Proceedings of the 7th International Conference on Asian and Pacific Coasts
(APAC 2013) Bali, Indonesia, September 24-26, 2013

GEOTECHNICAL ASPECTS OF COASTAL RECLAMATION PROJECTS

H.E. Ali [1] and J.S. Damgaard [2]

ABSTRACT: This paper discusses important geotechnical aspects of coastal reclamation projects, in particular it addresses the key considerations related to planning and specification of ground improvement in calcareous sands. Out of the many factors that govern the formulation of adequate and effective ground improvement specifications, the paper discusses two factors in more detail: the CPT-based Soil Behaviour Type charts and the importance of CPT testing locations. Both factors are directly related to the evaluation of the compaction level and the evaluation of the liquefaction potential of the reclamation fill.

Keywords: Coastal development, reclamation, ground improvement, CPT, soil behaviour type, hydraulic fill, calcareous sand.

INTRODUCTION

The use of coastal reclamations to provide land for developments has become widespread. Asia Pacific and the Middle East, in particular, have undertaken a number of projects in recent years. Reclamation is often the most cost-effective – or even the only – way of making land available in densely populated areas where space is sparse and expensive. Coastal reclamations can be used for recreational purposes, real estate, public infrastructure (e.g. airports and ports) and resource projects (e.g. the artificial islands constructed in the Arabian Gulf to facilitate oil and gas exploration).

A number of the reclamation projects in Asia Pacific are located in areas with challenging marine ground conditions and/or are utilising an unsuitable fill material, such as shell sand. New Hong Kong Airport is a case in point since it was built over natural soft cohesive soils using calcareous sand (Massarsch and Fellenius 2002).

Furthermore a number of the reclamation projects are located in areas with significant seismic activity. From a foundation perspective this can pose a substantial risk for partial or full liquefaction and, as a result, reduction of soil strength.

Developers are naturally looking to construct reclamation projects as fast and as cheaply as possible. Therefore, in the aim of initiating the construction early, it can occur that the investigation and analysis of the soil strength and the formulation of the required ground improvement approach will not receive as much attention as would be desirable. The result can be vague, insufficient and defective project specifications. This, in turn, can lead to cost and programme overruns, and claims.

This paper addresses the main geotechnical factors that need to be considered for coastal reclamations. The main mitigation factor is proper ground improvement (GI) specifications combined with a testing and monitoring regime. Therefore, the paper will make recommendations on certain aspects in this area. The main framework of the GI approach is discussed based on the Authors' experience gained through a number of major hydraulic fill reclamation developments. In terms of GI, the thrust of this paper will be vibrocompaction of coarse-grained calcareous fill. However, approaches in principle can be applied to other GI techniques.

FOUNDATION EVALUATION AND THE GROUND IMPROVEMENT FRAMEWORK

An important step in the planning, design and construction of a coastal reclamation is the decision as to whether ground improvement (GI) is required. That decision depends on a number of factors related to the loading and functionality of the development. Ground improvement will, however, almost always be required if the reclaimed land is meant to stay for a significant period and is going to act as foundation for standard structures.

Once it has been established that the reclaimed ground needs to be improved then it is prudent to spend time and efforts in establishing the optimum GI strategy for a given reclamation. This process will need to consider a whole range of factors. The most important of these factors have been summarised in Table 1 and they will be discussed in the following sections.

[1] Head of Geotechnical Section, COWI, Reemas Building, Al Quoz 1, PO Box 52978, Dubai, UAE
[2] General Manager Ports & Marine – Asia Pacific Division, SMEC International, Jl. Melaway 14, Kebayoran Baru, 12160 Jakarta, INDONESIA

Geotechnical aspects	Primary factors	Subsidiary factors	Design Parameters involved
Ground/fill condition	Fill characteristics	Fine content Carbonate/shell content Suitability for target improvement technique	Soil Behavior Type Index (I_c) Shell correction factor Suitability Number
	Natural ground conditions	Ground characteristics Natural hazards	Drained and undrained soil modulus Creep coefficient Shear strength parameters
Target design performance	Settlement	Short term settlement Long term settlemen	Method of analyses Allowable short and long term settlement
	Structral stability	Bearing capacity Other failure modes (sliding, overturning, deep-seated failure)	
	Seismic hazards	Liquefaction potential Seismic-induced settlement Bearing capacity and stability of retaining structures Lateral spreading	Method of analyses Acceptable safety factors Acceptable settlement criteria Peak ground acceleration Magnitude Scaling factor (MSF) Depth reduction factor (r_d) Soil Behavior Type Index (I_c)
Construction methodology	Dredging/reclamation	Type of dredging (suction, cutter-suction, etc.) Type of placement (bottom dumping, rainbowing, pipelines, etc.)	
Quality Assurance / Quality Control	Testing	Testing methodology Inspection regime Frequency and distribution of testing Dissemination and alignment between stakeholders	

Table 1 Summary of geotechnical aspects to consider in reclamation and ground improvement.

Ground/fill conditions

The type and characteristics of the original ground and of the available reclamation fill material is of paramount importance in assessing whether the desired functionality of the reclamation can be achieved and, if so, estimating the programme and budget for the works.

Filling material

The most important factor in the selection of the improvement methodology is the as-placed soil and fill characteristics. For reclaimed fill it is important to consider the as-placed characteristics rather than those related to the point of origin (i.e. borrow areas) since soil properties depend upon the nature of the placed fill after the processes of extraction or excavation, transport and placement.

Soil gradation and particularly the fine content usually control the selection of the GI methodology. A maximum limit of 30% fines content is often allowed (Hong Kong Port Works Design Manual: PART 3 2002).

However, if the intention is to use vibrocompaction for sand densification then the fines content needs to be much lower. Furthermore even small, say 3% to 5%, of cohesive material can cause the entire soil matrix to act as a cohesive soil.

The type of fill is another important factor since fill materials generally respond differently to GI, testing and seismic loadings (e.g. calcareous versus silica sand). This is especially important in the context of testing where special allowance for sand types has to be factored in. One representation of this is the compressibility correction factor or shell correction factor (SCF) that is used to offset the correlation of relative density against CPT tip-resistance to simulate the high crushability of calcareous sand. Therefore, special allowance for testing soil crushability and its impact on the testing methodology must be allowed for. Likewise, material-specific characteristics and behavior must be considered in the GI specification.

Natural soil

With respect to the existing natural material an important factor is whether it represents the entire soil column of the site or whether it is only located under the reclaimed soil. Many of coastal developments overlay problematic grounds such as soft marine deposits, karstic ground, corals, reef limestone, vuggy and weak sedimentary rocks that may affect the performance of coastal developments. Therefore, such ground must be assessed in relation to the functionality of the development, expressed through the target performance criteria that will be discussed later in this paper. For example the expected long term settlement induced by any underlying soft deposit must be considered in the overall settlement calculations.

Placement

Finally the placement methodology plays an important role in shaping the properties of the reclaimed soil. Without proper placement there is a risk of densification and stratification of the reclaimed fill with subsequent, undesirable consequences for the foundation strength and the magnitude of settlement. Therefore it is, as a rule, necessary to consider special precautions for the placement method in order to achieve better improvement performance.

Target design performance

The functional specification of the GI shall be based on well-defined target design requirements including:

- Bearing capacity
- Short- and long-term settlement
- Negative skin friction for deep foundations
- Liquefaction susceptibility
- Seismic induced settlement

In theory, a performance line for in-situ resistance in granular material can be determined from the quantified targets above. In practice, however, it is unfortunately normally the case that GI specifications stipulate either certain target relative density values or target index measurements such as CPT tip-resistance values without associating these values with target functional requirements. In our experience both approaches can lead to ambiguity and, as a result, disputes. A GI specification based on particular relative density values is the worst option since measuring relative density is disputable, unreliable and nonreplicable, whether in laboratory or in the field.

Construction methodology

As stated in ROM (Spanish National Port Authorities 1994): "*The characteristics of hydraulic fill will depend on the nature of the material remaining in the fill after the processes of excavation, transport and sedimentation have taken place. Hydraulic fill may have very different characteristics from those of the borrow materials at the point of origin*."

The method of placing the sand can result in different relative densities for the reclaimed fill different placing. For example, for filling below water dumping technique can have higher fill density comparing to rainbowing or pumping ashore through a spreader or diffuser at the end of a pipeline. Also filling above water particularly via discharging with a pressure pipeline always results in a higher relative density than filling below water level.

As the initial relative density before improvement has a major impact on the final compaction level after GI, it is important to specify or consider the possible placement methods in the specifications.

Quality Assurance / Quality Control

As part of quality assurance and control (QA/QC) of GI works, lab and in-situ testing are always required. GI specification must include detailed procedure of QA/QC so that testing technique, frequency and locations will be clearly specified.

More details on QA/QC procedures and requirement can be found in Van't Hoff and van der Kolff (2012)

DEVELOPING FIT-FOR-PURPOSE GROUND IMPROVEMENT SPECIFICATIONS

Many of the aspects discussed in the previous section are well known and are often partially or fully incorporated in GI specifications. However, based on the Authors' experiences, gained through various projects with major GI works for coarse-grained calcareous fill, some important aspects tend not to be addressed upfront and sometimes the consequence of that omission can be disputes at later stages of the construction or after completion of the works when it is realised that the desired functionality is not fully achieved.

As discussed above, factors controlling (i) the ground/fill behavior, (ii) the target design aspects such as bearing capacity and settlement, etc, and (iii) the QA/QC procedures, must be clearly and precisely defined in the specifications.

In the following sections, two simple yet important aspects will be highlighted merely as examples of different aspects and factors that can really affect the quality of the new coastal developments. Their impacts and their best-practice implementations are discussed hereunder.

Both aspects are related to CPT testing and evaluation procedures, namely; Soil Behavior Type Index (I_c) and CPT testing locations. Though these two aspects tends to be overlooked in GI specifications, both issues were found to have a major impact on the assessment of the overall GI quality and also for liquefaction potential and the calculation of seismic induced settlement.

Soil Behaviour Type (SBT)

CPT-based Soil Behaviour Type (SBT) charts are a predictive (profiling) tool to soil behaviour originally proposed by Robertson et al. (1986) and Robertson (1990). Since then, the SBT method has been progressively developed by various researchers (Robertson 2012). Accordingly, different versions of the SBT charts exist and this has led to inconsistent adaptation of this method. The non-normalized charts by Robertson et al (1986) defined 12 soil behaviour type (SBT) zones, whereas, the normalized charts by Robertson (1990) defined only 9 zones. The normalized 'SBTn' chart based on nine dimensionless and defined SBT zones, shown in Fig. 1, is the most recent. Furthermore, the soil SBTn index (I_c) is developed to numerically distinguish between the boundaries of Zones 2 to 7 as shown in Fig. 1.

In addition of being used in general ground profiling, SBTn charts and its associated index I_c are mostly used to distinguish between coarse-grained and fine-grained soils and provide an approximate estimation of the content of fines in the tested soils. I_c is an important parameter in identifying other soil characteristics such shear strength and deformational parameters from the CPT measurements. More importantly, it is used in the liquefaction potential assessment (e.g. Robertson and Wride, 1998). As such, proper estimation of I_c is very important in evaluation of compaction works.

The determination of I_c has many challenges that need to be addressed and agreed upon prior to the start of the evaluation of GI works. This includes the method used to calculate I_c, and consideration for the factors influencing the quantification of I_c such as stress exponent as will be discussed later.

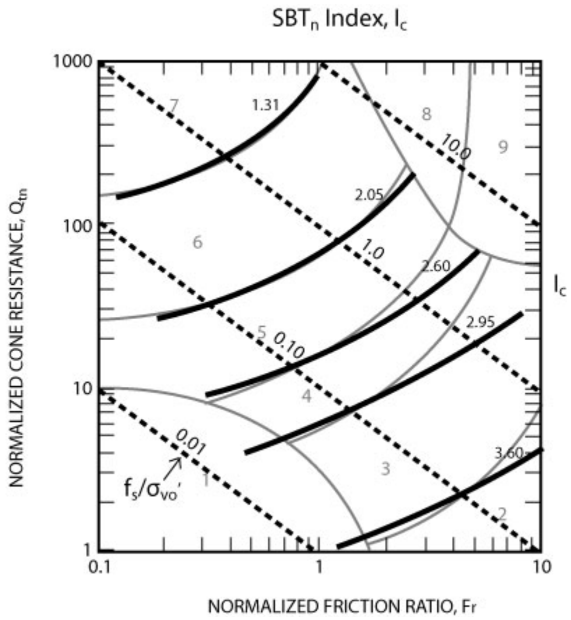

Fig. 1 SBTn chart with (I_c) and f_s/σ'_{vo} contours (Robertson 2012).

Impact of confining pressure

The value of I_c alone cannot identify the effect of the variation in confining horizontal effective stresses. The Authors have noted that the I_c values differ significantly between pre-compaction and post-compaction CPTs. This phenomenon has also been reported by Kirsch and Kirsch (2010). They, however, recommended using the pre-compaction CPT in any subsequent analyses and evaluations. However, based on the Authors' own observation of various GI projects, the pre-CPT results in calcareous shelly sand had indicated an artificially higher fine content based on an exaggerated I_c values. This significantly underestimates the liquefaction hazard and accordingly the seismic-induced settlement. The effect is attributed to the very low horizontal pressure in pre-compaction state that have a direct influence on the CPT tip-resistance as indicated by Robertson (2009). As such, determination of I_c in loose sand should be cautiously assessed. Same is noted also by Pease (2010)

The variation in I_c between pre-compaction CPT and post-compaction CPT soundings were also found to be dependent on the CPT testing location as seen in Fig. 2.

It was noted that I_c values differ remarkably according to the distance from the vibrocompaction probe. This suggests that such differences can be attributed to the reduction in lateral confining pressures due to the attenuation of compaction energy with distance from the position of the vibro-probe.

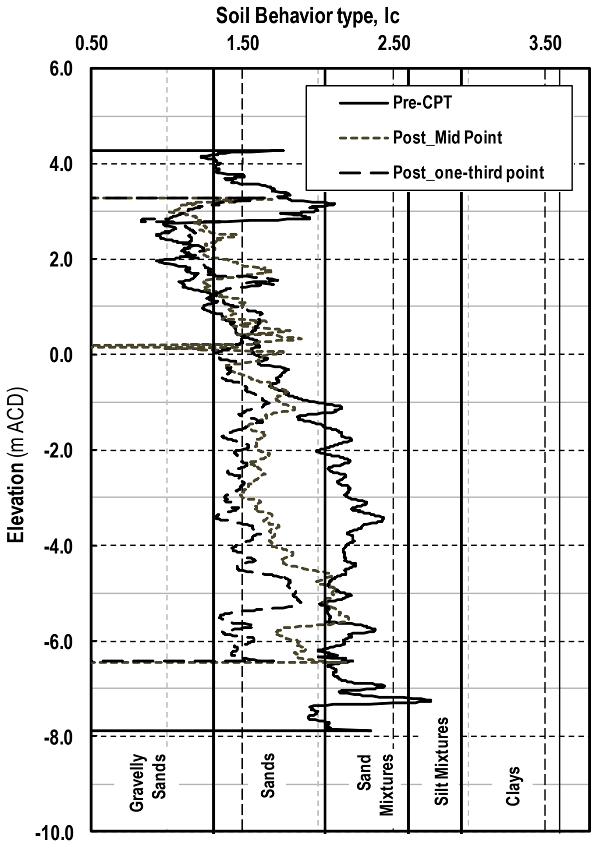

Fig. 2 Variation in I_c value based on the testing location.

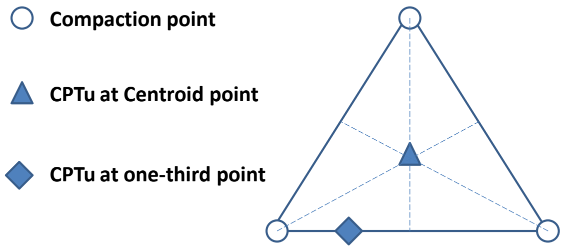

Fig. 3 CPT test locations

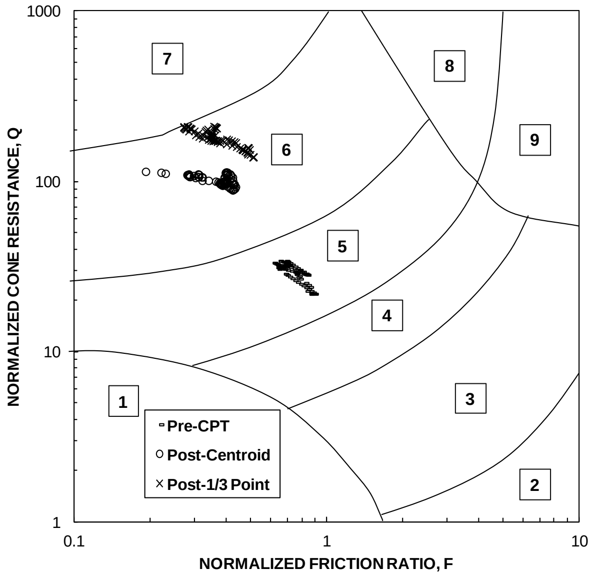

Fig. 4 CPT results posted on the normalized SBTn chart

To study these phenomena further, the points representing there CPT measurements for the elevation between -3.0 m and -4.0 m are shown on the SBTn chart in Fig. 3. The three CPT sounding are for one pre-compaction CPT and two post-compaction CPTs carried out at difference location within a 3.5-m triangle compaction grid for 11.0 m high reclaimed calcareous fill. Fig 3 illustrates the location of CPTu testing location within the triangle compaction grid.

It can be seen in Fig 4, that pre-CPT is located at different and higher soil type zone while the post compaction CPTs are located in the proper soil type zone that correctly represents the fill soil type. Furthermore, the same figure indicates that points located closer to the compaction probe are showing less I_c and hence lower fine-content. Also by comparing the results shown on Figure 4 with Figure 1, it can be seen that the centroid points always have higher sleeve resistance.

Stress Exponent (n)

The recent development in determination of SBTn chart by Robertson (1990) was achieved using a normalised cone penetration resistance, Q_{t1}, based on a simple linear exponent n = 1.0. Applying this method to the CPT measurement proved to overestimate I_c values for coarse grained soils, hence an over-estimation of fines content. Realizing that fact, a stress exponent value of n = 0.5 was recommended by Robertson and Wride (1998) and Youd and Idriss (2001) for SBTn - I_c in coarse-grained soils in order to assess liquefaction potential.

Recently, further modification to the stress exponent, n, were recommended namely to relate n to the soil type rather than being a constant value, even for coarse-grained soils (Robertson 2012). Zhang et al. (2002) proposed a linear transition of n values between fine-grained and coarse-grained soil types as shown in Fig. 4. Recently, Robertson (2012) suggested that the stress exponent n shall allow for a variation of both the SBTn -

I_c type and the stress level by using the following equation:

$$n = 0.381(I_C) + 0.05\left(\frac{\sigma'_{vo}}{p_a}\right) - 0.19 \quad (1)$$

where $n \leq 1.0$.and σ'_{vo} denotes the vertical overburden pressure and p_a is the atmospheric pressure.

Based on the equation above the variation in the stress exponent n at different values of I_c and the overburden pressure are shown in Figure 5.

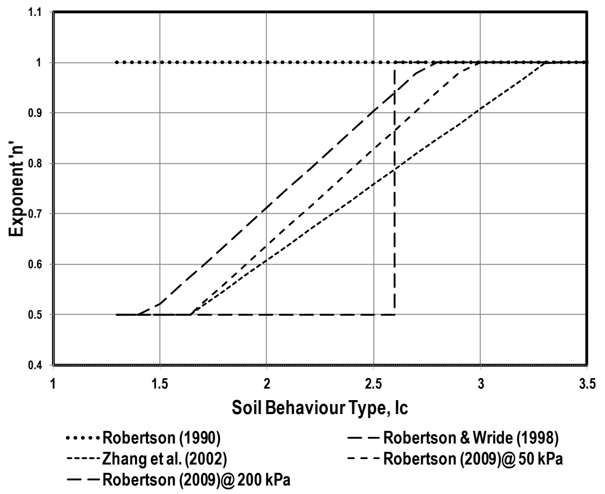

Fig. 5 Stress exponent based on different methods

Impact of sand characteristics

Despite the recent advancement in calculation of I_c, its applicability to different fill materials is still questionable. Authors have noted that a fixed value of $n = 0.5$ for coarse-grained medium dense to dense calcareous soils yields good results. Robertson (2009) implied that his recent evaluation of the stress exponent (Eq.1) might not be valid for calcareous sand. Schneider and Lehane (2010) also concluded that applying I_c for calcareous sand still requires further investigation. Schneider and Lehane (2010) indicated that field tests show no presence of fines in 'loose' soils, despite the apparent high measured I_c value. It is inferred by Schneider and Lehane (2010) that the over-estimation of I_c values is due to the decrease in the cone penetration resistance caused by the high compressibility (crushability) of calcareous sand.

It is important to note, however, that their conclusion was based on evaluation of loose strata with the calculated I_c based on a constant n value of 0.5. As discussed above, this observation, in fact, may be incurred by the low confining pressure as discussed earlier rather than compressibility. This is because crushability is significantly increased with the fill compactness and it is always minimal even for highly crushable sand at lower relative densities.

Pease (2010) warned that available techniques of determining I_c values may not be valid for cemented and aged sands and he recommended that site-specific correlation may be necessary in such cases.

In conclusions, it is, therefore, important to stipulate in GI specifications that site-specific evaluation of I_c shall be carried out at the target relative density.

Testing locations

Many ground improvement techniques and, in particular, vibro-compaction always produce vertically and laterally non-uniform compacted ground. Hence, it is crucial to identify the locations where testing shall be performed. The locations, distribution and numbers of in-situ testing shall be potentially capable of properly measuring the achieved densification level throughout the entire ground.

In order to evaluate the measurement variability caused by the test location in vibro-compaction works, a statistical analysis was conducted using a case-history involving an offshore artificially reclaimed island comprising 305 compaction boxes of 25×25-m size. The total depth of calcareous fill was about 19 m with 4 m above MSL. The GI was carried out with a heavy vibro-compaction probe (Keller S700) with 4-m triangular grid combined with light surface compaction using 26-ton roller compactor.

The CPT sounding were carried out in two locations namely centroid and one-third locations. The centroid point (defined as Points A) located in the center of triangular vibro-compaction grid while the one-third locations (defined as Points B) is the point located at one-third of the distance between two compaction points.

The ratio of the measured CPT tip-resistance between centroid and one-third locations was determined for the 305 boxes.

As shown in Fig. 6, the uppermost 4-m of the compacted fill, centroid points tend to show higher tip resistance than one-third points. Below 4-m depth, the ratio reversed and gradually increased to the favour of one-third points till a depth of about 14 m. Below that depth, the relative difference suddenly reduced to an average ratio of 106% to the favor of one-third points.

Since rod inclination causes the CPT cone to progressively deviate from the intended testing location with depth, it was necessary to rule out the impact of CPT rod inclination on the results. Accordingly, CPT soundings exceeded horizontal deviation of 2.0 m and 1.0 m were filtered out from the statistical analyses. Fig. 7 and Fig. 8 depict only the results of all CPTs records that passed the deviation limits of 2.0 m and 1.0 m, respectively.

By going deeper, the number of analysed boxes was gradually reduced and only 81 and 12 boxes, respectively, remained for the lowest testing 2-m depth interval (i.e. 16-18 m), for horizontal deviation limit of 2.0 m and 1.0 m, respectively.

While there was no discernible difference for the top few depth intervals, there was, however, considerable variation in the lower depth intervals where the ratio of the cone tip-resistance increased to almost 135% to the favour of the one-third for 1.0-m deviation limit. This indicates that, the weakest location within the vibro-compacted fill is located at the centroid locations and this can be measured only by straight CPT soundings with limited inclination. In this particular case, only 12 boxes out of 305 tested boxes passed the 1-m deviation criteria and utilized in the comparison shown in Fig. 8.

As such, it was concluded that centroids, in contradiction to what been always claimed, do not necessarily present the weakest location particularly for the uppermost few meters.

Also, it can be concluded that it is rather important to control rod inclination in similar tasks. Furthermore, inspecting more than one location is recommended as there is no such testing location that can be considered "the weakest point" for the entire filling depth. And testing more than one single point within the triangle is necessary to capture the compaction levels for the entire fill continuum.

Based on the above, it is important to identify the locations and practical inclination criteria in the GI specifications if CPT soundings are used. It would be preferable to have weighted averages for CPT tip-resistance measurements rather than arithmetic averages, particularly below 4 m depth. Authors would suggest a weighted average of 0.6 for centroid points to 0.4 for one-third points to be proposed in specification (as inferred from Fig. 6). For the top 4 meter, the arithmetic mean can be used.

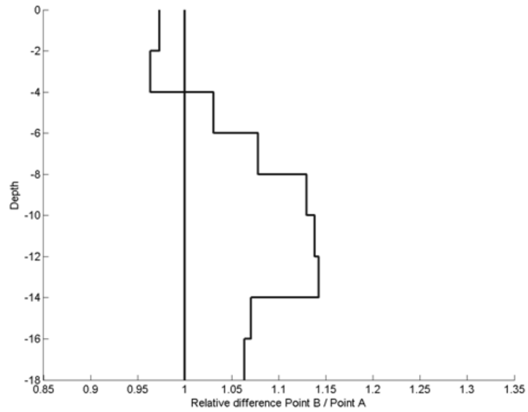

Fig. 6 Relative difference between Points A and Points B tip resistance for 305 compacted boxes with no inclination limit

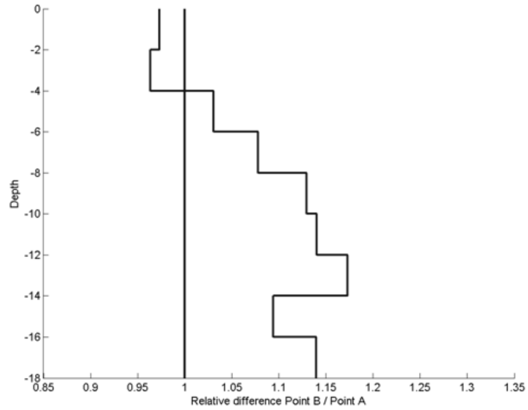

Fig. 7 Relative difference between Points A and Points B tip resistance for 305 compacted boxes with 2.0 m inclination limit

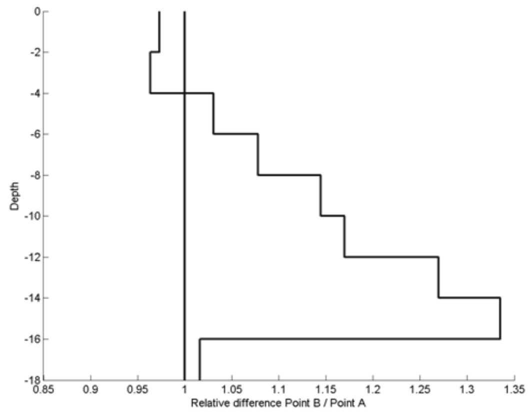

Fig. 8 Relative difference between Points A and Points B tip resistance for 305 compacted boxes with 1.0 m inclination limit

CONCLUSION

Coastal reclamation projects require ground improvement more often than not. The aim of the ground improvement is to achieve competent foundation conditions. Given the problems that have occurred in the past, this paper recommends that sufficient time and efforts are spent in formulating a site- and project-specific ground improvement strategy. The most important factors in determining that strategy are ground/ fill conditions, target design performance, construction methodology and QA/QC.

Two important aspects of developing fit-for-purpose ground improvement specifications are discussed in a bit more detail in the paper: Soil Behaviour Type (SBTn) charts and CPT testing locations.

SBT charts are used as profiling tools to classify the likely behavior of the soils. Proper estimation of the SBT index (I_c) is critical as it has a direct impact on the evaluation and the acceptance of the ground improvement works and also on the liquefaction potential assessment. As available methods for determining I_c may not be so accurate for certain cases such as calcareous sand, site-specific validation may be required for the I_c values.

Additionally, the testing location is another key-factor in the QA/QC process of evaluating ground improvement works. It was demonstrated that more than one testing location shall be considered, particularly for vibro-compaction works.

REFERENCES

Belotti, R. and Jamiolkowski, M (1991) Evaluation of CPT and DMT in Crushable and Silty Sands. Third interim report ENEL, C.R.I.S., Milano.

Hong Kong - Civil Engineering Office (2002), "Port Works Design Manual: PART 3 - Guide to Design of Reclamation" The Government of the Hong Kong Special Administrative Region.

Jefferies Mike and Been Ken (2006) Soil Liquefaction: A critical state approach, : Taylor & Francis, NY.

Kirsch, K. and Kirsch, F., (2010) Ground Improvement By Deep Vibratory Methods , CRC Press.

Massarsch, K. R. and Fellenius, B. H. (2002). "Vibratory compaction of coarse-grained soils," Canadian Geotech. J. 39: 695–709.

Pease, J. W. (2010). "Misclassification in CPT liquefaction evaluation," Second International Symposium on Cone Penetration Testing 'CPT10', Huntington Beach, CA, USA.

Robertson, P. K., 2012 "Interpretation of in-situ tests - some insights in ISC'4", Mitchell Lecture, Brazil, 2012.

Robertson, P.K. and Wride, C.E., 1998. Evaluating cyclic liquefaction potential using the cone penetration test. Canadian Geotechnical Journal, Ottawa, 35(3): 442-459.

Robertson, P.K., (2009). " DMT – CPT correlations. Journal of Geotechnical and Geoenvironmental Engineering,", ASCE, Vol. 135, pp 1762-1771.

Robertson, P.K., 1990. Soil classification using the cone penetration test. Canadian Geotechnical Journal, 27(1): 151-158.

Robertson, P.K., 2009. Interpretation of cone penetration tests – a unified approach. Canadian Geotechnical Journal, 46:1337-1355.

ROM: Spanish National Port Authorities (1994) " Geotechnical recommendations for the design of maritime and harbour works - Maritime Works Recommendations.

Schneider, J.A. and Lehane, B.M. (2010), "Evaluation of cone penetration test data from a calcareous dune sand," Second International Symposium on Cone Penetration Testing, 'CPT10', Huntington Beach, CA, USA. Volume 2&3: Technical Papers, Session 2: Interpretation, Paper No. 28.

Van't Hoff, J. and van der Kolff, A. N. (2012), Hydraulic Fill Manual: For Dredging and Reclamation Works - [s.l.] : CRC Press.

Youd et al. (2001), "Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils," ASCE, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 127, No. 10, 817-833.

Zhang, G., Robertson, P.K. and Brachman, R.W.I., 2002, Estimating Liquefaction induced Ground Settlements From CPT for Level Ground, Canadian Geotechnical Journal, 39(5): 1168-1180.