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Influence of compaction on Material Behavior Index from CPT for carbonate sands

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ABSTRACT: When performing land reclamation works by dredging and hydraulic fill placement, compaction of the granular fill is required. This can be necessary for different reasons such as bearing capacity improvement, settlement reduction, increase of (relative) density, increase of friction angle and/or liquefaction mitigation. When performing the liquefaction assessment based on the CPT according to the 'simplified' methods, often the Material Behavior Index I_C is used to estimate the fines content and apply a correction for the fines.

In this paper two case studies are discussed related to projects in the Middle East where the sand has a high carbonates content and compaction was performed by means of two commonly used techniques: Vibroflotation and Dynamic Compaction. Based on pre- and post-compaction CPT results performed for the quality control, the change in I_C is studied. This change becomes more clear as the compaction level becomes higher. Also, I_C derived from pre- and post-compaction CPT's is compared to the fines content derived from laboratory test results on in situ samples.

The results are discussed, and reliability, consequences and possible influence parameters are highlighted. Special attention is paid to the use of a 'Shell Correction Factor' to take into account the effect of crushing of the carbonate material in CPT cone resistance.

Keywords: compaction; material behavior index; CPT, liquefaction assessment; calcareous sand

1. Introduction

When performing large land reclamation works by means of dredging, the fill material is placed hydraulically and the relative density of the installed fill material will depend on several factors such as the equipment used, the material characteristics and placement above or below the water table [1]. Depending on the technical requirements that apply to the fill material, compaction of the granular fill often is required. This can be necessary for different reasons such as bearing capacity improvement, settlement reduction, increase of (relative) density, increase of friction angle and/or liquefaction mitigation. In this paper we will mainly focus on the liquefaction assessment.

When performing the liquefaction assessment based on the CPT according to the NCEER method [2] or according to Boulanger et al [3], the Material Behavior Index I_C is one of the approaches to estimate the fines content. A correction for the fines as developed by Robertson and Wride [4] is suggested in [2]; in [3] the calculation of the fines content based on I_C is discussed as the correction is applied in terms of a correction to the normalized q_c-value. Goal is in both cases to find a 'clean sand'-cone resistance. As this can be automated based on the CPT result, this approach is very popular.

In this paper two case studies are discussed related to projects in the Middle East where the sand has a high carbonates content (up to 100%) and compaction was performed by means of two commonly used techniques: Vibroflotation and Dynamic Compaction.

One of the issues with calcareous sand is that the material exhibits local crushing during compaction and during penetration with the CPT cone [5][6][7]. The measured CPT value is often corrected with a 'Shell Correction Factor' (SCF) [7][8][9] in order to obtain an equivalent 'silica sand'-cone resistance. In these projects, the calculation of the I_C and the liquefaction assessment is based on this corrected q_c-value. While the correctness of such approach might be a topic of discussion, it is standard practice and further analysis will focus on I_C calculated this way, however, using different values for the SCF.

Based on pre- and post-compaction CPT results performed for the quality control, the change in I_C is studied. Also, I_C derived from pre- and post-compaction CPT's is compared to the real fines content derived from sieving analysis performed on borehole samples.

2. Material Behavior Index

The soil classification system based on Soil Behavior Type (SBT) and the Material Behavior Index I_C being used for liquefaction analysis has been suggested by Robertson [10]. In the past years, further refining has been done and updates on the SBT-classification have been published [11] and [12].

I_C is calculated from the CPT according to following formula's [10]:

$$I_c = [(3.47 - \log Q)^2 + (1.22 + \log F)^2]^{0.5} \quad (1)$$

Where the dimensionless normalized CPT cone resistance Q and normalized friction ratio F are calculated by following relations:

$$Q = \left(\frac{q_{corr} - \sigma_{VO}}{p_a}\right) \cdot \left(\frac{p_a}{\sigma'_{VO}}\right)^n \quad (2)$$

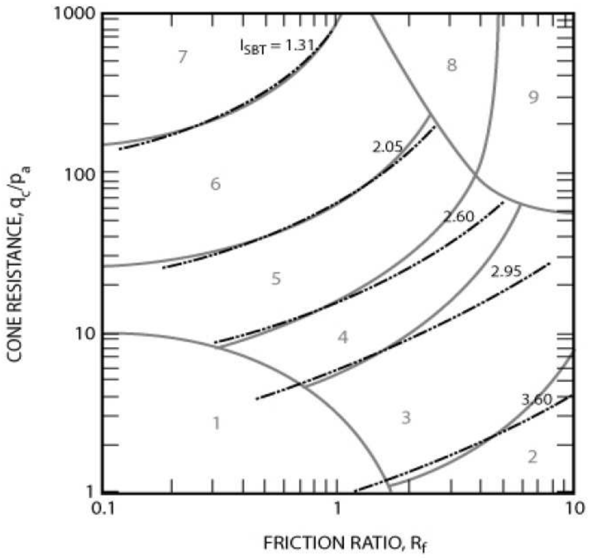
$$F = \left(\frac{f_s}{q_{corr} - \sigma_{VO}}\right) \cdot 100\% \quad (3)$$

Whereby:

1. σ_{VO}: Total vertical stress at time of CPT testing
2. σ'_{VO}: Effective vertical stress at time of CPT testing
3. $q_{corr} = SCF \times q_t$
4. q_t: Cone resistance corrected for pore pressure effects
5. f_s: Sleeve friction
6. p_a: Atmospheric pressure
7. n: stress exponent; varies with I_C, Eq. (4) and thus needs to be defined iteratively

$$n = 0.381 \times I_C + 0.05 \left(\frac{\sigma'_{V0}}{p_a}\right) - 0.15 \quad (4)$$

I_C is more and more used in daily practice for analysis of CPT's. Automatic soil classification is often based on I_C (Fig. 1), but also for many correlations, the I_C is the parameter used in correlations: fines content (see further), soil stiffness, state parameter, undrained strength and liquefaction assessment (see further).



Zone	Soil Behaviour Type (SBT)
1	*Sensitive fine-grained*
2	*Clay - organic soil*
3	*Clays: clay to silty clay*
4	*Silt mixtures: clayey silt & silty clay*
5	*Sand mixtures: silty sand to sandy silt*
6	*Sands: clean sands to silty sands*
7	*Dense sand to gravelly sand*
8	*Stiff sand to clayey sand**
9	*Stiff fine-grained**

** Overconsolidated or cemented*

Figure 1. Soil Behavior Type and Soil Behavior Index I_C (from [11] – $I_{SBT} = I_C$; boundary values given in the figure and do not coincide exactly with the original boundaries of soil classification).

3. Liquefaction assessment

During earthquakes loose packed granular soils can be sensitive for liquefaction. The concept of liquefaction is been studied for many years by different researchers. Typically, the susceptibility to the liquefaction is expressed in a factor of safety which is defined as the ratio of cyclic resistance ratio and cyclic stress ratio. If the factor is below a threshold value, liquefaction is prone to occur when the design earthquake strikes and it is advised to foresee mitigation measures, e.g. compaction of the soil.

For large land reclamation projects, typically the cyclic resistance ratio is estimated based on in-situ testing such as CPT. The advantage of using CPT for estimating the cyclic resistance ratio is versatile: fast, repeatable, economical, continuous data, etc. After performing the test, a fines correction factor needs to be applied to calculate the cyclic resistance ratio. Often, the soil material behavior index I_C is used to correct the cyclic resistance ratio for grain characteristics by a factor K_C (Eq. (5)).

When $I_C \leq 1.64$: $K_C = 1$;
When $I_C > 1.64$:
$K_C = -0.403\, I_C^4 + 5.581\, I_C^3 - 21.63\, I_C^2 + 33.75\, I_C - 17.88$ (5)

When I_C changes, K_C will change as well; a larger I_C leads also to a larger fines correction factor K_C. As illustrated in Fig. 2, a limited change of the value of I_C in the range of 1.6 to 2.6 may lead to an important change in K_C. When $I_C > 2.6$, the correction becomes useless as this soil type is considered as non-liquefiable.

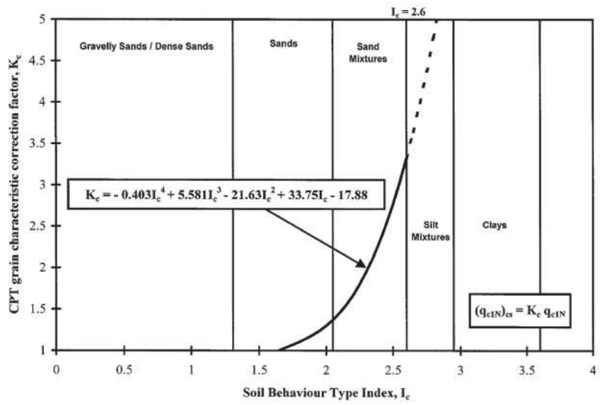


Figure 2. Grain characteristic correction to obtain clean sand equivalent penetration resistance in sandy soil (from [4]).

4. Shell Correction Factor

As mentioned in the introduction, the SCF is used to derive an equivalent cone resistance that would be found in silica sand with the same relative density and stress level (Eq. (6)).

$$SCF = \frac{q_{c,silica}}{q_{c,carb}} \quad (6)$$

The SCF has been discussed in multiple papers already, see among others [7][8][9]. Wehr [8] has given a formula for the SCF based on the relative density. Mengé et al [7] have analysed calibration chamber tests and came to the conclusion that the SCF must be function of the relative density and vertical effective stress (Fig. 3).

In the above discussion on SCF, the carbonates content is a missing parameter. In the Middle East, normally carbonates content (C_aCO_3 weight percentage) is very high: between 80% and 100%. However, the effect of crushing starts already at lower levels of carbonates and Mayne [9] has found that this effect becomes important for a relative density > 30% and is rather independent of carbonates content in the range 42% < C_aCO_3 < 98%.

An equation to calculate the SCF was developped by the authors to fit the curves given in Fig. 3, see Eq. (7).

$$SCF = (0.002 \times Dr + 0.4628) \times \sigma'^{0.23}_{v0} \geq 1 \qquad (7)$$

With Dr the relative density (in %). As indicated, the SCF should be minimally 1 and for low relative densities and low stresses this criterion will govern. Such behavior was also discussed by Mayne in [9].

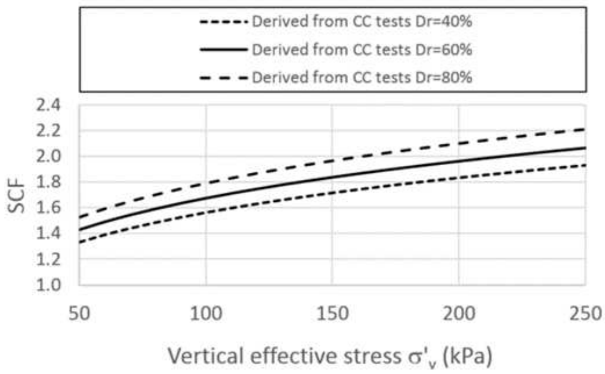


Figure 3. SCF in function of vertical effective stress and relative density (from [7]).

In many projects, the application of a SCF is a topic of discussion between the employers' consultant and contractor. Sometimes the use of a SCF is not allowed, thus completely denying the crushing effect; sometimes the crushing is recognised, but the SCF is fixed at a value of 1.3 or 1.5, independent of compaction level or stress state. It goes without saying that such approach represents large problems for the (soil improvement) contrator because indirectly this leads to higher compaction levels to be reached. The execution of calibration chamber tests to define the material dependent correlation between q_c and Dr would be the best approach; however practical and time constraints often lead to above conclusions.

In the analysis of the case studies below, three different approaches will be followed for the calculation of the I_C: SCF = 1; SCF = 1.3 and SCF derived by Eq. (7).

5. Case studies

The soil grain characteristics are inherent to the material and do not change by the compaction process. Although this is not fully correct for calcareous material in which locally crushing may occur due to the compaction process.

In general, the above statement would imply that the soil material behavior index should remain constant before and after compaction, or in the worst case, could become larger (finer material due to crushing).

Based on the CPT data of 2 large land reclamation projects in the Middle East, the change in material behavior index as a result of the compaction process and as the result of the selection of the SCF is studied.

5.1. Project A

Project A is a reclamation project in Dubai which is realized by dredging and hydraulic filling. Material is dredged in a borrow area and placed by pumping through land pipelines in a reclamation area. The material to construct the reclamation must fulfill following contractual specifications:

1. Percentage of particles smaller than 200mm: minimum 90%
2. Percentage passing 63 μm sieve: 10% maximum
3. Liquid limit: 30% maximum
4. Plasticity index: 6% maximum

In Figure 4 representative particle size distributions (PSD's) are given for the Project A. The carbonates content of this material varied between 80% and 95%. A representative pre and post compaction CPT is shown in Figure 5. The average depth to be compacted was variable up to the original seabed varying from a few m up to 15m.

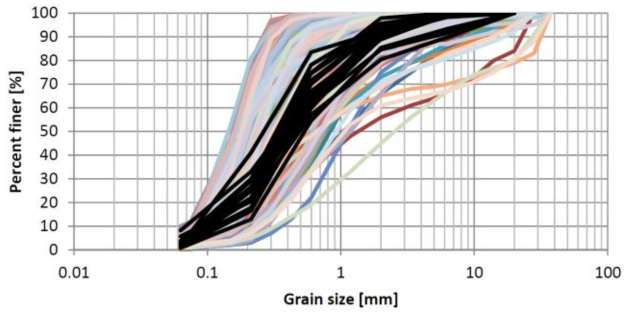


Figure 4. Particle Size Distribution for the sand at Project A.

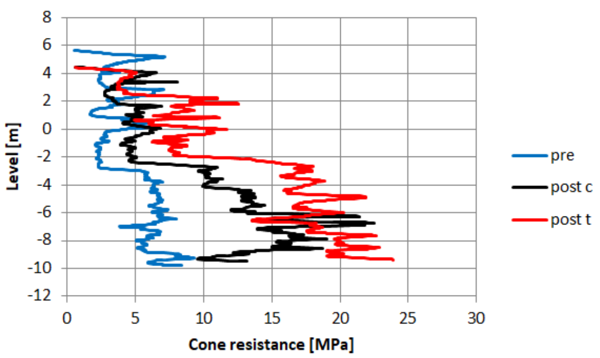


Figure 5. Representative pre and post compaction CPT at Project A, without SCF.

After placing the material, vibroflotation in a triangular grid is foreseen to densify the material to the required relative density. The quality control of the vibroflotation is done by means of Boreholes with SPT (pre and post compaction) and CPT's (pre and post compaction).

The post-CPT's are performed in such a way that the heterogenity of the compaction process is covered. For this project CPT's were performed at the centroid and at the one third distance between 2 compaction points, as indicated in Figure 6. The optimal starting grid spacing between the compaction point is determined based on a trial area. During execution of the project, the grid spacing can be adjusted in line with the variability of the soil conditions. In general the grid spacing for this projects was varying between 3.8m and 4.4m.

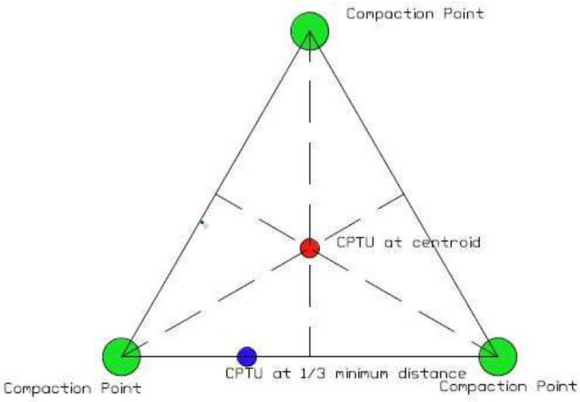


Figure 6. Quality process by means of CPT.

5.2. Project B

Project B is a land reclamation project in Oman. It is also a hydraulic fill project, however a stockpile was made in the reclamation area some years before the final reclamation works and part of the material was pushed in place by dry earth movement, leading to even more loose soil state. The particle size distribution is shown in Figure 7. From this figure it is clear that the fines content of this sand is in general higher than the sand used for project A. The carbonates content is varying strongly between 15% and 60%.

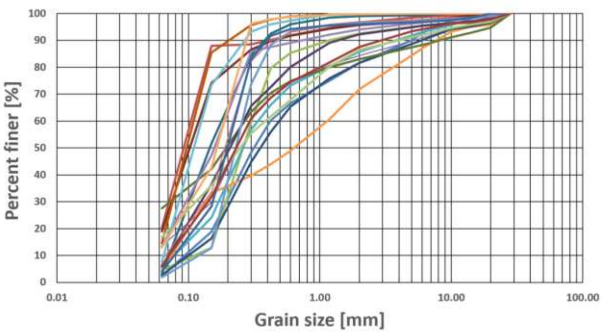


Figure 7. Particle size distribution for Project B.

Because of the higher fines content and the depth to be compacted (maximally down to 10m below final surface), dynamic compaction was considered the most appropriate technique. Works are performed to densify the material into the required stress state. The quality control is based on CPT's (pre and post). The location of testing is taken approximate between compaction impact points after backfilling with surface compaction.

As the carbonates content is varying a lot, no SCF was applied, although this would have been applicable for some locations and depth intervals.

6. Results

6.1. Working method

After calculating the soil behavior index, an average I_C is calculated over the relevant compacted depth of the CPT. After calculating the average value a comparison is made between the average I_C coming from pre and post compaction CPT's. The distance between the pre and post compaction CPT's is choosen as small as possible.

Several calculations have been performed based on the available CPT's:

1. Using the three mentioned approaches for SCF: 1, 1.3 and according to Eq. (7);
2. Average I_C over the full compacted fill depth;
3. Average I_C over following depth intervals from the top: 0-2m; 0-4m, 0-6m, 0-8m, full depth.

In order to present the difference between pre and post compaction CPT's, the difference pre minus post I_C is used: ΔI_C. A positive value means the post I_C is lower and thus represents a 'coarser' soil.

6.2. Project A

The dataset used in the analyses contains 371 CPT's performed before compaction, 371 CPT performed after compaction in the center point (denominated with c) and 371 CPT's performed at the one-third point (denominated t).

The results of the calculations are summarized in following figures. Figure 8 to Figure 10 illustrate the shift in SBT that occurs (based on the average value over the full compacted fill depth). A first conclusion is that the average I_C value in the pre-CPT always is higher than the average I_C value in the post-CPT. Due to the shift in the I_C value, the material classification shifts from zone 6 (sands – clean sand to silty sand) towards zone 7 (gravelly sand to dense sand). Depending on the SCF used, the shift is more pronounced. This seems to be most with the SCF according to Eq. (7).

The difference in smaller I_C intervals is illustrated in Figure 11 to Figure 13. The ΔI_C for the centroid CPT is generally situated in the range 0.2 to 0.4, while the ΔI_C for one third CPT is situated in the higher ranges.

Finally, in Figure 14 and Figure 15, the difference in I_C value is shown for different depth intervals; the first figure for the center location; the second figure for the one-third location. These figures only are given for the SCF according to Eq. (7) as this is theoretically the most correct approach. At the center location, the increase in I_C value between 2 and 8m depth is clearly more pronounced than for the one-third location.

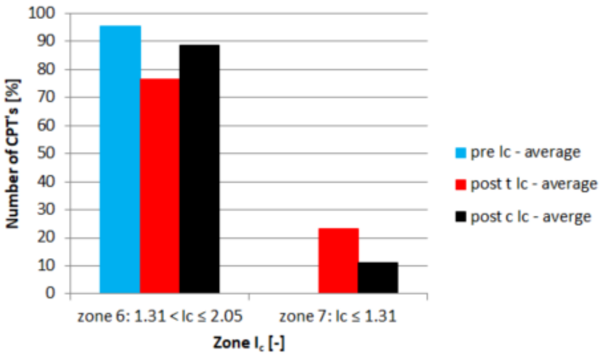


Figure 8. Shift in SBT (SCF=1).

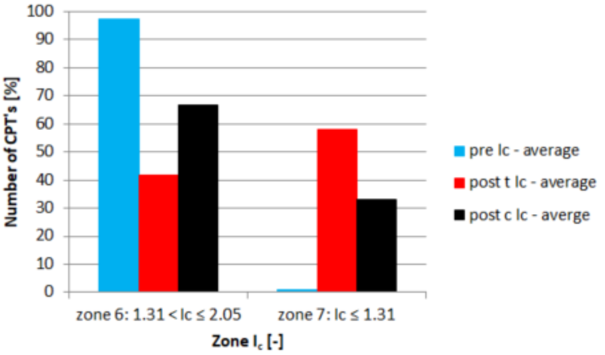


Figure 9. Shift in SBT (SCF=1.3).

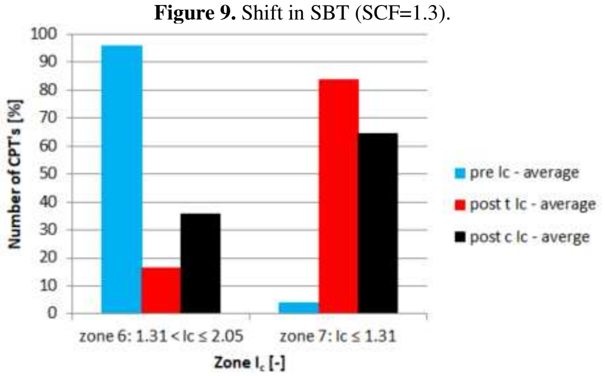


Figure 10. Shift in SBT (SCF=Eq.(7))

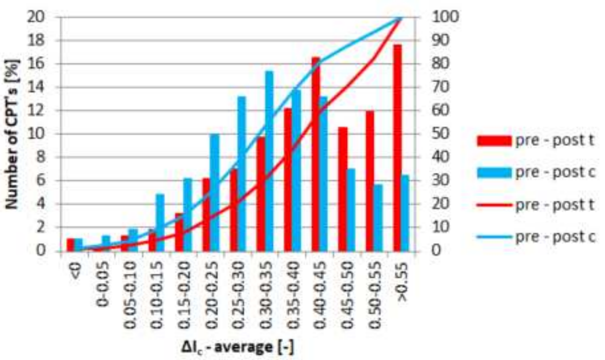


Figure 11. Difference in I_C with SCF=1.

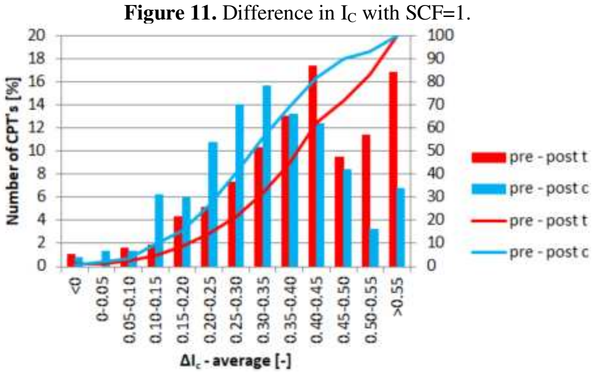


Figure 12. Difference in I_C with SCF=1.3.

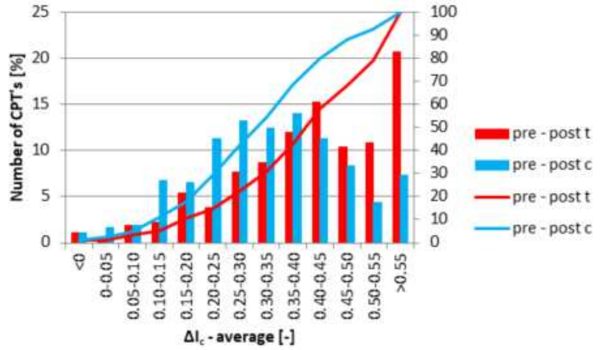


Figure 13. Difference in I_C with SCF according to Eq. (7).

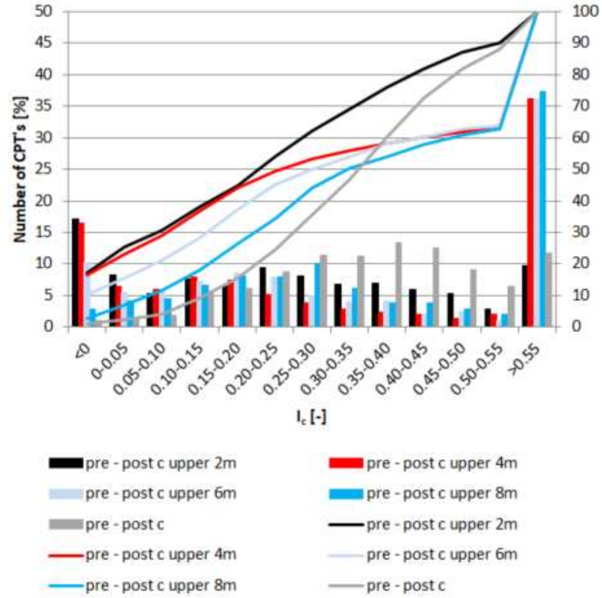


Figure 14. Change in I_C with depth interval for loc. c (SCF=Eq. (7)).

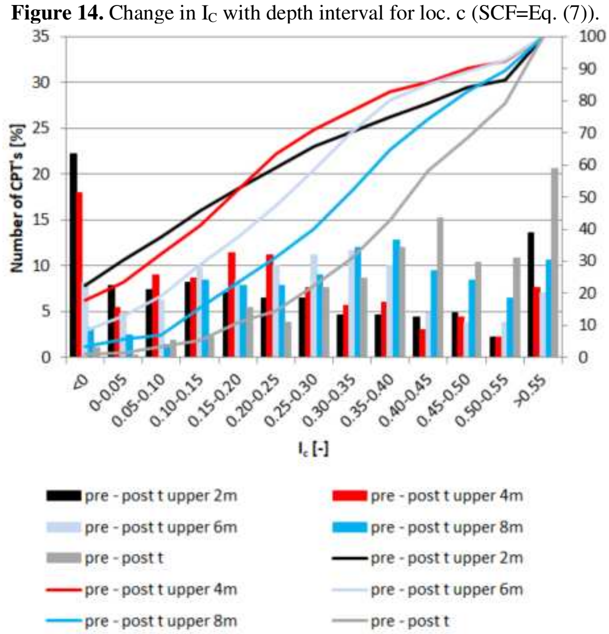


Figure 15. Change in I_C with depth interval for loc. t (SCF=Eq. (7)).

Analysing the above figures learns that a clear shift occurs in I_C value due to vibratory compaction. In fact one can expect that, depending on the compaction effort and the relative density achieved, the I_C value seems to become smaller. There is an influence of the location where the test is performed (c or t).

As illustrated in Figure 16 (after [13]), further away from the compaction point the achieved density decreases, so the effect of the compaction is less and the shift is less pronounced. However, also other effects are influencing the results, such as the selected SCF and the spread with depth of the compaction effort, away from the compaction point.

Rather unfortunate but unavoidable, the use of the SCF has an influence which is not related to the soil, but pure mathematical. The use of a SCF based on calibration chamber tests ([7] and Eq. (7)) seems to cause the largest shift which leads to an apparent lower fines content. This brings to discussion the use of Eq. (5) which leads to a lower correction factor and thus to a lower factor of safety against liquefaction.

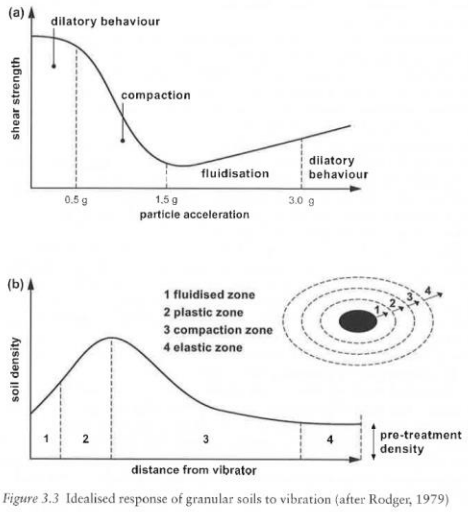


Figure 16. Idealised response of granular soils to vibration ([13]).

Apart from CPT's also borehole with SPT testing is performed at Project A. Borehole's are performed before and after compaction. During the borehole campaign sampling is performed by means of the SPT split spoon sampler. The soil retrieved by the split spoon sampler is subjected to soil classification testing. From the soil identification testing the fines content (mass smaller than 63μm) is determined. The CPT which is situated in the same area is studied and the I_C is determined in the same depth interval of the borehole sample. The data gained from pre- and post-compaction is kept separated in order to avoid differences due to possible crushing during compaction:

1. Pre BH data is compared with pre CPT data
2. Post BH data is compared with post CPT data

The results of the comparison is summarized in Figure 17, with I_C and SCF calculated based on Eq. (1) and (7). On the figure the correlation suggested by [14] is added. From the figure it can be concluded that large scatter occurs in the relation I_C-fines content and for this site, the given correlation is not applicable; at least a vertical shift would be needed.

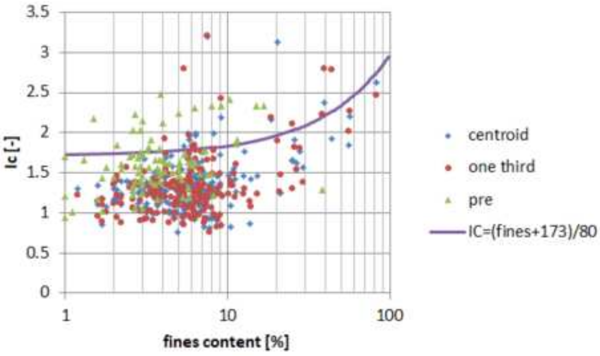


Figure 17. Comparison between fines content and BH data.

Similar comparisons have been made by others and are summarized and commented in [3]. Large scatter is also found in these studies (Figure 18) and local calibration is suggested. Above findings show that local calibration may not be straightforward and large diviations from the best fit curve need to be allowed. For this reason, the fines contents defined though I_C is also called the 'apparent' fines content by Robertson and can only roughly be estimated from I_C.

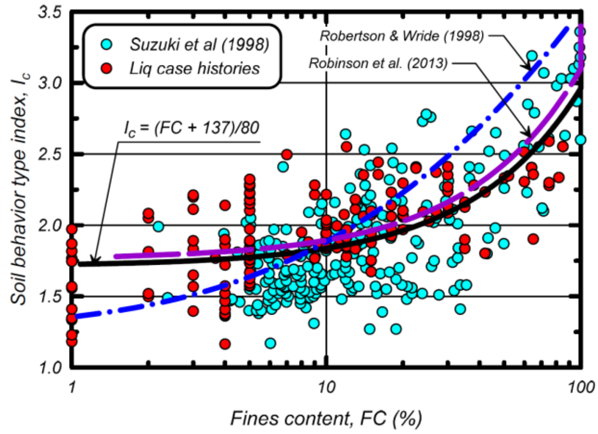


Figure 18. Correlations between fines content and I_C ([3]).

6.3. Project B

At the project site, 34 pre and 34 post compaction CPT's were performed. The soil classification based on the soil behavior type for the pre and post compaction CPT's is given in Figure 19, Figure 20 and Figure 21. Based on the pre-compaction CPT's most of the material is situated in Zone 5 (sand mixtures – silty sand to sandy silt), however based on the post-compaction CPT's most of the material is situated in Zone 6 (sands – clean sand to silty sand). This becoming more and more pronounced with increasing SCF.

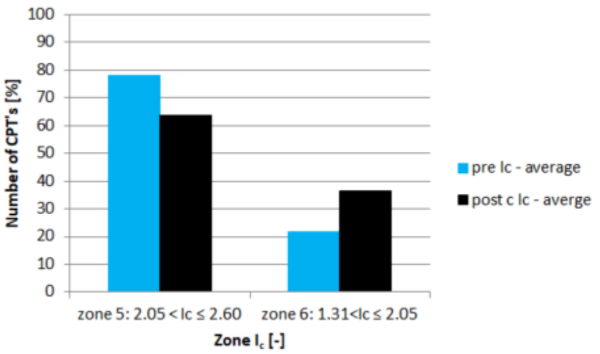


Figure 19. Classification of the material based on soil behavior type with SCF = 1.

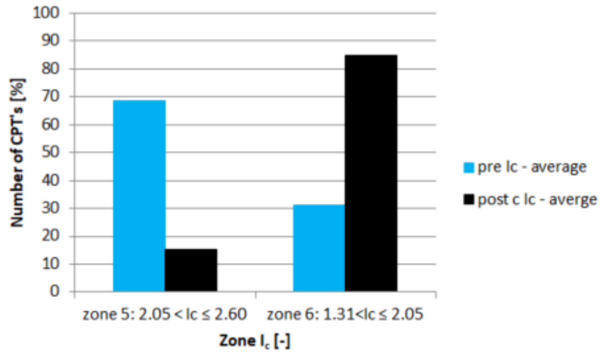


Figure 20. Classification of the material based on soil behavior type with SCF = 1.3.

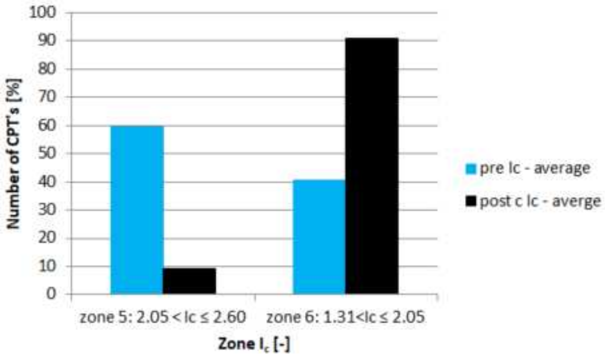


Figure 21. Classification of the material based on soil behavior type with SCF = Eq. (7).

The following figures give the comparisons of shift in I_C value between pre and post CPT's for the full compacted depth (Figure 22, Figure 23 and Figure 24) and for the defined depth intervals (Figure 25, Figure 26 and Figure 27). For each comparison, the three approached in terms of SCF was worked out. Again, the larger the SCF, the larger the shift in I_C.

From the figures it can clearly be seen that the largest shift is found in the top meters while the shift becomes less with larger depths; thus where the compaction energy is the largest, the highest shift in I_C value is obtained.

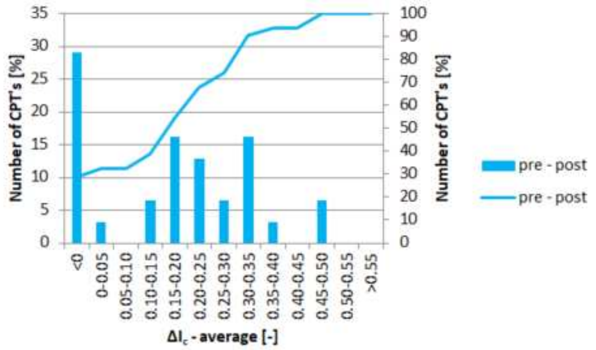


Figure 22. Difference in I_C with SCF = 1.

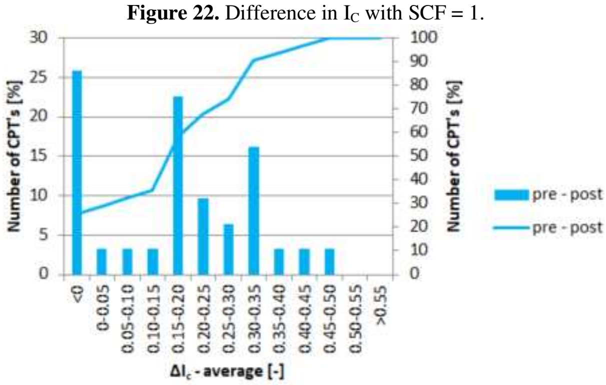


Figure 23. Difference in I_C with SCF = 1.3.

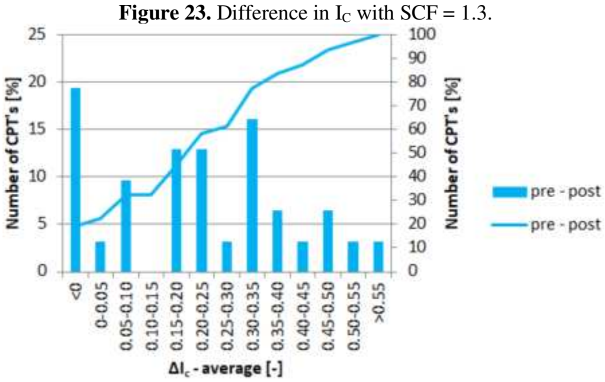


Figure 24. Difference in I_C with SCF = Eq. (7).

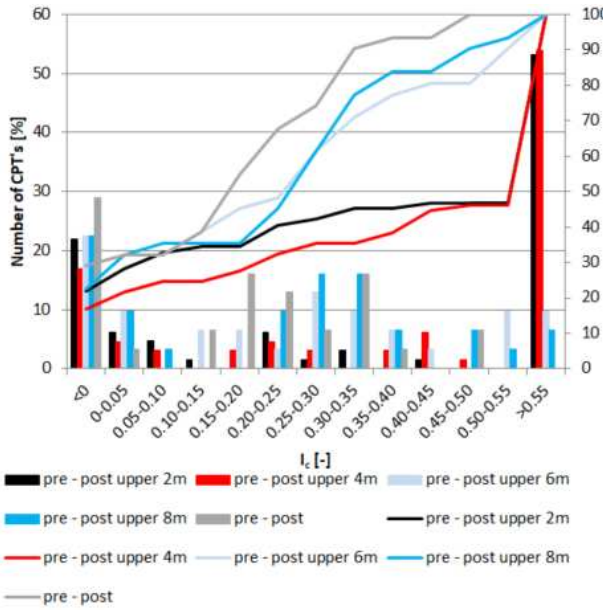


Figure 25. Change in I_C with depth (SCF=1).

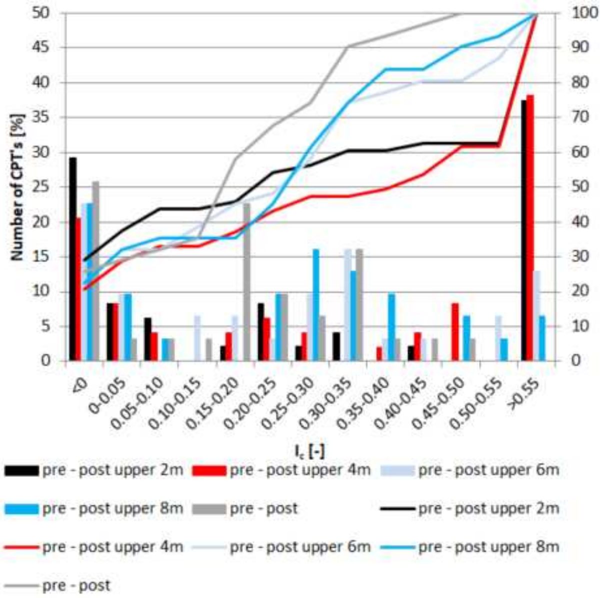


Figure 26. Change in I_C with depth (SCF=1.3).

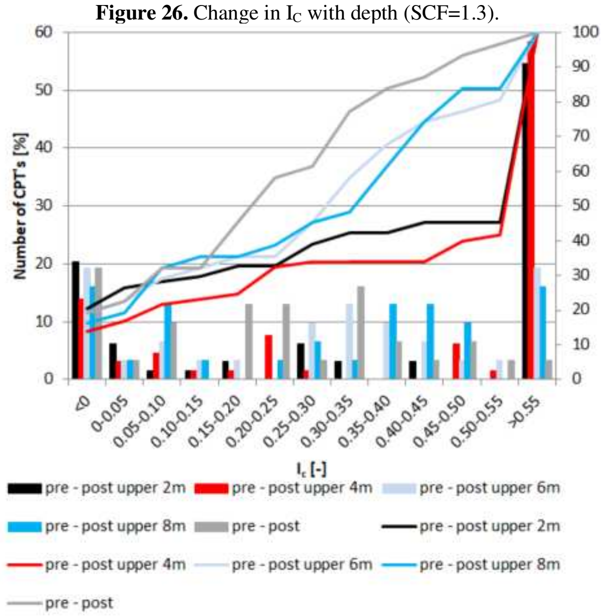


Figure 27. Change in I_C with depth (SCF=Eq. (7)).

7. Discussion

Research on change in I_C due to compaction was done by others already, for silica sand. In ref. [15] it is mentioned that after compaction the in-situ horizontal effective stress increases, meaning higher K_0. A higher K_0 will have an influence on the q_c with as a further result that the I_C is reduced. In general, the I_C between pre and post compaction CPT's changed by about a factor 0.3 as reported in [15]. These findings were based on data retrieved from a project were vibro-replacement was used as ground improvement.

Based on the data of Project A, it can be concluded that a clear shift I_C is present in the tested carbonate sands here, suggesting a lower fines content compared to the pre compaction CPT's. This cannot be true as one would at least expect a similar to a higher (due to crushing) fines content in calcareous sands. The shift is generally larger than 0.3 and depends on the SCF used and on the location the CPT is performed in the compaction grid.

When analyzing Figure 14 and Figure 15 more in detail in this respect, the CPT quality control points in the center seem to give a much larger shift than 0.3 in the depth intervals between 2 and 8m while for the CPT QC points at the one-third location the shift is much more evenly spread with depth.

The data of Project B also shows a general trend of decrease in the average I_C between pre and post quality control CPT's. Based on different scenarios analysed, one could conclude that an average shift in I_C-value calculated over the full compacted height of about 0.3 occurs. When looking into the effect of compaction with depth, the top depth intervals clearly show higher shifts than the deeper intervals. The use of different SCF's here – although maybe not always applicable due to the large scatter in carbonates content – seems to aplify this effect.

These considerations need to be seen in terms of effect on the liquefaction assessment. A lower fines content means a smaller correction factor for fines and thus a more conservative analysis. In [15] it is suggested to assess the liquefaction based on the pre-compaction apparent fines content. This is done by correcting al I_C-values with a value of 0.3, being the average shift defined between pre and post compaction CPT's.

While a different formula should be developed for the I_C, taking into account the higher horizontal stresses after compaction (this phenomenon also causes problems with correct I_C definition in naturally overconsolidated soils), the use of pre compaction apparent fines content defined via I_C is recommended. However, the calculation of a unique difference in I_C seems to be difficult depending on the ground improvement technique used and the location of the CPT QC point in the compaction grid. A correct practical approach does not exist at this point. A correction of I_C, based on an average ΔI_C defined per soil layer, depth interval and location of the CPT in the compaction grid, derived from comparison of pairs of pre and post compaction CPT's seems to be the best approach. This ΔI_C should be used with the corrected cone resistance (by means of a SCF) form the post compaction CPT's.

With regard to the SCF, it has been shown that this factor also may have an important effect on the shift in I_C value. When no site specific calibration can be done by means of calibration chamber tests, the use of Eq. (7) is suggested as it has been demonstrated by different researches that there is an important effect of crushing on the measured cone resistance. This effect becomes more pronounced at higher relative densities and stress states.

8. Conclusions

Data obtained from 2 large hydraulic reclamations is processed and analyzed. The material used to construct the reclamations can be classified as calcareous sand, however the material used at construction site of Project B has a higher fines content and somewhat lower carbonates content compared to Project A. Due to the higher fines content at project B, compaction works based on vibroflotation was only possible at Project A. At Project B it was decided to compact the reclamation material by dynamic compaction method.

Based on the average soil behavior index calculated on the data for both projects, it can be concluded that there is a shift between pre and post compaction data. There is also a difference between the average soil behavior index calculated for the post CPT's. Comparing centroid and one third CPT, shows that the soil behavior for the one third post CPT in general is lower than the soil behavior index for the post centroid CPT. Further, a difference depending on depth intervals has also been demonstrated. It seems that the difference in soil behavior type is the largest, where the largest compaction energy is applied.

This finding is further amplified when a SCF is used to take into account the crushing effects in calcareous sands. In this paper, it is suggested to use a SCF derived from calibration chamber testing as the use of a fixed SCF is not in accordance of the findings from earlier research and this might influence the I_C-value found. Thus, not only making the assessment of relative density erroneous, but also the estimation of apparent fines content.

The effect on the calculation of I_C and possible magnitude of the shift is discussed. While this shift would suggest 'coarser' material, this is not physically possible and the influence of this on further use of I_C needs to get the right attention. Especially when I_C is used to calculate a fines content correction in the liquefaction assessment according to the commonly used 'simplified' methods. Although the error made seems to be at the 'conservative', safe side, this does not lead to an economical design and should be clearly recognized by all parties involved.

The use of a correction based on comparison of the pre and post compaction I_C's is recommended.

Comparing borehole data and soil behavior index, it can be concluded that deriving the (apparent) fines content from the soil behavior index indicates large scatter. Quality control to define the 'fines content' (percent passing the 63 micron sieve) based on the I_C is not recommended.

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