Physical modelling of vibrocompaction in silica sand mixed with shells

Modélisation physique de vibrocompaction d'un mélange de sable siliceux avec coquilles

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ABSTRACT: The available sand for the soil replacement underneath a breakwater is mixed with shells, with variable shell contents ranging up to 50%. Based on the experiences the substituted sand in the foundation has to be compacted by vibrocompaction. Data from literature is not representative for the existing specific sand mixture. Therefore, in order to understand the behaviour of the sand shell mixture of the project site compacted by vibrocompaction, a series of tests in large calibration chambers combined with laboratory tests are designed and executed. The aim is to evaluate the sand shell mixture behaviour and to find practical correlations among the strength (from in-situ tests), relative density (from laboratory tests) and (in-situ) settlement due to vibrocompaction. The strength of sand shell mixture is tested with the Panda 2 dynamic cone penetrometer. The sand is tested for different degrees of compaction and for different vibration conditions. The results show that the settlements due to vibrocompaction and the increase in resistance are not perfectly correlated. Based on the observation, it is understood that the settlements cannot be used as the only acceptance criterion for the required strength during the vibrocompaction campaign and achieved strength should also be monitored.

RÉSUMÉ : Le sable disponible pour une substitution de sol sous une digue contient un pourcentage de coquilles élevé jusqu'à 50%. Pour améliorer la capacité portante, le sol substitué doit être vibrocompacté. Les éléments retrouvés dans la littérature ne représentent pas les conditions spécifiques de ce projet. Afin de mieux comprendre ce comportement, une expérimentation a été menée, comportant de tests de vibrocompaction physiques avec des chambres d'étalonnage et des essais en laboratoire. L'objet est d'évaluer les caractéristiques du mélange de sable-coquilles et de trouver une corrélation pratique entre la portance du sol (testée sur le site), la densité relative (obtenue d'essais en laboratoire) et le tassement (sur site) par la vibrocompaction. La portance est testée avec le pénétromètre dynamique Panda 2. Différentes conditions de densité avec différents tests de vibrocompaction sont considérées. Les résultats montrent qu'il n'y pas de corrélation parfaite entre le tassement et le gain en portance causés par la vibrocompaction. A partir de cette observation, il est conclu que les tassements ne peuvent être utilisés comme seul contrôle de qualité d'une campagne de vibrocompaction, sans suivi de la capacité portante du sol.

KEYWORDS: Large calibration chamber, Panda 2 dynamic cone penetrometer, sand shell mixture, settlement, vibrocompaction

1 INTRODUCTION

An offshore breakwater is designed for the construction of a LNG-terminal. Based on the geotechnical investigation, it is understood that the breakwater foundation consists of layers from very soft soil (on top) to resistant sediments (at greater depth). The top layer is soft soil consisting of a high plasticity clay. The N-value of the SPT (Standard Penetration Test) for this layer is zero. This means that the soil material at the location of the breakwater foundation is very soft and does not have the appropriate bearing capacity. Consequently, the top layer should be removed or improved. It should be mentioned that in encountering peat or soft soil deposits, a common solution is to excavate the peat or soft soil and replace it with fill material with good mechanical properties.

The sand materials in the available borrow area are mixed with shells. The shell percentage of the sand materials is variable and percentages up to even 50% are observed. In other words the available sand is a heterogeneous mixture. The breakwater foundation after the improvement becomes a permeable foundation. Pore water pressure variations occur under the prevailing wave conditions and its effect should be considered for the slope stability analysis of the breakwater (Mollaert and Tavallali 2016).

The sand materials in different projects and studies are different (calcareous or silica sand). Appling the data from the literature cannot be necessarily representative for the existing specific sand shell mixture. Therefore, in order to understand the mechanical properties and behaviour of the specific sand mixture of the project site (Tavallali and Mollaert 2016), geotechnical studies are needed.

After the sand backfilling there are always several questions that arise: if the sand compaction level is acceptable, if in future large settlement can occur, if the sand bearing capacity can accept the expected service load. However, there is relatively little relevant scientific information and experience available with silica sand with shells, let alone with their behaviour during vibrocompaction. To estimate the effect of different levels of compaction, as well as to obtain some geotechnical parameters as input for the design, there is an urge to obtain more relevant information on the behaviour of the used backfill material during and after compaction. Large chamber calibration tests can provide useful information and give an insight in the behaviour of the material during and after compaction for several combinations of pre-compaction and vibration.

The aim of the calibration chamber test, is to test the compactibility of the backfill material, by correlating the sand settlement, relative density and soil strength, obtained after a certain time of vibrocompaction. The behaviour of the backfilling sand in the large scale testing (which is more similar to reality) can be evaluated. Also some references to the possibilities of backfilling sand compaction and also the settlement/compaction behaviour would be obtained. The correlations of the different aspects are looked at in a relative way, e.g. does the soil strength after vibrocompaction increases in a similar way for loose or compacted sand. It should be noted that calibration chamber testing can provide additional information to laboratory testing. With the combination of the results from calibration chamber testing and laboratory tests useful information for design and execution is provided.

2 SHELLY SAND MATERIAL

The sand backfill material is sourced from an offshore borrow area located approximately 35 km from the project site. In order to be able to evaluate the behaviour of sand backfill material in the calibration chamber, some representative samples are needed. From several hopper loads of the trailing suction hopper dredger (that transferred the material dredged from borrow area to the breakwater foundation), about half a tonne sample were taken (see Figure 1). All the samples were mixed together to have the representative sample.

Figure 1. Sand material (mixed with shells) taken from trailing suction hopper dredger.

The physical and mechanical soil characteristics are investigated (Tavallali and Mollaert 2016). The sand-shell mixture consists of fine to medium sand (0.063 mm – 0.6 mm). The particles larger than 0.6 mm are mainly shells. The minimum density of the sand is 1516 kg/m³ and the maximum density of the sand is 2028 kg/m³. When only looking at the fraction smaller than 16 mm, the minimum and maximum density are, respectively, 1555 kg/m³ and 2036 kg/m³.

A sand is classified as a carbonate sand if its carbonate content is higher than 90%; while, a siliceous carbonate sand has a carbonate content of 50% to 90% (Clark and Walker 1977; Meigh 1987). It is assumed that the soils with carbonate contents of less than 50% to 70% behave similar to the non-calcareous soils and the carbonate grains play a less important role in the engineering response (Lunne et al. 1997).

The carbonate content of the sand is 27.9%. For the sand fraction smaller than 16 mm the carbonate content is 24.3% (Tavallali and Mollaert 2016). Based on the available information and the test results, it is concluded that sand materials which are used for the soil replacement in the breakwater foundation is silica sand with shells.

The sand used for the large chamber calibration tests is sieved to avoid particles larger than 20 mm. With this the largest shells were removed from the tested sand-shell mixture which reduces the effect of the crushability of the sand-shell mixture on the obtained results.

3 TEST PROCEDURE

Steel pipes with a diameter of 1.2 m and a length of 1.5 m are used as calibration chambers. A typical test set-up is shown in Figure 2. In some similar research smaller diameter (0.95 m) for the pipe (chamber) was applied (Al-Homoud and Wehr 2006). To reduce the boundary effects the pipes with a larger diameter of 1.2 m are used.

The tests involved testing the sand shell mixture used in the backfill, simulating a range of different states of the material. Varying degrees and combinations of pre-compaction and compaction due to vibration are tested. The chambers are divided in three sets of three chambers with different degrees of pre-compaction:

- Loose sand (C0): these chambers are not pre-compacted;
- Fully compacted sand (i.e. dense sand) (C2): this set of chambers are pre-compacted;
- Intermediate compacted sand (i.e. medium dense sand) (C1): this set of chambers are pre-compacted with half of the energy used to compact the fully compacted set of chambers (C2).

Figure 2. Execution of a Panda test on a chamber. The clamps at the outer side of the chamber are used to perform the vibrocampaction.

To compact the chambers, the chambers are filled in layers of about 15 cm. Each added layer of 15 cm is compacted by means of a stamper. The entire area of chamber is each time stamped twice in case of the chambers with fully compacted sand. For the chambers with intermediate compacted sand, the area is only stamped once per layer of 15 cm. To avoid the crushing of the shell present in the mixture, a softer material was attached to the bottom of the stamper.

Each of the three sets contains three chambers. Of these chambers, one is not vibrated (V0), one is vibrated until maximum settlement (V2) (or in other words maximum vibrocompaction) is reached and the last one is vibrated for half of the time necessary to reach full compaction (V1). The chambers which are not vibrated are considered as the reference state of the soil (for three different degrees of pre-compaction). For the chamber which is fully vibrocompacted, the vibration is performed in different steps. The vibration time and settlement after the vibracompaction are measured for each step. At the point where the settlement increment between two successive vibrocompaction is less than 0.5 cm, the soil is considered as fully vibrocompacted. The total cumulative vibration time is defined. This time indicates the vibration time (i.e. half of this time) for the intermediate vibrocompacted test chamber. The vibration is performed from the outer side of the calibration chamber. The vibration is applied on three different vertical levels of the chamber: bottom side, middle and top side of the chamber.

In between successive vibrocompaction sessions, the obtained soil strength is tested with the Panda 2 dynamic cone penetrometer. Each time three Panda-tests are executed in each chamber. Furthermore, three Panda tests are performed on each chamber before any vibrocompaction. The set-up of performing such a Panda test is shown in Figure 2. These Panda test results give an indication about the initial soil condition of each chamber. For practical convenience and mobility the Panda apparatus is used instead of CPT measurements. The settlement after each vibrocompation session is measured as well. After the Panda test, soil samples are taken, to determine the density of the material. The soil samples are taken at two different depths. One sample close to the top of the chamber and one sample in the middle of the chamber.

4 RESULTS

4 .1 *Initial soil condition of the chambers*

Before vibrocompacting the chambers (step T0), three Panda tests are performed per chamber (for the chamber with loose sand, medium dense sand and dense sand). The results of this initial condition (before any vibrocompaction is performed) of the chambers are presented in Figure 3. The Panda tests indicate that the obtained results are consistent for each pre-compaction level; the cone resistance for each pre-compaction level is similar. It is also noted that the scatter (i.e. the variance between the three Panda tests of one pre-compaction condition) of the cone resistance is increasing with the pre-compaction level.

The soil strength tested with the Panda 2 dynamic cone penetrometer as presented in Figure 3 also show no sharp peaks of sudden increase or decrease of the soil strength. Such sharp peaks are typically related to crushing of shells. The fact that no sharp peaks are present indicates that the effect of crushability of the tested (i.e. sieved) sand-shell mixture is marginal.

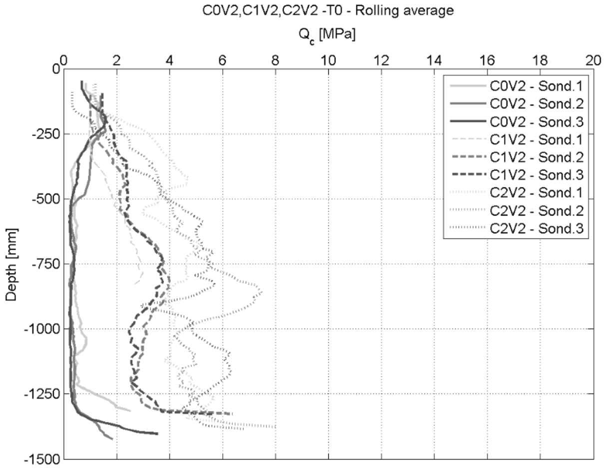

Figure 3. Results of the Panda tests of the initial condition (T0) of the chambers with loose (C0V2), medium dense (C1V2) and dense sand (C2V2) prior to any vibrocompaction.

4 .2 *Soil condition after vibrocompaction*

As an example, Figure 4 shows the Panda test results of the chamber with loose sand before any vibrocompaction (T0) and after two sets of vibrocompaction (T2) each with a duration of 1.5 minutes. The vibrocompaction is first performed in the middle of the chamber, followed by a second vibrocompaction at the bottom of the chamber. Before performing any vibrocompaction, the measured Qc-value is low (between 0 MPa and 5 MPa). After two sets of vibrocompaction each with a duration of 1.5 minutes, the Qc-value has increased up to 1 MPa at the top of the chamber and 20 MPa at the bottom of the chamber. These results show that with the given sand-shell mixture very high Qc-values up to 20 MPa can be obtained with vibrocompaction.

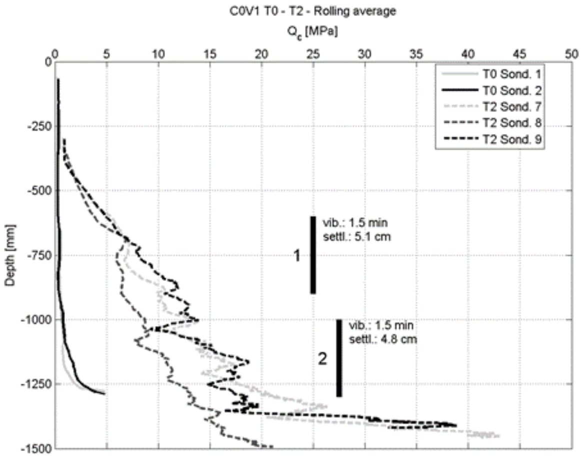

Figure 4. Results of the Panda tests of the chamber with loose sand (C0V1) before any vibrocompaction (T0) and after the second vibrocompaction (T2). The duration and location of the performed vibrocompactions are indicated with the thick black lines. Also the measured settlement after each vibrocompaction is indicated.

4 .3 *Influence of the vibration time*

After each session of vibrocompaction the settlements are measured. Figure 5 presents the settlements versus the time of vibrocompaction per chamber. Per set of chambers (loose, medium dense and dense sand) the settlements measured after the same vibration time are very similar. This indicates that the performed tests are repeatable. Only for the medium dense sand more deviation is noted between the measured settlements compared to the other sand conditions. Furthermore, the looser the sand before vibrocompaction, the higher the final settlements after the vibrocompaction. The settlements between two successive vibrocompaction sessions also decrease.

The test in the chamber with medium compacted sand and full vibration (see Figure 5) shows that a total vibration time of 6 minutes is long enough to reach about the maximum settlements (at least for medium dense sand). After the 6 minutes of vibration the settlement increase is negligible. This is used to determine the vibration time for the intermediately and fully vibrated chambers. To obtain fully vibrated chambers, the chambers are vibrated for at least 6 minutes in total. To obtain intermediately vibrated chambers, the chambers are vibrated for at least 3 minutes (half of the vibration time of the fully vibrated chambers).

An important outcome of the tests is that after some vibration the measured settlements do not increase that much, while Panda cone resistance (Qc) still does. In Figure 6 and Figure 7 the depth average Qc-values are given per chamber and after a certain time of vibration for respectively the top part of the chamber and the bottom part of the chamber. The increase in Qc-value at the top part of the chamber (Figure 6) is not in line with the increase of the settlements (see Figure 5). A clear increase in the Qc-value is noted after 3 or 6 minutes of vibrating whereas Figure 5 indicates lower settlements after these vibration times. The increase of the Qc-value at the bottom of the chamber (Figure 7) follows more the trend of the settlements: settlements and Qc-values seem to have the same trend. The fact that the increase in Qc-values over the depth of the calibration chamber is not perfectly correlated with the settlements, means that one should be careful when using in-situ settlement measurements as a criterion for the required strength during vibrocompaction campaign. In order to verify the strength of the in-situ sand-shell mixture during vibrocampaction campaign, CPT's should be used to confirm the achieved strength.

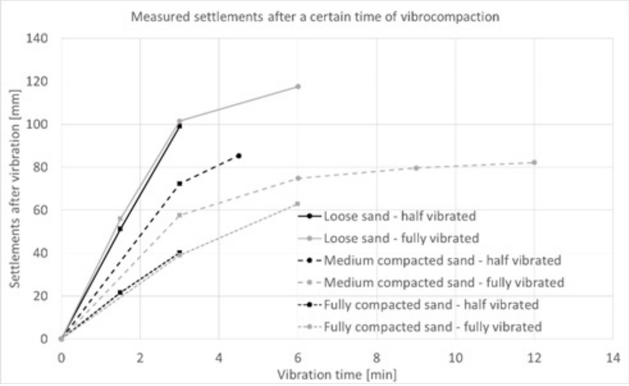

Figure 5. Indication of the settlements per chamber after a certain time of vibrocompaction.

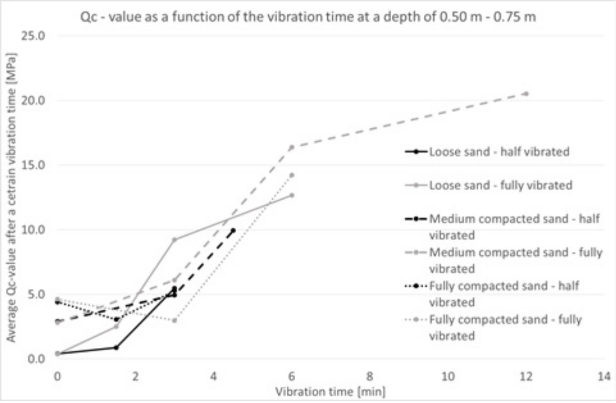

Figure 6. Indication of the depth average Qc-value per chamber after a certain time of vibrocompaction at a depth of 0.50 m - 0.75 m.

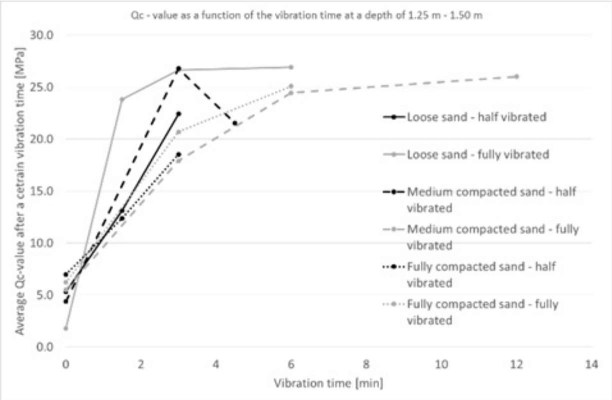

Figure 7. Indication of the depth average Qc-value per chamber after a certain time of vibrocompaction at a depth of 1.25 m – 1.50 m.

Figure 6 and Figure 7 confirm that vibrocampaction can be applied as an efficient soil improvement technique for the sand of the borrow area. A Qc-value of 5 MPa is quite easily obtained for all the initial sand conditions (loose, medium and dense).

The test results also indicated that performing vibrocompaction at the bottom of the chamber results in an increase in the Qc-value mainly at the bottom of the chamber. The influence on the upper part of the chamber is limited. A second vibrocompaction at mid-height of the chamber results in an increase mainly at the upper part of the chamber. At the bottom of the chamber also an increase is noted, but the increase is smaller than at the top of the chamber. This indicates that the location of the vibrator and thus the location of the applied energy has an influence on the increase of Qc-value.

5 CONCLUSION

Large calibration tests were performed with a sand shell mixture. In total three sets of chambers are analysed: loose sand, compacted sand and medium compacted sand. Per set of chambers three different vibration conditions are considered: not vibrated (or reference state of the soil), maximum vibration and medium vibration. In between successive vibrocompaction sessions, the obtained soil strength is tested with the Panda 2 dynamic cone penetrometer.

Test results showed that for the same degree of pre-compaction, the measured settlements after the same vibration time are very similar. This is a good indication for the repeatability of the large calibration chamber tests.

A further analysis of the results indicated that the settlements and the increase in Panda cone resistance are not perfectly correlated. Longer vibration times do have an influence on the Qc-value, although further settlements are limited. Therefore, one should be careful when using the settlements as an acceptance criterion for the required strength during the vibrocompaction campaign. A few CPT's should be considered to confirm the achieved strength.

Furthermore, the results showed that the location of the applied vibration energy has an influence on the increase of the Panda cone resistance.

Finally, the obtained results clearly indicate that with the given sand-shell mixture very high Qc-values up to 15 MPa and 20 MPa can be obtained with vibrocompaction.

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