Quality Control and Acceptance Criteria of Vibro Compaction Works for Mitigation of Liquefaction Potential

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ABSTRACT: This paper presents typical quality control methodologies and acceptance criteria prescribed in the Project Specifications of recently completed vibro compaction works which had the main purpose to reduce the potential of liquefaction. The authors comment on the applicability of these methods and criteria to other projects, highlighting possible modifications and opportunities for improvement. Novel ways of analyzing the results using the CPT-based I_c value together with recommendations for future studies are also discussed.

1 INTRODUCTION

This paper describes typical quality control methods and acceptance criteria prescribed in the Project Specification (PS) of recently completed vibro compaction works in the United Arab Emirates (UAE) and Europe. Besides reduction of static settlement, the main purpose of compaction was to reduce the potential of liquefaction. The treated soil consisted of a fine to medium sand, locally interbedded with silty and clayey lenses. A summary of the typical equipment and installation parameters adopted in such projects is provided in Figure *1* below.

BG - B41 VIBROFLOT	
Frequency	60Hz
Rotation speed	1,800rpm
Motor force	210kW
Eccentric force	450kN
Amplitude	32mm

INSTALLATION PARAMETERS	
Grid spacing	3.0-5.5m
Lift step	0.5-1.0m
Holding time	20-60sec

Figure 1. Typical equipment and installation parameters for vibro compaction works.

PS for vibro compaction usually adopt a performance-based approach. Specifically, the Contractor is allowed to select the installation parameters taking into consideration the capacity of its own vibro-equipment, given that a minimum level improvement of the soil is achieved. For the purpose of liquefaction prevention, the improvement shall guarantee the densification of the soil. In order to obtain a continuous profile of soil data that can be correlated to the relative density of the soil before and after compaction, Cone Penetration Tests (CPT) are generally adopted as verification tool. For this reason, this paper will focus on PSs with CPT-based performance criteria.

2 PS WITH CPT-BASED PERFORMANCE CRITERIA

2.1 *Performance line*

PS based on CPTs require that the value of the cone resistance (q_c) is maintained above a prescribed performance line in the tests carried out after the vibro compaction works. Based on our experience, the prescribed Performance Line (PL) is either constant or variable with depth.

Figure 2 below shows an example of these PLs together with the corresponding values of relative density (D_r) according to Baldi (1986) and Factor of Safety (FS) against liquefaction assessed after Youd et al. (2001) for a typical peak ground acceleration and magnitude in the UAE. In this case, both PLs prescribe target q_c values sufficient to maintain the FS above the minimum required value (e.g. FS≥1.2). However, the constant PL requires that the soil is compacted upon achieving much higher values of D_r compared to the variable PL. It should be considered that:

- In most cases, target q_c values corresponding to D_r between 65% and 75% (up to 85% in areas with high seismicity) are sufficient to mitigate the potential of liquefaction. Such level of densification is in line with present installation techniques and equipment capabilities;
- targeting D_r values above 85% by means of vibro compaction is either not achievable or requires an effort significantly higher than in general practice. This translates in unnecessarily higher cost and time for the vibro compaction works.

It is therefore recommended that a PL variable with depth is prescribed in the PSs. However, when the purpose of ground improvement is not solely the mitigation of the liquefaction potential but also the reduction of the static settlements, it may be necessary to increase the target q_c values in the near surface range. Further details of soil densification in the near surface range are provided in the following Section 2.2.

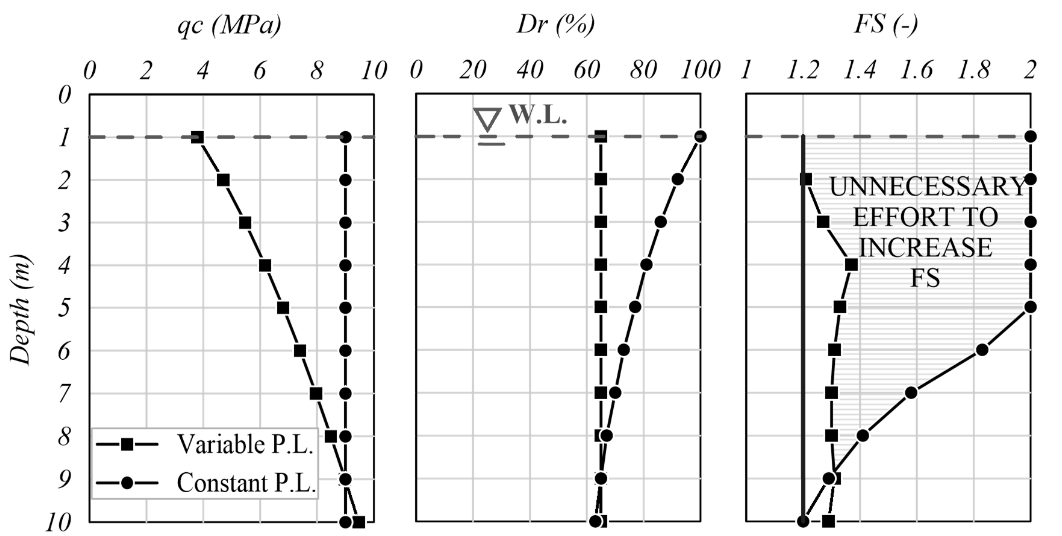

Figure 2. Examples of constant and variable Performance Lines.

2.2 *Compaction in near surface range*

Vibro compaction is effective when a certain level of overburden stress is applied to the treated soil. Therefore, this technique is not suitable to compact soil in the near surface range, i.e. in the top 1 m to 2 m. PSs should prescribe that the vibro compaction is terminated one or two meters below the working platform level and these top meters of soil are compacted in a second stage by means of a different ground improvement method including but not limited to Rapid Impact Compaction and High Energy Impact Rollers.

Generally, PSs require that the effectiveness of the vibro compaction works is evaluated based on the CPT results while the near surface range treatment is verified with different testing, such as in-situ density measurements or small size load tests. In our opinion, it is very useful to separately consider the quality control of the two ground improvement activities, because they are often carried out by different sub-contractors at different construction stages.

2.3 *Correction of CPT results in carbonate soils*

Nowadays, most land reclamations are formed in carbonate sands (i.e. UAE, Saudi Arabia, Singapore). Compared to silica sands, these soils respond differently to CPTs due to the highly compressible and more readily crushable nature of the carbonate grains. Carbonate sands also have different shape factors as grains are platy instead of round, which could make them drifting sideways from the approaching CPT cone. This leads ultimately to the need for corrections to the traditional empirical correlations between D_r and q_c, which are predominately derived for silica-based soil. PS for most projects in the UAE prescribe to correct the q_c value obtained by the CPTs by amplifying with a Shell Correction Factor (SCF) equal to or around 1.3. In some cases, the PS demands site specific correlations before a SCF can be applied. A large-scale Plate Load Test (PLT) is in our opinion a highly suitable method to assess a site-specific SCF. During a PLT the stress is applied onto a much larger volume of soil compared to the CPT and therefore the local crushability or movability of the grains that leads to reduced CPT resistance has much less impact on the compressibility of the soil in a PLT.

For a project recently completed in Dubai, a PLT was carried out as shown in Figure 3. The "real" q_c was back-calculated by varying its value to best fit the observed settlement. The SCF was then assessed as the ratio between the back-calculated "real" q_c and the average q_c provided by the CPT. The obtained SCF was equal to 1.7. This result is in line with the findings by Al-Homoud and Wehr (2006) by comparing a Dubai medium sand to a medium quartz sand in a calibration chamber. The authors propose a SCF value varying between 1.6 and 1.7 in the depth range (≈2·B) investigated by the previously described PLT.

A value of SCF equal to 2.1 was proposed in recent studies (Robertson, 2016) for hydraulically placed calcareous sand in Tangier, Morocco. This value was obtained as a function of the modified rigidity index, k_G^*, which is representative of the level of microstructure of granular soils. Based on these recent findings, it is recommended that the Contractor is always given the possibility to undertake a site-specific investigation in order to best calibrate the value of the SCF.

LOAD TEST DATA	
Footing size	2.5×2.5 m
Footing depth	0.0 m
Working load	150 kPa
Load test load	225 kPa

PS specified correlation between between E_s and q_c:
$\mathrm{Es} = 3 \cdot q_c$

Figure 3. Large scale plate load test.

2.4 *Filtering test results*

During the evaluation process, the CPT data are usually filtered in order to exclude from the assessment eventual silty/clayey layers with fines content higher than 10% which are not or only marginally compactable by vibro compaction. With reference to most common soil classification charts (i.e. Robertson, 2016), one of the following parameters is usually taken by the PS to indicate soils that are likely not compactable or only marginally compactable in-situ:

a) For reclamations with loose carbonate sands: Friction Ratio (F_r) in excess of 0.5%; or
b) Soil Behavior Type Index (I_C) in excess of 1.9, for both carbonate and silica sands;

Based on project history, vibro compaction Post CPT results are generally achievable when one of the aforementioned criteria is respected, together with additional two conditions:

- The clay content is less than 1% (for example, soil with 10% fines content but zero clay content often compacts better than a soil with 6% fines content but 2% clay); and
- Uniformity index $Cu = d_{60}/d_{10} > 2.0$.

For this reason, and in consideration of the fact that CPT based soil classifications only provide apparent (correlated) values of fines content, it is recommended that the PS requires to carry out laboratory analyses (both sieve and hydrometer analyses) on samples taken in proximity of post-compaction CPTs in order to compare the apparent fines content data of the CPT with site specific borehole data.

In addition, it should be considered that the CPT tip resistance is influenced by the soil properties ahead and behind the tip. Consequently, the measured q_c is not a true measure of the actual density of the soil near such interface. This effect may occur for a thickness that ranges from 36cm to 72cm, depending if a soft or stiff layer is approached (Campanella & Robertson,1988). It is therefore recommended that CPT data are also excluded for 0.5 m above and below soils deemed to possess greater than 10 % fines.

2.5 *Averaging test results*

PSs usually require to undertake in each verification cluster one test before and two tests after the ground improvement works. A typical size of the verification clusters ranges between 30m×30m and 50m×50m. The pair of post-CPTs have to be undertaken within the same triangle of the vibro compaction grid at ⅓ distance between compaction points and either at the midpoint of the distance between compaction points or at the centroid of the triangle formed by the surrounding compactions points. In order to evaluate the mitigation of the potential for liquefaction the average level of densification achieved within the soil mass should be considered. The centroid is the unique location that is giving the absolute lower-bound level of improvement while the midpoint provides indication of the improvement level lower-bound of approximately 91% of the triangle area, as shown below in Figure 4. The Engineer should therefore consider carefully whether to prescribe the achievement of the target q_c at the centroid location that is only representative for less than 10% of the total treatment area, which means that additional time and budget will be required to achieve such result, providing a level of improvement in a small localized zone that is well above to what may actually be necessary as an average over the whole area.

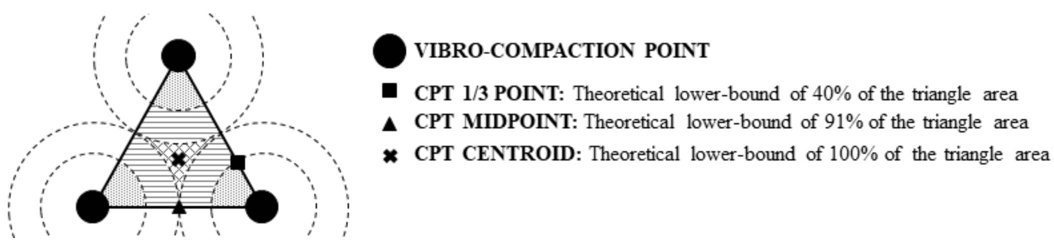

Figure 4. Typical location of post-CPTs.

The q_c profiles of the post-CPT pair are usually averaged after being amplified by the appropriate SCF, when necessary. In layers where q_c values of one CPT are excluded due to filtering; no average should be made. However, the profile of the remaining CPT should still be evaluated and compared to the PL. This is important to avoid that an excessive amount of data is excluded from the evaluation. PSs usually require to either adopt an arithmetic mean or a weighted mean. As previously shown in Figure 4, the Midpoint can be considered representative of the average achieved improvement for a larger influence zone and usually provides lower q_c values compared to the 1/3-point. It should be therefore preferable to adopt a weighted mean with higher weight given to the Midpoint profile over the arithmetic mean. The averaged profile is then compared to the PL in order to assess if the Vibro compaction was successful.

In some case, the PS allows to smoothen the averaged q_c profile by considering the rolling mean profile over one-meter depth zones. The adoption of the rolling mean is useful to avoid initial rejection of the Post-CPT (and subsequent time-consuming calculation of static settlements to prove the settlement criteria are still fulfilled) when only a small portion of the q_c profile lies below the PL. On the other hand, the presence of lenses of soil with average q_c below the PL may lead to the development of liquefaction induced settlements. For example, for the layer comprised between depth 9.0m and 9.5m in Figure 5 the settlement calculated adopting the rolling mean profile would be zero while the settlement assessed with the average profile would be a positive number. It is therefore recommended that smoothening techniques, such as rolling mean, are not implemented for the purpose of liquefaction settlement calculation.

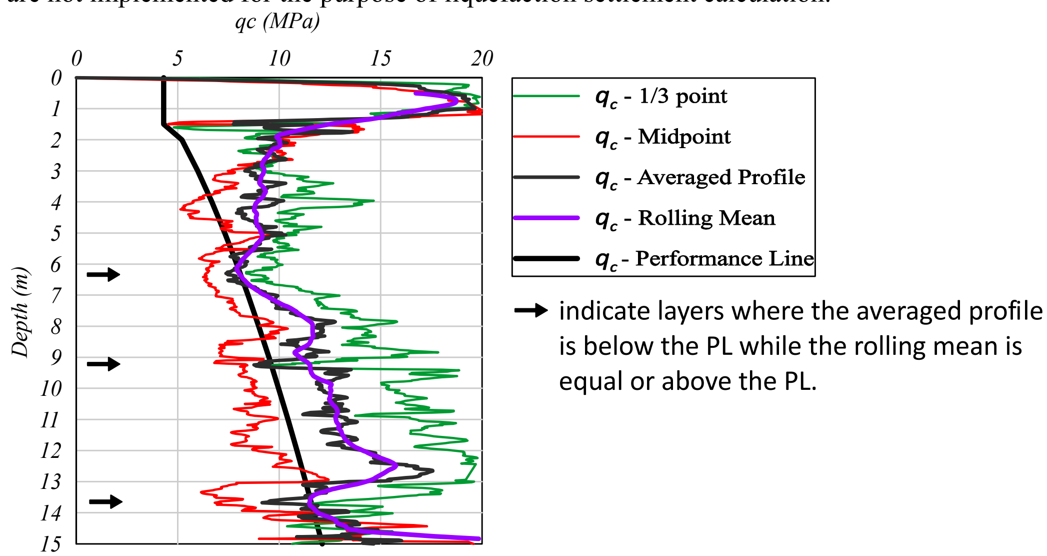

Figure 5. Comparison between averaged profile and rolling mean.

3 SUBSIDENCE AND DESIGN CRITERIA

Imperfections in such CPT values within a treated soil mass should not be considered as severely as for example defects within a pile foundation. As an example, when the average q_c profile lies below the PL with a limited soil layer, the overall performance of the soil mass in seismic conditions may or may not comply with the design criteria. In other words, some liquefaction settlement is likely to occur if the post CPT stays in part below the PL, but the magnitude of such settlements may still be within the acceptable limit. It is therefore recommended that the evaluation of the vibro compaction work is not solely based on CPT criteria but also accounts for other requirements, as described in this section.

3.1 *Subsidence requirements*

Subsidence of ground surface during vibro compaction is due to the void closure of the granular soil and therefore depends on both the in-situ density before compaction and the target relative density. PS can either prescribe a minimum subsidence percentage to be achieved or recommend to monitor the settlements only as a complement to the information gathered with the CPT sounding. In our experience, the induced settlement over the treated depth was in most cases found to be in the range of 5% to 10%, in rare cases of originally very loose sands also up to 15%. It should be mentioned that such values were for recent reclamations where a consistent fill method was adopted and all material was placed within the same construction phase. However, a unique value of the minimum required induced subsidence may not be applicable when:

a) a reclamation is placed and then developed in phases. This is because compaction works immediately adjacent to uncompacted zones may result in densification of those zones and therefore the soil would show variable in-situ density states;
b) filling material has a variable content of fines, because the uncompactable layers do not contribute to subsidence; or
c) variable thickness of layers placed by different filling methods, for example bottom dumping for lower part of profile and rainbow filling above.

In such cases, the minimum desired subsidence settlement should be derived by the difference between the target relative density and the density before compaction, accounting for the compactable layers only.

3.2 *Design criteria*

PSs can incorporate CPT-based and design criteria by prescribing to reach or exceed the q_c PL and, where that was not possible, to prove that static and/or liquefaction settlements do not exceed the limit allowable for the envisaged structures. When this approach is adopted, it is common practice that the evaluation of the settlement is undertaken by "*calculation methods approved by the Engineer*". It is our recommendation that PSs include additional details of approved methodologies and assumptions in order to reduce the risk of disputes at a later stage. With reference to liquefaction design, such details include but are not limited to:

- Size, embedment and load of foundations;
- Allowable settlement induced by liquefaction;
- Accepted correlations between soil testing results and soil parameter (e.g. $Es = \alpha \cdot q_c$);
- Accepted calculation methods for seismic settlements (i.e. Youd & al, 2001).

3.3 *Vibro compaction verification flow chart*

Verification flow charts are a useful tool to summarize how CPT-based criteria and other requirements are incorporated in the quality control process. Figure 6 shows an example of verification flow chart for vibro compaction works. It is known that after vibro compaction the dissipation of excess pore pressures and re-saturation of soil (dissolvement of air bubbles) in the ground takes two to four weeks. The q_c values increase during such period. For this reason, it is common practice to not undertake post-testing before 14 days after compaction. However, due to local variations of boundary conditions and fines content, the q_c values may increase slower in some cluster than others. Therefore, when the post-CPT verification of a cluster has failed, it may be useful to look at the overall subsidence. Should the observed settlement suggest that a sufficient average level of void closure was achieved, a second attempt of testing could be allowed after one week within the same cluster before deciding that additional vibro compaction work is required, as shown in this example flow chart.

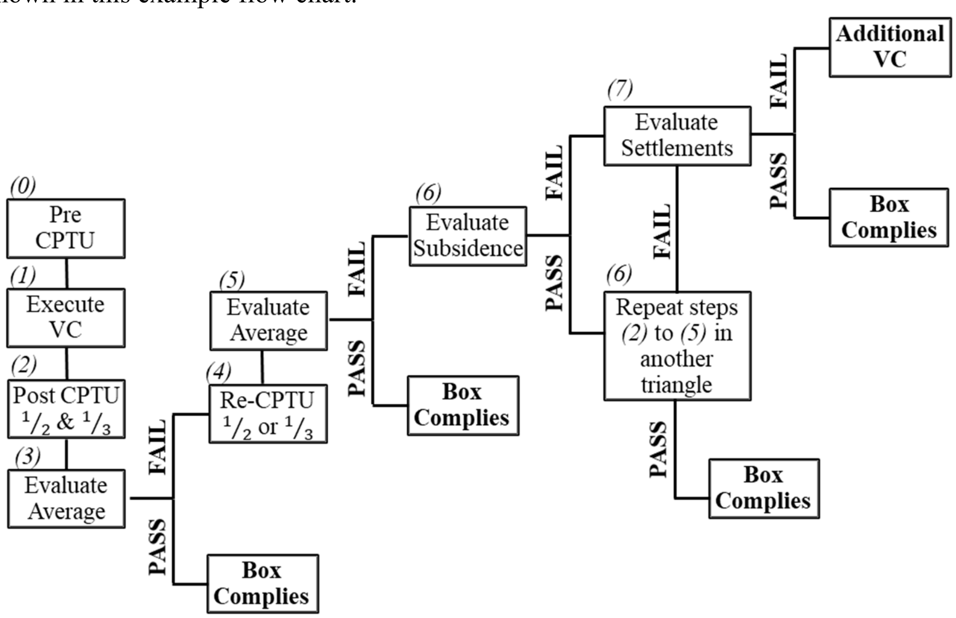

Figure 6. Proposed verification flow-chart for vibro compaction works.

4 RECOMMENDATIONS FOR FUTURE STUDIES

4.1 *Compressional state after vibro compaction*

For compactable layers, both q_c and sleeve friction (f_s) increase after compaction; however, the resulting friction ratio (Rf) values obtained by the post CPTs are generally lower than the initial values. An example of pre and post rolling mean CPT plots is provided in Figure 7; these plots are representative of the general trend observed in recently completed projects. The variation of the RF value results from the fact that compaction has a different impact on q_c and f_S. The tip resistance q_c increases exponentially with friction angle and therefore also with relative density, similarly to the end bearing capacity of a driven steel pile (Viggiani, 2003). On the other hand, the pile shaft friction coefficient is marginally influenced by the soil friction angle for an interface soil-steel and the increase is less than exponential. The observed variation in CPT sleeve friction f_S is more likely to be due to the modification of horizontal compression induced by vibro compaction, characterized by a higher horizontal to vertical stress ratio (K_h) compared to the in-situ initial ratio (K_0).

Van Tongeren (2018) studied dilatometer tests undertaken before and after a vibro compaction work. Results showed a post treatment increase of the Horizontal Stress Index, which is directly

correlated to the horizontal stress in the soil, up to four times the initial value. This suggests that sands treated by vibro compaction show an "over-consolidated like" behavior and therefore the in-situ effective mean pressure (p) is likely to be higher than the value for earth pressure at rest $(\sigma'_v+2{\cdot}K_0 \cdot \sigma'_v)/3$. Consequently, the such prestressed soil is likely to show a less contractive behavior, which correlates to a lower potential of liquefaction. In order to develop the current design practice and optimize future vibro compaction works, it is recommended that further studies are undertaken by comparing either pressuremeter or dilatometer tests pre & post compaction in order to correlate the increase of horizontal stress with the installation parameters and CPT results. Pre and Post CPTs should whenever possible be complemented by Seismic-CPTs that give an indication on the small-strain G-Modulus. In addition, the variation of the horizontal stress built up during vibro compaction should also be investigated over time to see if there are aging effects.

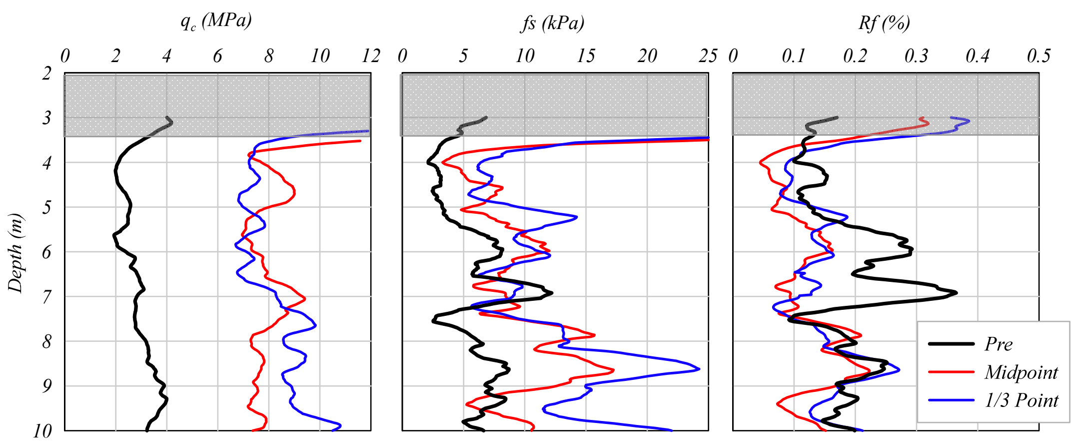

Figure 7. Example of pre & post CPT results.

4.2 *Variation in Ic index and SBTn classification*

As mentioned in the previous section, the resulting q_c and f_S pairs post compaction generally give a different RF compared to the same layer before compaction. It is a relatively common observation that this leads to the I_C index values decreasing after compaction (Degen at al, 2005 and Robertson & Cabal, 2012). This can be observed in the plots provided in Figure 8, which are representative of the general trend observed in recently completed vibro compaction works. The cloud of the $q_c - Ic$ pre-compaction points shifts towards the left (upper plots) and the classification based on SBTn index (Robertson, 2016) identifies a coarser material (bottom plots). This behavior is observed in both silica and carbonate sands and it is more pronounced for larger increase in q_c. In the SBTn classification chart, the post compaction points still lay inside the "normally consolidated" area, which is not in agreement with the "over-consolidated like" behavior post compaction described by Van Tongeren.

Based on these considerations, it is proposed that future studies are developed to investigate:

- comparison of I_C range pre & post compaction for each soil layer;
- correlation of I_C reduction to q_c improvement;
- correlation between I_C reduction and increase of horizontal stress; and

- correlation of pre & post I_C values to fines and clay content obtained from laboratory tests.

It is our aim to better understand such correlations with the aim of developing a systematic use of the I_C -q_c plots to be adopted in design and quality control of future vibro compaction works.

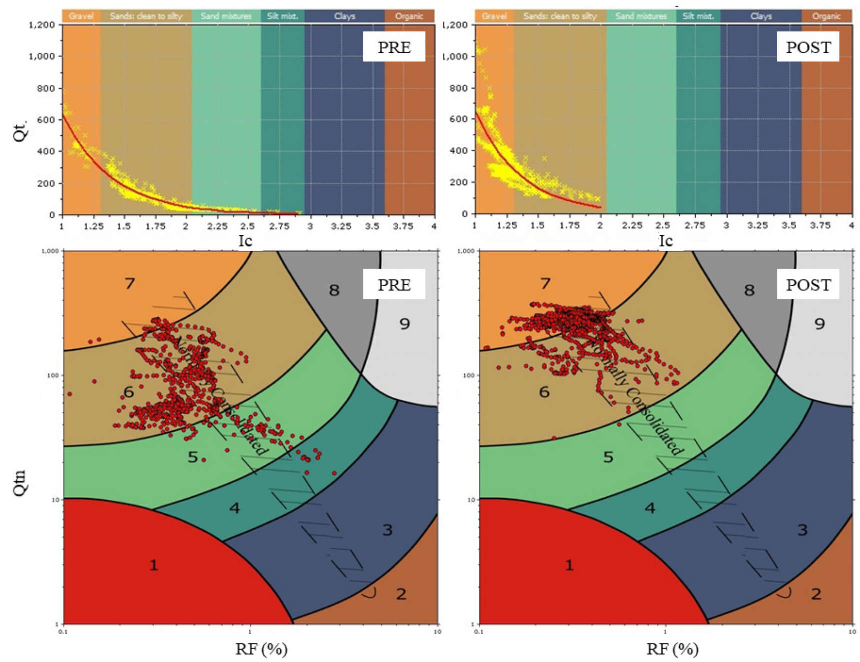

Figure 8. Example of pre & post vibro compaction I_C- Q_t plot and SBTn classification.

5 CONCLUSION

In conclusion, the main recommendations for future vibro compaction projects are:

- Adopt a variable q_c performance line;
- allow alternative compaction methods in the top 2m range;
- assess a site-specific SCF by means of large scale PLT or other site-specific testing;
- select filtering and averaging methodology based on realistic design requirements;
- adopt measurement of subsidence due to compaction as an additional component of the quality control protocol and design criteria, such as allowable settlement, as a complement to the CPT-based criteria; and
- undertake further studies to evaluate the variation of the horizontal stress induced by vibro compaction and variation of the apparent I_C value post treatment.

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