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Prediction of pile ultimate capacity from non-failed pile load tests: a case study from Sudan

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ABSTRACT: The pile load testing is generally carried out to 1.5 to 2.0 times the design load. This only reflects the load-settlement behaviour of the pile before reaching the ultimate capacity (failure). Therefore, extrapolation methods of load-settlement data are essential to estimate the ultimate pile capacity and choose an appropriate factor of safety. In this paper, three bored piles of 9.0 m length and different diameters were tested. Six extrapolation methods have been tried for the ultimate pile capacity evaluation. Mazurkiewicz's-Abdelrahman and Chin-Kondner methods gave ultimate capacity values near to those obtained by the theoretical calculations (All Pile software) with the nearest values for Test 2 (pile diameter 0.8 m). The remaining values with exception of Davisson method reflected under-estimated values (generally 50% of the theoretically estimated values). Davisson method is not applicable to the three pile tests data as the lowest offset value is 8.81 mm that exceeded the greatest settlements of the piles (6.34 mm). Consequently, no intersection between the Davisson offset line and load-settlement curves for the three piles. According to the AASHTO LRFD Specifications for pile shaft friction mobilisation, it can be said that for Pile 1, 83% of the shaft friction has been mobilised. Accordingly, Pile 2 and Pile 3 has mobilised 74% and 61% of the shaft friction respectively.

1 INTRODUCTION

To enable optimised pile foundation design, it may be very important to predict the actual ultimate axial pile capacity, which has been considered as a challenge due to the uncertainties in the prediction since the beginning of the geotechnical engineering profession, (Eslami1 et al. 2014). The geotechnical investigations generally estimate only static axial capacity of the piles as a guideline for foundation design. These investigations usually tend to confirm the theoretical calculations of the allowable bearing capacity of single pile by performing few pile-loading tests. Unfortunately, the tests are usually carried out up to only 1.5 to 2.0 times the calculated design load without reaching pile failure. This is most probably attributed to the cost of the test and time constraints. Consequently, the load-settlement behaviour of the pile during pile load testing under this loading may not reach the ultimate pile capacity. To obtain safe economical pile foundation design (optimised design) from the available pile load tests data, extrapolation methods of load-settlement data are essential to estimate the ultimate pile capacity and choose an appropriate factor of safety.

Many extrapolation methods and approaches were developed to achieve this objective and to eliminate or reduce as much as possible the uncertainties in the predictions. Several methods have been proposed in the literature, Birid (2018) and Paikowsky & Tolosko (1999):

- Chin-Kondner Extrapolation
- De Beer Yield Load
- The Hansen 80% Criterion
- Mazurkiewicz's-Abdelrahman et al. 2003
- Paikowsky & Tolosko (1999) Extrapolation Method
- The Davisson Offset Limit Load

This research attempts to predict the ultimate capacities for this case study using the above-mentioned methods.

2 GEOTECHNICAL STUDY AND SITE CONDITIONS

The study has been carried out on pile load tests performed on three working piles at the Headquarter building of Sudan Judiciary in Khartoum city according to ASTM D 1143. The geotechnical investigation for this building was carried out by Building and Road Research Institute (BRRI), U. of K. in July 2010. Five boreholes were drilled at the piles area. The boreholes at this area generally revealed existence of medium dense to very dense coarse grained (sandy: SC and SM) soils that were accompanied by hard fine grained soils (silt: MH and ML; and clay: CH and CL) layers with variable thicknesses. The piles were rested at 9.0 m depth. The five boreholes showed that the end bearing layer for the piles is a very dense sand layer except borehole No. 4 that reflects a 1.5 m thick lean clay, CL end bearing layer. Based on this, the ultimate and allowable bearing capacities of individual bored pile were calculated according to All-pile licensed computer program, Civil-Tech. Software, and a summary of the computed ultimate and safe pile bearing capacities are given in Table 1.

Table 1. Ultimate and safe pile bearing capacities according to All-pile software

Pile diameter (m)	0.6	0.8	1.0
Pile embedment below the ground level (m)	9.0	9.0	9.0
Ultimate estimated pile bearing capacity (kN)	1600	2100	2900
Design load (kN) (S.F. 2.5 to 3)	600	900	1000

3 STATIC AXIAL COMPRESSION PILE LOAD TESTS

Three static axial compression pile load tests have been carried out at the studied site in November 2017. These have been carried out by Engineering Services and Design (ESD) geotechnical consulting firm. Based on the request of the project consultant and the given information, Table 2 illustrates the types of piles and tests that were carried out.

Table 2. Details of Test Piles and Loadings

Pile Depth (m)	Pile Diameter (mm)	Design Load (kN)	Maximum Test Load (kN)
9.0	600	600	1000
9.0	800	900	1500
9.0	1000	1500	2250

It is well noted that the tests were carried out at one site on three piles embedded at the same depth (9.0 m), but only varies in diameters (0.6, 0.8 and 1.0 m).
A summary of the axial static compression pile load test results is shown in Table 3 below and Figure 1.

Table 3. Axial Compressive Test Results Summary

Test Pile Diameter (mm)	Length (m)	Max. Test Load (kN)	Max. Settlement (mm)	Elastic Rebound (mm)	Permanent set (mm)
600	9.0	1000	6.343	2.273	4.07
800	9.0	1500	4.315	1.478	2.838
1000	9.0	2250	0.865	0.488	0.378

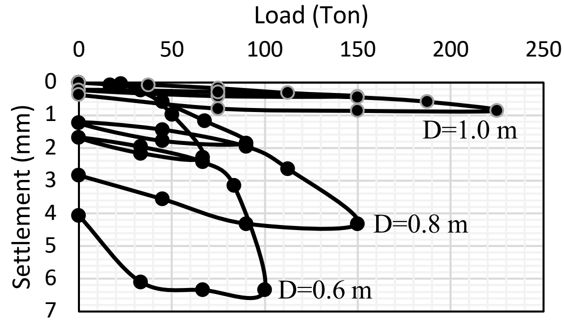

Figure 1. Static pile Load Tests Curves

4 RESULTS OF ULTIMATE PILE CAPACITIES PREDICTION

Some interpretation methods have been used to extrapolate the ultimate pile capacities for the three piles in this case study. The results of these methods are summarised in Table 4, whereas samples of graphs are shown in Figures 2 to 6.

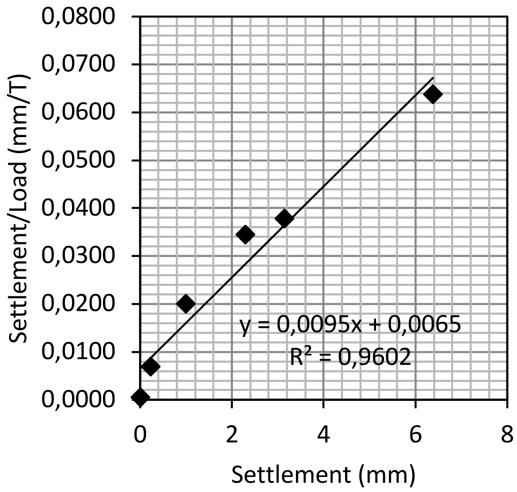

Figure 2. Diameter 60 cm, Failure Load =1050 kN
Chin – Kondner Method

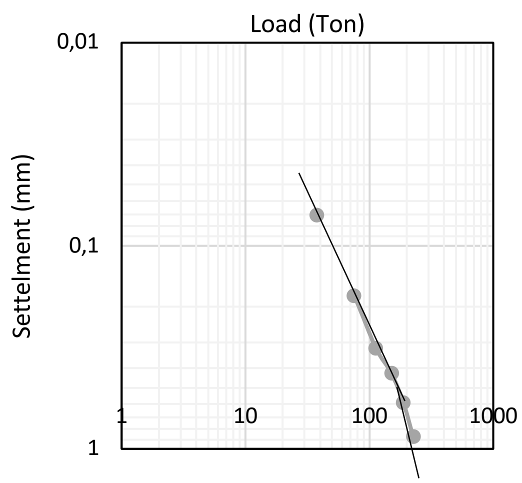

Figure 3. Diameter 100 cm, Failure Load =1500 kN
De Beer Method

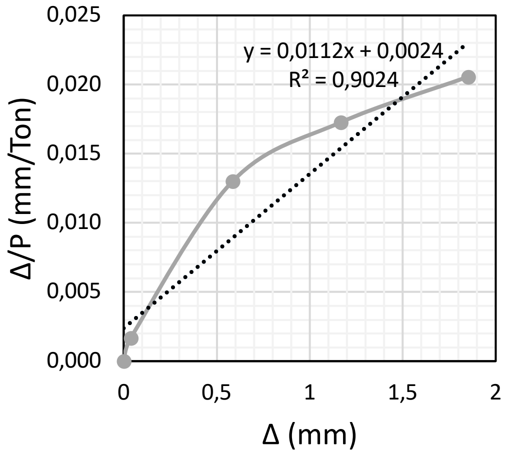

Figure 4. Diameter 80 cm – Failure Load = 960 kN Hansen's 80% Method

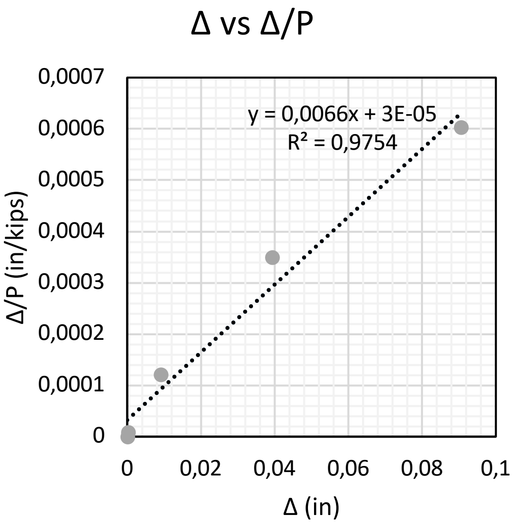

Figure 5. Diameter 60 cm, Failure Load = 660 kN Paikowsky & Tolosko Method

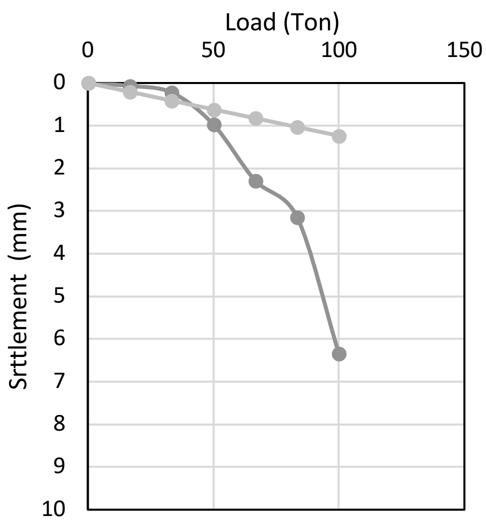

Figure 6. Diameter 60 cm – Davisson Method

Table 4. Ultimate Axial Compressive Pile Capacity Predicted by Different Extrapolation Methods for 9.0 m length piles

		Prediction Methods for Pile Ultimate Capacity, kN					
Pile Diameter (mm)	Design Load (kN)	Chin-Kondner	De Beer	Hansen 80%	Mazurkiewicz's (Abdelrahman)	Paikowsky and Tolosko	Ultimate Theoretical Load (Allpile)
600	600	1050	830	800	1170	660	1600
800	900	1780	450	960	2200	870	2100
1000	1500	4540	1500	2340	3300	1760	2900

5 ANALYSIS

The ultimate pile capacities predicted by the extrapolation methods have been compared by the theoretical ultimate capacity calculated by All-Pile method.

The results shown in Table 4 and Figures from 7 to 9 reflected that Mazurkiewicz's (Abdelrahman) and Chin-Kondner methods gave ultimate capacity values near to those obtained by the theoretical calculations (All Pile software) with nearest values for test 2 (pile diameter 0.8m). The remaining values with exception of Davisson method reflected under-estimated values (generally 50% of the theoretically estimated values). Davisson method is not applicable to the three pile tests data as the lowest Davisson offset value is 8.81 mm that exceeds the greatest settlements of the piles (6.34 mm). Consequently, no intersection between the Davisson offset line and load-settlement curves for the three piles.

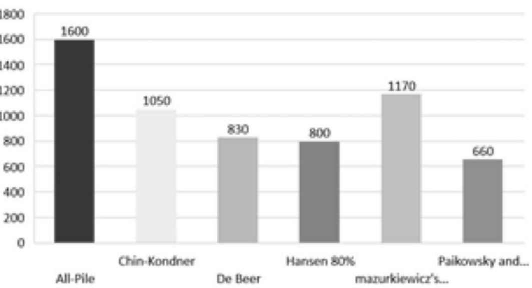

Figure 7. Ultimate Pile Capacity using different methods, D = 0.6 m

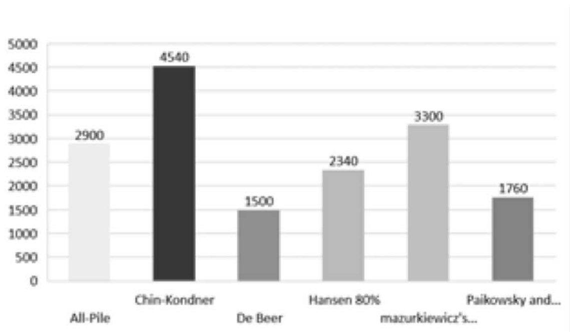

Figure 8. Ultimate Pile Capacity using different methods, D = 0.8 m

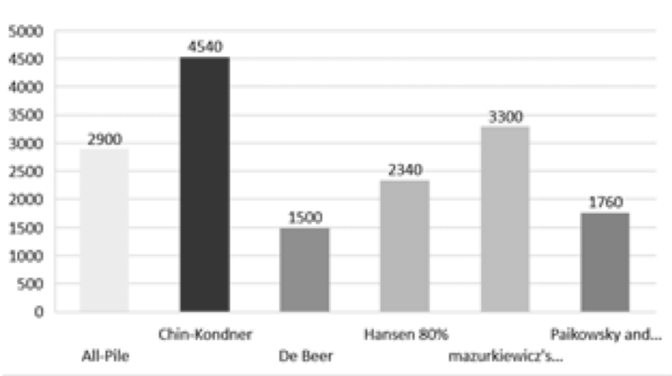

Figure 9. Ultimate Pile Capacity using different methods, D = 1.0 m

6 ANALYSIS OF SKIN FRICTION

According to the AASHTO LRFD Specifications, Zein & Ayoub (2016), the shaft friction is completely mobilised 0.2 % to 0.6 % of pile diameter in cohesive soils. Accordingly, and as per the summary shown in Table 5, it can be suggested that for Pile 1, 83 % of the pile shaft friction has been mobilised. On this basis, Pile No. 2 almost has mobilised 74 % of the shaft friction, whereas Pile 3 has mobilised around 61 % the shaft friction.

Table 5. Pile Mobilised Friction load F_s according to AASHTO LRFD

Pile Diameter (mm)	Settlement (mm)	ε D%	Friction stress f_s (KN/m^2)	Pile Mobilised Friction load F_s	Max. Test Load	Design Load
600	6.343	1.06	48.91	830	1000	600
800	4.315	0.54	48.91	1106	1500	900
1000	0.865	0.09	48.91	1383	2250	150

7 CONCLUSION

Pile tests were carried out on three working piles according to ASTM D 1143. These are constructed at the same area with the same length, but they only differ in diameters. The piles were installed in dense soil comprising of clayey silty sand and clay of low to high plasticity. The ultimate pile loads were calculated based on soil mechanics using the All-Pile programme. Allowable pile capacities were chosen by applying a suitable factor of safety ranging between (2.5 – 3.0).

It is thought that it is useful to predict the ultimate pile capacities using well known prediction methods available in literature. Six extrapolation methods were used in this research. The results of the findings are summarised in this paper.

Only two methods (Mazurkiewicz's-Abdelrahman and Chin-Kondner) showed results closest to the theoretical calculations. Davisson methods is found as not applicable to the data of this case study as the resulted settlements did not approach the Davisson offset limit. The mobilised shaft friction of the tested piles has also been predicted according to the AASHTO LRFD Specifications. For Pile 1, 83 % of the shaft friction has been mobilised. Accordingly, Pile 2 and Pile 3 has mobilised 74 % and 61 % of the shaft friction respectively. Generally, it can be said that Pile 3 of 1.0 m diameter is most probably overdesigned since only 60 % of shaft friction was mobilised and none of the tip resistance was mobilised.

8 RECOMMENDATIONS

It is recommended to increase the maximum test loads in pile load tests to at least 2.5 of the design load. This is expected to enable application of different extrapolation methods and better pile foundation design may be achieved. It is also strongly recommended that more research be carried out in this subject that can give more appropriate evaluation methods.

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