Assessment of an SPT-based approach for predicting the axial bearing capacity of concrete pile foundations installed by the driving and press-in methods

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ABSTRACT

Estimating the axial bearing capacity of displacement pile foundations in common soil types presents challenges in selecting a practical, reliable, and accurate solution due to validation limitations in the literature. This research addresses this issue by thoroughly examining the predictive accuracy of an SPT-based approach originally proposed by Décourt (1982, 1995). The study applies this method to predict the bearing capacities of concrete pile foundations installed by driving and press-in methods and compares the results with High Strain Dynamic Load Tests. The assessment reveals good agreement between the test results and the predictions. These findings substantiate the applicability of Décourt's empirical method in forecasting the axial bearing capacity of displacement pile foundations, particularly for concrete-driven and press-in piles, with practicality, reliability, and fair accuracy.

Key words: *SPT, Displacement pile, CAPWAP*

1. Background and objective

Solutions for predicting the axial bearing capacity of pile foundations may range from empirical to analytical methods in the order of increasing difficulty and the amount of data required. Empirical methods often involve correlations between shaft friction and tip bearing capacity derived from pile loading tests with in-situ testing results such as SPT N values and CPT sleeve and tip resistance.

In another way, analytical methods are developed based on classical soil mechanics theories. These methods involve the application of some crucial empirical factors such as the adhesion factor α, coefficient of lateral stress K_s, and pile tip bearing capacity factor N_q and N_c - all of which vary as a function of the pile's installation methods, except N_c. For example, the value of factor α and N_q for a concrete driven pile is different from that for a bored pile. Numerous solutions have been proposed in the literature to estimate these factors. However, application of most of them yield different results for the same situation, leading to doubts regarding their validity. Even with these challenges, it does not mean that applying analytical methods is impossible. Experience shared by Poulos (2017) may serve as a valuable guide on the application of such approaches, where he categorizes them as category 2 methods. Nevertheless, using analytical methods for a ground model containing both cohesive and cohesionless soil requires information such as undrained shear strength, internal friction angle, preconsolidation pressure and unit weight, preferably obtained from appropriate tests.

In many practical scenarios, SPT data is the sole resource, which is why SPT-based methods rank as the most practical choice. Many of these approaches are compiled by Poulos (1989). However, upon scrutiny, it is noted that each correlation is inconsistence for the same soil type and pile installation method, which makes it difficult to decide which solution shall be adopted. Clearly, before any appropriate selection for the most reliable and accurate solution can be made, the work of validation is strongly needed. It is also worth noting that none of the methods compiled by Poulos (1989) are developed for the concrete pile foundation installed by the press-in method.

In later years, Poulos (2017) reported an SPT-based approach developed by Décourt (1982, 1995), which is applicable to both displacement and non-displacement pile foundations and can be adopted for four common soil types: sand, sandy-silt, clayey-silt, and clay, making it quite attractive among other approaches in the same category. As will be presented in detail in subsequent sections, this method appears to be complete, simple to use and practical. However, the necessity to conduct validation remains the same. Hence, its performance will be assessed in this paper. Additionally, even though the method can be applied to some extent, the focus in this research will be limited to displacement piles.

Solid square cross-section concrete pile foundations installed by the driving and press-in method, along with driven spun piles with open ends, will be the subject of this assessment. Data collected from two countries, Cambodia and the Philippines, will be used, allowing the evaluation of the performance of Décourt's empirical method for displacement piles across various geological conditions and geotechnical characteristics possible.

2. Axial capacity of single piles

2.1. Basic approach

Generally, for a single pile foundation, the ultimate compressive load capacity P_u is calculated as the sum of the ultimate shaft capacity P_{su} and the ultimate base capacity P_{bu}, minus the weight of the pile, W_P. In turn, P_{su} and P_{bu} are related to the unit ultimate shaft and base resistances, so that P_u is calculated as follows:

$$P_u = \int f_s \, C \, dz + f_b \, A_b - W_p \qquad (1)$$

where f_s is the unit ultimate shaft friction; C the pile perimeter; dz is the increment of pile length along the shaft; f_b is the unit ultimate base resistance; A_b is the area of the pile base; W_p is the pile weight.

Various approaches for estimating f_s and f_b, mostly falling into empirical or analytical categories. However, in this research, only the empirical method proposed by Décourt (1982, 1995) will be introduced, for both displacement and non-displacement pile foundations. And the focus will be specifically on concrete pile foundations installed via the press-in and driving methods.

2.2. Décourt's (1982, 1995) empirical method

Empirical correlations with the results of SPT data usually take the following form:

$$f_s = A_N + B_N N \text{ (kPa)} \qquad (2)$$

where A_N and B_N are empirical numbers, and depend on the unit of f_s, and N is the SPT value at the point under consideration.

$$f_b = C_N \, N_b \text{ (MPa)} \qquad (3)$$

where C_N is an empirical factor; N_b the average SPT within the effective depth of influence below the pile base (typically 1 to 3 pile base diameters).

Décourt (1982, 1995) has developed correlations between f_s and SPT, which take into account both the soil type and the methods of installation. For displacement piles, $A_N = 10$ and $B_N = 2.8$, while for non-displacement piles, $A_N = 5$ to 6 and $B_N = 1.4$ to 1.7. For the base, value of C_N are shown in **Table 1**.

Table 1. Factor C_N for base resistance

Soil type	*Displacement piles*	*Non-displacement piles*
Sand	0.325	0.165
Sandy silt	0.205	0.115
Clayey silt	0.165	0.100
Clay	0.100	0.080

3. Description of data gathered from both countries

3.1. Cambodia

It is routine practice in Cambodia for almost all projects to investigate the geotechnical properties of the subsoil using the Standard Penetration Test (SPT). To conduct this in-situ test, the hammer used to drive the split spoon sampler is commonly of the 'donut' type, and the test is performed at every 1.5-meter interval unless specific instructions have been given. Subsequently, the Shelby tube is used to extract undisturbed samples from the ground. The application of other in-situ tests, such as the Cone Penetration (CPT) and Pressure Meter Test (PMT), is uncommon. For basic geotechnical investigation reports, laboratory tests such as natural unit weight, moisture content, Atterberg limit, grain-size analysis, and specific gravity are often performed. Unconfined compression and direct shear test are also conducted, but less frequently. Additionally, consolidation and triaxial tests are only carried out upon specific orders from the client.

Five case histories of the application of concrete pile foundations installed via the driving method are gathered from Cambodia. Among them, three cases are collected from Phnom Penh, and the other two are from Kampot. The distance between both cities is roughly 150 km. Two types of piles were used: the regular solid square cross-section with diameters of 0.3 and 0.4 meters, and length ranging from 7 to 12 meters, and spun piles with a diameter of 0.35 meters and lengths ranging from 10 to 13 meters. In total, 14 boreholes were drilled, and the axial bearing capacity of 29 piles was verified using High Strain Dynamic Load Tests, also known as PDA tests.

Subsoil characteristics of all five case histories collected from Cambodia can be roughly described as following: the upper layer consists of (i) made ground approximately 2 meters thick followed by a fairly homogeneous layer of (ii) very soft to soft clay down to a depth of 12 meters and then (iii) medium stiff clay down to a depth of 17 meters. Successively, six consecutive inter-bedded layers of (iv) very loose to loose sand, (v) stiff to very stiff clay, (vi) hard silt, (vii) medium dense sand, (viii) stiff to very stiff clay, and (ix) dense to very dense sand are under neath the upper thick clay layers.

3.2. Philippines

The data obtained from the Philippines consists of four different sites. Three of them utilized concrete piles installed by the driving method as foundations, while the remaining site used the press-in method. Information about their specific locations is not available. The testing interval of SPT is mostly every 1 meter. The driven piles used are of the regular type with solid square cross-sections of 0.4, 0.45 and 0.5 meters in diameter and lengths ranging from 28 to 45 meters. The piles installed by the press-in method are also of the regular type, with diameters of 0.45 and 0.5 meters. The total number of boreholes drilled was 12, and the number of piles that underwent High Strain Dynamic Load Tests to verify their compressive bearing capacity is 20.

The subterranean characteristics of four distinct sites in the Philippines predominantly encompass layers of very soft clay or silty clay extending to approximately 20 meters in depth, succeeded by layers of medium stiff to hard silty or sandy clay reaching depths of approximately 45 meters.

4. Validation procedure

In ideal conditions, it is preferable for the data source used to assess a method to be taken from borehole drilled exactly at the test pile location. However, such a circumstance is not practical. In many cases, even within the same project, the boreholes and the piles undergoing loading tests are situated at different points. Hence, it can be expected beforehand that the standard deviation exhibited during the comparison between the predicted compressive bearing capacity based on the method under validation and the test results can be high, depending on the irregularity of the geological profiles and geotechnical properties at each site. Nevertheless, with sufficient amount of data, such an assessment should be able to indicate the disparity between the predicted and measured values. This, in turn, should reveal the reliability of the forecasting method.

In this research, the forecasting method for displacement piles described in section 2.2 will be utilized. Its reliability in predicting the axial bearing capacity of concrete pile foundations installed by press-in and driving methods will be evaluated.

To assess this empirical method, the data described in section 3 will first be categorized into two groups. The first group will consist of all data collected from Cambodia, which is further divided into two subgroups.

The first subgroups will pertain to regular concrete driven piles in Phnom Penh and Kampot, while the remaining subgroup will focus on driven spun piles in Phnom Penh. Another group of data will be sourced from the Philippines, which also divided into two subgroups: one for driven piles and another for press-in piles. The compressive bearing capacity of each pile will be estimated, and the results will then be directly compared with the values obtained from High Strain Dynamic Load Tests. Presentation and discussion of the validation of each data group and of the overall will be made.

5. Results and discussion

The results of the comparison are illustrated in **Figures 1a** and **1b** for each data group separately and overall, respectively.

It can be noted immediately from **Figure 1a** that the scatter points exhibit less width for the projects containing data from a single site, which are the driven spun piles in Cambodia and the press-in piles in the Philippines. Additionally, for the Philippines' driven piles, even though the sources of data are collected from three different sites, the same behavior as above also occurs. The conclusion that can be drawn is that each site individually in the Philippines, being the subjects of this research, consists of a relatively uniform geological and geotechnical characteristics. Meanwhile, the concrete driven piles in Cambodia exhibit the widest scatter points among all data groups, indicating significant variation in geological and geotechnical conditions.

Marginally, overprediction for the spun piles in Cambodia and the driven pile in the Philippines, and underprediction for press-in piles in the Philippines and driven piles in Cambodia by the application of Décourt (1982, 1995) method compared to the results of High Strain Dynamic Load Tests may also be noted in **Figure 1a**. However, this deviation is not very meaningful, especially when the total axial compressive capacity is deducted by the factor of safety. The fact that this method is able to maintain such good performance in a field where there are so much uncertainties involved, and with minimal information about the ground, is already remarkable and should be practically sufficient.

To assess the overall performance of the same empirical method for pile foundations installed by driving and press-in methods across the geological and geotechnical conditions of the Philippines and Cambodia, validation for all data is as well conducted. **Figure 1b** illustrates the results of this comparison. Similar to the group-by-group assessment, this method worked quite satisfactorily, although it tended to slightly conservative.

Even though the data included in this study represent only a petite fraction of the world's subsoil, Décourt (1982, 1995) method is expected to be applicable to other regions as well, at least as a first-order estimate.

6. Concluding remarks

This study addresses the pressing need for reliable methods to predict the axial bearing capacity of pile foundations, crucial for ensuring the safety and stability of civil engineering structures. Through a thorough review of empirical and analytical approaches, with a focus on the empirical method proposed by Décourt (1982, 1995), we have explored the challenges and opportunities in this field.

By validating Décourt's method using data from Cambodia and the Philippines, we have demonstrated its effectiveness across diverse geological contexts, particularly for concrete pile foundations installed by the driving and press-in methods.

Very few papers have been published internationally related to geotechnical engineering practices in Cambodia. Our findings represent the first attempt to validate the Décourt (1982, 1995) method for displacement pile foundations in Cambodia and the Philippines.

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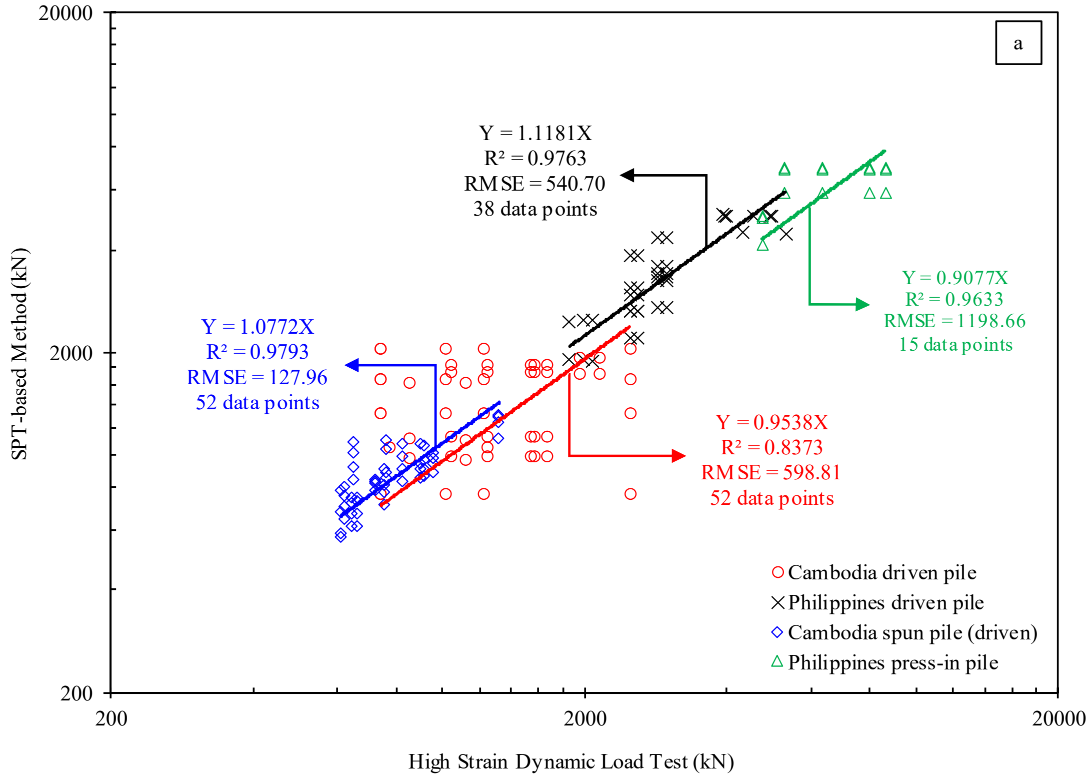

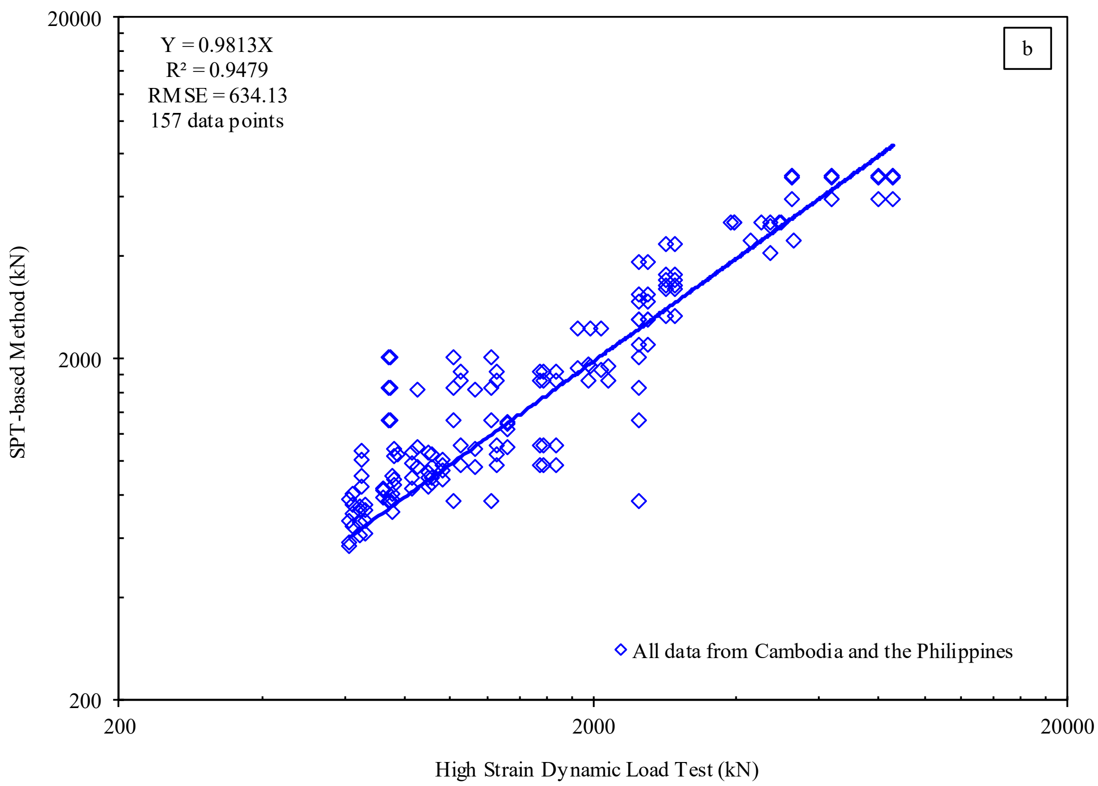

Fig. 1 Comparison between the prediction and the results of High Strain Dynamic Load Tests: (a). Group-by-group comparison, (b). Overall data.

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