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Bored Pile Capacity by Direct SPT Methods Applied to 40 Case Histories

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Abstract. In these last decades, the in situ tests have known considerable progress caused by the technological development reported in this area, their earlier use were in the foundation design. These technical improvements have permitted more real knowledge of the soils characteristics and/or behavior in different depths. They became good tools for a geotechnical engineer. Recently, the use of bored piles is multiply around the world because of their moderate bearing capacity suitable in many projects, relatively low cost, easy length adjustments, low vibration, and noise levels during the installation. An attempt is done in this paper to formulate and calibrated a new method based on the N-value from SPT. Data averaging, failure zone extension, and plunging failure of piles has been noticed in the proposed approach. A data base were collected and analyzed, including 40 full scale static pile load tests through a variety of grounds and stratigraphy around the world. The soil profiles range from soft to stiff clay, medium to dense sand, and mixtures of clay, silt, and sand. The pile embedment lengths range from **2** to **57** m and the pile diameters from **100** to **1220** mm. A performance analysis of the new SPT method is carried out with other prediction methods by using different criteria. The proposed method is suitable tool to practical design of bored piles, due to their consistent results.

1 Introduction

Many civil projects, such as large highway bridges, harbours and oil extraction facilities, cannot rely merely on shallow foundations, for their stability. Therefore, pile foundations are used to back up the superstructures by transferring the load from the soft surface layers to the firmer layers deep underground. Creating pile foundations under loading is a complex problem that is not well understood yet. Precisely predicting a pile's load-bearing capacity has always been a challenge for design engineers [1]. To estimate the load-bearing capacity of the piles, therefore, one or more of several pile loading tests (PLTs) and pile dynamic analysis (PDA) tests may be performed, depending on the importance of a project. Several methods and approaches have been developed to overcome the uncertainty in the prediction.

The methods include some simplifying assumptions and/or empirical approaches regarding soil stratigraphy, soil-pile structure interaction, and distribution of soil resistance along the pile. Therefore, they do not provide truly quantitative values directly useful in foundation design[1]. Due to the high cost and the time required for conducting such tests, however, it is a common practice for engineers to estimate the load-bearing capacity of piles using in situ tests, such as the cone penetration test (CPT), standard penetration test (SPT), dilatometer test and pressuremeter test, and then to apply a reasonable safety factor value during the design process to achieve a stable foundation [2].

Bearing capacity of piles can be determined by five approaches as follows:

• Interpretation of data from full-scale pile loading tests,
• Dynamic analysis methods based on wave equation analysis,
• Dynamic testing by means of the Pile Driving Analyzer (PDA),
• Static analysis by applying soil parameters in effective stress or total stress approaches,
• Methods using the results of in-situ investigation tests, directly or indirectly: the application of in-situ testing techniques has increased for geotechnical design.This is due to the rapid development of in-situ testing instruments, an improved understanding of the behavior of soils, and the subsequent recognition of some of the limitations and inadequacies of conventional laboratory testing [3]. In indirect methods, only soil parameters are obtained from SPT results and the methodology of the pile bearing capacity estimation is the same as for the static methods.

The Standard Penetration Test, SPT, is still the most commonly used in-situ test. Pile capacity determination by SPT is one of the earliest applications of this test that includes two main approaches, direct and indirect methods. Direct methods apply N values with some modification factors. However, considerable uncertainty exists regarding filtering and averaging the data relating to pile resistance, failure zone around the pile base,..ETC. Since pile capacity depends on the soil compressibility and the SPT is one of the most commonly used tests in practice for indicating the in situ compressibility of soils; the SPT blow count/300 mm (Nspt) along the embedded length of the pile and within the failure zone are used as a measure of soil compressibility for the purpose of this study. In addition, as suggested by Liao and Whitman

[4], for sand the value of Nspt is corrected for overburden pressure, as given below. This correction is not used for clays

Ncorrect = Cn x Nspt

Cn=$\sqrt{(95,76/\sigma'v)}$; where,
CN is the adjustment for effective overburden pressure
σ'v is the effective overburden pressure (kPa).

2 Pile capacity from SPT data

Two main approaches for application of SPT data to pile design have evolved: indirect and direct methods. In indirect methods employ soil parameters, such as friction angle estimated from the SPT data, Then the unit end bearing capacity of the pile (qp) and the unit skin friction of the pile (qs) can be evaluated from these strength parameters through formulas of semi empirical and theoretical methods. The indirect methods such as the strip-footing bearing capacity theory take no account of the horizontal stress, and neglect soil compressibility and strain softening. However, the authors consider that the indirect methods are not much suitable for use in engineering practice and there by will not discuss them any more this paper. Different from the indirect methods, the direct methods don't need to perform laboratory tests and calculate the intermediate values such as earth pressure coefficient and bearing capacity coefficient. These methods were described in detail in many a research report and the resume is given in Table 1.

Table 1. Current SPT direct methods for prediction of pile bearing capacity [5]

	References	K_s (kPa)	n_s (kPa)	N_s & zone of influence	Pile installation.
1	Bazaraa & Kurkur (1986)	135 if B≤0.5 m 270xB else (B in m)	0.67 if B≤0.5 m 1.34xB else (B in m)	Average within [D-3.75xB, D+B]	bored
2	Decourt (1982)	400 in sand 250 in residual silty sand	q_s=10x(N/3+1) (in kPa)		bored
3	Lopes & Laprovitera (1988)	98.4 in sand 87.0 in silty sand	1.62 in sand 1.94 in silty sand	Average within [D-B, D+B]	bored
4	Meyerhof (1976) CFEM (1985)	120 400	1 2	-Average within [D-8B, D+3B] -correction due to depth effect	bored driven
5	Shioi et Al (1982)	100 300	1 2		bored driven
6	Aoki et Velloso (1975)	286 in sand 228 in silty sand	2.00 in sand 2.28 in silty sand	Average of the 3 N values closest to pile base	bored
7	PHRI Standard (1980)	400	2	- average of N_1 and N_2 -correction due to ground water effect	driven
8	Reese et Al (1989)	60 if B=0.52-1.27 76/B if B>1.27 m (B in m)	3.3		bored
9	Robert (1997)	115 190	1.90 1.90	-correction due to depth effect	bored driven
10	Hansen-Burland (1973)	q_t= N_q. σ'v (D) N_q = Hansen's bearing capacity factor N_q =f(φ) φ derived from φ-N chart q_s = K_0.σ'v tgδ Burland's β formula K_0 = (1-sinφ).(OCR)$^{1/2}$ (OCR=1) intermediate roughness of pile shaft : δ= 0.75xφ		-Average within [D-B/2, D+2B] - correction due to ground water effect	

3 Case records data base

A database of case histories from the results of 40 full scale pile loading tests is compiled with information on soil type and results of SPT soundings performed close to the pile locations. The cases were obtained from different sources reporting data from many sites in many countries. Table 2 summarizes the repartition of the main characteristics of these tests. The soils at the sites are generally heterogeneous. The piles have a round cross section, the piles materials are concrete, and were installed with different techniques such as, CFA, DFP and others.

The data are subdivided in two groups; the first one is constituted of 25data, to calibrate the proposed method

The second is to validate the method.

Table 2. Description of the used database

Authors	Countries	N br	B	D	Nt
1	Different countries	15			Is corrected with the formulate suggested by Liao and Whitman for sand soils and calculated with the Eslami and Fellenius rule(1997)
2	Malaysia	1			
3	Texas	1			
4	Kuwait	1			
5	Malaysia	1			
6	France	1			
7	Texas	3			
8	Bangkok	10			
9	Malaysia	4			
10	Las Vegas	3			
B= 0,1 to 1,22m; D = 2,25 to 57,1m ; D/B= 11,9 to 74,26 Nt= 13,64 to 84 Total=40					

Nbr :data number ; **1:**Bouafia and Derbala[5]; **2:**Balakrishnan et al[6]; **3:**Reese and O'Neill [13]; **4:**Ismael [9];**5:**Amaludin and Hussein[8]; **6:**Bustamante and Gianeselli [7]; **7:**Briaud et al [10]; **8:**Thasnanipan et al [12]; **9:** Abdul Aziz and Lee[12]; **10:** Mackiewicz and Jonathan Lehman[15].

3.1 SPT averaging system

Natural soil deposits, particularly sands, produce blows number profiles with many peaks and troughs. The blows number variations reflect the variations of soil characteristics and strengths. Therefore, when determining pile toe resistance, which is a function of the soil conditions in a zone above and below the pile toe, an average must be determined that is representative for the zone. It is important to note that the pile diameter controls the extent of rupture surface below and above the pile toe. Therefore, the value must be a function of the pile diameter.

Usually two methods of averaging, arithmetical and geometrical, are used to find the mean value of a series of numerals. As a result, using the geometrical average method to obtain the logical representative of N values seems to be more accurate and relevant [1]. It should be noticed that the SPT values used for the geometric average should be at a constant spacing. The arithmetic average is only useful where the SPT values are uniform, i.e.,in homogeneous soils. The geometric average of the blows number over an influence zone that depends on the soil layering, which reduces, removes potentially disproportionate influences of odd peaks and troughs, which the simple arithmetic average used by the SPT methods does not do. Therefore, a filtering effect can be achieved directly By calculating the geometric average of the Nspt values, which is defined as,

$$N_{avr} = \sqrt[n]{(N1 \times N2 \times N3 \times \ldots . . N n)};\quad n: \text{data number}.$$

Consider the following series of 12 values : 5,5,2,5,25,5,6,3,6,6,30 and 6. The arithmetic and geometric averages are, respectively, 8,5 and 5,7. We conclude that the geometric average is closer to the dominant values, as opposed to the arithmetic average. Thus by taking the geometric average in a zone at the vicinity of the pile toe, a filtered representative value is obtained [1].

In order to obtain the unit base resistance of piles from standard penetration test results, the failure zone and failure mechanism should be specified around the base of the pile.

3.2 Influence zone for end bearing

Yu and Yang(2012)[16] summarize several proposals for the size of the influence zone and give short description, where A and B represent the range of the zone above and below the pile base Fig. 1. After careful analysis of the different zones of influence presented and applied on the database, we found interesting and practical to use the Esslami and Fellenius (1997) rule and offers the following two situations:

- When a pile is installed through a weak soil into a dense soil, we take a depth of 4B below the pile toe and 8B above.
- In the inverse situation we take a depth of 4B below the pile toe and 2B above.

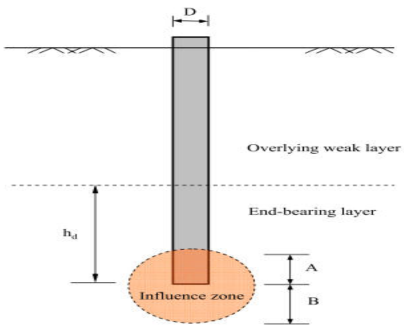

Fig. 1. Influence zone for averaging blows number near the pile base

3.3 Formulation of the proposed method

A new method has been developed for pile bearing capacity estimation, based on the results of standard penetration tests in different stratigraphy. There are several methods to predict the pile failure or ultimate load from pile load test results, among them, Davisson offset limit load, 80% Brinch Hansen criterion, Chin-Kondner and others. In this study the ultimate pile capacity Qu is taken to be at the plunging failure for the well defined failure cases and at the 1/10 of pile diameter for the cases where the failure load is not clearly defined, as suggested by many authors. The method is calibrated with 24 cases. We use the Esslami and Fellenius rule and the geometric averaging, noted **Nt** in this study.

4 Results and discussions

By plotting the variation of the tip resistance according to Nt, we found the presence of two sets, 80% of the data together in the first set, 20% in the second. The investigated sites in this study allowed us to identify these two different behaviors Fig.2 and Fig.3. The coefficient of determination is very acceptable in our situation, knowing that the drilled shafts mobilize more resistance along the shaft. Currently, the tip resistance is improved by grouting technology.

Set 1 : 20 DATA

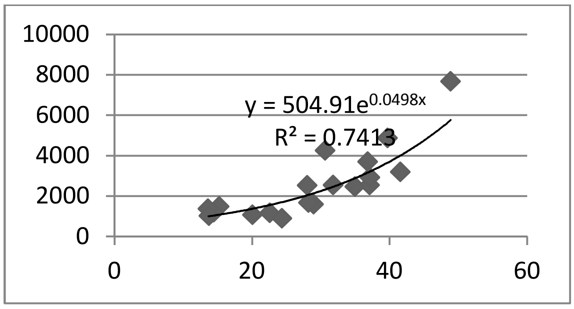

Fig.2. Variation of the base resistance with Nt; (y=ql; x=Nt)

The arithmetic averaging of (ql / Nt) for the 20 cases gives:

ql / Nt = 83.93

Set 2: corresponding to Nt≥40 and D/B≥20, we note 4 cases.

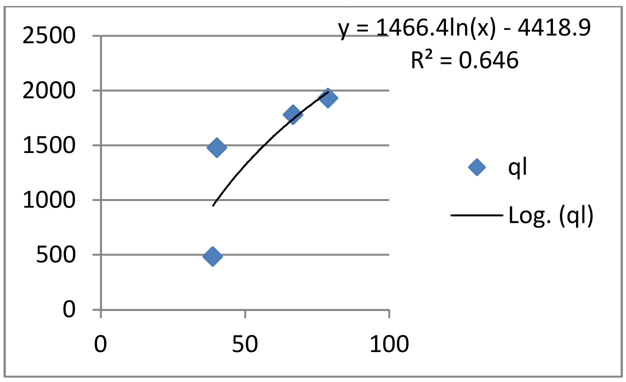

Fig. 3. Variation of the base resistance with Nt;(y=ql; x=Nt)

The arithmetic averaging of (ql / Nt) for the 4 cases gives:

ql/ Nt = 25,09

The arithmetic averaging of (ql / Nt) for the all cases(24) gives:, **ql/ Nt = 64,93 for : B=0,1 m to 1,22m**

The results are in concordance with those of Reese et al (1989) [5], which recommended:

ql /Nt =60 for B=0,52m to 1,27m

5 Validation

To compare the calculated and measured pile capacity for all case records, Fig.4 presents the results of the proposed method with the chosen methods. We conclude that the proposed method yields the good predictions for both piles. In this study we use the average value of the calculated and measured pile capacities ratio for all cases.

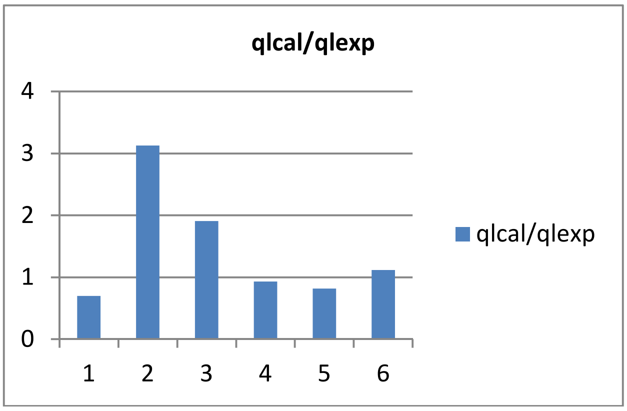

Fig. 4. Comparison of the proposed method with the other methods

Note:
1:Meyerhof (1976)/CFEM(1985) [5]; **2:**Decourt(1982) [5]; **3:**Aoki and Velloso(1975) [5];**4:**Hansen-Burland(1997) [5] ;**5:**Shioi et al (1982) [5]; **6:**proposed method.

5.1 Performance analysis

Statistical and probability approaches were engaged to verify the SPT predictive methods. Log-Normal methods have been considered to compare different approaches of pile capacity determination. The log normal distribution can be employed to evaluate the performance of the pile capacity prediction method [17].

The log normal distribution is acceptable to represent the ratio of (qlcal/qlexp) or (Qp/Qm); however, it is not symmetric around the mean, which means that the Log Normal distribution does not give an equal weight for under prediction and over prediction.

Based on the Log Normal distribution analysis, the probability that predictions fall within a ±25% accuracy level in these methods can be estimated between 0,75 and 1,25 as follows:

P(%)=100∫F(x); F(x): Log Normal distribution Fig.5

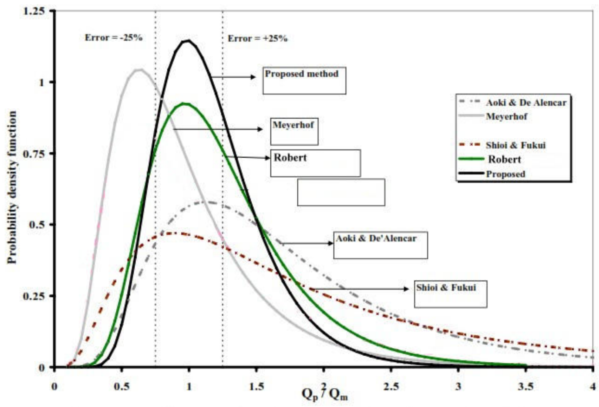

Fig.5. Log normal distribution diagram for different methods of pile capacity determination

Qp: the predicted base bearing capacity
Qm: the measured base bearing capacity

The results of this analysis are presented in Table 4.These results indicate that the proposed method has a better precision than others in predicting the pile bearing capacity.

Table 4. The probability of estimating within ±25% for four and proposed methods

Methods	Probability of estimating within ±25 % error (%)
Aoki and Velloso (1975) [5]	27
Meyerhof (1976) CFEM (1985) [5]	36
Robert (1997) [5]	42
Shioi et al (1982) [5]	20
Proposed method	63

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