Challenges in site characterization and work verification of compacted crushable sands

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ABSTRACT

During reclamation projects huge amounts of sands are dredged and placed to create artificial land. To increase the density and therefore to mitigate the potential risk of liquefaction as well as to increase the stiffness and internal friction angle of the sand, it is often necessary to compact the reclaimed sand. The performance targets for compaction are frequently verified by means of achieving a particular relative density that is generally correlated from Cone Penetration Tests (CPT). For many reclamation projects, due to the non-availability of local quartz or silica sands, crushable, carbonate or calcareous sands are used. In these crushable sands, due to the very high stress concertation below the CPT cone, the particles tend to crush. The well-known published correlations between the relative density and cone resistance are established for non-crushable silica sands and are thus not applicable to these crushable sands and can result in over treatment costing time and money. Usually, the crushing effect is quantified in a calibration chamber test and a project specific correction factor is introduced. Alternatively, to avoid this costly and time-consuming procedure the use of measuring the shear wave velocity with seismic CPTs (SCPT) is possible. The Cyclic Stress Ratio (CSR) for liquefaction analysis and other soil parameters required for the design verification can be correlated without being influenced by the crushing of particles due to the non-invasive procedure. This paper gives an overview of the common practice for work verification in crushable sand and shows an approach to determine the required compaction parameters using seismic CPTs.

Keywords: Reclamation, Sand Compaction, Verification Testing, Relative Density, Seismic.

1. Introduction

For reclamation projects huge amounts of sand are dredged and placed to create artificial land. Specifically, below the seawater level, the placed sand has a low in-situ relative density from about 20 to maximal 60% (Menge et al. 2016).

To increase the density and therefore to mitigate the potential risk of liquefaction as well as to increase the stiffness and internal friction angle, for a high number of projects it is required to compact the reclaimed sand. The difference of the particle arrangement between uncompacted (loose) and compacted (dense) sand is shown in Figure 1.

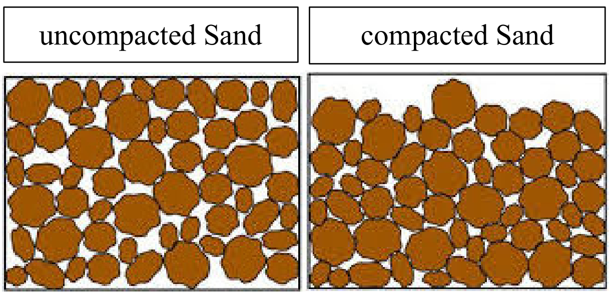

Figure 1. Difference of particle arrangement between uncompact (loose) and compacted (dense) sand

Most common compaction techniques used for the compaction of artificially placed sand are Vibro Compaction, Dynamic Compaction or Rapid Impact Compaction techniques.

Which of these beforementioned compaction techniques are most suitable for the specific projects depends on the required compaction depth, properties of the sand used for the reclamation and the performance targets of compaction.

Specifically, the sand properties play a significant role when it comes to evaluating the effectiveness of different compaction methods and possible achievable degree of compaction. Therefore, the knowledge of the properties of the sand, as e.g., the silt and clay content, uniformity index, particle shape and mineralogy are crucial for an effective planning of the compaction works.

2. Suitability of sand for compaction

2.1. Sand properties based on grain size distribution

As such, the critical part is the site characterization which in normal case will be undertaken by the Cone Penetration Tests, in conjunction with Boreholes and index property testing. The keys parts here to identify fines (passing 63 microns) and clays (passing 2 microns) and the current in-situ strength of the material and knowing this against the end requirements (specifications), with the chemical make-up (mineralogy) of the sand.

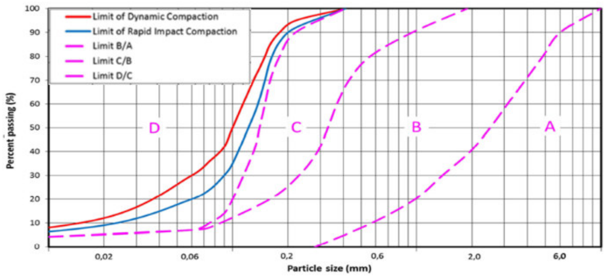

Figure 2. Soil suitability for different methods of compaction using the particle size distribution curves

Based on the grain size distribution curves shown in Figure 2, different zones (A to D) can be classified for the suitability of different compaction methods.

Zone A: The soils of this zone are very well compactable by all compaction methods. The right borderline indicates an empirically found limit where the amount of cobbles and boulders prevents compaction by vibro compaction because the vibroprobe cannot reach the compaction depth.

Zone B: The ideal range for compaction. The fines content is less than 10 % and the clay content is less than 1%.

Zone C: Compaction by Vibro maybe possible with extra time and efforts, or additional filling from the surface. Dynamic and Rapid Impact Compaction is still applicable without further limitations.

Zone D: Compaction without additional measures is not possible anymore. Soil reinforcement by Stone/Sand columns, Deep Soil Mixing or Rigid Inclusions might be necessary to achieve the design requirements.

Nevertheless, if extra energy is applied using Rapid Impact Compaction (blue line in Figure 2) or Dynamic Compaction (red line in Figure 2), boundaries regarding the fines and clay content can be stretched towards higher percentage of silt and clay. However, these techniques are limited in depth and so other solutions may be needed.

2.2. Soil properties based on Cone Penetration Test (CPT)

From the results of the CPT, the use of the software (CPTeT-IT) allows a rapid assessment of soil parameters from a wide range of published works, based on Robertson Soil Behavior Type Index, SBT Ic plots.

If the soils fall within the range of SBT Ic < 2.05, it is deemed liquefiable and compactable, and greater than 2.6 that it is non-compactable, and non-liquefiable. Hence the range of 2.05 – 2.6 is where it is non compactable but liquefiable where soil reinforcement would be typically used to mitigate risk of liquefaction.

For typical Vibro Compaction projects, soil suitability for deep compaction by vibratory methods was firstly assessed using the Massarsch (1991) compatibility chart based on the CPT data as shown in Figure 3 below prior to the application of Vibro Compaction and its subsequent evaluation.

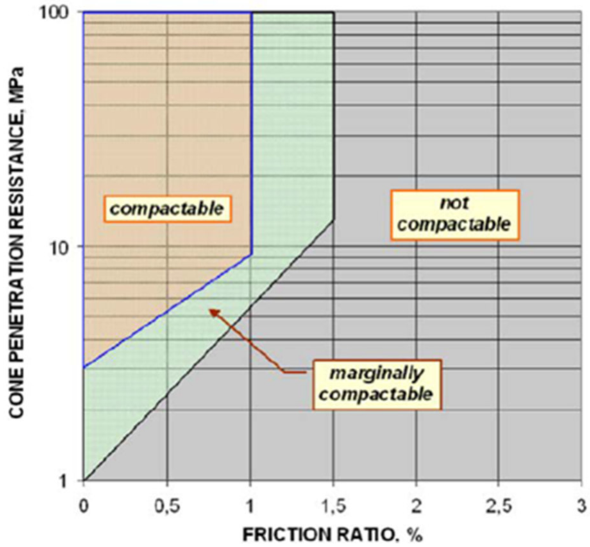

Figure 3. Soil classification for compaction based on CPT Data (Massarsch 1991)

2.3. Post-compaction quality control by Cone Penetration Test

For any typical compaction projects in general, as part of the quality control, Post-Compaction Cone Penetration Tests, Post CPTs undertaken and verified against the target performance specification to determine the success. As such in the case of Vibro Compaction projects the Post CPTs arranged in pairs from which a (VC) weighted average of the cone resistance, qc [MPa] values with depth calculated as follows: a test in the centroid of triangle of three compaction points, with typically 50% weightage, a test in the point on 1/3rd distance between two of these compaction points, with 50% weightage. This 50-50 weighted average of the pair of Post CPTs further translated into running average/ rolling mean over 1m thickness to flatten the cone resistance spikes for verification purposes.

However, in the case of Dynamic Compaction (DC) and Rapid Impact Compaction (RIC) projects, as the compaction prints are in the order of 1.5 to 2m in diameter, typically a pair of Post CPTs with one test on the compaction print and another off the compaction print carried out from which again a weighted average of cone resistance, q_c [MPa] values with depth typically with 50-50 percent weightage calculated and verified for performance.

The typical frequency for post compaction verification testing is in 25 m x 25 m to 50 m x 50 m boxes corresponding to an area between 625 m^2 to 2.500 m^2 per test.

A waiting duration of minimum 2 weeks is proposed between the compaction works and testing to allow for the pore water pressure dissipation and equilibrium conditions to occur. The resultant weighted rolling mean for 1m thickness of post compaction CPT cone resistance, q_c [MPa] values is plotted against the target value, and if the actual value exceeds the target CPT performance line cone resistance, then the works are considered acceptable.

In Figure 4 a typical example of a Vibro Compaction project in UAE, showing the pre-CPT blue line against the required (silica target) and corrected for crushable performance lines. The graph to the right is the Massarsch (1991) plot showing the suitability of the Pre-CPT for compaction by vibratory methods. The graph below shows the same information but with the heavy black line being the weighted average post CPT rolling mean demonstrating that the works exceeded the requirements.

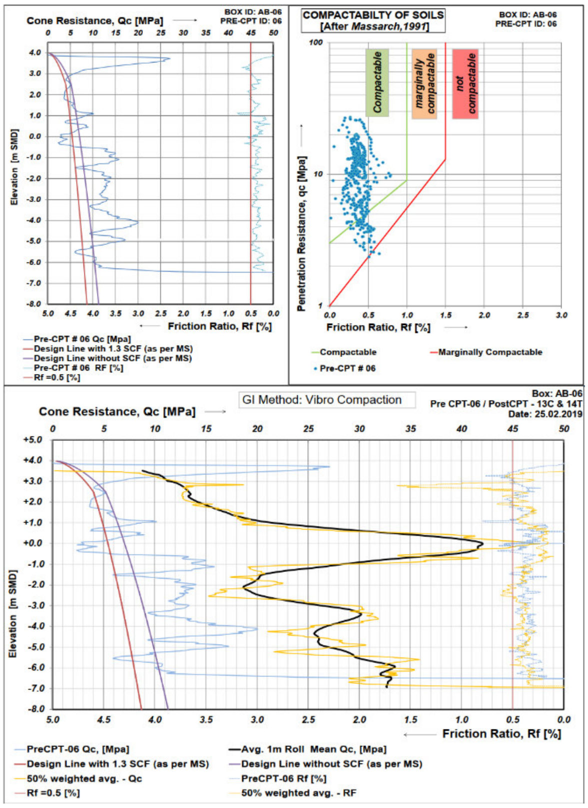

Figure 4. Post CPT Performance verification

2.4. Mineralogy

Sand is a naturally occurring granular material composed of finely divided mineral and rock particles. The mineralogy of sand can vary widely depending on its source and the geological processes that formed it. Common minerals found in sand include Quartz, Feldspar, Calcite, Pumice as well as Shell and Coral fragments.

Sand can be derived from various sources, including the weathering of rocks, erosion of mountains, and deposition by wind or water. Different environments, such as deserts, rivers, beaches, and dunes, can produce sands with distinct mineral compositions.

Crushable, carbonate sand (carbonate content > 90%) or calcareous sand (carbonate content between 50 and 90%), consist mainly of calcium carbonate ($CaCO_3$) like oolites, shell or coral fragments, where the sand particles are microscopic small shells or shell debris. Such sands are common in marine environment (e.g. at the sea bed) and therefore often used for sand reclamation projects. As a result of the limited hardness of the calcareous minerals that forms the main constituent of the particles, carbonate and calcareous sands are sensitive to crushing. Whereas rock based sands transported by rivers to the sea are often silica sands. The crushable sands are often related to the warmer seas (Gulf of Mexico, Arabian Gulf etc)

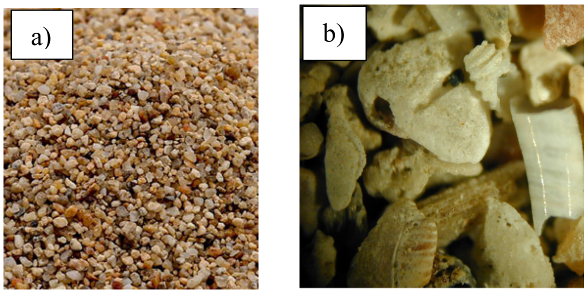

Figure 5. a) Silica sand b) Shell fragments forming sand

Other crushable sands can be for example Pumice sand. Pumice is a volcanic material that forms during volcanic events. During the initial eruption, magma erupts at such great speeds that it forms a molten froth. As this froth travels through the air it is rapidly cooled. During this cooling gasses get trapped in the froth, forming vesicles, or pores. Due to these pores in the particles the density of the Pumice sand is low, and the sand particles are sensitive to crushing (Figure 6).


Figure 6. Crushable pumice Lahar sand from Mt. Pinatubo in the Philippines

3. Effects of crushable sand on compaction and compaction verification

For sand compaction projects, the crushability leading to different behaviour during compaction and verification testing. Also, the geotechnical behaviours of crushable sands can be different from silica sands as high angularity also leading to high shear strength and liquefaction resistance.

However, in this paper only the effect of crushable sands on the verification testing shall be discussed.

After compaction the sand is usually in a medium dense to dense state. While in very loose to loose sands the sand particle below the cone of the CPT can move sideways, in medium dense to dense sand the particles have very limited to no space to move out. The limit from when the particle cannot move sideways anymore is a relative density of about 30% (Mayne 2014).

Hence, in medium dense to very dense sands the particles cannot easily move sideways below the cone and tend to crush due to very high stress concentration directly below the cone. E.g. for a cone resistance of 5 MN/m^2, considering a typical section area of the cone of 0.015 m^2, the force at the cone is 75 kN.

The influence of the crushing effect on the cone resistance has also been demonstrated by Ciantia et al (2016) by means of numerical calibration chamber tests for pumice sand using the Discrete Element Method

(DEM) (Figure 7). The results suggests that most particle crushing during cone penetration occurs at some distance below the cone tip.

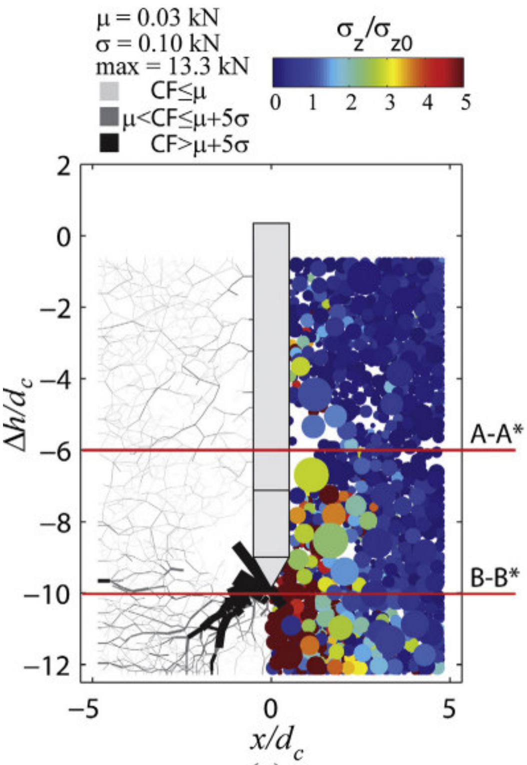

Figure 7. Stress concentration below the cone in uncrushable sand demonstrated in Discrete Element Method (DEM) (Ciantia et al 2016)

Hence, in medium dense to very dense sands crushable particles will not withstand the high forces and will break during the penetration of the cone into the sand.

This leads to a misinterpretation of the relative density of the sands as the actual measured cone resistance is not anymore determined by the density of the sand itself but on the resistance of the sand particles to break. As a result, in sands with the same relative density the CPT testing shows lower cone resistance in crushable sands than in non-crushable sands. It has been reported by Vesic (1965) that when silica sand, and a sand with 10% shells were compacted with the same efforts, the CPT reading was 50% less in the shelly sand even though the density was the same.

Once the $CaCO_3$ content reaches 40%, a further increase of it will not have further negative impact in the cone resistance (q_c) (Mayne 2014).

4. Implementation of correction factor for verification testing by Cone Penetration Test

The CPT performance line (design criteria) usually consisting of gradually increasing cone resistance (q_c) values over depth. The performance line is established for a constant targeted relative density (Dr) using the well-established correlations between the cone resistance (q_c) and the relative density (Dr) according to Baldi (1986) and Belotti and Jamiolkowski (1991). The performance line is set to mitigate the risk of liquefaction for specified seismic parameters and also enhance other soil properties like friction angle and soil stiffness.

Therefore, the target CPT line developed, against which the post CPTs results are used for performance verification, is in fact representing a particular constant relative density of the sand. If the cone resistance is however influenced by the crushing of the sand particles below the cone, a Correction Factor (CF) has to be implemented to correct the CPT results.

Several attempts have been made to establish the correction factor (CF) to "correct" the cone resistance (q_c) due to the impact of the crushing sand particles below the cone. The correction factor is a multiplying factor applied to the measured cone resistance (q_c) to calculate the corrected cone resistance ($q_{c,corrected}$) as a function of the relative density (1).

$$q_{c,corrected}(D_r) = q_c \cdot CF \quad (1)$$

The in-situ relative density and the correction factor must therefore be calculated in an iterative process. Alternatively, the relative density might be set to the target relative density to be achieved during the compaction works.

Belotti and Jamiolkowski (1991) firstly establish a linear correction factor between the cone resistance in non-crushable silty silica sands and crushable sands using calibration chamber tests (2).

$$CF = 1 + 0.015 \cdot (D_r - 20) \quad (2)$$

Al Hamoud and Wehr (2006) published a correction factor for calcareous UAE sands based on calibration chamber test carried out at the Karlsruhe University in Germany. The CPT_3 content of the sand was up to 90%. The results of the calcareous UAE sands were compared with the findings using the Karlsruhe Sand (medium quartz sand). The results were processed to establish an with the relative density D_r linear increasing correction factor (CF) (3).

$$CF = 0.0046 \cdot D_r + 1.3629 \quad (3)$$

Mayne (2014) suggested a correction factor which is increasing non-linear hyperbola with the relative density (4). The $CaCO_3$ content of the different sands analysed were between 43% and 98%.

$$CF = 6 - \frac{5}{1+(\frac{Dr}{100})^4} \quad (4)$$

Menge (2016) had established a correction factor as well based on calibration chamber tests (at 100 kPa vertical effective stress) carried out for an oil drilling islands project in the Arabian Gulf. The $CaCO_3$ content of the different sands analysed was between 93% and 98%. The correction factor as a function of the relative density as shown in Figure 8 is close to the correction factor defined by Al Hamoud and Wehr (2006).

Figure 8 provides a comparison of all the beforementioned correction factors as a function of the relative density (Dr). Specially the correction factor propose by Mayne (2014) differs significantly from the other approaches for high relative densities above 75%.

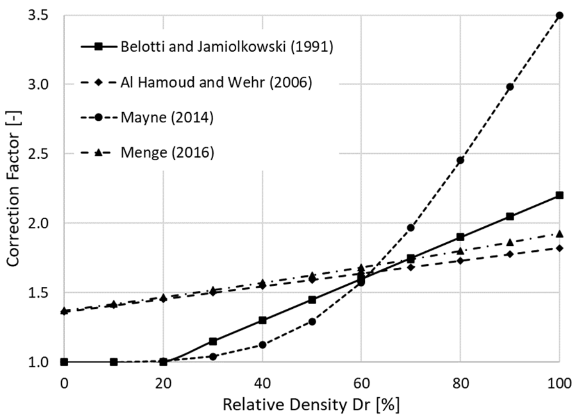

Figure 8. Correction factor depending on relative density based on different approaches

On the other hand, the calibration chamber tests with calcareous sands from the middle east presented by Al Hamoud and Wehr (2006) and Menge (2016) show matching trends for the correction factors. As sand sources are located in the Arabian Gulf, it is likely that both sands have similar properties and therefore a similar behavior during verification testing by CPT.

However, as crushable sands from different sources have usually different properties, it seems to be recommendable to establish a site-specific correction factor, especially for mayor and critical projects, in order do not under or overestimate the influence of the particle crushing during verification testing.

The most common and accepted way to establish the site-specific correction factor is the calibration chamber test (see above), which is time and cost intensive. Therefore, it would be beneficial to establish an alternative testing procedure using in-situ testing methods which can be effectively applied even on small compaction projects to establish a site-specific correction factor.

5. Alternative Testing using Seismic Cone Penetration Test (SCPT)

An alternative verification testing is possible by use of the Seismic Cone Penetration Test to assess a site-specific correction factor.

The theory of non-invasive testing is that the following assumptions apply: the usual in-situ tests (CPT, SPT, PMT) induce large strains and therefore crushing the carbonate or Pumice material. However, the measurement of shear wave velocity (V_s) by seismic methods is a small-strain test and thus does not induce crushing of the particles due to the higher compressibility of the carbonate and Pumice sand. The principles of seismic CPTs are shown in Figure 9.

Prediction of shear wave velocity V_s for offshore sands using CPT data based on Paoletti (2010) are calculated as given in (5).

$$V_s = 50 \cdot \left[(q_c/p_a)^{0.43} - 3 \right] \quad (5)$$

Where q_c is the cone resistance, p_a is atmospheric pressure and V_s expressed in m/sec.

Similarly, Robertson (2009) established a relation between the normalized shear wave propagation velocity (V_{sl}) and the normalized cone resistance $q_{c,1N}$ as shown in (6).

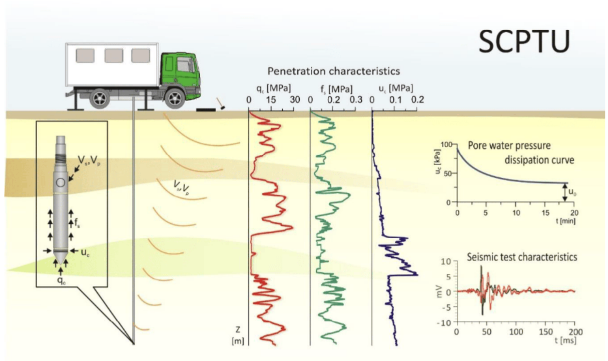

Figure 9. Description of Seismic CPT procedure and test results (Tschuschke et al 2020)

$$V_{sl} = \left[10^{(0.55Ic+1.68)} \, q_{c,1N} \right]^{0.5} \quad (6)$$

Where Ic is the Soil Behaviour Type Index obtained from static CPT data.

The normalized shear wave velocity (V_{sl}) is defined as shown in (7).

$$V_{sl} = V_s \cdot \left(\frac{pa}{\sigma' v0}\right)^{0.25} \quad (7)$$

In equation (8), σ'_v is the effective vertical stress at a certain depth.

From the above correlations from Poletti (2010) and Robertson (2009), the theoretical cone resistance $q_{c,th}$ can be calculated using the measured shear wave velocity (Vs) as provide in (8), (9) and (10).

Paoletti:

$$q_{c,th} = pa. \left(\frac{vs}{50} + 3\right)^{1/0.43} \quad (8)$$

Robertson:

$$q_{c,1N} = V_s^{\,2} / 10^{(0.55Ic+1.68)} \quad (9)$$

then

$$q_{c,th} = q_{c,1N} / C_q \quad (10)$$

Where C_q is the normalizing factor for cone penetration resistance (11).

$$Cq = \left(\frac{Pa}{\sigma' v0}\right)^{n} \quad (11)$$

Where p_a is atmospheric pressure in the same units used for σ'_v, effective vertical stress at a certain depth; n is exponent that varies with soil type. At shallow depths C_q becomes large because of low overburden pressure; however, values > 1.7 should not be applied. The value of the exponent n varies from 0.5 to 1.0, depending on the grain characteristics of soil.

Based on the above determined theoretical $q_{c,th}$ values calculated from V_s, the in-situ Correction Factor (CF) can be calculated as:

$$CF = \frac{qc,th}{qc} \quad (12)$$

In equation (10), q_c is the measured cone resistance from the same CPT tests where the shear wave velocity (V_s) was measured.

This procedure allows to establish a site-specific correlation factor (CF) considering the in-situ soil condition without carrying out cost intensive and time consuming laboratory tests. However, limitations regarding the applicability of the correlation provided by Paoletti (2010) and Robertson (2009) have to be considered.

Debats et al (2015) has followed a similar approach using Robertson equation to analyze SCPT date from a project in Tangiers, Morocco where the carbonate content of the reclaimed sand ranged from 75 to 95%.

By applying the based on Robertson (2009) established correction factor to the cone resistance measured and calculating the normalized shear wave velocities and comparing the measured shear wave velocity with the calculated shear wave velocity, Debats et al (2015) could show the adequacy of this method.

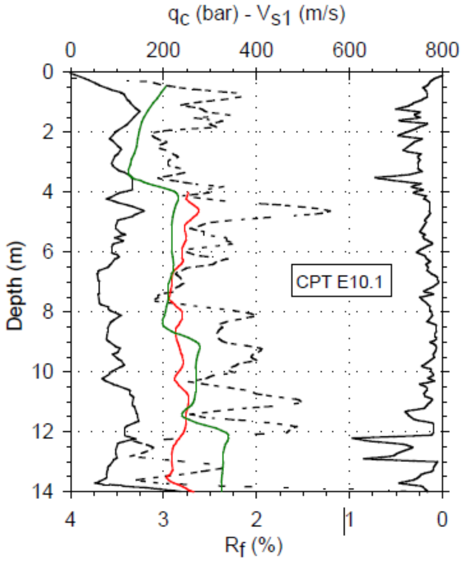

Figure 10. Application of the correlation SCF = f (Rf) on CPT E10.1 (Debats et al 2015)

Another advantage of using seismic CPTs is, that the Cyclic Stress Ratio (CSR) for liquefaction analysis (e.g. based on Youd T. L. et al. 2001) and other soil parameters required for the design verification can be correlated without being influenced by the crushing of particles due to the non-invasive procedure.

However, seismic CPTs are more time consuming and sensitive to project site activities, especially regarding sand compaction works. Therefore, the use of solely seismic CPT for the verification testing would slow down the construction process as compaction works would need to put on hold during testing.

Hence, as indicated in Figure 11, a testing procedure could be used by which the correction factor (CF) is established during the initial trail and then applied to the static CPTs, which are carried out with the common frequency. Seismic CPTs could be carried out in much lower frequency than static CPTs for validation and update of the correction factor established during the initial trial.

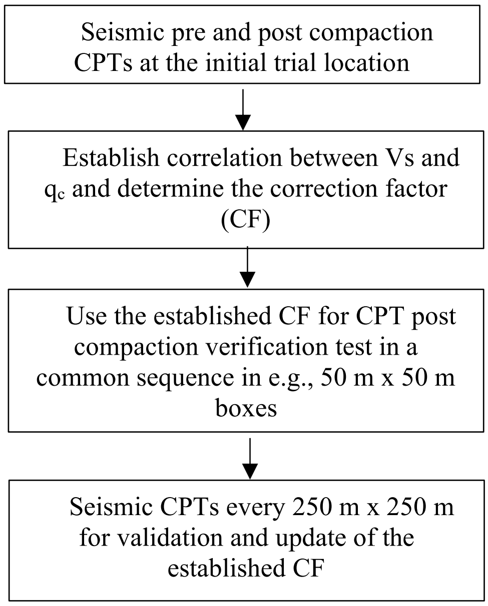

Figure 11. Suggested sequencing for verification testing using seismic CPTs

6. Conclusions

Most of the published literature available, methods of analysis and correlations regarding the verification testing of compacted sand relate to silica sands. The influence of the particle crushing is therefore not considered in such approaches. Those approaches need thus be adjusted to create representative results for crushable sands.

Those adjustments are usually done by the implementation of a correction factor. The most accurate but time and cost intensive way, is to establish the site-specific correction factor by mains of chamber calibration laboratory test.

However, especially for smaller compaction projects this might not be effective or possible and correction factors available in the literature might be used for considering the crushing effect. As the correction factor is solely depending on the properties of the used sand, the use of an correction factor established on the basis of sand from other sources might be not very accurate and can lead to under or overestimating of the effect of crushing particles on the results of the verification testing by CPT.

Alternatively, to avoid this costly and time-consuming procedure, the use of non-invasive testing of measuring the shear wave velocity with seismic CPTs (SCPT) and correlating with the actual measured cone resistance over depth at the same location to determine the correction factor can be proposed. This study would lead to more cost and time efficient works, and hence significant environmental benefits.

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