Evaluation of Bored Piles Load Capacity in Rock Bearing

تقييم قدرة تحمل الخوازيق المرتكزة فى الصخر

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Abstract

Rock socketed bored piles are particularly advantageous for conditions in which rock is near the ground surface underlying weak layers. This paper aims to predicate the ultimate capacity of bored piles supported in rock using analytical and mathematically based graphical approaches. Data-base of pile load tests from three projects constructed in Abu-Dhabi city in UAE were used, and Finite Element Analysis using 2-D Plaxis axisymmetric model has been developed to simulate the behaviour of such piles. The ultimate load predicted from the FEM method is compared with that estimated from the theoretical approaches. The pile working load with the corresponding settlements estimated from the theoretical approaches based on reasonable factor of safety were evaluated based on the results of pile load tests.

From this study it was found that, the results of pile ultimate load estimated from the static formula were closer to those predicted by the FEM, compared with those calculated by modified Chin and Hansen methods. Under the ultimate load settlement was about 2.3% of pile diameter. While the socket length of a pile into rock is an important factor, the strength and R.Q.D. of rock seem to be the most significant parameters even for lesser socket length. The limiting displacement, after which the applied axial load is shared between the side resistance and the base resistance, has found to vary between 0.3% to 1.1% of rock socketed pile length, depending on the rock strength and R.Q.D.

Key words:

Bored Pile, carrying capacity; Pile load tests; theoretical and Finite Element Analyses

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1-Introduction

Rock-socketed piles are often used to transfer heavy loads from a superstructure to competent rock layers. The loads are transferred to the surrounding rock mass through shaft and base resistance. Rock-socketed drilled shafts have been widely used as foundation elements for bridges. Rock-socketed piles have the particularly advantageous for conditions in which rock is near the ground surface. The bearing capacity of rock-socketed piles is calculated with various empirical correlations, which typically are obtained by a back analysis of the pile load tests. In the correlations, the unconfined compressive strength (σ_c) of rock is the most commonly considered parameter (Rosenberg and Journeaux 1976; Pells and Turner, 1980; Kulhawy and Goodman, 1980; Pells 1999). In the absence of pile load tests, axial capacity estimates of rock-socketed cast-in-place piles should be made by assuming that only the side resistance has mobilized, which will likely lead to conservative outcomes (Akguner and Kirit, 2012). The load transfer and load-settlement

Accepted: 25 October 2015

response of piles are quite different from those of drilled shafts, and that may be ascribed to the differences in slenderness ratios of these two types of foundations.

A significant portion of the applied loads on the socketed piles are transferred to the rock–pile interface at the side, since frictional side resistance commonly mobilizes at small relative displacements between the rock and the pile. Slippage occurs after the displacement on the pile side exceeds the threshold value (limiting displacement), after which the pile base capacity is mobilized (William et al., 1980, Carrubba, 1997).

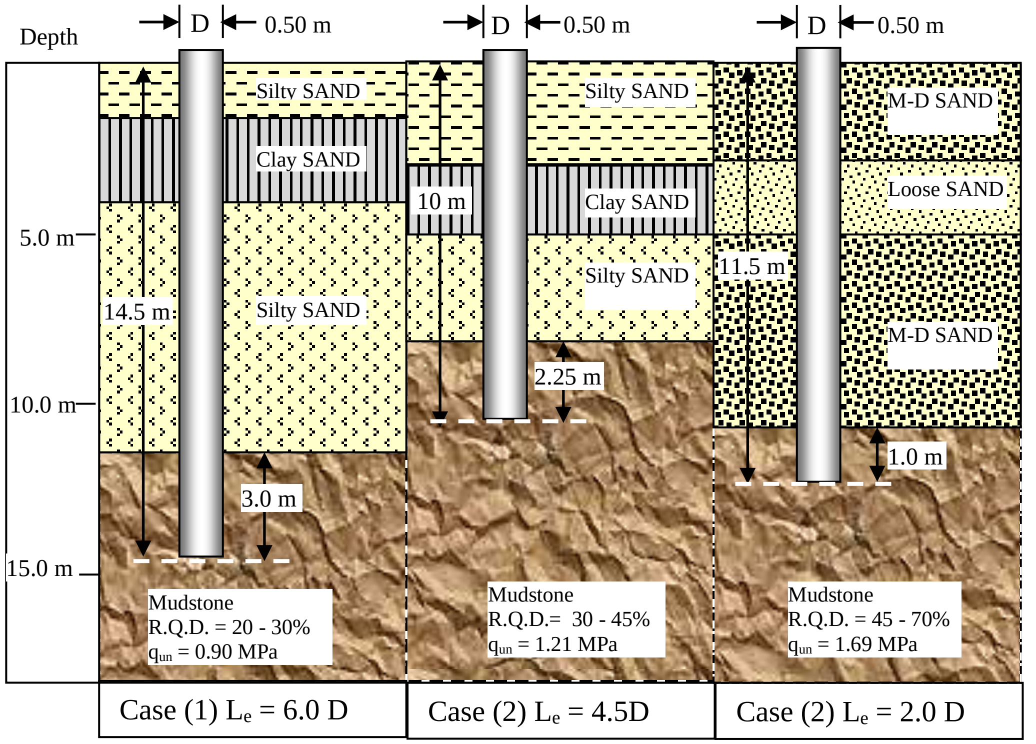


Figure (1) Subsurface profile and rock socketed pile for the three case studies

The aim of this study is to evaluate the effect of socketed length (L_e), the strength and Rock Quality Designation (R.Q.D.) on the carrying capacity of piles supported in rock. The results of pile load tests from three projects constructed in Abu-Dhabi city in UAE were used as data-base, the soil profile and pile socketed length for these three case studies are presented in Fig. (1).

As the pile load tests are often limited to 1.50 times, the ultimate load estimated from the available theoretical approaches was evaluated based on ultimate load predicted by the FEM.

In spite of soil profile of the three projects relatively varies from site to another, as well as, the rock strength and R.Q.D.; pile total and rock socketed lengths, the pile working load was fixed to 1000 kN for the three sites, and the pile load test to 1500 kN.

2. Finite Element Modeling of Single Pile

Using 2-D Plaxis the geometry of a single socketed-rock pile is simulated by means of an-axisymmetric model in which the pile is positioned along the axis of symmetry as shown in Figure (2). Both the soil and the pile are modeled with 15-noded elements. The interface elements are placed around the pile to model the interaction between the pile

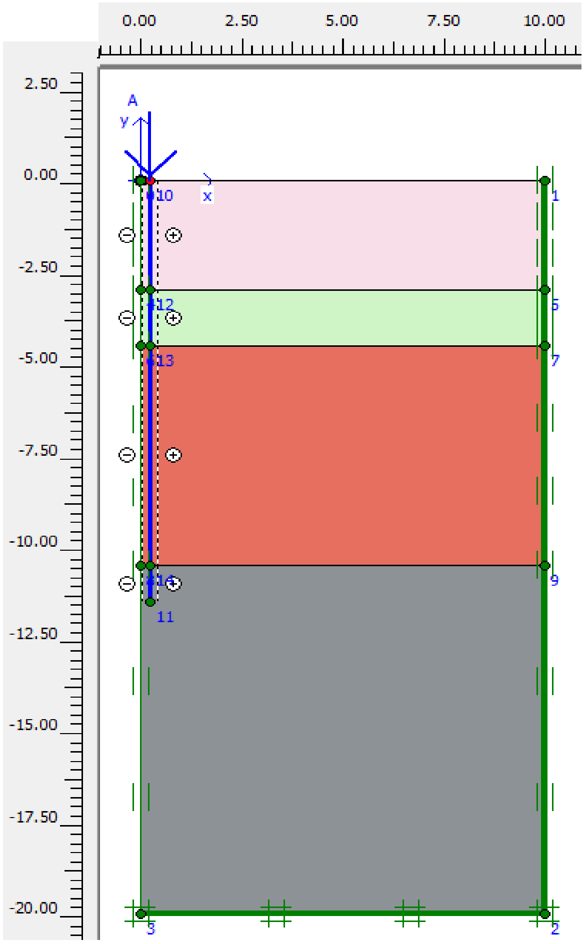


Figure (2) Geometry model of pile

And the soil. The pile is modeled with linearly elastic elements with a Young's modulus (E_p) = 28 x 10^6 kN/m^2, Poisson's ratio (ν_p) = 0.1, and other parameters are as listed in Table (1).

Table (1) Pile Material Properties

Parameter	Name	Pile	Unit
Type of behaviour	Type	Elastic	---
Normal stiffness	EA	5.5x106	kN/m
Flexural rigidity	EI	8.59x104	kN.m2/m
Equivalent thickness	d	0.433	m
Weight	W	3.53	kN/m/m
Poisson's ratio	ν	0.1	---

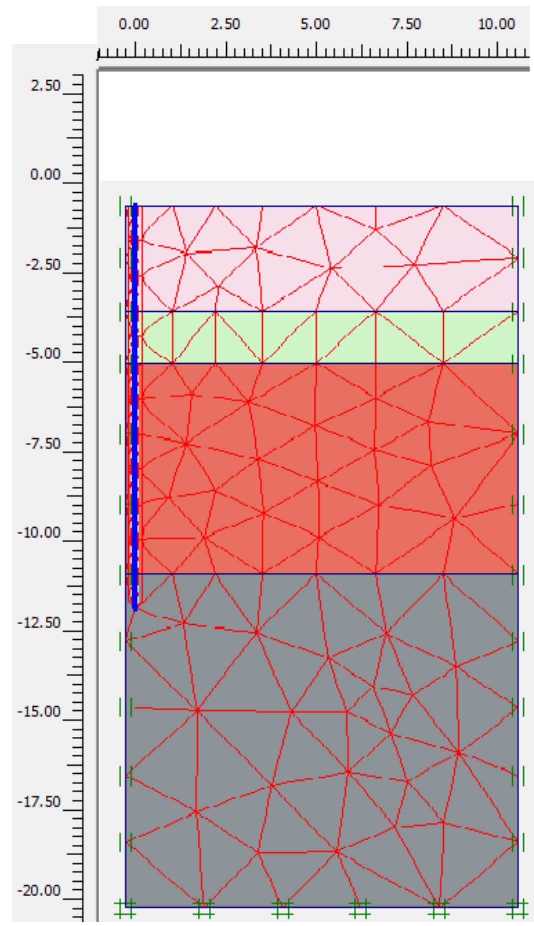


Figure (3) Finite Element Mesh

In order to model the pile load, a point unit load is created on top of the pile. The subsoil profile is divided as shown Table (2).

Mohr-Coulomb model (MC) as linear elastic perfectly-plastic model is used as a first approximation of soil behaviour in general. It is recommended to use this model for a first analysis of the problem considered. A constant average stiffness is estimated for the soil layer, this assumption let computations tend to be relatively fast and a first estimate of deformations can be obtained.

Table (2) Soil Layers Material Properties

Parameter	Name	Top layer	Case 1 Mudstone	Case 2 Mudstone	Case 3 Mudstone	Unit
Material model	Model	Mohr-coulomb	Mohr-coulomb	Mohr-coulomb	Mohr-coulomb	-
Type of material behaviour	Type	Drained	Drained	Drained	Drained	-
Soil unit weight above phreatic level	γunsat	15	18	19	20	kN/m3
Soil unit weight below phreatic level	γsat	18	18	19	20	kN/m3
Initial void ratio	einit.	0.5	0.5	0.5	0.5	-
Young's modulus	E	104	1.25x105	1.5x105	2.5x105	kN/m2
Poisson's ratio	ν	0.3	0.25	0.25	0.25	-
Cohesion	Cref	1.0	450	600	845	kN/m2
Friction angle	ϕ	30	-	-	-	0
Interface strength	----	Manual	Rigid	Rigid	Rigid	-
Strength reduction factor	Rinter	0.5	1.0	1.0	1.0	-

The mesh is generated with a global coarness to coarse. A local refinement is made in the pile cluster. The result of the mesh generation is plotted in Figure (3).

The load is applied up to 3500 kN in fourteen stages, with incremental rate of 50 kN for each stage.

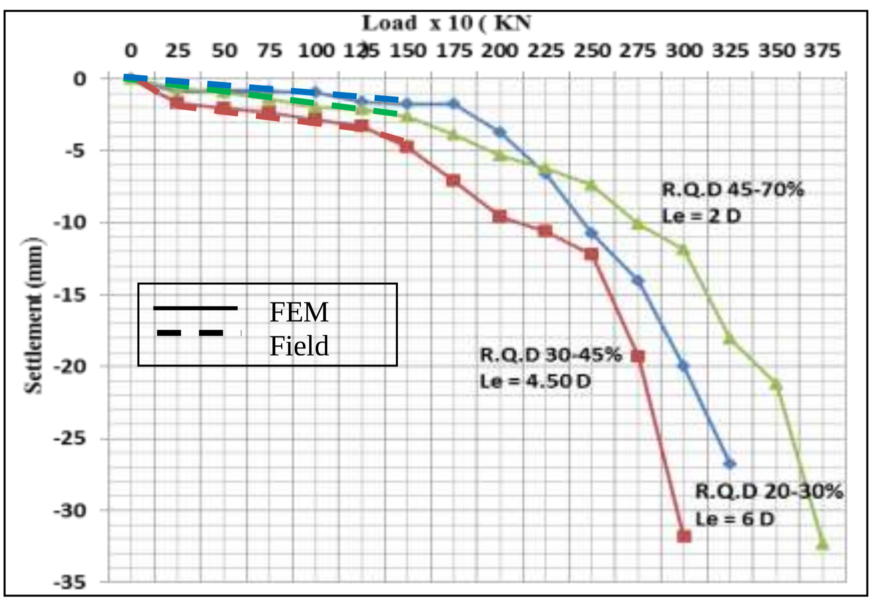


Figure (4) Results of FEM compared with the field load-settlement data

The results of FEM compared with the field load-settlement data are presented in Fig. (4) The results of FEM indicate that, in spite of case (3) has the least rock socketed-pile length; it has the highest ultimate pile load as for the site with higher rock strength and R.Q.D.

Therefore, it can be concluded that, while the socket length of a pile into rock is an important factor, the rock strength and R.Q.D. seem to be the most significant parameters affecting the pile carrying capacity.

The limiting displacement, after which the applied axial load is shared between the side resistance and the base resistance of a rock-socketed cast-in-place pile is found by Akguner and Kirit (2012) to be about 0.4% of pile length, in this study it varies between

0.3% to 1.1% depending on the rock strength and R.Q.D., with higher ratios for rocks with higher strength and R.Q.D.

Table (3) FEM Pile Ultimate Capacities and Settlement

Case Study	**(1)**	**(2)**	**(3)**
Ultimate Pile Load (kN)	**2600**	**2500**	**3050**
Settlement (mm)	**9**	**11**	**14**
Settlement /Diameter (S/D)	**1.80%**	**2.2%**	**2.8%**
Rock socketed pile length (Le) m	**3.00**	**2.25**	**1.00**
Settlement/Pile socket length (S/Le)	**0.3%**	**0.5%**	**1.1%**

Table (4) Field Pile working Load and settlement data

Case study	**(1)**	**(2)**	**(3)**
Pile working load (kN)	**1000**	**1000**	**1000**
Settlement (mm)	**1.00**	**3.00**	**2.00**
Settlement /Diameter (S/D)	**0.2%**	**0.6%**	**0.4%**

The results of Tables (3& 4) indicate that, for the cases under study the pile settlement does not exceed about 0.4% pile diameter under the working , while and ultimate loads it is about 2.3% (as an average value. The importance of this observation is for estimation the subgrade reaction (K_s) of such piles for numerical analysis applications. Sometimes, the subgrade reaction of piles supported in firm granular stratum is assumed as the pile working stress divided by 5 to 10% of pile diameter, this assumption may highly underestimate K_s for rock socketed piles

3. Pile Load Capacity in Rock by Theoretical Approaches

3-1 Static Formula (ECP, 2002)

The ultimate pile load (Q_u) can be computed as follows:

$Q_u = Q_b + Q_f$ .... (1)

Q_b: Load carried by end bearing

Q_f: Load carried by skin friction

$Q_b = A_b . q_b$ .... (2)

A_b = Area of pile tip,

$q_b = 2\ N_\phi\ q_{uc}$

$N_\phi = \tan^2 (45° + \phi/2)$

q_{uc} = Unconfined comp. Strength of rock, (Minimum in the bearing layer)

$Q_f = A_f . q_f$ ....(3)

A_f = Surface area of pile skin friction,

q_f = Unit skin friction = $\alpha\ \beta\ \underline{q_{uc}}$

α: is reduction relating to q_{uc} as shown Figure No.5

β: is a correction factor related to the discontinuity of the rock mass j as shown Figure No.6

$\underline{q_{uc}}$ = Average unconfined comp. strength of rock in socket bearing layer.

The rock quality designation (RQD) or the discontinuity spacing quoted by Tomlinson (1994, after Hobbs, 1975) as follows:

R.Q.D (%)	Fracture Frequency Per /m'	Mass Factor (j)
0–25	15	0.2
25–50	15-18	0.2
50–75	8-5	0.2-0.5
75–90	5-1	0.5-0.8
90–100	1	0.8-1

Friction and end bearing loads estimated by the static formula load, compared with the ultimate load predicted by the FEM and the project pile working load are shown in Fig. (5)

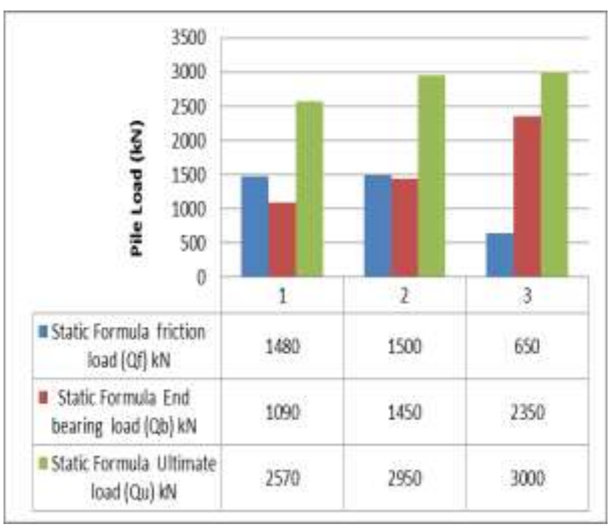


Figure (5) Friction and end bearing pile loads

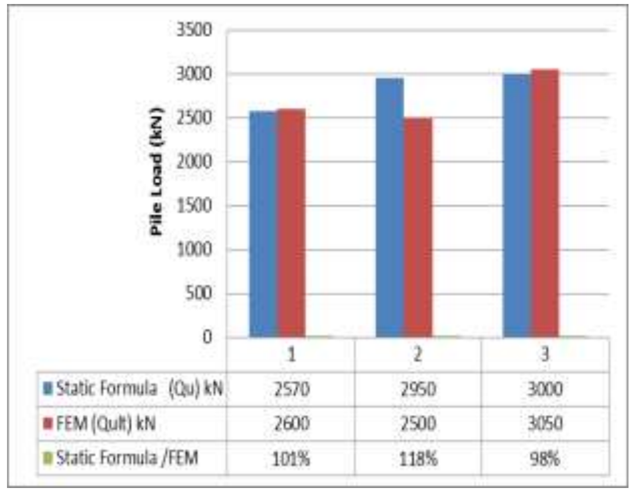


Figure (6-a) Static Formula and FEM pile ultimate load

From the comparison of Figures (5, 6-a & 6-b), the following observations can be drawn

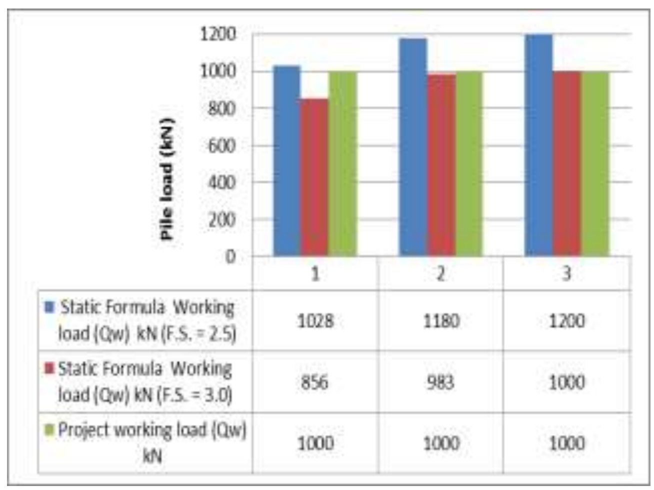


Figure (6-b) Static Formula and Field Pile Working

- ✓ End bearing of bored pile supported in rock is higher for rock with higher strength and R.Q.D. Penetration of bored piles in rocks with low strength and R.Q.D should be deeper than that in hard rock with high R.Q.D.
- ✓ The ultimate load estimated by the static formula is nearly close to that

predicted by FEM with variation of only about 5% as an average value.

✓ The pile working load estimated by the static formula based on factor of safety of 3.0 underestimates the prefixed project value by about 5% as an average value.

3-2 Chin and Hansen Approaches

3.2.1 Modified Chin Method, 1970

The ultimate load can be obtained from the slope (b) of a straight line represents the relationship between the field settlement (Δ) and the ratio of the settlement to the applied load (Δ/Q) as shown in Fig. (7, 8, 9), as follows:

$$Q_{ult} = \frac{1}{1.2b} \qquad \text{.................................. (4)}$$

Where:

Q_{ult} = Ultimate load

b = Slope of straight-line relation between Δ and (Δ /Q)

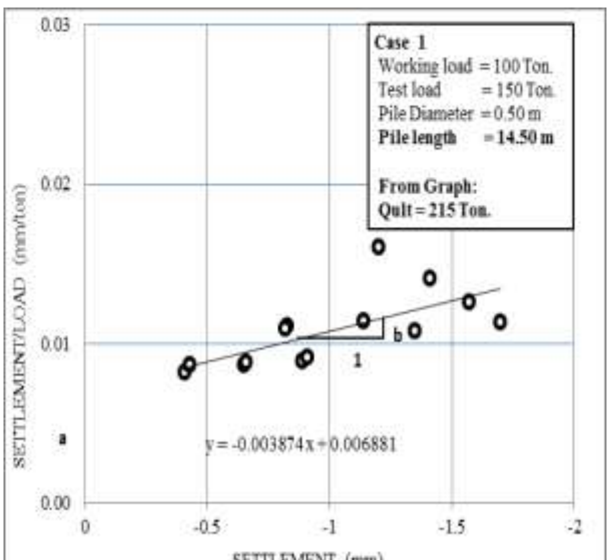


FIGURE (7) Determination of Ultimate Load by Modified Chin Method (Case - 1)

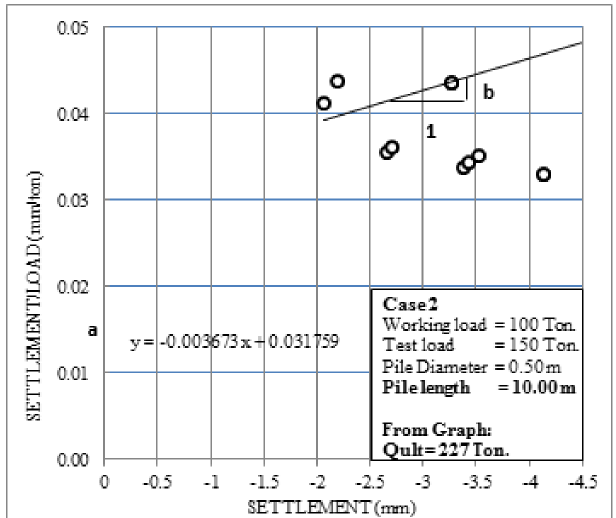


FIGURE (8) Determination of Ultimate Load by Modified Chin Method (Case - 2)

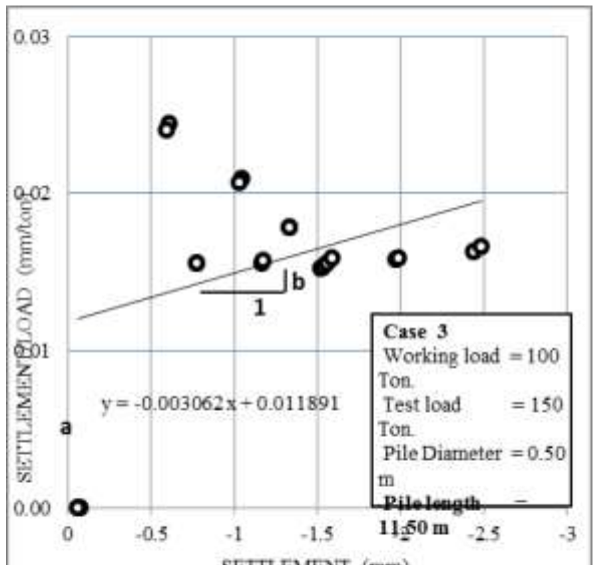


FIGURE (9) Determination of Ultimate Load by Modified Chin Method (Case 3)

3.2.2 Brinch Hansen Method (1961)

The ultimate load of the pile is considered as the load which gives twice the displacement of the pile head obtained for 90 % of the ultimate load.

The field load-settlement data are plotted in trial forms of hyperbolic model, until the settlement at the ultimate load (Q_{ult}) becomes doubles that under 0.9 Qult.

$$Q_{ult} = \Delta / (a + b\,\Delta) \quad \text{-------------------------} \quad (5)$$

a, b =as shown in Fig. (7, 8, 9)

Where: Q_{ult} =Load at settlement Δ.

Δ = Settlement (mm)

The ultimate load determined by Hansen method is shown in Fig. (10, 11 & 12)

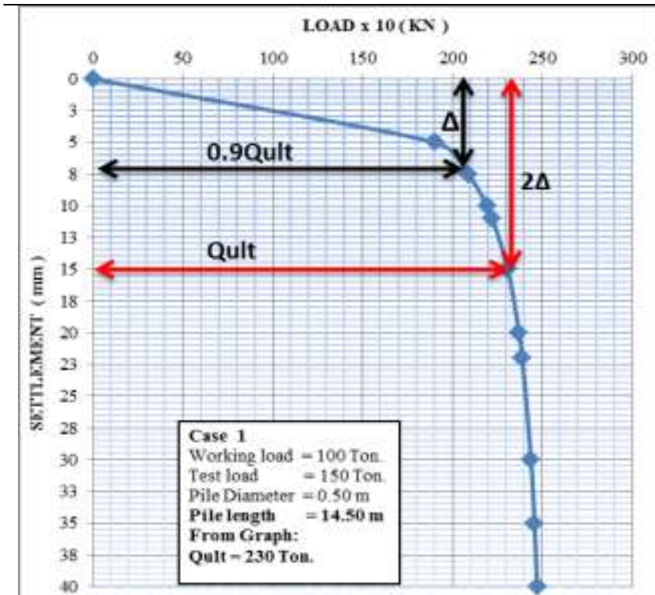


FIGURE (10) Determination of Ultimate Load by Brinch Hansen Method (1963) (Case - 1)

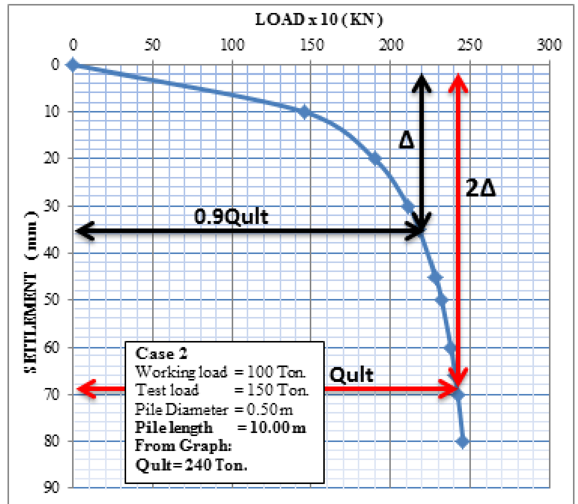


FIGURE (11) Determination of Ultimate Load by Brinch Hansen Method (1963) (Case - 2)

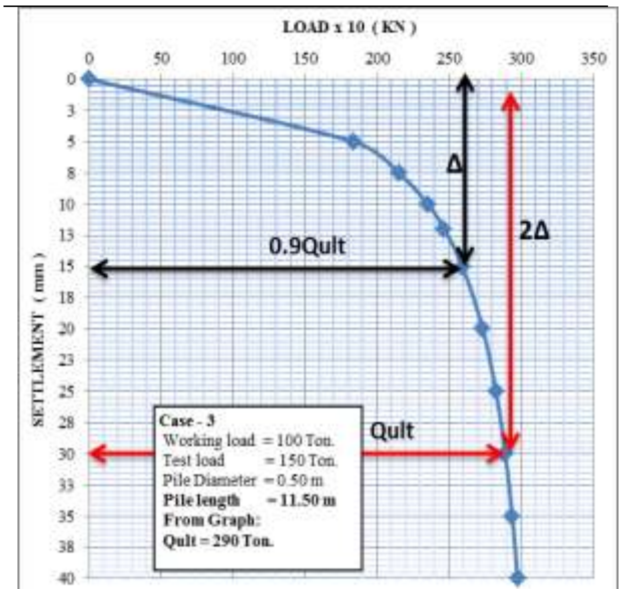


FIGURE (12) Determination of Ultimate Load by Brinch Hansen Method (1963) (Case - 3)

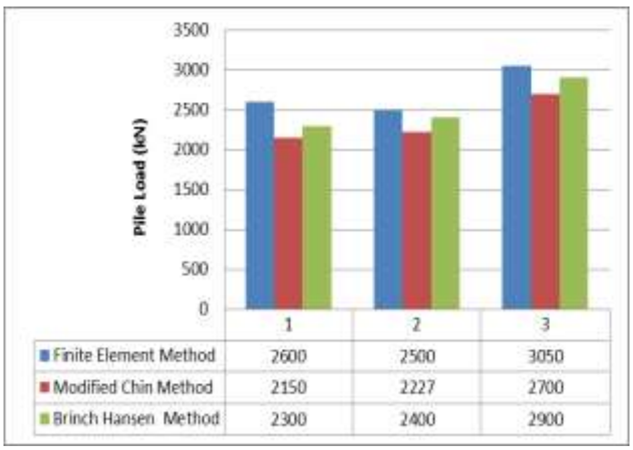
Table (6) Ultimate load and estimated corresponding settlement determined by Brinch Hansen method

Case study	(1)	(2)	(3)
Ultimate load (Qult) kN	2300	2400	2900
Settlement (mm)	15	70	30
Settlement /Diameter (S/D)	3%	14%	6%

From Table (6), the settlement estimated by Hansen method under the ultimate load is about 7% of the pile diameter (as an average value), which is much higher than that predicted by the FEM by about 3 times.

The results of the pile ultimate load estimated by modified Chin and Hansen methods compared with that predicted by the FEM is shown in Fig. (13).

The ultimate pile load computed by modified Chin and Brinch Hansen is less than that predicted by the Plaxis analysis by about 7% to 14%, with an average value of about 10%.



Akguner and Kirin (2012) mentioned that, the mathematically based graphical methods are sensitive to the selection of points in the graphical construction. The first few deviating data can be attributed to errors, such as small deformations in the loading frame, and the seating of the testing equipment, which may be ignored

4- Summary and Conclusions

This paper presents an evaluation for the working load specified for bored piles supported in rock. The ultimate pile load is predicted using 2D Plaxis model based on the results of pile load tests carried out at the three sites up to 150% of the working load, and the characteristics of soil profiles. The ultimate pile load estimated from the statically formula, as well as, some mathematically based graphical methods is evaluated. The following conclusions could be drawn:

1- While the socket length of a pile into rock is an important factor, the strength and R.Q.D. of rock seem to be the most significant parameters even for lesser socket length.

2- The limiting displacement, after which the applied axial load is shared between the side resistance and the base resistance of a rock-socketed pile, is found to be vary between 0.3% to 1.1% of pile length depending on the pile socketed length, rock strength and R.Q.D. values. The higher rock strength and R.Q.D, the higher required limiting settlement.

3- The ultimate load estimated by the static formula has found to be nearly close to that predicted by FEM with variation of only about 5% (as an average value), while that computed by modified Chin and Brinch Hansen methods is less by about 7% to 14%, with an average value of about 10%.

4- Pile settlement does not exceed about 0.4% pile diameter under the working, while under the ultimate loads it is about 2.3% (as an average value). The importance of this observation is for estimation the subgrade reaction (K_s) of such piles for numerical analysis applications. The settlement estimated by Hansen method under the ultimate load is about 7% of the pile diameter (as an average value), which is much higher than that predicted by the FEM by about 3 times.

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