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Compaction control and related stress–strain behaviour of off-shore land reclamations with calcareous sands

P.O. Van Impe[a,b,*], W.F. Van Impe[a,b], A. Manzotti[b], P. Mengé[c], M. Van den Broeck[c], K. Vinck[c]

[a]Ghent University, Laboratory of Geotechnics, Technologiepark 9, 9052 Zwijnaarde, Belgium
[b]AGE bvba Geotechnical Consultants, Rooseveltlaan 2, 9420 Erpe-Mere, Belgium
[c]DEME NV, Scheldedijk 30, 2070 Zwijndrecht, Belgium

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Abstract

When constructing off-shore land reclamations, one aims to ensure that the final soil mass fulfills certain minimal criteria related to shear strength, stiffness and resistance against liquefaction. In general, these characteristics improve with increasing density of the soil mass, which means that the above criteria are usually condensed into a single one: 'adequate densification'.

Quality control of reclamation constructions therefore focuses on the latter. Technical requirements are written based on one single parameter: the relative density D_r. On the site, this parameter is commonly determined indirectly using correlations with the cone penetration resistance q_c, making the CPT the main tool for quality control.

The paper presents data gathered during the design and construction of an off-shore land reclamation using calcareous sands. For this specific project, density control had to be done through the use of CPT.

Calibration chamber tests were performed to establish the CPT q_c–D_r correlation for the specific soil material. This correlation was used to analyse CPT results during construction of the site in order to determine the quality of compaction.

In a further stage, an elaborate laboratory study was performed to establish additional correlations between soil parameters and the stress–strain parameters. Furthermore, seismic CPT tests were executed on the site to test the relevance of the laboratory correlations and the 'relative density approach' in general.

It is shown that off-shore land reclamations have a very erratic stress-history, due to the different processes of depositing the soil material and the various densification methods. This stress-history is of great importance in the stress–strain behaviour of the site. Results also suggest that the CPT does not provide enough data to reliably predict soil stiffness when dealing with crushable materials. Specifically, in situ measurements show that there is no direct correlation between the small strain shear modulus G_0 and q_c.
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Keywords: Reclamation; Compaction control; Calibration chamber testing; SCPT; Calcareous sand; Resonant column; Bender element

*Principal corresponding author at : AGE bvba, Rooseveltlaan 2, 9420 Erpe-Mere, Belgium.
E-mail addresses: peter.vanimpe@age-be.net (P.O. Van Impe), william.vanimpe@age-be.net (W.F. Van Impe), alice.manzotti@age-be.net (A. Manzotti), menge.patrick@deme.be (P. Mengé), van.den.broeck.marc@deme.be (M. Van den Broeck), vinck.ken@deme.be (K. Vinck).
URL: http://www.AGE-be.net (P.O. Van Impe).
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1. Introduction

1.1. Land reclamation quality control

In the philosophy of reclamation quality control, the future stress–strain behaviour of the site is correlated to the density of the fill. Quality control is linked to 'adequate densification', which should guarantee that certain minimal requirements related to the soil behaviour (shear strength, stiffness or cyclic resistance ratio) will be obtained.

This concept is translated into technical requirements using parameters like relative density D_r or maximum dry density (MDD).

Densities are then determined on site either directly (in situ dry density measurement by e.g. the sand replacement method) or indirectly, based on correlations between density and the cone penetration resistance q_c.

During construction of the site, the CPT will be used as a control method to indicate areas where additional densification is required.

1.2. Relevance of using the q_c–D_r approach in compaction control

Authors believe there are ample reasons why the current approach does not reflect the 'quality' of a reclamation.

Firstly, the method depends fully on relative density D_r, which is an extremely unreliable parameter. It is a calculated value depending on particle density, bulk density, minimum and maximum density. Especially the latter are notoriously difficult to pin down as they depend strongly on the method with which they are determined. Moreover, each small error in the measurement of the above parameters has a larger than proportional effect on the final value of D_r.

Especially for crushable sands, this becomes problematic. The measured maximum density is only relevant as long as the sample does not crush. As soon as crushing starts taking place, we are in effect dealing with a different material. This should rule out the use of the proctor compaction to determine the maximum density, although it is the prescribed method in many tender documents.

Some other specific problems with dealing with crushable sands did become common knowledge over the past decade. As it has been shown for many years, the typical correlations between q_c and D_r are no longer valid, as significantly lower q_c values are developed in these sands as compared to silica sands under similar conditions. However, rather than abandon this approach, correction factors have been applied, based on the so-called 'shell-factor'. The shell-factor would be the ratio of the cone penetration resistance (at a certain stress level) for a crushable material and that for a reference (silica) material, and is therefore only relevant for the comparison between these two specific soil materials.

Unfortunately, in practice, this correction method has started a life of its own, losing on the way all connection to reality. It has come to the point where a value of the shell-factor is a result of a negotiation between two opposing forces: the contractor (aiming for the highest value, which would reduce the critical cone resistance limit and therefore the amount of compaction) and the owner or engineering office (aiming at the lowest value in order to force the contractor to perform the highest level of compaction).

Beside the problems on how to determine the compaction quality through CPT, one should question the general principle that – in these soils – adequate soil conditions are reflected by the relative density D_r:

- In many cases, what is assumed to be 'adequate' is not even specified. Technical requirements for a reclamation site rarely specify actual parameters relevant to the stress–strain behaviour.
- The value of the minimum relative density which guarantees 'adequate' soil behaviour is based on general correlations proposed in literature. But if we use – in the case of a calcareous soil – a correction factor to take into account the effect of crushing on the correlation with the cone resistance q_c, why do we still expect the others to be relevant? It has been shown again and again that the cyclic resistance ratio can be far greater in the case of calcareous sands, due to their irregular grain shape (LaVielle, 2008; Pando et al., 2012; Brandes, 2011).
- The effect of crushing is not taken into account, although crushing is inevitable when large compaction efforts are required. One could question if the effect of crushing itself does not negatively alter the soil behaviour, in a way that it compensates the beneficial effect of the increased density, i.e., should we fear 'over-compaction'?

1.3. Present research

The project presented in this paper was an off-shore land reclamation, consisting of two separate islands, located in the Persian Gulf. Typically for this region, the main soil material was a calcareous sand of biogenic origin (shells and coral).

Technical requirements stated that the CPT should be used to establish the degree of densification of the hydraulic fill (through q_c–D_r correlation, according to literature), combined with in situ dry density tests on the layers above the water table. Densification of the hydraulic fill was to be done by vibrocompaction, until values of relative density D_r were above 61% (equivalent to 90% MDD).

During this project, two research campaigns have been organized.

The main dredging contractor chose not to work with the so-called 'shell-factor' approach but instead – with the approval of the site owner and its engineer – organized extensive laboratory calibration chamber testing to obtain the actual relevant q_c–D_r correlation for the site material. As this was still at the very early stages of the project, calibration chamber tests were performed on materials coming from the two main borrow areas.

The second testing campaign was organized in order to check the validity of the q_c–D_r approach – specifically looking at the in situ soil stiffness – and to obtain data which could allow alternative quality control methods. This campaign

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