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Cone Penetration Test Applications in Offshore Structure Geotechnical Projects

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Abstract

Today, due to presence of some limitations in experimental procedures particularly issues of intervention in traditional methods, applicability of in situ tests in geotechnical studies is growing rapidly. In situ tests are very fast became a useful and efficient tool in determination of the characteristics parameters of seabed underground layers for offshore design specifically in deep water area. Vane Test, Pressure Meter and Cone Penetration Test (CPT) are the most frequently used in situ tests for geotechnical offshore studies. The CPT apparatus is one of the most effective in situ testing machines in geotechnical studies as well. Continuous record of results in seabed, possibility of recording water pressure, possibility of recognizing layers with more than 5 cm thickness of liquefied soils, repeatability of tests results, standard method of testing, intervention reduction of soil and speed of carrying out test are the most important characteristics of the CPT machine. In present work, it is attempted to briefly describe the application of CPT machines in geotechnical offshore designs. In the other words, we present cone penetration test applications in offshore structure geotechnical projects.

Keywords: Cone penetration test; CPT; offshore structure; Geotechnical projects; In situ test.

1. Introduction

Exact geotechnical recognition of soil layers of seabed is one of the most important stages of foundation design system for all the structures specifically for offshore structures. Determination of the status of stratification of geological profile of seabed, determination of density of non-dense sand sediment of sea bottom and measurement of undrained shear strength of clay and silt layers are issues which have the great importance in geotechnical studies of seabed. Using traditional methods of geotechnical studies such as sampling operation and laboratory tests are not so efficient in such cases.

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Executive sampling operation issues, frequent disturbance of samples and failure in conditions simulations in experimental testing led scientists and geotechnical experts toward increasing application of in situ tests in marine geotechnical studies area. Vane test, pressure meter (pressiometer) test and cone penetration test (CPT) are the most common types of tests. In what follows, we investigate the application of CPT test machine and application of results of this test for determination of specifications of seabed soil layers.

2. Required equipment for cone penetration test in offshore geotechnical studies

There are two main methods for carrying out in situ tests in offshore studies. In the first method (Figure 1), main excavation equipment pieces are in the vessel and excavation in the sea is performed via using drilling string of the vessel. Four main parts which are used in this method are included: tension cable (tensioner), drilling string, reaction frame and anchor. The combination of aforesaid parts comprised an appropriate penetrative system. In second method (Figure 1), drilling platform is deployed on sea bottom and all of the equipment are connected to the vessel via a cable.

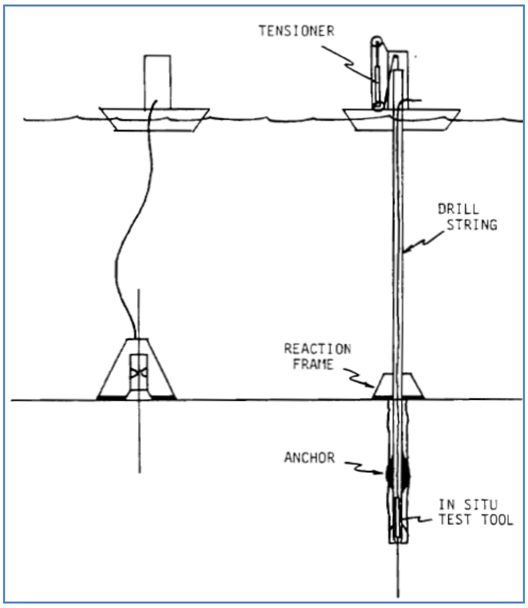

Figure 1: Systems to Place in situ testing tools

2.1. Evaluation of first method

In this method, the simplest case is to use uncompensated drilling system. In this case, drilling rods move in accordance with vessel movements and boring moves up and down with vertical oscillation of the vessel within drilled borehole. Simplicity of the method leads to its extensive use in offshore geotechnical studies. However, this method can only be used in cases in which excavation process doesn't require exact vertical control.

To perform CPT test using first method in seabed, a stabilized drilling system is required. Such stability includes retention of vertical movements of drilling rods at the end of borehole and supplying a reaction force against axial compressive load as much as 10 tons.

Anchor of drilling rod is a part of equipment which is used for stabilizing the drilling rod in seabed and preventing application of downward compressive loads to the boring. When equipment of test are fixed to the intended location and approached intended depth, before staring the test, it is necessary to isolate the system against application of excessive forces so that test is performed in controlled conditions of vertical movement. For this purpose, anchor of drilling rod is used which mechanism is so that it is fixed to a point upper than in situ test equipment on drilling rod. When system reaches the intended depth, anchor opens like a node and attaches to the wall of borehole. In this way, it avoids passing of excessive forces to the bottom. Anchor Wison III fabricated by Fugro Co. is an example of such anchors.

Two types of reaction frames are used in seabed for more stability of drilling rods. First type fixes the rod within seabed but it is not capable to apply downward compressive force to perform drilling operations and if such force is required, it must be supplied via in situ test equipment. A type of such reaction frame is fabricated by Fugro Co. as well as another type of reaction frame fixes drilling rod within seabed which is also equipped with jacks make it capable to apply compressive load as much as 10 tons. A frame of former type is fabricated by McClelland Company.

2.2. Evaluation of second method

In this method, drilling rod is deployed over seabed (Figure 1) and is connected to the vessel via flexible cables. This system is not able to exert drilling forces. However, it can produce a reaction as much as 20 tons to seabed. Products which are introduced by Fugro and McClelland companies are of heavy type while products of Woodward – Clyde Company and Lehigh University are lightweight and their launching procedure in seabed is easier. However, their application is limited to low depths about 10 m in soft soils.

Carrying out CPT test is possible by both main methods of offshore in situ tests by means of drilling rod as well as drilling platform in seabed. To be able to use results of CPT test in offshore geotechnical designs, testing procedures must be standardized, so that results of tests would have the reasonable level of accuracy and validity. For this purpose, operation of cone tip penetration within seabed layers must be performed according to standard and with 2cm/s velocity. Hence, exact vertical control must be applied to the penetration of drilling rod. Consequently, CPT machine usage in offshore designs is only possible by two methods. It means that it is necessary to either use the method of deployment of drilling platform in seabed or if we use drilling rods, method of in which the drilling must be stabilized. In Table 1, a summary of data available from various CPT tests in offshore studies is presented.

In normal CPT tests of seabed geotechnical studies, drilling is performed in depth of 1m at the bottom of borehole and then penetration is started. In such circumstances, by taking into account the depth of water, it is possible to drill in 3-7m per hour.

If deployment of drilling platform over seabed method is used, penetration operation continues till stability conditions are achieved in drilling platform, and capacity of cone tip and length of drilling rods must be sufficient. In Figure 2, a schematic of the CPT machine in seabed geotechnical studies is illustrated.

Table 1: Summary of data available from various CPT tests in offshore studies[7]

Name	Years of operation	Water design	Actual depth [ft]	Depth below seafloor [ft]		Operational method	Vessel type
				Design	Actual		
Stringray, downhole QS-CPT	6	2500	1200	600^{+}	600	SDS	With moonpool
Stringray, shallow QS-CPT	4	2500	1200	100	100 [4]	TSP	With moonpool
Wison III w drill string anchor	4	2100[1]	1000	[1]	800	SDS	Any drilling vessel
Wison III w/Seaclam	2	2100	650	[1]	330	SDS	Any drilling vessel
Swordfish	1.5	1800[1]	100	[3]	300	SDS	With moonpool
Seacalf	10	2100	740	100	100 [4]	TSP	Any oceanographic drilling vessel
MITS	4	1600	500	20	20	TSP	Any oceanographic drilling vessel

3. Using results of CPT test in offshore geotechnical studies

By means of CPT test, it is possible to record continuous profile of cone tip resistance (q_c), lateral friction (F_s) and pore water pressure (U) in depth of seabed. Using aforesaid data, it is possible to determine geotechnical characteristics of the seabed layers. Determination of seabed stratification, density of sand sediments, undrained shear strength of adhesive layers, determination of liquefied lenses, determination of the ultimate load bearing capacity of piles and recognition of horizontal low resistance layers of the soil are the most important applications of CPT machine in offshore geotechnical studies which are described as below.

4. Determination of seabed stratification conditions

Understanding of the stratification of seabed geological profile is the most important stage in the whole entire geotechnical studies. Implementation issues of sampling in depth of seabed as well as discontinuity of sampling operation prompted scientists to use in situ tests for seabed stratification determination. Owing to capabilities of cone penetration test machine such as continuous record of cone tip resistance parameters, sleeve friction and pore pressure in depth of layers, above test can be used for exact understanding of the seabed stratification. Various diagrams are presented by researchers such as Robertson in 1990 and Douglas and Olsen in 1981 [10]. By measuring cone tip resistance parameters, sleeve friction and pore water pressure during penetration, aforesaid diagrams can be used for classification of soils.

In this way, seabed stratification will be determined. By this method, it is possible to analyze layers with thickness of more than 5cm while in traditional methods, such accuracy for determination of layers cannot be attained since sampling operation is performed discontinuously in the depth.

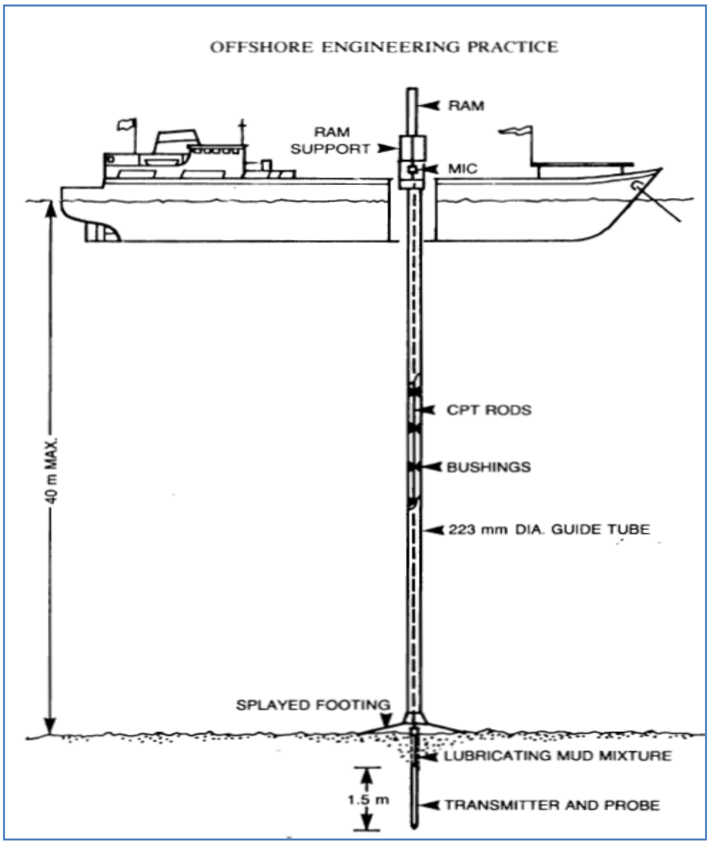

Figure 2: A schematic of the CPT machine in seabed geotechnical studies

5. Determination of the density of sand sediments

Behavior of non-dense sand sediments, which are accumulated at the bottom of sea, hydraulically is strongly affected by their relative density. Density measurement of this type of soils with common methods is cumbersome and even impractical and does not have sufficient accuracy. CPT test machine can be used as a useful tool for determination of the density of mentioned soils. Using profile of cone tip resistance recorded through the soil depth, relative density of the soil can be estimated and for this purpose, various diagrams are provided by scientists such as Baldi in 1986 and Jamiaolkowski in 1985 [10]. Determination of the relative density by cone tip resistance profile can be considered as the only logical solution for determination of relative density of sand soils in seabed which is itself a key parameter in liquefaction studies.

6. Determination of undrained shear strength of adhesive layers

The most important behavioral parameter of adhesive soils of seabed is the undrained shear strength (S_u). There are various methods for determination of undrained shear strength of such soils. In traditional methods, results of triaxial unconsolidated – undrained (UU) tests carried out over intact samples are used.

However, due to issues such as disturbance of sample and inaccurate simulation of pore pressure and overhead stress available in experiment, results of UU test are not having the satisfactory accuracy for determination of undrained shear strength of adhesive soils. In some cases, up to 40% reduction in shear strength is observed in this method [5]. In gas-charged sediments, determination of undrained shear strength by sampling traditional methods and carrying out UU tests leads to conservative results. Moreover, results of this method are highly distributed. Therefore, most of the engineers and geotechnical researchers intend to use in situ test for determination of undrained shear strength in adhesive soils particularly for layers at the bottom of seabed. In this regard, the mostly recommended in situ test is vane situ test (VST). Shear strength obtained by this test has lower distribution compared to shear strength obtained by UU tests. Therefore, today, VST has the special validity for determination of undrained shear strength. Researchers illustrated that in UU tests, yield shear strength is ¾ of that it could be presented in VST [9].

Results of CPT test can also be used for defining the undrained shear strength in adhesive soils. The main benefit of CPT over vane test is the possibility of determination of continuous profile of undrained shear strength in depth of seabed. In this way, exact recognition of narrow layers with low resistance is possible through results of CPT test.

Undrained shear strength of adhesive soils can be calculated by following formula from results of CPT test [3, 7, 10]

$$S_u = q_c / N_k \quad (1)$$

Where: q_c : resistance of cone tip

N_k: constant number which takes a value between 5 and 10 and is evaluated by linking experimental results and field studies. The value of constant number changes for various soils.

7. Determination of ultimate load bearing capacity of piles

One of the essential applications of CPT results is to determine ultimate load bearing capacity of piles in offshore designs.

Here, two methods are used practically are described. They are Ruiter-Beringen method and Schmertmann method.

Instructions provided by authors in [13] are represented briefly in Table. 2 and are explained in detail in it [10, 13]. This method can be used when maximum sleeve friction and maximum resistance of cone tip are 0.13 and 16 MPa, respectively.

Today, it is believed that in adhesive soils, load bearing capacity of piles increases under rapid loading and it reduces by reducing the loading speed. Same rule is applied for piles in offshore structures. That is, in piles which are implemented in offshore structures?

If wave loading is exerted to the pile within a few seconds, loading change is fast. However, if this load is applied within a few hours, loading occurs slowly. An issue which arises in this case is application of a method which can quantitatively the determine increase in soil resistance. In situ tests can help in this respect. For this purpose, penetration operation speed can exceed 2cm/s. Increase in load bearing capacity as a function of increase in loading speed is expressed as a percent of logarithm of loading speed. 10-15% increase in load bearing capacity is common. Schmertmann method is illustrated briefly in Table 3 and is described in detail in [3, 10, 14].

Table 2: The de Ruiter and Beringen Method

	Sand	**Clay**
Ultimate skin friction of pile	f[pile]=2400 psf	f[pile]=αq[CPT]/N_k
	f[pile]=f[CPT]	N_k~20
	f[pile]=q[CPT]/300 compression	α=1 in N.C clay
	f[pile]=q[CPT]/400 tension	α=0.5 in O.C clay
Ultimate point resistance of pile	q[pile]=average of q[CPT] within zone of pile point influence	q[pile]=N_Cq[CPT]/N_k with N_C=9 N_k~20
	q[pile]=limiting value, function of q[CPT] and OCR	

Table 3: Schmertmann method for determination of load bearing capacity of piles from CPT results

	All soils
Ultimate skin friction of pile	f[pile]=αf[CPT]
	Charts of α versus D/B for sands
	Charts of α versus f[CPT] for clays
Ultimate point resistance of pile	q[pile]=average of q[CPT] within zone of pile point influence

8. Determination of load – deformation curves of piles by CPT test results

Prediction of load – deformation curve for a loaded vertical pile is carried out by two types of curves; curve of change in friction between pile and soil with changes in vertical displacement of pile (f-W) and curve of changes in cone tip resistance with respect to vertical displacement of pile (q-W). the author in [4] stated that the Verbrugge presented a method for modeling f-W and q-W diagrams (Figure 3) by elastoplastic modeling.

Author stated in [3, 4] that Guaneselli and Bustsmante introduced a method for calculating of pile skin friction force and cone tip resistance measured in CPT test as follows

$q_{(pile)}=K_p.q_c$ (2)

$f_{(pile)}=K_s.q_c$ (3)

$f_{(pile)}<f_{lim}$ (4)

K_p, K_s and f_{lim} values are coefficients which are determined based on soil type and method of implementation of pile. Above method are presented based on results of 50 tests on onshore pile loading.

Slope of linear part of the curve is calculated from results of loading tests in real scale. These slopes can be determine using following relationships

$f/W=0.11(E/R)$ (5)

$q/W=1.56(E/R)$ (6)

where, R is the pile radius and E is the modulus of elasticity of the pile. For piles which are implemented using in situ method, E in KPa can be evaluated from following relationship in terms of resistance of cone tip of CPT

$E=3200+22q_c$ (7)

For piles which are implemented using pile driving method, E which is evaluated by using Eq. 7 must be multiplied by 3 and then applied to Eq. 5 and 6.

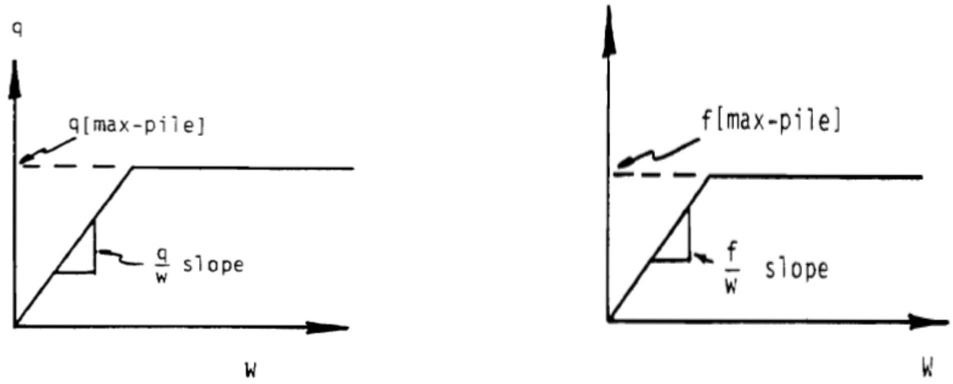

Figure 3: q-W diagram

9. Assessment of liquefaction potential of seabed layers using CPT results

Assessment of liquefaction potential of sand sediments in seabed is one of the most important seismo-geotechnical issues in offshore geotechnical design. Many researchers presented various theoretical methods including mathematical, numerical and experimental models obtained from study of experimental and field studies outcomes for investigation of the liquefaction phenomenon. In situ test method is a fast and effective method for determination of liquefaction potential of soils and has higher accuracy since in them issues such as disturbance of samples and application of local soil conditions in test is minimized. Today, cone penetration test is considered as the most effective method of in situ test in determining the liquefaction potential of soils. Reduction of soil disturbance, possibility of recognition of less than 5cm thickness of liquefying soils, repeatability of test results, and possibility of recording pore water pressure, standardized test procedure and rapid testing are the most important characteristics of CPT test.

Various methods are introduced by researchers for investigation of potential of liquefaction occurrence by means of CPT test results. The most important of which are as follows:

1. Assessment of potential of liquefaction by CPT results using the correlation between CPT and SPT tests [11, 12]
2. Assessment of potential of liquefaction by CPT results recorded in situ using triaxial cyclic tests results
3. Assessment of potential of liquefaction by CPT results calculated using theory of pore expansion and results of triaxial cyclic tests [8]
4. Assessment of liquefaction potential from historical records of CPT in liquefying sites (direct method) [15,16]

The newest and the most valid method for determination of liquefaction potential by using CPT results is direct method of using historical records of CPT in liquefied and non-liquefied sites. In this method, by study of recorded CPT data corresponding to liquefied and non-liquefied site without triaxial cyclic tests and using the correlation between results of CPT and SPT tests, diagrams are provided for determination of potential of liquefaction of soils.

The authors in [15] and the authors in [16] carried out researches in this field and presented their results as boundary curves of liquefaction in SSR-q_{c1} diagram for three cases of following soils (Figure 4):

1- Clean sand: D_{50} (mm)< 2.0, F.C (%)<5

2- Silty sand: 0.1<D_{50} (mm)< 0.25, 5<F.C (%)<35

3- Silty sand to sandy silt: D_{50} (mm)< 0.1, F.C (%)>35

10. Conclusion

Laboratory tests and in situ tests complement each other.

Today, due to presence of some limitations in experimental procedures particularly issues of intervention of traditional methods, application of in situ tests in geotechnical studies is rapidly growing. Cone penetration test machine is considered as one of the most effective tools for in situ tests in offshore geotechnical area. Continuous record of results in seabed, possibility of recording water pressure, recognizing layers with more than 5 cm thickness of liquefied soils, repeatability of tests results, standard method of testing, reduced intervention of soil and speed of performing the test are the most important characteristics of the CPT machine. In present work, it was attempted to briefly describe the applicability of CPT machines in geotechnical offshore designs. Method of positioning the machine and carrying out the test in seabed is explained and in another part of the paper, method of using results of CPT test including determination of the condition of seabed layers, determination of the density of sand sediments, determination of the undrained shear strength of adhesive layers, ultimate load bearing capacity of piles and assessment of the potential of liquefaction in layers of seabed in offshore geotechnical designs are implied.

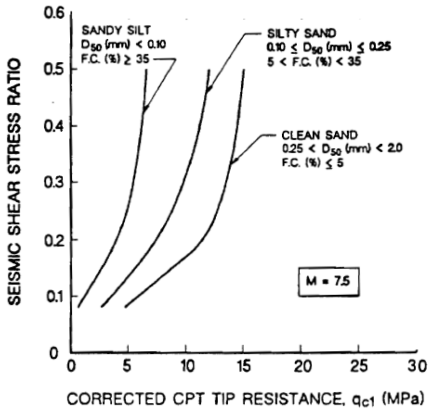

Figure 4: SSR-q_{c1} diagram

11. Recommendation

Using CPT method could be recommended in most of the offshore geomechanical investigation along with the other tests and devices for better accuracy and good performance.

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