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Assessment of the Theoretical Methodology Used in the Canadian Foundation Engineering Manual for Piles Design in Sand

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Abstract **-** Several design criteria exist in practice to calculate the bearing capacity of piles in various soil mediums. Piles in sandy soils, both bored or driven, have two types of resistance, either from the shaft side friction, which requires a small displacement to be mobilized, or a base bearing resistance that needs approximately ten times the displacement required for developing the side friction resistance to be fully mobilized. Many empirical, mathematical and even numerical estimations are used to predict each of these two components. Assessing the suitability of each of the existing methods is essential to achieve reliable pile designs. This paper assesses the theoretical equations used in the Canadian Foundation Engineering Manual (CFEM, 2006) for bored and driven piles in sand. Fifty different full-scale pile load tests with measured pile load capacities are presented and compared to the theoretical predictions of the CFEM to evaluate the validity and accuracy of these theoretical approaches in predicting the actual developed pile load capacities.

Keywords**:** pile capacity, driven piles, bored piles, shaft resistance, bearing resistance.

1. Introduction

Nowadays, high rise buildings exist in every large city around the world as a distinguishing characteristic of development and growing economy. These buildings usually have extremely high loads that cannot be carried by the supporting soils using conventional shallow foundation systems, which may exceed either their bearing capacity or the settlement limits. Then the use of piles, either bored or driven, maybe the only practicable solution to provide a suitable system that can maintain the serviceability of these structures beyond the allowable limits and transfer the external loads to a deeper competent stratum that is capable of supporting such high loads. Different types of piles of different shapes (e.g., circular, square) and materials (e.g., concrete, steel, FRP) are used in practice. Piles can be loaded axially in compression or tension, or they can be subjected to horizontal loads. Piles are also used to resist moments in tall structures and upward forces in structures subjected to uplift, such as buildings with basements below the GWT, buried tanks and wind turbines. The design method used for a particular pile foundation will depend on the soil in which it penetrates through, whether it is cohesive (clay) or cohesionless (sand), and whether the pile toe bears on soil or rock. Besides, the method of installation has a significant effect on the pile performance under subsequent loading.

Piles in sandy soils, which is the focus of this paper, both bored or driven, have two types of resistance, either from the shaft side friction which requires a small displacement to be mobilized or from a base bearing resistance that needs approximately ten times the displacement required for developing the side friction resistance to be fully mobilized. A number of empirical, mathematical and even numerical estimations are used to predict each of these two components. Assessing the suitability of each of the existing methods is essential to achieve reliable pile designs.

Piles in a cohesionless stratum are widely needed all over the world especially in areas with desert land that has sandy layers up to 100m depths like in the Southern States, Middle East and North Africa. This paper investigates fifty different full-scale pile load tests with measured pile load capacities from previous case studies of bored and driven piles in cohesionless soils, then compare the field measurements of the axial load capacities in compression with the results estimated using the theoretical equations provided by the Canadian Foundation Engineering Manual (CFEM, 2006) to assess their validity.

2. Data of Driven and Bored Piles Load Tests in Cohesionless Soils from Previous Researches

The paper introduces previous case studies using bored and driven piles in mostly sandy soils. For driven piles, which are widely used in offshore and terrestrial structures, several load tests in cohesionless soils are presented here on a variety of pile types. In addition, driving in cohesionless soils induces a higher capacity for the piles' group that can sustain greater loads. For bored piles, which are not preferred in sandy soils because of the reduced strength in the pile group due to boring and some difficulties in the installation as well, but in the same time, boring overcomes the noise and vibrations issues resulting from driven piles especially in urban centers and busy residential locations. The site location, piles properties and the maximum axial capacities are summarized in Table 1 below for driven piles and in Table 2 for bored piles.

Almost all the pile load tests under static axial loading result in a relation between the applied axial loads with the corresponding pile settlement (i.e., displacement) similar to the pile load test results example shown in Figure 1.

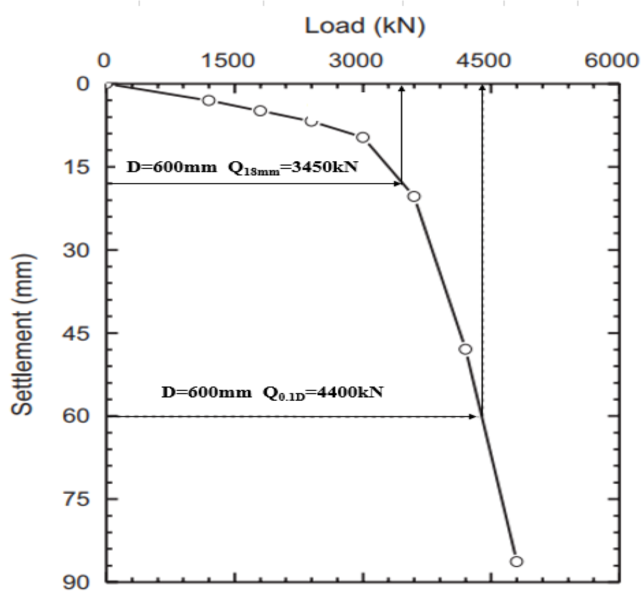

Fig. 1: Example of a pile load versus settlement in static loading test (ZJU-ICL Database, 2016).

However, several tested piles weren't loaded to failure, and several methods can estimate their ultimate capacities according to the procedures of the test itself. In case of the results contains the load-displacement curve as illustrated above, the pile capacity can be estimated according to IS: 2911 (Part 4)-2013 as the minimum value in the following two approaches, either two-thirds of the test load corresponding to 18 mm settlement or half of the test load corresponding to 10% of the pile tip diameter.

The data presented in Tables 1 and 2 are collected from several sources in different locations around the world to capture the effect of pile installation methods of boring and driving in the cohesionless media. Then, these values will be compared with the results calculated from the Canadian Manual using its recommended theoretical equations to assess their reliability in estimating the axial pile capacity.

Table 1: Site location, piles properties and maximum axial load capacities in driven piles load tests.

Driven Piles					
Site Location	**Pile Material**	**Diameter (mm)**	**Pile length (m)**	**Friction angle (Φ)**	**Pile Capacity (kN)**
China	Concrete	600	33	32	871
		600	39.8	32	2200
		600	29.3	35.5	2450
		800	29.2	33	2412
USA	Concrete	455	16.2	40	3600
	Steel	324	42.7	34	1675
		273	17.8	33	540
		356	20.29	35.7	1200
USA	Steel	457	6.1	36	1040
		457	8.9	37	1320
		457	12	38	1605
		457	15	38.5	1975
		273	7.8	35	220
		305	14.2	37.5	585
		406	14.6	36	810
		324	15.2	38	640
Netherland	Steel	356	6.8	39	1425
Japan	Steel	200	11	39	475
Italy	Steel	508	35.9	36	2600
Australia	Concrete	500	13.8	41	4250
Taiwan	Steel	609	34.3	39	4460
		609	34.3	38	4330
Brazil	Concrete	500	9	37.9	1568
		500	7.5	34.8	1567.5

Table 2: Site location, piles properties and maximum axial load capacities in bored piles load tests.

Bored Piles					
Site Location	**Pile Material**	**Diameter (mm)**	**Pile length (m)**	**Friction angle (Φ)**	**Pile Capacity (kN)**
Bolivia	Concrete	600	16.4	35	1667
		600	16.4	35	1600
		300	9.5	34.5	613
		300	9.5	34.5	400
USA	Concrete	410	5.6	36	560
		405	8.4	37	1019
		405	10.4	36	1019
		350	15.8	33	840
		405	7	38	1294
	Steel	393	6.5	35.5	738
		403	9.2	37.5	1352
		762	16.8	36	3425

Bored Piles (Continued)					
Site Location	**Pile Material**	**Diameter (mm)**	**Pile length (m)**	**Friction angle (Φ)**	**Pile Capacity (kN)**
Germany	Concrete	500	10.2	35	1299
		500	10.2	34	1005
Belgium	Concrete	430	8.7	36	627
	Steel	521	8.2	36.5	1334
Kuwait	Concrete	671	10.2	39.5	4697
		320	7.7	34	356
		399	10	36	756
		671	13	39	4270
		521	8.2	35.5	1263
		329	6.3	37	756
		408	5.8	36	765

3. Theoretical Design Approach of Piles Installed in Cohesionless Layers According to the CFEM

Piles are usually designed to overcome issues related to exceeding the foundation soil bearing capacity or the tolerable settlement. In addition, they are designed under compression or tension loads according to the structure function. Piles can be installed in the underground stratum using the following techniques: driving, boring, jacking or jetting, but the most well-known methods are either boring or driving. In sandy soils, driving is commonly used as it results in increasing the pile capacity due to the higher confining stresses around the pile shaft beside the densification of the soil below the pile's toe. For bored piles in sandy soils, the capacity is lower due to the drilling action that expands the voids in the soil around the pile, but sometimes boring is a more suitable technique rather than driving to avoid noise and vibrations issues as mentioned above.

Loads mainly transfer in piles from superstructures to the supporting soil using two mechanisms, the pile shaft friction that requires a settlement of about 5-10 mm to mobilize the side friction resistance, and the pile tip that needs a settlement of about 5-25% of the pile diameter to fully mobilizing the end bearing resistance. The CFEM recommends the following equations to calculate the pile capacity in sand for both cases, bored and driven:

$$Q_{ult} = Q_s + Q_b \quad (1)$$

For shaft resistance:

$$Q_s = q_s A_s \quad (2)$$

$$q_s = K_s \sigma'_\circ \tan\delta \quad (3)$$

For end bearing resistance:

$$Q_b = q_b A_b \quad (4)$$

$$q_b = \sigma'_t N_q \quad (5)$$

where:

Q_{ult} = total ultimate pile capacity force

Q_s = pile side resistance

Q_b = pile end bearing resistance

q_s = average shear stress resistance along the pile shaft
q_b = tip bearing capacity resistance at the pile toe ($q_b \leq q_L$)
q_L = max tip resistance (q_L=50 Nq tan (φ')
K_s = lateral earth pressure coefficient (For bored piles=K_o, low-displacement piles=1.4K_o and high-displacement piles=2K_o)
K_o = at rest lateral earth pressure coefficient
σ_o' = average effective overburden stress along pile length
σ_t' = effective overburden stress at the pile tip
δ = friction angle between the pile material and surrounding soil (For concrete=0.75φ, steel or timber=20o)
N_q = deep foundation bearing capacity coefficient (Meyerhof, 1976), the CFEM also presents ranges for Nq in Table (18.2) that will be assessed later compared to the Meyerhof values.

It should be noted that the effective overburden stress in sandy soils maintains constant after a specific depth called the critical depth which ranges from 15 D in loose sand to 20 D in dense sand, this behavior was captured through many field and lab tests which proved the negligible effect of the weight of soils below a specific depth.

4. Assessment of the CFEM Design Method Compared to Field Data

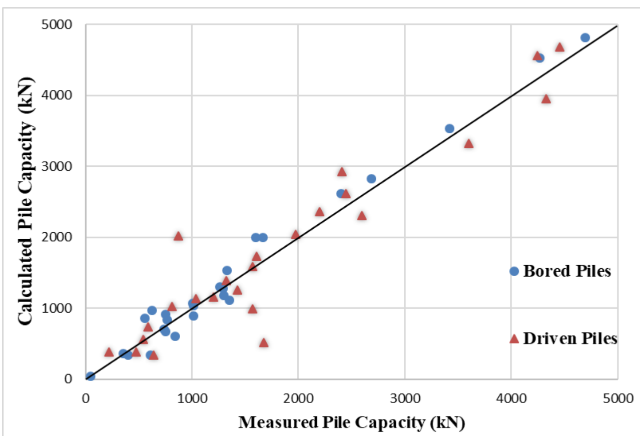

Fig. 2: Measured and calculated axial pile load capacities in cohesionless soils in both cases; bored piles and driven piles

The design of piles in any soil has several methodologies that are different according to each design manual. Using the data mentioned in section (2) is to compare the results from several axial piles load tests with those theoretically calculated from the CFEM. Moreover, this comparison enhances the reliability in the theoretical method that saves time required for sophisticated numerical modelling for the pile design. Figure 2 shows the results of the CFEM method and the actual pile capacities from the field data.

The CFEM provides ranges for N_q coefficient in Table 18.2 in the manual itself that differentiate between the values used for bored piles and those used for driven piles. Figure 3 compares the Meyerhof N_q values according to the friction angle with the corresponding CFEM values that are based on the soil classification. The figure shows that Meyerhof N_q values are overestimated rather than the CFEM suggestions especially in case of friction angles greater than 35°. Therefore, the predicted pile load capacities using the CFEM N_q values will give conservative results compared to the measured pile load capacities and those estimated from Meyerhof N_q values. In addition, the N_q ranges for driven piles give a closer estimate to Meyerhof values, which indicates to higher-end bearing capacity. This fact is related to the increase in the confining stress around the pile shaft during driving as explained above.

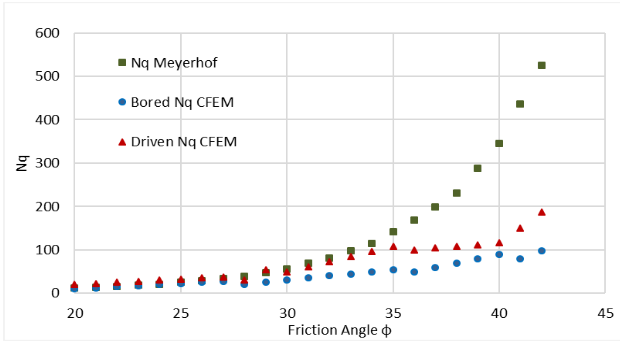

Fig. 3: Comparison between Nq values from Meyerhof and the CFEM

5. Conclusion

To conclude, the measured axial capacity data of the considered full-scale pile load tests provided the confidence in using the CFEM theoretical approach. Using this method in estimating the axial capacities gives an error of about 20% or less which is acceptable compared to the complicated inputs related to the soil stratifications and their influence around the pile shaft and beneath the pile toe as well. However, the CFEM recommends different ranges of the N_q coefficient for bored and driven piles which are underestimated compared to the well-known Meyerhof's N_q values, these values are acceptable for the purposes of safety especially in case of special structures. Finally, the demonstrated reliability in the calculating the axial pile load capacities eliminates the need to perform sophisticate numerical modelling which might take time and involves complicated features.

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