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Calibration of CPTU Factor N_{kt} for Two Recently Explored Areas of Indian Offshore

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Abstract. Cone Penetration Test with pore pressure measurement (CPTU) is an in-situ soil test which plays a vital role in offshore soil investigation for design and installation of all important offshore structures. The advantage of CPTU includes repeatability, relatively quicker collection of soil data at very close depth intervals and identification of thin layers of soil. This in-situ test along with laboratory testing of soil helps in more reliable identification of soil and assessment of engineering properties for offshore sites. One of the important engineering properties of clay is undrained shear strength (s_u). However, correct interpretation of s_u from CPTU data depends on proper value of the factor N_{kt}. A new study with some newly acquired data from two fields was carried out on about 12 (twelve) offshore sites of Indian offshore where specific calibration of the N_{kt} factor was carried out on the basis of s_u data from laboratory and Field vane (FV) shear tests (wherever available) of soil samples. The study was to derive the applicable N_{kt} factor for quicker and more reliable interpretation of s_u from CPTU data from the areas. Details of analysis and results from the study along with relevant statistical parameters are presented in the paper.

Keywords: CPTU; undrained shear strength; N_{kt} factor

1 Introduction

Soil investigation for design and installation of any important structure in the offshore invariably includes the in-situ test CPTU (Cone Penetration Test with pore pressure measurement). It is used in Indian offshore also for soil investigation works related to design and installation of offshore structures such as fixed jacket platforms, jack-ups, anchors etc. CPTU greatly facilitates proper identification of soil, demarcation of soil layers and assessment of soil properties at a site. This in-situ test along with laboratory testing of soils helps in better identification of soils and assessment of required engineering properties for offshore sites. Apart from rapid determination of soil stratigraphy and determination of many soil parameters using suitable correlations, the advantage of carrying out CPTU includes repeatability of the test at a site, collection of soil data at very close depth interval and identification of thin layers of soil. The test is used for deriving many soil parameters through various empirical correlations. One of the very important parameters, quite reliably interpreted from the test, is undrained shear strength of clayey soil (s_u), subject to the application of proper factors for interpretation of CPTU data. Undrained shear strength is correlated with the cone resistance (q_c) and pore water pressure (u_2) measured in the in-situ test. There are mainly three semi-empirical approaches to derive s_u from CPTU which are based on net cone resistance, effective cone resistance and excess pore pressure. Corresponding factors are N_{kt}, N_{ke} and $N_{\Delta u}$ respectively, which are applied on the corrected CPTU data for interpretation of s_u. However, there are wide ranges of values for the factors as published by researchers and an area specific correlation is recommended.

For proper interpretation of s_u from CPTU, use of appropriate factors is very important. Based on previous studies, for most of the western Indian offshore areas related to offshore production of hydrocarbon, generally, N_{kt} factor in the range of 15 to 20 is used. In this paper the factor N_{kt} has been presented for two new areas – one from the western offshore and the other from eastern offshore of India where a number of boreholes were explored in recent past. It was of interest to examine the calibrated value of N_{kt} with reference to s_u from laboratory tests and also separately, with reference to relatively higher quality tests such as UU (unconsolidated undrained) triaxial and FV tests for more reliable interpretation of the s_u of clays in those areas. The calibration was carried out for12 different sites, 6 from each of offshore areas.

2 General Description of the Offshore Areas

One of the areas of study is 'Ratna Field' from the western offshore of India. The other area is from the eastern offshore of India in Godavari delta. There has been relatively recent soil exploration in both the areas with several boreholes. Soil types in both the areas are predominantly clayey up to a significant depth below the seafloor as shown in Fig.1 and 2.

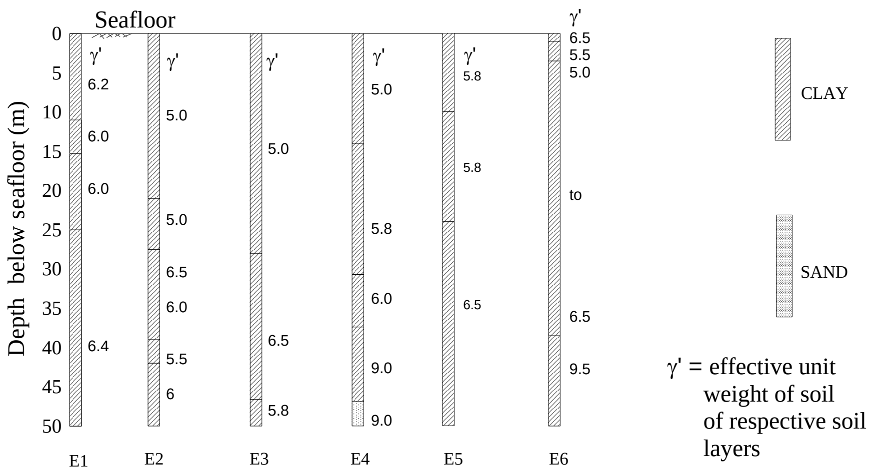


Fig. 1. Soil types up to 50 m below seafloor in the eastern offshore sites.

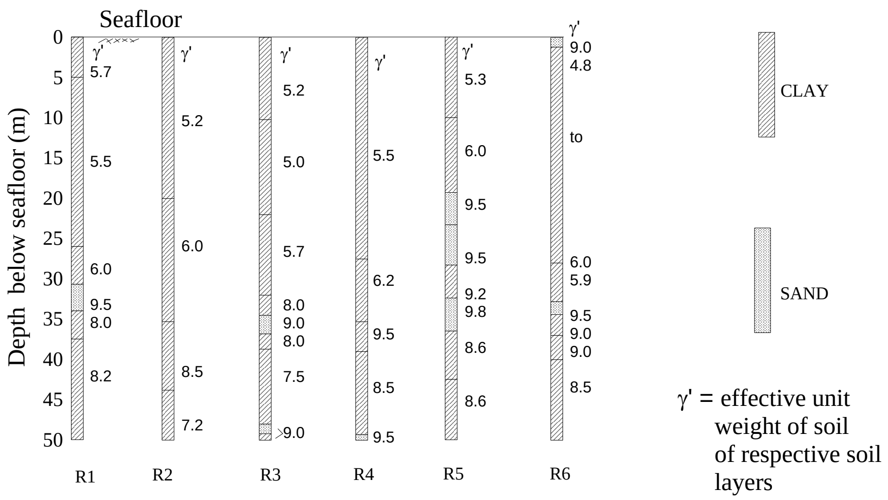


Fig. 2. Soil condition up to 50 m below seafloor in the Ratna Field sites

Both are shallow water areas. Approximate water depths in the sites of Ratna area was from 40 m to 58 m and for the sites in the eastern offshore, it was 14 m to 23 m.

3 Definition of N_{kt}

The cone resistance measured in the field requires correction due to "un-equal area effect" (Lunne et al., 1997) and it also needs to be brought to a common reference depth, i.e. seafloor level. The corrected cone resistance (q_t) is determined as per Equation (1). The relation between s_u and corrected cone resistance q_t is defined by the equation (2).

$$q_t = q_c + (1- a)\, u_2 \qquad (1)$$

where q_c = cone resistance with reference to the seafloor; u2 = pore pressure measured at position behind the cone and a = area ratio of the cone (0.75 for the tool used for the data presented in this paper).

$$s_u = (q_t - \sigma_{v0})/N_{kt} \qquad (2)$$

where σ_{vo}= total overburden pressure of soil with reference to the seafloor and q_t = corrected cone resistance referred to seafloor.

4 Analysis

For calibration of the N_{kt} factor, data from individual sites were studied. Data points for a site were selected from those depths only where both CPTU and s_u data (measured by laboratory tests or by Field Vane shear tests) were available. For every site,

N_{kt} factor was calibrated with two sets of data. One is where CPTU data is compared with directly measured s_u value. In this case, the s_u value at any depth used for the comparison is the arithmetic mean of all s_u values at that depth available from all laboratory tests. The other is where, s_u values from either UU (unconsolidated un-drained) triaxial tests or FV (Field Vane) shear tests were compared with CPTU.

4.1 Processing of directly measured s_u data

Depth-wise values of s_u from all laboratory tests and reducing them to two data sets from the two sites (R1- Ratna and E1- Eastern offshore) from both the areas, are shown in Fig. 3 and 4. Data for all other sites were processed similarly. When comparing CPTU data at a site with mean values of all laboratory s_u tests for deriving the N_{kt} factor, equal weightage was given to the different types of laboratory s_u tests.

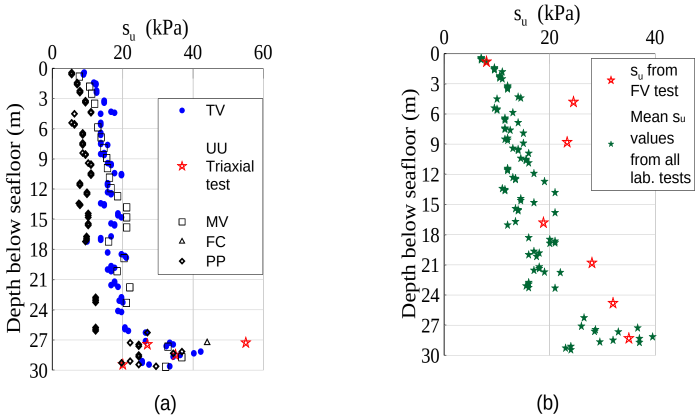


Fig. 3. R1 site of Ratna Field; (a) depth-wise s_u values of all laboratory tests; (b) depth-wise mean s_u values of all laboratory tests and FV tests

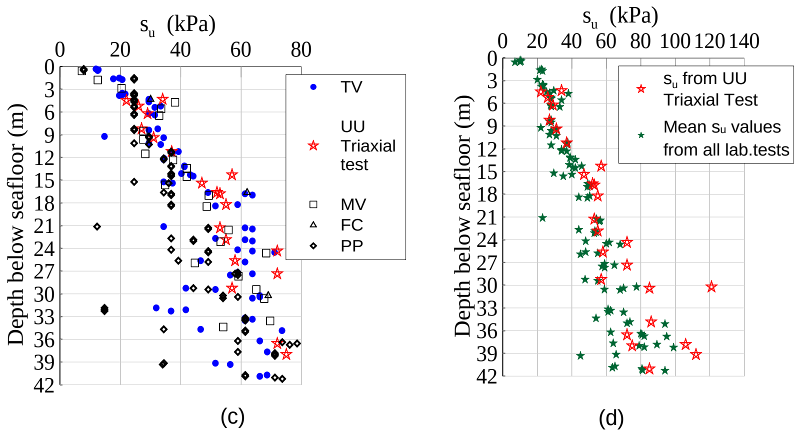


Fig. 4. E1 site of eastern offshore area; (a) depth-wise s_u values of all laboratory tests; (b) depth-wise mean s_u values of all laboratory tests and UU triaxial tests.

Twelve sites, 6 of them from Ratna Field and 6 other sites from the eastern offshore area were considered for the study. For the sites of Ratna Field, out of 6 sites, sufficient numbers of FV test data were available for 5 sites. In case of the eastern offshore sites, only UU tests were available for all the 6 sites.

It may be mentioned that FV test which is carried out in-situ, is considered as a high quality test for measurement of undrained shear strength especially, for soft and firm clays. Similarly, UU triaxial tests are considered to be of better quality compared to index s_u tests such as MV (miniature vane), TV (torvane), PP (Pocket penetrometer) and FC (Fall cone) tests.

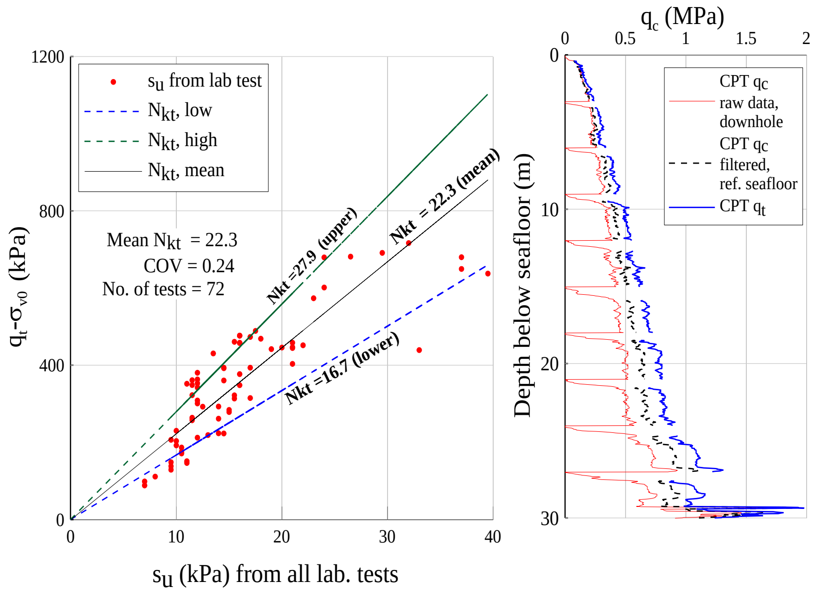
4.2 CPTU processing

Acquired CPTU data are considered as raw data which need some processing. It may be mentioned that the CPTU tests were conducted in downhole mode. It was in strokes of maximum 3 m length starting from specific depths below seafloor. The raw data were filtered to appropriately remove the disturbed or unreliable portions from every stroke. Further, the CPTU data were corrected for “un-equal area effect” given by Lunne et al., 1997 [1] and q_c (cone resistance) values were brought to the reference of seafloor. Details of the process followed for this paper were earlier described by Mahanta and Ghanekar, 2018 [2]. Values of effective unit weight selected for the calculation of overburden stress were based on laboratory-measured values as shown in Fig.1 and 2. Plots of raw as well as processed CPTU data for two locations are subsequently shown in Fig. 5 and Fig. 6. These plots are for one of the locations from each of the two areas. For all other locations also, similar analyses were carried out.

4.3 Determination of N_{kt} factor

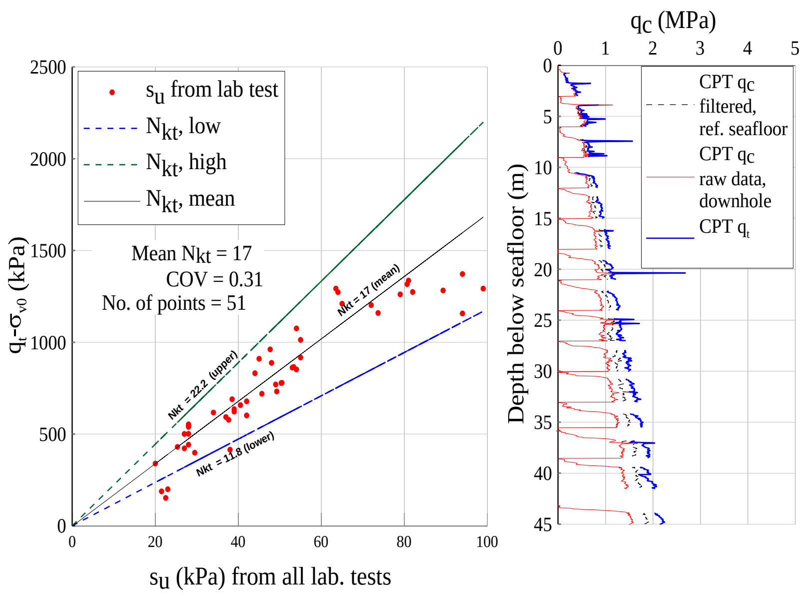
The factor N_{kt} was determined by comparing the net corrected cone resistance (q_t - σ_{v0}) with the s_u values directly measured at corresponding depths as shown in Fig. 5 to 8. N_{kt} factor derived on the basis of s_u measured by FV tests for Ratna Field and UU triaxial test for the eastern offshore area from one of the sites (R1 and E1) from the areas are shown in Fig. 5 and 8. Statistical processing was carried out following relevant DNV code [3].

It may be noted that comparison of CPTU data at a particular depth with measured s_u value was considered only when the depth of s_u measurement was within 2 cm of the depth of measurement for the CPTU data. For example, as shown in Fig. 4, there are results from 26 UU triaxial tests for E1 site. However, 15 UU triaxial tests only could be compared with CPTU data available at common depths (where difference of depth of q_c measured by CPTU and corresponding s_u measured directly, are within 2 cm) as shown in Fig. 8.



(a) **(b)**

Fig. 5. (a) N_{kt} factor for site R1, Ratna, based on all s_u data. (b) CPTU data



(a) **(b)**

Fig. 6. (a) N_{kt} factor for site E1, Eastern offshore area. (b) CPTU data

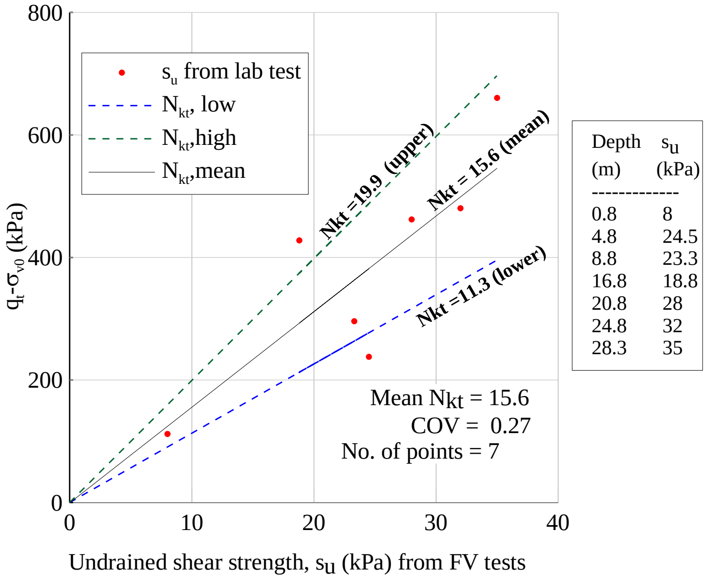


Fig. 7. N_{kt} factor based on s_u data from FV test for site R1, Ratna.

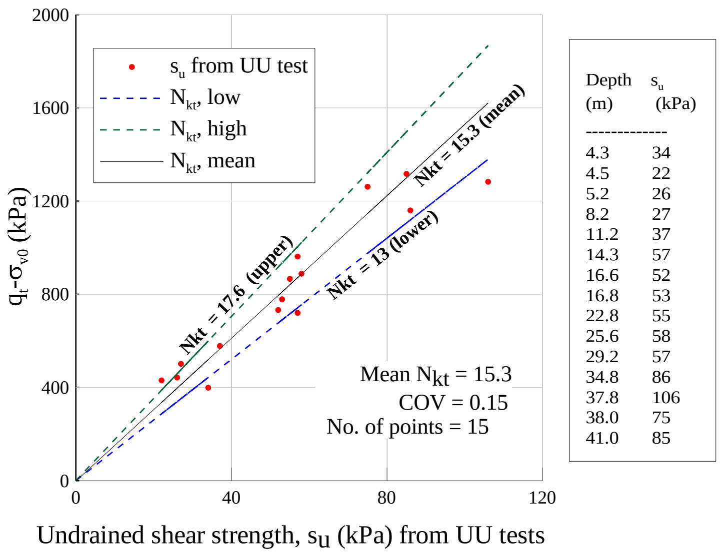


Fig. 8. N_{kt} factor for site E1, eastern offshore area based on s_u data from UU test.

Thus, uncertainty about mismatch of soil types was avoided in calibrating the N_{kt} factor for any of the sites. It is worth mentioning that boreholes for CPTU and sampling at any of the sites are generally adjacent to each other where both boreholes are separated by about 5 m. The analysis results are mainly based on CPTU and laboratory tests from available data points near seafloor up to a maximum depth of about 42 m, where data from both in-situ tests CPTU, FVT (in some cases), and laboratory tests were available.

5 Results and Discussion

Table 1 and 2 show the results in detail for the two areas which include coefficient of variation (COV) of the derived N_{kt} factors.

Table 1. Factor N_{kt} and corresponding COV derived for 6 sites of Ratna Field.

Site no.	N_{kt} value from (ref. all lab s_u tests)	No. of data points	COV (ref. all lab s_u tests)	N_{kt} value (ref. FV tests)	No. of data points	COV (ref. FV tests)
R1	22.3	72	0.24	15.6	7	0.27
R2	21.1	73	0.30	14.0	7	0.26
R3	22.4	73	0.25	17.7	7	0.15
R4	26.6	77	0.26	18.4	10	0.3
R5	20	62	0.25	15.6	7	0.24
R6	22.1	89	0.20	*	*	*

Note: * indicates that no data of FV test was available for the site

Table 2. Factor N_{kt} and corresponding COV derived for 6 sites of Eastern offshore Field.

Site no.	N_{kt} value from (ref. all lab s_u tests)	No. of data points	COV (ref. all lab s_u tests)	N_{kt} value (ref. UU tests)	No. of data points	COV (ref. UU tests)
E1	17.0	51	0.31	15.3	15	0.15
E2	17.6	58	0.26	21.9	8	0.28
E3	16.3	79	0.18	13.7	17	0.20
E4	18.1	36	0.28	12.1	9	0.24
E5	19.6	56	0.21	15.7	8	0.23
E6	13.6	75	0.15	13.5	14	0.25

Results of N_{kt} factors for all sites in Ratna Field and eastern offshore area are presented in Fig. 9 in graphical form.

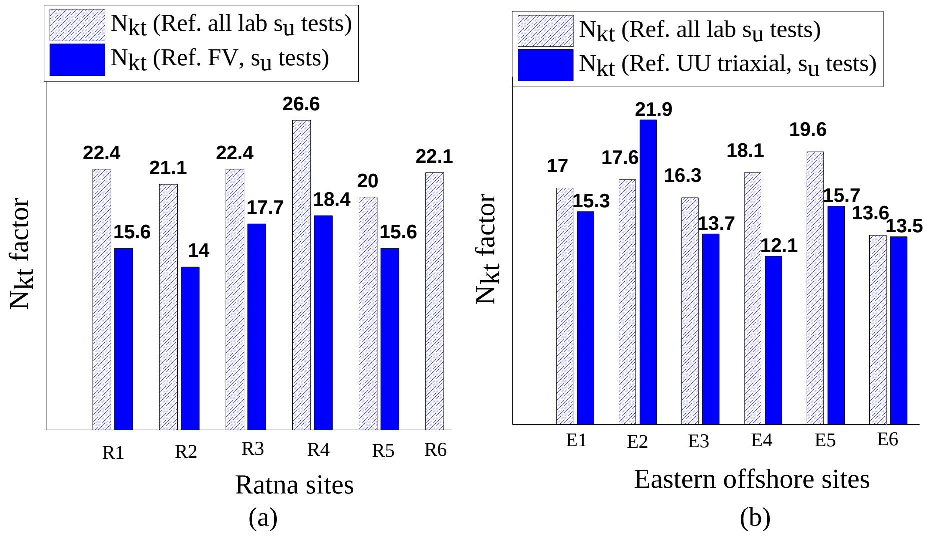


Fig. 9. Plots of N_{kt} factor calibrated for (a) Ratna and (b) Eastern offshore site.

From the study, it is found that there can be significant variation of N_{kt} factor depending on the reference laboratory tests. The difference of the calibrated N_{kt} value with respect to different types of reference s_u tests for any of the two offshore areas is attributed mainly to the possible disturbance of soil samples (compared to its undisturbed in-situ condition) before carrying out a laboratory s_u test, especially, in case of soft and firm clays. It also depends on the quality of the test.

Notably, mean N_{kt} value for Ratna Field is found to be relatively high at 22.4, when all laboratory s_u tests are considered for the assessment. Relatively higher value is attributed to possibly more disturbance in samples of Ratna sites due to higher sensitivity of near seafloor clay observed in the area compared to the other area of the study.

It is generally indicated from the analysis that higher quality tests lead to reduction in the calibrated value of $N_{kt.}$ Interestingly, derived N_{kt} value for the Ratna sites with reference to mean s_u from all laboratory tests is much higher compared to the value assessed with reference to FV tests. In case of Ratna Field, the mean value of the factor N_{kt} reduced from 22.4 to 16.3 when the reference was based on higher quality test (FV). Similarly, in case of the eastern offshore area, the factor reduced from 17 to 15.4 when relatively higher quality tests (UU), compared to all s_u tests carried out in laboratory were used for reference.

In some of the sites, the no. of data points for UU or FV tests were relatively less, partly due to matching of depths also, where variation between the depth of CPTU data and corresponding lab data was restricted to 2 cm only. Presented result is the best estimate that can be made with the available data. However, there is scope for augmentation of the data in future with new investigations.

Mean N_{kt} values along with the corresponding COV are shown in Table 3.

Table 3. Mean N_{kt} and corresponding COV derived for Ratna Field

Field	Mean N_{kt} value (ref. all lab s_u tests)	Mean COV (ref.all lab s_u tests)	Mean N_{kt} (ref. UU or FV tests)	Mean COV (ref. UU or FV tests)
Ratna	22.4	0.25	16.3 (FV)	0.24 (FV)
EOA	17.0	0.23	15.4 (UU)	0.23 (UU)

Note: EOA = Eastern Offshore Area

6 Conclusion and Recommendation

An important factor (N_{kt}) for interpretation of s_u from CPTU is calibrated by following statistical procedures with reference to laboratory and in-situ test data for two relatively new fields from Indian offshore (one from western and one from eastern offshore). Calibrated factors are determined with respect to arithmetic mean of s_u measured in various types of tests in laboratory, and also separately, with respect to relatively higher quality tests, i.e., either UU triaxial tests or FV tests.

Based on the study of data from 12 different locations from the two offshore areas, following observations are made:

1. Mean N_{kt} value for Ratna Field is found to be 16.3 to 22.4 with COV of about 0.24.
2. Mean N_{kt} value for Eastern offshore area is found to be 15.4 to 17.0 with COV of 0.23.

In the absence of site-specific calibration, authors recommend the ranges of N_{kt} factors for assessment of s_u from CPTU as given below.

1. N_{kt} factor in the range of 15-20 for Ratna Field.
2. N_{kt} factor of 13-18 for the Eastern offshore area

The mean value of 17.5 along with the recommended range of N_{kt} for Ratna Field remains the same as those generally used for other areas of western Indian offshore. The mean N_{kt} value recommended for the eastern offshore area is relatively lesser i.e. 15.5. However, authors recommend that wherever possible, field or site specific calibration should be carried out for interpretation of s_u from CPTU data.

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