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Evaluation of relative density and liquefaction potential with CPT in reclaimed calcareous sand

P. Mengé, K. Vinck & M. Van den Broeck
DEME N.V., Zwijndrecht, Belgium

P.O. Van Impe & W.F. Van Impe
AGE bvba Geotechnical Consultants, Erpe-Mere, Belgium

ABSTRACT: Land reclamation works in the Middle East often are realized with carbonate sands. Compaction of such underwater and above water hydraulic granular fills is generally realized by means of vibroflotation and/or dynamic compaction, resulting in an inhomogeneous fill of more compacted and less compacted zones. The aim of compaction should be to guarantee performance requirements of the fill, such as maximum long term residual (differential) settlements, minimum bearing capacity and liquefaction resistance during seismic events. Quality control of such fill is often realized by means of the CPT, however the quality assessment procedure is often ambiguous with regard to how to deal with the heterogeneity of the fill and with regard to the effect of crushing of the calcareous sand. In this paper the problem is illustrated and the approach used for a land reclamation project with calcareous sand is discussed.

1 INTRODUCTION

Land reclamation works in the Middle East often have to be realised with carbonate sands which are abundantly present in the region. Depending on the goal of the reclamation works, several performance requirements may apply: maximum long term residual (differential) settlements (under static loads and post-earthquake); minimum bearing capacity for foundation systems and liquefaction potential under seismic events. This often is translated into a minimum relative density or, derived thereof, a target CPT-q_c line.

Compaction of such underwater and above water hydraulic granular fills is generally realised by means of vibroflotation and/or dynamic compaction. Such operations are grid-oriented and inevitably result in an inhomogeneous fill of more compacted and less compacted zones. The quality control of the fill is mainly realized by means of the Cone Penetration Test (CPT). The quality assessment procedure to follow is often ambiguous and is mainly focused on point measurements while the real performance of the fill should be of main importance.

Compaction of calcareous sand and, even more, CPT testing of such sand causes crushing of the grains which influences the results. Evaluation of relative density of the compacted fill from CPT resistance by means of literature correlation formulascannot longer be applied as these formulas are valid for dry silica sand. As a simplified approach, often a 'Shell Correction Factor' (SCF) is used, which allows to derive an equivalent 'silica sand cone resistance' which is used for evaluation of relative density and assessment of liquefaction potential. The SCF is not a unique figure and depends on many factors, among which sand type, density and stress state. In order to overcome this problem for the case study, calibration chamber (CC) tests were performed on the saturated and dry calcareous sand used in order to define a site-specific correlation formula.

The working method for the quality control (QC) of the compacted hydraulic fill with regard to required (relative) density and liquefaction assessment is discussed in following sections, based on a case study of land reclamation work in the Middle East.

2 HYDRAULIC FILL

A general discussion on hydraulic fills is beyond the scope of this paper, but reference can be made to Chu et al. (2009) and van 't Hoff & van der Kolff (2012) where hydraulic fills for land reclamation works are discussed. One of the typical effects of underwater and above water hydraulic fills is the variation in density obtained depending on sand installation methods: under water by dumping, rainbowing, spraying or outflow of land pipe lines; above water by rainbowing or land pipe lines.

Table 1 gives an overview of the expected relative densities (D_r) taking into account the hydraulic installation method. As a result of this variation, compaction may be required depending on the project functional requirements.

Table 1. Typical relative densities as a result of hydraulic fill.

Placement method	D_r (%)
Spraying (discharge under water)	20-40
Dumping (discharge under water)	30-50
Land pipelines (discharge Under water)	20-40
Rainbowing (discharge under water)	40-60
Land pipelines (discharge Above water)	60-70
Rainbowing (discharge Above water)	60-80

3 LANDFILL REQUIREMENTS

In the Specifications, project functional requirements are translated into performance requirements or even further in more detailed technical specifications. The level of detail of such requirements differs depending on the type of contract. Typical landfill requirements for granular fill will discuss following items:

Suitable fill material: mainly granular material with limited amount of stones and limited fines content (generally less than 10% to 15% of particles smaller than 63microns). Main reason for the fines content limitation is compactability under water.

Allowable residual settlements: such settlements may originate from deeper layers below sea bottom level as well, but for the sake of this paper, focus is on settlements originating from the fill material itself. Settlements related to granular fill may result from self-weight auto-compaction (ageing) and deformations under service loads. When the project location is to be considered as a seismic region, post earthquake settlements may apply as well. Differential settlements are very difficult to demonstrate in pre-project phase, but may be a requirement and be a point of attention for execution method selection, during execution and testing.

Bearing Capacity: bearing capacity requirements define the type of footing, size, depth of application, load to be carried and factor of safety to be applied to define the 'safe bearing capacity'. Normally no deformation requirement is linked to such specification.

Slope stability: this is mainly valid at the edges of the reclamation and results in slope stability calculations based on the method of slices from which maximum slopes combined with a certain minimum friction angle will follow. In seismic regions, the slope stability will usually be realized with the pseudo-static method

Liquefaction resistance: when peak Ground Acceleration (PGA) and the Magnitude (M) are defined, the liquefaction assessment can be based on one of the many methods described in literature. Most commonly used is the NCEER method starting from CPT's performed after compaction.

It is clear from the above discussion that the compaction of the hydraulically deposited fill material may be necessary. The above discussed performance requirements are often translated into technical requirements such as minimum friction angle and a minimum relative density or relative compaction.

After deep compaction, the most practical means of QC over the full height of the fill is the CPT. At this stage, the evaluation method needs to be defined clearly, so as to be able to conclude whether or not the compaction is sufficient and the project functional requirements will be achieved.

4 CALCAREOUS SAND

Carbonate soils are defined as soils in which carbonate minerals predominate. They are widely distributed in the warm and shallow seas and oceans of the world's tropical and sub-tropical regions covering almost 40% of the ocean floor. Carbonate deposits are usually formed by accumulation of skeletal remains of small marine organisms from the upper waters of the ocean (bioclastic deposits), but may also have a non-organic origin, for instance, as a result of chemical precipitation from carbonate-rich water (oolites) (van 't Hoff & van der Kolff 2012).

Calcareous sand and its geotechnical engineering behavior is much discussed in literature (e.g. Coop & Airey 2003). For land reclamation QC, main issues are the crushability leading to different behavior during testing, high angularity leading to high shear strength and liquefaction resistance, cementation and load-deformation behavior depending strongly on stress history.

In the field of QC of land reclamation works, the focus will be on the influence of crushing on cone penetration testing and maximum density testing. For CPT this phenomenon has been covered since many years by several authors (Almeida et al. 1991; Wehr 2005, Mayne 2014, Van Impe et al. 2015). The cone resistance in calcareous sand for the same D_r and stress state is lower compared to silica sand. Consequently, typical correlations between q_c and D_r are no longer valid. Ideally, a site specific correlation should be derived through calibration chamber (CC) testing. As a simplified approach, sometimes the use of a 'Shell Correction Factor' (SCF = $q_{c,silica}/q_{c,calc} > 1$) is used.

However, when the q_c-value to be expected in calcareous sand is known, it must be considered unlikely that other correlations with the relative density parameter D_r (liquefaction susceptibility, compressibility, …) still hold. New correlations will have to be determined that should directly link in-situ measurements with the relevant soil parameters.

Maximum Dry Density (MDD) testing, needed to define relative density or relative compaction, is often performed by means of dynamic laboratory tests such as proctor compaction (to define the moisture-density relationship) or vibrating hammer compaction. Such techniques cause crushing of carbonate sand particles, resulting in a different particle size distribution and higher densities than can be reached in the field. To avoid such effect, authors have demonstrated by comparative testing that the vibratory table test (ASTM D4253) causes least crushing and is hence the recommended test to define the MDD of calcareous sand.

5 RELATIVE DENSITY CONSIDERATIONS

The use of relative density in geotechnics is widely spread because of the influence of degree of compaction on many parameters. However, often D_r proves to be an unreliable parameter. It is a calculated value depending on particle density, bulk density, minimum and maximum density. Especially the two 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.

6 CASE STUDY

6.1 *Project description*

The project considers off-shore land reclamation for the construction of oil drilling islands 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 fill had to be compacted to 90% MDD and that the reclaimed material had to resist an earthquake with PGA=0.15g and M=6. Additionally, a higher compaction requirement was valid to the top 0.9m. Bearing capacity and settlement requirements were applicable as well, but will not be discussed here. In zones of 25m by 25m, the CPT had to be used to establish the degree of densification of the hydraulic fill. In situ density tests were required in the top 0.9m layer.

Deep densification of the hydraulic fill was realized by vibroflotation, aiming to reach values of D_r above 62% (equivalent to 90% MDD). It was decided to perform CC testing in order to establish a site specific correlation between q_c, D_r and vertical effective stress (σ'_v).

6.2 *Sand characteristics*

CC tests were done on samples taken from the borrow areas where later on the material of the reclamation would be excavated. Samples from these areas are further referred to as BAE (borrow area east) and BAW (borrow area west). The additional testing campaign was undertaken during the actual construction phase. Testing material for this second campaign was taken from one construction site, as soon as it surfaced. This material will be denoted as S1 in this paper.

All materials were analysed to determine standard reference parameters: particle size distribution (PSD), carbonate content and index densities. Figure 1 shows the results of the PSD. A significant difference was noted in the particle size distribution of the sands from the borrow areas (BAW and BAE). The material S1 closely resembles the BAW material. The results of this basic reference testing are given in Table 2. As reference, literature data from other typical testing materials is mentioned as well.

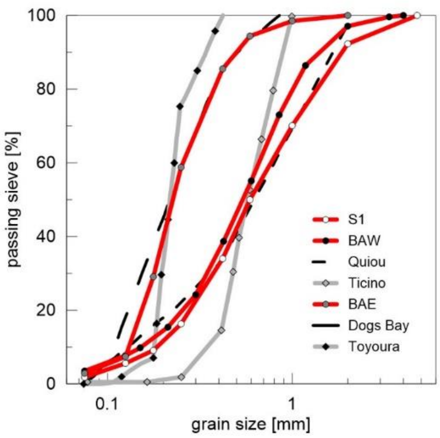

Figure 1. PSD of the BAE, BAW and S1 sands, with some literature reference testing sands.

Table 2. Overview of sand characteristics.

Sand	γ_s [kN/m³]	D_{50} [mm]	$CaCO_3$ [%]	e_{max} [-]	e_{min} [-]
BAE	2.84	0.23	93	1.551	0.979
BAW	2.84	0.57	98	1.392	0.843
S1	2.84	0.59	95	1.278	0.741
Dogs Bay	2.75	0.24	87-92	1.830	0.98
Quiou	2.72	0.71	77	1.281	0.831
Ticino	2.69	0.55	<	0.934	0.582
Toyoura	2.65	0.16	<	0.977	0.605

6.3 *Calibration chamber testing*

The calibration chamber tests have been performed in a centrifuge at ISMGEO, Bergamo, Italy. Thus, q_c-D_r relations could be established at a continuous range of overburden stresses, while the traditional calibration chamber tests only resulted in a single q_c-D_r-σ'_v data point for each test. In the centrifuge set-up, due attention was paid to cone diameter to mean grainsize ratio and chamber diameter to cone diameter ratio in order to minimize size- and boundary effects. Details of the setup and testing are given in Van Impe et al. (2015).

Centrifuge CC tests have been performed on BAE and BAW samples, both in dry and wet conditions. A significant impact of the presence of water was found, leading to much lower values of $q_{c,wet}$ compared to $q_{c,dry}$ at similar relative density and stress level. This effect has been noticed as well for silica sands, although to a (much) lesser extent. Jamiolkowski et al. (2001) states that the value of D_r would typically be underestimated by 7% to 10% for the sands considered in their research. For the BAE and BAW sand the error is rather 30% and the physical background of this phenomenon is unclear; possibly (micro-) cementation may occur in the dry sand which could not be proven. In the discussion below only the results of the wet CC tests will be discussed. Figure 2 shows the results of the tests on the wet BAW material.

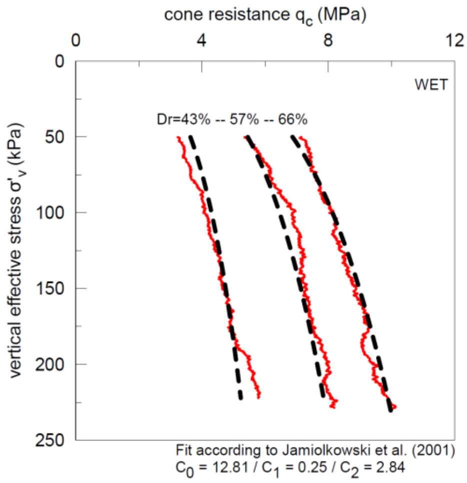

Figure 2. Results of the centrifuge CC tests on wet BAW material.

Jamiolkowski et al. (2001) proposed following form of q_c-D_r-σ'_v correlation:

$$\frac{q_c}{p_a} = exp^{D_r.C_2} . C_0 . \left(\frac{\sigma'_v}{p_a}\right)^{C_1} \qquad (1)$$

Where p_a is the atmospheric pressure in the same unit system of stress and penetration resistance (98.1 kPa); C_0, C_1 and C_2 are non-dimensional empirical correlation factors.

The data obtained from the CC testing was analyzed using the above correlation and the correlation factors defined. The correlation factors for BAW, BAE, for an average correlation and for typical research silica sands (Ticino-Toyoura-Hokksund; Jamiolkowski et al. 2001) are given in Table 3.

Table 3. Empirical coefficients for q_c-D_r correlation (1)

Coeff.	*BAE*	*BAW*	*Average*	*TS+TOS+HS*
C_0	13.09	12.81	12.95	17.68
C_1	0.29	0.25	0.27	0.50
C_2	2.68	2.84	2.76	3.10

Figure 3 shows the 4 correlations from Table 3 graphically. It can be noticed that, although both BAE and BAW sands have a clearly different PSD, they behave very similarly in the CC-tests. This indicates that PSD has less impact on the behavior of the material than its mineralogy. These correlations are valid for σ'_v > 50kPa; for lower stresses an adapted correlation applies (not further discussed here).

From these correlations a SCF can be derived. Figures 4 and 5 give the SCF in function of vertical effective stress and in function of D_r, also indicating SCF's as given in literature by Wehr (2009) and Mayne (2012). Figure 4 illustrates that the SCF is not a constant value, but differs with vertical effective stress. Figure 5 was derived for a vertical effective stress of 100kPa and demonstrates that the SCF which was proposed by Wehr perfectly matches the SCF derived here for a stress level of 100kPa. This proves that the sand found in the same region behaves similar under CPT testing. The SCF as suggested by Mayne seems not to correspond well and may be valid for other types of calcareous sands.

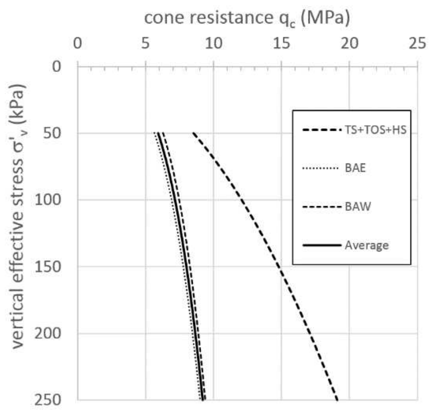

Figure 3. q_c-D_r-σ'_v correlations from Table 3 (D_r=62%).

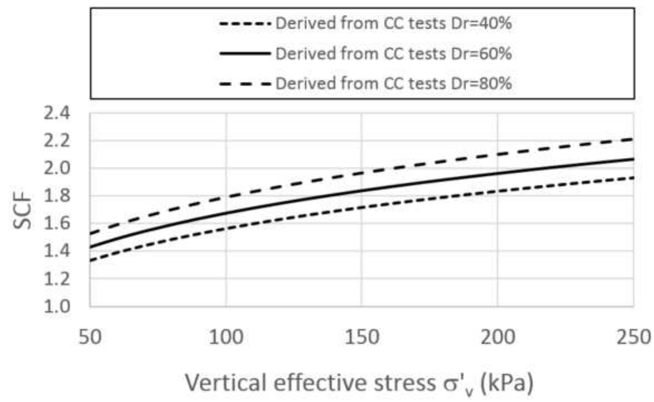

Figure 4. SCF in function of vertical effective stress and relative density.

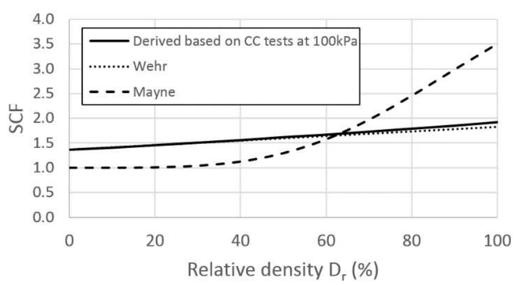

Figure 5. SCF in function of relative density.

Notwithstanding the findings with regard to SCF and its ease of use, authors prefer the more accurate scientific approach using the results of CC-tests to define the relative density of calcareous sands from CPT. Also note that for the calculation of the SCF the correlation (1) was used with the correlation factors as given in Jamiolkowski et al. (2001) for a series of silica sands (TS+TOS+HS) (also shown in Table 3). This correlation was selected because it is believed to be the most recent, well documented and fully corrected correlation. Should other correlations be used, other SCF's will be found.

6.4 *Relative density verification with CPT*

Deep compaction was performed by vibroflotation. Compaction is usually performed in a triangular grid with probe spacing between 3m and 5m. The zone of influence of each compaction point should overlap (Figure 6). However, there will be a gradient in degree of compaction when moving away from the compaction point and different levels of compaction will be found depending on the location of the CPT test. In Figure 7 two typical locations where CPT testing can be done are indicated: at the centroid of the compaction points and at 1/3 on the line between two compaction points. The first will theoretically give the lowest result while the second one is assumed to give the best result. To have a CPT diagram which is representative for the behavior of the whole fill, it is common practice to calculate an 'average' CPT curve from the two positions (i.e. at each level, the average of the two measured values is defined). This average curve is then used for evaluation.

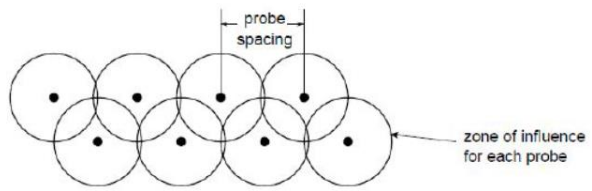

Figure 6. Zone of influence and probe spacing for vibroflotation.

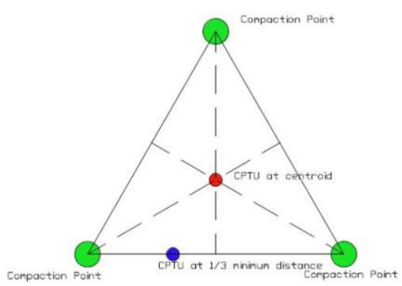

Figure 7. Post-vibroflotation testing locations related to a triangular compaction grid.

In Figures 8 and 9 the results of a pre- and post-compaction CPT's are given (the post compaction CPT is the average curve) for a zone where locally a layer with higher fines content is found. The target D_r is verified in the graph at the right of the figure. The D_r above the water table (horizontal line) clearly is very high while under water the expected low densities are found. In the post-compaction figure the D_r is verified again and should be above the target line. This is the case over most part of the figure, except for the zone with higher fines content (between -8m CD and -10.5m CD).

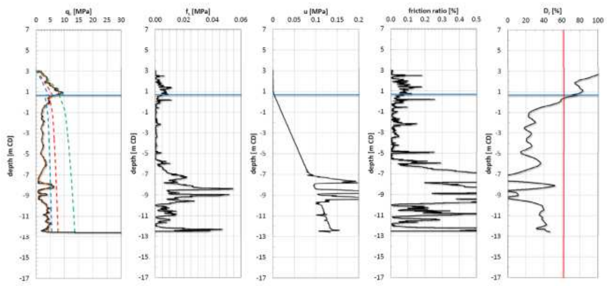

Figure 8. Pre-compaction CPT

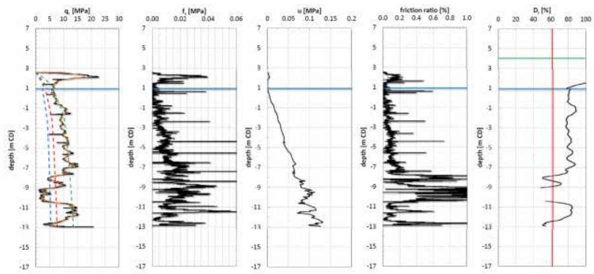

Figure 9. Post-compaction average CPT

In order to smoothen the result, a 'moving average' curve is calculated over 0.5m height (= average value calculated from all values 0.25m above and 0.25m below the considered level). When averaged q_c-results are below the target line, the total height over which the criterion fails is defined. For the CPT shown in Figure 9 this is the case for a height of 6.3%. Individual failing layer thickness has to be less than 0.5m and the total sum has to be less than 10% of the CPT height. More failure of the target line can only be accepted after 'Engineering Review' (ER). ER means that the effect of failing the target line is studied from a point of view of engineering behavior (static and post-earthquake settlements, bearing capacity, stability and liquefaction) and based on this evaluation it will be decided whether the realized fill can be accepted. When necessary, ER may include additional testing or boreholes with sampling and lab testing.

6.5 *Liquefaction analysis*

Apart from the relative density requirement, also liquefaction assessment is necessary. Hereto, the NCEER method is followed, based on the corrected CPT diagram. For correction, a SCF was calculated as described above and thus varied with compaction level and stress level. In order to take into account, the effect of the (limited) fines content, the procedure based on the soil behavior type-index I_c is used. For these calculations, the above mentioned averaging cannot be allowed and individual CPT's are evaluated. This leads to the discussion whether each individual CPT is representative for the behavior of the whole fill or whether averaging of the obtained factors of safety against liquefaction ($FoS_L > 1.25$) can be done for final assessment.

Authors believe the overall behavior cannot be evaluated on basis of individual CPT's at the 'worst' and 'best' CPT-locations and suggests to use (weighted) averaged FoS_L. Similar situations with soil replacement columns in liquefiable soils have been studied numerically (Rayamajhi et al. 2013).

In Figure 10 the results of one of the post-compaction CPT's is shown. In this figure the SBT I_c and FoS_L are displayed. Where the higher fines content occurs, the CPT 'fails'. Decision has to be made by means of ER whether this location needs re-compaction or other remedial actions.

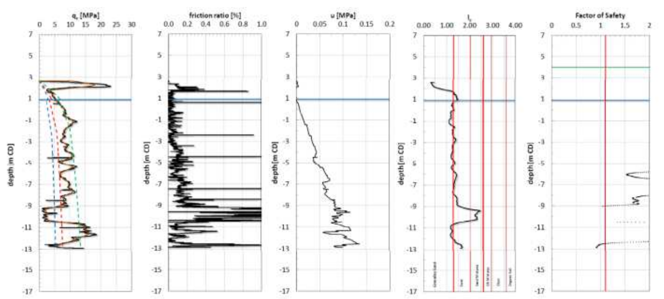

Figure 10. Post compaction CPT, liquefaction assessment

6.6 *Additional considerations*

The CPT's shown in Figures 8 to 10 have been chosen to show 'failing' CPT's. When performing hydraulic fill with crushable material under water, it is impossible to avoid locally sand with increased fines content to get included in the reclamation. The increased fines content was still rather limited as the material is classified as 'sand mixtures' based on I_c. In such cases ER is required to decide on what to do. Re-compaction, going through more than 10m of well compacted material is not an easy task and the final result may even be worse than the result obtained now. So when ER demonstrates that the 'performance requirements' of the fill and future structures are met, no further compaction is really necessary.

In case of failing layers, the Liquefaction Potential Index (LPI) (Li et al. 2006) may be an approach to estimate the probability of liquefaction to occur. Such LPI approach seems not to be globally accepted, but it would offer a systematic approach to evaluate a whole soil column instead of a soil element.

Ageing may be important in compacted sand; in general a time period of minimum 2 weeks is allowed between compaction and CPT testing.

Compaction quality testing as discussed above is focused on 'parameter testing', and not on the real engineering behavior, unless the concept of ER is applied. Direct testing of engineering behavior by means of large plate load tests (Zone Load Test) or in situ measurement of the shear wave velocity should be considered as preferable alternative approach.

Instead of using the NCEER method with corrected CPT values, cyclic triaxial and/or cyclic direct simple shear testing could be done to evaluate the liquefaction behavior of the calcareous sand. Such an approach avoids the need to use the NCEER correlations which may not be valid for this specific sand.

7 CONCLUSIONS

The problem of quality control of the compaction of large land reclamation works with calcareous sands is discussed and illustrated on basis of a case study. It is advised to perform CC tests at an early stage of the project. This approach allows to have an undisputable correlation between q_c, D_r and σ'_v. Liquefaction assessment is often performed according to the NCEER method, based on corrected CPT results. Because of the heterogeneity of the compacted fill, a specific approach was followed when evaluating the CPT's; this approach is illustrated in this paper.

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