Evaluation of the Bearing Capacity of the Board Pile in Collapsible Soil using A Laboratory Model

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Abstract. The pile's ultimate capacity or failure load must be computed by some criteria using load-settlement curve data gathered during the pile load test. Many scholars have proposed several approaches for evaluating the pile’s ultimate capacity in the past. This study compared different failure criteria to predict the ultimate load capacity for piles with two different lengths-to-diameter ratios embedded in gypseous soil with gypsum content of 60% under soaked and unsoaked conditions. Two types of piles were used. Floating pile and end-bearing pile. Davisson, Brinch Hansen’s 80 percent, Chin-Kondner, Mazurkiewicz's, and Brinch Hansen’s 90 methods that were used in this study predict a higher value of the ultimate pile capacity, whereas the Decourt Extrapolation method gave fluctuated value. Fuller and Hoy’s, Butler and Hoy's methods give far away value from realistic. On the other hand, Shen’s, ASTM, Terzaghi, and DeBeer's methods predicted an acceptable and realistic value. The failure criterion of (15%D) where (D) is pile diameter according to(ASTM D-1143) was adopted in this type of soil.

Keywords: Bearing capacity, gypseous soil, failure criteria, load settlement curve.

1. INTRODUCTION

Pile capacity can be divided into structural capacity, which depends on the material properties of the pile, and load carry capacity, which is directly related to the interaction between the pile and the soil, so soil properties surrounding the pile play the main role in assessing the geotechnical capacity of the pile. In collapsible soil, the dissolution of cementation bonds between soil particles during inundation increases the collapse potentially under vertical stress, high void ratio reduction, rapid settlement, and large deformation in collapsible soil structure [1, 4]. The gypseous soil is one type of collapse soil, so a large amount of gypsum content has a direct influence on the mechanical and physical properties of soil, such as specific gravity and solubility [Gs=2.32 and the range of solubility is (2-2.5) g/l for gypseous soil [5-7]. In Iraq, the most important soil collapse problems occurred in the Samarra vacationer hotel, the raised water tank in Karbala, and soil degradation and collapse under several establishments in Tikrit and Mosul City [8]. This is because the pile foundation in collapsible soil suffers from a sudden and rapid settlement due to the development of negative skin friction, which may lead to damage to the structure during inundation [9], so it is necessary to assess the severity of gypseous soil. This severity is usually assessed based on the value of the collapse potential of gypseous soil using a table proposed by [10].

Typically, the pile is designed based on theoretical equations provided by different codes. The design load needs to be verified by conducting a pile load test to assess the load capacity of the pile. The ultimate load capacity is a combination of end-bearing resistance pile and skin friction or can be defined as the load corresponding to the rapid settlement as a result of a sustained or slight increase of the applied load (plunging failure). Generally, there are four types of pile load tests: axial compression, pull-out load, laterally load, and dynamic load according to the ASTM - 1143D, ASTM D-3689 (1995), and ASTM D 3966-07. In the axial compression load, four basic methods are used to apply load on the pile [11]. These methods are the "Method of a Slow Maintained Load Testing (SM Test)", "Method of the Quick Maintained Load Test (QM Test)", "Method Using a Constant Rate of Penetration (CRP Test)", and the "Method of the Swedish Cyclic Test (SC Test)." Each of these methods had specific conditions and limitations. In some approaches, a large load is required to get to the pile's plunging failure load; therefore, the constant rate of penetration method is preferred [12].

Several criteria are proposed to calculate the ultimate bearing capacity depending on the graphical procedures based on the result of the load-settlement curve. These graphical methods were suggested 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) and others. The analysis study was conducted using different criteria to determine the board pile capacity installation in Baghdad city from the pile load test according to ASTM D 1143. The Chin-Kondner Extrapolation, Hansen (1963), and the Log-Log methods gave high estimates of the value for an ultimate load capacity of the pile. On the other hand, the Terzaghi method was adopted to estimate the ultimate pile capacity because it's an easy method, whereas the ultimate capacity of the pile is the value of the load corresponding to the settlement of its value about 10% from the pile diameter [13]. A laboratory model was used to investigate the ultimate pile capacity of the pile installation in gypseous soil. The load-settlement curve result was utilized to apply different failure criteria and choose the suitable criterion after comparing them with the theoretical calculation. Furthermore, Shen's Method (1980) gave acceptable results, while Brinch Hansen's 1963, Decourt extrapolation, and Chin-Konder extrapolation methods produced a high value [14]. All approaches can provide accuracy in the predicted ultimate load when the test load is high and close to the ultimate load limit, but the value begins to be overestimated under less load. In this study, Chin's, Mazurkiewicz's, and Decourt's methods are applicable, but Davisson and De Beer's methods cannot be adopted for non-failed piles. Therefore, it is challenging to recommend a method for evaluating ultimate pile capacity based on accuracy [15]. Nine methods were used in this research to evaluate the bearing capacity of the driven pile in different regions in Iraq. De Beer, Chin-Konder, and Vander Veen are the best approaches because the maximum bearing capacity generated with these methods is accompanied by a low pile settlement in spite of the Vander Veen method consuming time. The Fuller and Hoy and Davison methods gave good results with high settlement, whereas Brinch Hansen's 90% and Butler&Hoy methods gave acceptable bearing capacity with a very small settlement. Finally, the result showed the Terzaghi method [10% from pile diameter] is overstated and suggested (4%of pile diameter) is a good criterion in this study [16]. Many variables should be considered when evaluating ultimate load capacity by an empirical equation or computer software, such as pile type, the value of load applied, dimension, and material of piles construction. Brinch-Hansen, Chin-Kondner, and Decourt methods were selected to compare the result by software method. Both Brinch-Hansen, and software gave similar results to Chin-Kondner and Decourt methods, knowing that the last methods gave approximately similar results, but the study recommended that the Chin-Kondner and Decourt methods are not preferably unless the settlement failure occurred [17].

Bazaar and Luciano Decourt's empirical methods were used to determine the closest result of the field test, whereas the Chin, Mazurkiewiz, and Lastiasih methods were used to interpret the field result. Also, the pile loading test result was analyzed using the finite element method based on the results of empirical methods and interpretation of the ultimate bearing capacity of the field test. The results of this study showed the finite element approach, Luciono Decourt, and Lastiasih are the closest to producing ultimate bearing capacity using loading pile tests at failure [18]. The data from pile load tests for three different regions in Nasiriyah, southern Iraq was used to determine pile capacity by adopting various interpreting methodologies. For the 22 pile load tests, Chin-Kondner's ultimate load is 22% greater than Hansen's maximum load, which means these methods are unsuitable for predicting pile capacity. Decourt, DeBeer, and Mazurkiewicz's methods produced the closest average failure load, while Buttler-Hoy's approach exhibited the lowest failure load capacity [19]. It is challenging to select an appropriate failure criterion; thus, the designer engineer must be knowledgeable in past experiences and have accurate concepts of the ultimate pile capacity in order to adopt the failure criterion. In this study, different failure criteria were used to evaluate the appropriate ultimate capacity of the pile embedded in gypseous soil under different conditions, such as pile length to diameter ratio, type of pile (floating and end-bearing pile), densities, and state of soil (soaked and unsoaked conditions.

2. PROPERTIES OF PILES AND SOIL

All used piles are hollow steel piles with a (20) mm outer diameter and an (18.5) mm inner diameter with different lengths (300 mm and 200mm). The surface of the pile has been rough using a knurling machine, as shown in Figure 1. These piles are embedded in the soil in the box of the laboratory model with a dimension of (800×800×800) mm and made from iron, as shown in Figure 1. This study used two types of soil: collapsible (gypseous) and sandy soil, whereas a gravel soil layer was used at the base of a box of the laboratory model. Each soil's properties are presented in Table 1.

Table 1: Properties of soil used in the study.

Type of soil	Properties	Value
Collapse soil	Soil classification (Unified soil classification system)	SM
	Gypsum content	60%
	Liquid limit	26%
	Plastic limit	Non-plastic
	Maximum dry unit weight	17 kN/m^3
	Optimum water content	12.5%
	Cohesion	18 kPa
	Soil internal friction at filed dry unit weight (12.7 kN/m^3)	40°
Sandy soil	Soil classification (Unified soil classification sytem)	SW
	Maximum unit weight	17.2 kN/m^3
	Minumu unit weight	16 kN/m^3
	Cohesion	1 kPa
	The angle of internal friction	40°
Gravel soil layer	Unit weight	20 kN/m^3
	Cohesion	0 kPa
	Angle of interinal friction	38°

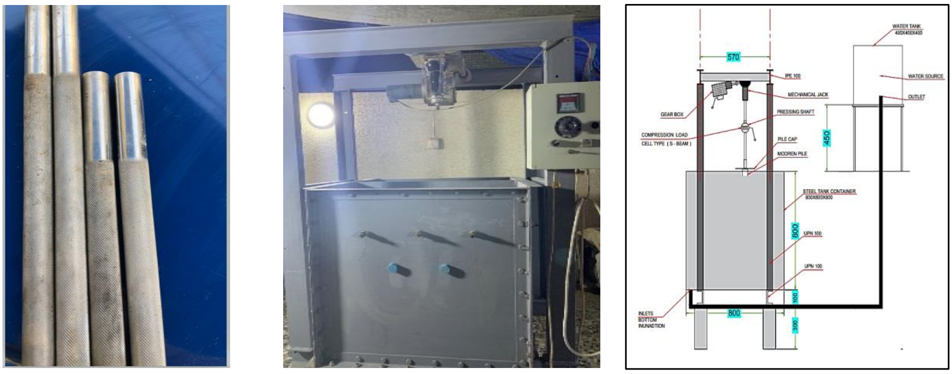

Figure 1: Model of piles, steel box container, and sketch for laboratory model.

3. PILE LOAD TEST

According to the ASTM D-1143, the Constant Rate of Penetration test Method was used in this study by gradually increasing the pressure load to penetrate the soil pile at a constant rate of 1 mm per minute. The load settlement curve resulting from the test can be interpreted by using different criteria. Two cases of soil were prepared to represent the floating pile case and end-bearing pile case:

<u>Soil Case (A)</u>

A 50 cm thickness of the layer from gypsum soil was compacted over a layer of 10 cm thickness from gravel using three different dry unit weights on the standard compaction curve (14.6, 17, and 14.8 kN/m^3) with water content (5.5%,12.5%, and 22.7%) respectively which were determined from the compaction curve, the first is on the dry side, the second is maximum dry density, and the third on the wet side as shown in Figure 2 by using a hand hammer.

<u>Soil Case (B)</u>

A layer of 40 cm thickness from the sand soil (end-bearing layer) was compacted at a dry unit weight of 17.2 kN/m^3 under a layer of gypseous soil with a 10 cm thickness, which was prepared at three different dry unit weights, as mentioned in the soil case (A), at the base a layer of gravel 10 cm thickness was compacted by using a hand hammer.

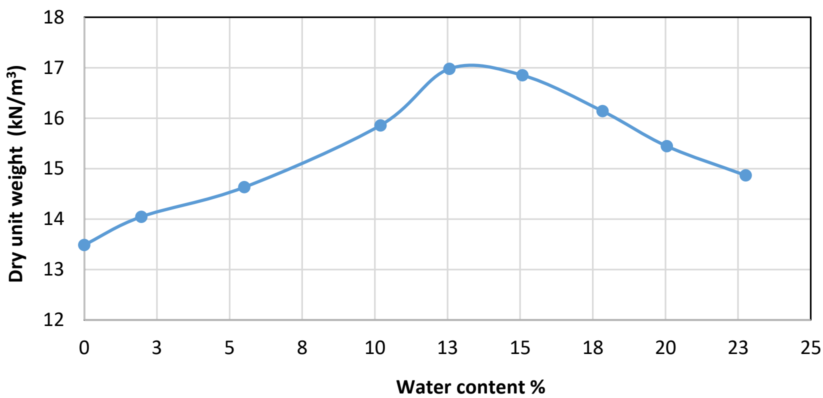

Figure 2: Standard compaction curve of gypseous soil.

After preparing soil and embedding the piles, as shown in Figure 3, a mechanical jack is used to apply axial compression load on the pile, as shown in Figure 3. The load cell (S shape) measures the load applied to the pile with a capacity that varies from the ultimate load, as shown in Figure 4. Each pile has a cap with a dimension of (10x10) cm made from an aluminum plate with a thickness of (2) cm to ensure the load transfers as a centered load on the pile head, as shown in Figure 4. LVTD measures the pile's settlement, and the load cell and LVDT are connected with a data logger box to read the result, as shown in Figure 5. For full saturation conditions, the soil will be soaked for 24 hours. Water through three opens at the bottom of the box of the model. These opens are connected with three pipes and provided with water from a tank made from steel with dimensions (40×40x×40) cm, located at a height of 45 cm from the upper layer of soil.

Figure 3: Piles embedded in soil and mechanical jack.

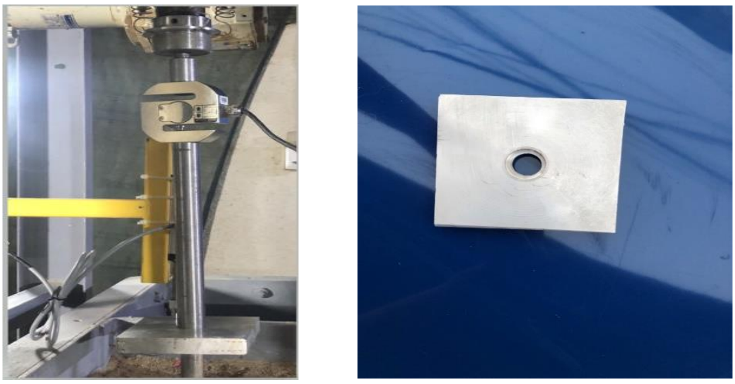

Figure 4: Load cell and pile cap.

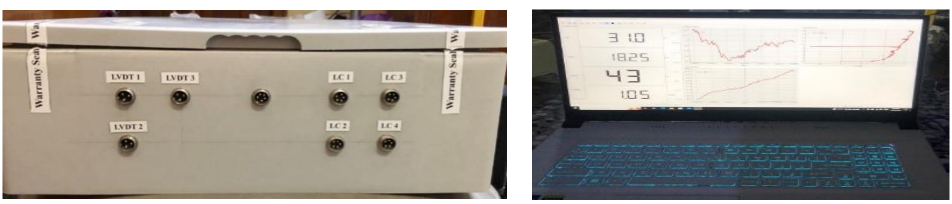

Figure 5: Data logger box and computer.

4. RESULTS OF PILE LOAD TESTS:

The pile load test result for unsaturated and saturated soil is presented as a load-settlement curve. The two pile lengths are considered in this study (30) and (20) cm. The pile was installed as a bored pile in the compacted soil at different densities. Soil case A simulates the case of a floating pile in gypseous soil for soaked and unsoaked states, as shown in Figures, While soil case B simulates the end-bearing pile for both soaked and unsoaked states, as shown in Figures 6 to 11.

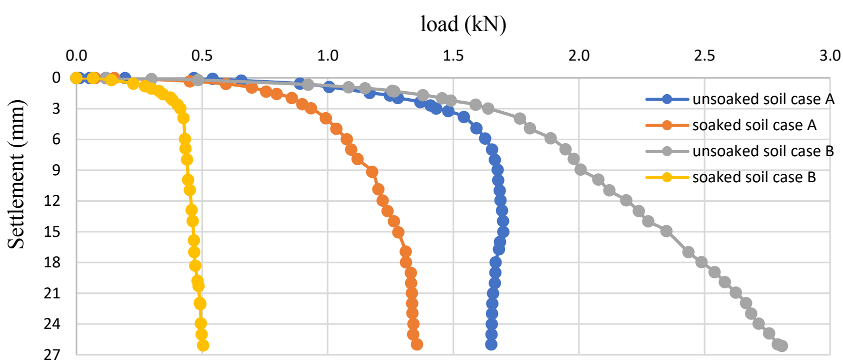

Figure 6: Load-settlement curve for pile with a length of 30 cm and γ=17 kN/m³, embedded in soil case A and soil case B

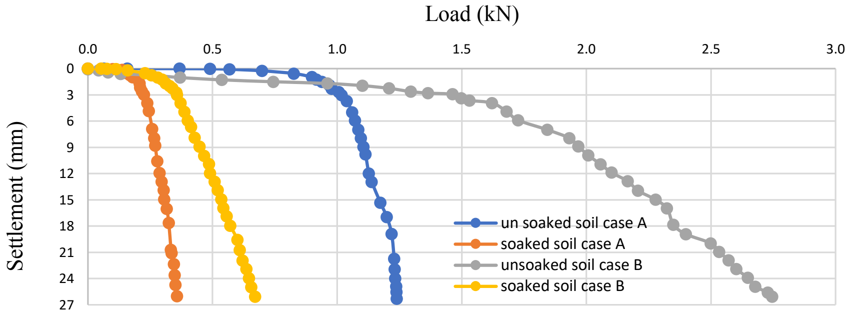

Figure 7: Load-settlement curve for pile with a length of 30 cm and γ=14.6 kN/m³ , embedded in soil case A and soil case B.

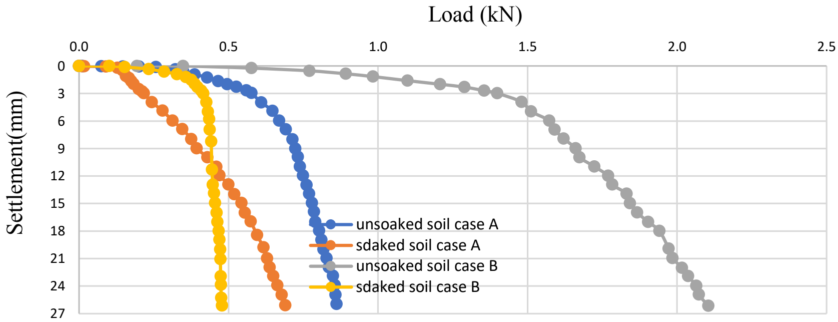

Figure 8: Load-settlement curve for pile with a length of 30 cm and γ=14.8 kN/m³, embedded in soil case A and soil case B.

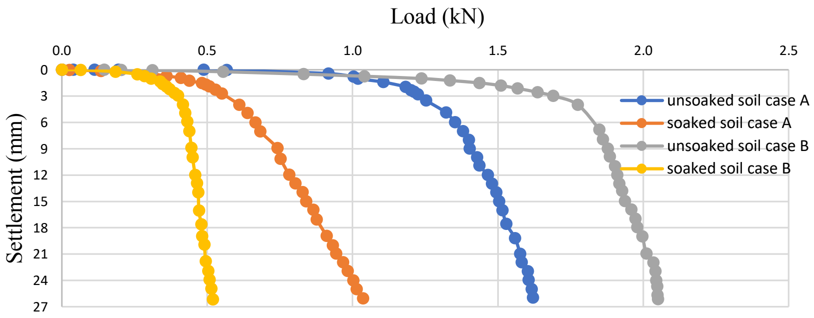

Figure 9: Load-settlement curve for pile with a length of 20 cm and γ=17 kN/m³, embedded in soil case A and soil case B.

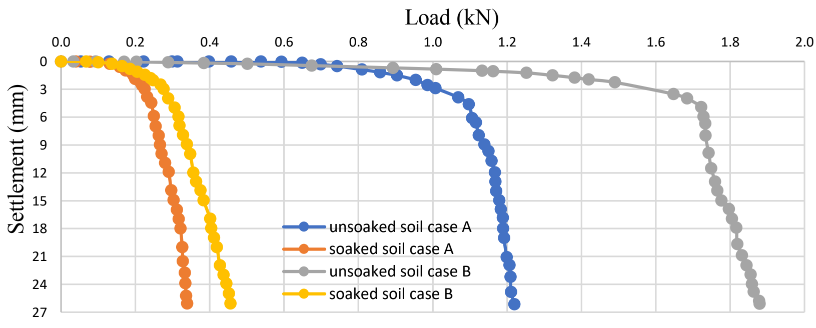

Figure 10: Load-settlement curve for pile with a length of 20 cm and γ=14.6 kN/m³, embedded in soil case A and soil case B.

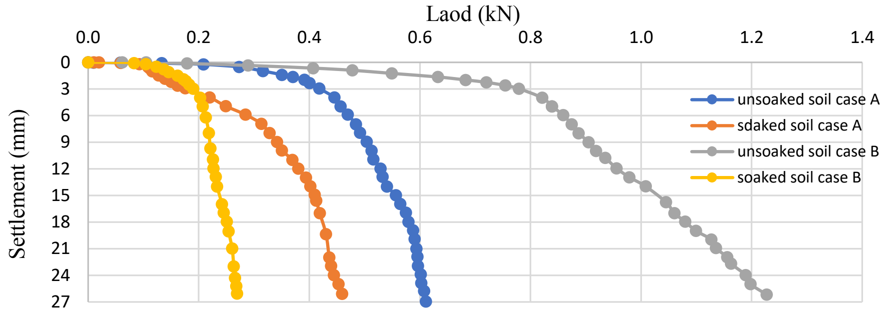

Figure 11: Load-settlement curve for pile with a length of 20 cm and γ=14.8 kN/m^3 , embedded in soil case A and soil case B.

The presented load settlement curves have been adopted to evaluate piles' ultimate load-carrying capacity in the conditions as mentioned earlier. Different criteria have been considered to achieve this evaluation, as discussed in the following section (section 5).

5. FAILURE CRITERIA USED IN THIS STUDY.

The data result from the pile load test for each dry unit weight under both soaked and unsoaked conditions was evaluated using different criteria. These criteria are:

5.1 Davisson Method

It is proposed by Davisson (1972) to estimate failure load, which corresponds to the elastic movement of the pile [20] according to Equation (1):

$$\mathrm{Qult} = 0.15 + \mathrm{D}/120 \quad (1)$$

Where D=diameter of the pile in inches.

5.2 Terzaghi Method

The pile load capacity is equal to the load provided by settlement, equal to 10% of the pile diameter, as determined by the load-settlement curve [21].

5.3 ASTM D-1143 Method

When the pile continues penetrating, the load corresponding to the total pile penetration at least 15 % of the average pile diameter or width can be considered the ultimate load [22].

5.4 De Beer's Yield Load Method

This method was proposed by Dee Beer(1968). The load-movement data is plotted in a double-logarithmic diagram. The intersection point between the logarithm line for the load and the logarithm line of settlement is represented as the failure load [23].

5.5 Brinch Hansen's 80 Percent Method

Hansen, 1963 suggested a definition for pile capacity as the load that gives four times the settlement of the pile head, and it's taken as 80% of that load. This load can be obtained by plotting the settlement against the square root of the settlement divided by its load value [24]; the ultimate load can be calculated from Equation (2) and the ultimate settlement from Equation (3):

$$\mathrm{Qult} = 1/(2 \times \sqrt{\mathrm{C1C2}} \quad (2)$$

$$\Delta\mathrm{u} = \mathrm{C2}/\mathrm{C1} \quad (3)$$

C1 is the slope of the straight line, C2 is the y-intercept of the straight line, and Δu is the ultimate settlement.

5.6 Chin-Kondner Method

Chin-Kondner,1970 proposed this method to estimate the ultimate capacity of the pile. After plotting the curve of the relationship between displacement versus displacement divided by the corresponding load [25], the ultimate load can be calculated from Equation (4):

$$\mathrm{Qult} = 1/\mathrm{C1} \quad (4)$$

Where C1 is the slope of the straight line.

5.7 Decourt Extrapolation Method

Decourt (1999) proposed this method. It was divided by each load with its corresponding settlement and plotted the resulting value versus the applied load. The decourt load was determined from the intersection of the regression line with the load axis [21].

5.8 Brinch Hansen's 90 Percent Method

Hansen's suggested this method by plotting the load settlement curve, finding the load(Qult) and settlement (δ) that gives twice the pile head settlement as obtained for 90 percent of the Qult load; this is a failure load [11].

5.9 Shen's Method (1980)

In this method, the ultimate capacity load of the pile was determined by plotting the log load against the settlement. The result was a curve with a straight line at the tail. At the start of this, a straight line represented the ultimate load [26].

5.10 Fuller and Hoy's Method

The ultimate load capacity in this method was determined by the intersection of the tangent of the curve (load- settlement curve) that had a slope of 0.05 inch/ton with the load axis [27].

5.11 Butler and Hoy's Method

This method is somewhat similar to Fuller and Hoy's Method, where the ultimate load was determined from the intersection point between the tangent of the curve (Load-settlement curve), which has a slope of 0.05 inch/ton with the initial straight portion of the curve [28].

5.12 Mazurkiewicz's Method

Mazurkiewicz (1972) proposed this method, assuming that the shape of the load-settlement curve is a parabola. By drawing vertical parallel lines from the settlement axis, which intersects with a curve, horizontal straight lines are drawn wherever these lines intersect with the vertical load axis, and the line with the angle of 45 degrees is plotted. Finally, the extended straight line that passes through the segments' intersections with the horizontal lines and will intersect with load axes represents the ultimate load capacity [29]. The results of ultimate load capacity according to these failure criteria for each pile were summarized in Table 2 to Table 5 for each pile.

Table 2: Ultimate load capacity(kN) for soil case (A) pile length =30 cm.

Name of method	γ=14.6 kN/m^3		γ=17 kN/m^3		γ=14.8 kN/m^3	
	unsoaked	soaked	unsoaked	soaked	unsoaked	Soaked
Davisson method	1.22	0.33	1.168	1.35	0.32	0.29
Terzaghi method	0.98	0.21	1.28	0.84	0.5	0.19
ASTM D-1143	1.02	0.23	1.4	0.92	0.53	0.22
De Beer method	1.106	0.21	1.43	1.12	0.56	0.2
Brinch Hansen80%	1.44	0.34	1.9	1.32	0.82	0.76
Chin-Kondner	1.235	0.35	1.7	1.39	0.87	0.75
Decourt's Extrapolation	0.77	0.23	0.75	1	0.7	0.27
Shen's method	1.007	0.24	1.62	1.09	0.61	0.47
Brinch Hansen90%	1.23	0.27	1.59	1.34	0.86	0.175
Fuller and Hoy method	1	0.234	2.04	0.4	1.428	0.4
Butller and Fuller	1.623	0.204	1.55	1.08	0.63	0.387
Mazurkiewicz method	1.25	0.387	1.82	1.43	0.9	0.816

Table 3: Ultimate load capacity(kN) for soil case (A) pile length =20 cm.

Name of method	γ=14.6kN/m^3		γ=17kN/m^3		γ=14.8kN/m^3	
	unsoaked	soaked	unsoaked	soaked	unsoaked	soaked
Davisson method	1.19	0.32	1.58	0.91	0.57	0.33
Terzaghi method	0.96	0.2	1.19	0.52	0.38	0.14
ASTM D-1143	1	0.225	1.24	0.56	0.42	0.18
De Beer method	2.03	0.2	1.21	0.55	0.42	0.16
Brinch Hansen80%	1.47	0.324	1.78	0.93	0.6	0.44
Chin-Kondner method	1.2	0.344	1.61	1.03	0.62	0.49
Decourt's extrapolation	1	0.2	1.1	0.7	0.5	0.17
Shen's Method	1.1	0.243	1.2	0.64	0.455	0.36
Brinch Hansen90%	1.1	0.254	1.58	0.74	0.6	0.5
Fuller and Hoy	1.02	0.234	1.27	0.755	0.45	0.346
Butller and Fuller	1.05	0.214	1.29	0.71	0.43	0.306
Mazurkiewicz method	1.45	0.377	1.67	1.12	0.65	0.48

Table 4: Ultimate load capacity (kN) for soil case (B) pile length =30 cm.

Name of method	γ=14.6kN/m³		γ=17kN/m³		γ=14.8kN/m³	
	unsoaked	soaked	unsoaked	soaked	unsoaked	soaked
Davisson	2.52	0.525	2.52	0.47	1.79	0.46
Terzaghi	1.1	0.32	1.4	0.34	1.2	0.38
ASTM D-1143	1.6	0.36	1.65	0.42	1.4	0.42
De Beer	0.96	0.328	1.26	0.344	1.098	0.395
Brinch Hansen80%	3.02	0.587	2.696	0.514	1.098	0.516
Chin-Kondner	2.94	0.658	2.858	0.503	2.083	0.445
Decourt's extrapolation	2.13	0.35	1.8	0.45	1.1	0.3
Shen's Method	1.932	0.387	1.887	0.425	1.51	0.413
Brinch Hansen90%	2.1	0.388	1.887	0.425	1.673	0.425
Fuller and Hoy	2.041	0.326	2.04	0.4	1.428	0.4
Butller and Fuller	1.623	0.326	1.93	0.387	1.326	0.397
Mazurkiewicz	3.06	0.714	3.6	0.51	2.296	0.479

Table 5: Ultimate load capacity(kN) for soil case (B) pile length =20 cm.

Name of method	γ=14.6kN/m³		γ=17kN/m³		γ=14.8kN/m³	
	unsoaked	soaked	unsoaked	soaked	Unsoaked	soaked
Davisson method	1.77	0.38	1.95	0.48	1.07	0.24
Terzaghi method	1.27	0.22	1.5	0.35	0.62	0.17
ASTM D-1143	1.55	0.28	1.7	0.4	0.78	0.19
De Beer method	1.38	0.268	1.69	0.4	0.821	0.203
Brinch Hansen80%	1.917	0.416	2.1	0.5	1.129	0.266
Chin-Kondner	1.886	0.45	2.083	0.515	1.219	0.268
Decourt's extrapolation	0.99	0.46	0.73	0.4	0.88	0.17
Shen's method	1.728	0.318	1.848	0.42	0.838	0.207
Brinch Hansen90%	1.722	0.305	1.774	0.42	0.839	0.207
Fuller and Hoy	1.633	0.285	1.735	0.398	0.816	0.199
Butller and Fuller	1.612	0.265	1.684	0.387	0.765	0.183
Mazurkiewicz method	1.735	0.469	2.143	0.52	1.224	0.295

6. CONCLUSIONS

It is necessary to verification the theoretical equations results used to calculate the ultimate pile capacity in the design process with the many empirical methods used to select the failure criterion by utilizing the load-settlement curve after conducting the pile load test. Hence, the pile load test is an advantageous and basic method for estimating the ultimate bearing capacity of pile foundation and settlement. Through the application of different failure criteria methods to determine the bearing capacity of the pile within the scope of this study:

- Through the load-settlement curve, the effect of gypsum content and dry density plays the main role in the bearing capacity of the pile under different pile dimensions because the gypsum particles act as cementation bonds and fill pore voids but when immersion with water, the gypsum is beginning dissolution, causing a high reduction in volume and strength of soil, leading to the rapid settlement and then reduces in the bearing capacity of the pile.
- The Davisson method, Brinch Hansen's 80 percent, Chin-Kondner, Mazurkiewicz's, and Brinch Hansen's 90 Methods predict a higher value of ultimate pile capacity.
- The Decourt Extrapolation method fluctuated value when comparing the results with each other and gives unreliable values, while Fuller and Hoy's, Butler and Hoy's Method gives values that can be considered still far away from the real value.
- She's, ASTM method, Terzaghi, and DeBeer methods predicted an acceptable and realistic value in soil cases A and B, both in soaked and unsoaked conditions, because the settlement corresponding to the ultimate capacity calculated by these methods is an acceptable value, especially when gypseous soil is inundation with water and exhibited a high reduction in volume.
- Generally, no specific failure criterion would be specified to be used in determining the ultimate capacity of the pile, and several conditions should be taken into consideration, the most important of which is the type of soil and pile, additionally, the experiences of the design engineer can play a main role in determining the suitable failure criterion. In this study, the (15%D) according to(ASTM D-1143) is a very convenient criterion to calculate the maximum loading capacity in this type of soil.

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