Interpreting Load-Settlement Curves of Pile Foundations by Graphical Methods

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ABSTRACT

In Geotechnical Engineering, deep foundation systems, especially pile foundations, are typically used when shallow foundations are inadequate due to design criteria in terms of bearing capacity, settlement, liquefaction and stability. The load settlement behavior of the pile foundations can be determined realistically by full-scale loading tests conducted on the piles after the pile construction. In this study, it was tried to determine the ultimate bearing capacity of the diriven and bored piles manufactured in different soil conditions using the load-settlement data. For this, 9 different graphical methods such as Tangent, Fuller-Hoy, Butler-Hoy, De Beer-Wallays, Chin Kondner, Decourt, Brinch Hansen 80%, Mazurkiewicz and the Corps of Engineers have been used. Among these methods, there are considerable differences between the predicted ultimate bearing capacities of the piles which decreases to 35% for the piles loaded up/over to the collapse load, and increases up to 120% for the piles loaded below the failure load. In generally, methods of Brinch Hansen, Mazurkiewicz, Chin Kondner and Decourt predict the pile capacity greater than maximum test load and the other ones predict smaller than it. The closest average collapse load was obtained from methods of Corps of Engineering and Butller-Hoy.

Keywords: Bearing capacity, field pile loading tests, graphical methods.

INTRODUCTION

Pile loading experiments stand out as the most reliable approach that can be applied to determine load-bearing capacities and load-settlement behavior of piles. Because this experiment is a full scale model experiment. The application purposes of pile load tests are determining the pile capacity, prediction pile service load after pile construction, determining load-settlement relation of pile foundation.

Static loading experiments are a type of pile loading experiments. Axial pressure and axial tensile tests are the types of static loading experiments. The standards used for these experiments are ASTM D 1143-81 (1994), ASTM D-3689 (1995), ASTM D 3966-90 (1995), ASTM D 3966-07 (2013), ASTM D-1143/D1143M (2013). The principles of the experiments and the points to be noted are detailed in these standards.

The most reliable way of estimating the ultimate bearing capacity of the piles under vertical loads is to apply the static axial loading test. These experiments are carried out by measuring the settlements of the piles against these loads by applying predetermined loads to the pile. It is estimated that from the data obtained as a result of these experiments, the settlement of the pile will take place on the service load and ultimate load. As a result of these obtained results, it is reached that the load bearing capacity of other piles to be produced in the project area will be sufficient.

Several criteria have been proposed in the literature depending on settlement restriction to determine the ultimate bearing capacities of the piles under axial compression and tension loads. However, by analyzing the load-settlement curve obtained from the pile loading tests, many graphical methods developed by Hansen (1963), Mazurkiewicz (1972), Chin-Kondner (1970), Decourt (1999), Corps of Engineers (1991), Fuller and Hoy (1970), Butller and Hoy (1977) and De Beer and Wallays (1989) have been proposed to find the pile bearing capacity.

Lastiasih and Sidi (2014) concluded that, using 130 pile loading test results, many graphical methods predict the failure load of pile if the pile is loaded up to ultimate pile capacity. Decourt (2008) improved some correlations using test result of standard penetration, cone penetration and menard pressuremeter to predict pile capacity when the pile loading test results did not achieved. Petek et al. (2012) evaluate the full scale loading test results of driven pile and they concluded that there was %20 difference of pile capacity among the graphical methods.

In this study, the ultimate capacities of the piles were determined by using 9 different methods and the results were interpreted by using the pile load test data on 3 piles constructed in different areas.

GRAPHICAL METHODS USED TO DETERMINE PILE CAPACITY

In the literature and in various standards, it is possible to find many criteria and methods for interpreting pile loading test results to determining the ultimate load capacity of the test pile. These methods can be summarized as methods for interpreting the distribution of load-settlement data with various criteria that limit total settlement, plastic settlement or settlement/load ratios.

Method of Brinch Hansen %80

Hansen (1963) proposed a definition for ultimate pile capacity as the load that gives four times the settlement of the pile head as obtained for 80% of that load. This '80%- criterion' can be estimated directly from the load-settlement curve, but it is more accurately determined in a plot of the square root of each settlement value divided by its load value and plotted against the settlement. This graph continues linearly after a certain point. Normally, the 80%-criterion agrees well with the intuitively perceived "plunging failure" of the pile. The following simple relations can be derived for computing the ultimate capacity, Q_u;

$$Q_u = \frac{1}{2\sqrt{C_1 \cdot C_2}} \tag{1}$$

where, C_1: slope of the straight line, C_2: intersection of load axis of the straight line.

Mazurkiewicz Method

Mazurkiewicz (1972) suggested a method of extrapolating the load-settlement curve, assuming it is same as a parable. In this method, vertical parallel lines with equal distance to settlement axis are drawn and the curve is intersected, then horizontal lines are drawn, starting from each point of intersection to the load axis. Straight line segments make an angle of 45 degrees with the load axis are plotted, each with ends at the point of intersection of the load axis and the next horizontal parallel line. Finally, the line passing through the intersections of the segments with the horizontal lines and then this line extended to load axis. This intersection point gave the ultimate bearing capacity of pile.

Chin-Kondner Method

The method proposed by Chin (1970), in a study based on work by Kondner, allows the extrapolation of the failure load in the static load tests. In this method, a settlement/load-settlement graph is drawn by dividing each load value by the settlement value corresponding to this load value. The points on the graph show a linear trend after a certain value (Chin, 1970). The inverse of the slope of this line ($1/C_1$) gives the ultimate bearing capacity of pile.

Decourt Method

In the Decourt (1999) method, a load/settlement vs load graph is drawn. The curve in the resulting graph becomes linear when it approaches axis of abscissas and intersects the abscissas when it is extended. Linear regression analysis is applied to these points with linear trend. The ultimate bearing capacity of pile can be obtained by dividing the value at intersection of vertical axis and the regression line by the slope of the regression line.

$$Q_u = \frac{C_2}{C_1} \tag{2}$$

where; C_2=value at intersection of vertical axis and the regression line, C_1=slope of the regression line

Tangent Method

In this method, the ultimate bearing capacity of piles can be determined by drawing first tangent lines to the starting and ending portions of the load-settlement curves; the intersection point of these two tangents was assumed to represent the ultimate bearing capacity of pile.

Corps of Engineers Method

This method is mostly used by the U.S. Army Corps of Engineers (1991). In this method, load-settlement curve is drawn first, and then three different loads are detected. The firs load (Q_1) is the load corresponding to the 6.4 mm settlement level. The second one (Q_2) is the load corresponding to the point obtained by the tangential method. The third one (Q_3) is the load corresponding to the point at where the line make an angle of 0.025 mm/kN intersects with load-settlement curve. The average of these three load values is considered as the ultimate bearing capacity of pile.

Fuller and Hoy Method

In the Fuller and Hoy (1970) method, the ultimate load is determined by finding the point at where the line make an angle of 0.127 mm/kN intersects with load-settlement curve.

Butller and Hoy Method

In this method, a line make angle of 0.127 mm/kN which tangent to the load-settlement curve, as in the case with Fuller-Hoy method, is drawn. In addition to this, a new line tangent to the initial part of the load-settlement curve is drawn. Finally, the load at which corresponds to intersection of these two lines is the ultimate bearing capacity of pile (Butller and Hoy, 1977).

De Beer and Wallays Method

In the De Beer and Wallays (1989) method, the load-settlement graph is plotted on a logarithmic scale for both axes. If the load applied to test pile passes the ultimate load, it is observed that the points on the graph are located around the straight lines on the different slopes. There is no result to be obtained from the slope of these straight lines, but the point where the straight lines intersect is the point at which the reaction of the pile to the applied load changes, and the load corresponding to this point is the ultimate load.

EVALUATION OF FIELD PILE LOADING TEST RESULTS

Design Features of Pile Foundations

In this study, authors evaluate the full scale pile loading test results performed in the field for three different piles. Load-settlement data of pile 1 and pile 2 were taken an existing study (Dinç, 2010) and load-settlement data of pile 3 obtained from loading test results achieved from pile load test performed in Konya Industrial Zone, Turkey. Load-settlement curves and design features of test piles are given in Fig. 1 and Table 1, respectively. Pile 1 and pile 2 can be classified as mini piles because of their dimensions and they are prefabricated driven piles. Pile 3 can be classified as cast-in-situ reinforced bored piles. It is understood that, pile 1 and 2 were loaded up to the ultimate load (Q_u). Because there is no significant change in the amount of load carried by the pile with further increasing deformations. Pile 3, however, was loaded not to ultimate capacity but it was loaded up to the 2.25 times of design load, Q_d=1600 kN (Fig. 1).

Table 1. Design features of test piles

	Pile 1	**Pile 2**	**Pile 3**
Construction process	Prefabricated	Prefabricated	In-situ
Pile type	Driven pile	Driven pile	Bored pile
Pile diameter, D (m)	0.3	0.3	1.0
Pile length, L (m)	7.6	8.0	25.0
Soil profile	Sandy loam	Sandy loam	Soft clay
Design load (kN)	200	350	1600
Maximum test load (kN)	520	800	3600
Total settlement, δ_T (mm)	36.01	16.09	4.02
Plastic settlement, δ_P (mm)	29.74	11.00	3.05

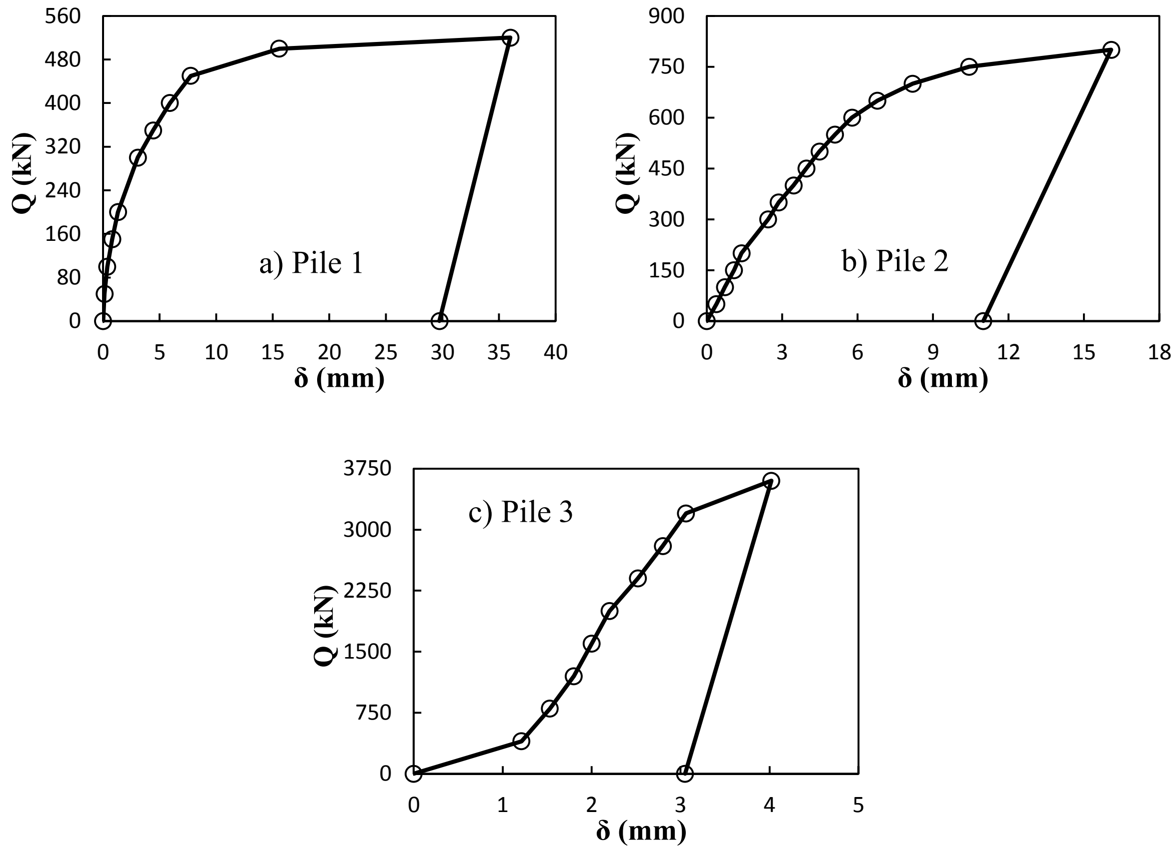


Figure 1. Load-settlement curves obtained from field pile loading tests

Ultimate Bearing Capacities of Piles

Firstly, ultimate bearing capacities of test piles (Q_u) determined by using above mentioned graphical methods and these results compared with each other. For example, determination of the ultimate capacity of pile 2 using 9 different graphical methods is given in Fig. 2. Then, the safety factors (FS) were obtained by dividing the Qu values found in each method by the project loads for all piles;

$$FS = \frac{Q_u}{Q_d} \tag{3}$$

where; Q_u=ultimate bearing capacity of pile, Q_d=design load of pile

Ultimate bearing capacities of test piles, according to different methods, changes from 408.3 kN to 555 kN for pile 1, 661.7 kN to 974.6 kN for pile 2 and 3100 kN to 6993 kN for pile 3. The differences between minimum and maximum predicted ultimate pile capacities are 35.9%, 47.3% and 125.6% for pile 1, pile 2 and pile 3, respectively. Ultimate bearing capacity value of a pile may change in a wide range according to the methods used to determine pile capacity. Therefore, the most logical way to determine pile capacity is using average failure load ($Q_{u,avg}$)obtained from several methods. Then, ultimate bearing capacity of test piles may be accepted as 495.8 kN, 784.3 kN and 4409.9 kN for pile 1, pile 2 and pile 3, respectively (Table 2).

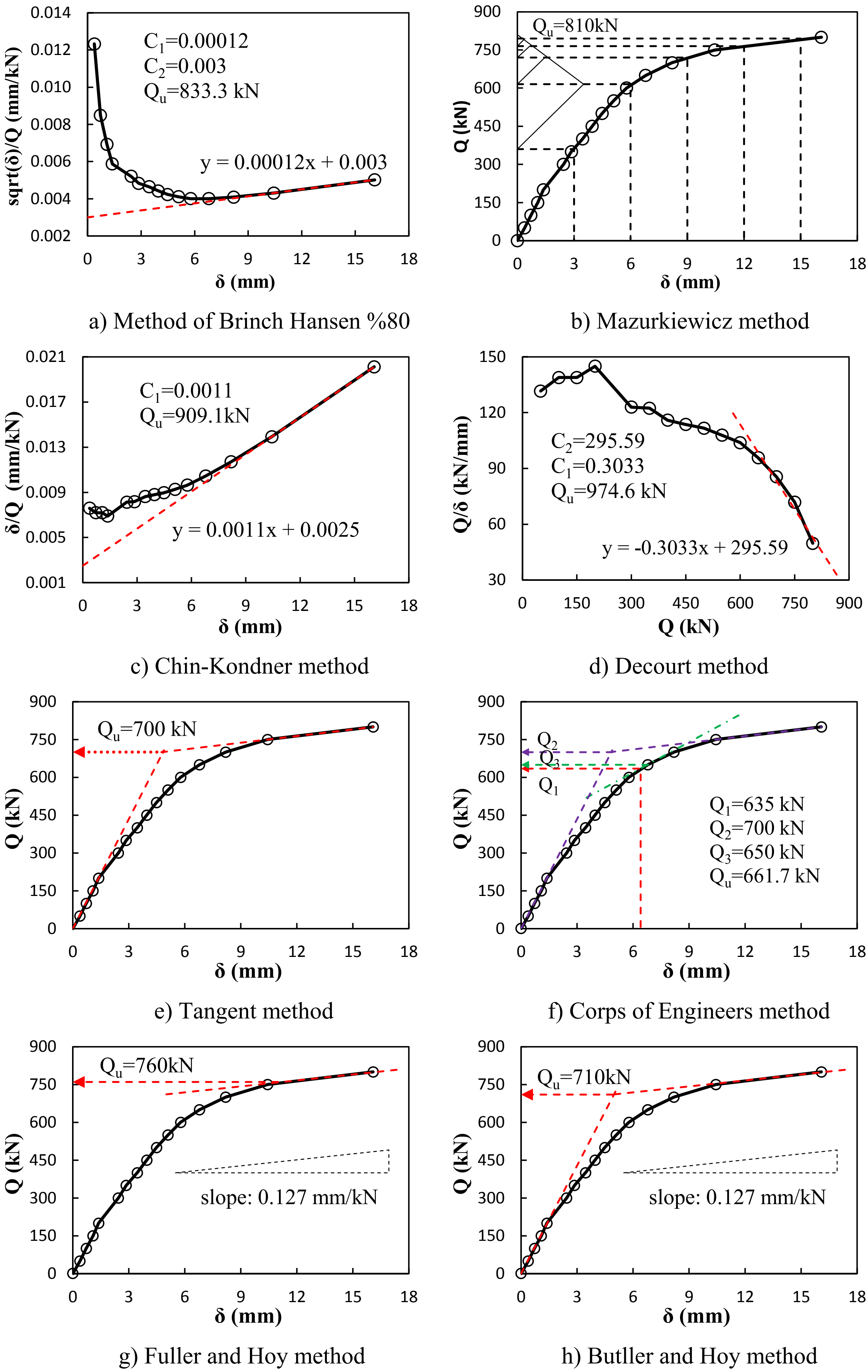
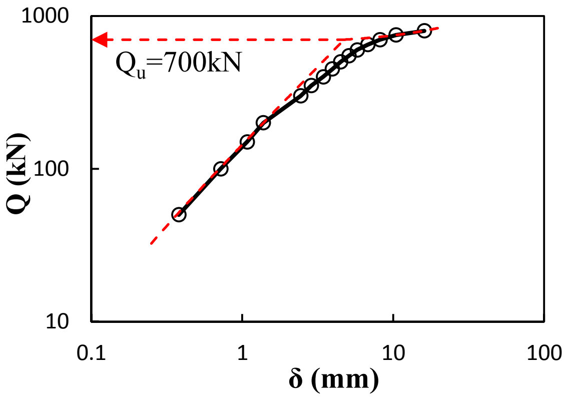


Figure 2. Graphical methods used to determine ultimate capacity of pile 2



ı) De Beer and Wallays method

Figure 2 *(continued)*. Graphical methods used to determine ultimate capacity of pile 2

Table 2. Failure loads of piles found by different methods and the safety factors (FS)

Methods	Pile 1		Pile 2		Pile 3	
	Q_u (kN)	FS	Q_u (kN)	FS	Q_u (kN)	FS
Brinch Hansen %80	527.0	2.64	833.3	2.38	6993.0	4.37
Mazurkiewicz	520.0	2.60	810.0	2.31	3700.0	2.31
Chin Kondner	555.0	2.78	909.1	2.60	5882.0	3.68
Decourt	543.0	2.72	974.6	2.78	5984.0	3.74
Tangent	502.0	2.51	700.0	2.00	3100.0	1.94
Corps of Engineers	408.3	2.04	661.7	1.89	-	-
Fuller-Hoy	485.0	2.43	760.0	2.17	3320.0	2.08
Butter-Hoy	420.0	2.10	710.0	2.03	3200.0	2.00
De Beer and Wallays	502.0	2.51	700.0	2.00	3100.0	1.94
Average ($Q_{u,avg}$ or FS_{avg})	495.8	2.48	784.3	2.24	4409.9	2.76

Table 2 gives security numbers obtained by different methods for test piles. The average of these security numbers is FS_{avg}=2.48 for pile 1. The maximum load is 520 kN and the safety factor according to this load is FS =520/200=2.60 for pile 1 since design load is 200 kN. This value is very close but greater than FS_{avg}=2.48. In this case, it is understood that pile 1 is loaded over the ultimate bearing capacity. The average of security numbers is FS_{avg}=2.24 for pile 2. The maximum load is 800 kN and the safety factor according to this load is FS=800/350=2.29. This value is very close but greater than FS_{avg}=2.24. Pile 2 is also loaded over the ultimate bearing capacity. In Table 2, the average of the security numbers obtained for the different methods is FS_{avg}=2.76 for pile 3. The maximum load is 3600 kN and the safety factor according to this load is FS=3600/1600=2.25. This value is smaller than FS_{avg}=2.76. In this case, it is understood that pile 3 is loaded smaller than its ultimate bearing capacity. The greatest ultimate bearing capacity and factor of safety are obtained from the methods of Chin Kondner and Decourt for Pile 1 and pile 2. Brinch Hansen method, for pile 3, gives the greatest values in addition to these methods. This situation may be occurred if a pile is not loaded up to the ultimate capacity. The smallest pile capacity and safety factor are obtained for all piles by Corps of Engineers method. In addition to this, Butter-Hoy and De Beer-Wallays methods also give small values.

In generally, methods of Brinch Hansen, Mazurkiewicz, Chin Kondner and Decourt predict the pile capacity greater than maximum test load and the other ones predict smaller than it (Table 3). The closest values to the maximum test load were obtained except from Corps of

Engineers and Butter-Hoy methods for pile 1. Brinch Hansen, Mazurkiewicz and Fuller-Hoy methods give the loads closest to maximum test load for pile 2. The closest values to the maximum test load, for pile 3, were obtained from Mazurkiewicz and Fuller-Hoy methods. If the settlement value is smaller than 6.4 mm such as in the pile 3, the Corps of Engineers method cannot be used. After that explanations, it can be said that all methods can predict the ultimate pile capacity correctly if the test pile is loaded up to the ultimate capacity, if not many methods such as Tangent, Corps of Engineers, Fuller-Hoy, Butter-Hoy, De Beer and Wallays predict the pile capacity smaller than the real value.

Table 3 shows the mean ratio (Q_u/Q_{avg}) of the ultimate load (Qu) found by a certain method to the average ultimate load (Q_{avg}) values found by all methods for the same pile. Thus, it has been determined which method gives a closer result to the mean capacity (Q_{ave}). It can be misleading to using any method to determine the ultimate bearing capacity of a pile. Finding individual results with different methods and getting their average values helps to stay on the safer side. The following result can be concluded that the failure load values obtained from the Brinch Hansen, Chin Kondner and Decourt methods predict pile capacity greater than average capacity for all piles according to the other methods.

Table 3. Comparison of ultimate pile capacity with average failure load and maximum test load for each method.

Methods	Pile 1		Pile 2		Pile 3	
	$Q_u/Q_{u,avg}$	Q_u/Q_{max}	$Q_u/Q_{u,avg}$	Q_u/Q_{max}	$Q_u/Q_{u,avg}$	Q_u/Q_{max}
Brinch Hansen %80	1.06	1.01	1.06	1.04	1.59	1.94
Mazurkiewicz	1.05	1.00	1.03	1.01	0.84	1.03
Chin Kondner	1.12	1.07	1.16	1.14	1.33	1.63
Decourt	1.10	1.04	1.24	1.22	1.36	1.66
Tangent	1.01	0.97	0.89	0.88	0.70	0.86
Corps of Engineers	0.82	0.79	0.84	0.83	-	-
Fuller-Hoy	0.98	0.93	0.97	0.95	0.75	0.92
Butter-Hoy	0.85	0.81	0.91	0.89	0.73	0.89
De Beer and Wallays	1.01	0.97	0.89	0.88	0.70	0.86
Average	1.00	0.95	1.00	0.98	1.00	1.22

CONCLUSIONS

In many projects, some of the manufactured piles are loaded to determine the pile bearing capacity. This is the most reliable way to determine the pile capacity. However, it is not easy to determine the point where the pile has reached its ultimate capacity on the load-settlement curve. In this study, it was tried to determine the ultimate bearing capacity of the diriven and bored piles manufactured in different soil conditions using the load-settlement data. For this, 9 different graphical methods such as Tangent, Fuller-Hoy, Butler-Hoy, De Beer-Wallays, Chin Kondner, Decourt, Brinch Hansen 80%, Mazurkiewicz and the Corps of Engineers have been used.

According to the values of the ultimate loads obtained by different methods within the scope of the study;

1. There can be considerable differences between the predicted ultimate bearing capacity values of the piles according to the method used. This difference decreases to 35% for the piles loaded up/over to the collapse load, and increases up to 120% for the piles loaded below the failure load.

2. In generally, methods of Brinch Hansen, Mazurkiewicz, Chin Kondner and Decourt predict the pile capacity greater than maximum test load and the other ones predict smaller than it.
3. If the pile is loaded up to the ultimate pile capacity, the results obtained by the methods give a result close to the maximum test load, if not, greater values than maximum test load is obtained.
4. The failure load values obtained from the Brinch Hansen, Chin Kondner and Decourt methods predict pile capacity greater than average capacity for all piles according to the other methods.
5. It has been found that if the average of the safety factors obtained for different methods is close to the calculated safety coefficient for the maximum test load, the determination of the bearing capacity by the different methods of the loaded piles will be within acceptable limits.
6. It has been determined that the values closest to ultimate loads are obtained by Mazurkiewicz and De Beer method.
7. The Corps of Engineering and Butller-Hoy method gave the smallest ultimate values.

Although the Mazurkiewicz method has the closest value to the ultimate load, some operations are performed on the load-settlement graph to determine the ultimate load. These operations can increase the error margin. In the Chin Kondner and Decourt methods, it is stated that the ultimate load test data is predefined functions and that these functions are expressed by the asymptote, that is, the defined ultimate load is analytically determined. The advantage of analytical determination of ultimate load is that the result of the assessment is not dependent on the scale of the applicant and the graph drawn when compared to graphical methods. Therefore, a single method of evaluating the results of the pile loading test may lead to a misleading situation.

In addition, no assessment was made of the criteria for the scope of this study. However, for many batches, acceptance prerequisite is largely a settlement criterion from bearing capacity. In this context, it will be the most realistic approach to evaluate the results by taking into consideration the settlement criteria as well as determining the bearing capacities of the piles.

As a continuation of this study, it is planned to evaluate the pile loading test results with more literature methods and to make a statistical study on this subject.

REFERENCES

ASTM D1143/D1143M-07. 2013. Standard Test Methods for Deep Foundations Under Static Axial Compressive Load. *ASTM International*, West Conshohocken, PA, 2013, https://doi.org/10.1520/D1143_D1143M

ASTM D1143-81. 1994. Standard Test Method for Piles Under Static Axial Compressive Load. *ASTM International*, West Conshohocken, PA, 0, http://www.astm.org/cgi-bin/resolver.cgi?UOP43

ASTM D 3689-90. 1995. Standard Test Method for Individual Piles Under Static Axial Tensile Load. *ASTM International*, West Conshohocken, PA, DOI: 10.1520/D3689-90R95

ASTM D 3966-90**.** 1995. Standard Test Method for Piles Under Lateral Loads. *ASTM International*, West Conshohocken, PA, DOI: 10.1520/D3966-90R95

ASTM D3966/D3966M-07. 2013. Standard Test Methods for Deep Foundations Under Lateral Load, *ASTM International*, West Conshohocken, PA, https://doi.org/10.1520/D3966_D3966M

Brinch Hansen, J., 1963, Discussion, Hyperbolic Stress-Strain Response of Cohesive Soils, *Journal of Soil Mechanics*, Foundation Division ASCE, V. 89 No.SM4, 241-242.

Butler, H.D. & Hoy, H.E. 1977. User's Manual for the Texas Quick Load Method for Foundation Load Testing, *FHWA*, Office of Development, Washington, D.C., FHWA-IP-77-8, 59.

Chin, F.K. 1970. Estimation of Pile Not Carried to Failure, *Proceedings 2nd Southeast Asian Conference on Soil Engineering*, Singapore, 81-90.

De Beer, E.E. & Wallays, M. 1989. Franki Piles with Overexpanded Bases, *La Technique des Travaux*, No:333, 48.

Décourt, L. 1999. Behaviour of Foundations Under Working Load Conditions, *Proc. of the 11th Pan-American Conf. on Soil Mechanics and Geotechnical Engineering*, Dolguassu, Brasil, V. 4, 453-488.

Décourt, L. 2008. Loading Tests: Interpretation and Prediction of their Results. *Congress on From Research To Practıce In Geotechnıcal Engıneerıng*, 452-470.

Dinc, H. 2010. Determination of pile bearing capacity with *Osteberg cells*. MS thesis, İTÜ, İstanbul.

Fuller, F.M. & Hoy, H.E. 1970. Pile Load Tests Including Quick Load Test Method Conventional Methods and Interpretations, *Highway Research,* Record No.333, pp. 78-89, Transportation Research Board, USA.

Lastiasih, Y. & Sidi, I.D. 2014. Reliability of Estimation Pile Load Capacity Methods. *J. Eng.* Technol. Sci., Vol. 46, No. 1, 1-16.

Mazurkiewicz, B.K. 1972. Test Loading of Piles According to Pollish Regulations, Royal Sweedish Academy of Engineering Sciences, Commission on Pile Research, Report No.35, pp20, Stocholm.

Petek, K.A., Mitchell, R.A., Buechel, G.J. & Goodyear, D. 2012. Full Scale Instrumented Pile Load Test for the Port Mann Bridge, Surrey, British Columbia, Canada. Full-Scale Testing & Foundation Design, 362-375.

U.S. Army Corps of Engineers. 1991. Design of Pile Foundations. Engineering Manual 1110-2-2906, Washington, DC 20314-1000.