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Evaluation of Bearing Capacity for Cast In-Situ Bored Piles

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Abstract. Pile is a structural element constructed to overcome heavy loads from super structure, when proper bearing strata is not available at shallow depth. In Kerala, the low land and marine areas consists of soft clay, laterite and sandy soils. These soil have low bearing capacity and shear strength, causing excessive settlement and can lead to failure of structures. The prediction of bearing capacity of a bored cast in-situ pile is a complex problem, as it depends on installation method, concrete quality, ground condition and pile geometry. It is considered that the reliable method for finding bearing capacity is pile load test, which is time consuming and costly. The bearing capacity can also be analysed by empirical and analytical methods using soil data and SPT data.

In this paper, the IS code method, α – method, β – method, and four SPT methods have been employed and summarized for comparison. Seven interpretation methods are used to interpret the failure load and a suitable failure criterion has been determined. A database of 15 bored piles is collected from different sites in Kerala. The above chosen SPT methods are calibrated by the trial and error to propose a new formula. The Log- Normal approach is employed to all methods and the distribution graph shows that the proposed formula predicts results with more accuracy and less scatter than other methods.

Keywords: SPT, Pile load test, Bored pile, Bearing capacity.

1 Introduction

The use of bored cast *in-situ* piles has multiplied around the world. Bored cast *in-situ* piles have a moderate bearing capacity, low cost, reduced vibration during installation, and allow easy length adjustments. The complex nature of the embedment ground of piles and lack of suitable analytical models for predicting the pile bearing capacity are the main reasons for the geotechnical engineer's tendency to pursue further research on this subject [5].

The prediction of bearing capacity of a bored cast *in-situ* pile is a complex problem. It is necessary to consider factors such as the boring method, installation process, quality of concrete, ground conditions, and experienced expertise while designing piles. The method of installation has a great impact on pile foundation i.e., drilling can cause vibration and disturbs the surrounding soil. Even after the installation of the pile, changes may occur in the soil naturally with time. The appropriate pile capacity can be obtained only by conducting a pile load test. The conduction of the pile load test for small projects is not economical. In such cases, other methods can be adopted for the prediction of pile bearing capacity. Various methods have been developed for predicting the pile bearing capacity by considering soil-pile interaction, soil stratigraphy, and soil resistance. Interpretation of bearing capacity can be done by graphical methods, load test, dynamic analysis, dynamic testing methods, static analysis, and SPT methods.

The static method in the IS 2911- Part 1/Sec 2 to determine the bearing capacity of bored cast *in-situ* pile contains many parameters that need to be evaluated using trigonometric functions or graphs and tables. The Static method uses the concept of critical depth for cohesive and cohesionless soil to find the angle of internal friction.

Recently using the results of penetrometer tests like Standard Penetration test and Cone Penetration test to estimate the bearing capacity of piles had been the subject of a considerable number of researchers and several approaches have been proposed [3]. Pile capacity by SPT is one of the easiest and earliest applications used. Due to SPT's simplicity of execution, a field engineer finds the method to be one of the most amiable and reliable ones [4]. There are two types of SPT methods to find capacity, direct and indirect methods. Direct methods apply N values directly whereas in indirect methods friction angle and undrained shear strength values are required to find capacity. By using SPT data the simplest form of the equation can be formed. With such an equation, pile load test can be avoided i.e., only SPT value and area of the pile are necessary. Also, the SPT method can be applied to find the capacity of any kind of soil.

Amel Benali [1] developed a new method for pile capacity estimation based on the SPT test in different stratigraphy. The Eslami & Fellinius rule was applied and calibrated with 24 pile cases [1]. To obtain the unit base resistance of piles from SPT results, the failure zone and failure mechanism should be specified around the base of the pile [1].

Amol Shah [2] performed regression analysis on the parameters to obtain a specified link between bearing capacity and other parameters like cohesion, angle of internal friction, diameter, and depth of pile. The results show that there is no need to refer to a myriad of factors that need to be evaluated using trigonometric functions or by the use of graphs and tables unlike the equations recommended by the Indian Standards [2].

2 Database Records

Pile load test data and corresponding soil investigation report of fifteen bored cast *in-situ* piles installed along the coastal areas of Kerala were collected. The sites in these areas are covered by laterite, silty sand and clayey sand. The soil report indicates a weak bearing strata at shallow depth, leading to the construction of a pile foundation. The diameter of piles varies from 0.5 m to 1 m and embedment length varies from 6 m to 35 m. Out of 15 sites, five sites have cohesive soil and other sites are covered by cohesionless soil. The summary of pile data is as given in Table 1.

Table 1. Summary of Pile data collected

Pile no	Location	Soil	Pile Diameter (mm)	Pile Length (m)	Test Load (T)	Total Settlement (mm)
1	Chala bypass, Kannur	Cohesionless soil	700	18.87	380	25.32
2	Pottamal, Calicut	Cohesionless soil	700	12	225	1.36
3	Kannur	Cohesionless soil	750	11.8	270	9.04
4	Cochin- coast guard	Cohesionless soil	600	15.15	368	3.24
5	Cochin- coast guard	Cohesionless soil	500	12.85	260	4.38
6	Kunnamangalam, Calicut	Cohesive soil	500	6.65	80	1.61
7	Kunnamangalam, Calicut	Cohesive soil	700	8.48	157	5.03
8	Pallipuram, Cochin	Cohesionless soil	600	34.6	210	4.27
9	Azheekkal, Kannur	Cohesionless soil	500	27	63	0.146
10	Annakara, Thrissur	Cohesionless soil	500	12	45	1.91
11	Elamkunnapuzha	Cohesive soil	500	8.2	33	12
12	Elamkunnapuzha	Cohesive soil	500	11.5	33	12
13	Calicut	Cohesive soil	500	7.5	42	3.627
14	Kannur	Cohesionless soil	600	24.37	181	0.73
15	Trivandrum	Cohesionless soil	1000	34.96	450	5.8

3 Determination of Bearing Capacity

3.1 Pile capacity by Interpretation

In some cases, the piles not loaded to failure, so the interpretation methods are used to interpret the failure load. Interpretation methods are graphical methods plotted using load and settlement data obtained from the pile load test. The chosen interpretation methods are Van der Veen's (1953), Hansen's (1963), Chin's (1970), Mazurkiewicz's (1972), Ahmad & Pise's (1997), Decourt's (1999) and Tangent Intersection method.

From the results of the failure load, the failure criterion is chosen as Ahmad & Pise's method. The results show that the capacity of piles is over-estimating in Decourt's and Van der Veen's, while Chin's and Mazurkiewicz's gives comparatively reliable results. The bearing capacity obtained by the tangent intersection method is under-estimating.

3.2 Pile capacity by Empirical and Analytical Methods

In this paper, we have chosen the static method, α method, β method, and four SPT methods to compare and validate the results. The summary of these methods are as given in Table 2.

Table 2. Summary of Analytical and Empirical Methods

SNo	Method	Unit Base resistance	Unit Shaft resistance	Remarks
1	IS Code Method (IS 2911-2005)	For Cohesive soil $Q_b = C_p N_c A_p$ in (KN) For cohesionless soil $Q_b = P_D N_q A_p$ in (KN)	For cohesive soil $Q_s = \sum_{i=1}^{n} \alpha_i C_i A_{si}$ in (KN) For cohesionless soil $Q_s = \sum_{i=1}^{n} K_i P_{Di} \tan\delta_i A_{si}$ in (KN)	α-Adhesion factor in IS-2911 $\delta = 3\phi/4$
2	α Method (only for cohesive soil)	$Q_b = C_u N_c A_p$ in (KN)	$Q_s = \sum_{i=1}^{n} \alpha_i C_i A_{si}$ in (KN)	α - Adhesion factor from Dennis and Olsen Curve
3	β Method (Cohesive and Cohesionless soil)	$Q_b = \sigma_v N_q A_p$ in (KN)	$Q_s = f_s A_s = A_s \beta \sigma_z$ $f_s = K_o \tan\delta\, \sigma_z = (1-\sin\phi) \tan\delta\, \sigma_z$ in (KN)	$\delta = 3\phi/4$
4	Aoki & De'Alencar (1975)	$r_t = (k/1.75)\, N_b$ in (MPa) N_b = average of 3 values of N around pile base	$r_s = (ak/3.5)\ N_s$ in (Kpa) N_s = average value of N along pile embedment depth	Failure criteria: Van der Veen method For sand: a=14, k=1 For clay: a=60, k=0.2
5	Meyerhof (1976)	$r_t = n_b N_b$ in (MPa) N_b = average of N between 8B above to 4B below pile base, N_b <=50	$r_s = n_s N_s$ in (Kpa) N_s = average value of N around pile embedment depth	Failure criteria: Min slope of load-settlement curve n_b=0.12 – 0.40 n_s=1-2
6	Bazaraa and Kurkur (1986)	$r_t = n_b N_b$ in (MPa) N_b = average of N from 1B to 3.75B around pile base	$r_s = n_s N_s$ in (Kpa) N_s = average value of N around pile embedment depth	n_b=0.06 – 0.2 n_s=2-4
7	Decourt (1995)	$r_t = k_b N_b$ in (MPa) N_b = Average value of N around pile toe	$r_s = \alpha\ (2.8N_s+10)$ in (Kpa) N_s = average value of N around pile embedment depth	Failure criteria: Van der Veen method For sand: k_b=0.325, α = 0.5 to 0.6

For clay: k_b=0.08,
α = 0.1

NOTE: A_p- C/S area of pile tip in m^2; A_{si}- Surface area of pile shaft in ith layer in m^2; N_c and N_q- Bearing capacity factors; C_p- average cohesion at pile tip KPa; C_u- cohesion at pile tip in KPa; C_i - cohesion at ith layer in KPa; σ_v- average effective overburden pressure; σ_z- effective overburden pressure; δ - effective angle of internal friction; K=Coefficient of earth pressure; P_p- effective overburden pressure at pile tip; P_{Di}- effective overburden pressure at ith layer.

The results of Empirical and Analytical methods are as shown in Table 3.

Table 3. Pile bearing capacity calculated by empirical and analytical methods

Pile No	Test Load (Ton)	Is Code Method (Ton)	α Method (Ton)	β Method (Ton)	Aoki & D'alencar Method (Ton)	Bazaraa & Kurkur's Method (Ton)	Decourt's Method (Ton)	Meyerhof's Method (Ton)
1	380	558		2517	1745	651	834	360
2	225	394		2336	1183	529	870	234
3	270	282		2310	1488	493	876	288
4	368	415		3167	1366	542	820	295
5	260	303		2551	1017	421	586	214
6	80	126	85	845	245	220	174	122
7	157	254	164	1939	641	318	319	279
8	210	306		1659	964	435	650	179
9	63	85		683	288	160	267	47
10	45	52		397	214	78	142	69
11	33	45	43	361	167	105	153	61
12	33	48	48	277	126	103	114	66
13	42	67	57	449	185	140	161	67
14	165	389		1649	1009	454	718	280
15	450	915		3339	2472	699	1788	572

The following points are noted in the bearing capacity obtained by empirical and analytical methods,

1. The capacity of only five piles can be estimated by α method as this method applies to only cohesive soils. The β method can be applied to both cohesive and cohesionless soils.
2. The SPT methods estimate bearing capacity without considering cohesion and excessive pore water pressure occurring around the pile. Thus this method of SPT may not be reliable for low permeable soils like clay and silt [2].

3. Out of four SPT method, Bazaraa & Kurkur does not contain any failure criteria. It is purely based on empirical analysis.
4. The end bearing SPT value varies for all four methods. This may cause uncertainty in bearing capacity values.
5. The bearing capacity estimated by the β method and Aoki & D'alencar is over-estimating.
6. Meyerhof method gives reliable values of capacity compared to all other chosen methods.

3.3 Proposed Method

A new SPT method has been proposed by trial and error to find the bearing capacity of bored cast *in-situ* pile. In this paper, the most commonly used seven methods to interpret the failure load are selected. The failure load obtained by interpretation methods were analysed and compared to decide the failure criterion.

The selection of the failure zone and failure criterion is necessary to find the unit base resistance. The ratio of Qp/Qm (Predicted bearing capacity divided by measured bearing capacity) was calculated and the failure criterion is selected as Ahmad & Pise's Method. Ahmad & Pise's method is also known as Modified Chin's method.

The SPT value of soil varies along the depth due to the heterogeneity of soil. This variation of N value can cause uncertainty in bearing capacity. The application of end bearing N value varies for each method. The end bearing and shaft SPT value is chosen by calculating the average of the N value along the depth. There are two methods to find the average, namely Arithmetic mean and Geometric mean.

The arithmetic mean is calculated by the formula,

$$N_a = \frac{(N_1 + N_2 + \ldots\ldots + N_n)}{n} \tag{1}$$

The geometric mean is calculated by the formula,

$$N_g = (N_1 \times N_2 \times \ldots\ldots \times N_n)^{1/n} \tag{2}$$

The average calculated by geometric mean shows pertinent results compared to the arithmetic mean. Thus, geometric mean was used to find SPT value at the end bearing and shaft.

After analysing the different ways of selecting the failure zone of influence, it is found practical to use the Eslami and Fellenius rule (1997) [5]. The end bearing N value is taken as the average of N between 4B below and 8B above the pile tip. The use of Eslami and Fellenius rule gave consistent results of capacity.

From the overall capacity obtained by Ahmad & Pise method, the end bearing and shaft resistance were determined using IS 2911. Thus by attaining the percentage of shaft and end resistance, a trial and error method was followed to form the new formula. By following the geometric averaging and Eslami & Fellenius rule, the new formula is proposed as below.

For Cohesionless soil:

$$Q_u = Q_b + Q_s = 60 * N_b * A_b + 1.35 * N_s * A_s \quad (3)$$

For Cohesive soil :

$$Q_u = Q_b + Q_s = 48 * N_b * A_b + 1.20 * N_s * A_s \quad (4)$$

Where Q_u is the overall capacity in KN, Q_b is the end bearing capacity in KN, Q_s is the shaft resistance capacity in KN, N_b is the average of N between 4B below and 8B above the pile tip, N_s is the average value of N along pile embedment depth, A_b is the cross sectional area of pile tip in m^2 and A_s is the surface area of pile shaft in m^2.

4 Validation

The capacity obtained by the proposed method is compared with the empirical and analytical methods by the Log-Normal distribution method. This method can estimate the performance prediction of all the methods. In the Log-Normal distribution method, a graph is plotted between Q_p/Q_m and probability density function.

At first, Q_p/Q_m is calculated and the natural logarithm for Q_p/Q_m is measured for each pile. To find the probability density function, the mean (μ_{ln}) and standard deviation (σ_{ln}) for the natural logarithm of Q_p/Q_m is calculated as follows:

$$\mu_{ln}\left(\frac{Q_p}{Q_m}\right) = \frac{1}{n}\sum_{i=1}^{n} \ln\frac{Q_p}{Q_m} \quad (5)$$

$$\sigma_{ln}\left(\frac{Q_p}{Q_m}\right) = \left[\frac{1}{n-1}\sum_{i=1}^{n}\left[\ln\left(\frac{Q_p}{Q_m}\right) - \mu_{ln}\right]\right] \quad (6)$$

The probability density function is calculated as follows,

$$F(x) = \frac{1}{\sqrt{2pi}\sigma_{ln} x}\exp\left[-\frac{1}{2}\left[\frac{\ln(x)-\mu_{ln}}{\sigma_{ln}}\right]^2\right] \quad (7)$$

Where Q_p is the predicted value by various methods chosen and Q_m is the measured value of pile capacity by pile load test, $x = \left(\frac{Q_p}{Q_m}\right)$, μ_{ln} is the mean of $\ln\left(\frac{Q_p}{Q_m}\right)$ and σ_{ln} is the standard deviation on $\ln\left(\frac{Q_p}{Q_m}\right)$.

The Log-Normal distribution graph shows a wide difference in the capacity obtained by all the methods and proposed method. The under and over-estimation of capacity can be clearly understood. The scattering of the proposed method was found to be low and it showed better precision. Figure 5 shows the Log-Normal distribution of all the methods chosen for analysis.

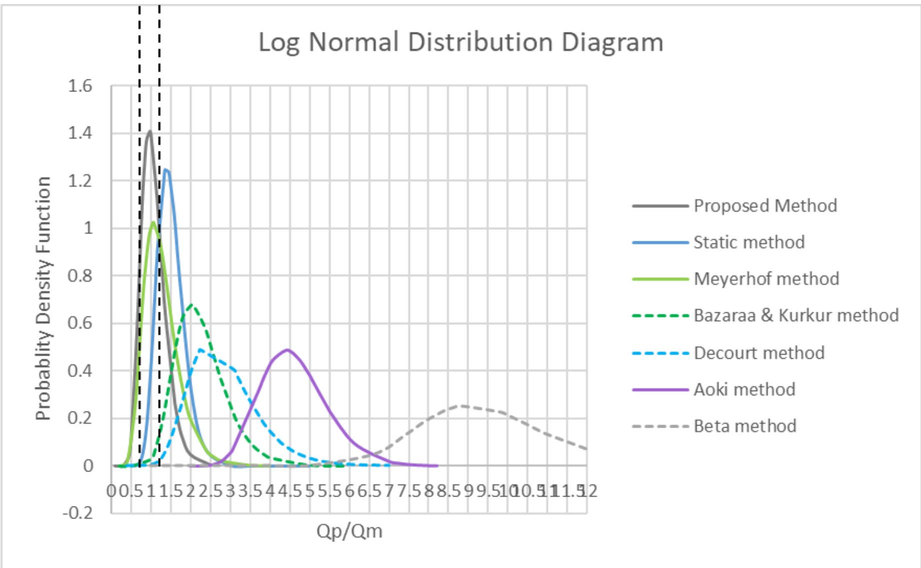

Fig. 1. Log-Normal distribution for different methods of pile bearing capacity

Based on the Log-Normal analysis, the probability that the prediction falls within $\pm$25% of all the methods is estimated by the below formula.

$$P\ (\%) = 100\int_{0.75}^{1.25} f(x)\,dx \qquad (8)$$

The Log-Normal approach also predicts the degree of scattering of uncertainty. The more the standard deviation, the higher is the degree of scattering and uncertainty. Here β Method has the higher degree of uncertainty. The results of performance prediction for the methods is presented in table 4.

Table 4. Probability that performance lies within $\pm$25% error

S No	Method	Probability of estimating within $\pm$25% error
1	IS Code Method	62
2	β Method	12.65
3	Aoki & De' alencar Method	24
4	Bazaraa & Kurkur Method	33.85
5	Decourt Method	24.35
6	Meyerhof Method	51.2
7	Proposed Method	70.5

5 Conclusions

The bearing capacity determination of pile is always a complex problem faced by engineers and researchers. Among all the methods for capacity calculation, the SPT method is found to be flexible in terms of estimation, cost, and time. In some cases, unpredictable values are obtained. The geological changes that may occur in soil and the surrounding resources with period of time is one the reasons causing failure of the pile. This uncertainty of capacity may be due to errors in calculation, instrumental error, and unskilled workforce.

A wide range of peaks and troughs was observed in pile capacity obtained by different methods. This can predict capacity as a tedious problem.

Though α method gives reliable results of capacity, its application is limited to cohesive soils. Hence this method was not considered for comparison with the proposed formula.

The scattering of the curve indicates the over and under-estimation of the methods. In Figure 1, it can be noted that the scattering is low for the proposed method. The β method has the highest degree of scattering and hence the capacity is over-estimating.

The calculation of the probability of error shows that the proposed method has better precision performance compared to other chosen methods. Meyerhof method and IS code method also give a reliable value of bearing capacity.

References

1. Amel Benali., Ammar Nechnech., Ali Bouafia.: Bored Pile Capacity By Direct SPT Methods Applied to 40 Case Histories. Civil and Environmental Research, Vol. 5, 118–122 (2013).
2. Amol Shah., Pinki Advani., Jitendra Patel., Harshit Soni.: Estimation of Load Carrying Capacity of Bored Cast In-Situ Piles. International Journal of Engineering Technology Science and Research 4(9), 814–819 (2017).
3. Karimpour-Fard., Eslami, A.: Estimation of Vertical Bearing Capacity of Piles Using the Results CPT and SPT Tests. In: 4th International Conference on Site Characterization, pp. 1055-1062. Taylor & Francis Group, Brazil (2012).
4. Sanatombi Thounaojam., Parbin Sultana.: Prediction of Bearing Capacity of Bored Cast-In Situ Piles. IOSR Journal of Mechanical and Civil Engineering e-ISSN: 2278-1684, 01–06 (2015).
5. Shariatmadari, N., Eslami, A., and Karimpour-Fard, M.: Bearing Capacity of Driven Piles in Sands from SPT–Applied to 60 Case Histories. Iranian Journal of Science & Technology, Vol. 32, 125–140 (2008).
6. Aoki, N., De'Alencar, D.: An Approximate Method to Estimate the Bearing Capacity of Piles. Proceeding of the Fifth Pan-American Conference on Soil Mechanics and Foundation Engineering, pp. 367-376. Buenos Aires, Argentina (1975).
7. Bazaraa, A. R., Kurkur, M. M.: N-Values Used to Predict Settlements of Piles in Egypt. In Proceedings of In Situ '86, pp. 462-474. New York (1986).
8. Bengt, H.F.: The Analysis of Results from Routine Pile Load Tests. Ground Engineering, pp.1931 (1980).

9. Chin, F. K.: Estimation of the Ultimate Load of Piles not carried to Failure. Proceedings of the 2nd Southeast Asian Conference on Soil Engineering, pp. 81–92. Singapore (1970).
10. Decourt L.: Prediction of Load - Settlement Relationship for Foundations on the Basis of the SPT. Ciclo de Conferencias International, pp.85-104. Leonardo Zeevaert, UNAM, Mexico (1995).
11. Decourt, L.: Behavior of Foundations Under Working Load Conditions. Proceedings of the 11th Pan-American Conference on Soil Mechanics and Geotechnical Engineering, pp. 453–488, Vol. 04. Foz Dulguassu, Brazil (1999).
12. Hansen, J. B.: Discussion on Hyperbolic Stress-Strain Response – Cohesive soils. ASCE Journal for Soil Mechanics and Foundation Engineering, 89, (SM4), 241–242 (1963).
13. IS 2911- Part 4: Code of practice for design and construction of pile foundations- Load test on piles, Bureau of Indian Standards, New Delhi (1985- Reaffirmed 2010).
14. Meyerhof, G. G.: Bearing Capacity of Settlement of Pile Foundations. The Eleventh Terzaghi Lecture. ASCE Journal of Geotechnical Engineering, Vol. 102, GT3, 195-228 (1976).
15. Van der Veen, C.: The Bearing Capacity of a Pile. Proc. Third International Conference Soil Mechanics Foundation Engineering, pp. 84–90, Vol. 02. Zurich (1953).