ABSTRACT: Soil investigation is a pre-requisite for design and analysis of any important foundation. In soft clay, the recovery of sample is normally less in length than attempted. Level of disturbance is generally significant in the samples which have implication in the quality of soil data. Cone Penetration Test (CPT), which is an in-situ test, proves to be a proper complement to the deficiency in the process of investigation by sampling and subsequent laboratory tests. This paper discusses the various aspects of this in-situ soil test highlighting its important role in the design of different kind of foundations for offshore, especially those related to offshore exploration of oil and gas.

INTRODUCTION
Cone penetration test is carried out by pushing a metallic cone with a friction sleeve into the soil. It generally has 60 degree tip angle with a projected cross sectional area of 10 cm² or 15 cm² of the base. The standard rate of penetration is usually 2cm/sec. Tests, where pore pressure is also measured is called CPTU or PCPT (piezo cone penetration test). Resistances are measured to find out the type of soil, sequence of layers and their properties. Usually, the sensors in the tool measure three basic parameters. They are cone resistance (qc), sleeve friction (fs) and pore pressure (u) as the tool is penetrated in the soil. There are correlations between the measured resistances and soil parameters. Keeping in view the importance of this in-situ test, it is performed in almost all the important soil investigation projects as a primary in-situ test in the offshore prior to installation/construction of foundation. Design and installation of foundation in soft clay in the offshore is risky mainly because of uncertainty in the evaluation of property of the soil and sensitivity of the soil parameters for design and installation. Various aspects of the CPT and its relevance to different types of foundations are discussed especially for foundations in soft clay.

INTERPRETATION
There may be two modes of the test in the offshore. They are seabed mode or down-hole mode [1]. In the seabed mode the sensors measuring resistances are zeroed at the seabed level while in the down-hole mode, they are zeroed at the bottom of the hole. The resistance measured by the sensors are recorded by the on board computer system through the umbilical and subsequently produced as graphs. Although many engineering parameters are interpreted from the test in clay, the most important parameter interpreted through the test is undrained shear strength (Su). Again, measurement of pore pressure (by PCPT) is used to find the corrected cone resistance (qc) and sleeve friction and it has correlations with the nature and properties of the soil. Measured sleeve friction helps in classification and in determination of properties of the soil. However, it is reported that measurement of sleeve friction is often less accurate and reliable than that of cone resistance in spite of considering careful corrections related to pore pressure [1,2].

For clays, undrained shear strength is correlated with CPT as per the following:

\[ Su = \frac{(qc - \sigma_v)}{N_k} \]

where \( qc \) = cone resistance; \( \sigma_v \) = total in-situ vertical stress; and \( N_k \) = empirical cone factor, generally considered as 15 to 20 for many areas in Indian offshore.

In soft clays occurring offshore, accuracy of measurement of low shear strength may be affected significantly due to pore pressure effect on the cone resistance and sleeve friction [1]. Therefore, direct correlation of finding \( Su \) without the measurement/correction of pore pressure may lead to some kind of variation depending on the tools due to effects of different area ratios. Incorporation of the pore pressure aspect in the measured cone resistance and the sleeve friction has lead to the parameters- corrected cone resistance and corrected sleeve friction. In such corrected parameters, the pore pressure effect on the cone and sleeve resistances are taken into account depending on the geometry of the tool. Thus with the three basic parameters \( q_c, f_s \) and \( u \) measured, normalized parameters of cone resistance, sleeve friction and pore pressure are further used for interpretation of soil [2].

When correction to the cone resistance is carried out, the undrained shear strength in clayey soil can be interpreted by the expression:

\[ Su = \frac{(qt - \sigma_v)}{N_{kt}} \]

where \( N_{kt} \) = cone factor after taking into account the pore pressure effect on the cone resistance.

Typical plots of cone resistance data of an offshore site acquired from ONGC’s geotechnical vessel “Samudra Sarvekshak” is shown in the Fig. 1. CPT’s are carried out in 3m strokes in down-hole mode from the vessel. Due to limited space of the paper, the low values of \( q_c \) are not displayed in larger scale.
Fig. 1 PCPT (3 m strokes, down-hole mode) results at a location in western offshore, India

The undrained shear strength can also be determined from the measured pore pressure \([1]\). It, however, depends on the position of pore pressure element in the tool. The parameter i.e. friction ratio \(R_f\) is derived from the sleeve friction resistance \(f_s\) and cone resistance expressed as percent.

\[
R_f = \left( \frac{f_s}{q_c} \right) \times 100\%.
\]

With sleeve friction and cone resistance corrected for pore pressure effects,

\[
R_f = \left( \frac{f_s}{q_c} \right) \times 100\%.
\]

It is observed from data of many sites in Indian offshore areas that in case of clays this ratio is generally more than 2. However, in sensitive clays and sandy clays, it may be lesser.

The undrained shear strength and the type of clay can be assessed with reasonable accuracy and consistency from the test.

**RELEVANCE TO FOUNDATIONS IN OFFSHORE**

Every soil investigation project has a particular purpose. In the offshore sites, clay layers occurring in soft condition near the seabed are very common and often it is practically not possible to extract sufficient length of relatively undisturbed sample by the conventional push sampling. The test plays an important role in such soils. To elaborate the importance of layers of such soft soil, where it is very useful, some common foundations used in the offshore is discussed below.

**Mudmat Foundation**

Offshore jacket structures are generally founded on piles. However, before the piles are driven the jacket is to be supported on the seabed. Mat foundation is designed for this temporary support. It is usually at the level of the mud line, termed as “mudmat” designed as base of a jacket structure of a fixed offshore platform. The jacket load is initially supported by the mud mat. The role of the mud mat is important till the piles are driven to sufficient depth. Depending on the soil condition at the seabed, and the loads anticipated during the installation time, the size and shape of the mat is designed. The loading on the mat is known to sufficient level of accuracy for the duration of installation.

It is the soil condition that may have a lot of uncertainty. If the soil bearing capacity at the seabed is poor, which normally is the condition in many of the offshore sites, the size of mudmat would be relatively large and also susceptible for problem of settlement. With low strength of the clay, sampling with even thin walled push sampling is disturbed.

In addition to disturbance, length of recovery is normally lesser than attempted. Therefore, estimating soil property solely based on samples leads to uncertainty in the design and installation. In such circumstance the in-situ test data is very useful in determining the stratigraphy and strength-deformation properties in the zone of interest. Pore pressure response indicates the field behaviour of the soil that could be easily missed without CPT.

**Jack-up Foundation**

Mobile offshore Jack-up rigs have two types of foundations—one is “spud can” and the other is “mat”. While spudcan type is suitable for variety of soils, mat type rig is suitable mainly for sites where there is soft clay near the seabed.

Performance of the mat type foundation is very much dependent on the correct assessment of the soft soil near the seabed. Its penetration into the seabed is calculated applying the soil properties below the mat. Correct assessment of properties of the soft soil is the key to near correct prediction of penetration of the mat into the seabed and subsequent settlement. Importance of being correct in such calculation is underlined from incidents of unbearable differential
suitable for deployment of jack-up rig or there is problem of occurrence of such foundation followed by costly operations.

Being a quicker process, CPT can also be carried out at multiple points for a large foundation with almost immediate result and interpretation.

For spud can type foundation, “punch through” is a potential problem in deploying a rig at many sites. Simply describing, punch through is a sudden uncontrolled penetration of a loaded leg of the jack-up platform due to foundation failure that often give rise to damage of the rig and loss of operation time. Such events may have large amount of financial implication apart from the risk to human life. It may happen mostly in cases- when the spud can foundation is over a layer with higher bearing capacity overlying a relatively weaker layer. Therefore, it is necessary to know the soil profile precisely, before deploying the jack-up at a site to prevent any such situation at an offshore site. Sampling and testing the soil may not completely reveal such a combination of soil profile. Recovery of depth wise continuous samples is normally not achieved in sand and soft clay. As such missing small layers of soil is quite possible. Since the thickness and nature of soil are the vital parameters in the assessment of spudcan type foundations, CPT proves to be a very useful tool in such cases to indicate in advance about occurrence of undesired condition by getting a continuous soil profile.

This test can help in deciding quickly whether a site is suitable for deployment of jack-up rig or there is problem of punch through/rapid penetration/high penetration. Cone penetration results can present an early and almost clear indication for suitability of deployment of jack-up rig and it can save a lot of time required for sampling and detailed laboratory testing, if the CPT indicates clear problem of deployment. Time saved in an offshore operation saves a big amount of cost of project.

Fig. 2 is a spudcan penetration curve derived from the CPT data shown in Fig. 1. The bearing capacity curve clearly indicates the possibility for punch-through for a jack-up leg with spudcan diameter 14m and maximum preload of 45MN. In this case the strength and thickness of the layers of clay occurring below 3.5m along with their thickness are required to assess the foundation behaviour. CPT gives enough indications for the required data in such cases. Sometimes it is difficult to predict the behaviour of the soil, based on sampling only, whether it will behave as drained or undrained. Pore pressure measurement in the PCPT helps in this regard to consider the behaviour in a realistic way.

Retrieval of large foundations of mobile jack-ups sometimes becomes a big problem in the offshore. Clayey soils occurring at the base of jack-up rig foundations generate large suction force opposing the retrieval of such foundation. Type of soil occurring below the foundation and its permeability are important data related to this problem [4].

CPT data can provide advance indication about such difficulty and help in taking up preventive action.

![Fig. 2 Assessment of Spudcan penetration (Diameter =14m) based on soil parameters derived from CPT data](image)

**Piles for Fixed Jacket Platform**

Calculation of axial capacity of a pile requires soil data of the entire length of the pile including some depth below the tip. Apart from axial capacity, lateral load-deformation behaviour is an important input in the design of piles. Significant level of lateral load and moment are generated due to the environmental forces.

Occurrence of soft clay near the seabed is found in many of the offshore locations. Correct assessment of design strength and other properties of the soft clay near the seabed are important mainly from lateral load-deformation point of view. The lateral capacity, stress and deflection of a pile mainly depend on a few layers near the seabed.

Further, degradation of the elastic modulus in clays with cyclic loading requires good quality of soil data in soft clays. Therefore, the accuracy of the soil investigation near the seabed is critical to the successful design of the offshore pile.

Underestimating the strength of the soil may lead to uneconomic design of the pile. On the other hand overestimating the strength parameters may lead to pile overstress and large lateral deflection, when subjected to design load. As such, for offshore piles, CPT has special relevance in predicting the load-deformation behaviour of piles and determination of stresses and deflection in the pile through proper assessment of layer depth and properties of the soil layers.

**Seafloor Stability and Pipeline Route**

Soil type and their strength below seabed govern the stability of the seafloor against any disturbing forces. This in-situ test
can be used to assess the layering of seabed soil and their lateral variation for an area. Further advantage of the CPT is that it does not miss even a thin layer. In the soft clay profiles, its results present a clear picture about the shear strength gradients with respect to depth, which are vital data for analysis of seafloor stability. Study of soil-pipeline interaction and pipeline stability on a soft clay seabed require the property of the soil for a shallow depth. CPT is useful in getting it rapidly along a route. In case of trenching for pipelines the parameters of strength and nature of the soil helps in deciding on the strategy of trenching/ burial of pipelines.

**Foundation in Deep Water Site**

Occurrence of soft clay below the seabed is common in many deep water sites including the eastern part of Indian offshore. Sampling and CPT are challenging tasks in such sites due to the high depth of water, pressure and environment associated with it. Apart from investigating pipeline routes, high quality information about the in-situ soil behaviour is required to design and install foundations in the deep water. Suction caissons or piles are some of the foundations in the deep water. It may be mentioned that installation and assessment of load bearing capacity of suction foundations are dependent on high quality results of investigation. Sampling in such deep water sites is susceptible for disturbance due to weak strength of the soil samples. Disturbance of deep water clays also takes place due to large volume expansion due to release of dissolved gas from pore water of deep water samples because of relief of stress [5]. Sampling from soils below 1500m of water depth may give as much as 0.7% of volumetric expansion even if no gas is present [5].

The test plays an important role in assessing the in-situ properties in addition to complementing the information acquired through shallow geophysical survey, sampling and subsequent testing. Deep water CPT system has been developed to perform in water depth of 4000 meters (A. P. van den Berg), which indicates its extremely useful role in the geotechnical investigation in the deep water.

**CONCLUSION**

CPT has become an inseparable part of offshore soil investigation for design and analysis of foundation, especially in soft clays where the undisturbed sampling is very difficult and costly to acquire. It can be of great help in finding soil parameters closer to reality. Its result is almost immediate so far as investigation time is concerned. Combination of cone resistance, sleeve friction and pore pressure from CPT present a clearer picture about the soil condition.

In problems like jack-up rig deployment the test has been very useful in deciding rapidly whether a site is suitable for deployment of jack-up rig. For offshore piles with soft clay occurring near the seabed, the test is very helpful in prediction of lateral load-deformation behaviour, stresses and rundown length during installation in soft clay sites at seabed. For design and installation of foundations like mudmat and suction caissons in soft clay, it can improve accuracy of soil data that is vital to successful design and installation.

Data from the test play a key role in accuracy and quality of investigations, even when there is successful sampling and availability of other test results. Advantage of the test is also found in detection of soil layers with small thickness, which matters a lot in the analysis of stability of seabed and foundations.

For correct interpretation of the data and to make full use of the test results, measurement of pore pressure and correlations with the local experience are essential. Finally, it can be concluded that CPT will continue to play a very important role for the design and installation of offshore foundations.

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