Shaft Friction of Bored Piles in Hard Clay

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Abstract

The precise prediction of maximum load carrying capacity of bored piles is a complex problem because it is a function of a number of factors. These factors include method of boring, method of concreting, quality of concrete, expertise of the construction staff, the ground conditions etc. besides the pile geometry. The performance of pile load tests is, therefore, of paramount importance to establish the most economical design of piles especially where bored cast-in-situ piles are to be provided to support a structure.

This paper describes the experience gained from four pile load tests at a site in the North West Frontier Province of Pakistan where a new cement plant is going to be installed. Geotechnical investigations at the site were carried out to a maximum depth of 60 m. The subsoils at the site are predominantly hard clays within the investigated depth with thin layers of gravels / boulders below 40 m depth. Perched water was encountered at various horizons. Four piles of diameter varying from 660 mm to 760 mm and length ranging between 20 m and 47.5 m were subjected to axial loads.

The load test data were analyzed using various state of the art techniques including intercept of two tangents, point of change of slope, 6 mm net settlement [1], *90 percent and 80 percent Hansen* [7], *limit value Davisson* [2], *and Chin* [3]. *Based on a comparison of pile capacities from these methods with the theoretical values, recommendations are made on the approach to estimate the pile capacity in hard clays. Using the pile load test results, back calculations were also carried out to estimate the appropriate values of pile design parameters such as undrained cohesion and adhesion factor.*

Key words: Shaft friction; end bearing; hard clays; adhesion factor; cohesion

1. Introduction

Pile foundations are the part of a heavy structure used to carry and transfer its load to the bearing ground located at some depth below ground surface. Depending upon various factors like nature of substrata, depth of ground water table, depth of stronger stratum, type and quantum of load to be supported etc., piles are designed. Pile testing is considered a fundamental part of pile foundation design. It is one of the most effective means of dealing with uncertainties that inevitably arise during the design and construction of piles.

In Pakistan improvement in foundation practice has led to an increased reliance on bored cast-in-situ RC piles for supporting tall and heavily loaded structures and cross drainage structures. New cement plant at Kohat also comprised some heavily loaded structures and needed to be supported on piles. Before the construction of bored cast-in-situ working piles, four test piles were subjected to loading tests. This paper presents an analysis of pile load tests data collected from these four pile load tests on cast-in-situ bored piles.

Results of these pile load tests have been compared with the load carrying capacity of the pile computed by empirical relations proposed by different researchers. In addition seven different methods to interpret ultimate load from load/settlement relationship have been used with the purpose to select the method most suitable for local conditions. Similarly tip bearing and shaft resistance have been interpreted from

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load/settlement relationship. The percentage of load taken by piles along with slip needed to develop full mobilization of shaft friction, in local conditions, have been computed.

From the experience of load testing of four piles in hard clays in Pakistan, the authors have attempted to establish the pile design parameters for local conditions from back calculations of pile load tests results. This study aims to provide guidelines regarding the pile design parameters most appropriate for local conditions and the best procedure for estimating ultimate capacity from pile load tests in hard clays.

2. Pile Design Parameters

Various field and laboratory tests have been carried out during the geotechnical investigations for the evaluation of subsurface conditions and the pile design parameters (undrained cohesion C_u and adhesion factor α) at the project site.

Figure 1 shows the variation of undrained cohesion (C_u) at various depths at the project site. The undrained cohesion was determined through unconfined compression tests on undisturbed samples collected from the boreholes. There is a large scatter of the undrained cohesion values at different depths at the project site; however, average values based on boreholes near the test pile have been taken as shown in Table 1.

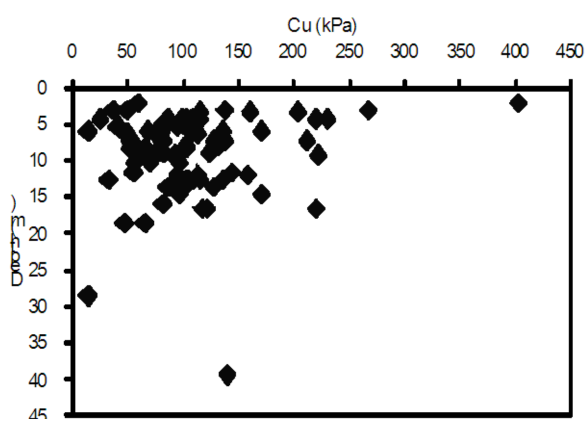

Figure 1: Variation of un-drained cohesion (C_u) with depth at the project site.

The α values from different sources based on undrained cohesion (C_u) of clay are shown in Table 1.

The theoretical pile capacities have been estimated from static equations using undrained cohesion (C_u) of Table 1 and an average value of adhesion factor (α) = 0.6. Theoretical pile capacities are summarized in Table 2.

3. Pile Load Tests

Four pile load tests were performed on piles of 660 mm and 760 mm diameters and of lengths varying from 20 m to 47.5 m. The ASTM D1143 [8] test procedure was followed, in general, for pile load tests.

The reaction load was arranged through a system of jacking bearing against the dead load resting on a platform. The dead weight was supplied by piling soil filled plastic bags on the platform as shown through Plate 1. The platform was supported on three wide flanged girder beams (reaction beams) placed side by side (and bolted together) over the jack. A hydraulic jack system comprising a 550 tons jack (Plate 2), pressure gauge, oil reservoir, pump (Plate 3) and piping was used in this test.

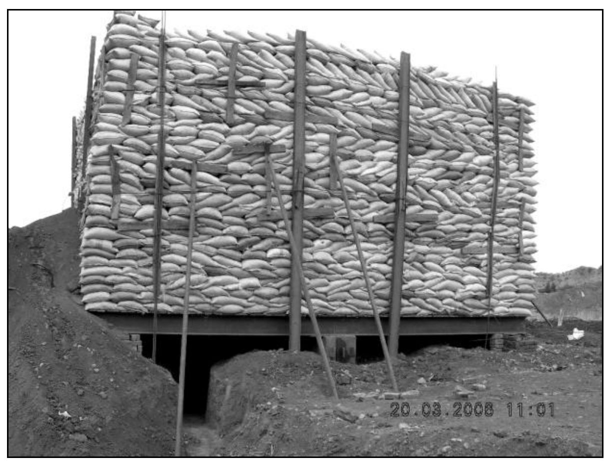

Plate 1: A view of soil filled bags on loading platform to obtain dead load reaction

Settlement of the piles was recorded by means of three settlement gauges capable of reading to 0.01 mm precision. These gauges were capable to record a total settlement of about 30 mm. The gauges were mounted on two reference I-beams. The stand for the gauges was bearing on the steel plate placed on the pile head (Plate 2). The reference beam supports were at a clear distance > 2.5 m from the test pile.

All piles except Test Pile No. 2 were loaded in one cycle. Each increment (about 25% of the design load) was maintained for a maximum period of two hours or when settlement rate was observed to be less than 0.25 mm per hour. The average of the three gauges gives settlement after each interval.

Table 1: Adhesion factors (α) from different sources

Test Pile No.	Undrained Cohesion (C_u), kPa	Bowles [4]	EM 1110-2-2906 (1991) [5]	NAVFAC DM 7.02 (1986) [6]	EM 1110-1-1905 [7]
1	106	0.70	0.50	0.60	0.55
2	98	0.72	0.50	0.60	0.55
3	98	0.72	0.50	0.60	0.55
4	129	0.65	0.50	0.60	0.55

Table 2: Theoretical Pile Capacities in Clay

Test Pile No.	Pile Dimensions		Ultimate Pile Capacity		
	Length	Diameter	Skin Friction (Q_s)	End Bearing (Q_b)	$Q_u=Q_s+Q_b$
	m	mm	kN	kN	kN
1	20.0	660	2639	324	2963
2	21.5	660	2678	304	2982
3	33.7	760	4827	412	5239
4	47.5	760	8505	530	9035

Table 3: Summary of pile load test results

Test Pile No.	Pile Dimensions		Applied Load (maximum)	Total Settlement	Net Settlement
	Length	Diameter			
	m	mm	kN	mm	mm
1	20.0	660	5219	13.575	10.303
2	21.5	660	4522	20.767	13.803
3	33.7	760	5425	9.157	3.93
4	47.5	760	5396	4.283	0.03

Plate 2: A view of the jack, settlement dial gauges, and reference beams used under the loading plat-form.

Plate 3: Oil reservoir pump and pressure gauge

Test results reveal that piles of 660 mm diameter settled more than 12 mm while settlement of the 760 mm diameter piles was observed less than 12 mm. Summary of these load tests is given in Table 3 and load vs. settlement plots are shown in Figure 2.

Ultimate capacity of each test pile has been determined from the load-settlement curve using the methods described in Table 4.

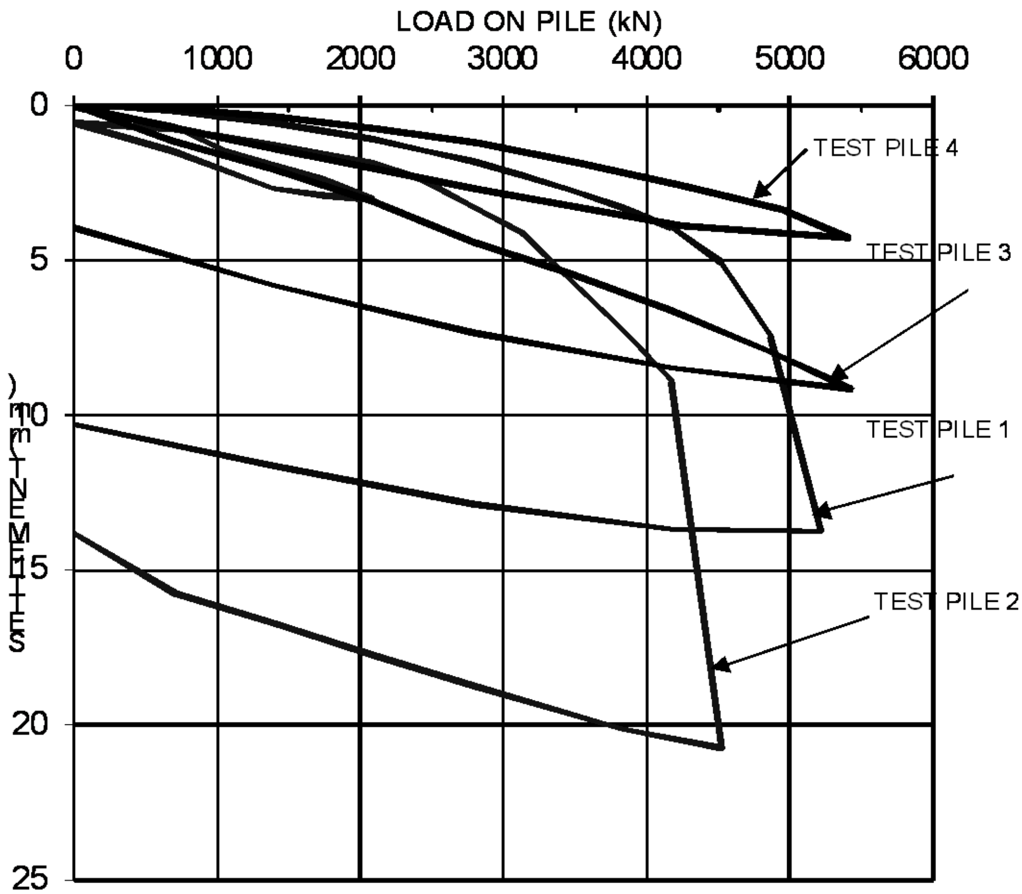

Figure 2: Load-settlement graphs for four pile load tests in clay.

Table 4 Summary of ultimate loads (Q_u) determined from pile load tests results using different methods.

Sr. No.	Method	600 mm diameter piles		760 mm diameter piles	
		Test No. 1	Test No. 2	Test No. 3	Test No. 4
		Q_u (kN)	Q_u (kN)	Q_u (kN)	Q_u (kN)
1	From intercept of two tangents	4610	4020	6280	5935
2	From point of change of slope	4875	4170	6865	6525
3	From 6 mm net settlement [1]	5000	4315	6130	6720
4	90% Hansen [7]	4560	3945	[1]-	7620
5	80% Hansen [7]	5180	5230	[2]-	[2]-
6	Limit value Davisson [2]	4170	4465	7850	7455
7	Chin method [3]	5815	4905	[3]-	9190

[1] Using 90% Hansen, 1963 method the extension of curve through a trend line of 5th polynomial, does not provide results for test pile no.3.
[2] 80% Hansen, 1963 methods does not provide results for settlement < 12mm
[3] Load Settlement data obtained from Test pile no. 3 does not provides results for Chin method

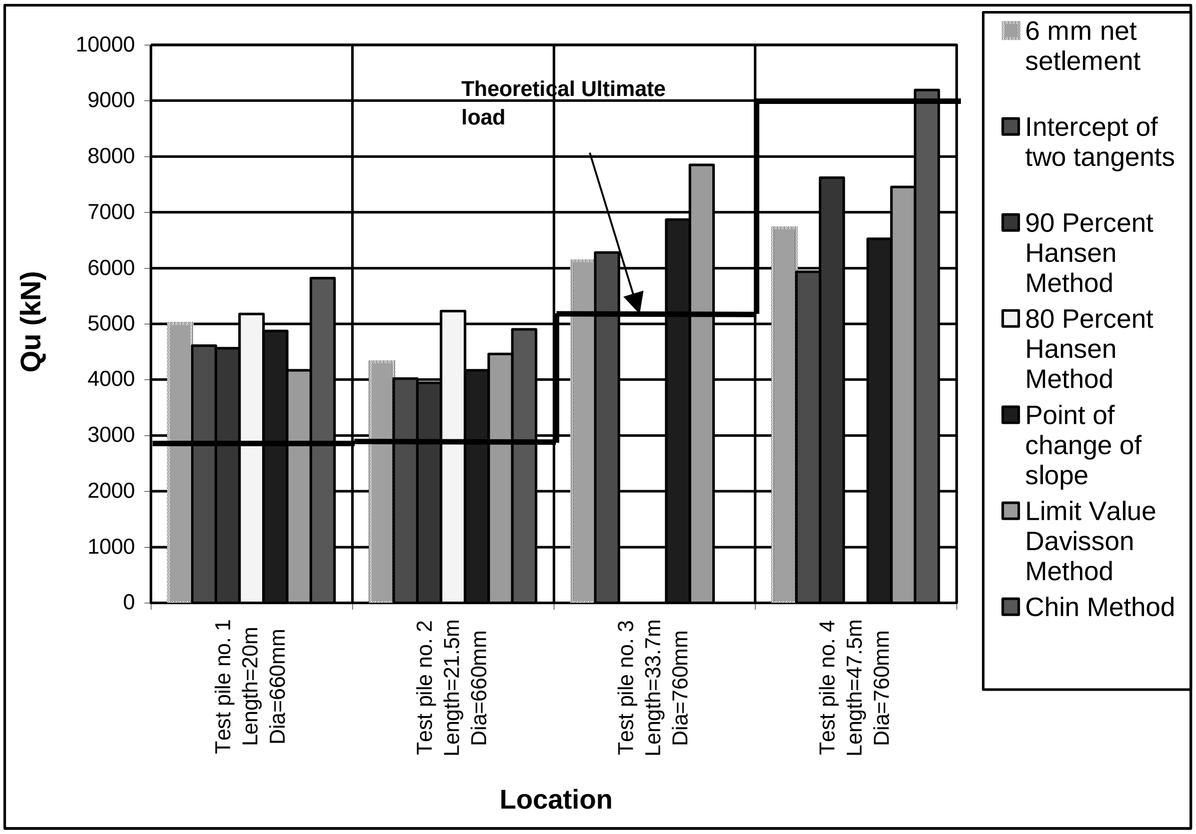

Figure 3: Ultimate loads using different methods.

Figure 3 shows a comparison of ultimate loads, obtained using various methods of estimating the ultimate load from the pile-settlement curves. This figure illustrates that three methods (Intercept of two tangents, point of change of slope and 6 mm net settlement) of estimating the ultimate pile capacity yield ultimate loads closer to each other for all the test piles. Figure 3 also shows that:

- All the methods provide ultimate load more than the theoretical pile capacity determined using pile design parameters described in Table 1, except for pile No. 4 using Chin method.
- 80% Hansen [7] method cannot predict ultimate load for pile settlement <12mm (Test pile Nos. 3 and 4)
- 90% Hansen [7] method does not predict ultimate load for test pile No. 3, however, for test pile No. 4, the ultimate load has been predicted by extending the load settlement curve by 5th polynomial that resembles typical load settlement curve.
- Limit value [2] method has been used to predict ultimate load for test pile Nos. 3 and 4 (pile settlement < 12mm) by extending the load settlement curve by 5th polynomial that bear a resemblance to the typical load settlement curve.
- Chin method [3] provides ultimate load higher than theoretical pile capacity for pile settlement > 12 mm but approximately equal to theoretical pile capacity for test pile No. 4, having settlement < 12 mm. On the other hand, load settlement data from test pile No. 3 are insufficient to predict ultimate load.

Based on the above discussion and findings, it is recommended to estimate the ultimate load in hard clays by taking the average of loads obtained from intercept of two tangents, point of change of slope and 6 mm net settlement methods.

Interpreting tip bearing (Q_b) and shaft resistance (Q_s) components by Van Wheele (1957) [9] method indicates that at failure about 7 to 20 % of load was taken by the piles at the base, and that up to 80 to 93 %

of load was resisted along the shaft. These findings are abstracted in Table 5.

Table 5: Load sharing between shaft and base in hard clay

Test Pile No.	Ult. skin friction (%)	Ult. base resistance (%)
1 (settlement >12mm)	92	8
2 (settlement >12mm)	93	7
3 (settlement <12mm)	80	20
4 (settlement <12mm)	88	12

Based on the load test results, study of the relevant literature and different techniques to find ultimate load from pile load test results, pile design parameters are back calculated as shown in Table 6.

For test pile No. 1 and 2 where the pile settlement was greater than 12 mm and shaft friction was fully mobilized, the values of Cu and α are obtained from back calculations. However, for test pile Nos. 3 and 4 where pile settlement was less than 12 mm and shaft friction was not fully mobilized, only α values are obtained from back calculations using Cu values from Table-1.

Table 6: Pile design parameters from back calculations in hard clay.

Test Pile No.	Parameter	
	Adhesion factor (α)	Undrained cohesion (C_u) kPa
1	0.84	127
2	0.97	90
3	0.765	98
4	0.42	129

The results in Table 6 show that there is a great variation of pile design parameters for the piles loaded to settlement > 12mm and the piles loaded to settlement < 12mm. Figure 4 presents the variation of α obtained from back calculation of pile load tests by different theoretical methods.

For test piles settling >12 mm, the value of α from back calculations is 16 %, 44%, 33% and 40 % higher than those recommended by [4, 5, 6, 7] respectively. Therefore, the value of α should be increased to the above percentage for theoretical estimation of ultimate pile capacity.

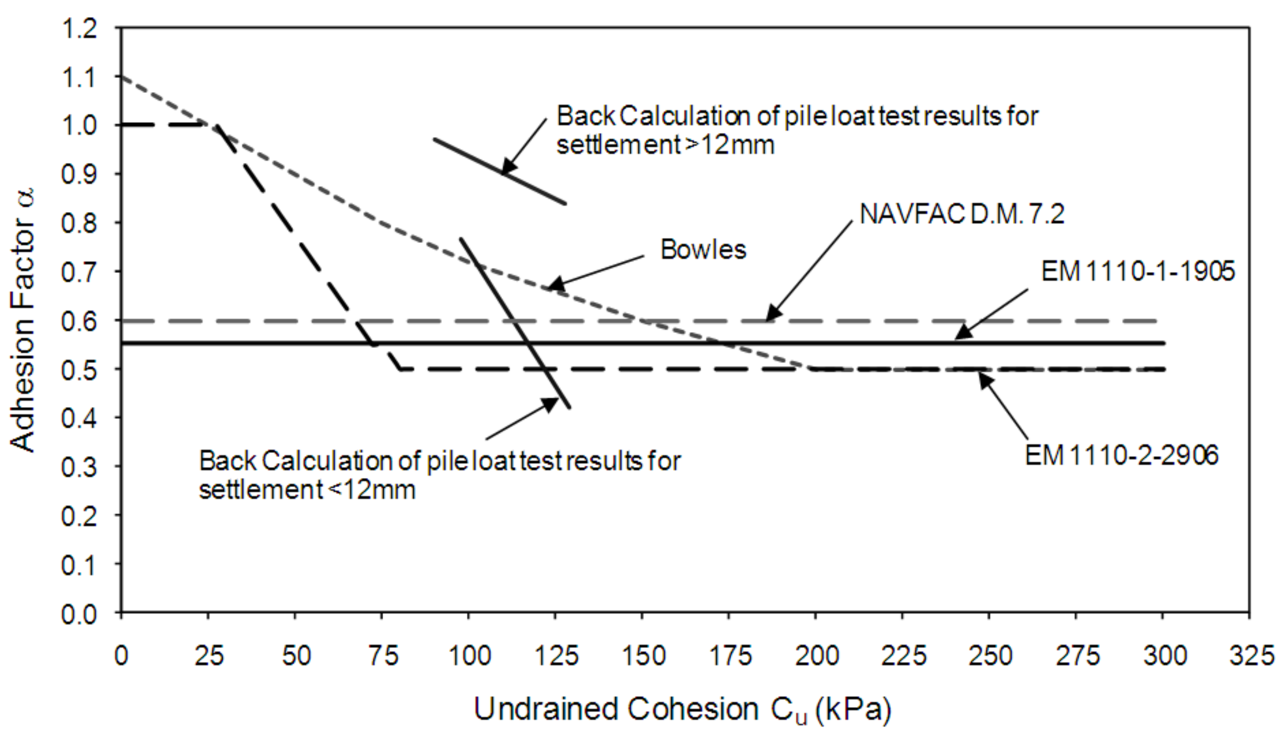

Figure 4: Relationship between adhesion factor α and undrained cohesion C_u. (From sources noted)

For test pile No. 3 settling < 12 mm, the value of α is 6 %, 34%, 21% and 28 % higher than that recommended by the above four sources respectively.

On the other hand, for test pile No. 4 for which net settlement is nearly equal to zero, the value of α is 54 %, 19%, 43% and 31 % lower than that recommended by the above four sources respectively.

Figure 4 also shows that the gradient of line for pile settlement > 12 mm is mild as compare to gradient of line for test pile settlement < 12 mm which is steep.

4. Conclusions

- The ultimate loads determined from load/settlement curves of load tests by methods in Table 2 are higher than theoretically computed capacities for all the piles except the pile for which net settlement is nearly equal to zero.
- The best method of estimating ultimate load from pile load test results is to use the average value of ultimate loads obtained from three methods (i.e. two tangents method, load corresponding to 6 mm net settlement and load at point of change of slope of load settlement curve).
- For bored pile at failure (for pile settlement > 12 mm) about 8 % of load is resisted by the pile at the base, and that up to 92 % of load is resisted along the shaft.
- The pile design parameters obtained from back calculations of pile load test data for piles loaded to settlement > 12 mm are entirely different from piles loaded to settlement < 12mm (Table-6).
- For our local conditions, the value of α in current practice is on conservative side, and should be increased to the recommended trend as shown in Figure 4 for theoretical estimation of ultimate pile capacity.

The above conclusions are based on load test data on four piles only. There is a need to include several more pile load tests data in order to validate the above conclusions and express them in more general terms.

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