Field trial benchmark of shell correction factor for Dubai calcareous sand

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ABSTRACT
Sand used in the construction of marine structures in areas with seismic activity generally needs to achieve a minimum density, often expressed as relative density, to avoid excessive deformations or flow liquefaction during or after seismic loading. As a consequence, during construction, verification testing is required to confirm this minimum relative density is achieved. Due to its advantages these tests are generally cone penetration tests (CPT). However, the typical correlations cannot be directly applied for calcareous sand. It is known that the cone resistance in calcareous sand is lower than found in silica sand of similar density with differences varying with factors between 1.3 to 9.

This study discusses the determination of the performance of a breakwater containing a hydraulically placed sand core of calcareous sand. The design of the breakwater was optimized to require a minimal required relative density of 40% in order to have limited damage during the design earthquake. Performance testing by CPT required a realistic correlation between CPT tip resistance and relative density to guarantee the required density was achieved.

From a literature review a relative density correlation in combination with a shell correction were selected for this project. To determine if the chosen correlations could be safely applied, a field trial benchmark was conducted. The field trial, consisting of a 6m high sand body placed at various densities, was designed to have similar stress situations as the underwater sand core of the breakwater.

From the comparison of the measured field density and the correlated density from the CPTs a number of observations were made. Although there is a large spreading between the correlated density and measured field density the trend found using all the measurements led to a reasonable fit with the chosen literature correlations.

1 INTRODUCTION

For the construction of land reclamations and other nearshore developments sand is often used as source material of choice due to its relative abundance and suitable geotechnical properties. Depending on the material properties and placement technique, the density of the sand placed below the water table is typically low, in the order of 40%, putting the material at risk of strength degradation or even liquefaction during seismic events.

A large amount of literature correlations are available to determine the relative density of sand based on Cone Penetration Test (CPT) tip resistance allowing for the assessment of the liquefaction risk. However, when performing the CPT in carbonate sands, found in abundance in the Arabian Gulf, the high stresses at the CPT tip can cause crushing of the carbonate material thus underrepresenting the CPT tip resistance when compared to silica or quartz sands at the same density. Often a so-called Shell Correction Factor (SCF) is applied to correct the measured tip resistance for this crushing effect.

This paper discusses the design, execution and results of a benchmarking trial performed by Van Oord Dredging and Marine Contractors as part of a land reclamation project in the United Arab Emirates. Part of the project consisted of the construction of a submerged breakwater core, which needed to achieve a certain minimum relative density. Reclamation works were executed by trailing suction hopper dredger with carbonate sand obtained from an earlier reclamation in the vicinity.

To verify the achieved density in the breakwater core, CPTs were performed. Purpose of the benchmark trial was to verify a proposed relation between relative density and CPT tip resistance taking into account the crushing effect. The paper describes the background of the proposed relation, the set-up of the trial and the execution of the trial. Finally, we discuss the trial results focusing on the suitability of such a trial.

2 SITE CONDITIONS

2.1 Seismic Conditions

The considered project is located in a low to moderately active seismic zone. Seismicity in the region is typically occurring the Zagros collision zone and the Makran subduction zone caused by the collision of the Arabian Plate and the Eurasian Plate. The Dubai seismic hazard is controlled by large-to-great size distant earthquakes occurring in the Zagros Belt and Makran Subduction located respectively 140 and 220km from Dubai (Dubai Seismic Network website).

2.2 Reclamation materials

The reclamation material consists of calcareous sand originally dredged offshore from the Dubai coast. The typical carbonate content of this sand is in the order of 90%.

3 BACKGROUND

3.1 Relative density – CPT correlation

The use of relative density (D_r) to determine the soil state is a generally accepted design practice in many countries. Due to the large amount of experience with this parameter it has not yet been replaced by more advanced modelling like critical state soil mechanics, despite its shortcomings.

Over several years correlations have been established between cone resistance (q_c) and relative density (D_r). In most correlations, the (normalized) cone resistance is correlated to the relative density through a number of constants in combination with the effective stress and in some cases the OCR. Baldi et al. (1986) conducted extensive calibration chamber studies on moderately compressible Ticino quartz sand and obtained the following relationship to evaluate D_r for normally consolidated soils.

$$D_r = 1 / 2.41 \ln(q_c / (157 (\sigma'_v)^{0.55})) \qquad [1]$$

Where q_c and σ'_v are respectively the cone resistance and the effective vertical stress in kPa. Various authors have published other relationships or adaptations of the above-mentioned relationship including Kulhawy and Mayne (1990) and Jamiolkowski et al. (2001).

3.2 Calcareous sand

Calcareous soils are widely distributed in the oceans in tropical and subtropical regions of the world (latitude 30 degrees north to 30 degrees south). These soils are formed from the skeletal remains of corals, shells and algae from the upper waters of the ocean (Lunne et al, 1997; Mitchell and Soga, 2005), see Figure 1.

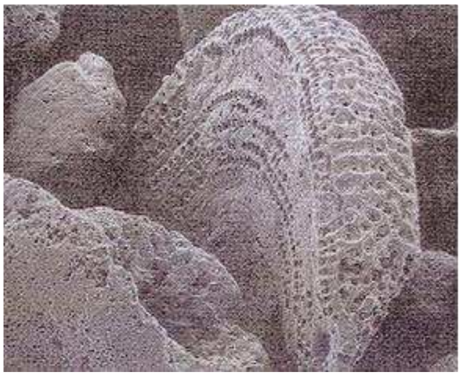

Figure 1: Electron photomicrographs of calcareous sand from Guam. Magnification is 45x (Mitchell and Soga, 2005; courtesy of I. Noorany)

The main geotechnical properties of calcareous sands, which influence the engineering properties, are:

- On Moh's hardness scale, calcareous sands have a value of 2 to 3 compared with a hardness of 7 of quartz sands.
- The particles have a high angularity.
- Grains can be curved plates (shells), thin-walled and hollow or porous.
- Variable cementation and occurrences of calcareous depositions at higher void ratio than silicate sediments.

The above features make calcareous sands more compressible than silica sands and more susceptible to particle crushing. This is mainly caused by the shape, the hollow thin walled nature and mineral hardness of the material. The flat shapes (shell fragments) are more susceptible to crushing than silica shapes with the same dimensions and the angular particles induce high stress concentrations.

The influence of the compressibility of the soil on the cone resistance has been demonstrated by many authors. Figure 2 shows the influence of differently compressible soils with the same relative density compiled by Robertson and Campenella (1983).

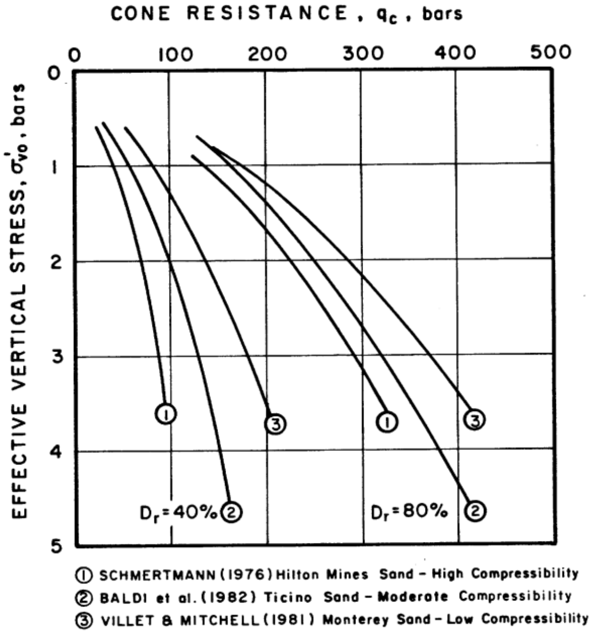

Figure 2: Effect of sand compressibility on q_c, σ'_{v0}, D_r relationships, after Robertson and Campenella (1983)

3.2.1 CPT correction factor

Based on the above it could be concluded that the cone penetration test is not a suitable testing method for carbonate sands. However due to its ease in application and the, often similar, problems with comparable tests, the CPT, with correction, is still often applied in this material.

There are different methods of taking into account the compressible nature of calcareous sand. The first is to consider the compressibility in the correlation from cone resistance to relative density by adjusting the constants. Another option is to apply a correction factor to the measured cone resistance in calcareous sand to make it comparable with measurements in Silica sand. This correction factor is known as the Shell Correction Factor (SCF).

The main advantage of the use of a Shell Correction Factor for the cone resistance instead of an adjusted correlation between the cone resistance and other parameters is that only one value needs to be corrected. From this adjusted cone resistance other correlations can still be used and not all other applied correlations need to be corrected.

Various authors have published on this subject and a great variety of shell correction factors can be found in literature. Table 1 shows a selection of some shell correction factors available from literature.

It can be observed that different sands have different shell correction factors. This is due to the nature of calcareous sands, where the origin of the material has significant impact on its engineering properties and can vary greatly from site to site despite all being classified as calcareous sand.

It is therefore of importance to select an appropriate correction factor for the project location. Ideally, one would derive a specific correlation for each project based on a series of laboratory testing, for example calibration chamber testing. For this project the correlation from Wehr (2005) was however identified as being appropriate. This was because Wehr (2005) performed calibration chamber tests on sand from the same region. The field benchmark was conducted to verify the applicability of this correction.

4 TEST SETUP FIELD BENCHMARK

4.1 Principle of the trial

The principle of the field trial was to compare actual measured densities, using the sand replacement test, to correlated densities based on CPT tip measurements. The sand replacement test should give an accurate representation of the in situ density unaffected by crushing of the carbonate particles. Combined with minimum and maximum density tests on the same material the relative density of the material can be determined. Comparing this relative density with the correlated relative density from the CPT tip resistance will provide a benchmark for the proposed relation.

Prior to the benchmark trial it was already agreed that the derivation of a site-specific correlation between CPT tip resistance and relative density would require a larger scale and more controlled method of testing. The benchmark did not have the purpose to derive such a correlation, rather to verify the applicability of the proposed correlation. One of the purposes was therefore also to investigate the suitability of the trial set-up for verifying the applicability of the proposed correlation with a sufficient degree of confidence.

Table 1, Shell correction factor for carbonate sands (after Van ‘t Hoff and van der Kolff, 2012)

Author	Description	Shell correction factor
Vesic, 1965	Comparison quartz sand /quartz sand with 10% shells	2.3
Jamiolkowski et al., 1988	Relative density related to cone resistance on various types of sand	Up to 2.4
Belloti and Jamiolkowski, 1991	Comparison Quiou carbonate sand /Ticino sand	1.3 to 2.2 $\sim 1+0.015*(D_r-20)$
Almeida et al., 1992	Comparison Quiou carbonate sand /Ticino sand	1.8 to 2.2
Van Impe et al., 2001	Comparison Quiou carbonate sand /Mol sand (date adapted from Belotti et al., 1991)	2 to 4.8
Van Impe et al., 2001	Comparison Dogs Bay carbonate sand /Mol sand (data adapted from Yasufuku et al., 1995)	3.4 to 9.9
Wehr, 2005,	Comparison of Dubai sand to quartz sand (after removal of large shell fragments)	1.36 to 1.82 $\sim 0.0046*D_r+1.363$

4.2 Design of field benchmark

To allow for realistic comparison, the field benchmark needed to be performed in similar conditions as the submerged breakwater core. However, for accessibility, constructability and to allow for a controlled trial, the test setup was constructed onshore instead of offshore.

The core of the breakwater would be about 10m in height and constructed under water. To achieve similar effective stress conditions a 5m high embankment was constructed in dry conditions. Following the need to mitigate liquefaction the target relative density for the breakwater core was 40%. The benchmark was therefore focused to test on a range of relative densities from as low as is practically possible up to around 70% to allow for benchmarking of the relation at the ranges expected on site.

To achieve the desired relative density range, the test embankment was divided in two sections. The first section aimed for a low range of relative densities, around 40%. The second section aimed to have a higher range of relative densities of 40 to 70%.

A large embankment was constructed to avoid boundary effects or interference between adjacent CPTs while allowing the CPT equipment to access and operate safely. Figure 3 presents a sketch of the embankment with locations of CPTs.

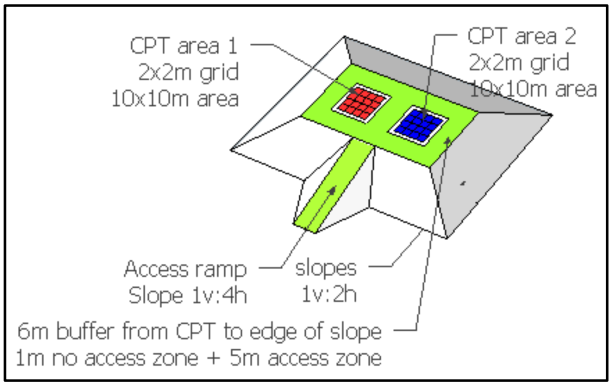

Figure 3: Sketch of trail embankment

4.3 Execution of field benchmark

The construction of the embankment and subsequent testing was targeted at controlling the relative density such that the achieved density stayed within the range of interest. Initial placement trials were therefore performed with different techniques followed by in field density testing on the placed material. It was found that the lower density could best be achieved by loosely placing the material in layers with an excavator. The higher densities could be achieved by placing the material in layers while driving over the placed layers with an excavator.

After completion of the construction Cone Penetration Testing were executed in a two 10x10m area on top of the embankment. Based on the results of these tests the locations of interest for field density testing were determined. Test locations were chosen based on the criteria that the predicted relative density was in the range of interest and no elevated fine content was identified based on the CPT friction ratio.

Excavation was performed by excavator in thin layers, taking care not to disturb the soil below the excavation level. At the determined locations field density tests were performed. Tests were executed taking care not to include the hole made by the CPT.

4.4 Observations during execution

Some challenges were encountered during execution of the trial. One of them was that the low-density area proved difficult to access in a safe manner with the CPT equipment. A smaller number of CPTs could be executed in this area than was initially proposed.

5 FIELD TEST RESULTS

5.1 Laboratory results

The sands in the project region are not only characterized by a very high Carbonate content but also have relatively high shell content. The shell content is usually defined as the percentage of shells of the material larger than 2mm. It is noted that this definition provides limited information as it does not present any information on the influence of the shells on the total sample. Therefore, the percentage of shells of the total sample is provided. Table 2 shows the properties of the sand used for the benchmark test.

Table 2, Properties of benchmark sand

Result	Nr	ave	min	max	standard dev
Gravel [%]	10	15.9	7	35	7.73
Sand [%]	10	81.4	63	88	7.19
Silt/Clay [%]	10	2.7	2	8	1.79
Shell content [% of material > 2mm]	10	66.6	36.7	95.0	16.3
Shell content [% of total weight]	10	9.6	5.1	12.8	2.8
$CaCO_3$ [%]	10	94.4	93	95	0.92
Max Density [Mg/m^3]	10	1.45	1.42	1.51	0.028
Min Density [Mg/m^3]	10	1.32	1.29	1.37	0.029
Particle density [Mg/m^3]	10	2.8	2.8	2.8	0.012

5.2 CPT results

The CPTs performed are presented in Figure 4. The figure shows the cone resistance against the depth in m Local Datum (m LD). It can be observed that the CPTs done in the medium density area show relatively large difference over the depth. This is due to the placement technique where the excavator placing the material drove over the placed layer to compact it. It is clear that the cone resistance from the low density area is much lower than the medium density area and more constant. A total of 6 CPTs have been performed in the low area and 26 CPTs in the medium density area.

5.3 Field density test results

A total of 56 field density tests have been done of which 26 in the medium density area and 21 in the low density area. Figure 5 shows the results of the field density tests. The locations of the field density tests were chosen after an analyses of the CPT result with the aim to get an even coverage of relative densities in the range of interest.

5.4 Used standards

The tests were performed to the standards agreed upon for the project as presented in Table **3**.

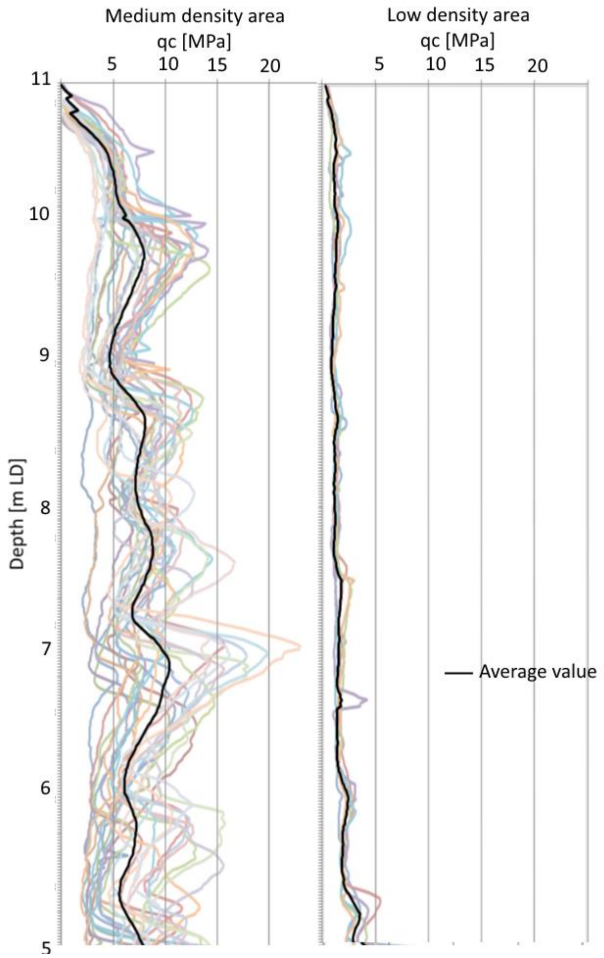

Figure 4: Average cone resistance (q_c) for the medium density and low density test area.

6 RESULT ANALYSES

To determine if the CPT correction proposed by Wehr (2005) can be used for the calcareous sand at the project location, the test results from the field density tests are compared with the correlated results from the CPTs. It is however observed from Figure 5 that some of the in situ dry density values found are lower than the minimum density. This is most likely due to slightly moist conditions of the sand during construction of the benchmark. These conditions allowed for a loser packing than is created achieved during the minimum density tests in the laboratory.

In addition, there is some uncertainty in the laboratory tests. The maximum density was determined using a vibrating table test, instead of using a hammer. This is usually considered a good alternative in order to prevent crushing during the determination of the maximum density. However, both the minimum and maximum density tests typically show a large spread. Therefore a large number of tests were done.

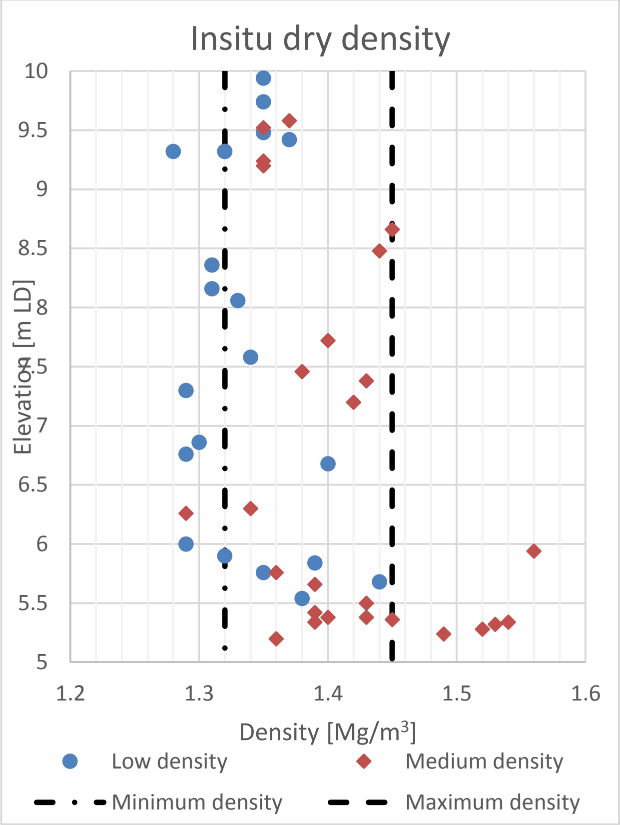

Figure 5: Results field density test against elevation

Table 3: Used standards

Test	Standard
Field density	BS 1377: Part 9: 2.2: 1990, AMD 17229:2007
Minimum density	ASTM D4254-14, Method A
Maximum density	ASTM D4253-2014, Method 1A and 1B
Particle density	BS 1377: Part 2: 1990 Clause 8.3
Particle size distribution	BS 1377: Part 2: 1990 Clause 9.2
Carbonate content	BS 1377: Part 3: 1990
Shell content	BS 812* adapted

6.1 CPT vs field density

Figure 6 shows the results of the relative density correlated from the CPT results against the measurements from the field density tests. It is noted that there is a large spread in the results. It can be observed that the, though a slight overlap, the low-density area has produced low cone resistance and the medium-density area has produced higher cone resistance. However, for the relative density determined with the FDT nearly all values are above the equal line.

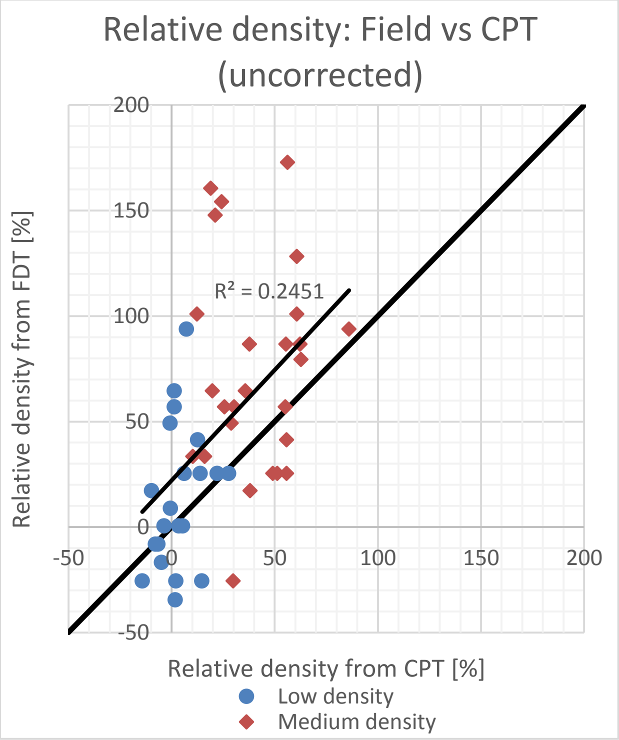

Figure 6: Relative density from FDT against the uncorrected cone resistance value

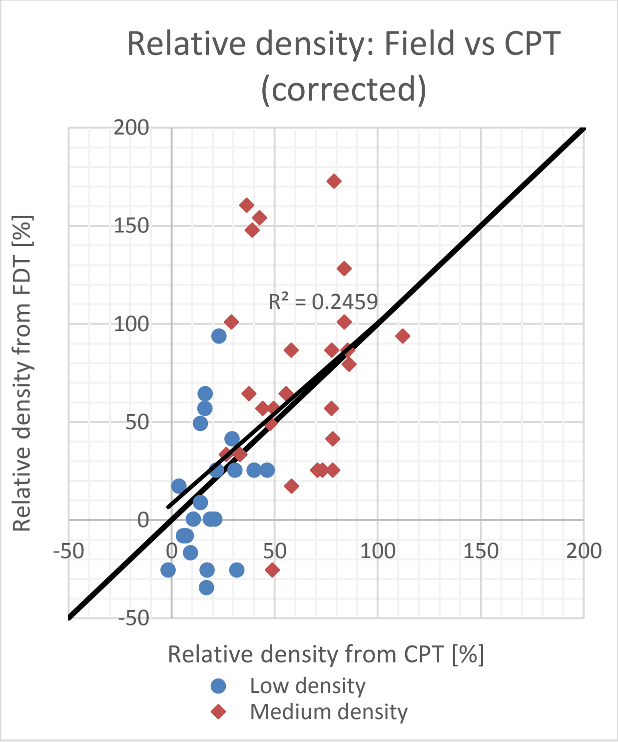

Figure 7: Relative density from FDT against results from the corrected cone resistance value

The large spread on the results of the FDT is a cumulative result of the margin of error on the results of the FDT itself and both the minimum and maximum tests done in the laboratory. Despite the large spread the linear trend from the results is parallel to the equal line, though with a low reliability value of $R^2 = 0.2451$. This would indicate that a correction on the CPT cone resistance would lead to a better fit between the relative density from the FDT and the CPT correlation.

In Figure 7 the results of the field density tests are plotted against the results from the relative density gained from the corrected cone resistance using the Wehr (2005) shell correction factor. Note that the trend line for the corrected CPT measurements is nearly equal to the equal line, meaning that despite the large scatter of the measurement data the correlation holds true for the average measurement. The large spread remains, similar to the results of the uncorrected CPT analyses, as presented above.

It is noted that the main effort of this benchmark focuses on the low cone resistance. As this is the range of interest for the project.

7 DISCUSSION

The aim of this benchmark was to validate the literature correlation up to a relative density in the order of 40-60%. No effort was made to compact the soil to higher relative densities, therefore this benchmark can only validate that the proposed correlation is valid up to 60% relative density. For the purpose of the project, this was sufficient as it was aimed to achieve at least 40% relative density.

It is observed that some of the determined relative densities are negative for both field density tests and CPT correlation. This is possible due to the combination with placement method, dropped from an excavator bucket, and slightly moist sand. This can lead to a looser density than reached with the standard test method for minimum density.

From the results, it is observed that the correlation of Wehr (2005) fits reasonably with the field density tests. It is noted that there is a large spread in field density measurements compared to the results from the corrected correlation.

As was already pointed out the spread of the results follows from the fact that the tests were not performed in laboratory conditions but in created in situ locations. Besides the usual spread from the field density tests the determination of the minimum and maximum density is also relatively uncertain.

As mentioned before this benchmark is focused on low relative densities, therefore the application of the correlation to high values of q_c is not validated. Using the correlation on high values of q_c therefore has a larger margin of error.

A laboratory environment should lead to more accurate test results. It is however more expensive and time consuming to get enough test results. It is therefore not always possible to do enough laboratory experiments, e.g. calibration chamber tests, in the available project planning and budget. With the benchmark performed for this project it is aimed to compensate the reduced accuracy of field tests compared to laboratory tests by doing a large number of field tests.

8 CONCLUSION

From the results it can be observed that there is a large cloud of data, a trend can be identified but with a very low reliability. This is not surprising as for this benchmark an attempt is made to compensate for the crushable nature of carbonate sands with an empirical correction, which in turn is applied to the empirical correlation between CPT tip resistance in combination with the in situ stress and relative density. This method is not reliable enough to determine a shell correction factor. It is however argued that it can show that a properly determined shell correction factor can be benchmarked in the field with test done in engineering practice.

It can therefore be concluded that a benchmark in the project area can work if a laboratory-derived correlation is available. In order to get sufficient reliability the following aspects should be addressed:

- Correct and consistent performance of min/max density
- On site determination of how to best place the soil in layers to achieve the target densities.
- Correlations are valid within certain ranges of Dr and for certain values of q_c.
- Exclude as many boundary effects as possible, e.g. slope effects
- Execute sufficient tests, both CPTs and in situ density tests.

Taking into account the above-mentioned requirements it is judged that a literature correlation can be benchmarked, using the benchmark method described in this paper.

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