Early Applications of DMT in Dubai in Two Main Projects for Natural and Artificial Earthfill Silty Sand

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ABSTRACT: DMT was used to confirm the overconsolidated nature of upper sandy fill soil that was previously compacted with Vibro Compaction for a very prestigious project site in the Palm Jumeira in Dubai. The question was raised to justify relatively high shear wave velocity (Vs) measured with a MASW log. The earthfill, made up of silty fine Sands, was originally constructed by dredging from the sea bed and hydraulically laid at the Crescent of Palm Jumeira in Dubai, and was stabilized with deep compaction using the Vibro Compaction method (VC) before 8-10 years. No reliable method exists to correlate the OCR of sand with CPT test results. DMT was used to establish the M/qc ratio and confirm the over-consolidated nature of the existing soil.

The design of large diameter flexible steel oil storage tanks is typically made according to the requirements of API650 (2007) that requires strict limits on the total and differential settlements. The prediction of settlement below the tanks using theoretical estimates with numerical methods or simple assessment methods depends mainly on estimates of the soil modulus of deformation. Without DMT, the estimates are made based on Nspt or CPT tests results that would underestimate the modulus resulting in high settlements and suggesting the need for deep ground densificaton/improvement. Site specific correlation was developed for a large site between DMT based M and CPT tip resistance (qc) indicating at least 50% increase over the CPT based M. The data includes records of BHs Nspt, CPTU and DMT tests indicating excellent correlation and reliable modulus estimates.

1 INTRODUCTION

DMT was only recently introduced for practical use in Dubai and the Gulf Area in General. This paper describes two main of the early applications of DMT in main projects.

The several man–made islands in Dubai present a convenient area of application of DMT and SDMT for both assessment of the deep man made earth fill, design and control of deep ground improvement procedures and assessment of liquefaction potential (Marchetti 2001). Further, the construction of large diameter oil storage flexible steel tanks presents another important area where DMT can provide valuable information to accurately assess the settlement of tanks. This paper presents some of the recent applications of DMT in this area.

2 CASE 1: APPLICATION OF DMT AT MAN-MADE ISLAND IN DUBAI

An introduction to provide a background on the typical construction history and stabilization of man-made islands in Dubai is 1st presented.

2.1 *Background on Man–made Islands Construction and Stabilization in Dubai*

Dubai is part of United Arab Emirates. It lies on the Arabian Gulf. Dubai area is distributed physiographically into main land and coastal areas in a ratio of 9:1. The main land is mostly occupied by aeolian/desert sand dunes (80% of the area) with hard encrustations of local/in land sabkha’s in areas with near surface water table and thin sheets of aeolian sand overlying the local fans of gravels.

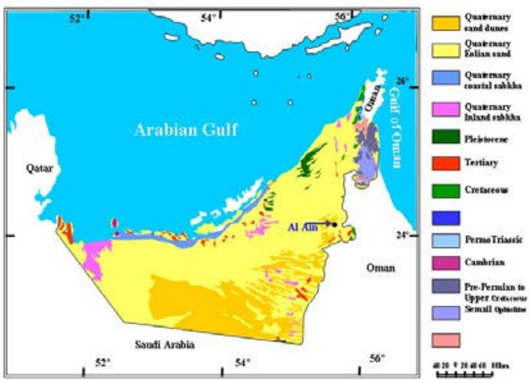


Fig. 1. Map of UAE location showing Dubai

The sand dune near coastal belt is enriched with carbonate source material from the sea-shells and carbonate rocks.Dubai is Famous of its tall towers and several man made islands.

Fig. 2. Sattelite Image of Dubai and coast line

The 50 Km long coastal belt along Arabian Gulf coast is marked by raised beach deposits of calcareous oolitic sand. The above dune and coastal/ beach sediments range in age from pleistocene to recent quaternaries deposits. Underlying these recent deposits early to middle tertiary group of rocks dominantly carbonate rich rocks, are encountered up to a depth of at least 200 m. Several Man-made Islands were constructed along the shore line of Dubai. The first was Palm Jumeira Island having an approximate diameter of 8 Km.

Fig. 3. Typical shapes of man made islands

The islands were constructed with silty sands dredged from adjacent sea bed and laid by hydraulic filling with heights ranging between 12 – 18 m above original sea level

Fig. 4. Typical photos of sand dredging operations

Subsurface geological and geotechnical conditions in the island are described as follows. Results of Typical Test Borings in the Island would show the following profile:

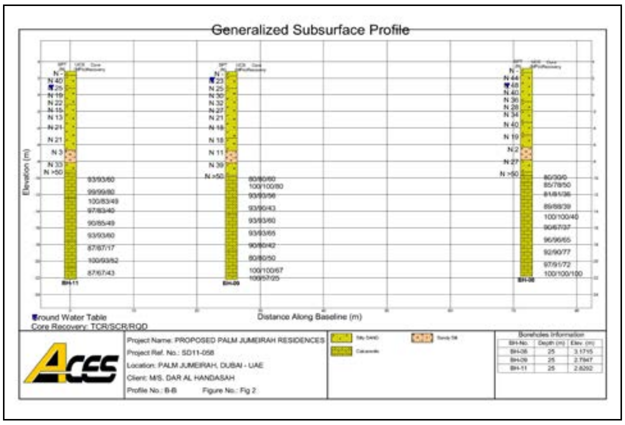


Fig. 5. Typical Subsurface conditions within PJ Island

An upper layer of man hydraulically laid sandy fill of 12-18 m in depth sitting on a thin, weak sea bed layer of very silty SAND to sandy SILT followed by Cap rock of Calcarenite and Sandstones. Grain Size Distribution & Classification of sandy fill indicates the soil is mainly of slightly silty to silty fine Sand with high carbonate content.

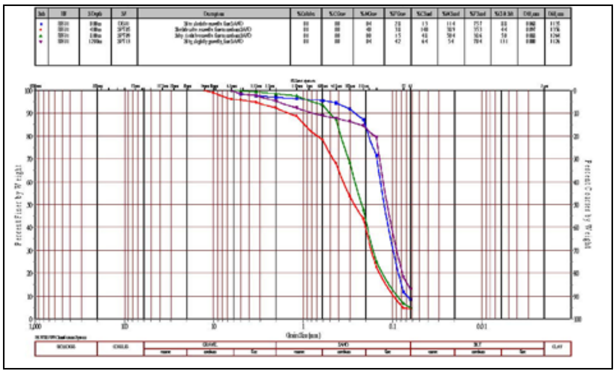


Fig. 6. Typical GSD of dredged sand

Grain Size Distribution of Typical Samples show the fill is of fine, uniform (poorly graded) Sand (SP to SP-SM as per USCS & A3 as per to AASHTO Classification). Silt content in thin localities and within sea bed layer may reach >50% but of none or low plasticity. Carbonate content exceeds 70% and is >90% for many samples.

2.2 *Ground Densification and Verifications*

Stabilization and densification of the upper sandy fill is essential to improve its Engineering performance and mitigate such hazards as liquefaction and high differential settlements and long term creep movements. Common Methods used are Vibro Compaction/ Replacement and Dynamic Compaction/RIC for shallow sand depths. Vibro

Compaction is most widely and commonly used method although other methods were also used.

Fig. 7. Typical photos of VC process and action

Vibro Compaction is applicable to sandy soils with limited % of fines (Typically <15%). Relationship between range of applicability vs CPT tip resistance and Friction ratio is commonly used.

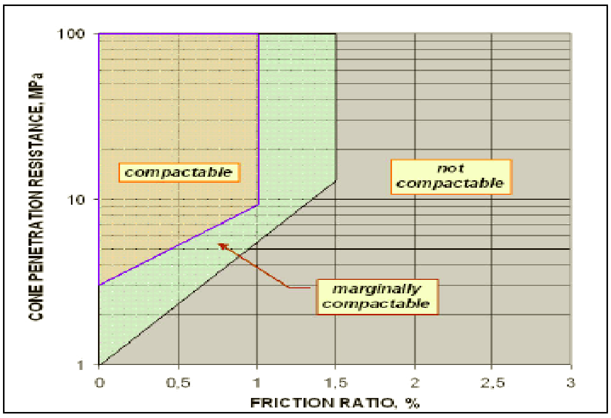


Fig.8. Schematic for suitability of VC method vs CPT

Soil Classification for Deep Compaction Based on CPT data (After Masarsch, 1991). Weak Soils with Friction ration < 1% are generally suitable up to 1.5% compaction may produce some improvement.

The use of Robertson CPT-based Profiling (SBT) (Robertson 2009) is very effective to establish the localities of high silt content / high friction ratio which are not likely compactable. Vibro compaction is well known time and cost effective method and is described by the following simple schematic drawings and typical photos. As depicted in the below figure, the vobroflot is usually jetted into the ground to the desired depth of improvement. The soil densifies during withdrawal of the vibroflot as a result of lateral and torsional vibrations while the vibroflot is repeatedly inserted and withdrawn in about 1m increments.

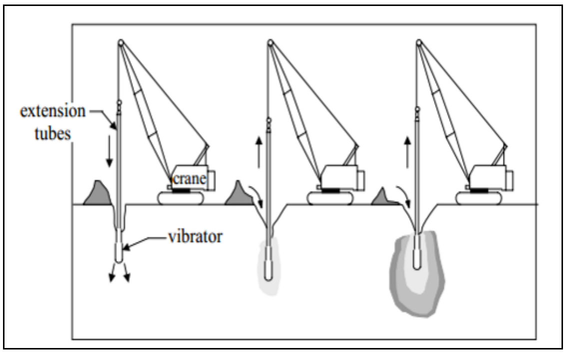


Fig.9. Schematic diagram of the equipment and process of soil densification using vibrocompaction technique (Adopted from Hayward Backer 1996).

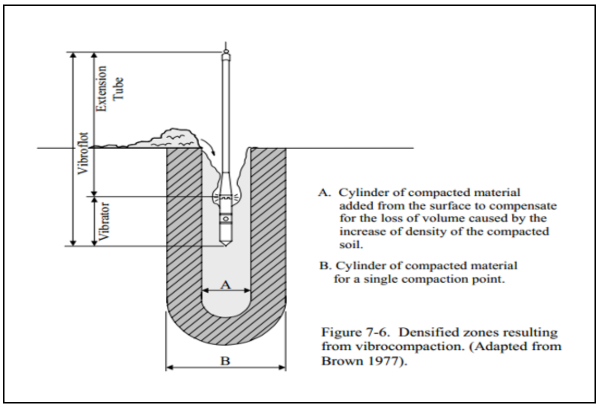


Fig. 10. Schematic of VC mechanism

The cavity that forms at the surface is backfilled with sand or gravel to form a column of densified soil (Mitchell & Gallagher, 1998). The schematic of a densified zone is further illustrated in the shown figure.

2.3 *Typical Pre-compaction CPT*

Typical CPT test result is shown in Fig.11 (Pre - Compaction).

Comments: The Pre CPT Shows tip resistance qc of <5 MPa in general. Friction ratio generally <1 to 1.5, except in thin localities.

Robertson SBT (Soil Behaviour Type Classification) (Robertson 2009), indicates Silty sand to Sandy Silt in general that matches physical samples.

Post Compaction indicates CPT tip resistance >10 MPa can generally be achieved.

Verification is also conducted with zone load tests to confirm the soil modulus and proposed surface foundation performance following deep ground improvement.

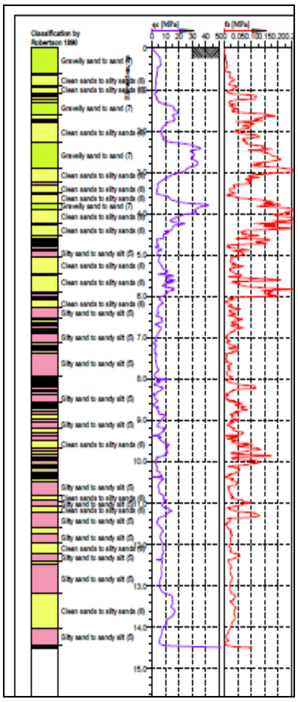
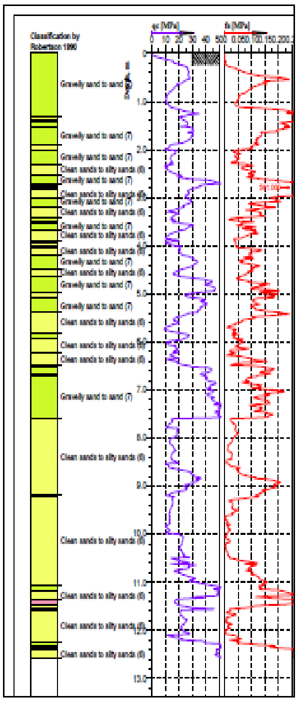
Typical pre compaction CPT result	Typical Post Compaction CPT
	

Fig. 11. Typical Pre and Post Compaction CPT results

2.4 *Zone Loading Tests*

Conducted to confirm stiffness of compacted soil mass and performance of proposed shallow foundations. Below is typical setup and results of zone load test. Settlement is monitored with horizontal inclinometer at different time/loading steps.

Fig. 12. Set up of zone load test

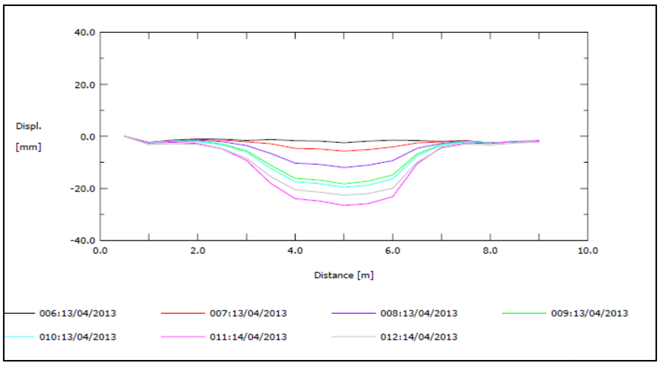


Fig. 13. Settlement monitored by horizontal inclinometer

Interpretation for modulus is accomplished by Back analysis (FE is typically adopted).

2.5 *Actual Performance*

Several roads, buildings on shallow and deep foundations exist since more than 8-10 years by today and performing very well. No published data exists about actual performance of the foundation, however the observed evidence indicates very well and satisfactory performance of the compacted earth fill. Testing showed remarkable stiffness and strength increase with aging. Fills tested after several years of laying are stiffer than young fills.

Fig. 14. Typical light weight and heavy structures in PJ

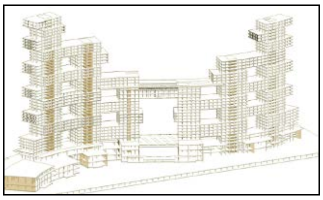
2.6 *Application of DMT in Palm Jumeira*

The site of a prestigious new project lies on the crescent Palm Jumeira.

The site area is >150,000 sq. m with 4 towers of 160-190 m height range. The architectural design of the project will make it a new land mark in Dubai.

Satellite view of PJ showing the proj. location.	Project location on the Crescent.
	

Fig. 15. General location of the site on Crescent of PJ



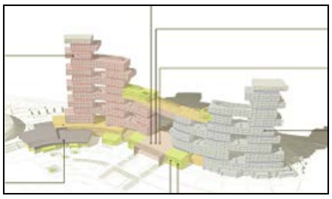


Fig. 16. View of the project Architecture

The subsurface ground conditions are typical of the Palm Jumeira in general as indicated in the below generalized subsurface profile.

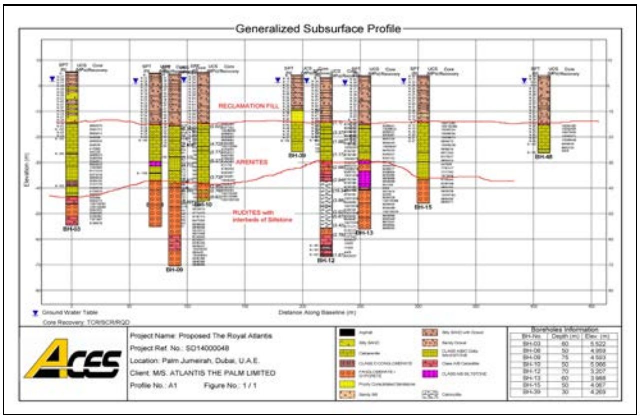


Fig. 18. Generalized subsurface profile along the site

The upper silty sand earthfill was previously deep compacted with Vibro Compaction since more than 8 years and hence the CPT tests results indicated dense conditions as indicated in the below typical CPT test result with an upper OC crust as clearly shown.

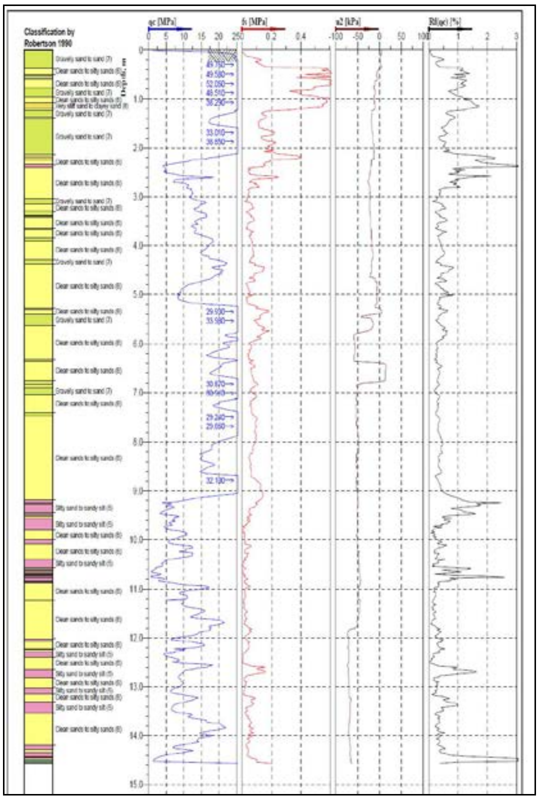


Fig. 19. CPT result indicating the high soil stiffness

Seismic studies included several seismic in-situ tests to be conducted to measure the shear wave and other dynamic properties of the site. The typical MASW (multi channel analysis of surface waves) result in the vicinity of the above CPT test result is shown. It shows the shear wave velocity of the upper sand generally exceeds 400 to 500 m/s particularly within the upper 10 m.

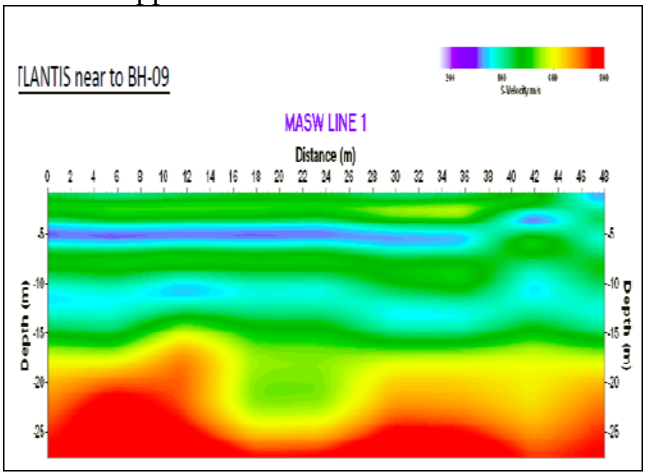


Fig. 20. Tyical MASW profile

This was explained by the over-consolidated nature of the soil due to aging effects as reflected by the CPT results. However, a more specific justification was required.

Accordingly, few DMT tests were conducted at selected locations to establish the constrained modulus (M) profile and establish the DMT (M)/CPT (qc) ratio that would indicate the OC nature of the sand. The below is the result of typical DMT (M) and CPT (qc) in MPa obtained.

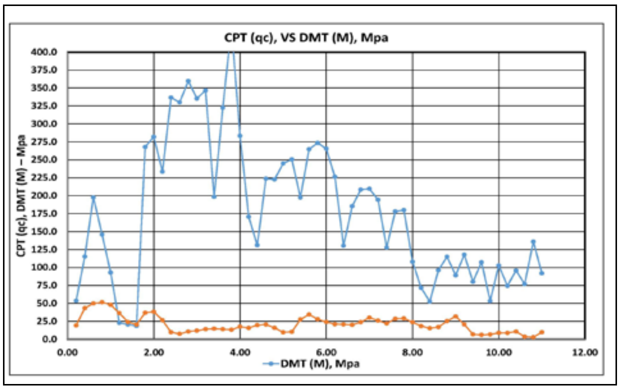


Fig. 21. DMT (M) and CPT (qc) in MPa vs Depth

The M/qc ratio is presented in the below graph and the 1m rolling average is also indicated.

M/qc ratio shows that it is greater than 8 for the upper 8 m and exceeding 25 within the upper OC crust.

This is a clear confirmation of the OC nature of the earthfill and provides the necessary justification of the MASW results.

It further provided general good matching with CPT and MASW results

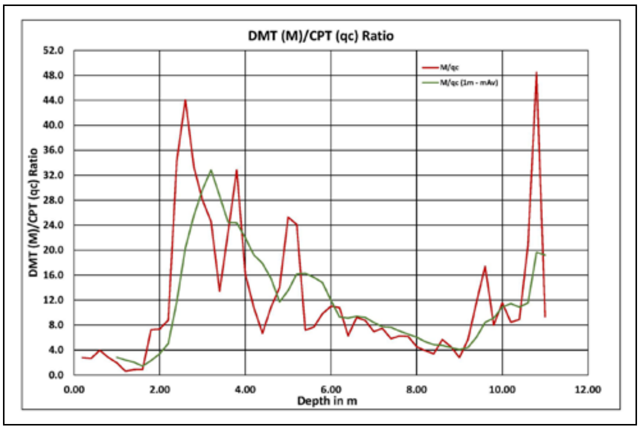


Fig. 22. M/qc ratio vs depth

3 CASE 2: SETTLEMENT OF LARGE DIAMETER OIL STORAGE TANKS

DMT was used in 3 Tank Farm Projects in the Port of Al-Fujeira in UAE for accurate assessment of the proposed large diameter tanks settlement. The oil storage tanks are typically constructed within the ports close to coastal lines where relatively poor soil conditions exist. Therefore, accurate assessment of foundation settlement is very important to decide if ground improvement is required or not. The settlement estimates depend on the assessed soil modulus (E) or constrained modulus (M). For silty sandy soils that are generally encountered in that area, the estimates are generally based on Nspt and CPT (qc – tip resistance) tests results, which would generally result in low range values of E. This is mainly as estimates of E require the use of some empirical correlations between N or qc vs E. Some of the most commonly used relations are:

$E = N_{60}$ (MPa) – Ciria Report 43, 1995
M = 4 qc for (qc <10 MPa)
M = 2qc + 20 MPa for (10 < qc < 50 MPa)
M = 120 MPa for (qc > 50 MPa)

Where, M = constrained modulus based on the Empirical method proposed by Lunne and Christopherson (1983) which is based on Calibration Chamber tests, representing normally consolidated (NC) sands (Unaged and uncemented silica Sands).

The Eurocode 7, recommends (E = 2.5qc MPa), which is also consistent with the above estimate of M for NC conditions of sand. For OC sands, the following relation is typically recommended:

M = 5 qc for (qc < 50 MPa)
And M = 250 MPa for (qc > 50 MPa)

The relation between M, Shear Modulus G and Young's Modulus E are given below based on Poisson's ratio ν.

$M/G = 2(1-\nu)/(1-2\nu)$
$G/E = 2 (1 + \nu)$

The effect of over consolidation (stress history) is a main factor that is generally underestimated with CPT based M or E estimates.

3.1 *Effect of Shear Strain/Loading Level*

The foundation settlements shall be assessed for shear strain in the range of 0.1% (This is established based on observations made for well designed actual foundations). The shown graph presents relationship that relates the E/qc vs. soil relative density (Loose / Dense), but main important, the level of loading or shear strain.

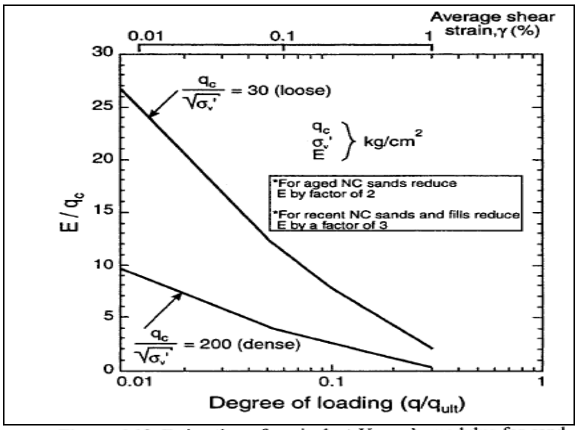


Figure 6.13 Estimation of equivalent Young's modulus for sand based on degree of loading (Robertson, 1991).

Fig. 23. Estimation of equivalent young's modulus for sand bases on degree of loading (Robertson, 1991)

For detailed description of CPT-based assessment of Engineering parameters of different types of soils, refer to "Cone Penetration tests in Geotechnical Practice" by T. Lunne, P.K. Robertson, and J.J.M Powell, 1997. Conclusion: With absence of reliable procedure to estimate OCR of sands from the results of CPT or Nspt tests, then, the above is only illustration of the amount of conservatism or risk which the interpreter has to take to estimate M or E for his calculations! For large diameter tanks (>50 m), the use of conservative estimates of Es would result in settlements exceeding the maximum permissible limit (API 650) and hence deep ground improvement and other expensive solutions would be needed. The below shows illustration of the sensitivity of settlement of the tank to the modulus E of the upper overburden soil layer. Typical settlement analysis of 68 m Dia tank for range of E modulus of the upper overburden silty Sand for 300 kpa uniform Hydrotest pressure.

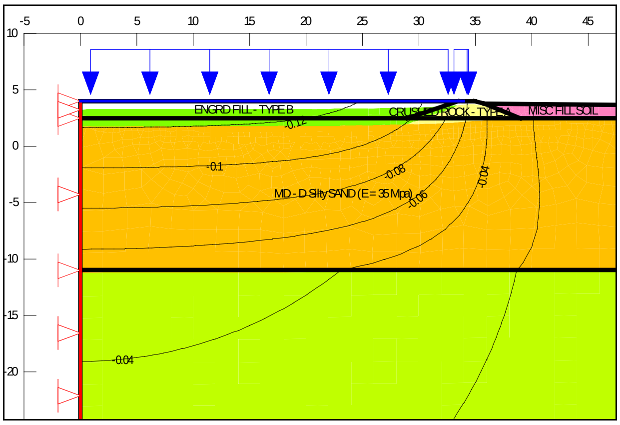


Fig. 24. E = 35 MPa – Settlement at tank edge = 60mm

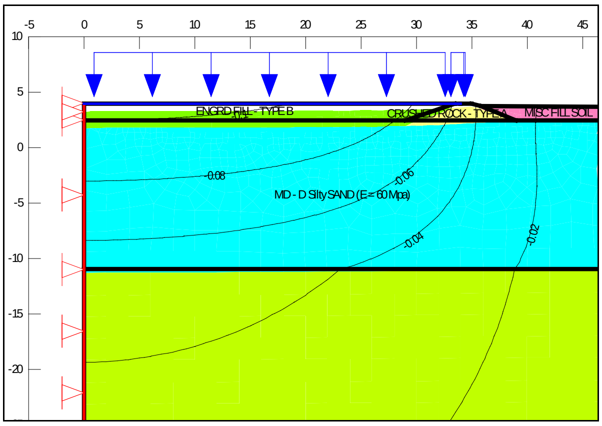


Fig. 25. E = 60 MPa – Settlement at tank edge = 45 mm

Local experience has indicated that actual tank settlements under hydrotest loading test are much less than the theoretical estimates of tank settlements based on the above Nspt and CPT methods. The actual measured settlements are typically <50% of the theoretical estimates. The cost of deep ground improvement with Vibro-Compaction or Stone Columns is several hundred thousands of dollars per each large diameter tank, in addition to several months of delay of the project. It is also important to point out that the hydrotest conducted (API 650) at the completion of construction of each tank is a preload that causes most of the permanent settlement component to take place and subsequent unloading and reloading of the tank during its operational life time would follow the more stiff reloading / unloading modulus with in-significant movements as experienced with so many existing tanks of various diameters. Therefore, the accurate and reliable assessment of the soil modulus is very significant for confidence of the estimated foundation settlement. DMT was therefore introduced to provide reliable and direct measurement of in-situ modulus of the soil and provide site – specific correlation to the other penetration tests as Nspt and mostly CPT that are widely used. Case Study: The layout of one typical site is shown below indicating the proposed storage tanks having diameters of 68 m and 36 m for the small ones. All the tanks will be designed for an average max. hydrotest load of up to 300 kPa.

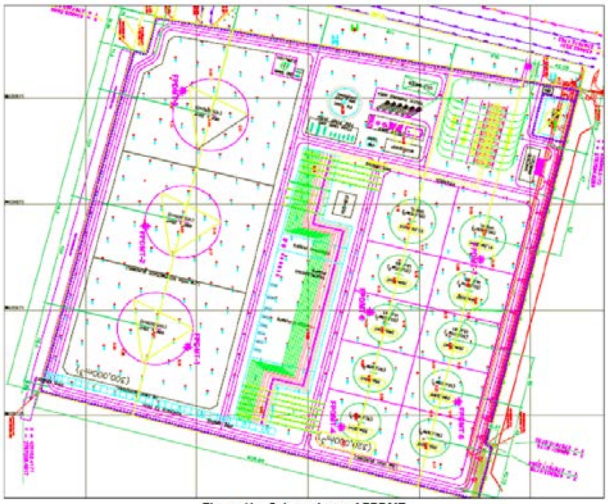


Figure No. 5: Locations of FPDMT

Fig. 26. Site layout showing main storage Tanks

Typical General Site Photographs

Fig. 27. Site photos showing leveling rockfill

Typical photo of the site showing MASW survey in progress and indicating upper rockfill leveling layer. The main design criteria is that the shell plate settlement under max. load not to exceed 50 mm (preferable), however, settlements up to 100 mm settlement may be tolerated by the owner, provided the settlements are uniform (differential settlements between edge points at 10 m arc length not to exceed 13mm) and most of the settlements to be of short term nature (to take place during the hydrotest). The investigation for this Tank farm project consisted of a number of geotechnical boreholes drilled up to 40m depth, CPT and DMT tests in addition to geophysical survey with MASW (Multi Channel Analysis of Surface Waves). The typical results obtained are shown in the below diagrams indicating the MASW survey results, typical CPT, Cross Sectional Profile, and DMT results.

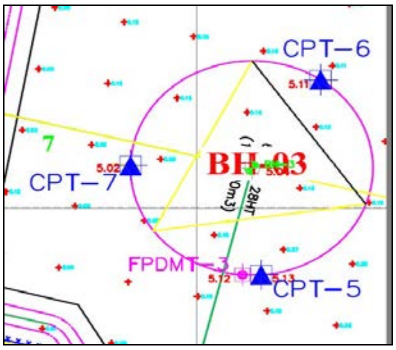


Fig. 28. Layout of BHs (1 at centre), CPT (3 on edge) & DMT (1 on edge) for each large diameter Tank

Fig. 29. Layout of 3 MASW lines covering all tanks locations

The typical geological cross section indicated the site is made up of thin upper rockfill layer of 1-4 m thickness that was constructed to provide a level platform with thickness increasing towards the sea side, underlain by medium dense to dense fine silty sand that is followed by bedrock of very weak to weak Sandstone and conglomerates. GWT exists at 2.5 m depth approximately. Generalized subsurface profile showing the main soil and rock layers

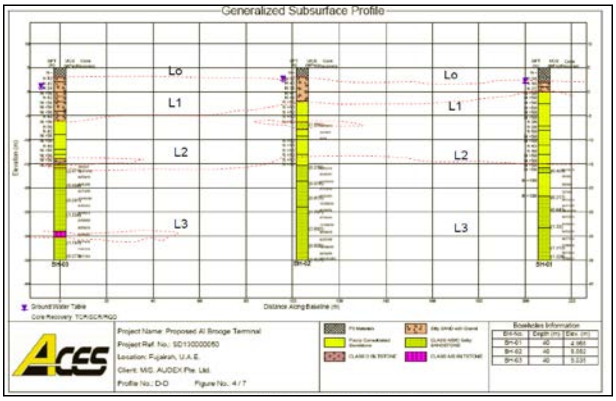


Fig. 30. Subsurface profile indicating general homogeneity

Graphical presentation of Nspt results of all boreholes indicating Medium dense to Dense soil with few localized weak lenses / pockets. The DMT tests also indicate similar behavior as indicated below.

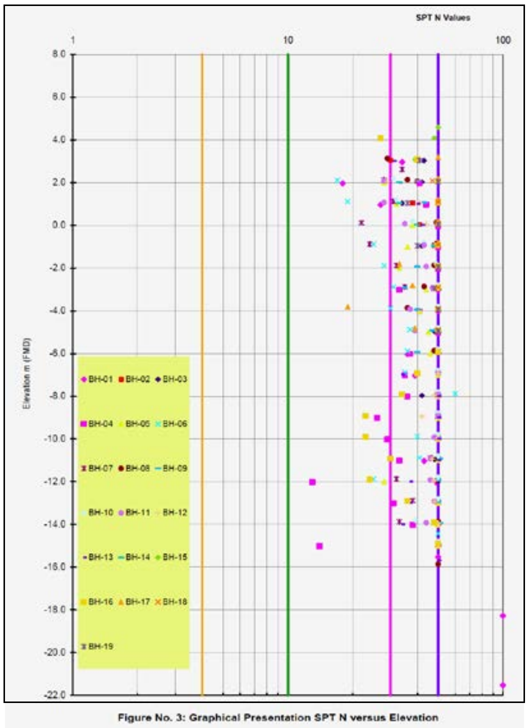


Fig. 31. Nspt Vs elevation from all boreholes

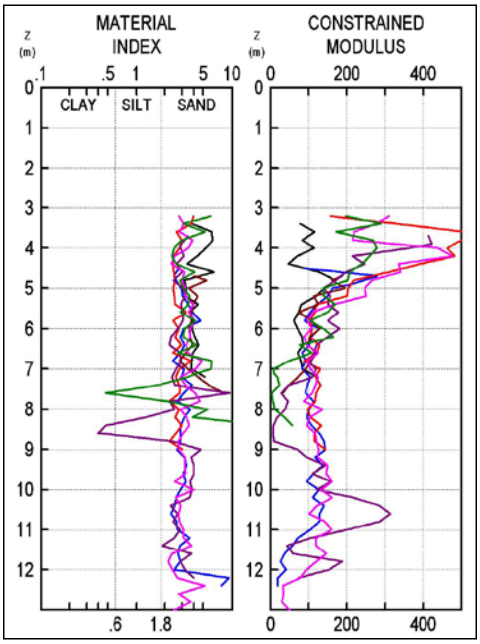


Fig. 32. Summary of all the 7 DMT tests conducted

The DMT results indicate OC upper soil followed by weaker materials. Typical CPT test result indicating 3 m of pre-drilling though rockfill cover, and also showing to OC sand followed by Medium dense silty Sand.

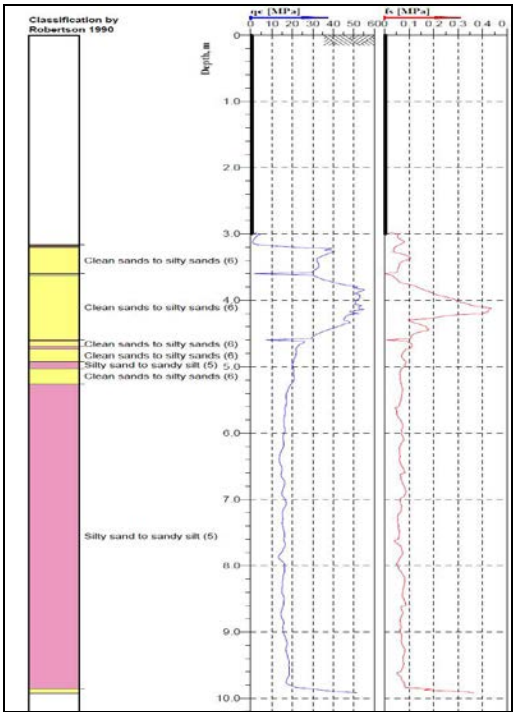


Fig. 33. Typical CPT Test Result with SBT profiling

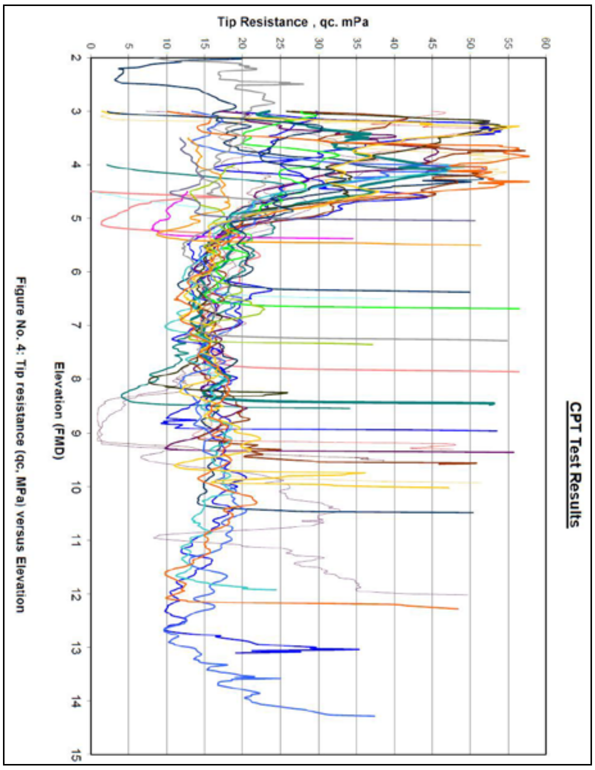


Fig. 34. All CPT results vs depth (qc (MPa) vs depth (m))

CPT (qc) profile of all tests indicating upper very dense OC crust followed by medium dense to dense silty sand with qc of 15-20 MPa, with localized few weak pockets. Good matching between Nspt and CPT results is noticed. The main parameter controlling the settlement estimates of the sand is obviously the modulus of deformation E.

Based on Nspt and CPT results, Es average was estimated to be 35-40 MPa, resulting in settlements exceeding 50 mm at the large diameter tank edges. Based on direct measurement of DMT, M average was slightly around 100 MPa, and E is >60 MPa. The typical DMT (M) / CPT (qc) ratio is shown in the below graph.

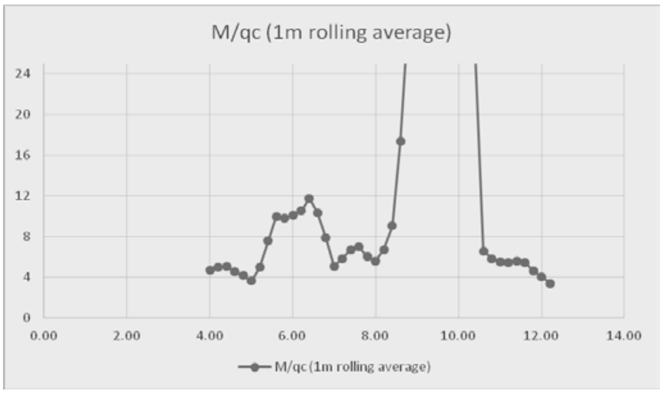


Fig. 35. M/qc ratio obtained

It shows that M/qc may safely be taken as 6 instead of 4 as adopted for NC sand, which means that for average qc = 15 MPa, then M = 90 MPa and E will be >60 MPa. This is at least 50% greater than the typical CPT based estimates adopting NC sand conditions. The final recommendation suggested that no deep ground improvement is necessary for settlement limitation. Vibro Compaction was only suggested for the main tanks to improve the stiffness within potential weak localities as indicated by the CPT and some of the DMT results. The project construction phase has commenced and the next step will be the observation of the results of actual hyrotests that are planned for each of the tanks, which will provide the final confirmation on the foundation ground behavior. As stated previously, previous experience has indicated that the actual results of settlements are less than the theoretical predictions. This will increase the confidence in the methods adopted for the soil modulus estimates.

4 CONCLUSION

The use of DMT in Dubai is relatively recent. The early applications presented in this paper indicate that DMT would be of great value to identify the effects of previous stress history and over-consolidation of either man made and stabilized embankments or natural sandy soils, resulting in better understanding of actual foundation soil behavior and avoiding expensive foundation solutions that may not be necessary. With future accumulated experience, a more rich data base would be established that would increase the level of confidence of the use of DMT for in-situ modulus estimates and to provide a site specific calibration to other commonly used penetration tests as CPT and SPT. The documentation of results of full scale hydrotests on large diameter storage tanks provides great opportunity for that purpose. Further, applications for design and quality control of deep ground improvement projects and liquefaction potential assessment form other wide area of future use of DMT in Dubai.

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