Vibratory deep compaction of hydraulic fills

Le compactage vibratorie des remblais hydrauliques

A. Gökalp, R.Düzceer
Kasktas A.S., Istanbul, Turkey; alpgokalp@superonline.com

KEYWORDS: Hydraulic fill, vibro compaction, vibroflotation, CPT, compaction energy

ABSTRACT: This case history describes the compaction of loose hydraulic sand fills by vibroflotation method. A total of 1,034,000 m^3 of hydraulic fills covering an area of 181,000 m^2 were vibro compacted to a minimum relative density of 70% as of February 2003. The physical properties of the hydraulic fills and the details of the vibro compaction works are presented and the results of the quality control tests are discussed.

RÉSUMÉ: Le compactage par la méthode de vibroflottation des remblais hydrauliques en sable lâches est décrit dans cet article. Jusqu' à Février 2003, un volume total de 1,034,000 m^3 de remlai couvrant une superficie de 181,000 m^2 a été compacté par cette méthode, à une densité relative minimale prescrite de 70%. Les propriétés physiques des matériaux de remblai et les détails des travaux de compactage ainsi que les résultats des essais de contrôle de la qualité du compactage sont discutés.

1 INTRODUCTION

The proposed port, which is situated on the east cost of the Mediterranea n Sea has been under operation since 1965. Due to the development of the maritime transport methods and port facilities in the recent years, a development plan was required to meet 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 hinderland, 2,600,000 m^3 of dredging works and 1,300,000 m^3 of vibro compaction works.

Only the general information of the dredging works, the characteristics of the hydraulic fill and the operational details of the vibro compaction works including the quality control program pursued in the project are discussed in this paper because of the length restriction.

2 SOIL INVESTIGATIONS & SUBSOIL CONDITIONS

A comprehensive soil investigation programme was implemented at the proposed site. A total of 13 cone penetration tests (CPT) and a total of 65 borings, with standard penetration tests (SPT), in the range of 28 m to 100 m, sampling of disturbed and undisturbed samples and laboratory tests (grain size and hydrometer analyses, atterberg limits, consolidation tests, CU triaxial tests) were carried out. In 1998 an additional soil investigation including a series of 20 vibrocore tests with sampling of underwater soil and 10 electric cone penetration tests were also conducted in order to obtain additional information on the pyhsical properties of material to be dredged and the upper soil layers.

On the basis of the soil investigations, sandy layers have been encountered within the quays area. These sandy layers contain fines content between 2 to 10 percent, classified as poorly graded sand (SP) and poorly graded sand with silt (SP-SM). The sandy material consist of 0.4% to 5.6% of gravel, 92.2% to 95.1% of sand and 1.9% to 7.5% of silty and clayey materials. The minimum and maximum dry densities of the sand fill vary between 12.40 to 14.30 kN/m^3 and 16.20 to 17.73 kN/m^3 respectively. The coefficient of uniformity, C_u is between 1.5 and 25 and the mean grain size D_{50} ranges from 0.13 mm to 0.38 mm.

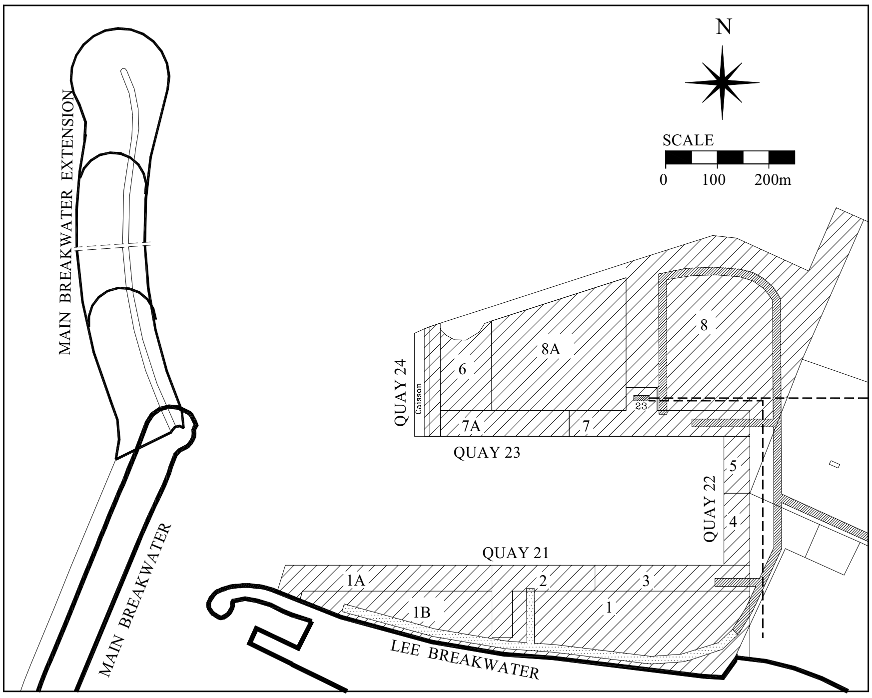

Figure 1. Site Plan

3 DREDGING WORKS & THE CHARACTERISTICS OF THE HYDRAULIC FILL

Based on the results of the vibrocore and electric cone penetration t ests carried out in 1998-99, the dredged sandy material was approved to be used as hydraulic fill material. The dredging works were mainly performed in the area defined by the Existing Quay 22 and 23, the future Quays 21, 22, 23 and the turning circle to a level of -14.0 m; in the manoeuvring area limited by the Main Breakwater extension, Quay 24 and the basin to a level of -15.0 m; and the new entrance channel of the port to a level of -16.0 m.

A Cutter Suction Dredger was selected as the most suitable equi pment for execution of the dredging works since the dredged material was dumped into the quay reclamation areas. The dredged materials were pumped throughout floating and land based pipelines to the reclamation areas. Pipelines and water outlets were insta lled 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 used for dredging unsuitable and surplus material and disposal into the open sea.

Sand for hydraulic fill was controlled by obtaining five samples of the dredged material for each 20,000 m^3 of fill material. Sieve analysis tests according to the ASTM E -11 were performed on those selected samples and the dredged fill materials complying with the following criteria were defined as suitable for hydraulic fill.

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

The results of sieve analysis are shown in Figure 2., where each line corresponds to the average of the five sieve tests performed on samples taken from the fill. The average of the coefficient of uniformity, C_u and the coefficient of curvature, C_z 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 as a hydraulic fill material.

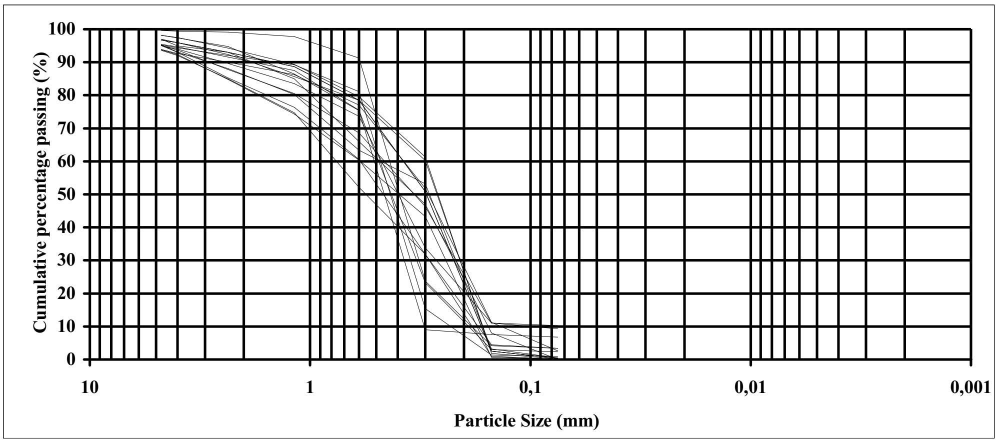

Figure 2. The results of sieve analysis tests performed on samples taken from the hydraulic fill

4 VIBRO COMPACTION WORKS

Since the predicted settlements for the foundations of the various structures and container storage areas are not tolerable and the risk of liquefaction is high, the loose hydraulic sand fills whose thickness varies from 3.0 m to 12.0 m are implemented to be vibro compacted by vibrofloatation method 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 selected for the vibro compaction works. In October 2001, a test area of 1,000 m^2 prepared at Zone 8 was vibro compacted. Installations were carried out with an equilateral triangular grid having a triangular side of 2.5 m and a compaction energy of min. 750 KJoule per meter was applied to the hydraulic fill.

After the treatment two sets of three CPT tests each, located at the mid (C -8 & C-12) and quarter (C-9 & C-11) of one of the triangular grid sides and at its centroid (C -6 & C-10) were carried out four days upon completion. The construction specification required that after compaction minimum D_R of 70%, 75% and 85% of the hydraulic fill are to be achieved at the centroid of the triangular grid, the mid and quarter of one of the triangular grid sides respectively. The corresponding curves of q_c along the vertical beneath a certain point for the required value of D_R were calculated, based on the following relationship (Jamiolkowski, 1985). See equation (1). The average and standard deviation of the q_c values along the depth of a certain point obtained from CPT tests were calculated and compared with the minimum required D_R Criteria after q_c values were normalized by the in situ state of stress. Since the results of the CPTs performed after the treatment were in good conformity with the compaction criteria, the method of statement used in the installations of the preliminary test was approved as the operational parameters.

$$D_R = -98 + 66 \cdot \log\left[\frac{q_c}{(\sigma'_{vo})^{0.5}}\right] \quad (1)$$

5 QUALITY CONTROL TESTS

A strict quality control and quality assurance 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 vibro-compacted area in order to verify compliance with the specified compaction criteria. Thus as of February, 2003 a total of one hundred fourteen CPTU tests were performed by an independent laboratory. (Table 1) 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.

Table 1. Results of quality control tests as of February 2003

Quay No	Zone No	Completed Area	Completed Volume	CPTs Performed
23	Zone-8	63,000 m^2	268,640 m^3	37 no.
	Zone-8A	58,400 m^2	394,560 m^3	30 no.
	Zone-6	14,600 m^2	112,550 m^3	7 no.
	Zone-7	3,500 m^2	37,050 m^3	6 no.
	Zone-7A	10,000 m^2	91,205 m^3	16 no.
21	Zone-3	3,300 m^2	15,250 m^3	1 no.
	Zone-2	14,500 m^2	64,200 m^3	9 no.
	Zone-1	13,700 m^2	50,800 m^3	8 no.
	Total :	**181,000 m^2**	**1,034,255 m^3**	**114 no.**

The compaction process is monitored using an electronic process control system capable of recording actual compaction data in real time; compaction energy, amount of water and depth of the vibratory probe versus time in order to assist the operator and to control and collect the actual vibro compaction data.

Two sets of CPTs performed before and after the vibro compaction installations at two different areas in Zone 8A and the compaction energy applied to the soil by the vibratory probe in the vicinity of CPT test locations were shown in Figure 3 and tabulated in Table 2. It was observed that the increase in q_c decreases as the fines content in the hydraulic fill increases although the compaction energy applied to the fill is the same.

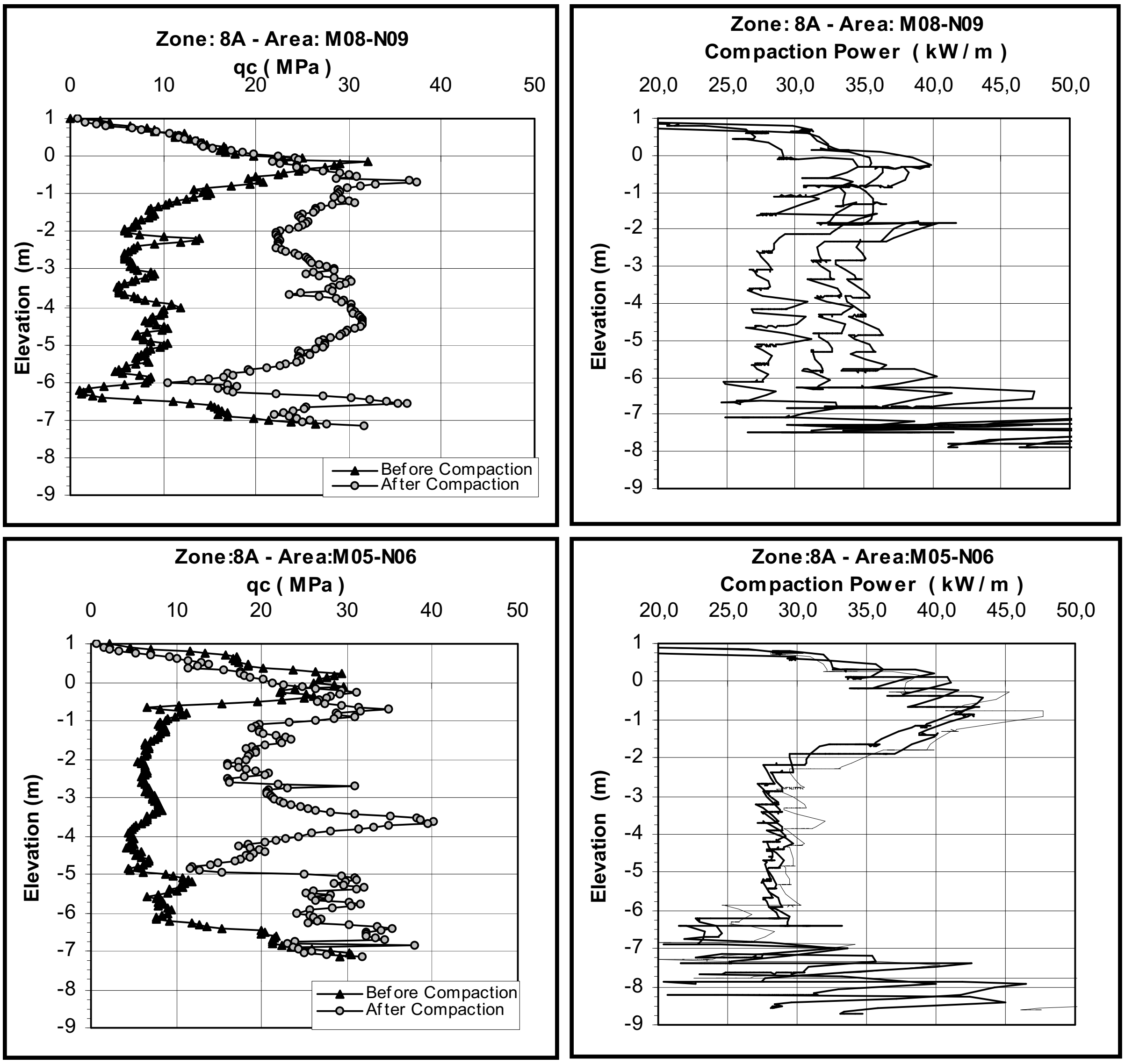

Figure 3.CPTs performed before and after vibro compaction & compaction energy applied to the fill (At two different areas in Zone 8A)

Table 2. Increase in q_c obtained from CPTs and the corresponding compaction energy applied to the fill

Zone No.	Area No.	Average q_c (Before Compaction)	Average q_c (After Compaction)	Ave. Compaction Power (kW / m)	Increase in Δq_c (%) (q_c aftter- q_c before) / q_c before
8A	M05 - N06	12.10 MPa	23.70 MPa	30.9 kW	75% to 375%
8A	M08 - N09	17.50 MPa	26.10 MPa	32.7 kW	50% to 390%

6 CONCLUSION

As a result, the successful execution of vibro -compaction in this project illustrates the effectiveness of the selected method for densification of loose hydraulic fill. The specific findings of the project are:

1. Installations were successfully carried out with an equilateral triangular grid having a triangular side of 2.5 m and a compaction energy of min. 750 KJoule per meter was applied by a 100 kW vibratory probe, having a maximum operating speed of 3000 rpm (50Hz) with a corresponding maximum centrifugal force of 400 kN to the hydraulic fill during installati ons.
2. The compaction process is successfully monitored by an electronic process control system capable of recording the actual compaction data in real time in order to assist the operator and to control and collect the actual vibro compaction data.
3. 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 co nformity with the values obtained for similar soil conditions. It is also observed that the cone resistance (q_c) could be increased by a factor of 1 to 4 .
4. It is observed that even thin layers of sil t 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 strafication exactly.
5. Since the dredging works were carried out by different types of dredgers (cutter suction dredger and trailing suction hopper dredger) and the methods used for placement of the dredged material were also different, the hydraulic fill was encountered as non -homogeneous.
6. The suitability number (S_N) was calculated using the formula suggested by Brown (1977) and it is observed that the hydraulic fill material is Good to Fair.

REFERENCES

Brown R.E. (1977) “Vibroflotation compaction of cohesionless soils”, Journal of the Geotechnical Engineering Division, pp.1437-1451.

Düzceer R., Gökalp A. (2001) “Technical Report on densification of hydraulic fills by vibro compaction method at Extension of Ashdod Port”, Internal Technical Report, İstanbul, Turkey.

Lee, K.M., (1999), “Effects of placement method on geotechnical behavior of hydraulic fill sands”, Journal of Geotechnical and Geoenvironmental Eng., No. : October, pp.832- 846.

Sladen J.A., Hewitt K.J., (1989) “Influence of placement method on the in situ density of hydraulic sand fills”, Can. Geotech. Journal, Vol. 26, pp.453 –466.

Slocombe B.C., et.al. (2000) “The densification of granular soils using vibro methods”, Getechnique 50, No.6, pp. 715-725.