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EVALUATION OF MEASURED AND INTERPRETED FAILURE LOADS OF BORED PILES IN ALLUVIAL SOIL DEPOSITS

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ABSRTACT: This paper presents an evaluation of the ultimate load carrying capacity of bored piles measured directly and obtained from selected methods of load test data interpretation based on different failure criteria. Large scale bored piles were installed in alluvial soil deposits and statically loaded to failure. The measured failure loads varied from 195 to 520kN and pile displacements of 1.3 to 2.7%D were required to mobilize such loads for the considered test conditions. The pile shaft friction component contributed over 83% of the total measured ultimate capacity and was fully mobilized at displacements of 0.2 to 0.8%D. A rigorous analysis was carried out to compare the measured and interpreted pile failure loads and evaluate the performance of six published load test interpretation methods. Based on the evaluation results, the L_1-L_2 and the Fuller and Hoy's interpretation methods indicated the best overall performance in estimating the failure loads. The De Beer and Van der Veen methods revealed similar and fairly good evaluation ratings whereas the Davisson interpretation method showed a relatively poor performance. The Chin's method exhibited a gross overestimation of measured ultimate capacities and among all yielded the poorest overall performance.

Keywords: Bored Piles, Pile Load Tests, Failure Loads, Pile Settlement, Load Test Interpretation Methods

1. INTRODUCTION

Bored piles or "drilled shafts" types of deep foundations are commonly used to support heavy loaded structures due to its relatively easy erection, low vibration, and flexibility in size selection to suit variable loading and subsoil conditions. The two important aspects considered in the design of bored piles are the pile load carrying capacity and anticipated settlements due to applied loads. The axial pile carrying capacity can be indirectly evaluated using a theoretical approach based on Terzaghi's bearing capacity equations or semi-empirical and empirical methods based on correlations with in-situ tests data such as CPT and SPT. Generally, these methods tend to estimate pile capacities with variable degrees of accuracy.

The most accurate approach for evaluation of the pile capacity is to perform full scale load tests representing the actual pile behavior normally expressed in terms of a load-deformation relationship. However, the disadvantages of this direct method include the relatively long time required and high costs incurred in performing such tests. Moreover, it would not be feasible to perform pile load tests in the stage of project planning stage. They are often conducted during the construction phase on production piles which cannot be loaded to failure.

Three different shapes of load-displacement relationship curves may be obtained from pile load test results as illustrated in Fig. 1 [1]. The maximum resistance of the test pile is given by the peak value of curve A and the asymptote value of curve B in this figure. If the load-displacement relationship resembles the shape of curve C, as is often the case for bored piles, then it will be very difficult to evaluate the ultimate resistance or capacity of the pile tested.

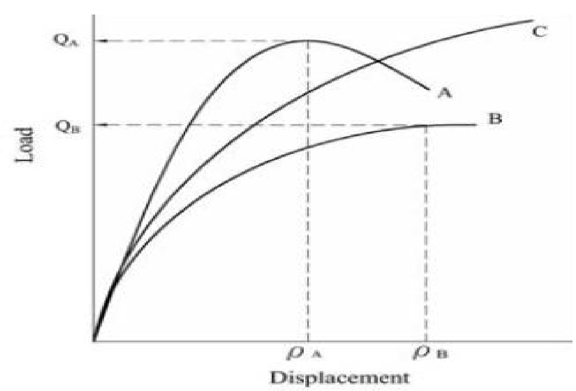

Fig.1Typical load-displacement curves of pile load tests

Many interpretation methods have been proposed in published literature for the evaluation of the failure loads from pile load test data on the basis of three main criteria:

(i) Mathematical modeling; failure loads interpreted from theoretical models generally correspond to the asymptote of the load-displacement curve which is extrapolated by employing a mathematical rule. Examples of methods based on mathematical models are the Van der Veen [2] and Chin [3] methods.

(ii) Pile settlement limitation; which may be sub-grouped under absolute settlement limit, settlement limit per unit load, settlement limit as a function of pile diameter, limit of settlement rate with respect to load or settlement. Most of the published interpretation methods are based on this criterion. Examples of the methods based on settlement limitation include the methods proposed by Tomlinson [4], Vesic [5], Hansen's 90% Criteria [6], Fuller Hoy [7] and De Beer [8].

(iii) Graphical construction; these methods define the failure load as the point of intersection of a specified line with the load-displacement curve, as the load at which two specified tangents to the curve or as a point at which a specified line drawn from the curve intersects the load axis. The methods proposed by Davisson [9] and modified later by O'Rourke and Kulhawy [10] and the L1-L2 method developed by Hirany and Kulhawy [11] represent graphical construction methods examples.

In Sudan, bored piles have been introduced and used as a feasible foundation system in the construction industry since the 1960's [12] however; the research studies carried out on their suitability for Sudanese soil conditions are still limited. The present work aims to study the ultimate capacity of bored piles from direct measurements and the application of some interpretation methods of load tests data.

A field test program comprised mainly of testing large scale instrumented piles installed in some Sudanese soils and loaded to failure was undertaken at a site in Khartoum. An evaluation of the performance of six known load-settlement curve interpretation methods was made and presented.

2. SITE CONDITIONS AND PILE LOAD TESTING

The site at which this study was conducted is located on the left bank of the Blue Nile in West Soba district in Khartoum city, Sudan. The site investigation included drilling boreholes, carrying out in- situ SPT and CPT and performing laboratory testing of representative soil samples.

The subsurface soil profile is comprised an upper medium dense, low plastic clayey sand (SC) layer overlying very stiff to hard of highly plastic silty clay (CH). The latter is underlain by hard low plastic clayey silt (ML) resting on medium dense to very dense poorly graded sand (SP).

The large scale pile load tests consisted of instrumented bored piles of 0.2, 0.3 and 0.4m diameters and 3.5 to 6.0m embedment lengths installed in different soil types.

The maintained load test procedure specified in ASTM D [13] was followed during load testing. The test piles were loaded in increments of the estimated allowable loads and each load was maintained until a pile settlement rate of 0.25mm/hour was reached. The test piles were instrumented with strain gages and load cells to facilitate separate determination of the end bearing resistance and shaft friction components of the total pile capacity at any depth. More details on these tests are given elsewhere [14].

3. PILE LOAD TEST RESULTS

Fig.2 illustrates the applied load versus total pile settlement curves for the total resistance, shaft friction and end resistance determined for a typical test pile.

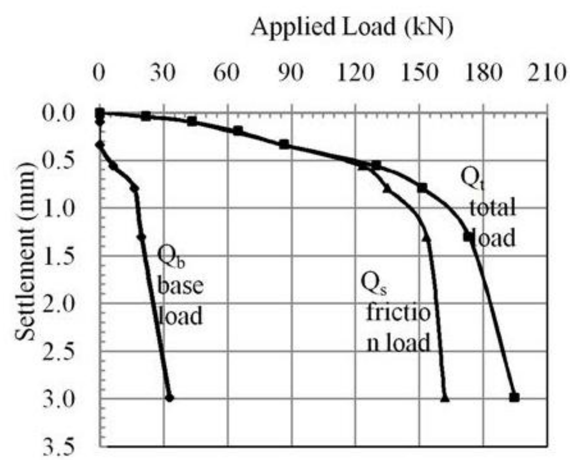

Fig.2 Typical load-total settlement curves for total, shaft friction and end bearing for test pile A-1.

The criteria used to define the failure load or ultimate axial carrying capacity of the large scale bored piles tested is indicated by a rapid progressive settlement of the pile under a constant load. For each pile tested, the maximum shaft friction mobilized in each soil layer and the base resistances components were also determined.

The pile failure loads and the corresponding total settlements were determined from load tests on the eight large scale bored piles are listed in Table 1.

Table 1 Pile failure loads and total settlements for tested piles and subsoil conditions

Bored pile	Pile diameter	Pile length	Pile portions embedment in different soil strata (m)					Pile failure load	Total pile settlement
designation	(m)	(m)	CL	SC	CH	ML	SM	kN	S_t (mm)
A-1	0.20	3.5	-	2.0	1.5	-	-	194.6	2.985
A-2	0.20	5.0	-	2.0	2.5	0.5	-	283.7	5.340
A-3	0.20	6.0	-	-	2.5	1.0	0.5	308.0	3.970
B-1	0.30	3.5	-	2.0	1.5	-	-	315.0	4.375
B-2	0.30	5.0	-	2.0	2.5	-	0.5	443.0	4.47
B-3	0.30	6.0	2.5	2.0	2.5	-	1.0	400.0	5.425
C-1	0.40	3.5	-	2.0	1.5	-	-	460.0	5.775
C-2	0.40	5.0	-	2.0	2.5	0.5	-	522.5	5.340

4. DISCUSSION OF STUDY RESULTS

4.1 Pile Load-settlement Relaionships

The load-settlement curves pertaining to the total, shaft friction and end bearing resistances established for the piles tested indicated that the loads applied were fully resisted by the friction mobilized along the upper portions of pile shaft until a certain displacement was reached in each test. Subsequently, the load increments were partly taken by the soil resistance at the pile base and partly by the friction along the pile shaft. Then the load portion transferred to the pile base increased gradually until a maximum value corresponding to limit or failure load was reached. At this point, the shaft friction and base resistances were fully mobilized.

The instrumentation system installed in the test piles facilitated the determination of shaft friction and end bearing components at any depth.

As may be noted from the load displacement curve in Fig. 2 and also revealed for other test piles a typically well defined break was indicated as expected for bored piles installed in cohesive soils.
Figure 3 shows a histogram representing the measured shaft friction, end bearing and total failure loads for tested piles.

The total pile head displacements corresponding to determined failure loads ranged from 3mm in test pile A-1 in Table 1 to 5.8mm in C-1 with an average value of 4.71mm. The total pile settlement to diameter ratio (S_t/D) varied from 1.34% in C-2 to 2.67% in A-2 giving an overall average ratio of 1.71%D.

Figs. 2 and 3 indicate very clearly the significance of the shaft friction resistance which contributed 83 to 92 percent of total carrying capacity at failure determined for the test pile types and soil conditions considered. According to the AASHTO LRFD Specifications [15], the shaft resistance component is typically fully mobilized at displacements of 0.2 to 0.8%D in cohesive soils and 0.1 to 1.0% in cohesionless soils. For the soil types considered in this study, the observed total pile settlement corresponding to such a condition varied from 0.2 to 0.6%D which fits very well within the above displacement range reported for similar soils.

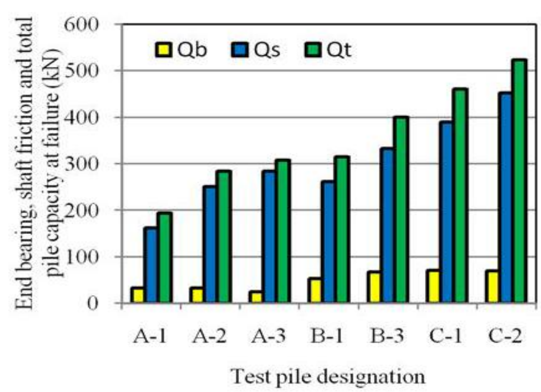

Fig.3 Measured end resistance, shaft friction and total pile capacity at failure

It has also been indicated that the settlements induced by loads in end bearing are different for bored piles in different soils and that the end bearing resistance is typically fully mobilized at displacements of 2 to 5%D in cohesive soils [15]. In granular soils, they indicated that the displacement for ultimate end bearing to be 5%D but recognized the increase in capacity at larger displacements. A displacement of 1.3 to 2.7%D was required to fully mobilize the end bearing component of the failure loads in the pile load tests conducted implying that the end bearing component could be mobilized in some cohesive soils at displacements lower than the reported 2%D value.

A comparison was made between measured pile capacities and those determined from the six selected interpretation methods to examine their accuracy for the evaluation of pile failure loads.

4.2 Evaluation of Load Test Interpretation Methods

4.2.1 Selected Methods

In general, there is no unique criterion that can clearly define a “failure load” or “bearing capacity” of a pile and the approach selected for interpreting a load-settlement curve should account for its characteristics and the soil condition.

Six well known and widely used interpretation methods based on different criteria have been selected from published literature for the evaluation of the ultimate bored pile capacity from load test data. These included two methods on theoretical models (Van der Veen and Chin), two methods based on settlement limitation (De Beer and Fuller Hoy) and two methods based on graphical construction (Davisson and Hirany and Kulhawy L_1-L_2).

The selected methods are listed in Table 2 along with the definitions and criteria adopted in analysis for piles failure. The failure loads determined from the application these interpretation methods are listed in Table 3.

Table 2 Pile load test methods interpretation methods selected for evaluation

Category	Method	Definition of interpreted ultimate pile capacity
Mathematical model	Van der Veen [2]	Q_{ult} is P_{ult} that gives a straight line when ln [1-P/P_{ult}] is plotted versus total settlement. P=varies applied load, P_{ult}= ultimate load.
Mathematical model	Chin [3]	Q_{ult} is the inverse slope 1/m of a line S/P= ms+c, where P=applied load, S=total settlement.
Settlement limit	Fuller and Hoy [7]	Q_{ult} is the load on the load-settlement curve where the tangent is sloping at 0.14mm/kN
Settlement limit	De Beer [8]	Q_{ult} is the load at the change in the slope on a logarithmic scale load-settlement curve.
Graphical construction	Davisson [9]	Q_{ult} occurs at a displacement equal to the pile elastic compression line [pl/AE] offset by 0.15+D/120, where P=load, L= pile length, A=area, E=Young’s modulus, D=pile dia.(in.)
Graphical construction	Hirany and Kulhawy L_1-L_2 [11]	Q_{ult} is the load beyond which a small increase in load produces a significant increase in movement (i.e. transition point to final linear region).

Table 3 Summary of measured pile failure loads and corresponding interpreted values

Pile reference	Van der Veen	Chin	Fuller and Hoy	De Beer	Davisson	L_1-L_2	Measured failure load (kN)
A-1	194.6	227.3	194.6	173.0	210.7	173.0	194.6
A-2	201.0	294.1	276.4	276.4	276.4	276.4	283.7
A-3	308.0	357.1	285.0	224.0	308.0	280.0	308.0
B-1	281.3	357.1	295.0	281.3	333.2	281.3	315.0
B-2	443.0	636.9	553.8	553.8	499.8	443.0	443.0
B-3	412.0	454.6	380.0	360.5	426.3	360.5	400.0
C-1	402.0	540.5	435.0	469.0	509.6	402.0	460.0
C-2	307.5	1250.0	530.0	570.6	847.7	400.0	522.5

4.2.2 Comparison of Measured and Interpreted Failure Loads

For the purpose of general analysis, the failure loads determined from the application of the interpretation methods listed in Table 3 were compared to those measured for the eight bored piles tested. The ratio of interpreted to measured failure load (Q_i/Q_m), expressed in percent, were plotted in histograms form in Figs. 4, 5 and 6 for the methods based on theoretical modeling, settlement limitation and graphical construction criteria respectively. In these figures, the 100% line represents a basis for comparison such that values of (Q_i/Q_m) higher and lower than 100% respectively indicate over-prediction and under-prediction of the ultimate measured pile capacity.

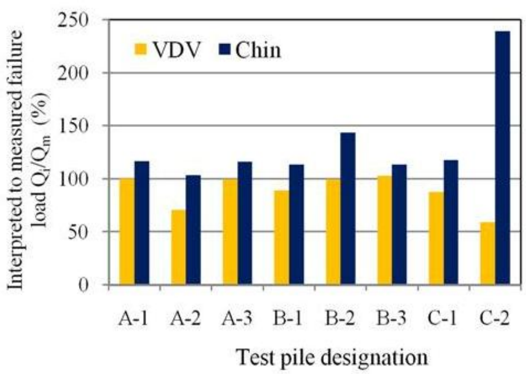

Fig. 4: Percentage of Q_i/Q_m for methods based on theoretical modeling

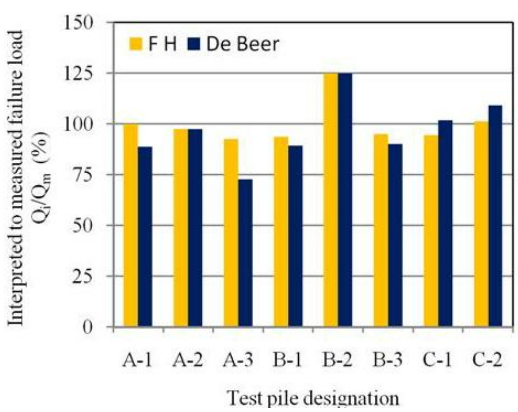

Fig.5 Percentage of Q_i/Q_m for methods based on settlement limitation

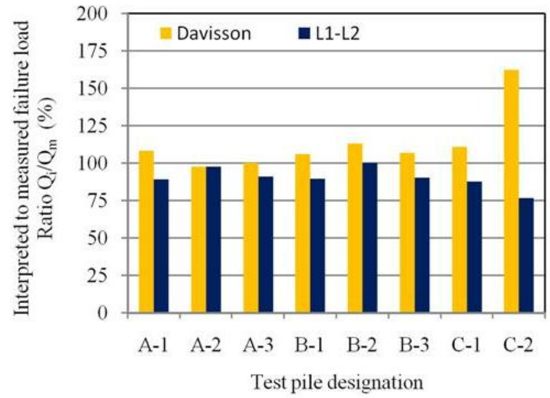

Fig.6 Percentage of Q_i/Q_m for methods based on graphical construction.

From a general comparison of the sets of (Q_i/Q_m) ratio illustrated in Figs 4, 5 and 6, it may be noted that:

(i) In Fig. 4, the Chin and Van der Veen interpretation methods based on theoretical modeling gave conflicting results of the Q_i to Q_m ratio whereby the failure load is consistently overestimated by the former and somehow underestimated by the latter. The average Q_i/Q_m ratio varied considerably from 88.7% to 133% for the Van der Veen and Chin methods respectively with discrepancy ranges of -49 to 3% and 3 to 139%.

(ii) The Fuller and Hoy and De Beer methods based on settlement limitation compared very well with measured failure loads as revealed from the average Q_i/Q_m values that were very close to 100% (96.8 and 100%) and the relatively small discrepancies of -7.5 to 25% in the former and -17.3 to 9.2% in the latter. This close agreement between the Q_i and Q_m can also be inferred from the patterns of the histograms shown in Fig. 5.

(iii) The Davisson and L_1-L_2 methods gave average Q_i/Q_m values of 90.1 and 113% respectively with corresponding discrepancies of -2.6 to 62.2% and -23.4 to 0. Thus, these methods gave comparison results that are much better than the methods based on theoretical models and slightly worse than those based on settlement limitation. Such a pattern may be inferred from histogram trends shown in Fig. 6.

In general, it may be noted from the results of comparison of Q_i and Q_m that the Davisson and Chin methods tend to grossly overestimate failure loads, whereas the Fuller and Hoy's De Beer, L_1-L_2, and Van der Veen methods tend to underestimate pile capacity.

4.2.3 Interpretation Methods Performance Evaluation

A rigorous analysis of the measured and interpreted load test data similar to that suggested by Briaud and Tucker [16] and Abu-Farsakh and Titi [17] was undertaken to rank the performance of the six selected interpretation methods for the evaluation of pile failure loads according to the following criteria:

(i) Regression Analysis; a regression analysis was conducted to obtain the best fit line for the Q_i and Q_m pile capacities and the corresponding coefficient of determination (R^2) were determined. The method is considered the best when the R^2 is closer to one.

(ii) Statistical Analysis; the mean (μ) and standard deviation (σ) of Q_p/Q_m are indicators of the accuracy and precision of the method. The method is considered the best when μ of Q_p/Q_m is closer to one and σ of Q_p/Q_m is closer to zero. The mean and standard deviation were calculated from the following equations.

$$\mu\left(\frac{Q_i}{Q_m}\right) = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{Q_i}{Q_m}\right) \quad (1)$$

$$\sigma\left(\frac{Q_p}{Q_m}\right) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\left(\frac{Q_p}{Q_m}\right) - \mu\right)} \quad (2)$$

(iii) Cumulative Probability (P50) and (P90); which quantifies the ability of different methods to predict the measured pile capacity. The concept is to sort the ratio Q_p/Q_m for each method in an ascending order. The smallest Q_p/Q_m is given number i=1 and the largest is given i=n where n is the number of piles considered in the analysis. The cumulative probability value for each Q_p/Q_m is given by:

$$CP_i = \frac{i}{n+1} \quad (3)$$

Each ascending ratio Q_p/Q_m is plotted versus corresponding values of the cumulative probability function, CP_i% then the 50% and 90% cumulative probability value of the ratio Q_p/Q_m can be determined. The method is considered the best when P_{50} value is closer to one with the lowest P_{50}-P_{90}.

For each of the pile test results interpretation methods considered for evaluation a rank index (R) which is the algebraic sum of the ranks obtained from the different criteria is adopted to quantify the overall method performance. The limiting values of the final ranking index are 3 and 18 for the highest and the lowest overall performance respectively, thus the method with the lowest R value is considered as the best and vice versa. The results of performance evaluation for the six interpretation methods according to these criteria for bored pile failure capacity are presented in Table 4.

Based on the final ranking index (R) evaluation in Table 4, the L_1-L_2 method developed by Hirany and Kulhawy indicated the best overall performance according to the evaluation criteria and may therefore be considered as the most accurate method. The Fuller and Hoy's method ranked very close and is rated second to the L_1-L_2 method.

Table 4 Evaluation of performance of different interpretation methods

Method	Regression analysis			Statistical analysis			Cumulative probability function			Ranking results	
	R^2	Regression equation	r_1	μ	σ	r_2	P_{50}	P_{90}	r_3	R	Final rank
Van der Veen	0.529	Q_p=0.63Q_m+87.72	6	0.89	0.161	3	0.96	1.0	1	10	**4**
Chin	0.717	Q_p=2.54Q_m-413.8	5	1.33	0.416	6	1.20	2.4	6	17	**6**
Fuller and Hoy	0.886	Q_p=1.12Q_m-39.81	3	1.00	0.106	1	1.00	1.3	3	7	**2**
De Beer	0.897	Q_p=1.32Q_m-119.5	1	0.97	0.416	4	0.96	1.3	4	9	**3**
Davisson	0.847	Q_p=1.7Q_m-195.7	4	1.13	0.206	5	1.08	1.6	5	14	**5**
L_1-L_2	0.889	Q_p=0.78Q_m+42.56	2	0.90	0.070	2	0.88	1.0	2	6	**1**

R^2= Coefficient of Determination, r_1= Rank Index based on Regression Analysis, r_2= Rank Index based on Statistical Analysis, r_3= Rank Index based on Cumulative Probabilities, R= Overall Ranking Index

The De Beer and Van der Veen methods indicated very close overall performances with each other and were ranked in third and fourth places respectively. The application of the latter two methods requires carrying out pile load tests to failure as was done in this study. The Davisson method showed a rather poor overall performance in interpreting the failure loads of tested piles.

Among all, the Chin's method yielded a significant overestimation of failure loads and exhibited the poorest overall performance confirming a previous finding of interpretation of load tests data for bored piles installed in Sudanese soils [18]. Similar observations were also reported in two previous comparison investigations for different interpretation methods [19, 20] in which the Chin's method gave an average 93% overestimation compared to the lowest interpreted failure loads in both studies.

5. CONCLUSIONS

The following conclusions may be drawn from analysis and interpretation of the results of the load tests carried out to failure on eight large scale bored piles installed in Sudanese alluvial soils:

(i) The total failure loads of bored piles tested varied from 195 to 520kN with total displacements ranging from 3.0 to 5.8mm and settlement to pile diameter ratio (S_t/D) of 1.34% to 2.67%. The general patterns of the load-settlement curves of the total failure loads, shaft friction and end bearing obtained were typical to those reported in literature.

(ii) The pile shaft friction component of failure loads contributed 83 to 92% of total measured capacities and was fully mobilized at displacements of 0.2 to 0.6%D for the soil types tested. A displacement of 1.3 to 2.7%D was required to fully mobilize the end bearing and total failure loads. In both cases, the observed settlement ratios fall within the reported limits for cohesive soils.

(iii) Comparison of the measured and interpreted pile failure loads showed that the Davisson and Chin methods tend to grossly overestimate pile failure loads whereas the other four methods tend to underestimate them.

(iv) The analysis conducted for evaluating the performance of interpretation methods on the basis on statistical and cumulative probability criteria revealed that:

(v) The Hirany and Kulhawy L_1-L_2 and Fuller and Hoy's methods yielded very close agreement between interpreted and measured pile capacities and showed the best overall performance.

(vi) The De Beer and Van der Veen methods revealed similar performance ratings and ranked next to the L_1-L_2 and Fuller and Hoy's methods.

(vii) The Davisson method showed a relatively poor performance in giving close estimates of bored piles failure loads.

(viii) The Chin's method exhibited a gross overestimation of the ultimate pile capacities and, among all, yielded the poorest performance evaluation.

(ix) Finally, it should pointed out that due to the relatively small number of load tests conducted, the above performance evaluation results should be considered as indicative at this stage until they have further been verified.

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