hydraulic fills. A total of 17 CPTUs in a designated zone was performed before densification by vibroflotation method (Fig.2).

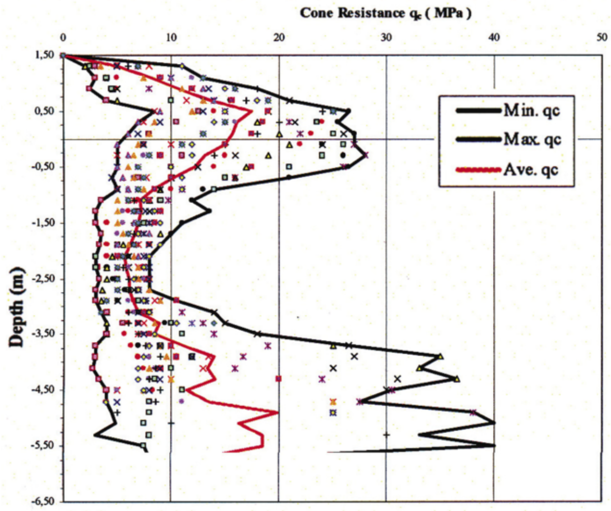


Figure 2. CPTU tests performed BEFORE Densification of Sand Fills

It was encountered that the average cone resistance, q_c value along the depth of hydraulic fill vary from 4.2 MPa to 20.6 MPa with an average value of 10.8 MPa. Since different types of dredgers and placement methods carried out during dredging works, hydraulic fills were encountered as non-homogeneous with an initial relative density of 35 to 55%.

Massarsch (2002) proposed that compatibility of soils can be classified by means of a conventional soil classification chart with the friction ratio along the abscissa and the cone resistance along the ordinate Figure 3 shows the compatibility of hydraulic fills based on the results of 17 no. of CPTUs performed before densification. It was encountered that the initial state of hydraulic fill is compactable to marginally compactable and there are some thin layers of silt and clay.

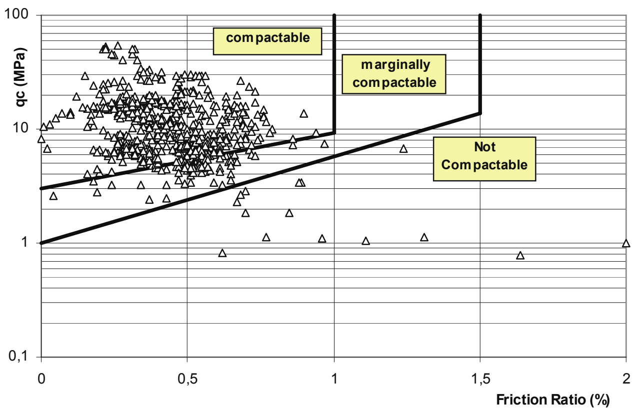


Figure 3. Soil Classification of Deep Compaction based on CPT data (After Massarsch, 1991) on CPTU tests

4 DENSIFICATION WORKS

Since the predicted settlements for the foundations of the various structures are not tolerable and the risk of liquefaction is high, the loose hydraulic fills are required to be densified by vibroflotation method. The hydraulic fills whose thickness vary from 3.0 to 12.0 m are implemented to be densified to a minimum relative density of 70 % down to a depth of 1 m below the existing seabed level.

A 100 kW vibratory probe having a maximum operating speed of 3000 rpm (50Hz) with a corresponding maximum centrifugal force of 400 kN was employed. Installations were carried out with an equilateral triangular grid having a triangular side of 2.0m to 3.0m and a compaction energy was applied depending on the soil type of the hydraulic fill encountered by the CPTUs performed before the densification.

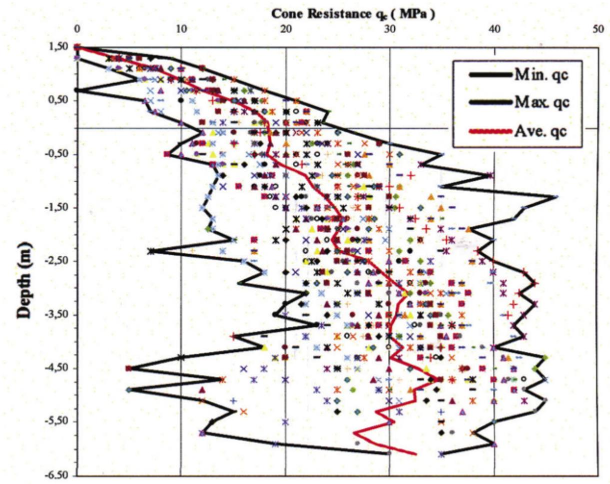


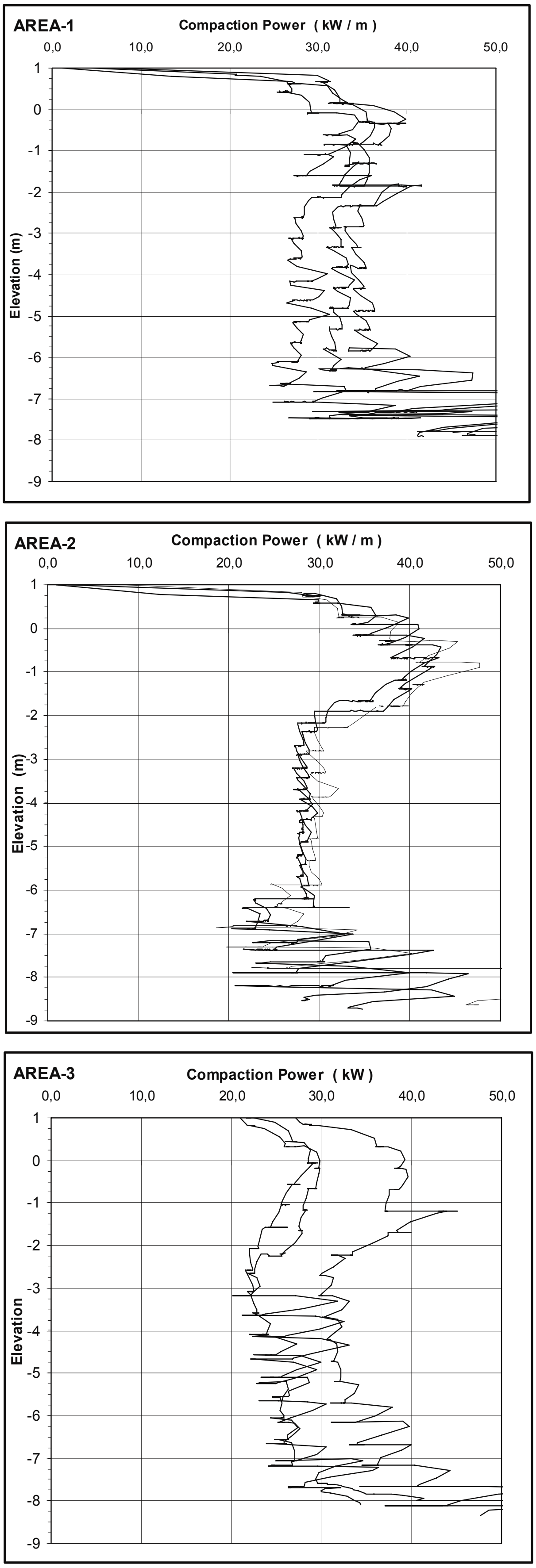
Figure 4. CPTU tests performed AFTER Densification of Sand Fills

After the densification a total of 36 CPTUs in the same designated zone were carried out minimum four days upon completion. (Fig.4) It was encountered that the average cone resistance, q_c value along the depth of hydraulic fill vary from 12.1 to 35.1 MPa with an average value of 23.9 MPa and the average relative density of the densified hydraulic fill successfully exceeded the specified minimum relative density of 70% in good conformity with the specified criteria.

5 QUALITY CONTROL TESTS

A strict quality control program pursued in the project implemented the static cone penetration test with pore pressure measurement (CPTU) as a primary quality control. Each CPTU is carried out for every 1,600 m^2 of densified area in order to verify compliance with the Project's requirements. Consequently a total of one hundred fourteen CPTU tests were performed. Based on the test results it was not only concluded that the average relative density of the compacted hydraulic fill successfully exceeded the specified minimum relative density of 70 % but also revealed that the measured density values are in conformity with the values obtained for similar soil conditions. (e.g. Sladen & Hewitt, 1989)

In addition to the primary quality control tests, the densification process is monitored and documented by using a sophisticated continuous computerized data collection system mounted on the vibroflotation equipment in order to obtain and control the actual applied densification data in real time; to assist the operator of the vibroflotation system and to optimize equipment performance.



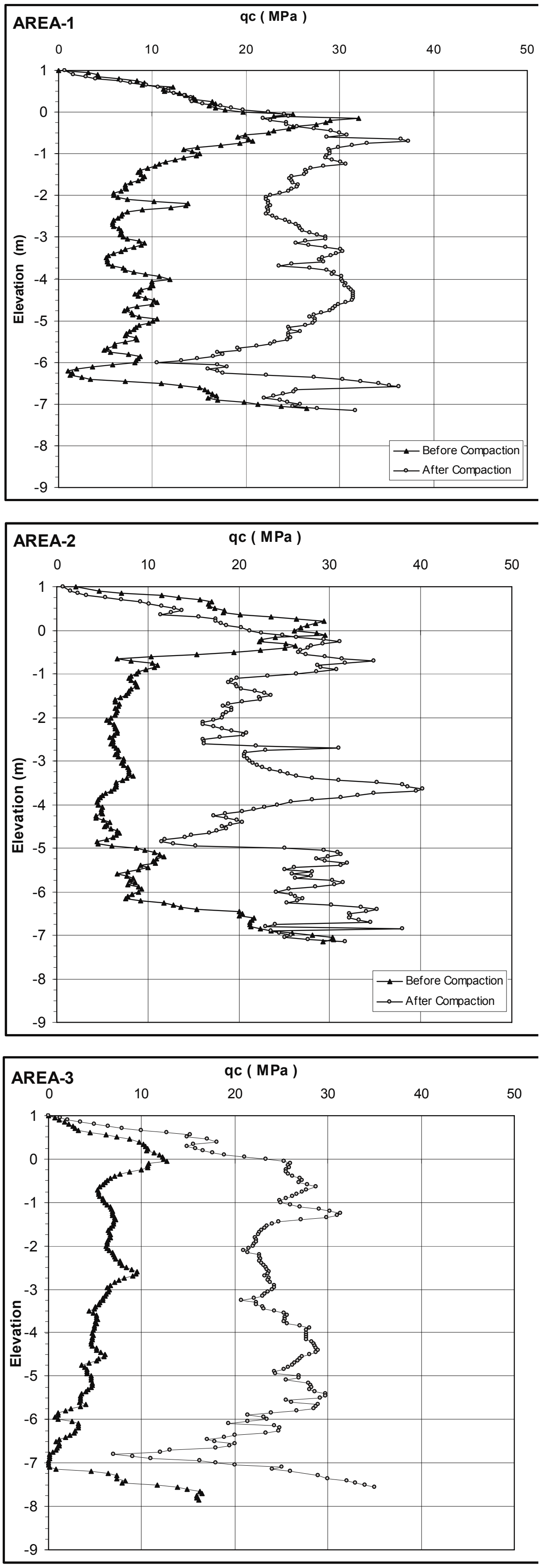


Figure 5. CPTs performed BEFORE and AFTER densification of Hydraulic Fills at three different areas

Figure 6. Applied incremental compaction energy vs. depth at three different areas in the vicinity where CPTs were performed.

Three sets of CPTs performed before and after the densification by vibroflotation method and the energy applied to the soil in the vicinity of CPT test locations at three different areas are shown in Fig.5 & Fig.6.

The change in the soil characteristics after densification was evaluated and the results show significant increase in cone resistance, q_c. Table 1 summarizes the densification properties; such as total and average applied energy, total densification time, average q_c values before and after the densification. It is encountered that the q_c values are increased by 50% to 280% for gravelly sand fills (Area 1 & 3) by increasing the total densification time while incremental compaction power of ~30 kW/m remains the same. Higher energy is required to be applied and the densification duration is extended as it can be seen from the following Table while using the same incremental compaction power for the densification of the silty-sandy soils.

Table 1. Summary of Densification Characteristics

Area No	Total Applied Energy (kJoule)	Ave. Applied Energy (kJoule/m)	Total Time (min.)	Ave. q_c before (MPa)	Ave. q_c after (MPa)	Δqc (%)
1	17,055	1,915	8.6	17.5	26.1	50
2	26,552	3,190	13.9	12.1	23.7	95
3	17,408	1,910	11.3	6.4	24.6	280

Applied incremental compaction power vs. increase in cone resistance, Δqc (%) graphs for three soil types namely silt, sand and gravely sand are presented in Fig. 7 and tabulated in Table 2.

Table 2. Increase in q_c obtained from CPTs and the corresponding incremental compaction power

Soil Type	Applied ΔE (kW/m)	q_c before compaction (MPa)	q_c after compaction (MPa)	Δqc (MPa)	Δqc (%)
Silt	31.7 - 33.0	1.0 - 1.9	9.5 - 20.2	9.2-18.8	450-1500
Sand	28.8 - 39.5	4.8 - 11.0	11.2 - 40.7	6.5-33.9	70 - 555
Gravely Sand	28.4 - 44.3	6.6 - 23.4	17.9 - 35.0	3.76-22.3	17 - 275

Upon completion of CPTU tests, the Janbu modulus number, m were determined for each type of soil by using the equations proposed by Massarsch (1994). Then settlement of the hydraulic fills was calculated by using these modulus numbers in Unisettle program (Fellenius and Goudreault, 2000) The results reveal that the actual settlement measured at site are in good conformity with the calculated ones.

6 CONCLUSION

As a result, the successful execution of vibroflotation method in this project illustrates the effectiveness of the selected method for densification of loose hydraulic fill. The findings obtained from the project are as follows:

- Installations were successfully carried out with an equilateral triangular grid by a 100 kW vibratory probe, having a maximum operating speed of 3000 rpm (50Hz).
- Densification process is monitored and documented by using a sophisticated continuous computerized data collection system mounted on the vibroflotation equipment.
- Based on the quality control test results it was not only concluded that the average relative density of the compacted hydraulic fill successfully exceeded the specified minimum relative density of 70 %, but also revealed that the measured density values are in conformity with the values obtained for similar soil conditions. It is also observed that the cone resistance (qc) could be increased by a factor of 1 to 4.
- It is observed that even thin layers of silt and clay in hydraulic fill can negatively affect the densification process. Thus a detailed soil investigation including CPTU is recommended in order to detect soil stratification accurately before and after densification.
- Actual settlement measured at site are in good conformity with the calculated ones by Janbu method.

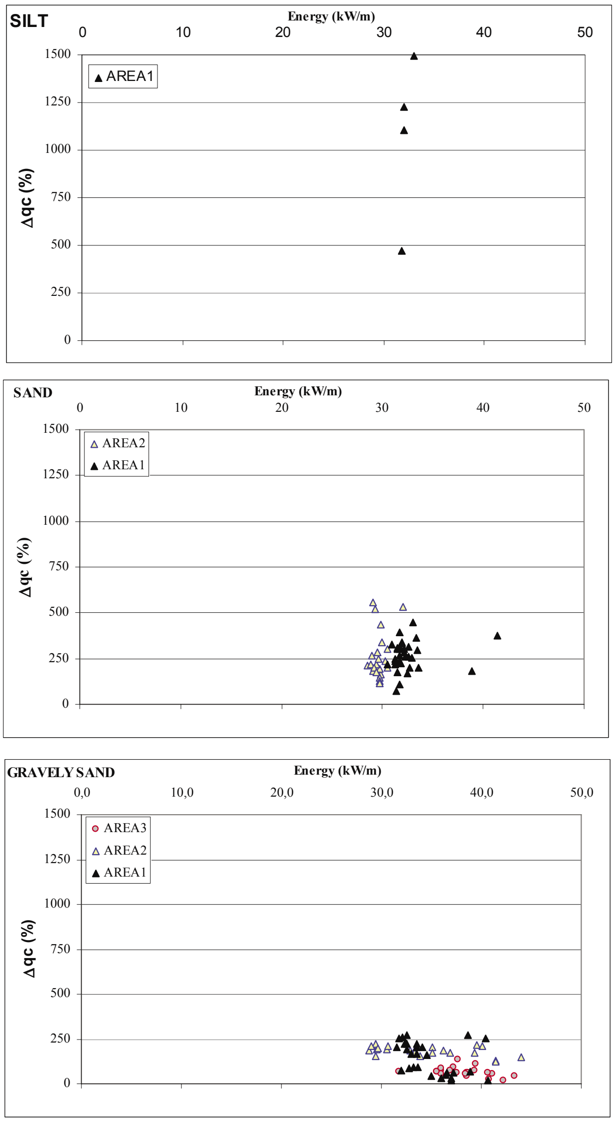


Figure 7. Applied incremental compaction energy vs. increase in cone resistance, Δq_c (%) for three different soil types

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