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Compaction Control of Offshore Land Reclamations by In Situ Tests

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ABSTRACT: When performing land reclamation works by dredging and hydraulic fill placement, the contractual requirements and environmental situation will dictate the need for Ground Improvement. Land reclamations works involve extensive filling works where large volumes of fill must be placed. With such Ground Improvement, the need for quality assessment/quality control (QA/QC) becomes obvious.
The paper discusses typical situations with land reclamation works where 'suitable' and 'unsuitable' materials are defined for the realization of land reclamations. Subsequently several requirements are given which lead to the need for monitoring and testing. Sometimes even very high numbers of tests and monitoring positions/types are required, leading to an intensive testing infrastructure to be set up, dedicated organization, testing database, leading to an important cost.
The availability of 'suitable' material and its mineralogy may lead to compromises between 'textbook' materials and economically available materials. In such cases, testing and demonstration of the 'functional' behavior becomes even more important.
Several approaches are possible and a reflection can be made whether – for the large volumes of material to be placed during land reclamation works – 'parameter testing' is the right way to go and whether the focus should not be on 'performance testing', allowing for some non-conformities in the stringent contractual specifications, but guaranteeing that the reclamation is fit for its functional or performance requirements.
In the present times where environmental aspects become increasingly important, more and more reclamations are performed with 'less suitable' or even 'unsuitable' materials, such as clay or silt material with low bearing capacity. After the installation of a sand cap and the necessary Ground Improvement, such reclamation is able to do the job it is designed for. Apart from different Ground Improvement techniques, also alternative testing and monitoring techniques may be required for such situations.

Keywords: land reclamation; ground improvement; in situ testing; CPT; performance behavior.

1. Introduction

When performing large offshore land reclamation works, this is commonly done by means of large dredging equipment. The fill material, which mainly will be granular fill, is dredged from an offshore borrow area and pumped into the reclamation area. Typical volumes of several million m³ to tens of million m³ up to 100 million m³ in exceptional cases are required for such projects. Finding a suitable bollow area with sufficient 'suitable' material is a first technical challenge for such projects.

The reclamation areas are coastal or marine areas where often the natural soil is of low quality (very soft to soft clay, silt, mud) with large compressibility. Sometimes the reclamation works are combined with dredging works at the same location (e.g. harbour developments, local removal of soft soil, presence of contaminated soils, …) and the dredged soils may be defined as 'unsuitable'. More and more such soils will have to be re-used in order to avoid offshore dumping, which is not environmentally friendly, and to limit the requirement of offshore mined granular soils, again because of environmental reasons. In some countries even no suitable soil can be found locally and also in such situations, the re-use of low quality soils may be required. In the case the local soils are contaminated, confined disposal/reclamation areas and adapted Ground Improvement techniques may be applicable.

Locally available 'less suitable' material may be used as well. Such materials may be granular material with a too large fines content or with a mineralogy that influences its behavior (e.g. carbonate sands, pumice sands, diatomaceous deposits). In such cases the local material may be used, but will require adapted testing procedures and/or corrections.

Dredging can be done hydraulically or mechanically. A description of execution methods is given in [1]. The mining of offshore granular material will mostly be done by means hydraulic dredging (by means of Trailing Suction Hopper Dredgers – TSHD) while the dredging of local soft soils preferably is done by means of mechanical dredging in order to avoid large volume change and process water loaded with fines, leading to turbidity issues. Hydraulic dredging of soft soil will lead to a mixture of the local soil with water which behaves as a slurry and needs (self-weight) consolidation before further capping is possible.

When fill material is placed hydraulically, 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 ([2]). 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.

As this paper is focussing on the use of in situ testing, the QA-part of QA/QC will not be discussed in detail. However, good execution statements and execution monitoring may be one of the solutions to limit extensive in situ testing.

Before the QC is discussed, more background will be given on the specific issues of dredging for land reclamation to fully understand the effects this can have on the result in the reclamation area. After this introduction, the quality control approach in the dredging world, considered 'best practice', is described. In practice, however, every project is different and the contract with its technical specifications as described by the employers engineer may be different; sometimes even incorrect or impossible to conform with.

2. Land Reclamations by hydraulic pumping of granular material

In the majority of the land reclamation works, the fill material will be granular material that needs to fulfil the contract requirements for 'suitable' material. When dredging is done with a TSHD, the filling of the hopper can be done with or without overflow of the process water. With overflow is much more economical, but/and leads to washing out of the fines (= particles < 63 micron) that get lost through the overflow. This causes some turbidity in the borrow area, but this effect is minimised with present dredging equipment and is commonly accepted unless specific local counter-indications occur (e.g. sensitive marine fauna and flora). In case the dredging is done nearby by means of a Cutter Suction Dredger (CSD), the material composition as it is in the borrow area will be pumped to the reclamation area.

The hydraulic filling of sand in a reclamation area can be done by means of several techniques as described in [1] and [2]. Deposition above water or below water makes an important difference. In both cases, the process water may cause segregation, leading again to washing out of the finer particles from the coarser material. This may lead to several effects: turbidty in the area where the process water is released and concentration of finer particles close to the outlet of the process water (the weir-boxes). When this last aspect occurs, the quality control will show concentrations of fines (lenses of silty/clayey material) in the reclamation and this needs to be taken into account. The segregation phenomenon is more severe when pumping above water, but, at the same time, when the reclamation is fully above water, this can be managed better as well. The process water with high fines content can be pumped to a siltation basin (when the necessary space is available) where the water is cleared for release to the environment.

When pumping fill material under water, the segregation effect is less severe, but cannot be managed. Sometimes a layer of silt material is found in front of the more sandy material installed. In such case the silt may get trapped under the sand or may be squeezed forward. In both cases, measures are to be taken. One of such measures, in case the situation is not acceptable and massive deposits of unsuitable material occur, is to provide a smaller dredger in the reclamation area (when the water depth is sufficient!) and dredge the fines in front of the sand deposit slope and pump them to a siltation basin.

Finally, depending whether the material is installed under water or above water, its density will be different. Above water the density typically will be around 65% relative density, while under water the density will be lower and rather around 40% relative density (Figure 1).

Placement Method	Relative density
Discharge under water (spraying)	20 - 40 %
Discharge under water (dumping)	30 – 50 %
Discharge under water (overflow)	20 – 40 %
Discharge under water (rainbowing)	40 – 60 %
Discharge above water (free flow through pipe)	60 - 70 %
Discharge above water (rainbowing)	60 – 80 %

Figure 1. Relative densities achieved with different installation techniques (after [2]).

3. Requirements

In most land reclamation works, the contractual 'Specification' will define which type of material can be used for the reclamation works, will define the density to be reached and will give requirements about the bearing capacity and allowable (differential) settlements. When the reclamation is in a seismic active area, the afore mentioned requirements may be related to the design earthquake as well (liquefaction requirement, stability of the slopes, post earthquake settlements).

A critical point are the applicability of the requirtements on the fill material alone, or on the full soil column of natural soil and fill. Certainly settlement requirements will be applicable for the full soil column, but in case of poor quality subsoil, this may require different ground improvement techniques for the fill and for the natural soil. As such, required depth of treatment should always we clearly described.

The in situ testing generally involves following parameter testing:

1. Fill material quality (by sampling with particle size distribution, plasticity tests and chemical tests: carbonates content, sulfate content);
2. Fill material shear strength (effective friction angle);
3. Fill material stiffness;
4. Fill material permeability;
5. Fill material density by in situ density tests in the top few meters (generally above the water table, but to be limited to 3m for practical reasons)
6. Fill material density test by CBR in the top layer
7. Fill material (and possible natural soil) relative density (pre-defined relative density or derived from a liquefaction assessment)
8. Fill material sampling and testing by borehole (BH) and SPT testing
9. Sometimes also other in situ tests may be required: PLT, DPT, DMT, PMT, CPTu-S

Typical testing frequencies are:

1. Fill material sampling on board of every hopper load and in the reclamation 1 per 5,000m³ à 10,000m³; testing for particle size distribution, and chemical tests;
2. In situ density: 1 per 2,000m² to 5,000m²;
3. Maximum Dry Density (MDD) testing (frequency not always clear);
4. CPT in a grid of 50m by 50m (sometimes 100mx100m, but as well 25mx25m); testing before (lower frequency) and after ground improvement;
5. BH's with SPT in a grid of 100mx100m.

The testing frequencies as mentioned above will lead to thousands of tests to be performed in a typical land reclamation project. In the situation of Ground Improvement, this will require CPT and BH testing before and after Ground Improvement works, leading to even more testing. Even more when QC of vibrocompaction works is done by 2 CPT's per test location (see further).

QC testing on land reclamation projects requires a site laboratory with staff and laborants, site people to collect the samples; drilling equipment, on site CPT testing equipment. All this monitored by a qualified geologist or geotechnical engineer and a QA/QC engineer.

The large number of tests have to be reported on a daily basis to clients' engineer and other parties involved; smooth reporting requires a well established data management and database that is agreed upon from the start of the project with all involved parties, laboratory, drilling company, CPT company need to report in agreed formats. Ideally, AGS format should be used for this by all parties involved.

4. Reclamation Material Quality

Granular material that can be found locally is characterised by its particle size distribution (PSD), fines content (< 63 micron); average particle diameter d_{50} and Dmf (is a calculated average that is needed to calculate dredging productions). A typical requiremment is a fines content of maximum 10% (sometimes 15%), mainly because of vibro-compaction requirements (see Figure 2).

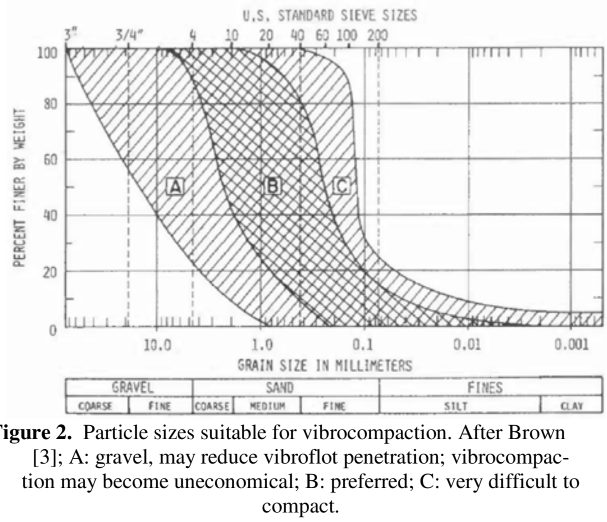


Figure 2. Particle sizes suitable for vibrocompaction. After Brown [3]; A: gravel, may reduce vibroflot penetration; vibrocompaction may become uneconomical; B: preferred; C: very difficult to compact.

When the fines content criterion is not met, this does not necessarilly lead to an unacceptable situation. Other compaction techniques (e.g. Dynamic Compaction) or above water compaction, layer by layer with rollers may still reach acceptable compaction results.

Locally available sand often will have more than 10% fines and when the dredging is done without overflow with a TSHD or with a CSD (Cutter Suction Dredger), these fines will be pumped to the reclamation area where segregation cannot be avoided and a limited layer of fines is found back at the bottom of the sand fill. Whether this is a problem depends on the natural subsoil (does this contain compressible material?) and the project settlement requirements.

In many regions, the offshore sand has high carbonates content (sometimes even 90-100%). Such sands are 'crushable' and may generate fines during dredging, pumping and hydraulic transport. Even more, during standard testing the crushing behavior will influence the test results that need to be corrected. This will be discussed in a separate section in this paper.

Other examples of 'difficult' granular materials are pumice sands (contains porous crushable particles from volcanic origin) and diatomaceous deposits (silica skeletons of organisms which are very porous and crushable, leading to very low material densities).

When reclamations have to be realized with 'unsuitable materials', the behavior of the dredged material in the reclamation area is the main problem. Large volume changes may occur due to (self weight) consolidation and loading. The installation of a sand cap with a minimal thickness becomes a challenge. The bearing capacity of the consolidating slurry is low, so the installation of the sand cap may become problematic. Furthermore, after full consolidation, the height of the top of the sandcap needs to be at the pre-defined final reclamation level.

5. Quality Control of granular fill

With the large volumes to be applied and due to the variable nature of soil and the installation methods used, variations are to be expected, even after treatment, and this should be taken into consideration in every testing scheme. Some level of 'non-conformity' should be acceptable.

The primary purpose of testing is to assess the *performance* of the treatment. The choice of test method should be influenced by the objective of ground treatment. Too often contractual specifications, even with EPC-contracts, focus on fill material properties, or 'parameter testing' while the overall behavior is the real final goal. Performance testing should become more common in large land reclamation works.

In the next sub-sections, some typical techniques used in present-day practice are described, both for the 'parameter testing' as for 'performance testing'. However, many techniques exist, but some are less used or less accepted by employers consultants. Some of these techniques will be summed up and shortly commented as well. In the following paragraphs the basic laboratory testing for particle size distribution, chemical tests, plasticity limits and other lab tests will not be discussed.

5.1. QC by parameter testing

5.1.1. CPT or CPTu

This test is most used in present practice and the existing literature correlations with CPT allow to define many parameters for granular soils:

1. Soil type; possible with the help of the SBT-index I_c (SBT = Soil Behavior Type);
2. Fines content, indirectly via I_c;
3. Suitability of the material for compaction (Figure 3)
4. Relative density via literature correlations;
5. Effective friction angle;
6. Settlement calculation;
7. Soil drainage characteristics;
8. Liquefaction assessment;
9. Post-EQ deformations.

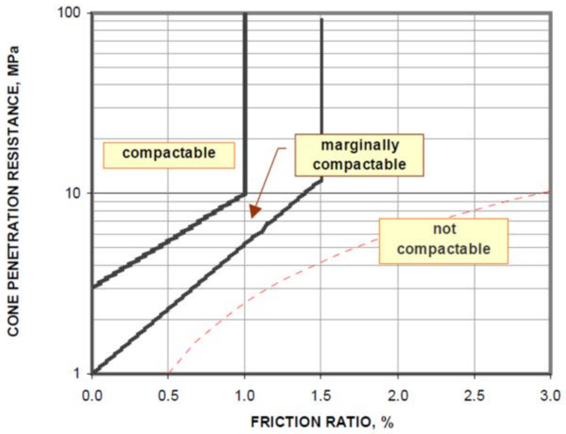


Figure 3. Suitability of material for compaction (after Massarsch [4]).

This very wide range of possibilities and the fact that the test is quasi continuous over the full height (measurements typically every 2cm) and can be executed very efficiently and operator-independent, makes the CPT the most used instrument.

The use of CPTu is often required, but as the reclamation is generally realised with sand and partly above the water table, the porewater pressure measurement may become problematic: time loss for qualitative execution with full saturation of the cone for every individual test and loss of saturation in the top well compacted granular layers leading to negative porewater pressures. For this reason, often the measurement of the porewater pressure for reclamation QC is omitted and limited to a specific CPT's also focusing on natural subsoil for example.

Primarily, CPT is used to verify the fill material layering and its relative density. The presence of more silty layers or lenses of silt/clay can clearly be detected.

Relative density may be a requirement as such, or may be a result of the assessment of shear strength, which is related to relative density and stress level, or of the liquefaction assessment. Defining relative density from CPT is normally done by means of the Baldi equations [4] or the Jamiolkowski equation [10], which were derived from calibration chamber tests on silica sands. Apart from these, several other correlations exist in literature, which may lead to discussion on the one to be used. Ideally this is fixed in the Specification.

Shear strength may be derived from CPT as well, allowing to verify whether the required minimum effective friction angle is reached. The existing correlations for silica sands typically give rather high values and this often leads to discussions with the employers engineer on reliability, representativity or even, in the framework of Eurocodes, the fact whether the obtained value is a representative value, a mean value or something else. The only solution to this discussion, however, is to perform triaxial testing in the laboratory, but with the practical limit that no undisturbed samples can be taken and thus testing needs to be done on reconstituted samples with all related discussions on representative sampling from the large fill sand volume and sample preparation technique as a consequence.

When a Ground Improvement technique is used such as vibrocompaction, which is performed in a triangular grid, the question arises where the test should be done. In Figure 4, two possible locations are given: the centroid point of the compaction points or the 1/3-position on the line between two compaction points. The first point is considered to give the worst result, while the second is considered to give the best result. A conservative approach would be to only test the centroid, but this may be overconservative and not economical as it does not represent the overall behavior of the fill.

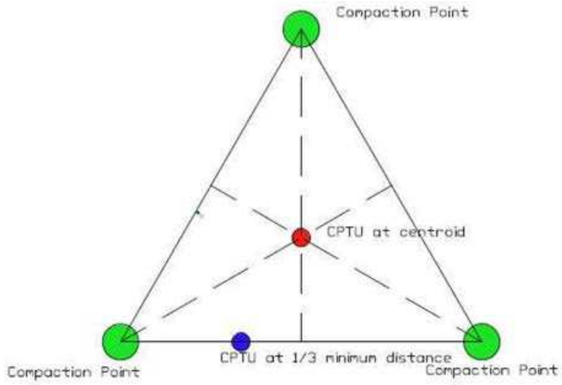


Figure 4. QC by means of CPT – testing locations.

The approach followed in several projects where the Specification did not define the point to be taken, was to perform two tests in the two described points and calculate the arithmetic average between the two (in horizontal direction).

As a CPT (and certainly an average curve as described above) in dense sands often shows large scatter with high and low values, the further analysis is commonly performed on a 'smoothed curve' defined by calculating a running average (in vertical direction) over 0.5m to 1.0m as agreed with the employers engineer. Such analysis will prevent too many discussions on small layers (CPT values are measured every 2cm) which would fail the preset criterion.

As explained before, some level of non-conformity still should remain acceptable. Locally higher fines contents may occur, or even silt/clay lenses may get burried in the sand. In such situation 'engineering review' should be possible in order to allow limited inclusions. Typically 10% of the fill height is allowed to 'fail' the criterion. Sometimes different values are used above and below the water table as the effect on settlements may be larger and more realistic measures can be taken above the water table. The above principle is only acceptable when at the same time it can be demonstrated that the settlement and bearing capacity requirements will be met.

Settlements can be calculated from the CPT where the compression constant or compression ratio is linked to the cone resistance ratio with the effective stress. A simple Terzaghi calculation allows to predict the settlements. In some projects, settlement calculation from CPT has to be performed according to the Schmertman method.

Bearing capacity is calculated based on the soil layering as derived from the CPT (stratigraphy and soil types when applicable) and the shear strength values. When performing Ground Improvement, very often the compaction result over large heights of the fill is even better than required. This positive aspect also will be taken into account in such an analysis.

An important assessment to be made is the liquefaction. 'Simplified' methods have been published in literature describing several methods starting from the CPT. Most commonly used is the NCEER method [7] and Boulanger and Idriss method [10]. Apart from several parameters and coefficients to be defined as described in these methods, the most important aspect is the correction for fines content. In the NCEER method this commonly is done based on the publication of Robertson and Wride [9], using the SBT I_c. Alternatively, a fines content can be found from laboratory testing and a correction factor can be calculated based on this value. This, however, does not give a continous adaptable approach to go with the CPT and is rather applicable when performing a liquefaction assessment based on the SPT. Another alternative is to calculate the fines content based on correlations with the I_c. Such correlations have been proven to show large scatter (see Figure 5, [10]) and thus may not be fully correct as well. As none of these methods is fully correct, in practice, one has to select a method (preferably defined in the Specification) and stick to it throughout the project. 'Shopping' for the most conservative approach too often disturbes the competition and leads to technical discussions with little theoretical ground.

It has been demonstrated in literature that Ic, when calculated from a pre-compaction CPT changes versus the calculation based on a post-compaction CPT. Main reason for this is the sensitivity of the CPT for horizontal stresses which will have increased due to compaction efforts. Theoretically, the pre-compaction Ic-value should be used, however this is difficult to link with the post-compaction CPT's when not performed at exactly the same location. This may be another source of error.

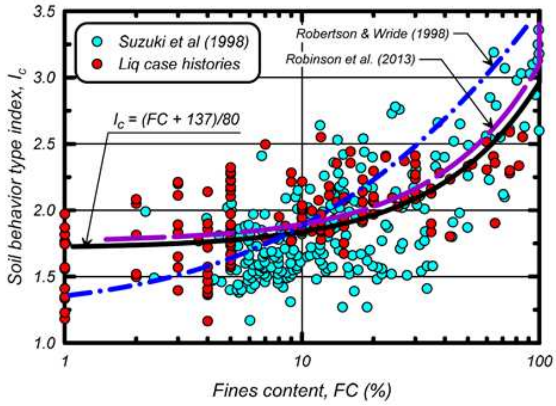


Figure 5. Correlations between fines content and IC ([10]).

A final remark to the use of CPT's after Ground Improvement is the aging effect. Ideally, CPT's should only be performed after all excess porewater pressures have disappeared and some aging of the soil skeleton structure has occurred. Typical waiting times in projects are limited to a few days or 1 week. Ideally, waiting times should be 2 weeks or even 1 month.

5.1.2. Other in situ testing techniques used

As CPT often gives unreliable results in the top m and because often higher requirements are applicable in this zone because of the pavement foundation layer, typically in situ density tests are to be performed in order to compare to the MDD (Maximum Dry Density). The MDD-value typically is defined by means of the Modified Proctor test.

The percentage of the MDD achieved in the field is designated as the relative compaction. Sometimes erroneous definitions of required compaction are given by mixing up relative density and relative compaction. This should be avoided as the difference can be large, depending on material type and required compaction level.

Figure 6. Execution of a sand replacement test.

In situ density is measured by means of the core sampler or sand replacement test (when larger particles occur). Such test, certainly when it has to be performed in a trial pit at a certain depth, may become quite operator-sensitive (Figure 6). More and more nuclear testing is being used, allowing to perform a very large number of tests. Local rules related to the management of such apparatus may still be a limiting factor, however in the countries where such apparatus are available already, cooperation with a local company mostly solves the permitting issues.When the MDD-value of the fill material needs to be defined, it often remains unclear in the Specification how many of such tests have to be performed. Typically, one MDD test is done per 10 in situ density tests and as long as the material source was similar (although with dredging operations this may be a relative concept). Studying the variation in MDD based on the tests may learn as well whether more or less frequent testing is required.

In some projects, a requirement for the 'air voids' is given. This concept is understood to be important for collapsible soils, however with the material used for reclamation works and the compaction level being shown by means of the relative density or relative compaction, this requirement is thought to be meaningless.

Testing of the top layer by means of the in situ CBR test is also common and a requirement related to pavement design. A typical required value is CBR > 15%.

An alternative for the CPT is a BH with SPT. Apart from the fact that this approach gives a fill material sample, there is no advantage whatsoever to perform SPT tests. Far too often, local drilling machines with SPT equipment are not calibrated and calculating the several correction factors to find N_{60} is the first problem to overcome. Furthermore, the result obtained is maximally 1 blow count per 50cm (more often the standard distance of one blow count per 1.5m). Further, the literature correlations with other soil parameters (relative density, friction angle) are less numerous and less documented. With regards to the liquefaction assessment, this remark may not apply as the simplified methods such as the NCEER originally have been based on SPT results. In general practice of land reclamation QC, SPT is mainly used for sampling, but no other derivations are made based on the blow count when CPT is available. The fact that samples are available at different depths where also CPT is performed may help in the discussion of the fines content. This is useful for the liquefaction analysis and as a contractual check of the fines content. A contractual check of the fines content based on a calculated value via I_c and an existing correlation should never be accepted because of the large scatter; unless a site specific correlation is made.

The PLT is absolutely worth to be mentioned here, although this instrument could be seen as a performance testing equipment. Typical PLT's have limited dimensions with 60cm as an upper limit. This makes the zone of influence about 90cm to 120cm (1.5 to 2 times the diameter), which still is limited. Typical result is the stiffness derived in a specific testing stress range. In some countries, the virgin loading stiffness is considered, while in other countries the reloading stiffness is considered, including the ratio of the reloading stiffness to virgin loading stiffness which has to be smaller than 2, thus indicating the extent of preloading that was created by the Ground Improvement works. In fact, in those countries where this test is used, this test replaces the in situ density test and should achieve more recognition as a superior alternative. Typical discussion point when this test is suggested as alternative is the relationship between relative density or relative compaction and the stiffness modulus derived from the PLT. While this is merely an issue of experience with the PLT, a correlation can easily be made on the large land reclamation works for further general use. One of the additional advantages over in situ density tests is the fact that larger particles will have less influence on the result, while the core sampler or the sand replacement test may be influenced depending on the presence of stones in the sample or not. An example of a PLT is shown in Figure 7, where a PLT is performed on a gravebed in order to test the stiffness of freshly installed gravel.

Figure 7. 600mm PLT test on a gravel bed.

The light versions of DPT is a test commonly known for compaction control in road construction. However, in large land reclamation projects, this test is less common. There does not seem to be real reasons for this, apart from the fact that it is a rough dynamic test that is more difficult to link to different soil parameters.

In the framework of liquefaction assessment, testing for the shear wave velocity V_s may be useful. CPTu-S testing or MASW testing has been performed, but in none of these projects this was a contractual requirement. However, one could raise the question whether such larger volume testing would not be more appropriate and fit in the plea for performance testing.

Some Ground Improvement contractors promote the use of the PMT. The change in ratios of the $E_{m,after}/E_{m,before}$ or $p_{L,after}/p_{L,before}$ is an indication of the compaction achieved, not necessarily the absolute value of these parameters. The disadvantage of this test is that only a limited people really have experience and knowledge of all the test details and the interpretation.

Furthermore, it is not a continuous test, the PMT is performed at depth intervals of minimally 1m. As a final disadvantage, the test is executed much slower than the CPT.

The PMT measures a larger soil volume and does not give the level of detail as a CPT; this can be considered as an advantage as well. However, with the necessary engineering review as discussed before, such 'average' result can be obtained with the CPT as well. On the other hand, the stiffness testing is a step in the direction of performance testing.

Finally DMT may be the test which should get more attention, but seems to remain stuck in research and exceptional applications. Ground Improvement by vibrocompaction causes some degree of overconsolidation and this can be better captured by the DMT. As such, the derived soil type and parameters may be more correct. Also in crushable soils, this test is reported to give better results and is less influenced by the crushability of the soil particles.

Unfortunately, this test is slower than CPT testing and is less commonly used in the world of daily geotechnical applications. Therefore no employers engineer puts this test in the Specification.

5.2. QC by performance testing

In the preceeding sections, several references have been made to performance testing. In general this means that one has to test the bearing capacity and the deformation behavior of the fill material. And this by means of testing a large soil volume without looking into the soil parameters at small scale, but just testing the overall behavior.

The most common way of testing large soil volumes is by making a trial embankment. Typical dimensions are 30m by 30m and 3m high. Thus realizing a vertical stress increase of about 50kPa while having a zone of influence of 45m to 60m, which normally is the representative depth over which settlements will occur.

Monitoring of the soil behavior can be done with settlement beacons, extensometers and inclinometers. In case there are fine grained layers exhibiting consolidation behavior, also porewater pressure transducers can be installed to study the time-settlement-consolidation behavior in the framework of Ground Improvement techniques such as surcharge with PVD's.

The ZLT (Zone Load Test) is in fact a large PLT. The plate has the dimensions of a footing and the basic idea behind the test is a real dimension bearing capacity test. A description of the ZLT is given in [11]. Typical dimensions within the land reclamation works are a plate of 3m by 3m and a loading of 150kPa, to be reached in minimum 5 steps; allowable long term deformation is 25mm.

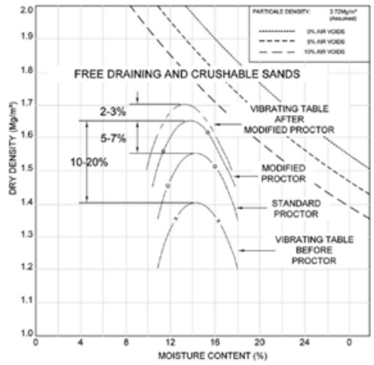
This test setup requires a reaction frame anchored in the ground or a kentledge system as used in pile load tests (Figure 8). In order to allow extrapolation to long term loading, the last loading step needs to be kept constant for a period of 48h. In the Middle East with large temperature variations, special attention has to be paid to shading off the setup and numerically filter out temperature effects. Extrapolation of the results typically is done based on the method explained in [12].

Figure 8. ZLT setup.

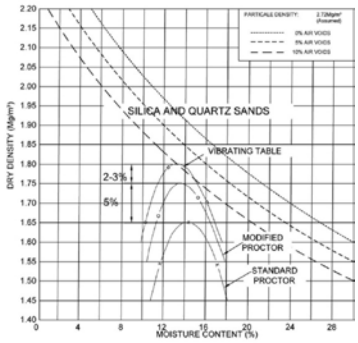
6. Calcareous sand

In this paper, specific attention is paid to calcareous sand reclamations because such projects come along regularly and, each time again, lead to discussions with employers engineer or are treated over-conservatively.

As mentioned before, the presence of an important carbonates content leads to a different behavior of the material due to crushing. At present, the value of $CaCO_3$ from which the influence becomes important is thought to be about 40% (based on field experience and Mayne [13]). In the Proctor test more fines are produced, leading to a higher density, not reachable in the field. In the CPT tests, crushing occurs due to the high stresses around the cone and the cone does not 'feel' the right in situ cone resistance or relative density as was the case in the calibration chamber tests on silica sands.



(a)



(b)

Figure 9. Differences in achievable MDD-values depending on the testing method for free draining and crushable sands (a) and for silica and quartz sands (b) (from [14]).

The problem with the proctor test is solved by doing an alternative compaction test: the vibratory table test (according to the ASTM D4253). In [14] the results of several tests on a crushable material are shown.

The problem with the influence on the CPT-value is mostly solved by the introduction of a Shell Correction Factor (SCF), which is the ratio of the cone resistance measured in a silica sand at a certain relative density and stress state to the cone resistance measured in a crushable sand under the same relative density and stress state:

$$SCF = \frac{q_{c,silica}}{q_{c,carb}} \tag{1}$$

In literature this phenomenon has been described by several authors, already for decades. A SCF has first been proposed by Wehr [15] based on tests for the Palm Islands. For a relative density of 60%, the SCF is 1.64 and even becomes larger as the relative density increases. However, in seveal projects in the Middle East, when this phenomenon is recognised in the Specification, more and more the SCF is limited to a unique value of 1.3. This approach is conservative and uneconomical, leading to a need for much more compaction effort than really required.

Author was involved in a project in Abo Dhabi where a similar discussion was held and it was decided to perform calibration chamber (CC) tests on the material used for the project. Calibration chamber tests were performed at ISMGEO in Italy in the centrifuge, allowing to cover a whole stress range in one flight. These tests have been reported on several occasions ([16][17]). The results of the CC tests are shown in Figure 10. A similar equation as used by Baldi and Jamiolkowski has been fitted to these results (see Figure 10 and Figure 11). Sand from two different borrow areas has been used, with clearly different visual shell presence (both with a carbonates content of almost 100%). The results for the SCF found for a vertical stress of 100kPa are almost identical to the factor published by Wehr (Figure 12). Based on the tests, it was also possible to derive a formula for the SCF as shown in Figure 13, where also dependency of the vertical effective stress has been taken into account.

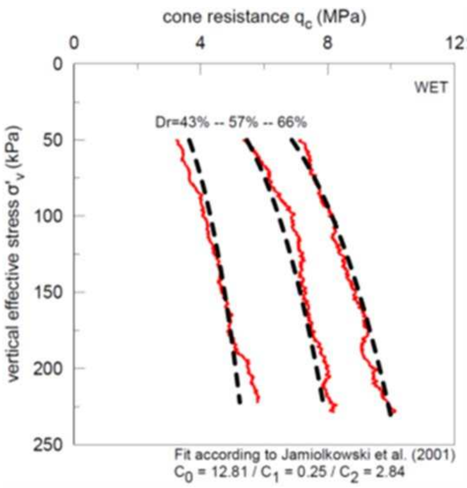


Figure 10. Results of the CC tests and fitting.

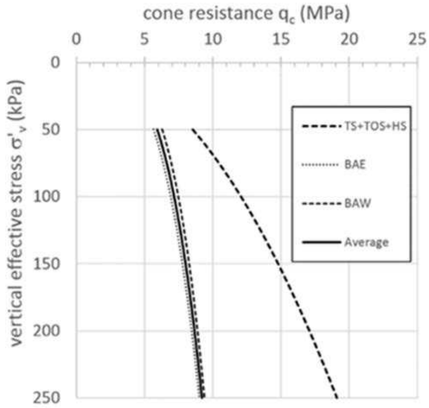


Figure 11. Comparison of the expected cone resitance at 60% relative density based on Jamiolkowski (2001) and the correlation found from the CC tests; The ratio is the SCF.

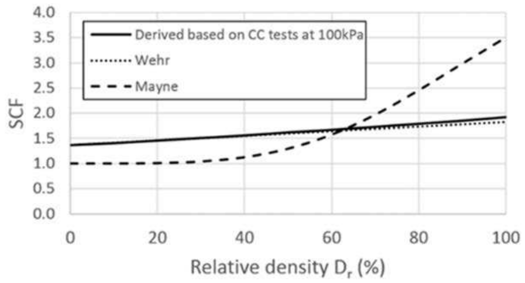


Figure 12. SCF by Wehr [15], Mayne [13] and as derived here.

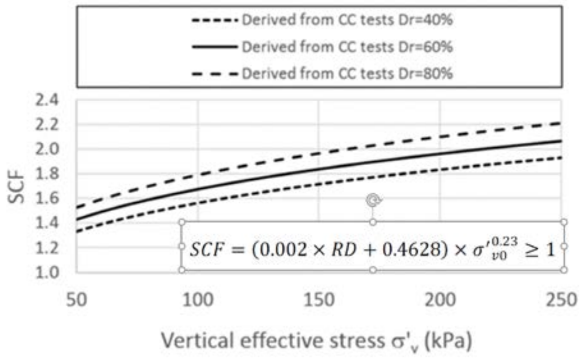


Figure 13. SCF in function of relative density and effective stress.

These tests have allowed to apply a correct correlation between CPT and relative density on the concerned project. For this check, no SCF was needed. However, a SCF still was derived as the ratio of the q_c-value from the Jamiolkowski formula and the (average) result found here. This SCF was used for the liquefaction assessment, based on the afore mentioned simplified methods.

One could question whether the use of the simplified liquefaction assessment approach is still valid based on a CPT which is corrected for compressibility. The shear strength of the calcareous sands is much higher than silica sand, due to its angularity. At the same time the permeability will be higher because of the larger porosity. As such, it is to be expected that the liquefaction resistance of the calcareous sand is larger than the for silica sands at the same relative density and stress conditions. Literature is not fully clear on that assumption and several papers can be found going in both directions, depending on the type of calcareous sand used in the research. The only correct approach would be to perform cyclic triaxial tests and cyclic simple shear tests. This was tried at a similar project in the Middle East, however discussion on representative sampling for the laboratory testing and sample preparation techniques even could not get solved with employers engineer; which led to cancelling of the testing. However, there is still a large saving potential in performing such tests by employer in pre-tender phase or commonly employer-contractor early in the project phase, based on shared opportunity-risk.

7. Land reclamations by means of the use of unsuitable material

Because of environmental reasons, or because of the limited availability of suitable material, more and more reclamations are made with clay, silt or silty sand found locally. In such cases, hydraulic dredging may not be the best approach from a material behavior point of view, although hydraulic dredging and pumping is generally the most simple approach to get the material where it is required in land reclamation works.

After hydraulic dredging of a clay material, it becomes a slurry that needs to settle and consolidate under its own weight before sufficient strength is reached in order to allow the installation of a granular capping layer that will allow access to the land and the application of Ground Improvement, monitoring and testing. Typically surcharge with the use of Prefabricated Vertical Drains (PVD's) will be used. In such situation one should also take into account the large volume changes that will occur: from in situ density to a slurry, a volume change factor (or bulking factor) of 2 to 3 applies (temporary). After capping and consolidation with surcharge, the original volume may be achieved again or even a lower volume may be reached. However all this requires a temporary storage volume and material behavior that needs to be predicted well.

In such cases preliminary testing of the material, including large columns tests and shear strength tests in function of the slurry density/water content is required. The definition of the constitutive relationships between void ratio and effective stress and void ratio and permeability are indispensable in order to allow for a large strain model to be set up to predict time related deformations. Monitoring mainly will focus on settlements (when not accessible, by survey drones for overall settlements, lateron by settlement beacons and extensometers) and porewater pressure transducers.

Final testing by means of CPTu allows for settlement calculation taking into account the effective layering of soft soils and the effect of overconsolidation that may be reached by means of the temporary surcharge.

In order to study the stability of capping works and further loading, in situ vane tests will be performed in the various steps of the consolidation.

8. Monitoring

Monitoring is an important part in QC in large projects. Typically monitoring focusses on the settlement behavior by means of settlement beacons which are installed as soon as the reclamation is above water. These instruments typically are installed in a grid of 100m x 100m, but sometimes also in a closer grid. Modern techniques with drone surveys and numerical comparison of subsequent surveys of untouched land also allows to define settlement charts. However, this technique is mainly used in areas which are not safely accessible.

In case no reliable local survey reference is available, one or two deep datums may be installed.

Settlement monitoring of a bund, trial embankment or stockpile may also be performed by means of settlement tubes. The vertical position of such tubes is measured at discrete time intervals by means of the hydrostatic water pressure measuring device.

Prediction of final settlements of consolidating soil often is done by means of the Asaoka method, by the hyperbolic method or by numerical fitting in which, via in house developped software, automatically multiple parameters can be varied in order to find the most probable solution.

Other monitoring techniques are extensometers; mostly magnetic ring extensometers are used in land reclamation works where important deformations are to be expected.

When consolidation of the subsoil comes into the picture, piezometers will be installed, however, when PVD's are used, the results may be influenced by the presence of the PVD's of which the position at depth is not always perfectly known.

In order to monitor the stability of the side slopes, bunds and/or revetment structures of a reclamation, inclinometers are used.

More and more the readings of such monitoring equipment is automized with solar powered dataloggers and can be read by means of a phone connection from whereever in the world.

9. Conclusion

In this paper the Quality Control of land reclamation works is discussed. In order to fully understand the problem some more general information is given on the dredging and borrow areas where the fill material needs to be sourced.

The used in situ testing techniques are discussed and – for most of them – briefly commented. The most commonly used test is the CPTu and this has been discussed more extensively. The problem of interpreting the test and why some 'non-conformities' should be allowed was argued.

The often occurring issue of crushable sands was discussed and the solution with SCF or CC tests were discussed. While the CC testing gives a solution for the relative density derivation, the liquefaction assessment based on the simplified methods still was based on a corrected CPT-result, based on the defined SCF. Avoiding this requires more (laboratory) testing such as cyclic triaxial testing and cyclic simple shear testing. For a contractor such testing in an active project may require too much time and leaves room for too much uncertainty/risk which should be carried by both parties, employer and contractor.

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