

Case Reviews of the Cone Penetration Tests as a Geotechnical Decision Support Tool in the Niger Delta

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Abstract: This paper highlights the extended applications of the Cone Penetrometer Test (CPT) for geotechnical decision support in the determination of depth of foundation embedment, optimum depth of excavation, vertical settlement distribution, determination of total consolidation settlement and the assessment of deep shear failure risk with the use of case studies in the Niger delta. These applications are more critical in site conditions where retrieval of soil sample is difficult due to extremely weak or where soil layers are very thin such that are missed during regular boring programmes. In these instances, the (CPT) serves as a vital geotechnical analysis for better and informed decisions, offering economical, high-resolution, nearly continuous data for accurate identification of soil layers and boundaries, efficient and reliable data for various applications, including pavement, swamp rig and offshore foundation design. The CPT data can often be integrated with data from other sources, processed through various analytical and modelling techniques to unravel findings that facilitate strategic and operational choices. Its advantages of rapid data acquisition, cost-effectiveness, and the ability to characterize soil conditions over large areas, which aids in foundation design and risk assessments, provide the enablement for geotechnical analysis and decision support.

I. Introduction

The use of the Cone Penetrometer in the Niger Delta dates back to the 1980s. Hardly any major geotechnical investigation in the region excludes the CPT (Abam and Okagbue 1997). The CPT is a powerful tool for the understanding and characterization of soils, offering rapid, continuous, and behavior-based *in-situ* data that improves soil classification, stratification, and property estimation. This is especially valuable for problematic soils (e.g., liquefiable, sensitive, peaty, collapsible, expansive), where behavior under load is critical and traditional sampling may be unreliable or disturbed. CPT is equally effective for classifying soils based on behavior type (SBT), especially when traditional sampling is difficult or when undisturbed samples are hard to obtain (Sandven and Watn 1995, Schneider *et al* 2008, Macedo *et al* 2024). The key roles of CPT in problematic soil characterization include behavior-based soil classification in which CPT provides continuous profiles of cone resistance, sleeve friction, and pore pressure, enabling soil behavior type (SBT) classification systems that are more closely linked to *in-situ* behavior than traditional textural methods (Eslami, *et al*; 2017).

The capability of the CPT (and CPTu) for assessing soil layering and variability is well documented (e.g. Lunne *et al.*, 1997). Reliability of the CPT in soil classification has witnessed considerable improvement as demonstrated by Robertson, (2016). The development of updated SBT charts and new classification formats (e.g., triangular charts using q_c , f_s , and u_2) in the last 10 years, have resulted in improved identification of soils, particularly problematic soil types. According to Farahbakhsh & Ching (2023), the CPT's high-resolution, nearly continuous data allows for accurate identification of soil layers and boundaries, even in highly variable or thinly interlayered soils enabling very reliable soil stratification and spatial variability to be determined. With advances in Artificial intelligence, advanced probabilistic and machine learning approaches using multiple CPT soundings have further enhanced the detection of heterogeneity and stratification, which is crucial for problematic soils that often exhibit abrupt changes in properties (Marzouk, *et al* 2024).

The value of the CPT for identifying variability within similar soil units was demonstrated by Ramsey, (1997) in Figure 1, using data from Site Z. Although the eight CPTs at this site were separated laterally by approximately 25km, the cone resistance profiles at seven of the eight locations are similar indicating a relatively uniform depositional environment over the area of interest. The anomalous cone resistance profile at the eighth site was later attributed to the presence of a nearby salt intrusion (diapir), which had increased the lateral effective stresses in the vicinity of the test.

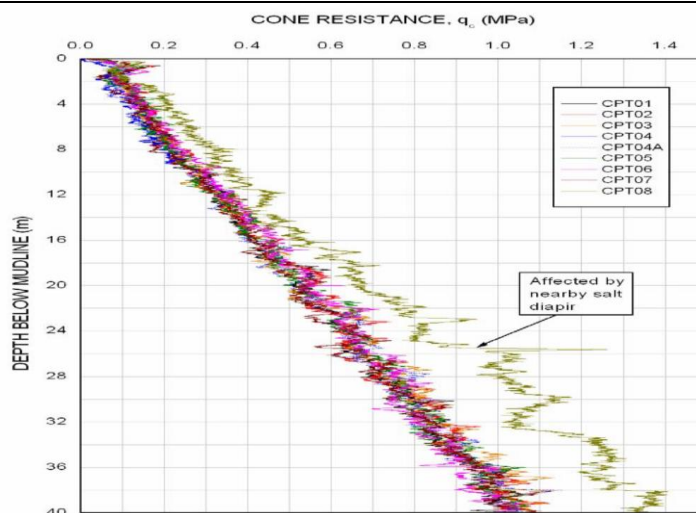


Fig. 1: Identification of anomalies (After Ramsey 1997)

In the same vein, CPT data can be directly transformed to estimate key soil parameters (e.g., strength, density, plasticity) and to quantify uncertainty and spatial variability, which are essential for risk management in geotechnical design (Mayne 2007b, Mayne and Peuchen 2012, Senneset et al 1989). Thermal properties have also been correlated with the CPT (Vardon & Peuchen 2021). According to Robertson (2009) these published correlations provide a useful means of predicting soil property values from CPTs. Modern computational models (Yu 1998, Tumay 2008, Uzielli et al; 2013, Wang et al; 2018) relying on probabilistic approaches and machine learning have been used to reduce uncertainty and further refine estimates of soil properties. CPT correlates strongly with other site investigation tools (e.g., SPT, ERT), thus providing a robust framework for comprehensive soil characterization and cross-validation, especially in complex or problematic ground conditions (Tokimatsu, et al 1995, Karlsrud et al 2005).

In urban areas, CPT is favored because of its minimal disturbance and in offshore or deepwater investigations due to its adaptability to various deployment platforms (Lehane, 2011). Challenges in interpreting CPT data, such as reliance on site-specific correlations, are acknowledged, emphasizing the need for careful analysis and when the need arises, correlation with borehole and laboratory data which significantly enhances the benefits. For a better understanding of soils condition, Gumilar et al (2024) carried out correlation of CPT, SPT and ERT data. Its rapidity, economical and detailed subsurface profile capability as often recommended it as a complement or alternative to borehole sampling (Ramsey, 2010). Its versatility and expanding applications to Environmental Site Characterization with the incorporation of advanced sensors for soil moisture, resistivity and contamination detection, thus broadening its application scope. The development of the seismic cone and the seismic piezocone (Campanella, et al; 1986, Mayne 2014) has also extended the use of CPT in the design of dynamic foundations.

While the CPT offers numerous advantages, its effectiveness can be limited by the need for site-specific correlations and potential challenges in data interpretation, which may affect decision-making in complex geotechnical scenarios. The Cone Penetration Test (CPT) offers several advantages as a decision support tool in geotechnical engineering compared to traditional site investigation methods. Its ability to provide continuous profiles of soil properties and its cost-effectiveness make it a preferred choice for many applications.

Key benefits of using CPT include: Continuous Data Acquisition, Enhanced Accuracy and Efficiency and Cost-Effectiveness. CPT provides a continuous record of soil resistance, allowing for detailed stratification and identification of soil layers, which is often more challenging with discrete sampling methods (Marzouk et al., 2024). This continuous data helps in understanding soil variability and aids in the design of more effective investigation layouts (Marzouk et al., 2024). The integration of machine learning with CPT data enhances the accuracy of soil classification and parameter estimation, leading to better-informed engineering decisions. CPT is quicker to deploy and can cover larger areas in less time compared to traditional drilling methods, resulting in significant time savings.

The use of CPT can lead to reduced costs in subsurface investigations, as it minimizes the need for extensive laboratory testing and multiple boreholes. It has been shown to correlate well with traditional methods, providing reliable data without the associated costs of extensive drilling (Stern & Fox, 2011). While CPT presents numerous advantages, it is essential to acknowledge that traditional methods still hold value, particularly in complex geological settings where direct sampling may be necessary for validation or when specific soil characteristics need to be assessed in detail.

Comparison with similar tools

The use of Cone Penetration Testing (CPT) in geotechnical design offers several advantages over traditional methods like the Standard Penetration Test (SPT). By providing a continuous profile of soil properties, the CPT enhances the resolution of stratigraphic interfaces and allows for more precise identification of soil transitions. This capability leads to improved site

characterization, which is crucial for effective geotechnical design. Furthermore, through continuous profiling of soil layers, the CPT is able to capture small changes in stratigraphy that SPT may miss (Marzouk et al., 2024). The method provides detailed measurements of cone tip resistance, sleeve friction, and pore water pressure, which are essential for understanding soil behavior (Robertson 2014).

The integration of CPT with traditional methods has refined boring programs, leading to more efficient site investigations and reduced costs (Marzouk et al., 2024). CPT's expediency and repeatability facilitate quicker data collection compared to SPT, which can be more labor-intensive (Robertson 2014). Recent studies emphasize the importance of data quality in CPT, with ongoing revisions to international standards aimed at enhancing reliability. CPT minimizes soil disturbance during testing, preserving the integrity of the soil structure, which is particularly beneficial in partially-cemented soils.

Although SPT remains widely used due to its established methodology and familiarity among practitioners, the CPT offers significantly more benefits because of the wide range of applications. Even so, it can be argued that the integration of both methods can provide a more comprehensive understanding of subsurface conditions, leveraging the strengths of each technique for optimal geotechnical design outcomes.

CPT data offers improved reliability for geotechnical design by providing continuous profiles of soil properties, enhanced data quality through revised standards, and better calibration methods, which address limitations of traditional methods like SPT, leading to more accurate Geotechnical Design Models. CPT data offers precise information on undisturbed soil structure, minimizing disturbances that can occur with SPT. This capability enhances the accuracy of geotechnical design profiles, particularly in partially-cemented soils, making CPT a vital complementary test to SPT. CPT data offers continuous profiles of soil resistance, providing more detailed subsurface information than SPT. It enables accurate determination of geotechnical parameters, enhances understanding of soil behavior, and supports reliable input for advanced dynamic analysis in geotechnical design.

A major disadvantage of performing CPTs is the limited thrust that can be applied to the cone, either due to the limitation on the magnitude of reactive force, or due to the risk of damage to the cone. As a consequence, CPTs tend not to be the tool of choice for accurately assessing the depth to rock-head (i.e. bedrock), or deep soil profiling in coarse-grained soils, or heavily overconsolidated fine grained soils. This does not suggest, however, that boreholes always produce better results.

II. Methods Of Investigation

Cone Penetration Testing (CPT)

Hydraulically operated, GMF type, static hydraulic penetrometer of 10 KN capacity was used in the cone resistance soundings in accordance with ASTM D-5778. Continuous sounding procedure was adopted in the test. The Cone Penetration Tests were driven to refusal at each of the case study sites.

Boring

A Conventional boring method that consists of the use of the light shell and auger hand rig was used in the boring operation. All samples recovered from the boreholes were examined, identified and roughly classified in the field. Standard Penetration Tests (SPT) were performed every 1.5m advance through cohesionless soils. The main objective of this test is to assess the relative densities of the cohesionless soils penetrated. The penetration resistance profiles in blow counts with depth are indicated on the borehole logs. The lithology of the boreholes are presented in the **Appendix**.

Bearing Capacity Computations and Analysis

The ultimate net bearing capacity q_n of a shallow foundation was calculated using the Terzaghi's relationship expressed as:

$$(\text{for strip}) q_{nu} = CN_c + P_o (N_q) + 0.5\gamma BN_\gamma \quad 1$$

where: γ = the bulk density of the soil below the foundation level

C = the undrained shear strength of the soil

P_o is the effective overburden pressure at the foundation level

N_c, N_q, N_γ = Terzaghi's bearing capacity factors obtained from charts

In adapting to the CPT, undrained strength values calculated as shown in equation (2) were substituted into equation (1):

$$C_u = \frac{q_c - \sigma'_{vo}}{N_k} \quad 2$$

Where

$q_c - \sigma'_{vo}$ = net cone resistance

N_k = Cone factor

Using combinations of these relationships, the allowable bearing pressures was obtained for various foundation depths after applying a Safety factor of about 2.5

Settlement of Foundation

Foundation Settlement was predicted for a net load of $\Delta\sigma$ using the relationships:

$$S = m_v \Delta\sigma \cdot H_o \quad 3$$

Where s = total settlement

H_o = thickness of compressible layer

m_v = coefficient of volume compressibility

$\Delta\sigma$ = increase in vertical stress due to applied pressure

Prediction of the settlement is made from the summation of the vertical strains at each test interval caused by the foundation load as described by Abam and Tse (2009). The soil beneath the foundation is divided into layers and the coefficient of volume compressibility m_v is obtained for each layer. The method of prediction generally used is that proposed by de Beer and Martens (1957), Kulhawy and Mayne (1990). Estimating Soil Properties for Foundation Design where the constant of compressibility is given as (Smith and Pole 1980):

$$C_s = 1.9 \frac{C_r}{P_{o1}} \quad 4$$

Undrained strength was evaluated using the relationship:

$$C_u = (q_t - \gamma' dh) / N_k \quad \text{with } N_k \text{ taken as 15 for the region} \quad 5$$

This value of undrained strength was then substituted into Terzaghi equation for bearing capacity as shown in equation

$$\text{Bearing Capacity} = (5.7 C_u + \gamma' dh) / FS \quad 6$$

$$\text{Compressibility } C_s = 1.9 q_t / (\gamma' dh)$$

$$\text{Net load } Q_{\text{Net load}} = \frac{(\Delta\sigma \times x y)}{(2 + x)(2 + y)}$$

Incremental Settlement was then evaluated by:

$$\Delta S = 2.3 dh / [C_s \log \frac{(\Delta\sigma_o' + Q)}{\Delta\sigma_o'}] \quad 7$$

Cumulative Settlement was evaluated by summing the incremental settlements using the relationship:

$$\sum_{dt=0}^H \Delta S_i + \Delta S_{ii} + \dots \quad 8$$

The percentage Settlement was evaluated by the relationship:

$$\frac{\sum_{dt=0}^H \Delta S + \Delta S_i + \dots}{H} \times 100\% \quad 9$$

Where:

dt = thickness of test lamination

H = Depth of sounding

P_{o1} = effective overburden pressure at point tested.

C_s is substituted into, $p_i = \frac{H}{C_s} \text{Loge } \frac{P_{o2} + \Delta\sigma_z}{P_{o2}}$ to obtain the consolidation settlement.

$$C_s \quad P_{o2}$$

Where $\Delta\sigma_z$ = vertical stress increase at the center of the consolidating layer of thickness H .

P_{o2} = effective overburden pressure at the center of the layer before any excavation or load application.

Case Review 1: Idiagbon Road, GRA, Port-Harcourt, Nigeria

The site is on the flood plain of the Ntawoba creek with a number of buildings and with a perimeter fence in place. Most of the buildings are uninhabited. A few buildings have developed dampness caused by excessive floor wetness due to ingress of groundwater. Some others have developed severe cracks (Fig.2) consistent with poor control of differential settlement.



Fig.(2) Differential settlement evidenced by cracks on the building

Geologically, this site is underlain by the Coastal Plain sands, which in this area is overlain by soft-firm silty clay sediments belonging to the Pleistocenian Formation. The general geology of the area essentially reflects the influence of movements of rivers, in the Niger delta and their search for lines of flow to the sea with consequent deposition of transported sediments. The surface deposits in this area comprise silty sand- and sandy clays. The sandy layers underlying the top clay are predominantly medium to dense in relative density and fine-medium in grain sizes.

The Lithostratigraphy of the project area with the undrained strength profiles of two diametrically opposite test points derived from CPT superimposed is shown in Fig.(3). The evaluation uncovered two primary soil zones beneath the site. A top layer of soft-firm silty and sandy clay occurring between (0.0 – 7.0m) underlain by fine-medium particle sized sand which is initially loose but becomes increasing medium dense in relative density with depth. The undrained strength of the silty sandy clay varied from very low strength (20kN/m^2 to 100kN/m^2), between 1-3m (Fig.4) with corresponding moderate to high compressibility. The resultant consolidation settlement ranged from 80mm to 240mm, which in addition to being excessive triggered differential settlement with the resultant development of cracks on the building as evidenced in Fig. 2.

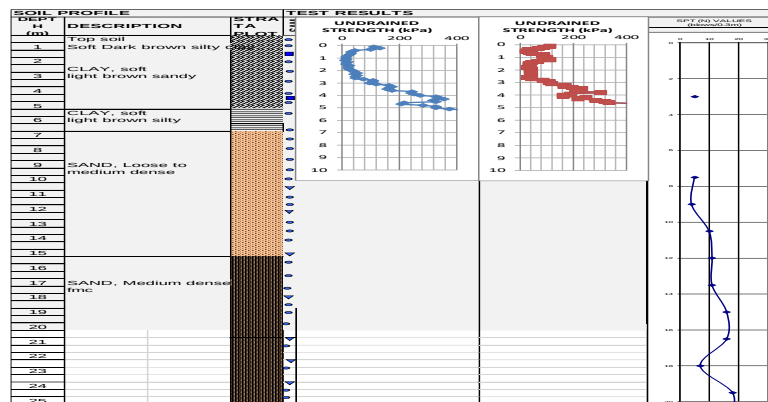


Fig.(3) Stratigraphy Underlying project area

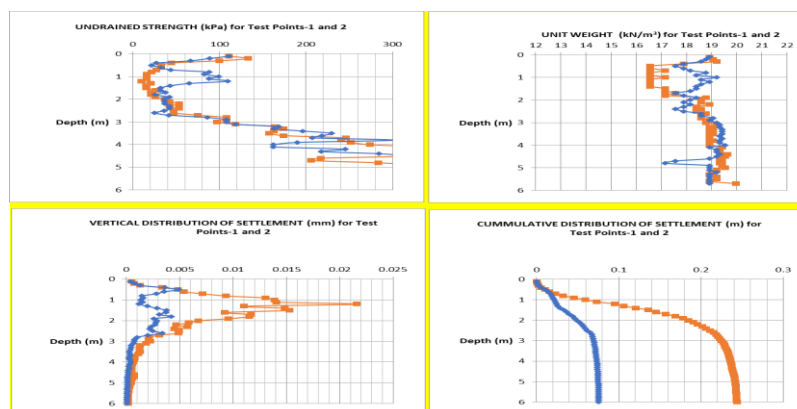


Fig.(4) Comparison of soil properties at Idiagbon Street, PortHarcourt

Case Review 2: CPT use for foundation construction decisions

This case study considers the foundation construction of a large storage tank connected to rigid skid systems intolerant of settlement exceeding 25mm. The project location is underlain by tropical lateritic soils, comprising silty and sandy clay (Fig.5). These soils exhibit lateral and vertical variations in strength and compressibility, and are frequently affected by seasonal changes in its moisture levels. The undrained strength which varied from 50kN/m² to 110kN/m² was considered inadequate for the foundation of a large storage tank having diameter of ϕ 76m and a height 22m, generating a net load (stress increment) of 220kN/m² when fully loaded. The computed consolidation settlement from this stress increment ranged from 150mm to 200mm with the top 6m contributing roughly 84% (Fig.6). This was considered excessive and unsatisfactory.

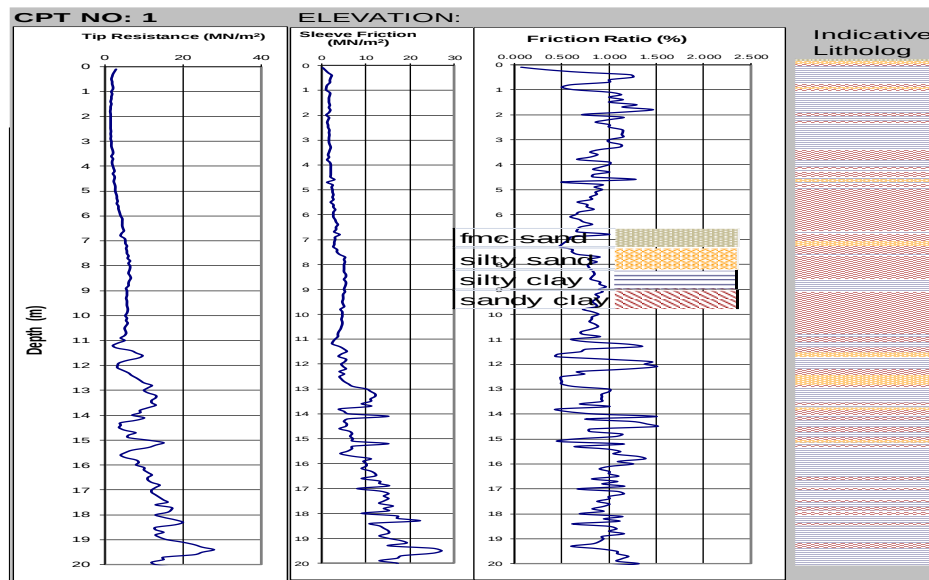


Fig.(5) Use of CPT in lithological identification and stratigraphic boundary delineation

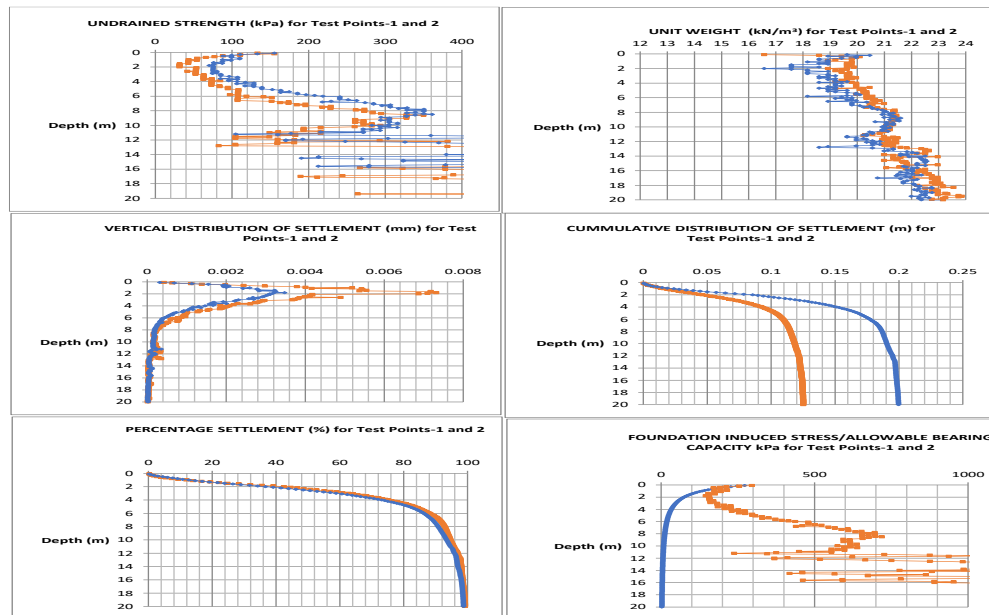


Fig.(6) Derived soil properties

Secondly, the soils within the top 3.6m exhibited a bearing capacity that was consistently lower than the induced stress increment (Fig.7a). This implied that the soil was incompetent and unable to safely support the storage tanks without the risk of failure. A similar comparison was carried out in a neighbouring location with slightly improved soil conditions at which several storage tank facilities were planned (Fig.7b) which showed that only marginal additional excavation may be needed even when the stress increment is doubled. Due to the combination of poor bearing characteristics and high total settlement which is unacceptable for the rigid skid systems, it was decided that the top 4m of the soil be excavated and replaced by sand compacted in lifts of 200mm as described in detail by Abam (2016). The risk of failure was subsequently evaluated and found to be considerably reduced.

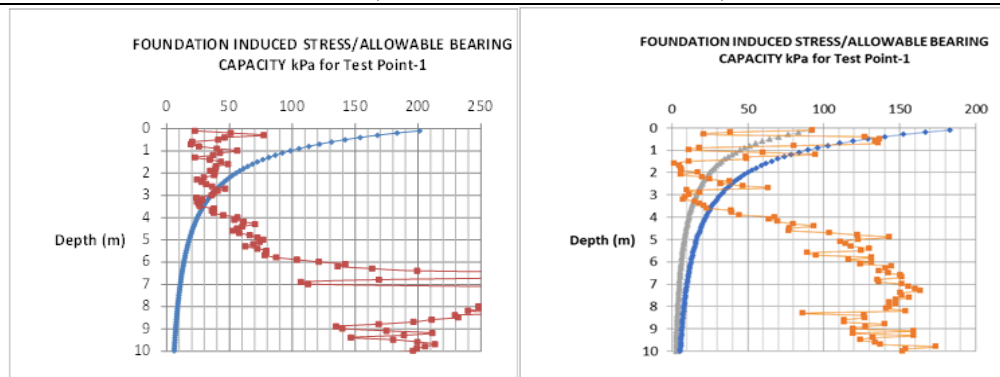


Fig.(7) Assessing the depth of excavation

Case Review 3: Swamp Rig Operation and Assessment of Deep Failure Risks

This case review explores Swamp rig operations at multiple locations within the Sombreiro-Warri deltaic plain where the geology comprises very soft, underconsolidated silty clay sediments with considerable difficulty for sediment recovery within the top 4m during drilling. Derivation of undisturbed soil properties therefore relied mostly on CPT. A vertical profile of the undrained strength, allowable bearing pressure and unit distribution of consolidation settlement for two representative locations from the riverbed are presented in Figs.(8 and 9) with values based on laboratory test superimposed. The total consolidation settlement was derived from the cumulative summation of the unit contributions as described in equations (7 and 8) which depth profile is shown in Fig.(8).

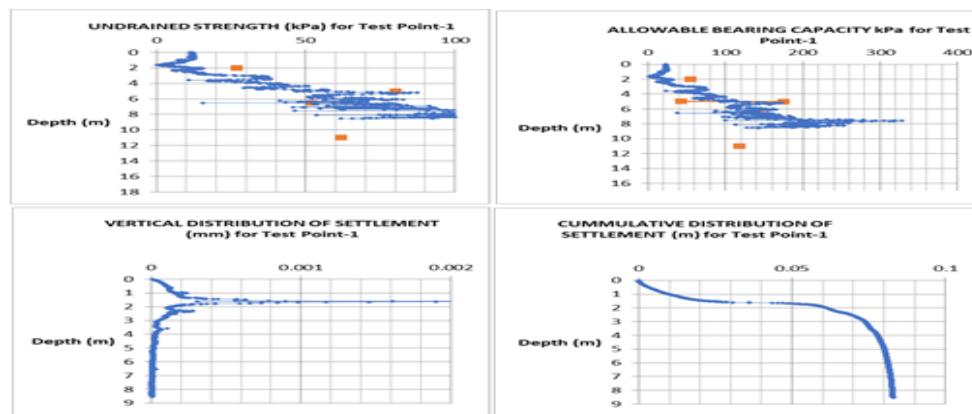


Fig.(8) CPT derived soil properties

The two locations show very different undrained strength as well as bearing resistance behaviours. The movement of the swamp rig into drilling position would require excavation of about 4m depth from the ground surface exposing stronger formation as in the case of Fig.8 and weaker formation as shown in Fig.9. Both cases present some risks of foundation failure at 0-2m in the case Fig.10(a) and between 5m – 6m depth in the case of Fig.10(b). The management of these risks will also require different approaches. Whereas additional 2m thick excavations can result in risk reduction as illustrated in Fig.10(a), backfilling with sand by 2m would be advised for the case in Fig.10(b). By backfilling, the induced stress increment at the vulnerable depth will be lowered thus reducing the risk of deep failure.

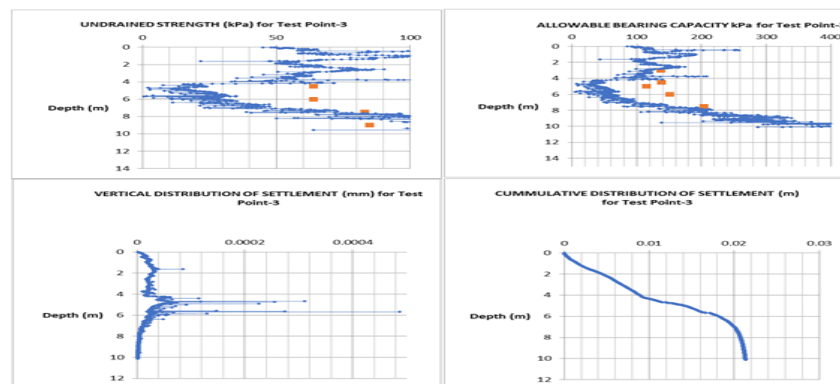


Fig.(9) CPT derived soil properties

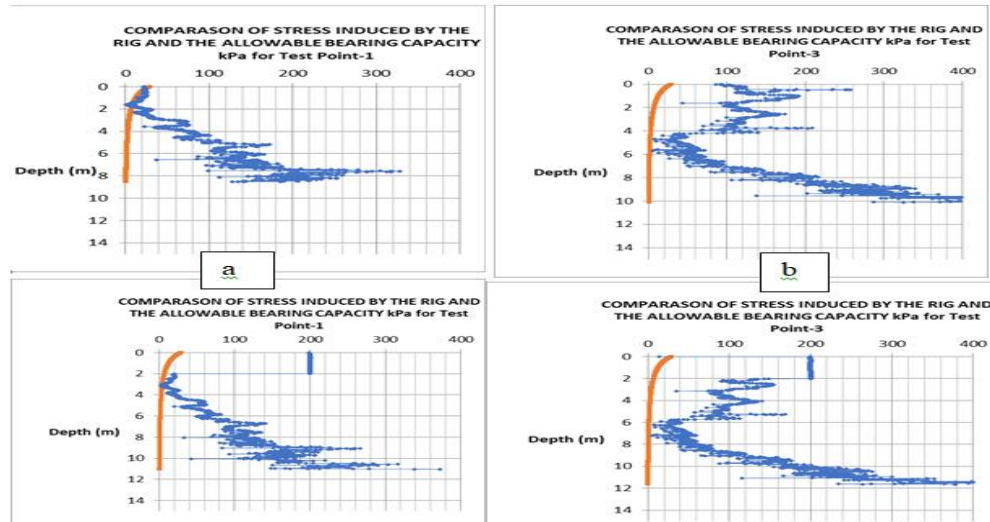


Fig.(10) Deep shear failure risks assessment

Analysis of the results in another example (Fig.11) show that the bearing capacity is considerably improved, however the bearing resistance of a thin section of the natural soil below the sandfill is lower than the stress increment induced by the rig. This could be taken care if the thickness of the sandfill is increased to 2.5m. Secondly, the predicted consolidation settlement values are considerably reduced to between 20mm and 60mm, which to a large extent can be accommodated in the drilling process.

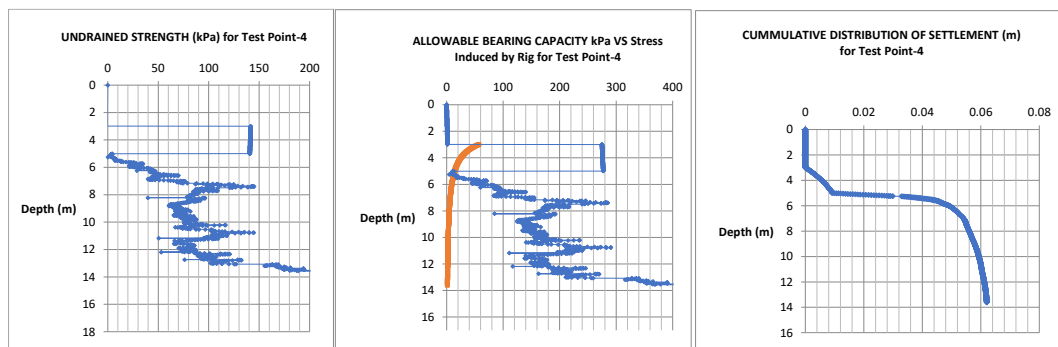


Fig.(11) Predicted foundation performance after sand replacement

In order to drill at this location some riverbed improvement is required. It is recommended that an additional 2.5m depth be excavated from the riverbed and backfilled with granular material preferably sand. The sand backfill would provide the required bearing resistance to prevent shear failure of the sub-soil beneath the rig. Secondly, it will reduce the settlement to an acceptable level and ensure operational stability of the rig.

III. Conclusion

The CPT is an excellent tool for assessing soil layers and soil variability. CPT data offers increased resolution, improved precision in stratigraphic transitions, faster site characterization, reduced costs, and enhanced repeatability compared to traditional methods like SPT and in this way enhances sustainability. It allows for continuous soil property profiles and better assessment of subtle changes in soil layers. CPT offers flexible, capacity for a variety of geophysical probes, enabling the determination of a wide array of subsurface properties. It overcomes limitations of traditional methods like SPT, particularly in difficult problematic soils, enhancing data quality and reliability enabling applications for risk assessment and management. Although CPT has limitations, in terms of guaranteeing target penetration in very dense granular soils or in fine-grained soils containing coarse gravel-sized, or larger, inclusions, it is in no way less desirable than the borehole. Results of CPT when complimented by laboratory testing significantly enhances the benefits of CPT.

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