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Comparison of Ultimate Pile Capacity Based on Theoretical and Pile Load Test Methods

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Abstract

The estimation of axial load carrying capacity of bored piles is a complicated problem because it depends upon number of factors which may include boring method, concrete quality, concreting method, experience of the staff and the ground conditions. Validation of pile design through testing of piles either test piles or working piles is considered an essential part of deep foundation design. This is recognized as being the most reliable means of dealing with the uncertainties that may rise during design and construction phase of pile foundations.

In this paper, different theoretical methods have been used for the evaluation of pile capacities and then their comparison with the pile load test evaluations have been made for the project of Rathoa Haryam Bridge being constructed in Mirpur Azad Jammu & Kashmir at Mangla reservoir. The subsoil at the bridge site consists mostly of lean clay with ground water table at a shallowest depth of 0.3 m below NSL during the period of field investigations. Six pile load tests have been conducted on test piles with length in the range of 35 m and 45 m and with diameter of 1000 mm.

Based on pile capacity analysis, it has been revealed that the theoretical method for pile capacity estimation by NAVFAC DM 7.02 gives 20% to 40% lesser pile capacity relative to the pile capacity evaluated from pile load test data. The SPT method proposed by Decourt gives higher pile capacity relative to the pile capacity derived from pile load test data and therefore, it is not recommended to be used for cohesive soils. The CPT based methods suggested by Schmertmann and Philipponnat give close results to each other but with a difference of 10% to 20% relative to the pile load test interpretation and may be considered reliable methods for cohesive soils. Pile capacities from the pile load test interpretation by Limit Value method and 90% Hansen method match closely whereas the 6 mm net settlement method gives slightly lower estimate of pile capacity as compared to the other load test methods. The best approach for pile capacity evaluation from pile load test data is to use the average value of pile capacity of all the load test interpretation methods.

Key Words: Pile Capacity, Standard Penetration Test, Cone Penetration Test, Pile Load Test, Theoretical Methods

1. Introduction

Piles are like a column element the function of which is to transfer the load of the structure through friction and bearing to greater depth in the ground. Depending on numerous factors including nature of strata, water table depth, quantum and type of load etc., piles are designed. Testing of the piles is considered as a necessary part of the design of pile foundations which is considered as the most suitable means to overcome the uncertainties that can occur in the design and construction stage of piles. In recent years, the application of in-situ testing techniques has increased for pile foundation design. The most commonly used in-situ tests are Standard Penetration Test (SPT) and Cone Penetration Test (CPT).

This paper presents different methods of estimating pile capacity based on theoretical and empirical methods (based on SPT and CPT) and their comparison with pile capacity evaluated from pile load test data on cast-in-situ bored piles for the project of Rathoa Haryam Bridge being constructed in Mirpur Azad Jammu & Kashmir at Mangla reservoir. On the basis of this comparison, the methods giving close results relative to the interpretation of load test evaluation are recommended as the suitable methods for pile capacity determination. In addition, four different methods to estimate ultimate capacity from pile load test data have been used to find the most suitable method for pile capacity determination. Further, based on the results of pile load tests, an attempt has been made to evaluate pile design parameters from back calculations. This will be helpful in providing the pile design parameters suitable for local ground conditions.

Many researchers in the past have tried to estimate pile capacity from load test data. These researchers include Waheed [20], Sharafat [1], Akbar et al [5], Dewaikar and Pallavi [10], Nabil [13] and Radwan et al [2].

Waheed [20] did work on estimation of pile capacities using in-situ tests and pile load test data. On the basis of his research study it was concluded that SPT method proposed by Touma and Reese could be used for the estimation of pile capacity as it gives 12% to 20% lesser capacity relative to the capacity evaluated from the pile load test. The CPT based method proposed by Schmertmann could be used to estimate the pile capacity as it gives 15% to 30% lesser capacity relative to the capacity evaluated from the load test data.

Sharafat [1] did work using pile load test data and geotechnical investigation data of four different projects in Pakistan for the determination of pile capacity. On the basis of his research study, it was concluded that Reese and Wright method, Mayerhof method and State of California Department of Transportation method may be used to evaluate the pile capacity in sandy strata as these methods give close results relative to the load test interpretation. Decourt method and Touma and Reese method give variable results in similar subsurface conditions.

Akbar et al [5] presented the work on the basis of four pile load tests at a site in Khyber Pakhtunkhwa, Pakistan. On the basis of his research study, it was concluded that the most suitable method of estimating the ultimate pile capacity from pile load test data is to use the average of three methods (i.e., 6 mm net settlement, two tangents method and point of change of slope). The pile design parameters attained form back calculation of the pile load test data for piles load to settlement greater than 12 mm are completely different from piles loaded to settlement less than 12 mm.

Dewaikar and Pallavi [10] presented the analysis of the field pile load tests data for the estimation of ultimate pile load. This analysis is based upon forty pile load test results obtained from various buildings and infrastructure sites located in Mumbai area of India. The collected data is analyzed using different semi-empirical and graphical methods available in the literature.

Nabil [13] did work on behavior of bored pile groups on the basis of a field testing program at a site in South Surra, Kuwait. The program consists of load testing on single bored piles in compression and tension. Two pile groups each consisting of five piles were tested. The pile spacing in the groups was two and three pile diameters. The estimated group efficiency of piles is 1.22 and 1.93 for pile spacing of two and three pile diameters respectively.

Radwan et al [2] suggested a new approach for the design of large diameters bored piles in cohesionless soil. The research is based on results attained for thirty case histories of bored piles collected from various construction projects. Mohr-Coulomb model is used in numerical model. Ultimately statistical study is carried out to assess the accuracy, reliability and improvement of design based on new approach comparing with estimate of the Egyptian code [12].

2. Pile Design Parameters

The subsoils at the bridge site consist mostly of lean clay (CL). Thin layers of lean clay with gravel, sandy lean clay, lean clay with sand and gravely lean clay are sandwiched erratically. The consistency of the strata along the depth is from soft to hard. Ground water was encountered at a shallowest depth of 0.3 m below NSL during field investigations. Atterberg limit tests performed reveals that liquid limit (LL) for all the soil samples tested is in a range of 24 to 40%. The plastic limit (PL) test performed shows the plastic limit values in a range of 17 to 23%, whereas plasticity index calculated based on above results range between 7 and 17. The subsurface soil parameters are shown in Table-1.

Table 1. Subsurface soil parameters

Depth (m)	Classification Symbol	Unit Weight (kN/m^3)	Cohesion "cu" (kN/m^2)
0-10	CL	17.2	39.2
10-20	CL	17.7	58.8
20-60	CL	18.14	245

A variety of laboratory and field tests were performed at the site for the determination of subsurface conditions and pile design parameters. Cohesion is determined on the basis of unconfined compressive strength test on samples obtained from boreholes. Twelve unconfined compressive strength tests were performed which resulted in to cohesion in the range of 14 to 217 kPa. The average values of cohesion on the basis of boreholes close to the test pile location have been selected as given in Table-3. The value of α is selected on the basis of cohesion cu from different sources as shown in Table-3. Theoretical pile capacity have been calculated using static equation on the basis of cohesion cu from Table-3 and adhesion α. Methods of estimating ultimate pile capacities have been summarized in Table-4. The pile capacities calculated using theoretical methods have been summarized in Table-5.

The empirical methods used to evaluate the pile capacity are based on SPT and CPT data. There were nine (9) SPT boreholes, nineteen (19) CPT soundings and six (6) pile load tests performed at the site. The maximum depth up to which SPT boreholes reach is 60 m and that for CPT is 30 m. The SPT profile along with soil parameters with depth is shown in Figure 1 and the CPT profile is shown in Figure 2. Based on SPT-N values, the consistency of subsoil up to 10 m depth is soft to stiff, from 10 to 25 m it is stiff to very stiff and form 25 to 40 m it is hard. The variation of SPT-N values and cone tip resistance qc values with depth is shown in Table-2.

The SPT based method used for the determination of pile capacity is Decourt method [9]. The CPT methods used for pile capacity evaluation are Schmertmann method [16] and Philipponnat method [8]. The pile capacities calculated using these methods are summarized in Table-5.

Table 2: Variation of SPT N and tip resistance qc

Depth (m)	Variation of SPT-N value	Variation of cone tip resistance qc (MPa)
0-10	1-21	0.29-7.96
10-20	4-40	0.78-12.77
20-30	10-59	1.56-15.53
30-40	14-70	-
40-50	24-71	-
50-60	24-85	-

3. Pile Load Tests

Six pile load tests were performed at the site on piles of 1000 mm diameters and length in the range of 35 m to 45 m. The procedure followed for the pile load tests is ASTM D1143 [6].

In performing pile load test, four settlement gauges were used to record the settlement of the piles. These gauges were connected on two reference I beams. Each load increment is applied up to 25% of the design load. The averages of the four gauges give settlement after each load interval. Summary of the pile load tests is given in Table 6 and load vs settlement curves for all the tests are shown in Figure 5.

The arrangement of reaction load was made using a system of jack bearing against dead load which is resting on a platform. The dead load was supplied by using concrete blocks at the platform as shown in Figure 3. The hydraulic jack, settlement gauges and reference beams used under the loaded platform are shown in Figure 4. The reference beam supports were at a clear distance of greater than 2.5 m from the test pile. The ultimate capacities of all the test piles have been determined from load settlement curves using methods described in Table 7.

On the basis of the pile load test results, back calculations have been done to calculate pile design parameters as shown in Table 8. The values of cu and α are determined from back calculations for test pile No. 3, 4, 5 and 6 in which settlement was recorded greater than 12mm and the shaft resistance was expected to fully mobilized. However, for test pile No. 1 and 2 in which settlement was recorded less than 12mm and shaft resistance was not fully mobilized, only α values are determined from back calculations using cu values from Table 3.

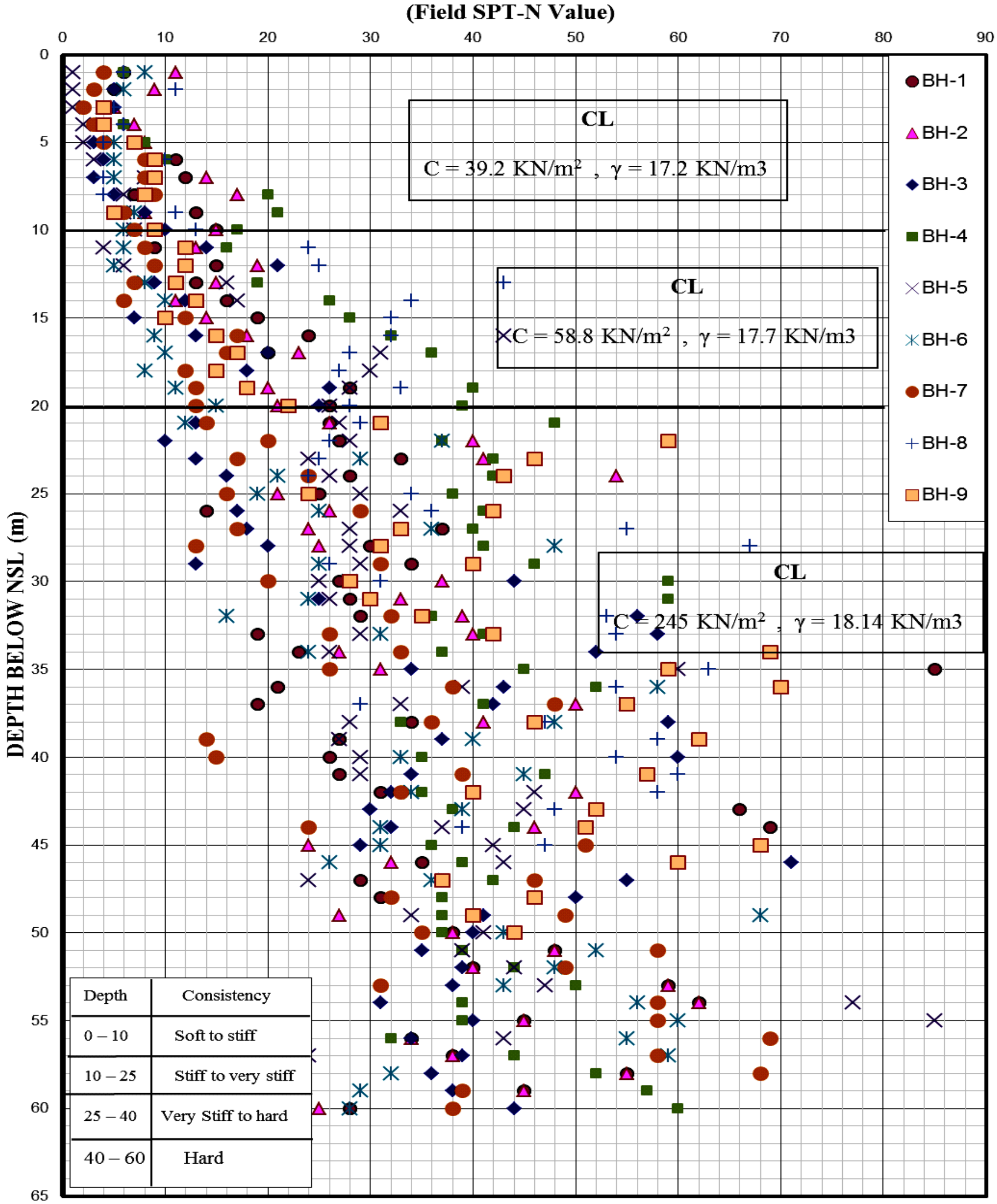

Fig. 1: Variation of SPT N with Depth

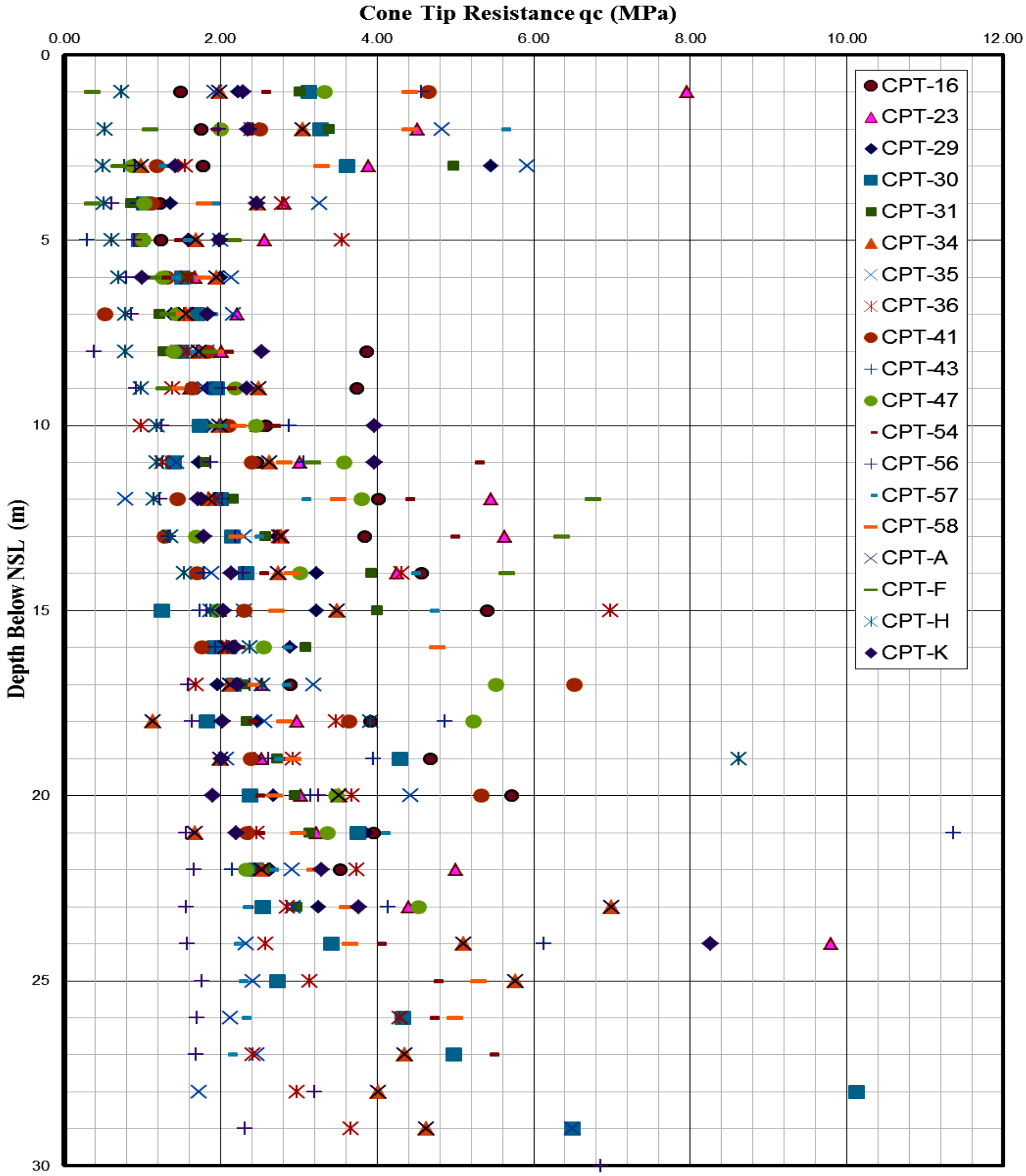

Fig. 2: Variation of Cone Tip resistance with Depth

Table 3: Adhesion factor α from different sources

Test Pile No.	Undrained Cohesion cu (kPa)	NAVFAC DM 7.02 [15]	Bowles [7]	Gunaratne [14]	EM 1110-2-2906 (1991) [18]	EM 1110-1-1905 [19]
1	115	0.60	0.72	0.74	0.50	0.55
2	103	0.60	0.78	0.79	0.50	0.55
3	71	0.60	0.84	0.89	0.50	0.55
4	103	0.60	0.78	0.79	0.50	0.55
5	115	0.60	0.72	0.74	0.50	0.55
6	71	0.60	0.84	0.89	0.50	0.55

Table 4: Methods of Estimating Ultimate Pile Capacity

Method	Shaft (Qs) and Tip (Qp) resistance	Remarks
NAVFAC DM 7.02	Qs = αc Qp = cNc	c = Cohesion, Nc = Bearing capacity factor α = Adhesion factor
Decourt	Qs = α(2.8N_{60}+10) Qp = Kb Nb	α = 1 for non displacement piles in clay N_{60}= Average SPT index normalized to 60% energy Nb = Average SPT index in the vicinity of pile toe Kb = is a base factor, 80 for clay
Schmertmann	Qs = αc fs Qp = (q_{c1} + q_{c2}) / 2	αc = Reduction factor which varies with fs fs = Sleeve friction q_{c1} = Average cone tip resistances of zones ranging from 0.7D to 4D below the pile tip q_{c2} = Average cone tip resistances over a distance 8D above the pile tip
Philipponnat	Qs = qcs αs / Fs Qp = Kb $q_{ca(A)}$ + $q_{cb(B)}$ / 2	qcs = Avg. cone tip resistances for each soil layer along the pile shaft αs = Empirical factor that depends on pile type (1 for bored piles) Fs = Empirical factor that depends on soil type (50 for clay) $q_{ca(A)}$ = Average cone tip resistances within 3D above the pile tip $q_{cb(B)}$ = Average cone tip resistances within 3D below the pile tip Kb = Bearing capacity factor that depends on the soil type (0.5 for clay)

Table 5: Theoretical and Empirical Pile Capacities

Test Pile No.	Pile Dimensions		Ultimate Pile Capacity			
	Length (m)	Diameter (mm)	NAVFAC DM 7.02 (Tons)	Decourt (Tons)	Schmertmann (Tons)	Philipponnat (Tons)
1	45	1000	1014	1343	1124	1202
2	35	1000	714	877	1218	1104
3	40	1000	584	1392	949	1022
4	36	1000	738	956	993	948
5	40	1000	1055	817	868	960
6	45	1000	671	1682	920	854

Table 6: Summary of Pile Load Test Results

Test Pile No.	Pile Dimensions		Applied Load	Total Settlement	Net Settlement
	Length (m)	Diameter (mm)	(Tons)	(mm)	(mm)
1	45	1000	1000	9.4	1.09
2	35	1000	800	7.28	1.7
3	40	1000	1000	102.69	88.47
4	36	1000	1200	43.53	31.23
5	40	1000	1200	43.13	28.72
6	45	1000	800	13.78	2.41

Table 7: Summary of Ultimate Capacity from Pile Load Test

Sr. No.	Method	Test No.1 Qu (Tons)	Test No.2 Qu (Tons)	Test No.3 Qu (Tons)	Test No.4 Qu (Tons)	Test No.5 Qu (Tons)	Test No.6 Qu (Tons)
1	Slope and tangent [4]	1300	990	580	1185	1180	995
2	Limit value [4]	1320	1000	500	1175	1170	1000
3	90% Hansen [4]	1320	1000	665	1220	1205	1000
4	6 mm net settlement[3]	1230	940	490	1120	1100	920

Table 8: Pile design parameters from back calculations

Test Pile No.	Parameter	
	Undrained Cohesion cu (kPa)	Adhesion Factor (α)
1	115	0.73
2	103	0.75
3	54	0.75
4	154	0.60
5	133	0.63
6	94	0.69

4. Results and Discussions

The results obtained from the estimation of ultimate loads from all the methods are shown in graphical form in Figure 6, Figure 7 and Figure 8. The theoretical method by NAVFAC DM 7.02 gives 20% to 40% lower estimate of capacity relative to the capacity interpreted from load test data. Decourt method gives variable pile capacities. For pile No. 1, 2, 4 and 5 it gives close results relative to the load test methods. But for pile No. 3 and 6, it gives higher ultimate capacities due to uneven variation of SPT-N values in that area i.e., SPT-N value is much less at top and much more at bottom.

Both the Schmertmann and philipponnat method give close results relative to the load test evaluations. Interpretation results from Limit Value method and 90% Hansen method give close resemblance to each other, whereas the AASHTO 6 mm net settlement method gives slightly lower estimates of pile capacity as compared to other load test interpretation methods.

On the basis of the above findings and discussion, theoretical method NAVFAC DM 7.02 can be recommended to calculate ultimate capacity in cohesive soils. The SPT based Decourt method cannot be used in cohesive soils as in some cases it gives very high capacities. The two CPT based methods Schmertmann and Philipponnat can be used to estimate ultimate capacity in cohesive soils as they give close results relative to the pile load test interpretation.

However, it is suggested that average of the four load test interpretation methods (Slope and tangent, Limit value, 90% Hansen and 6 mm net settlement) may be used to estimate the ultimate pile capacity for better interpretation.

Fig. 3: Loading platform with concrete blocks

Fig. 4: A View of Jack, reference beams and the settlement gauges

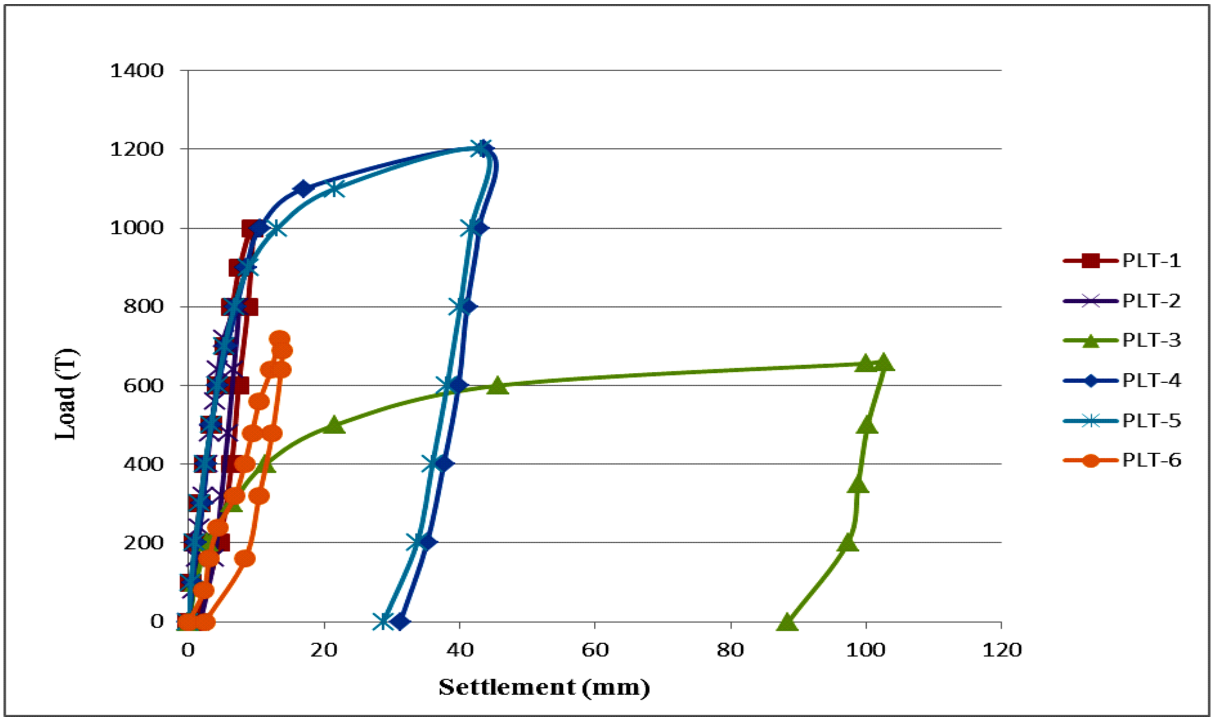

Fig. 5: Load Settlement curves for six pile load tests

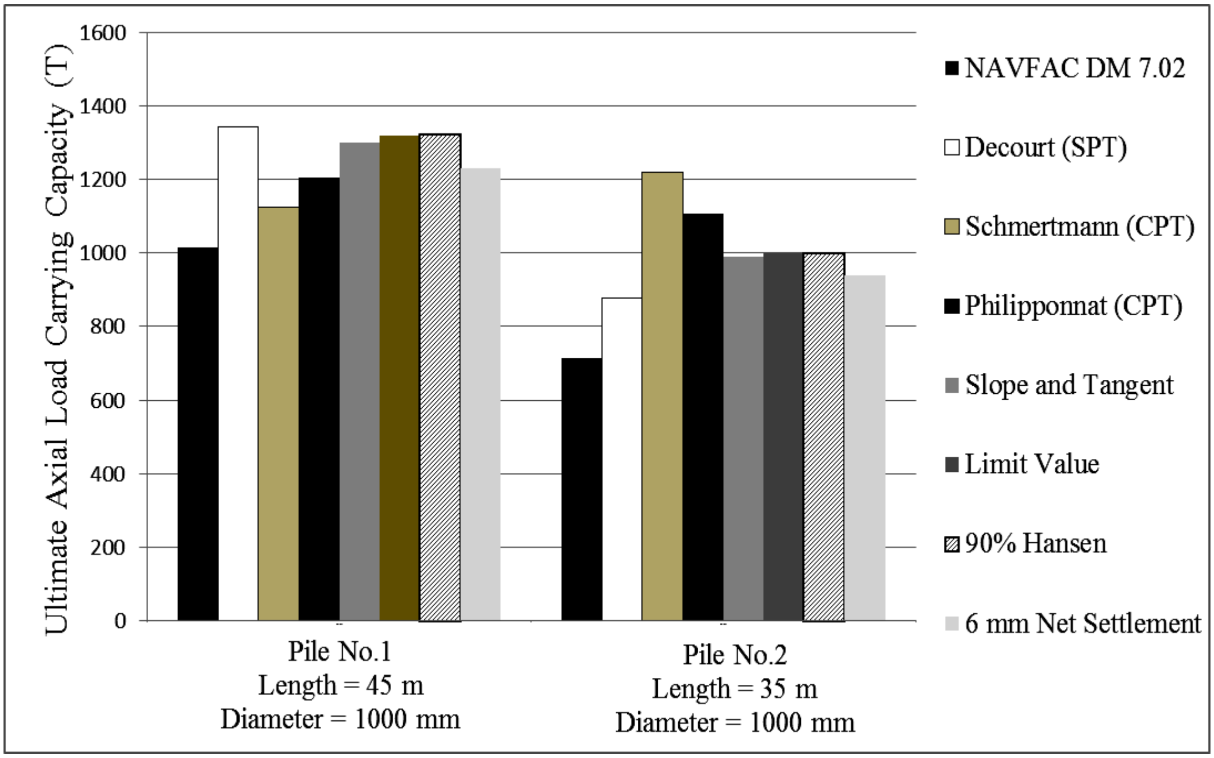

Fig. 6: Ultimate capacity using different methods for pile No.1 and 2

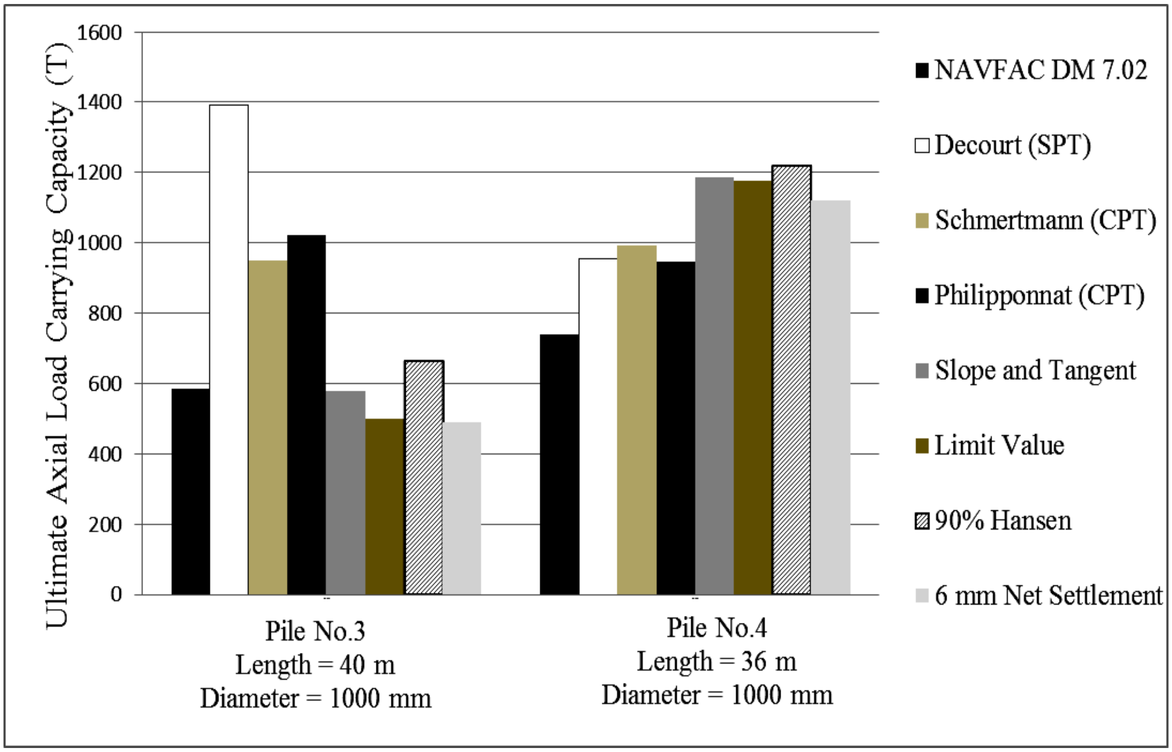

Fig. 7: Ultimate capacity using different methods for pile No.3 and 4

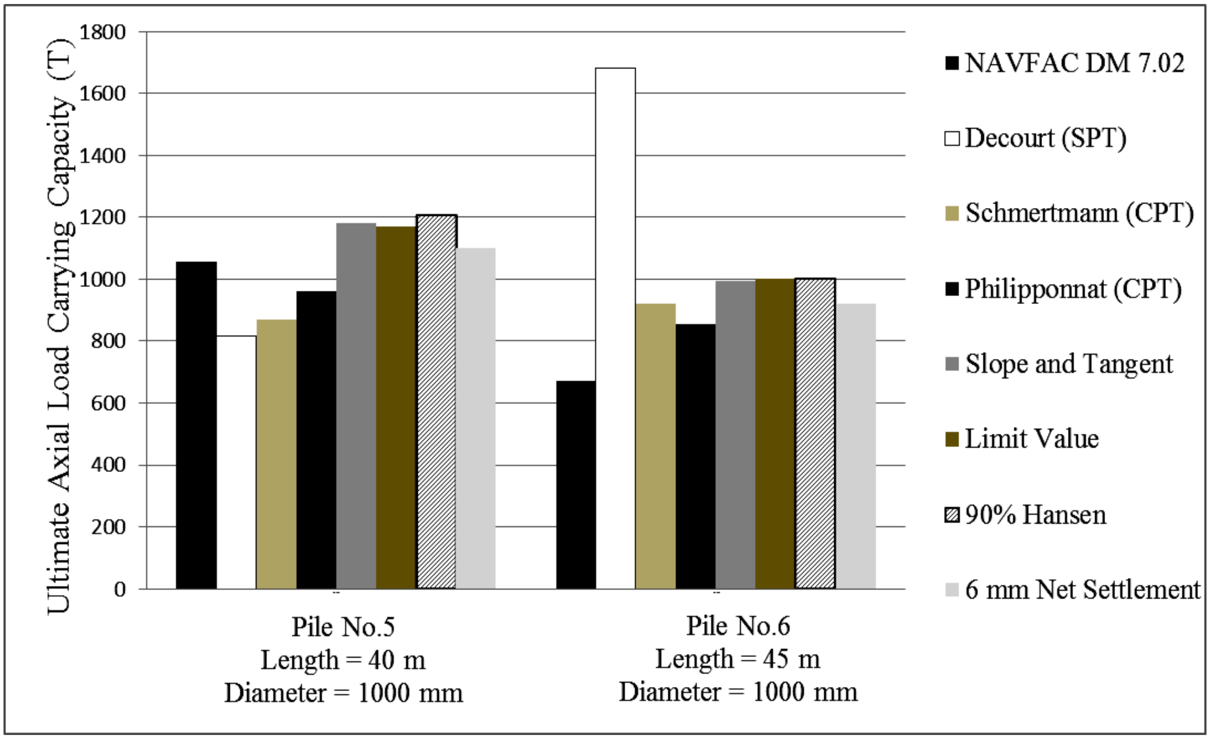

Fig. 8: Ultimate capacity using different methods for pile No.5 and 6

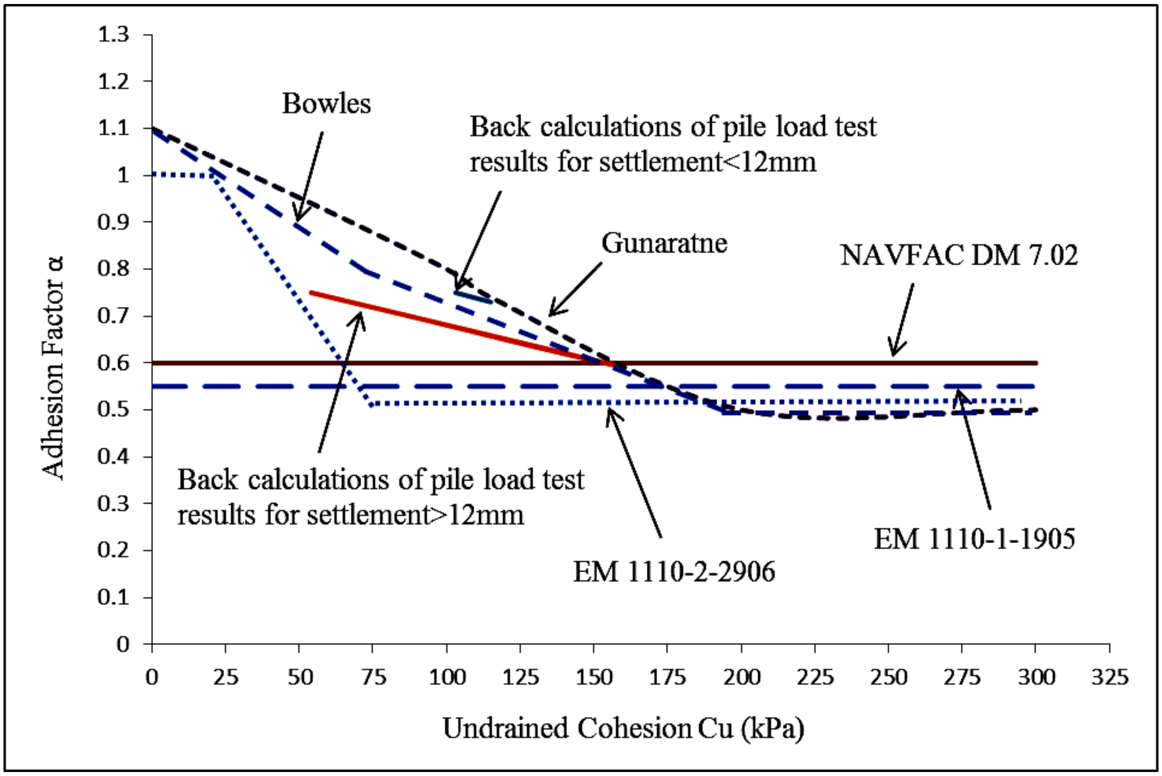

Fig. 9: elation between undrained cohesion Cu and adhesion factor α

Figure 9 shows variation of α determined from back calculations of pile load test results. For test piles settling greater than 12mm, the value of α determined from back calculations is 9%, 33% and 21% higher than that recommended by [15], [18] and [19]. The value of α is 19% and 23% lower than that recommended by [7] and [14]. The value of α should be adjusted to above percentages for evaluation of ultimate pile capacity for local ground conditions. For test piles settling less than 12mm, the value of α determined from back calculations is 20%, 48% and 34% higher than that recommended by [15], [18] and [19]. The value of α is 3% lower than that recommended by [14]. Figure 9 also shows that there is a minor difference in slope for piles settling less than 12mm and greater than 12mm.

5. Conclusions

The following conclusions are based on the comparison of theoretical and pile load test methods.

- It is obvious from the results that theoretical evaluation by NAVFAC DM 7.02 gives 20% to 40% lower estimate of capacity relative to the interpretation of load test evaluations. As capacity is on safer side therefore it may be considered a reliable method for cohesive soils.
- Decourt method gives variable pile capacities. As in some cases it gives very high capacities therefore it may not be considered a reliable method.
- Schmertmann method and Philipponnat method give close results with a difference of 10% to 20% relative to the load test interpretation and are considered reliable methods for cohesive soils.
- Interpretation results of Limit Value method and 90% Hansen method match closely because in many cases the ultimate load point comes in the straight portion of load settlement curve.
- The 6 mm net settlement method gives slightly lower estimate of capacity as compared to other load test evaluation methods because in many cases we have to extrapolate the net settlement curve to find the ultimate load.
- The most suitable method of estimating ultimate capacity based on pile load test results is to use average of ultimate capacity obtained from four methods (i.e Slope and tangent, Limit value, 90% Hansen and 6 mm net settlement).
- The value of α should be adjusted to the recommended trend shown in Figure 9 for determination of ultimate pile capacity for local ground conditions.

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