Ground Improvement at Chek Lap Kok: Review of Vibrocompaction at Hong Kong's New Airport

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The new Hong Kong airport at Chek Lap Kok is being constructed on a 1248 hectare site of which 928 hectares is reclaimed land. Part of the reclamation consists of marine sand fill. Site investigation, including the CPT and shear wave velocity testing, indicated that the sand was in a relatively loose state state below the water table, with relative densities in the order of 20 to 40%. Vibrocompaction was carried out at three different areas of the reclamation in order to increase the relative density of sand fill, thereby increasing its' stiffness and strength, and creating an improved and more uniform material for follow on construction.

The method for acceptance testing for the vibrocompaction was based on the use of the CPT, with the acceptance criterion set as a tip resistance value of either 8 MPa or 15 MPa, depending on required degree of compaction.

This paper presents the results of the vibrocompaction and discusses some of the factors encountered during the compaction that can lead to apparent non-conformance with the specification. Conclusions are drawn from the work with recommendations that should be considered for future vibrocompaction works. A knowledge of the initial state of the sand including index properties, relative density and compressibility, is important when selecting an acceptance criterion. An inappropriate acceptance criterion may cause unnecessary delays of the work and increased costs as a result. The use of shear wave velocity measurements as a compliment to the CPT testing is also discussed as valuable information on the state of the sand can be derived from this method of testing.

Keywords: *Vibrocompaction, Ground Treatment, Sand Fill, Chek Lap Kok*

Introduction

The new Hong Kong airport at Chek Lap Kok is being constructed on a 1248 hectare site, of which 938 hectare is reclaimed land. The reclamation comprises 197Mm^3 of fill material and, of this, approximately 76Mm^3 is marine sand fill.

Site investigation indicated that the placed sand fill was in a relatively loose state below the water table. It was recommended that vibrocompaction should be carried out to create a more uniform fill with an increased density which would minimise the potential for future settlement due to both creep and vibration loading. Vibration loading could result from dynamic pile installation or seismic effects.

The areas selected for compaction were where ground improvement was specifically required to prevent excessive differential settlement, underneath utilities, tunnels and where driven piling would be undertaken in the future. The sand was also compacted in areas beneath future structures with shallow foundations. Two degrees of densification were established, defined as heavy and light compaction respectively. The compaction intensity and the compaction acceptance criteria varied for these two degrees. The three areas (Areas 1, 2 and 3) within the first phase of construction of the airport at which vibrocompaction was carried out are shown in Figure 1. The total area compacted was 58 hectares; and included 39,000 compaction points. The average cost was HK$14/m^3 of sand.

This paper describes the vibrocompaction carried out at the three areas, the method of acceptance testing, the results of the vibrocompaction, and non-conformances which occurred during the works. Experience drawn from the vibrocompaction and recommendations for future work is also discussed.

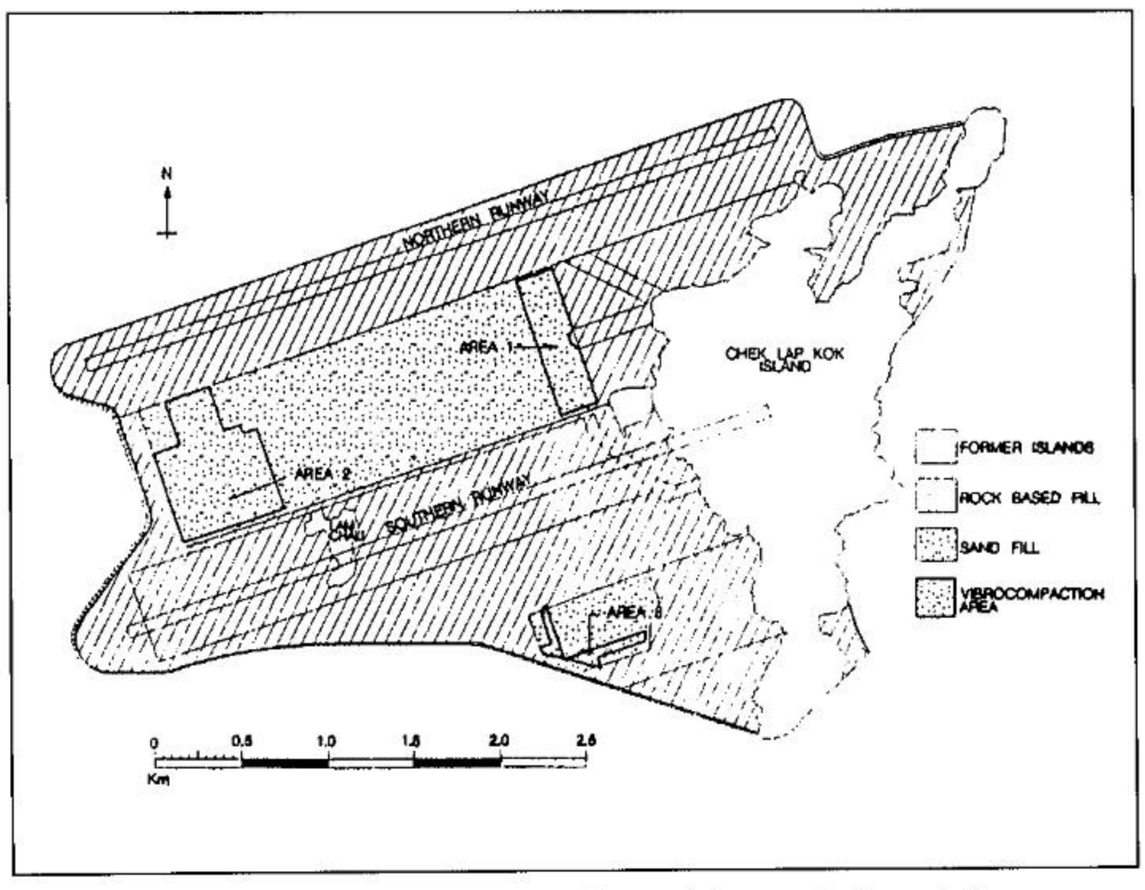


Figure 1 – Airport Platform, Location of Areas 1, 2 and 3

Properties of the sand fill

The sand fill was won from marine borrow areas within Hong Kong territorial waters. The placement of sand materials was carried out using bottom dumping, 'rainbowing' and pipeline method. For further details on construction of the reclamation, refer Newman et. al. (1995). The final reclamation platform is typically +6.5 mPD with a mean tide level of +1.3 mPD and the tidal range typically between 0 mPD and +2.5 mPD.

The sand fill generally comprises a sub-rounded to rounded, well graded fine to coarse sand with some fine gravel, with a specific gravity of 2.64. The fines content is generally less than 5% with a mean grain size (D_{50}) of 0.8mm and an average uniformity coefficient (D_{60}/D_{10}) of 4.5. Figure 2 shows a typical grading envelope for the sand fill derived from 50 test results. Void ratios using the method set out in BS1377:Part 4 (4.2 and 4.4) (1990) determined e_{max} as 0.77 and e_{min} as 0.40.

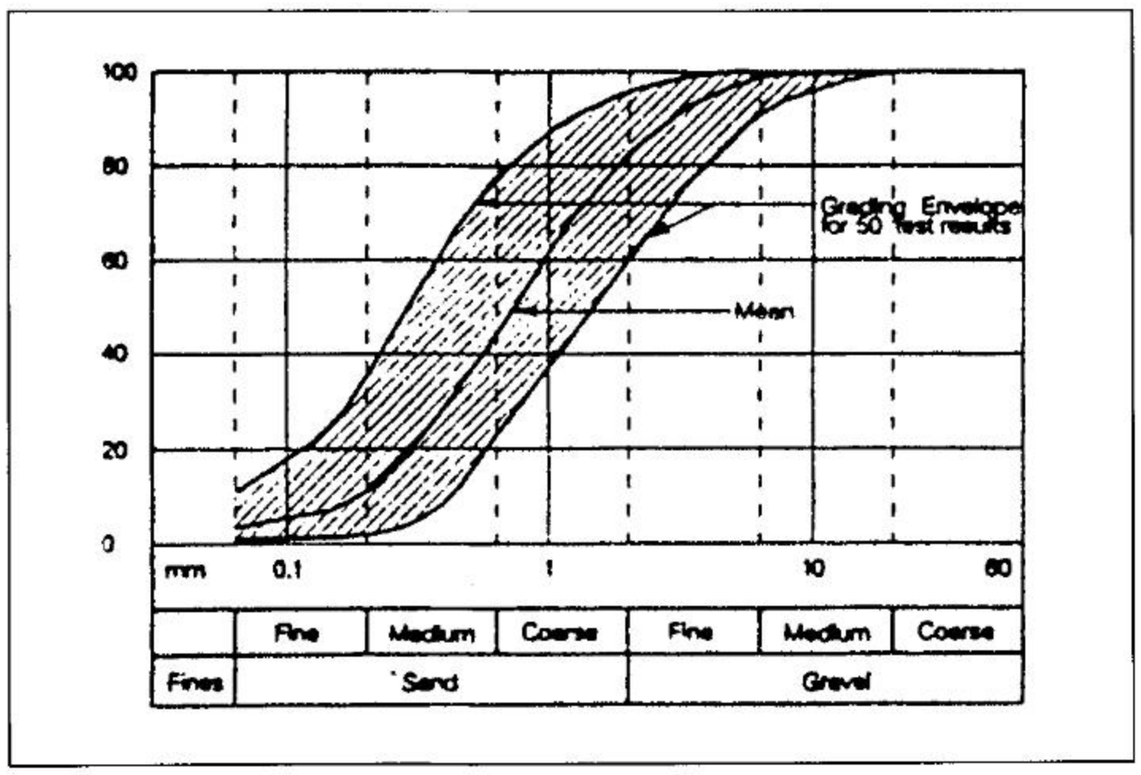


Figure 2 – Grading Envelope for Area 1 & 2

Mineral	(% by weight)
Quartz	84-92
Feldspars	5-10
Carbonate (calcite, shell)	2-7
Other minerals	< 0.5

Table 1 – Typical Sand Mineralogy

Laboratory tests were carried out to determine the mineralogy of the sand using X-ray diffraction and petrographic analysis. The mineralogy (Table 1) of the sand reflects the fact that it is a marine won material with relatively high carbonate (calcite and shell) content as opposed to silica sand such as river sands. The carbonate content is particularly important when considering the compressibility of the sand.

In Situ State Prior to Vibrocompaction

It is difficult to obtain undisturbed samples of sand for testing and it is also very difficult to measure in situ density directly. Relative density is therefore often determined from correlation with other parameters that can be measured in situ.

The in situ relative density of the sand at Chek Lap Kok was estimated from Cone Penetration Testing (CPT), Standard Penetration Testing (SPT) and shear wave velocity measurements using both seismic CPT (SCPT) and Spectral Analysis of Surface Waves (SASW).

The CPT was used as the primary means of quality control for the placement of sand fill. Testing was carried out soon after the sand was placed and also immediately before vibrocompaction commenced. In the three areas approximately 60 CPTs were carried out soon after placement. The relationship between tip resistance and relative density has been discussed by Jamiolkowski (1985), Schmertmann (1978), Lunne and Christoffersen (1992) and others. A composite CPT profile of the as-placed sand fill in Area 1 is shown in Figure 3; this is superimposed with the relative density as a function of overburden pressure as determined according to the method proposed by Jamiolkowski (1985). This shows that the relative density of the sand below the water table before vibrocompaction was generally 20-40%.

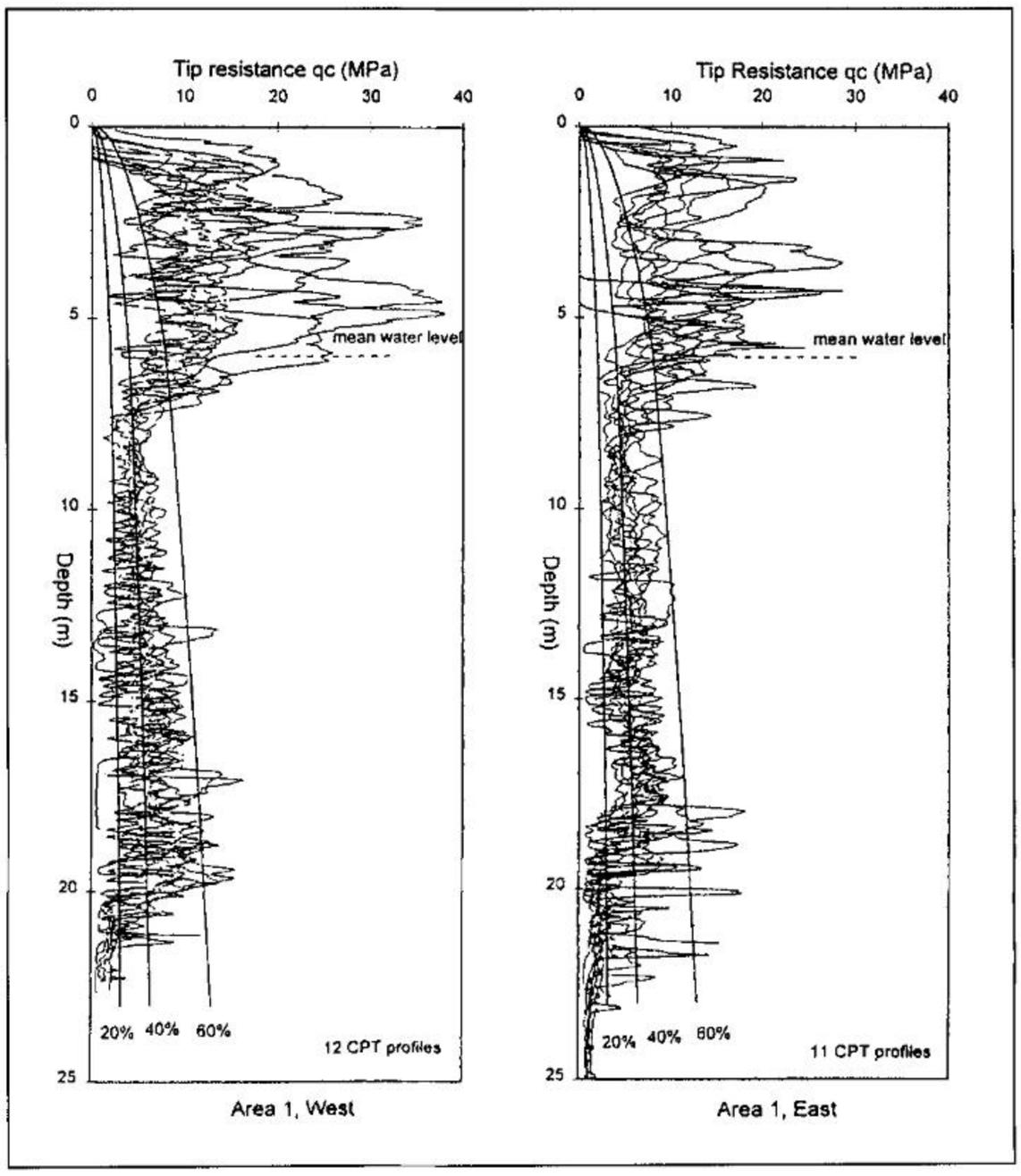


Figure 3 – Composite CPT plot in Area 1 for sands prior to vibrocompaction

It should be noted that no direct relationship has been established between relative density and tip resistance (q_c). Robertson and Campanella (1989) pointed out that the compressibility of the individual sand grains as well as the sand matrix has a significant effect on tip resistance (q_c) and sleeve friction (f_s) values. Carbonate sands tend to be more compressible than pure quartz sands. Tests on the sand, including classification and mineralogical tests, indicate that the Chek Lap Kok sand is moderately compressible.

The shear wave velocity was determined from both SCPT and SASW testing. A relationship between void ratio (e), effective overburden pressure (P'_o) and in situ shear wave velocity (V_s) for the Chek Lap Kok sand was developed by Robertson (1994) and others from laboratory tests using bender elements in triaxial samples of the sand with various known void ratios and confining stresses. This relationship is as follows:

$$V_s = (A\text{-}Be)\ (P'_o/P_a)^{0.25} \qquad (1)$$

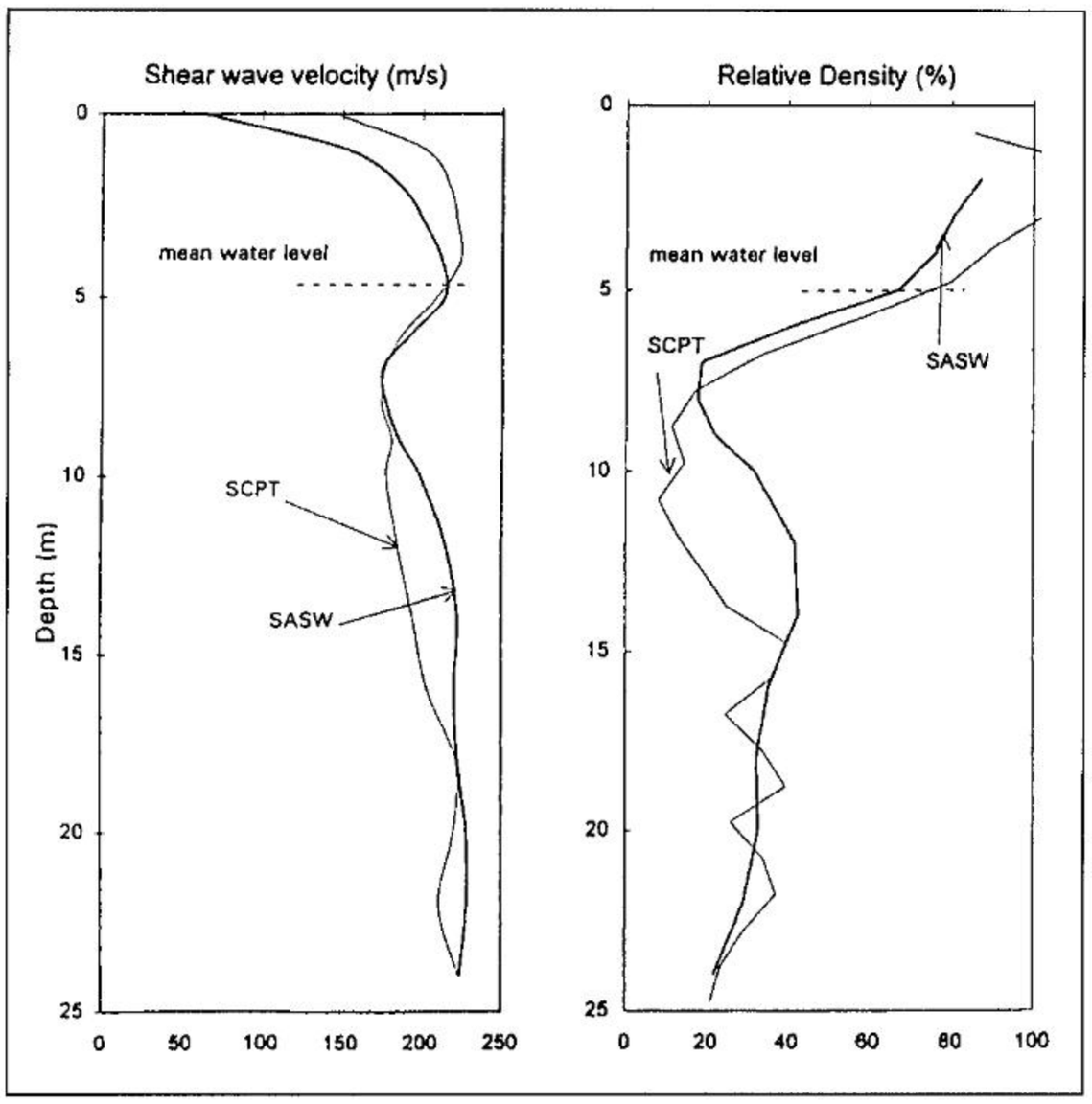


Figure 4 – Shear wave velocity and relative density from seismic CPT and SASW in Area 2

where A and B are soil constants of 356 and 253 respectively specifically derived values for Chek Lap Kok sand (Robertson, 1994) and P_a the atmospheric pressure, assumed to be 100 kPa.

The in situ velocity profiles from the SCPT and SASW testing were then used to determine the relative density (D_r) using voids ratio according to the equation:

$$D_r = (e_{max} - e) / (e_{max} - e_{min}) \quad (2)$$

The results shown in Figure 4 indicate that the relative density in the sand fill below sea level is typically 30-40% while above the sea level it is considerably denser, up to 90%.

Densification Criteria

At Chek Lap Kok the CPT was specified as the method for acceptance testing for the vibrocompaction. Together with the SPT this is the most common method used worldwide for acceptance testing. Generally the CPT is preferable as it gives a continuous profile and is fast, relatively precise and reproducible in standard conditions. In addition the friction ratio and porewater pressure can be monitored. The friction ratio can be used to interpret the fines content, which has an effect on the tip resistance/relative density relationship.

The purpose of the vibrocompaction was to increase the relative density to a uniform 55-80% as it was generally considered that this is sufficient to mitigate surface settlement due to ground borne vibrations. The CPT tip resistance (q_c) acceptance criteria were set at 8MPa and 15MPa which are values commonly adopted in Hong Kong. Using the relationship given by Jamiolkowski (1985) this corresponds with a relative density at 10 m depth of 56% and 74% for light and heavy compaction respectively. This was considered acceptable for design purposes at Chek Lap Kok.

The three areas shown on Figure 1 were sub-divided into smaller areas, requiring either heavy or light compaction, depending on future land use, foundation construction method and programme constraints. The CPT criterion was required to be met for the full thickness of the fill except the top 2 m where vibrocompaction tends to loosen material as a result of the low confining pressure.

The Contractor conducted a trial compaction to develop a method which would meet the acceptance criteria. A small trial area (30 x 30 m) was vibrocompacted to demonstrate that the required increase in tip resistance (q_c) could be achieved. The objective of the trial area was to optimise the spacing between the compaction points and confirm the pulling criteria for the vibroflot. The pulling criteria are the withdrawal rate of the vibroflot, as seconds per 0.5 m lift, and the maximum current supplied.

Two types of vibroflot were used, referred to as the V32 and S300, with the model used dictating the spacing of the compaction points. The V32 vibroflot, being heavier and of lower vibrational frequency, allowed for a greater spacing between points than the lighter and higher frequency S300 vibroflot. The methods used for light and heavy compaction are summarised in Table 2.

	Light Compaction (q_c > 8 MPa)	**Heavy Compaction (q_c > 15 MPa)**
Grid spacing	4.6m triangular (V32) 4.0m triangular (S300)	3.7m triangular (V32) 3.5m triangular (S300)
Pulling criteria	30sec/0.5m lift or 200A whichever occurs first	30sec/0.5m lift or 200A whichever occurs first

Table 2 – Contractor's Compaction Method

Results

Typical CPT profiles after compaction for both a heavy compaction and a light compaction area are shown in Figure 5. A total of 248 CPTs before vibrocompaction and 300 CPTs after vibrocompaction for acceptance testing were carried out. The average compaction depth was 17 m, 20 m and 7 m in Area 1, 2 and 3 respectively.

Generally these results show that in the top 5 m, i.e. less than 100 kPa overburden pressure, as expected the vibrocompaction did not achieve any significant improvement. The greatest improvement was below water table. The initial loose state with relative densities of 20-40% increased to typically 60-80%. The upper 2 m showed disturbance and loosening caused by the vibrocompaction. To compact these near surface layers, conventional roller compaction methods have to be used. Alternatively, additional sand could have been placed prior to vibrocompaction and subsequently removed, leaving the top part of the formation level in a denser state.

The majority of the CPTs carried out after vibrocompaction met the required criteria of 8MPa or 15MPa. In some parts, however, non-conformances were noted, particularly in the heavy compaction areas. The non-conformances were investigated and in some areas further densification was carried out to achieve the required CPT criterion. The reasons for non-conformance were usually one of the following: -

(i) Early refusal of CPT penetration due to dense strata (failure of test method, not compaction)

(ii) Sand fill not amenable to compaction (due to high fines content)

(iii) Slower than expected "ageing" of the sand (see below)

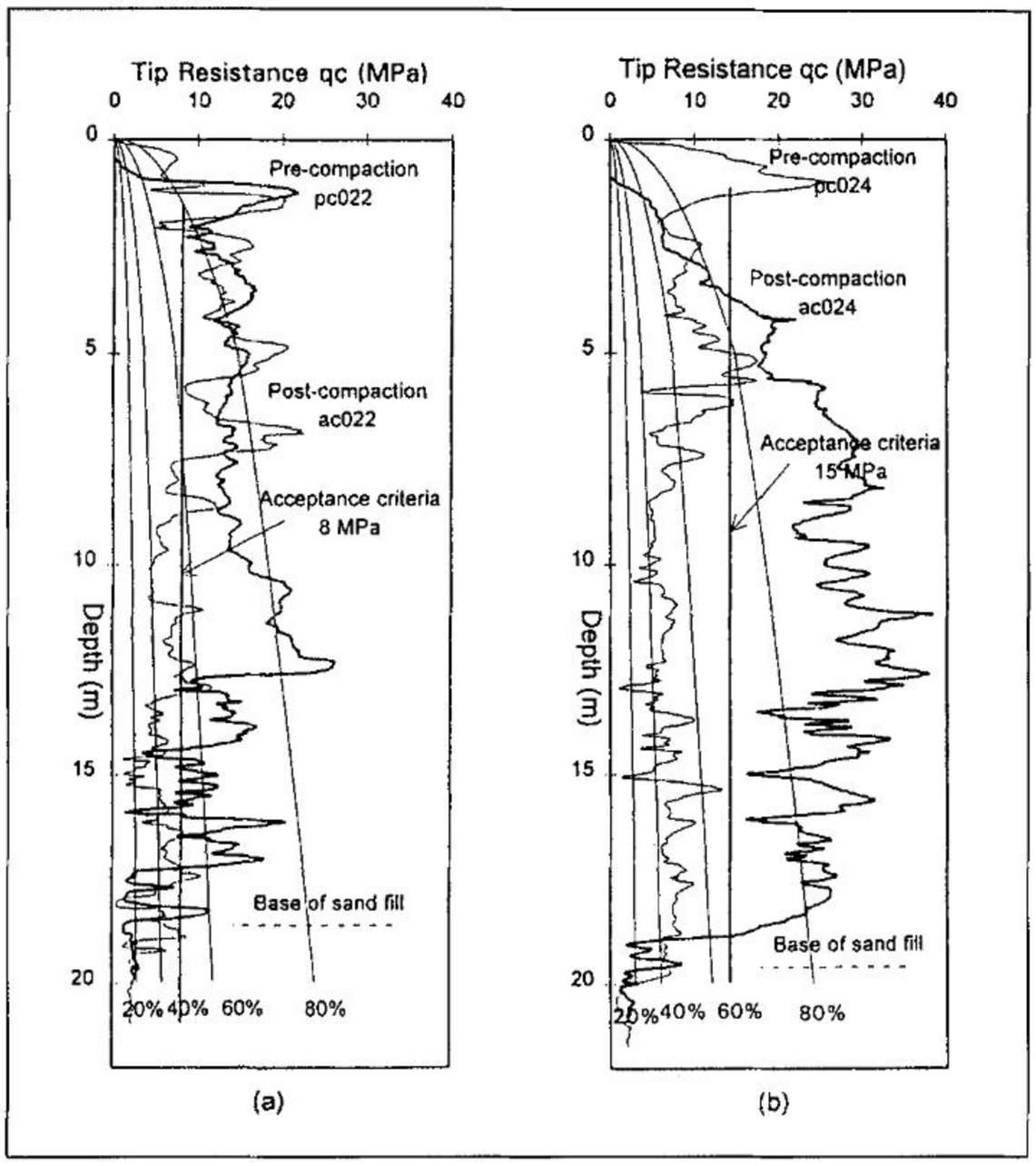


Figure 5 – Typical CPT plot before and after vibrocompaction for (a) light and (b) heavy compaction

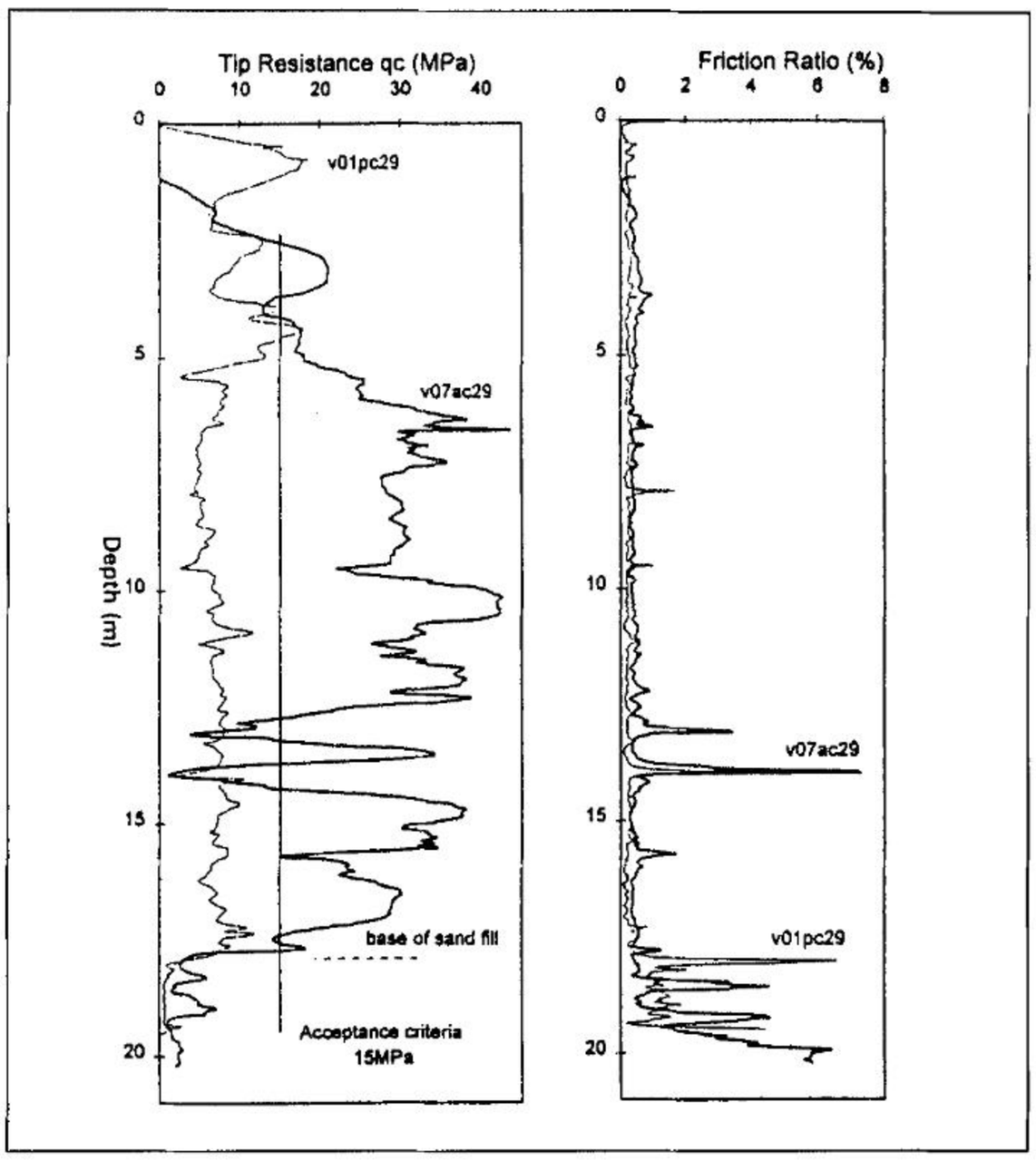


Figure 6 – Example of uncompactable horizons within the sand fill

Sometimes CPT penetration refusal occurred above the dredge level because very dense stratum was encountered. At these locations CPTs were repeated after pre-boring through the hard, or dense, layer. In some cases, the compaction records also confirmed the presence of high density layers as indicated by rapid increases in current drawn during the pulling of the vibroflot.

Some horizons within the sand, typically less than 1 m thick, could not be compacted to the required q_c value due to the presence of clayey or particularly silty sand. A clayey or silty horizon within the sand is generally characterised by a relatively high friction ratio (>2%) in combination with a low q_c value as shown in the classification chart proposed by Robertson (1990). Within the sand fill there are sometimes horizons which include some 'clay balls', which are agglomerations of fines produced during the sand extraction and pipelining. The extent of these horizons is dependent on the amount of handling and reworking of the sand between borrow pit, dredger, stockpile and pipeline. An example of clayey/silty layers within the sand fill is shown in Figure 6 at 13 m and at 14 m depth. The q_c value at these depths drops from more than 30 MPa to less than 5 MPa and the friction value increases from less than 1% to over 3%.

In areas where low q_c values were encountered CPTs were repeated and samples were retrieved and analysed to identify the soil type. As discussed above, sand compressibility can significantly influence q_c and f_s values. Highly compressible sands tend to have low q_c and high f_s values. A horizon of sand fill with a higher shell content can show a similar CPT profile to a clayey layer and hence further investigation is required to determine the soil type.

In the period following vibrocompaction the sand fill showed an increase in both strength and stiffness. This process is commonly referred to as "ageing". Immediately following vibrocompaction the apparent "ageing" is due to dissipation of air and water pressure, the process then continuous due to cementation and creep. The maximum specified time of 7 days after vibrocompaction for compliance by CPT testing was not sufficiently long in some locations for the dissipation of air and water pressure. One means to overcome this was to lower the air/water ratio of the vibroflot jet, this resulted however in a reduction in the productivity. The alternative measure was recompacting these areas. Due to one such slow gain in strength, one part of Area 2 was recompacted. The recompaction resulted in very high q_c values, many showing >20 MPa. As an example, Figure 7 shows a CPT which did not initially meet the criteria.

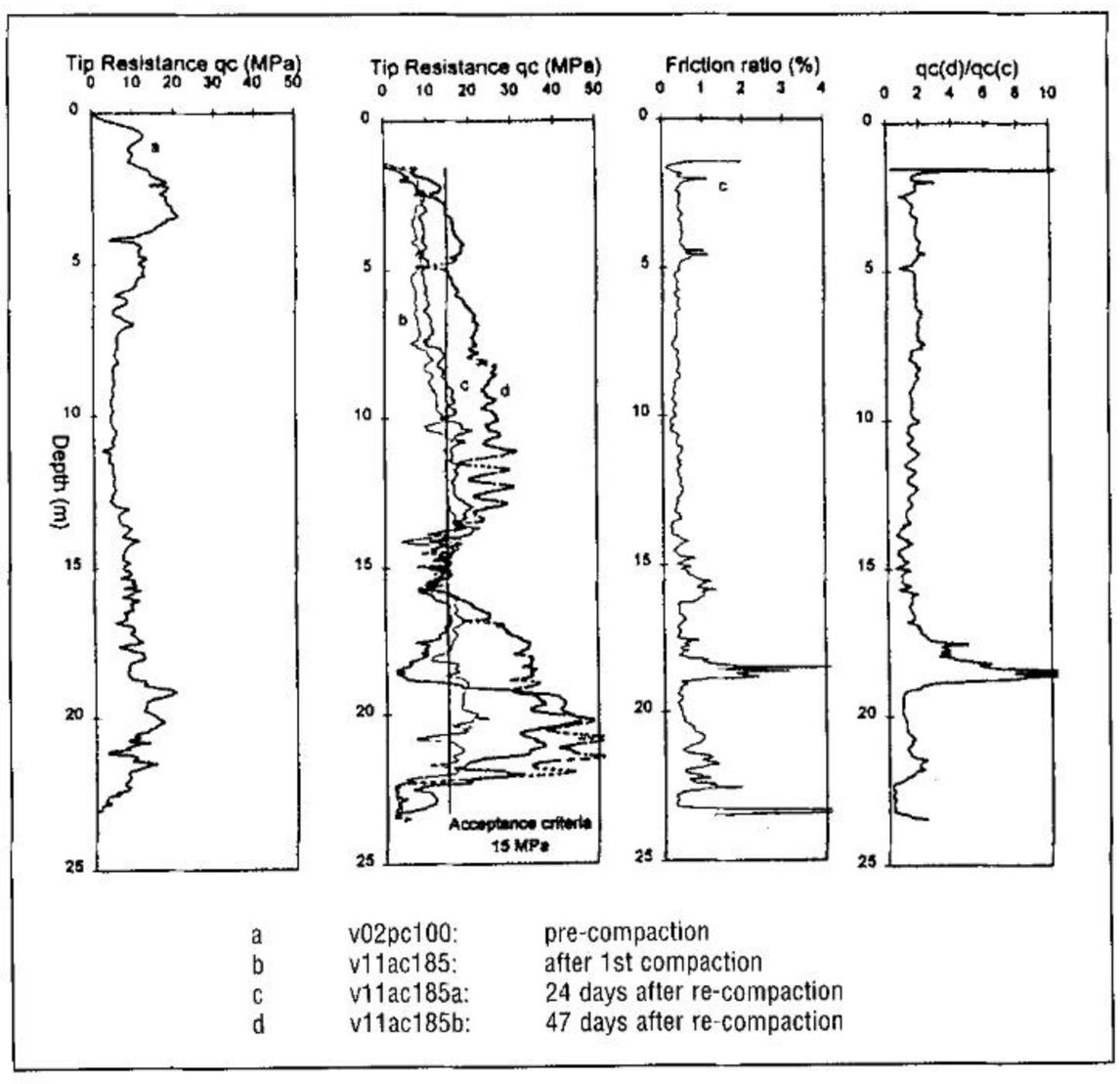


Figure 7 – Effect of recompaction

The area was then recompacted and CPTs carried out 24 and 47 days respectively after recompaction. The increase in tip resistance is clearly visible between 3 m and 13 m depth where the q_c value effectively doubled between the two testing occasions.

Settlement

The compaction of the sand particles into a denser arrangement resulted in settlement of the ground. The ground level at each CPT was monitored before and after compaction and the induced settlement was used as a secondary measure to assess the degree of improvement in terms of gain in relative density. The induced settlement is a function of the initial state of the ground (initial relative density), the thickness of compactible material and the extent of compaction. From an assumed initial void ratio (e_0) in conjunction with the measured compaction depth (d), and the difference between pre- and post-compaction ground levels (Δd), it was possible to estimate the average percentage settlement and a final average void ratio for the entire compaction depth, using the equation:

$$e = e_0 - \Delta d/d(1 + e_0) \qquad (3)$$

The relative density is then derived from Equation (2). As an example, an assumed initial relative density of 40% and an induced settlement of 7% of layer thickness equates approximately to a relative density of 75%.

The limitation with this method is that the initial relative density has to be assumed, and the values for minimum and maximum density may not be valid or constant for the full thickness of the sand fill (Simms, 1994). However, it is a useful guide to obtain an approximate estimate of the degree of compaction achieved.

The induced settlement is quoted as a percentage of the original fill thickness. Typically the average settlement was 5.8% for light compaction areas and 6.8% for heavy compaction areas. The maximum induced settlement tended to be those heavy compaction areas which had the lowest initial density. A part of Area 1 showed an induced settlement of 10%. This could be explained by the fact that this sub-area was filled only some four weeks prior to compaction whereas other areas were improved several months after reclamation. The amount of "ageing" prior to vibrocompaction was hence limited. Area 3 also showed a relatively high percentage of settlement which was attributable to the basal 3 m of fill being in a relatively loose condition prior to compaction.

Conclusion and Recommendations

The method of compaction used was generally successful in achieving the desired acceptance criteria in the conditions encountered on site. Knowledge of the sand mineralogy, grain size and shape is important to set realistic and appropriate acceptance criteria to avoid the contractor being faced with meeting unrealistic targets, potentially leading to delays and increased compaction costs.

The short ageing period of 7 days allowed between compaction and acceptance testing, which was necessitated by a very tight construction programme may have been counter-productive. An increase of this period could have reduced the number of non-conformances and hence the areas that required recompaction. In future work, the "ageing" of the sand after vibrocompaction should be studied more closely during the trial compaction to establish an acceptable time limit for compliance with the criterion.

The use of CPT as the method of acceptance testing have many benefits and is widely used. However, both assessment of the initial state of the sand and acceptance testing after vibrocompaction can be improved using a combination of CPT and shear wave velocity testing (SASW and SCPT). The advantages shear wave velocity testing has over conventional CPT is that the testing is non-destructive, provides bulk values rather than location specific values and the measurements are not affected by the compressibility of the sand. Velocity data can provide more insight into the relative density and compressibility than just the CPT.

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