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Densification of Reclaimed Soils with the Utilization of the Vibro Compaction Technique—A Case Study

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Abstract

This paper presents a case study of the extensive soil improvement work carried out on a reclamation project on the shores of United Arab Emirates. The project consisted an area of approximately 480,000 m^2 for recreation purposes. Following the dredging work, approximately 6.8 million cubic meters underwent densification using the vibrocompaction method. The general aims of such analysis are to investigate the effectiveness of vibrocompaction as a method of soil improvement and appraise the selection of this method as the most appropriate soil treatment technique necessary for the adequate densification of the overall loose soil masses. The efficiency of the vibrocompaction technique to densify thick granular-based soil formations of considerable thickness and the benefits obtained, equated to other soil treatment methods, was assessed through a comprehensive post quality control program including field and laboratory post-compaction testing. Based on the analysis conducted it is concluded that soil strength of the reclaimed materials achieved a noteworthy improvement reaching comfortably the required degrees of densification.

Keywords

Reclamation, Dredging, Manmade Islands, Compaction, Soil Improvement

1. Introduction

Vibrocompaction is a densification method for increasing the density of granular soils by the action of a vibratory probe or poker that is lowered into the ground using air and water. The purpose of vibrocompaction is the improvement of the soil geotechnical parameters that are vital in foundation appraisals.

The effectiveness of such a method depends on the in-situ soil conditions. The results of vibrocompaction actions are not similar for all soils treated. More precisely, the granular soils show diverse outcomes compared to those of clayey formations where such technique is not appropriate because of the existence of high fraction of fines (*i.e.* silt and Clay). Vibrocompaction provides excellent compaction results in cohesionless soils [1] where the subsequent necessities are satisfied:

- Satisfactory footing bearing capacity is accomplished.
- Absolute settlements are reduced to tolerable limits.
- Horizontal earth stiffness is improved.
- Danger of liquefaction in the compressed zones is alleviated.

This paper presents a case study of the extensive soil improvement work carried out on a reclamation project on the shores of United Arab Emirates.

2. Literature Review

2.1. Vibro Compaction Procedures

Vibrocompaction relates to the treatment performed on non-cohesive earths. For loose sandy soils, where natural dry densities are less than the maximum dry densities, the influence of vibrations resulting in a re-arrangement of the soil grain structures. The soil particles are re-arranged unconstrained and unstressed under the gravity action to the denser possible phase. The void ratio and compressibility of the improved soils is reduced, while, their angle of shearing resistance is amplified. By refining earth factors (such as friction angle, density, deformation modulus), it is likely to significantly surge the bearing capacity and to decrease the settlements under the enacted footing loads. The lessening in void ratio that lead on soil settling depends on particle structure, earth shape and vibration power.

The dense state of soils through the vibrocompaction method is accomplished through many activities that happen. Every densification point is advanced by insertion of vibrator jointly with the addition pipes above the designated location by means of an accompanying gantry. The vibrator is dropped with its motor running while water is discharged from vibrator's bottom tip. The vibrator gradually sinks into the soil under its own weight and the resulting vibratory action, with a rate depending on the initial soil compaction. The sinking speed of the vibrator is usually between 1 m and 2 m per minute. Once the design anticipated depth is attained, next the descending drive of the vibrator is stopped, with the water jetting altered from the tip of the vibrator to the top of the vibrator. The volume of water is also regulated to aid in the compaction of the in-situ earth particles. The vibrator is later steadily extracted from the lowest ground triggering densification of the neighboring sandy formations that are re-arranged to a solider phase of compaction. Such retraction is happening unhurriedly enough for increasing the vital compaction, normally, at an amount of 0.5 m per minute. The compactness increases effects to a growth of the vibrator confrontation that, eventually, rising the motor energy. The energy surge is the foundation for governing the densification procedure.

The superficial soil around the vibrator displays a sinking movement having a cone shaped depression produced by the increased compactness of the sandy formations. This depression can be occupied by either site or imported cohesionless foreign soils. Consequently, a solid earth tube is shaped whose operative diameter is based on the particle size distribution, the earth compactness, and the vibrator features. The post-densification consistency is attained by introducing compaction points in appropriate arrangements.

Vibrocompaction is typically appropriate for compacting sandy formations. As the fraction by weight of fines (particles finer than No. 200 sieve) surpasses 15%, the vibrocompaction is not competent. This is mostly accredited to the low permeability of material with extreme fines that is not letting the rapid dissipation of pore water pressure essential for compaction.

The compaction grade is typically checked via the subsidence of the ground that has happened. Usually densification is more successful at the middle of the advanced compaction point and declines with circular distance. Naturally, the radius of effect shrinkages from about 2 m for clean sands to 1 m in sands comprising of a considerably proportion of fines. Depths that vibrocompaction is appropriate attaining, as a minimum, 30 m.

In the vibrocompaction technique the necessary densities to be accomplished are obtained by providing surplus earth materials. Coarse sandy soils with minor or no fines proportions resembles to the utmost fill for such ground improvement technique permitting densification to be accomplished on a faster speed. The suitability number (SN) [2] for the grading of backfill/in situ formations appropriate for vibrocompaction is given as follows with the related rating shown in **Table 1**:

$$SN = 1.7\sqrt{\left[\frac{3}{D_{50}^2} + \frac{1}{D_{50}^2} + \frac{1}{D_{10}^2}\right]}$$

where:

D_{50} = diameter in the grain size distribution curve equivalent to 50% finer.

D_{20} = diameter in the grain size distribution curve equivalent to 20% finer.

D_{10} = diameter in the grain size distribution curve equivalent to 10% finer.

Vibrocompaction technique is based on two fundamentals, specifically, depth and grid/spacing. The in-situ earth features are of a pronounced significance as vibrocompaction is applied for treating the existing formations. Assuming elastic theory philosophies, the depth effect region of the stress bulb on neighboring earths is appropriate for depths not bigger than 2B to 4B (depending of footing category either spread or strip), where B is the width of the footing. In case of raft/mat footing, next, such depth is reduced to 0.5B to B. Hence, earths that need to be treated are usually not depth extreme. Generally, allowance of the

Table 1. Suitability number and rating for the backfill grading.

Suitability Number	0 - 10	10 - 20	20 - 30	40 - 50	>50
Rating	Excellent	Good	Fair	Poor	Unsuitable

vibrocompaction to enter around 0.3 m into the solider underlying earth deposits is satisfactory for relocating the loads to the tougher incompressible underlying stratums. n contrast, once features of vibratory machinery or liquefaction potential are introduced, depths of improvement might modify/surge as causes such as dynamic settlements have to be accounted for.

The level at which the earth features of a zone (upon which foundations will be positioned) is enhanced ruled by the spacing of the vibrocompaction scheme. Consequently, chief scope of the vibrocompaction is suitable strength-density-incompressibility at locations in amongst densification points with the minimum number of points (extreme spacing) to be accepted. The spacing of vibrocompaction points is based on the earths to be improved. Definitely, loose earths necessitate lesser spacings equaled to soils display an early solider phase of densification. Improved earth features to be attained are being a controller of the radial distance in which earth particles will be compacted under the vibratory action of the method. Compaction of the earths mostly depends on soils friction angle, cohesion and permeability. Through the procedure of vibrocompaction the friction angle (typically appropriate to sandy soils) is amplified. Cohesion, appropriate to silts and clays, is enlarged with fine content increasing, while, permeability resembles to the competence of water flowing over earth media that in turn disturbed by the fine content occurrence in relation to time-rate perception. Earths comprised of sandy soils include voids letting water to be flow on a considerably relaxed mode compared to clayey formations where a substantial quantity of fines occur.

The circular zone of operative densification from the point of improvement (for earths where vibrocompaction is appropriate e.g. fines less than 15%) is not only depends on soil features but also on the precise features of the vibrator used. Usual radius, where formations have been compacted, has a flexible variety between 1.5 m to 3 m. Vibrocompaction begins on a pre-determined point arrangement following either a triangular or a rectangular spacing configuration with points spread out at numerous distances, usually, varied between 1 m to 3 m. Such spacings, based on earth characteristics and vibrator requirements, are satisfying the densification necessities even of earths locations at between densification points. Determination of the ideal grid spacings should be defined when accomplishing pilots with dissimilar spacings. Nevertheless, throughout the preliminary design phase of a ground treatment scheme, a satisfactory grid spacing shall be used (defined after pilot procedures).

Earth compactness are comparatively amplified once the vibrocompaction technique is applied. The nominal necessities that convey to the essential vibrocompaction work are measured by the degree of compaction attained in contradiction to the stated project goals. Such surges at earth densities are confirmed by relationships with cone penetration tests (CPT), standard penetration tests (SPT), pressure meter tests (PMT) and other in-situ probes that are usually undertaken both before and after ground improvement. Before proceeding to main production work within a vibrocompaction scheme, trial(s) is undertaken for comfortably specifying optimum parameters to be used leading to considerations of proper compliance of the project specifications at a most favorable cost. Such trials usually include three sets of spacing between compaction points to be used supplemented by both pre/post quality control tests for verifying densification of the treated soils to adequate limits. Control of performance within vibrocompaction work is also determined through the trial procedures. Such control is acquired by using consistent procedures establishing lift heights of the vibrator, compaction time per lift, and corresponding energy. These parameters can be further adjusted within the main production work being area soil specific.

The performance requirement can be checked by calculating the allowable bearing capacity for a shallow foundation as provided within the project conditions. The allowable bearing capacity will be derived from the ultimate bearing capacity by applying a relevant safety factor. In general, the parameters used in the calculation of long-term bearing capacity in non-cohesive soils are the cohesion and friction angle. The first is conservatively considered to be zero in non-cohesive material. The effective friction angle can be derived from laboratory testing or from relations with the data acquired from the penetration tests. The bearing capacity can also be determined from field tests (e.g. Plate Load Tests—PLT).

Overall settlement comprises of the various settlement elements. These settlement elements, namely, static and dynamic, are taken from the contributions of vertical imposed load upon a shallow footing and induced settlements due to liquefaction potential failure, respectively. Static settlements are further elaborated to immediate, primary consolidation, and, creep settlement components. In general, both the primary consolidation and creep components are mostly existent in cohesive soils. Within soils that have low permeability and substantial thickness characteristics, those settlement contributions are fairly important compared to immediate settlement component. This is attributed to the procedures of slow dissipation of the excess pore water pressures induced by the static load. For granular soils with a moderately high relative density (after the vibrocompaction treatment), the static load induced settlements will be relatively small. In that case there will hardly be any long-term settlement (primary consolidation).

Liquefaction assessments are, in general, based on approaches defined within the National Center for Earthquake Engineering Research (NCEER) reports accompanied by international criteria/codes and supplementary recommendations. The analysis is based on the estimation of cyclic resistance ratio (CRR) corresponding to the soil strength, and cyclic strength ratio (CSR), which relates to the induced seismic actions.

2.2. Quality Control

The quality control process ensures the work will deliver a ground arrangement that will meet the requirements. The plan performance program summarizes the measures for the vibrocompaction work, the quality control program documents these measures as well as the testing. The quality assurance program describes the evaluation of aspects of the work and testing and addresses any conformance matters. The subject procedures cover inspection and relevant quality records related to vibrocompaction work. The quality procedure on the compaction work consists of the following steps:

- Assessment of existing geotechnical information.
- Trial explicit method statements and installation.
- Compaction process.
- Post treatment geotechnical investigations.
- Receipt of accepted treatment work.

<u>Before Vibro compaction</u>

Before commencing any soil treatment scheme, a survey of the site shall be undertaken followed by pre-treatment penetration tests as well as appropriate soil sampling. Depending on the field/lab geotechnical results, the suitable treatment method is identified and associated parameters are assigned through a preliminary soil improvement design, which is to be tested within the treatment trial. Before carrying out any ground improvement in a concerned area, the following survey/geotechnical investigations are recommended to be performed:

- Survey of existing ground levels shall be initially carried out within the area of concern; without which no ground improvement can be initiated.
- Pre-treatment penetration tests, usually cone penetration tests (CPT), are undertaken in the middle of the corresponding area(s) before beginning of any ground treatment development to determine the nature of the subsoil and the essential improvement method to be utilized.
- It is also recommended that above pre-treatment scheme is also reinforced by undertaking additional exploration boreholes within the weak soil formations. Standard penetration tests (SPT) shall be undertaken at those boreholes and, in addition, associated soil samples shall be retrieved, especially in the presence of cohesive nature materials where undisturbed samples are required. Corresponding field and laboratory testing shall be carried out in accordance to relevant ASTM standards. Pre-treatment frequency of the exploratory boreholes shall be decided based on the area that is to be improved and applicable project specifications.
- Lab tests on samples retrieved from the exploratory boreholes shall include, but not be limited to wet sieve analysis/hydrometer, minimum/maximum density, strength, and carbonate content tests.

Vibro compaction Trials

For the areas where ground improvement is to be executed trials are scheduled in consideration to the intended vibrocompaction work. Different vibrocompaction elements will be tested to define the ideal parameters:

- Spacing between the vibrocompaction points depending on the used vibroprobe, properties of the soil to be compacted, and, proposed construction-imposed loads.
- Increment of raising-steps of the vibrator.
- Holding time per step depending on the used vibroprobe and the properties of the soil to be compacted.
- Feeding of the soil material from the surface.

The trials should demonstrate that the techniques and equipment are able to meet the acceptance criteria. Field work within soil treatment trials shall commence as follows:

- Locating of reference points and pre-treatment penetration tests.
- Determination of the position of the vibrocompaction points dependent on the relevant test grids.
- Carrying out the survey, and, pre-treatment geotechnical tests to determine the initial soil levels/properties.
- Execution of the vibrocompaction within the trials.
- Post treatment survey and quality control tests including penetration tests.
- Post treatment penetration tests shall be undertaken, preferably, at the centroid of a triangle grid and at the one third distance between two successive vibrocompaction points followed by an evaluation assessment.
- Digital and contour plans of soil subsidence shall be developed.

Vibro compaction / Surface Compaction Work

When the trial has demonstrated to the satisfaction that the selected techniques and methods are successful and meet the requirements, the ground improvement by vibrocompaction is started. The activities to be included are the following:

- Survey and pre-treatment geotechnical tests to determine the initial soil levels/properties.
- Post treatment quality control tests including penetration and plate load tests (PLT).
- The quality control for the vibrocompaction is mainly carried out by executing post penetration tests usually cone penetration tests (CPT).
- Cone penetration tests (CPT) are recommended to be taken at frequencies of 1000 m^2 of worked surface (unless otherwise provided within the specifications) comprising of a set of two tests at the centroid of a triangle grid and at the one third distance between two successive vibrocompaction points.
- Post treatment cone penetration tests (CPT) shall be undertaken within two weeks after execution of vibrocompaction work for comfortably allowing the dissipation of excess pore water pressure.

- Cone penetration tests (CPT) equipment is recommended to have a 20tn capacity, be self-anchoring, have a cone diameter of 45 mm, and a penetration velocity 2 cm/sec.
- Digital and contour plans of ground settlements/heaves should be developed.

Based on above mentioned testing and subsequent evaluation the necessity for either undertaking supplementary post treatment tests or additional/alternative treatment method(s) shall be decided.

The following testing should be undertaken for the superficial soils at specified lifts where the conventional rolling techniques are applied for determining the degree of compaction achieved:

- In situ density tests shall be carried out either on the final ground surface or at a determined depth (within a trench) for identifying the achieved compaction within respective soil horizons based on the lift heights placement.
- Identification of the optimum moisture content/maximum dry density relationship using a 4.5 kg hammer (Modified Proctor Test) shall be provided through laboratory tests. It is recommended that samples for such laboratory testing to be retrieved from specific locations where the in-situ density tests are carried out.
- Above-mentioned field/laboratory tests (within both vibrocompaction and surface compaction) shall be undertaken following the corresponding ASTM standards.

3. Vibro Compaction Case Study Project

The project consisted of the reclamation and compaction of an area approximately 480,000 m^2 for real estate and recreational purposes. The areas were reclaimed using dredged material and contained by revetments, breakwaters underwater rock bunds and groynes.

The zone was hydraulically filled with marine sand up to a level of 5.5 m above mean sea level. The thickness of the treatable fill material, was between 13 and 15 m. The upper 1.0 to 2.0 m consisted of a crust of dense, slightly silty, calcareous shelly sand with a CPT tip resistance "qc" value ranging from 5 to 10 MPa. This was followed by 12 to 13 m of loose, slightly silty calcareous sand with CPT tip resistance "qc" values ranging from 3.5 to 5 MPa with occasional minor dense layers in mid profile. The soil profile before the vibro compaction works is shown in **Figure 1**.

3.1. Developed Performance Lines

Normally, project specification on vibrocompaction projects are converted to a CPT performance line or an equivalent relative density. Numerous formulae exist defining the relationship between CPT tip resistance "qc" value and the relative density. In this project, the relative density was assessed by the methods described in [3] [4] and [5]. These methods are shown in **Table 2**.

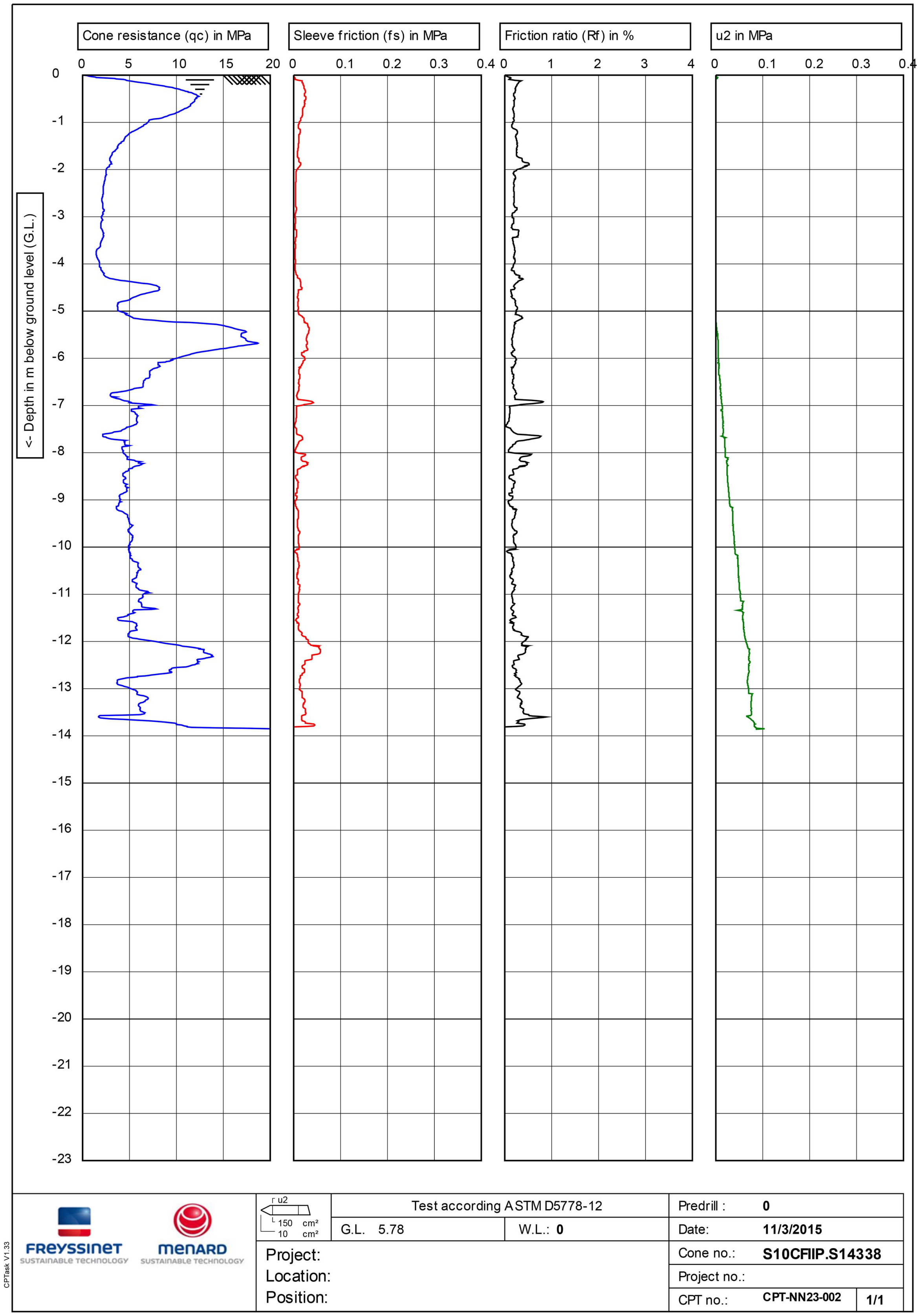


Figure 1. Soil Profile before vibro compaction work.

Table 2. Relationships between CPT Tip resistance and relative density.

Baldi et al. (1986) *modified by Lune* (2006)	$D_r = \frac{1}{C_2}\ln\left(\frac{q_c}{C_0\left(\sigma'_{vo}\right)^{C_1}}\right)$ $C_0 = 157$, $C_1 = 0.55$, $C_2 = 2.41$ (*applicable for Normally Consolidated soils*)
Jamiolkowski et al. (1985)	$D_r = -98 + \left(66 * \log_{10}\frac{q_c}{\left(\sigma'_{vo}\right)^{0.5}}\right)$
Kulhawy & Mayne (1990)	$D_r = 100\sqrt{\frac{1}{305OCR^{0.2}}\left(\frac{\left(q_t/\sigma_{atm}\right)}{\left(\sigma'_{vo}/\sigma_{atm}\right)^{0.5}}\right)}$ *where* $OCR = 1$ *for Normally Consolidated soils*

where: D_r = Relative Density; q_c = Cone Penetration Test Tip Resistance; σ'_{vo} = Effective Vertical Stress.

The final performance line was equal to an average relative density of 65% calculated using the average of the three relationships shown above ([3] [4] and [5]) with the addition of a Shell Correction Factor (SCF) equal to 1.3. The developed performance line showing both the minimum relative density (60%) and the average relative density (65%) is provided in **Figure 2**.

The soil tests indicated that the dredged material had a shell content of 80%, which warranted the use of a Shell Correction Factor. Initial calculation of SCF = 1.6 was determined using methodology described in [6]; however, a final SCF = 1.3 was used.

3.2. Trials Methodology

A trial area was carried out to determine the best compaction parameters (vibroflot grid spacing and holding times) associated with the equipment used on site. The trial was carried out utilizing a type V48 vibroprobe, which was operated in a tandem configuration. Details and specifications of a V48 Vibroprobe are provided in **Figure 3**.

Five different grid spacings were piloted in a triangular pattern with each grid having two different holding times per 1.0 m lifts (30 and 40 seconds). Details of the trial area parameters are shown in **Table 3**.

Two post compaction CPTs were carried out in each grid to determine the most efficient configuration to achieve project performance line. One test was carried out in the centroid location and one test in the one third location. Locations of the post compaction testing scheme are illustrated in **Figure 4**. The final approval as per project specifications was based on the average of both tests plotted against the project performance line.

Based on the results of the trial area, a grid of 3.8 m was used for the main vibrocompaction work, with 1.0 m grid typical for V48 vibroprobe and 40 second hold time.

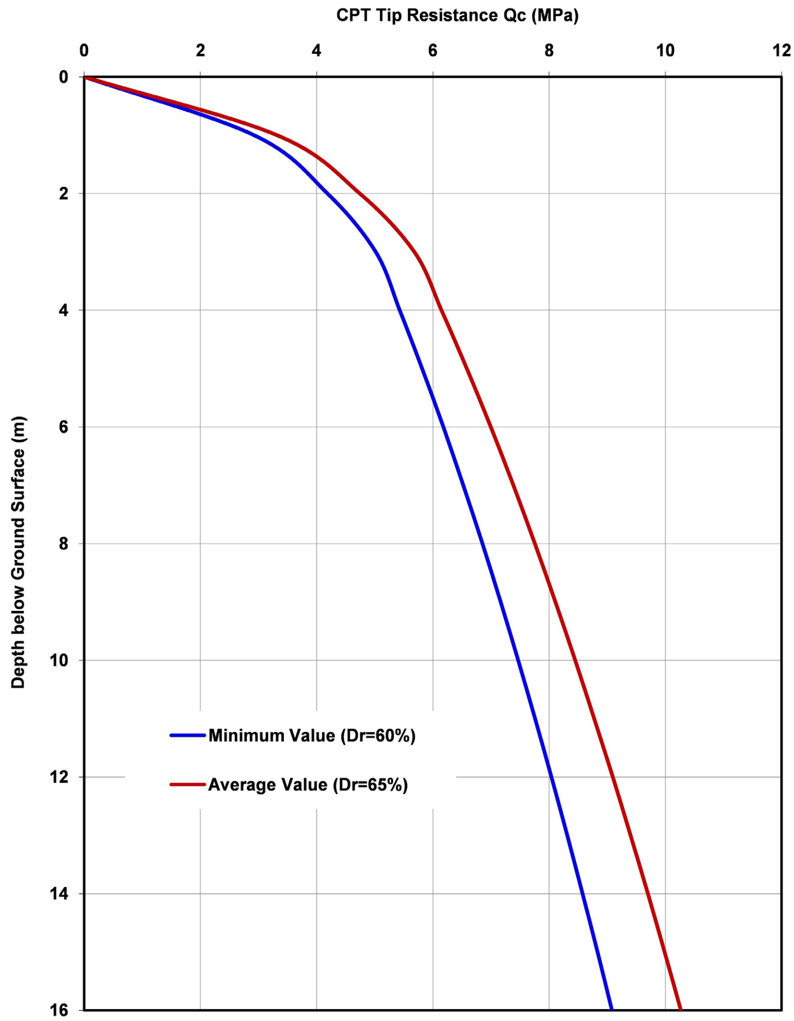
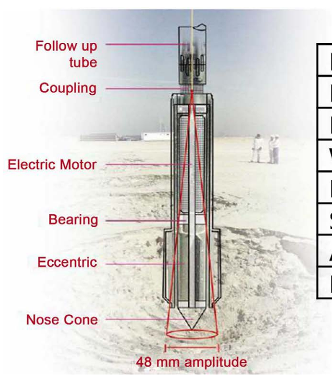


Figure 2. Performance line.



Machine name	V48
Length [m]	4.08
Diameter [mm]	378
Weight [kg]	2600
Motor [kW]	175
Speed [min-1]	1200-1500
Ampli. [mm]	26-48
Dyn. Force [kN]	230-470

Figure 3. Details and Specifications of a V48 Vibroprobe.

3.3. Vibro Compaction Main Works

The site was divided into boxes of 625 m^2 (25 m × 25 m), which made it easier to monitor progress on site and simplified the verification and handover process. A pre-compaction CPT was carried out in each box prior to commencement of the

Table 3. Details of the trial area parameters.

Compaction grid (m)	Area per compaction point (m^2)	Holding Time (s)
3.6	11.22	30 40
3.8	12.51	30 40
4.0	13.85	30 40
4.2	15.28	30 40
4.4	16.76	30 40

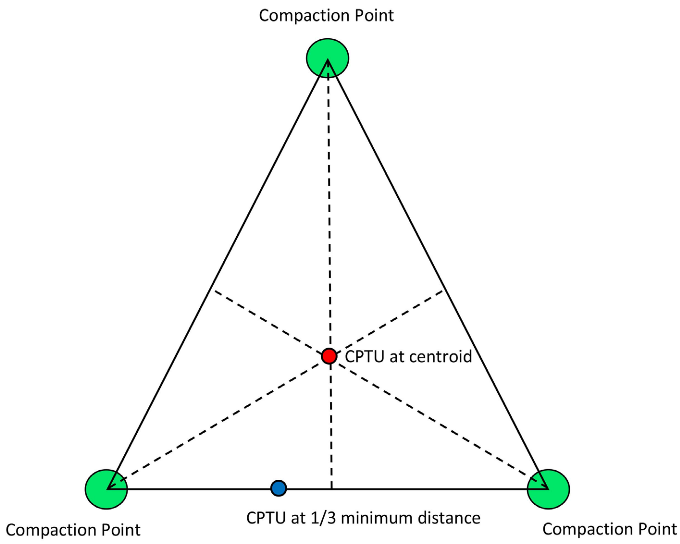


Figure 4. Location of post compaction testing.

compaction to verify that the soil was compactable and did not include any non-compactable material.

Main work progressed on site using the grid determined in the trial area utilizing a tandem configuration as shown in Figure 5. Following the compaction procedures, a method of verification described below was followed to verify that project specifications were achieved.

3.4. Verification of Acceptance Criteria

Compliance of the post tests with project requirements was done using a two-stage verification scheme. Stage 1 being the performance line and Stage 2 being detailed calculations. This method of verification is quickly becoming the standard in vibrocompaction jobs.

Figure 5. Tandem vibrocompaction configuration.

Stage 1—Quick Acceptance Criteria

The primary stage was comparing the Post CPT tests to the performance line (See **Figure 3**). This stage entailed the following criteria:

- All post-compaction CPTu tip resistances including a rolling average of 0.4 m are higher than the performance line associated with the minimum target relative density of 60%.
- Maximum 10% of the averaged post-construction CPTu tip resistance at each test location was allowed to be below the average target relative density of 65% below water table.
- No allowance of the averaged post-construction CPTu tip resistance at each test location was allowed to be below the average target relative density of 65% above water table.
- Soils with I_c greater than or equal to 2.05 were neglected in the assessment of the compaction in addition to 10 cm above and below that layer.

CPTs that met or exceeded the performance line and were in line with the mentioned criteria were deemed to have achieved the project specification. The CPTs that did not meet the performance line were evaluated using Stage 2 verification.

Stage 2—Detailed Calculations

CPTs that did not satisfy Stage 1 requirements were subjected to a longer verification process, which entailed carrying out detailed calculations that were based on the project requirements:

- A maximum total (static plus seismic) average settlement for isolated footings for 200 kPa for 2.5 m by 2.5 m footing at 1.0 m below the final grade level shall not exceed 25 mm.
- A maximum total (static plus seismic) average settlement for raft foundations

settlement: 100 kPa for a 15.0 m by 15.0 m footing at 1.0 m below the final grade level shall not exceed 50 mm.

- Liquefaction:
  - If factor of safety against liquefaction is greater than 1.25 for each individual test, ground is considered safe against liquefaction occurrence and no further calculation will be undertaken.
  - If factor of safety against liquefaction is equal or greater than 1.0 and less than 1.25 for any individual test, ground is considered to be marginally safe and further analysis required to quantify possible liquefaction-induced damage, e.g. ground settlement with the earthquake magnitude of 6.0 and peak ground acceleration at ground level of 0.21 g will be calculated.
  - If factor of safety against liquefaction is less than 1.0 for any individual test, ground is considered unsafe and liquefaction mitigation measures required, e.g. further densifications of the reclamation fill.

If the total maximum settlement of both static (isolated footings) and dynamic is less than 25 mm/static (raft) and dynamic is less than 50 mm as well as required bearing capacity is greater than specified and minimum factor of safety for each individual test is equal or greater than 1.0, then the ground improvement work is considered successful and CPT deemed achieving project specification.

4. Results and Discussion

Cone Penetration Tests

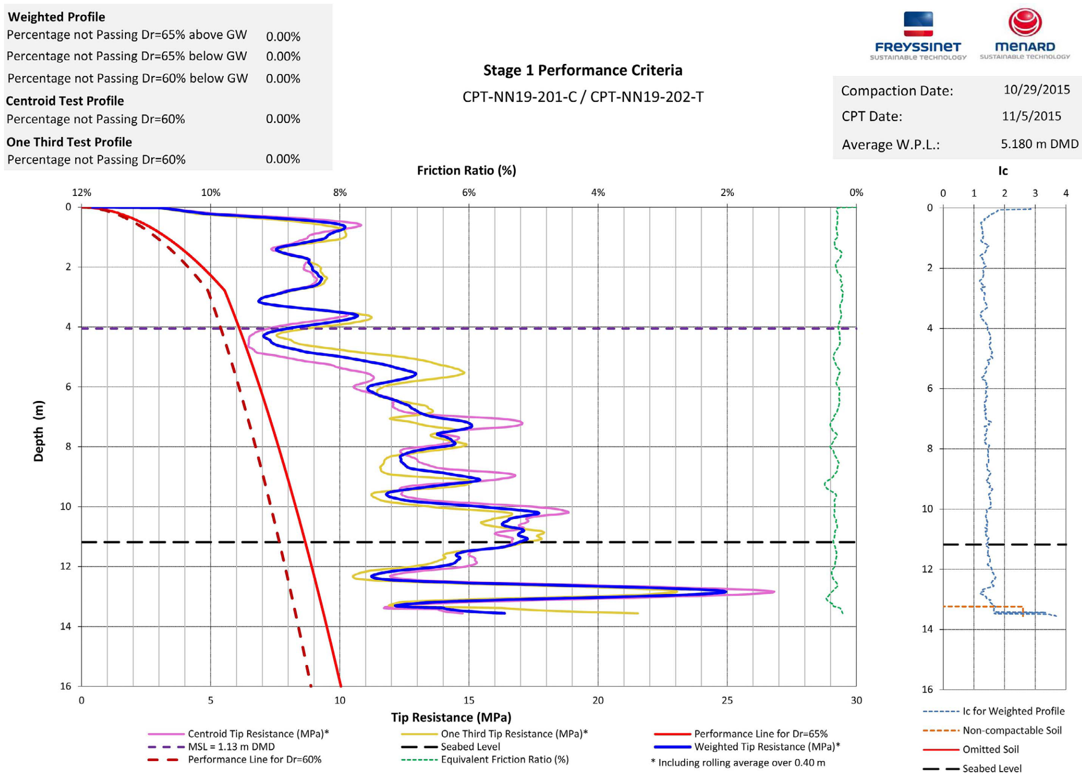
The post CPTs carried out after compaction clearly showed excellent improvement. As expected, the degree of improvement in the 1/3rd location was slightly higher than the centroid location (**Figure 6** and **Figure 7**) due to its proximity to the vibroflot location. Vibrocompaction work increased the CPT tip resistance by a factor of more than 2 (**Figure 9**).

The vibrocompaction effectively achieved a higher relative density than 65% with a grid area of 12.5 m^2, which was a larger increase than mentioned by [7] for the chosen grid. This is likely due to more powerful vibroflots that were used on the project and/or more energy (longer holding times) that were used during execution.

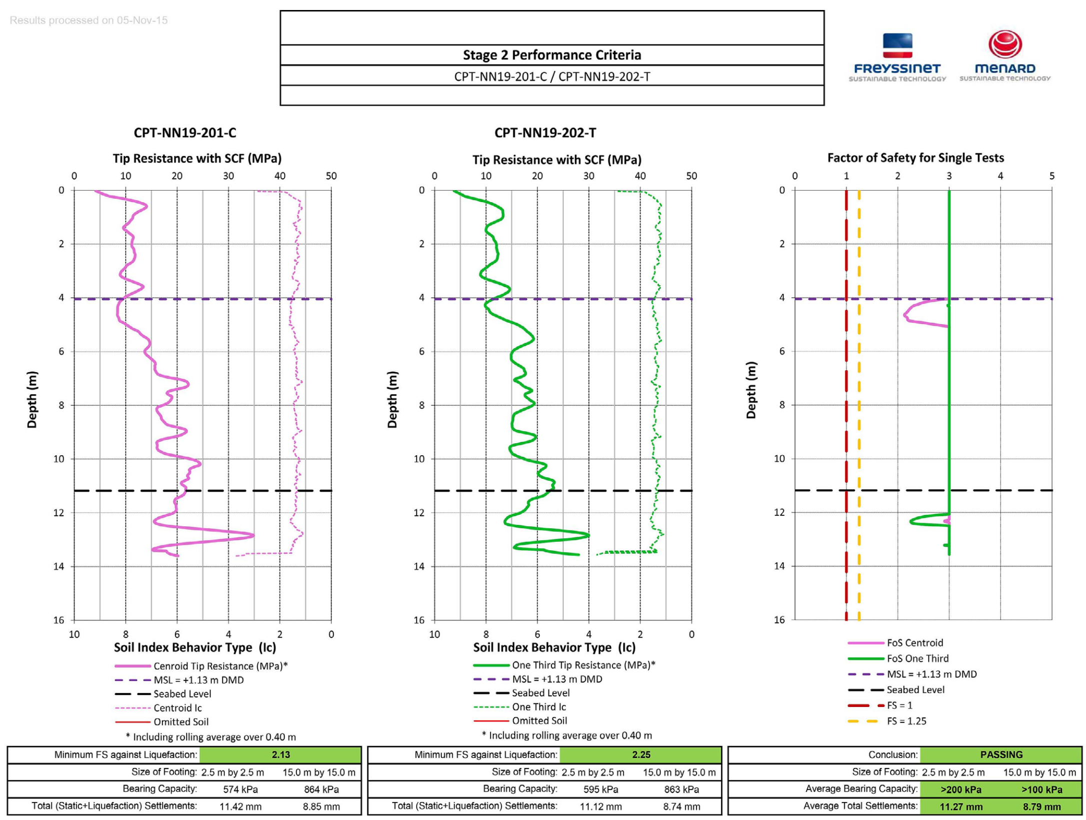
The difference between the Pre CPT and the average Post CPT having completed 14 days post-construction is shown in **Figure 8**.

Shell Correction Factor (SCF)

Cone Penetration tests carried out in carbonate shelly sand tend to exhibit lower tip resistance compared to the tests carried out in silica sands. This is due to the crushing effect of the cone tip penetrating the shells. As per [8], the ratio between the tip resistance in silica sand and in carbonate sand in medium dense material (50% - 70%) can be as high as 1.5 and closer to 2.0 in very dense material. The uncorrected post test results in carbonate sand also tend to remain in the region of 4 - 8 MPa ([9] [10]).



(a)



(b)

Figure 6. Post testing results passing the performance line and achieving project requirements.

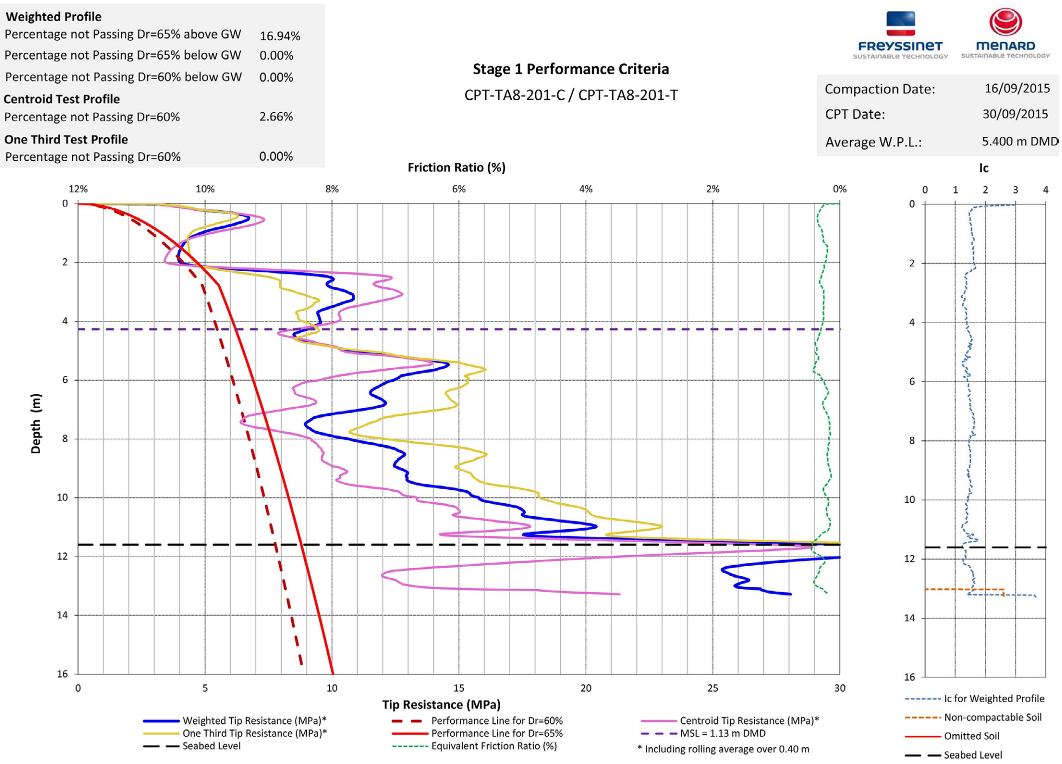


Figure 7. Results of Post testing indicated some tests did not meet Stage 1 requirements, which resulted in Stage 2 analysis.

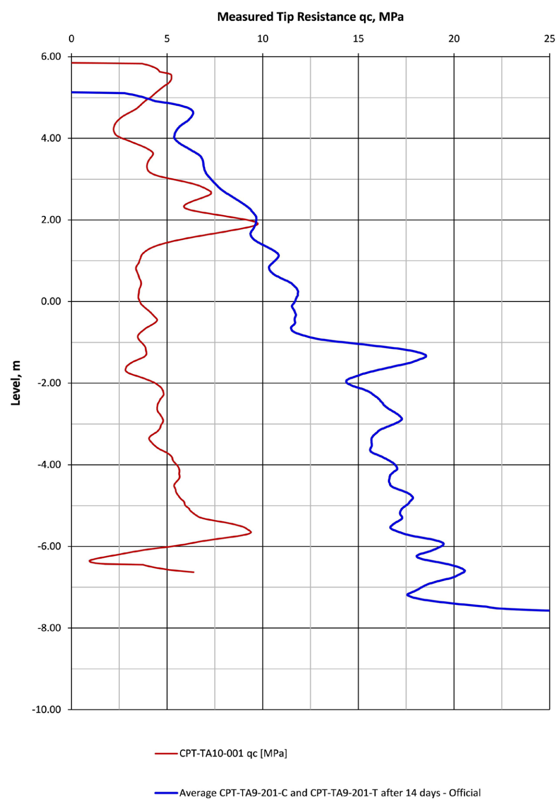


Figure 8. Difference between Pre CPT and Post CPT.

The cone penetration test from the project showed very low friction ratio (Rf% < 0.5%), which is consistent with carbonate shelly sands. Based on the post improvement results, the uncorrected CPT tip resistance was around 6 to 10 MPa, which is within the range from literature. The value of 1.3 was a conservative value to use but was also the norm considering no site-specific calibration chamber tests were carried out to determine the actual SCF value. A site specific SCF could have decreased the amount of compaction required in the project thereby reducing costs. Recently, the use of seismic CPTs have gained popularity as a cheap and quick method to determine a site specific SCF.

Ground Subsidence

The vibrocompaction induced ground subsidence generally ranges between 5 to 10%. This value is dependent on many factors, such as nature of the fill and when the fill was placed. The fresher the fill, the more subsidence is expected during ground improvement. The measured ground subsidence on site due to vibrocompaction was ranging between 3.5% to 4.5%, which was slightly lower than the average mostly because large portions of the fill were placed weeks in advance and had already settled under its own weight and some portions had stockpiles of material placed on top causing settlement to occur before vibrocompaction work commenced on site. It is important to have a good idea of what the ground subsidence will be during compaction, especially in relation to the project's final ground elevation to be able to better understand the amount and cost of material required to reach that level.

2 Step Verification

In the Gulf region, specifications for compaction jobs and specifically vibrocompaction jobs consist of target CPT performance lines, which equate to other requirements the owner/engineer requires. These types of project requirements are popular because they are very easy to verify by a direct comparison with the in-situ CPT test result. These can also be problematic.

During CPT testing, a rod is pushed at a constant rate and a continuous measurement is made of the resistance of the soil. This means that even the thinnest and smallest layers are picked up during the test. In some cases, after vibro compaction, some small thin layers might not meet the required performance line, but also do not have a significant effect on the performance of the soil mass. In cases like these, which are very common in fill compaction jobs, a two-stage verification method is crucial for the success of the project. This method helps in avoiding or reducing over-compaction, which causes delays in projects and increases costs.

In current project, the two-stage verification process was used extensively (an example is provided in **Figure 9**), which limited the amount of re-compaction carried out on site thus allowing the project to be handed over within contracted period. This method of compaction verification has become the standard in most ground compaction sites in the region.

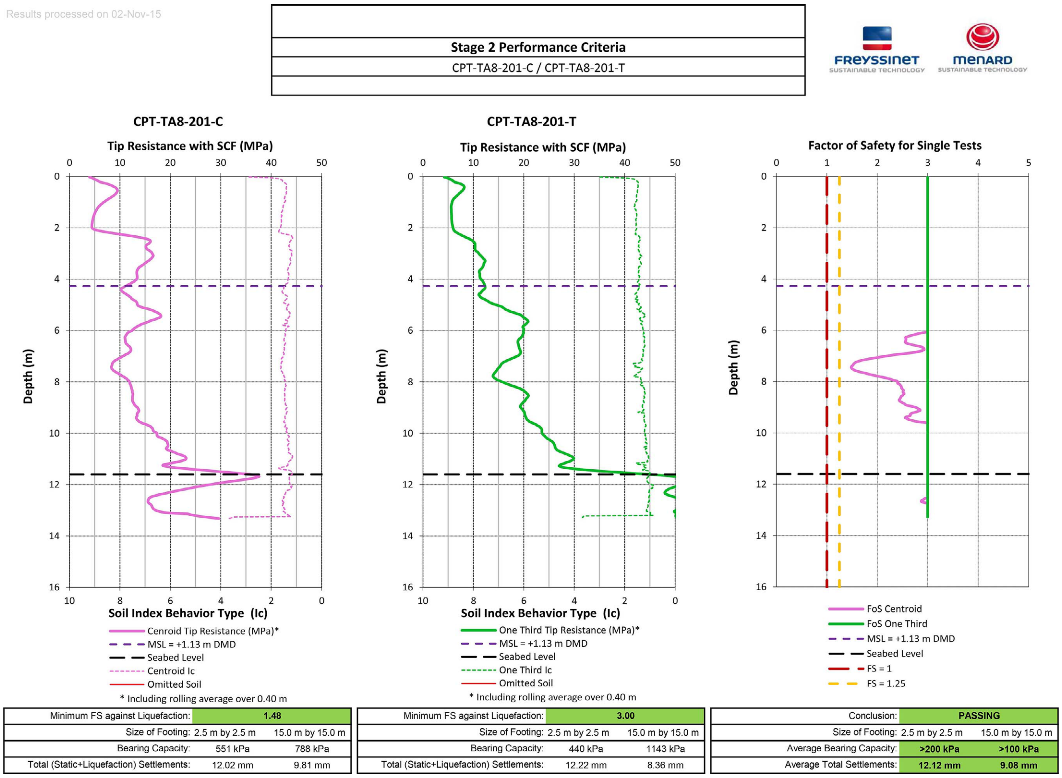


Figure 9. Results of Stage 2 analysis indicate that all CPT tests achieve project specifications.

5. Conclusions

Vibrocompaction is a very common ground improvement technique used in granular material with fines content not exceeding 15%. The boom in reclamation projects in the Middle East has also brought vibrocompaction to the forefront as the lead compaction method for such projects. The project described on this paper was completed successfully, and lessons learnt and procedures implemented during that project have become the industry norm.

- A robust and well-distributed pre-compaction testing campaign is crucial to assess the initial density of the in-situ material as well as to identify layers and pockets of soil with high fines/non-compactable soil. This will help in determining the amount of energy required to reach the target performance line and/or to plan for remedial action of the non-compactable soil.
- In calcareous shelly material, it is important to have a site-specific Shell Correction Factor (SCF). Traditionally this can be done by carrying out an expensive and time-consuming Calibration Chamber Test. Recently seismic CPTs (SCPTs) have proven to be a great tool in determining a site specific SCF.

Adoption of the two-stage verification methodology is crucial as it allows for quick verification using the performance line and a more robust check, when required, to verify the functional requirements (settlement, bearing capacity and liquefaction). Nowadays, this has become an almost ubiquitous clause in all vibrocompaction contracts.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Moseley, M.P. and Kirsch, K. (2004) Ground Improvement. 2nd Edition, Spon Press, New York. https://doi.org/10.1201/9780203489611

[2] Brown, R.E. (1977) Vibroflotation Compaction of Cohesionless Soils. *Journal of the Geotechnical Engineering Division*, **103**, 1437-1451. https://doi.org/10.1061/AJGEB6.0000538

[3] Lunne, T. (2006) Guidelines for Use and Interpretation of CPTU in Hydraulically Constructed Fills. NGI Report 20041367-3.

[4] Jamiolkowski, M., Ladd, C.e., Germaine, J.T. and Lance lotta, R. (1985) New Developments in Field and Laboratory Testing of Soils. State-of-the Art Report. *Proceedings of the* 11*th International Conference on Soil Mechanics and Foundation Engineering*, San Francisco, 1985, 57-153.

[5] Kulhawy, F.H. and Mayne, P.W. (1990) Estimating Soil Properties for Foundation Design. EPRI Report EL-6800, Electric Power Research Institute, Palo Alto: 306 p. https://www.epri.com/

[6] Al-Humoud, A.S. and Wehr, W. (2006) Experience of Vibrocompaction in Calcareous Sand of UAE. *Geotechnical and Geological Engineering*, **24**, 757-774. https://doi.org/10.1007/s10706-005-1707-8

[7] Barksdale, R.D. and Bachus, R.C. (1983) Design and Construction of Stone Columns Volume 1. Report No: FHWA/RD/-83/026. Federal Highway Administration, Office of Engineering and Highway Operations, Research and Development, Washington.

[8] Jamiolkowski, M. and Pasqualini, E. (1992) Compaction of Granular Soils: Remarks on Quality Control. *Grouting*, *Soil Improvement and Geosynthetics*, **2**, 902-914.

[9] Debats, J.M. and Sims, M. (1997) Vibroflotation in Reclamations in Hong Kong. *Proceedings of the Institution of Civil Engineers—Ground Improvement*, **1**, 127-145. https://doi.org/10.1680/gi.1997.010301

[10] Debats, J.M., Pardessus, N., Racinais, J. and Olgun, C. (2015) In-Situ Determination of the Shell Correction Factor in Carbonate Sands. *Proceedings of the* 6*th International Conference on Earthquake Geotechnical Engineering, Christchurch*, New Zealand, 2015, p. 9.