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Uncertainty in Capacity of Spudcan Foundation from CPT Data

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Abstract. Cone penetrometer is the most commonly used instrument over the decades for profiling in-situ undrained shear strength at offshore soft clay seabed soil, which is a necessary parameter to determine the bearing capacity of various offshore foundations, such as spudcan, mudmat, and pile foundation for different offshore structures. It is observed that the undrained shear strength estimated by the cone penetration test (CPT) is highly uncertain due to inherent variability, transformation, or model uncertainty and measurement uncertainty. Therefore, the ultimate capacity of such foundations is inherently uncertain due to the uncertainty in input soil shear strength. This paper examines the degree of uncertainty involved while determining soil parameters from CPT data of soft clay seabed soil using a probabilistic approach. The uncertainty in predicting the bearing capacity of spudcan foundation is assessed using Monte Carlo simulation considering the variability of the undrained shear strength of the soil. Finally, the deterministic capacity of the foundation is compared with the probabilistic approach.

Keywords: Cone Penetrometer; Undrained Shear Strength; Uncertainty; Spudcan.

1 Introduction

Mobile jack-up rigs are most commonly used to explore oil in the offshore industry. These are mainly composed of three structural legs attached with spudcan foundation. Typically Spudcan is considered a circular type foundation with a shallow conical underside and a protruding spigot to penetrate smoothly into the seabed soil. During the installation period, Preloading is applied as twice the vertical working load for an additional factor of safety, and the spudcan is allowed to penetrate into the soil until maximum soil resistance to the load is reached. Thereafter loading is reduced, and the hull is lifted upward for operation.

Primary sources of uncertainty for spudcan capacity is due to inherent soil variability. Soil properties vary substantially within the geological layers. Hence, it isessential to consider the spatial variability of soil properties. Various past studies shed light on this aspect. Shu et al. [19] investigated the influence of spatially varied undrained shear strength on the failure mechanism and bearing capacity statistics of spudcan foundation. They generated nonstationary and stationary random field and mapped intoa finite element model. Li et al. [17] studied the effect of different coefficient of variation (COVs) on spudcan bearing capacity. Li et al.[18] focused on the effect of scale of fluctuation and aspect ratio of soil properties on failure mechanism and bearing capacity of spudcan foundation. Tang and Phoon[20] described the model uncertainty to estimate the bearing capacity of circular footing on dense sand. This paper aims to an evaluation of uncertainty associated with bearing capacity estimated from ISO/FDIS 19905-1 [10]. The inherent variability and scale of fluctuation are estimated from CPT data of Indian western offshore soft clay sites. The total uncertainty of the undrained shear strength of clay is estimated considering transformation uncertainty, measurement uncertainty, and inherent variability associated with CPT. The model uncertainty of bearing capacity equation recommended in ISO/FDIS 19905-1 [10] is evaluated based on the centrifuge test results obtained from the literature. The uncertainty in the bearing capacity of spudcan is estimated using Monte Carlo simulations and compared with deterministic capacity.

2 Uncertainties of Undrained Shear Strength

For any geotechnical design of the foundation, it is essential to consider the uncertainty involved in the soil properties. To quantify the total uncertainty involved in soil property, three types of uncertainties are mainly considered, which are inherent soil variability, measurement uncertainty, and transformation uncertainty.

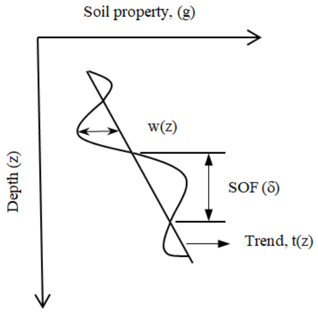


Fig. 1. Model for the inherent variability of soil.

2.1 Determination of inherent soil variability

The in-situ soil property lacks homogeneity and becomes highly variable in vertical and horizontal directions due to complex geological and environmental processes. The soil property $g(z)$ can be expressed as the summation of the mean property trend function $t(z)$ and the fluctuating component $w(z)$, as shown in Fig. 1.

$g(z)= t(z)+w(z)$ (1)

where z is the depth. Mean, variance, or the coefficient of variation (COV) and the scale of fluctuation of soil property are the parameters that represent inherent soil variability [1]. Phoon and Kulhaway [2]suggested the fluctuation component can be expressed as COV, which is the ratio of the standard deviation of fluctuating component, $w(z)$, and trend of mean soil property, $t(z)$.The scale of fluctuation (SOF) is the distance within which the soil properties are significantly correlated. Small SOF denotes quicker variation around the mean property trend where large SOF values are the representation of correlation with a large distance.

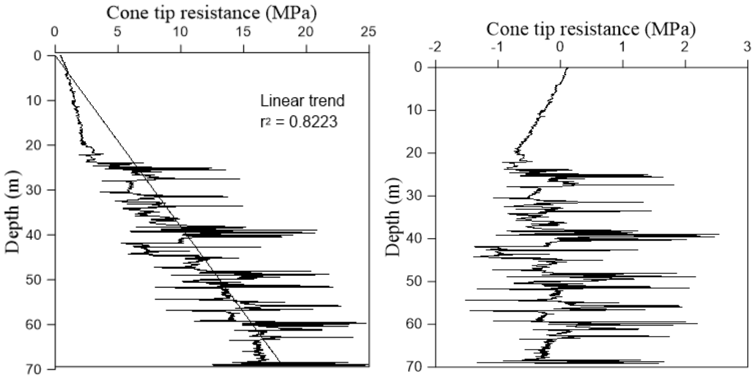
There are various methods to determine the SOF (δ). This paper presents the most widely used method of fitting the theoretical model to the sample autocorrelation function[12,13] to determine δ as [1, 3],

$$\rho(\tau) = exp(-\frac{2|\tau|}{\delta}) \tag{2}$$

Where τ is the lag distance. The sample autocorrelation function is determined by the following equation,

$$\hat{\rho}(\tau) = \frac{\sum_{i=1}^{n(\tau)}[w(z_i) - \bar{w}][w(z_i + \tau) - \bar{w}]}{[n(\tau) - 1]\hat{\sigma}^2} \tag{3}$$

where $n(\tau)$ is the numbers of data pair separated by lag distance τ. $\bar{w}$ and$\sigma^2$is the mean and variance of $w(z)$. To determine the soil inherent variability, CPT data from Indian western offshore sites of soft clay is considered. The CPT tests were carried out in downhole mode. The tests were carried out in several strokes and having each stroke length of 3m. The initial part of each stroke was removed due to soil disturbance [22]. The trend line is fitted to the dataset by the ordinary list square (OLS) method, and the de-trended data is obtained by subtracting the trend value from the soil property value, as shown in Fig. 2. The sample autocorrelation was determined for each depth of 0.02 m depth interval and fitted to the exponential function (Fig.3). The inherent soil variability (COV_w) and δ_{su} are estimated as 24% and 1.65m, respectively.



(a) (b)

Fig. 2. Cone tip resistance with depth: (a) trended data (b) de-trended data.

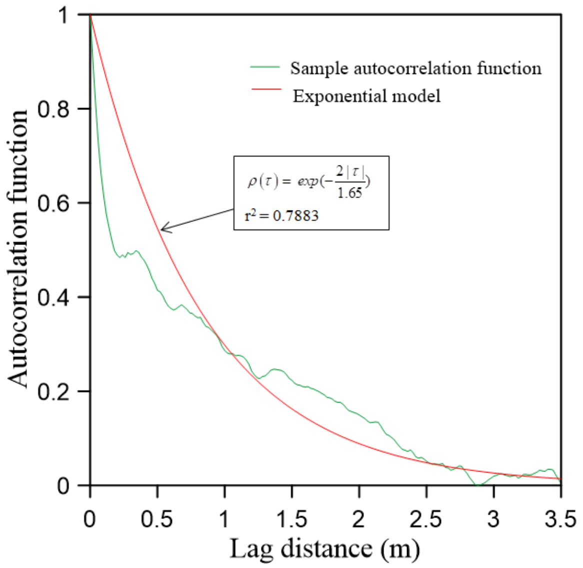


Fig. 3. Autocorrelation function with lag distance

Table 1. Transformation uncertainty with respect to three reference test [11].

s_u test type	Mean D_K	COV of D_K (%)
CIUC	0.0789	35
UU	0.0512	29
VST	0.0906	40

2.2 Measurement and transformation uncertainty

Measurement uncertainty occurs due to the equipment handing procedures, inaccuracies in instrument measurement. This error ranges between 5-15% [2]. On the other hand, to convert any geotechnical data into actual design property, transformation model is needed. Transformation models are obtained from experimental fitting which leads to transformation uncertainty. A transformation model for CPT measurement is given below [11].

$$\frac{s_u}{\overline{\sigma}_{vo}} = D_k \frac{(q_t - \sigma_{vo})}{\overline{\sigma}_{vo}} = (m_{DK} + \varepsilon)\frac{(q_t - \sigma_{vo})}{\overline{\sigma}_{vo}} \tag{4}$$

where,s_u is the undrained soil shear strength, q_t is the corrected cone resistance,σ_{vo} and $\overline{\sigma}_{vo}$are the total and effective overburden pressure respectively, D_K is uncertain model slope, m_{DK} represents mean of D_K and ε is the transformation uncertainty.In the current scenario, transformation uncertainty arises due to the conversion of field cone resistance value to the undrained shear strength of soil considering a bearing capacity factor. This study uses this uncertainty value for three laboratory tests of consolidated isotropic undrained triaxial compression test (CIUC), unconsolidated–undrained triaxial compression test (UU), and vane shear test (VST) [11] as shown in Table 1.

2.3 Estimation of total uncertainty

The total transformation uncertainty for undrained shear strength from CPT data considering spatial average length (L) was estimated using the equation as given below [11],

$$COV_{\xi a}^2 \approx \frac{[\Gamma^2(L)COV_w^2 + COV_e^2]}{(1-\frac{\sigma_{vm}}{t})^2} + COV_\varepsilon^2 \tag{5}$$

Where COV_w is the inherent variability, COV_e is the COV of measurement error, COV_ε is the COV of transformation uncertainty, σ_{vm} is the total overburden pressure up to the length L, t is the mean soil property trend, Γ^2(L) is the variance reduction function expressed as the ratio of δ_{su} to the spatial average length (L).

$$\Gamma^2(L) = \frac{\delta}{L} \tag{6}$$

The influence zone of spudcan is generally up to 2-3 diameter in soft soil [4], therefore in this study, a spatial average length of 25 m is taken considering spudcan average diameter of 12m. For the uncertainties of 35%, 29%, and 40% corresponding to three respective reference tests, the $COV_{\xi a}$ are 40.4%, 35.3%, and 44.8%.

3 Determination of Model Uncertainty

In this study, the bearing capacity of spudcan foundation is determined based on the equation provided in ISO/FDIS 19905-1 [10]. To characterize the model uncertainty of the bearing capacity equation, the model factor [20] is estimated as the ratio of the measured capacity of spudcan from the centrifuge test results to the estimated capacity from ISO/FDIS 19905-1[10] approach,

$$M = \frac{q_{u,m}}{q_{u,c}} \tag{7}$$

Where M is the model factor, $q_{u,m}$ is the measured ultimate bearing capacity from the centrifuge tests, and $q_{u,c}$ is the predicted ultimate bearing capacity from the bearing capacity equation given in ISO/FDIS 19905-1[10]. In order to estimate the model factor, a total 17 numbers of centrifuge data are collected and compared with the predicted ($q_{u,c}$) data estimated from the equation according to the ISO approach. The centrifuge data are summarized in Table 2. Hossain et al.[8] performed the test by using a 30mm diameter spudcan at an acceleration level of 200g. Jun et al.[7] used a 60 mm diameter spudcan at 1g acceleration level, and Hossain and Randolph[6] used a 30 mm diameter spudcan at 50g acceleration level. All other tests were performed at an acceleration level of 100g. As the spudcan diameter typically ranges from 10-20 m [6,16], hence in the present study spudcan diameter ranges from 0.06m – 6m are termed as small diameter spudan and diameter of 12m - 14m are considered as large diameter spudcan. The predicted capacity of spudcan ($q_{u,c}$) for clay are determined as [10],

$$q_{u,c} = s_u N_c + \gamma' d \tag{8}$$

where s_u is the undrained shear strength of clay, N_c is the bearing capacity factor [9,10], γ' is the effective unit weight of soil, and d is the depth of embedment at the level of maximum bearing area. The bearing capacity factors of circular conical foundation onclays recommended in ISO 19905-1 [10] provided by Houlsby and Martin [9] is considered to calculate the spudcan bearing capacity. The comparison between measured and calculated bearing capacity is presented in Fig. 4.

Table 2. Centrifuge test database for spudcan on clay

Reference	s_u (kPa)	D (m)	$q_{u,m}$(kPa)	N_c[10]	$q_{u,c}$(kPa)
Li et al. [14]	25.4	12	259	6.92	270.52
	25.4	12	274.3	6.92	270.52
Craig and Chua [4]	63	14	580	5.32	367.16
	87	14	690	5.27	485.69
	39	14	450	5.23	226.37
	12	14	150	5.46	82.85
	29	14	250	5.59	184.39
Hossain et al. [8]	13	3	156	6.96	115.56
	18	6	180	7.45	211.75
Hossain et al. [5]	12	3	126	7.1	114.6
Xie et al.[15]	35	12	353.67	7.45	393.98
	35	12	318.30	7.4	387.94
Jun et al.[7]	14	0.06	88.42	5.57	78.07
Hossain and Randolph [6]	15.6	1.5	171.6	7.18	128.18
	12	3	132	7.18	118.51
	12.81	6	141	7.18	156.68
	11.82	3	130	7.18	117.22

The measured bearing capacity of spudcan agrees well with the calculated capacity in the case of small diameter spudcan. All the small diameter spudcan fall within 95% confidence interval, whereas all the large diameter spudcan fall outside the 95% confidence interval.

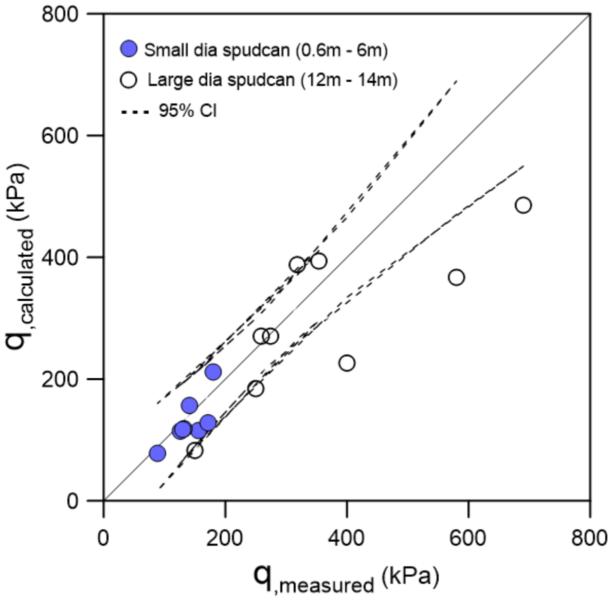


Fig. 4. Comparison of measured and calculated spudcan capacity

The cumulative probability distribution of the model factor is shown in Fig. 5, which is lognormally distributed with a mean (μ_M) of 1.2 and COV_M of 25%.

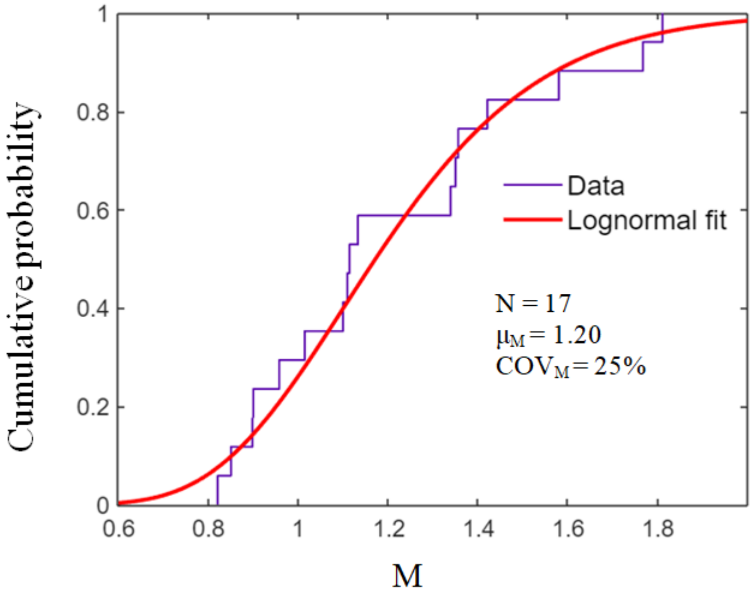


Fig. 5. Cumulative probability distribution of model factor.

4 Probabilistic Bearing Capacity

The probabilistic bearing capacity of spudcan foundation is determined using the Monte Carlo simulation technique. To generate the realizations of s_u, a lognormal distribution having the total uncertainties (COV$_{\xi a}$) of s_u are considered as 40.4%, 35.3%, and 44.8%, respectively, with mean values (μ_s) of 18.44 kPa, 11.97 kPa, and 21.17 kPafor three reference tests, i.e., CIUC, UU, and VST, respectively. These mean values of s_u are achieved from Indian Western Offshore CPT data using a suitable transformation factor ofD_k (Table. 1) for three reference tests. *MATLAB* function '*lognrnd*' is used to generate realizations of s_u. The equations for generating s_u data are given in Table 3, where $s_{u,\ CIUC}$;$s_{u,\ UU}$,and $s_{u,\ VST}$ are the undrained shear strength corresponding to uncertainty level of 40.4%, 35.3%, and 44.8%, respectively. The equations used are in the form of *lognrnd*(μ, σ, n) where n is the sample size and μ, and σ are the logarithmic mean and standard deviation of s_u, respectively

Table 3. Equations for generating realizations of s_u.

Reference test type	Equations
$s_{u,\ CIUC}$	*lognrnd*(2.83,0.38,1000)
$s_{u,\ UU}$	*lognrnd*(2.42,0.34,1000)
$s_{u,\ VST}$	*lognrnd*(2.99,0.42,1000)

The model factor (M) is incorporated into the Monte Carlo (MC) simulation to determine the modified bearing capacity ($q'_{u,c}$) as,

$$q'_{u,c} = Mq_{u,c} \tag{9}$$

M is considered as a lognormal random variable with a mean 1.2 and COV of 25%, as described in the previous section. A total of 1000 sample realizations are used. The typical distribution of q_p corresponding to reference test CIUC with probabilistic mean value ($\mu_{q,\ CIUC}$) is presented in Fig. 6.The mean values of q_p(μ_q) are 331.8 kPa, 253.8 kPa, and 376.1 kPa, with a COV of 42.7%, 39.5%, and 44.4%, respectively. The probabilistic bearing capacities of spudcanalso follow a lognormal distribution. The characteristic bearing capacity (μ_k) for 95% confidence interval corresponding to reference tests CIUC, UU, and VST are 323 kPa, 247.5 kPa, and 365.7 kPa, respectively, which are determined using Eq. (10),

$$\mu_k = \mu_p(1 - Z_{\alpha/2} V \sqrt{\frac{1}{n}}) \tag{10}$$

where μ_p is the probabilistic mean bearing capacity, $Z_{\alpha/2}$is the standard normal variate, V is the COV of bearing capacity and n is the sample size.

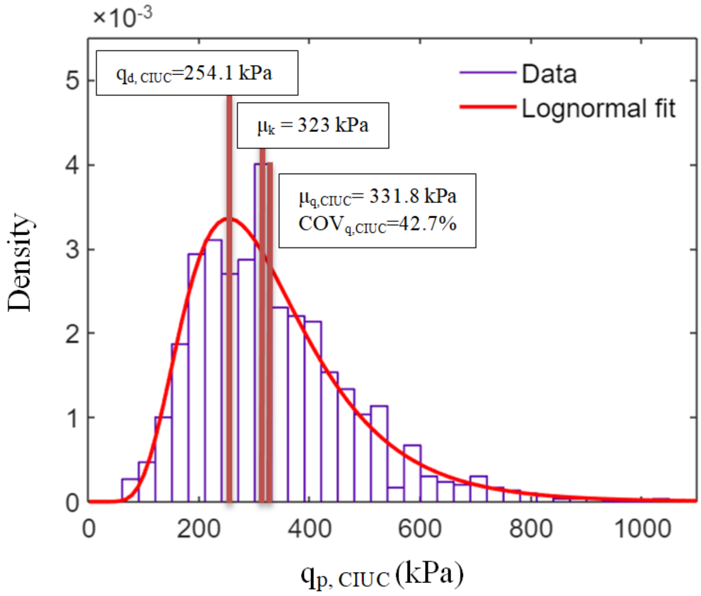


Fig. 6. The probability density function of modified bearing capacity corresponding to$s_{u,\ CIUC}$.

The modified deterministic spudcan capacities (q_d) are calculated using Eq. (8) by taking M into consideration as a deterministic model factor. For CIUC, UU, and VST three reference tests, the bearing capacities are 254.1 kPa, 202.5 kPa, and 275.5 kPa, respectively. It is observed the significant variation between probabilistic and deterministic bearing capacity, which depends on the uncertainty level of s_u corresponding to three reference tests. In the case of the UU test the deterministic capacity is closer to the probabilistic capacity because of lower s_u uncertainty.

5 Conclusions

In this study, the total uncertainty for s_u from Indian Western offshore CPT data was evaluated for estimation of probabilistic spudcan bearing capacity. A total of 17 numbers of centrifuge test data on spudcan were compared to the calculated spudcan capacity as per ISO recommendation. Based on this study, the following conclusions are made

1. The measured bearing capacity values of small diameter spudcans agree well with the calculated values. All the small diameter spudcans lie within a 95% confidence interval; however, most of the large-diameter spudcans lie outside this interval and show more scatter.

2. The model factor (*M*) for spudcan capacity can be considered as a lognormal random variable with a mean of 1.2 and COV of 25%.
3. Probabilistic spudcan capacity is evaluated by Monte Carlo simulation using s_u as a lognormal random variable with a total uncertainty of 40.4%, 35.3%, and 44.8%, respectively. Modified spudcan capacity is achieved by incorporating the model factor (*M*) into the simulation. It is observed that the modified probabilistic bearing capacity varies significantly from the deterministic capacity corresponding to reference test VST because of the high uncertainty of s_u.

This limited study shows that there is a need to assess the bearing capacity of spudcan foundation considering inherent and model uncertainty. Further research is required in this direction, considering a large number of centrifuge and field load test data to calibrate the model uncertainty.

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