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CDC Compaction at Berth 9 Extension Felixstowe, UK

J.W. Vink * , J.W. Dijkstra

Cofra bv, Kwadrantweg 9, Amsterdam 1042AG, The Netherlands

Abstract

In February 2015 Cofra Dynamic Compaction (CDC), a heavy Rapid Impact Compaction (RIC) technique to compact granular subsoil, was performed on the Berth 9 Extension project in Felixstowe, UK. The extension consists of a 15.000m2 reclamation between sheetpile walls. The compaction of the reclamation was required to reduce future settlements and improve the properties of the sand behind the quay wall. An extensive compaction trial was performed before the start of the project to assess the compaction procedures and work method in relation to the specifications but also to assess the impact of the compaction on the Quay wall. Compaction effort was monitored during compaction with the use of the crane monitoring system which registers the (induced) settlement with increasing blows. The effect of the compaction has been measured with the use of pre- and post-compaction CPT's. The main quay wall displacements were continuously monitored by a manual station and a robotic total station. During the trial an inclinometer was used to gather more data. The paper focusses on the gathered data, findings and observations during the project and the compaction trials.

Keywords: Cofra Dynamic Compaction, CDC, Rapid Impact Compaction, RIC, Compaction, granular soil, sand, densification, heavy tamping

1. Introduction

Berth 9 of United Kingdom's largest port, the Port of Felixstowe, has been recently extended with 190m and 16.000m2 of additional quay. During the construction of the quay, tubular piles, tubular piles combined with sheet piles and sheetpiles were installed around the area to be reclaimed, see Fig.1. After closure of the basin, the basin was filled with dredged sand up to a level of approximately +0m Chart Datum (CD). A stockpile material was used to fill the reclamation further up to a level of +2m CD. From this level the reclamation was compacted till 8-9 meters

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* Corresponding author. Tel.: +31-204-623-586 ; fax: +31-206-941-457.
E-mail address: jan-willem.vink@cofra.com

below the compaction surface using the Cofra Dynamic Compaction (CDC) method, a heavy rapid impact (RIC) method using 16 ton hammers. The compaction of the reclamation was required to reduce future settlements and improve the properties of the sand behind the quay wall. Before start of the compaction works extensive compaction trials were performed to assess compaction procedure, the working method and to determine the effectiveness in relation to the specifications and the sheet pile walls. This article discusses the compaction of the fill. Please refer to Fig.1(b) for an overview of the project site and locations of trial areas.

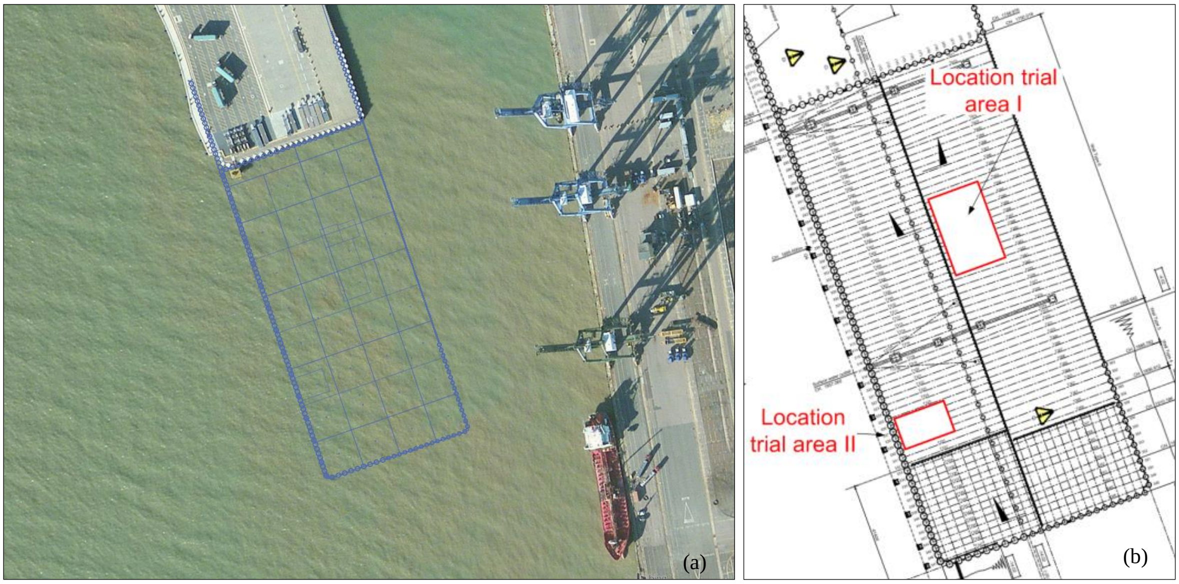


Fig1. (a) aerial overview Bert 9 Extension, (b) trial Area locations within reclamation

Nomenclature

RIC	Rapid Impact Compaction
CDC	Cofra Dynamic Compaction
MQW	Main Quay Wall
BC	Before Compaction (Pre)
AC	After Compaction (Post)

2. Requirements

2.1. Requirement for the compaction of the fill

The requirement for the compaction of the fill was determined from two boundary conditions. The first condition involved the residual settlement of the future surface. This was limited to 7cm over 2 years and 13.5cm over 20 years [3] and included any settlement from the London clay below the fill. After subtraction of the settlement from the London clay, the actual allowable settlement of the fill was translated to a minimal cone tip resistance (qc value) profile using the constraint modulus. The second condition, a minimal friction angle profile of the sand, was determined in cooperation with the designer of the Quay wall. The friction angle was translated to a minimal cone tip resistance (qc value) using the Bolton method (1986). The Bolton relation was checked during the project using a large shear box test, see Fig. 2. It shows that the relation is applicable for the material on site with D50 value of 190 µm. Both profiles were combined to come to the minimal cone tip resistance profile as given in Table 1.

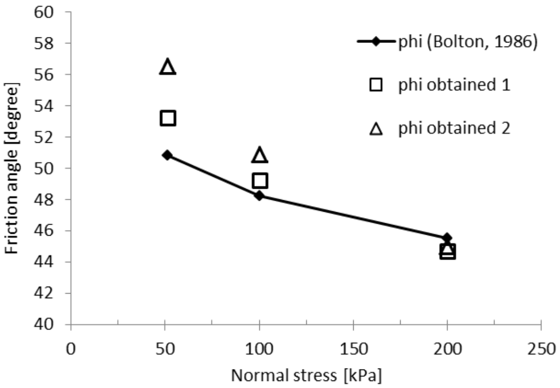


Fig. 2: Relation between Bolton prediction for the specific relative density used in the tests and actual shear box results

Table 1. Design parameters for the CDC compaction section.

From [m CD]	To [m CD]	Re [%]	Qc [MPa]	phi [Degrees]
2.0	-3.0	60-70%	10-15	42
-3.0	-5.0	30-40%	5-6	35
-5.0	-12.5	20-30%	4-5	32

2.3. Requirements deformation wall

After the structural Quay design was finished a deformation profile was determined for the Quay wall. The maximum deformation of the different wall sections, including filling, was set to 240mm. As the installation of the wall and filling up to compaction level also introduced deformations, the actual allowable deformation to occur during the compaction was set at maximal 50mm.

2. Compaction method

2.1. General Work method

The RIC method used for the compaction uses a hydraulically accelerated weight of 16 tons that is dropped with a frequency of minimal 40 times a minute from a height of 1.2 meters onto a foot which remains in contact with the ground. Because the used foot, with a large diameter ranging from 1.5m to 2.6m, experiences enough resistance in the granular soil it transfers the kinetic energy into compression and shear waves. The shear waves, in combination with the dense compaction grid used during the compaction operations with overlapping zones of influence, lead to homogeneous and effective compaction. The process is illustrated in Fig. 3.

2.2 Quality Control System and Stop Criterion

The on-board quality control system is an important part of the used RIC system. During the compaction operations several parameters are logged and displayed on the display of the operator. The operator has the possibility to indicate three different stop criteria on the display, being number of blows, the induced settlement (average settlement per blow of the last three blows) and total settlement. Due to the mostly heterogeneous soil conditions on project sites the more advanced induced settlement (settlement per blow) is often used as a stopping criterion for each compaction point to achieve homogeneous compaction. The use of the induced settlement requires a statistical analysis of post the compaction CPT tests during a compaction trial.

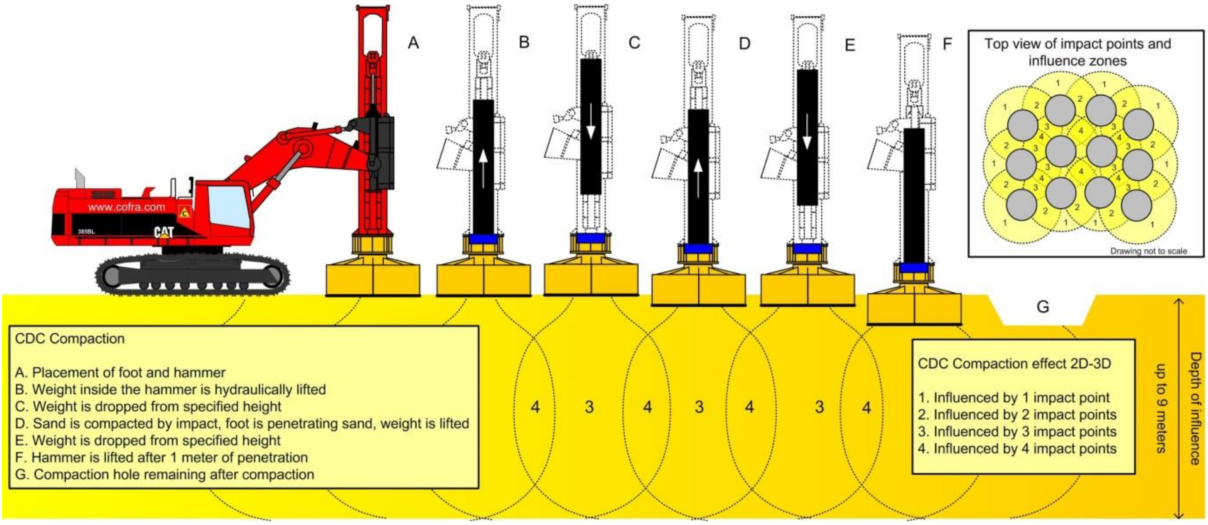


Fig. 3.Illustration of RIC work method and overlap of influence zones RIC

3. Compaction Trial

3.1. Trial set up

Compaction trials were performed before the actual compaction started to determine the operational criteria in relation to the requirements. The project was started with a trial to investigate the grid distance and stop criterion in relation to the required CPT profile. Also, the lateral compaction influence was researched. This trial was followed by a second trial next to the Main Quay Wall (MQW). In this trial the most optimal operational procedure of the first trial and work method for the actual compaction works was used to investigate the minimum working distance from the wall in relation to the deformation of the wall.

3.2. Operational criteria

From the trial results it was concluded that the following operational procedure was most optimal:

- Compaction grid size - 2.75mx2.75m
- Stop criteria - amount of blows is 35 (full blows at 1.2m drop height)

A less advanced stop criterion had to be used in this case due to the changing site conditions during compaction. The actual compaction level was situated inside the construction pit well below the high water level. The pit flooded two times a day. This led to high and changing water levels within the sand and to different reactions of the foot during compaction. It was therefore not possible to use settlement per blow as a stop criterion. This can be observed in a zoom of the operational data in Fig. 4. From the Figure it can be concluded that there is no relation between the three parameters plotted, which is normally the case under homogeneous conditions. It was therefore chosen to insert enough energy into the ground so that high compaction levels were achieved and homogeneous compaction was met.

The result of the homogeneous compaction is shown in Fig. 5. In this figure the pre- and post-compaction cone resistances over depth are shown at a compaction location and around a compaction location. As can be observed from the graph there is little to no difference in qc values between the CPT locations. This indicates that a homogeneous compaction has been created in the subsoil due to sufficient overlap of compaction influence zones. It is also shown that the compaction criteria are well achieved, with only at the level of -3m CD a small dip in the resistance due to a local inclusion of finer material.

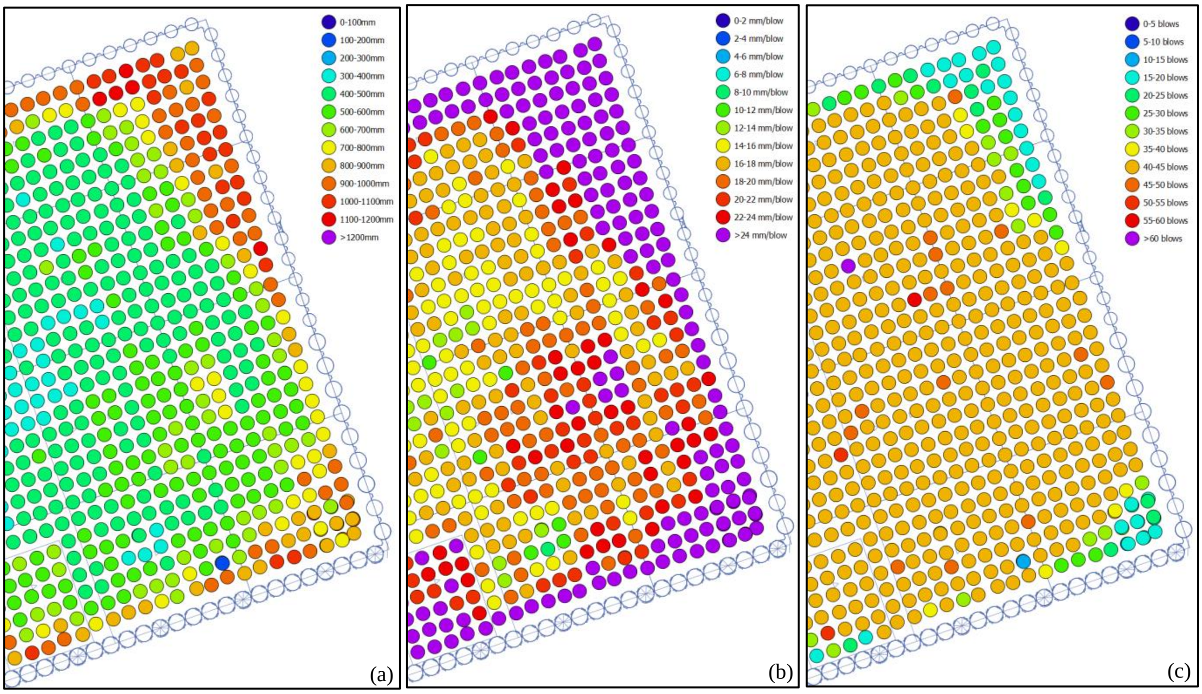


Fig. 4. (a) Total Settlement, (b) induced settlement and (c) number of blows.

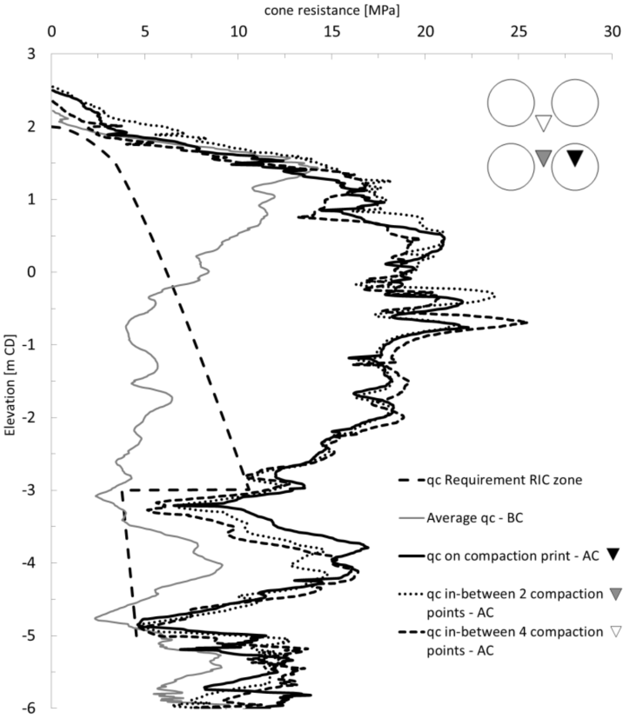
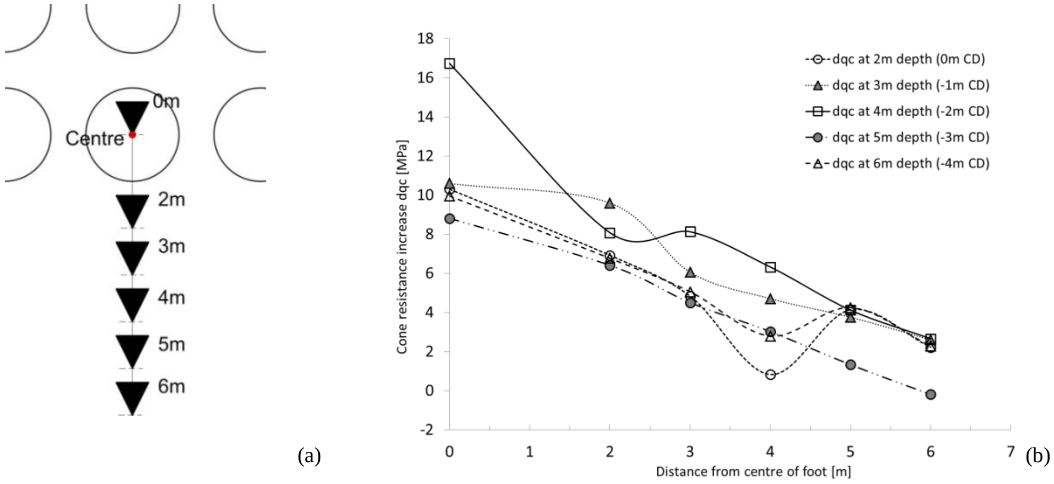


Fig. 5. Average cone resistance before compaction (BC), cone resistance after compaction (AC) and required qc

3.3. Lateral compaction influence

Within the trial additional research was performed to assess the actual lateral influence of the compaction outside the compacted prints. This was performed to be able to estimate the compaction levels at the MQW when a larger distance was to be kept from the MQW. Fig. 6. presents the outcome of the review. Fig. 6.(b) presents the cone resistance increase on fixed distances from the center of the compaction foot at various depths. It implies a more or less linear decrease of compaction influence with distance from the center of the foot. The effect of the compaction is in this case observed up to 6m from the center of the foot at different compaction depths.

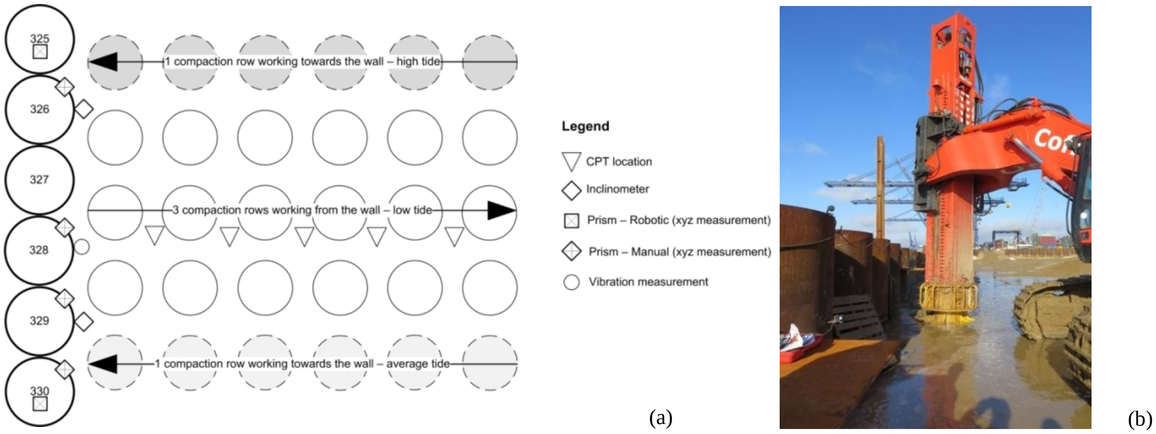


(a) (b)

Fig. 6. (a) CPT locations to research lateral compaction influence, (b) Cone resistance increase (dqc) at various depths plotted against the distance from the centre of the compaction foot. Lateral variations in soil conditions due to the rain bowing method of placement of the sand cause small deviations

4. Main Quay Wall Trial

The safe working distance from the MQW was determined using a separate trial. During the trial the deformation of the quay wall was measured and checked with the given boundary values. The compacted fill properties adjacent to the wall were investigated and it was assessed whether working from or towards the wall would have an effect on wall deformations. The gathered data was corrected for the tidal conditions. Fig. 7. presents the work sequence and the locations of the monitoring equipment during the trial.



(a) (b)

Fig. 7. (a) MQW trial set up, (b) compaction point close to the wall

The MQW was monitored at regular intervals during the compaction using prisms and a robotic station. For the trial 5 additional prisms were added and monitored during and after the compaction of a point using a manual station. This made it possible to continuously assess the displacement while compacting and, in case of exceeding a limit value, being able to stop the compaction operations. The limit value of 50mm was added to baseline displacement measurement of MQW taken just before compaction. This was to include any movement due to tidal differences.

An example of the results of the manual xyz measurement, during RIC compaction in 3 rows working from the MQW, is given in Fig. 8. The figure presents the total deformations over time for all the piles compared to the baseline taken at the start of the compaction sequence. The measurements show that the compaction operations can be performed very close to the MQW. The closest locations were approx. 40cm (edge of the foot and the wall) from the MQW, please refer to Fig. 7.(b) for an impression.

Inclinometer measurements were also performed during the trial, please refer to Fig. 8.(b). In this case over the length of pile 326 and 329, see Fig 7.(a) for the locations. This was performed by lowering an inclinometer probe in to a tubed box which was welded over the length of the pile. During the trials all of the piles in the trial area, except pile 330, were not filled with sand.

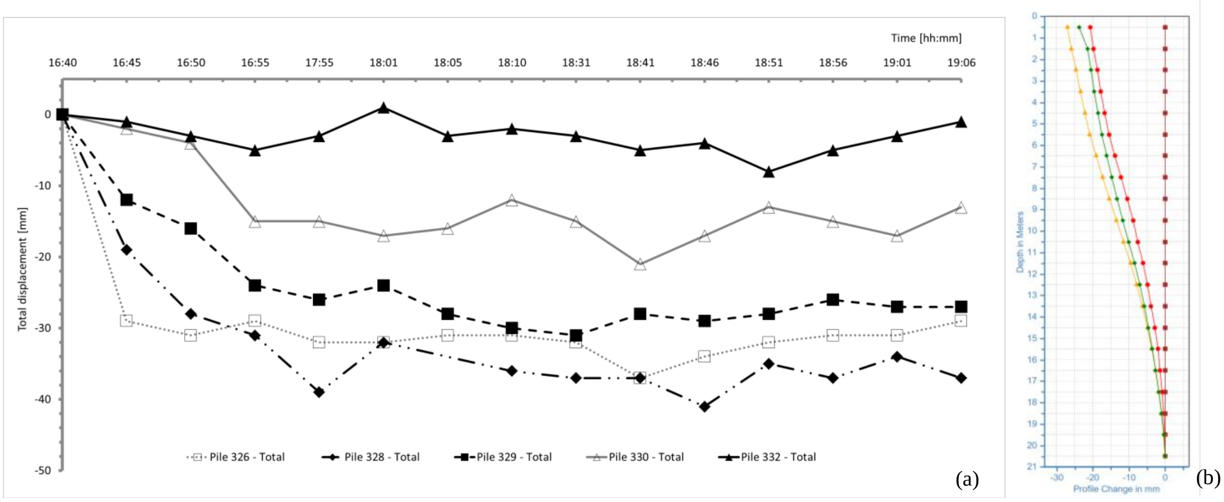
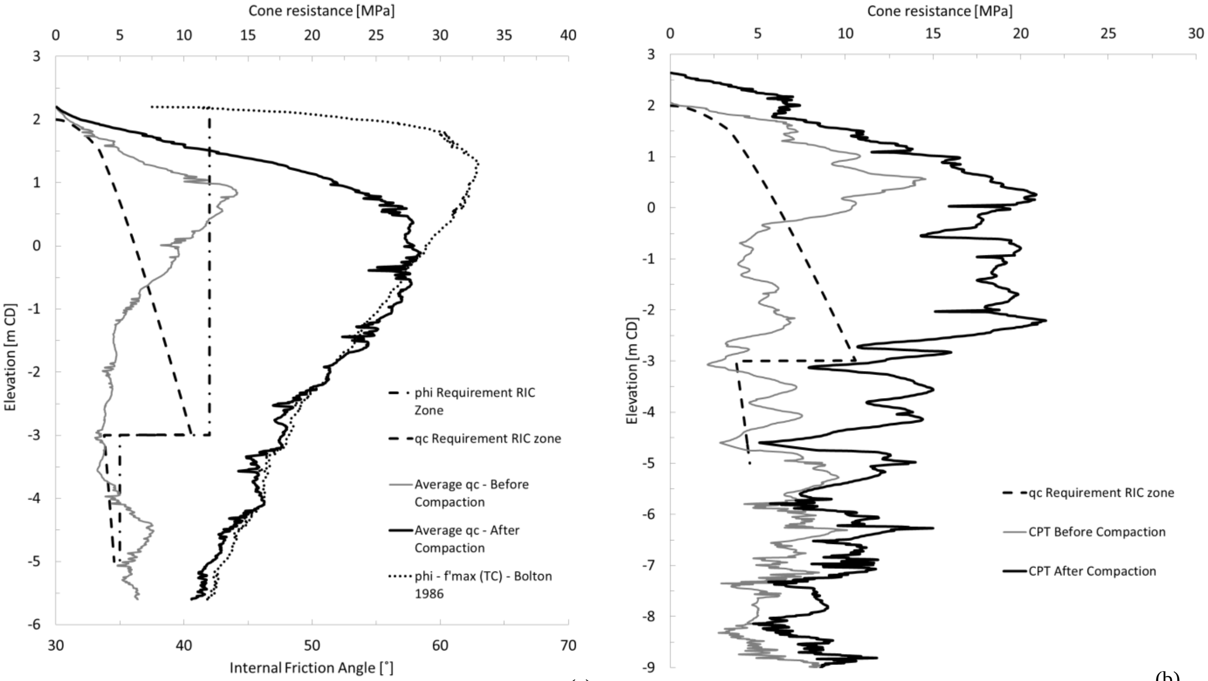


Fig. 8. (a) Total displacement from manual xyz measurements from baseline and (b) inclinometer– 3 compaction points moving backwards from the wall. Each point is a compaction location

The deflections of the MQW remained within 40mm during the trial and complied with the set requirement. Deflections measured by the inclinometer were generally smaller than the deflections measured by the xyz total station and robotic station. This is plausible as the inclinometer did not extend to the top of the pile towards the xyz prism, mounted on the top of the piles. Deflection generally occurred during the compaction of the two closest points to the wall which corresponds to lateral influence zone shown in Fig. 6. After a review of the all the data, also the data from the actual work, it was observed that deflections seem to be more permanent for a filled pile. An empty pile showed more elastic deformations reducing the deformation after compaction.

5. Compaction Results

After the trial permission was given to complete the full area using the operational pattern. Fig. 9.(a) presents the average cone resistance of all the 31 CPT's executed after compaction including the requirement of the cone resistance over depth. Fig 9.(a) also presents the average internal friction angle (Triaxial Compression) over depth as calculated using the Bolton method (1986), including the requirement of the friction angle. It can be concluded that the average cone resistances and friction angles after compaction are well above the requirements. In the upper 5m the cone resistances are generally extremely high (up to an average value of around 25MPa). The depth of influence of the compaction was approximately 8 to 10.5m, with the largest improvement in the top 7 meters, please refer to Fig. 9.(b) for a before and after CPT of a single CPT location .



(a) (b)

Fig. 9 (a) average cone resistance of all Before (Pre) and After Compaction (Post), (b) maximum compaction influence depth measured

6. Conclusions and Recommendations

The compaction operations and CPT test data have shown that the used 16 ton RIC compaction technique has compacted the hydraulically placed material present at the Felixstowe Berth 9 Extension project to values above the cone resistance and friction angle requirements. Deflections of the quay walls were measured by xyz monitoring and inclinometer measurements. From the readings it can be concluded that deflections remained within the given limitations during production and there are no significant deformations even when working closely, up to 40cm next to the wall.

References

[1] Bolton, M. D., The strength and dilatancy of sands. Geotechnique 36, No. 1, (1986), 65-78

[2] Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowski, M., Pasqualini, R. (1986), Interpretation of CPTs and CPTUs; 2nd part: Drained Penetration of Sands. Proceedings of the Fourth International Geotechnical Seminar, Singapore, 143-56

[3] Felixstowe Dock and Railway Company (2013), Port of Felixtowe – Berth 9 Quay Extension, Tender Document, Volume 2 – Employer's Requirements, Section 2, Civil Works, Revision T2, October 7th 2013

[4] Final Report: Factual Report CDC compaction, Berth 9 Extension Felixstowe, by Cofra b.v., C2897-R-02-JVIN-rev1, July 2015