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Comparison of Single and Group Bored Piles Settlement Based on Field Test and Theoretical Methods

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ABSTRACT

Bored piles settlement behavior under vertical loaded is the main factor that affects the design requirements of single or group of piles in soft soils. The estimation of bored pile settlement is a complicated problem because it depends upon many factors which may include ground conditions, validation of bored pile design method through testing and validation of theoretical or numerical prediction of the settlement value. In this study, a prototype single and bored pile group model of arrangement (1*1, 1*2 and 2*2) for total length to diameter ratios (L/D) is 13.33 and clear spacing three times of diameter, subjected to vertical axial loads. The bored piles model used for the test was 2000 mm in length, and 150 mm in diameter has been constructed in soft clayey soils. Furthermore, different theoretical methods have been used for the estimation of bored pile settlement, such as Poulos and Vesic's methods and then their comparison with the pile load test data based on the quick pile load test as presented in (ASTM-D1143, 2007). In general, the theoretical method for estimation the bored pile settlement by Poulos and Vesic's gives higher value of the settlement for the single and group bored pile compared to the pile settlement results obtained from field pile load test data. Therefore, it is not recommended to be used for soft clayey soils. On the other hand, Hansen's 90% and Butler and Hoy's results may be considered reliable interpretation method to compute the settlement of single and group bored pile.

Keywords: settlement, single and group bored pile, theoretical analysis. Pile load test.

مقارنة هبوط ركائز الحفر المفردة والمجموعة على أساس الاختبار الحثلي والطرق النظرية

علي ماجد الكناني
طالب دكتوراه

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يعتبر سلوك هبوط ركائز الحفر في ظل التحميل الرأسي هو العامل الرئيسي الذي يؤثر على متطلبات التصميم لركائز الحفر المفردة أو المجموعة في التربة الرخوة. يمثل تقدير هبوط ركائز الحفر مشكلة معقدة لأنه يعتمد على العديد من العوامل التي قد تشمل ظروف الأرض، والتحقق من صحة طريقة تصميم الركائز ومن خلال الاختبار والتحقق من صحة التنبؤ النظري أو العددي لقيمة الهبوط. هذه الورقة تصف اختبار نماذج حقيقية من ركائز الحفر المفردة والمجموعة وبترتيب (1 * 1، 1 * 2 و 2 * 2) لنسب الطول الإجمالي إلى القطر (13.33) وبنسبة تباعد ثلاث مرات قطر الركيزة، معرضة للأحمال المحورية

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العمودية. يبلغ طول نموذج الركيزة المستخدمة في الاختبار 2000 ملم، وقطره 150 ملم وقد تم تشييده في تربة طينية. علاوة على ذلك، استخدمت طرقاً نظرية مختلفة لتقدير هبوط ركائز الحفر، مثل طرق Vesic و Poulos ثم مقارنة هذه النتائج بنتائج اختبار تحميل الركائز استناداً إلى فحص التحميل السريع كما هو موضح في المواصفة ASTM-D1143-07. بصورة عامة، الطريقة النظرية لتقدير هبوط الركائز المقدمة من قبل Vesic's و Poulos تعطي قيمة أعلى للهبوط بالنسبة للركائز الفردية والمجموعة بالمقارنة بحسابات الهبوط التي تم الحصول عليها من بيانات اختبار التحميل الحقلية. من أجل ذلك، لا ينصح باستخدامها في التربة الطينية الرخوة. من ناحية أخرى، أعطى Hansen's 90 % و Butler و Hoy's نتائج أوثق لبعضهما البعض، ويمكن اعتبارهما أساليب تفسير أمينه لحساب هبوط ركائز الحفر المفردة والمجموعة. الكلمات الرئيسية: الهبوط، ركائز حفر مفردة ومجموعة، تحليل نظري. اختبار التحمل لركائز الحفر المفردة والمجموعة.

1. INTRODUCTION

The existing subsoil on a particular site might not be adequate for supporting the superstructure, buildings, dams, bridges, and because of the bearing capacity or may not be safe to support the given load. The Pile Foundation is one of the most general shapes of the foundation. A deep foundation is usually used for construction on weak soils that are characterized by low shear strength and high compressibility, and on good soil when the structure experiences heavy loads and moments (El-Mossallamy, 1999). Vertical Pile is usually designed to resist axial loads that generally work on piles head by creating shaft resistance (SR) and base resistance (BR) (Lee, and Charles, 2004).

There are many methods for estimating the settlement of deep foundations, empirical, simple hand calculation methods, complex finite difference, and numerical finite element analyses. Clay deformation is affected by an increase in the load where the external load works. If there is a soft thickening layer beneath the pile base, the pile group will undergo essential settlements, while the single pile settlement remains nearly unaffected by the compressible layer (Poulos, 2005). The impact of the compressible layer on the settlement is usually convenient for increasing the number of the pile in the group, because of the interaction of neighboring piles; the pile group's conductance of under the loads is always a different form of the single pile (Poulos, 2005). The general behavior of a pile group is related to efficiency. (Khari, et al., 2013) explained that an increase in the number of piles in-group decreases the group efficiency owing to the increasing of overlapped stress zones and active wedge. (Ivšić, et al. 2013) studied the assessment of empirical equation and in-situ pile load test conducted to calculate bearing capacity and settlement of bored piles in soft soils. (Deb, et al., 2016) explained that the behavior of pile groups under the applied loads is generally different from that of a single pile due to the interaction of neighboring piles. On the other hand, the increase in the number of piles in-group decreased group efficiency due to the increased overlapping regions and effective wedges. (Arham, and Mujtaba, 2017) explained that the best approach of evaluation pile capacity and settlement is interpretation results of Hansen 90% method because of the equivalent accurate values and reliable for cohesive soils. This paper presents different methods of estimating bored pile settlement based on theoretical methods (based on Vesic and Poulos) and their comparison with pile settlement evaluated from pile load test data on cast-in-situ single and group bored piles constructed in Al Nasiriyah city.

2. FIELD INVESTIGATION AND SOIL SAMPLING

The site of the conducted study was located at the distance 100 m on the right bank of the Euphrates River, in Al Nasiriyah city 375 Km southeast of Baghdad, Fig. 1. The site investigation included drilling borehole 10 m in length, carrying out in situ SPT and performing the laboratory testing of the repressive soil samples as shown in Fig. 2. The engineering properties of the soil are represented in Table 1 to Table 4.

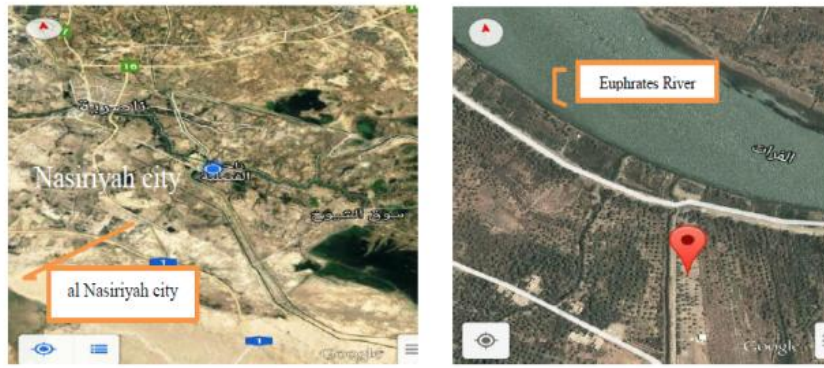


Figure 1. Site location.

Table 1. Results for corrected SPT at the specified depth.

Depth (m)	SPT
1.0-1.5	5
5.5-6.0	7
7.5-8	8

Table 2. Soil description and classification.

Depth (m)	Water table (m) from the top of B.H	γ_{wet} kN/m ³	Particle Size Distribution		USCS
			Clay %	Silt %	
0.0-1.0	0.75	----	----	----	Fill
2.0-2.5		20.48	61	39	CL
2.5-3.0		21.02	70	30	CH
3.5-4.0		21.98	72	28	CH
4.5-7.5		21.5	60	40	CL
7.5-8.0		23.4	62	38	CL

Table 3. Results of undrained shear strength.

Depth (m)	$q_{unconfined}$ (kPa)	c_u (kPa)
1.5-2.0	73	36
2.5-3.0	42	21
3.5-4.0	76	38
4.5-5.0	86	43

Table 4. Soil properties.

Depth (m)	Sample Type	L.L %	P.L %	P.I%	G.s
0-1	D.S	32	15	17	2.51
1.5-2.0	U.S	34	19	15	2.62
2.5-3.0	U.S	60	29	31	2.78
3.5-4.0	U.S	59	30	29	2.76
4.5-5.0	U.S	35	21	14	2.58
8.0-10.0	D.S	36	21	15	2.61

3. FIELDWORK OF BORED PILE CONSTRUCTION

Method of bored piling that includes boring the borehole into the soil, and after that, introducing steel reinforcement and casting the concrete to make a pile. The drilling of the bored pile is usually done using a rotary drilling machine. The field rotary drill machine consists of the rotary drill through the drilling bucket then by the rig hoisting device and drill rod of the drilling bucket dumping hole is proposed, so the cycle, constantly borrows dump, until the drill to the design depth. The borehole was drilled mechanically by a spiral-plate with a shaft diameter 150 (mm) joined with the cutting ring, to assist the cutter in clays, a little water may be added to the borehole. On the other hand, the fieldwork program consists of seven piles represented in single and two pile groups; the first one consists of (1*2) pile and the second consists of (2*2) pile as shown in **Fig. 3**. Many limits influenced the depth and diameter of bored piles such as mechanical requirements of the boring machine and the length to width ratio (L/D). The processes of construction of bored pile involve boring a circular borehole into the soil with 150(mm) in diameter and 2000(mm) in length, and then installing Steel reinforcement cage is made from main longitudinal bars 6 Ø10 mm, overfull pile length and transverse bars Ø8 (mm) in step 0.15 m. The details of steel reinforcement are based on (ACI-318, 2014).



Figure 2. Field investigation.



Figure 3. Construction steps of bored pile.

4. EVALUATION OF THE PILE LOAD TEST RESULTS BASED TO INTERPRETATION METHODS

To compare the total settlement results of the pile load test for bored pile, three methods were used to estimate the amount of settlement in the bored pile based on the results obtained by the vertical loading test. In general, no specific method or criteria that can clearly describe the total settlement. In other words, these methods, include settlement requirements, mathematical and graphical methods for calculations (Prakash, and Shama, 1990).

4.1 Brinch Hansen's 90% Method (1963)

This method is based on trial and error and settlement limitations. This method has represented the relationship between load and movement; the ultimate bearing capacity is given the twice movement of the pile head as represented by 90% of the ultimate bearing capacity.

4.2 Butler and Hoy's Method (1977)

The failure load of the pile is defined as the load at the intersection of a line tangent to the initial straight-line portion of the load-settlement curve intersection with a line tangent to the load-settlement curve where the slope of the line reaches 0.05 inches/ton. This method is applicable for the quick pile load test.

4.3 Fuller and Hoy's Method (1970)

This method is based on settlement limitations. The failure load of pile is defined as the load at the intersection of the tangent of the load - settlement sloping off at 0.05 inches/ton with tangent parallel elastic line. This method is applicable for the quick pile load test. Therefore, the mathematical representation of settlement based on the ultimate load defined in interpretation methods as explained in Fig.4.

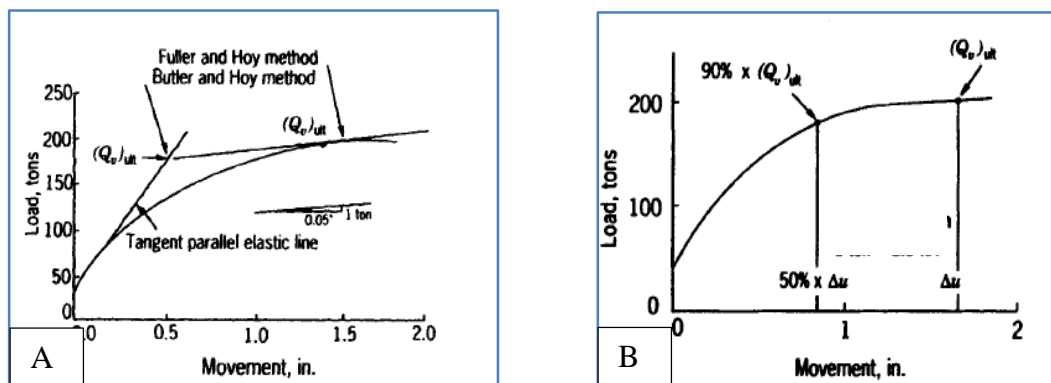


Figure 4. Interpretation methods of pile load Test, (A) Hansen's 90% Method, and (B) Fuller and Hoy's and Butler and Hoy's methods (after Prakash and Shama, 1990).

5. PILE AND PILE GROUP SETTLEMENT

Most deep foundations requirements for the designing method will have the total accepted settlements of no more than about 12 mm. Therefore, many engineers often do not practice any settlement calculations for pile or group pile foundation, so the engineer must have the ability to recognize and calculate them. The total settlement estimations of a single pile and pile group are consisting of the elastic settlement of a single pile and consolidation settlement below the pile group. Furthermore, the elastic settlement of single pile always related to many factors, such as;

the relative stiffness of the pile material and the surrounding soil ($K_{ps} = E_p/E_s$), the ratio between length to diameter ratio (L/D). In other words, the relative stiffness of the base (E_{sb}) and over the pile length and the modulus of elasticity of the soil and distribution ranges along the depth of the pile. Therefore, various methods have been proposed to analyze and calculate the total settlement for the single pile and pile group as described by

A- Method 1: as described by (Budhu, 2011):

1- (Poulos, 1989) as cited by (Budhu, 2011) explained an excellent discussion to calculate settlement based on various numerical procedures, the total settlement of a single pile consists of Settlement based on Skin friction as explained in Eq. (1):

$$I = \frac{\text{noitcirflla}Q}{L \cdot sE} = SE^{\rho} \tag{1}$$

$$I = 0.5 + \log\left(\frac{L}{D}\right)$$

2- (Poulos, 1989) developed an estimation for elastic settlement for floating pile as explained in Eq. (2):

$$\rho_{ES} = \frac{Q_{all\ friction}}{E_s \cdot D} \cdot I_p \tag{2}$$

I_p : influence factor is influenced by the L/D and K_{ps} , as shown in Fig5.

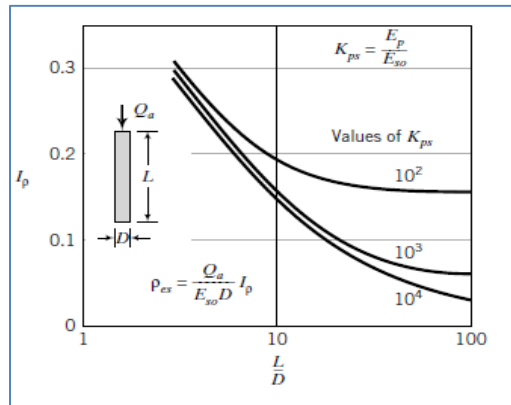


Figure 4. Influence factor for vertical settlement of a single floating pile (after Poulos, 1989 as cited by Budhu, 2011).

A- Settlement based on end bearing assuming the pile base is a rigid and punches on the surface of the soil transferred at a depth. The base settlement based on (Timoshenko, and Groodier, 1970) is explained in Eq.(3):

$$\rho_b = \frac{Q_{base}}{r_b \cdot G_b} \cdot \frac{1-\nu}{4} \tag{3}$$

Where; ν , Poisson’s ratio of soil, r_b and G_b are the radius and shear modulus at the base.

B- The Elastic shortening of the single pile is presented in Eq.(4):

$$\rho = C \cdot \frac{Q_{all\ friction}}{E_p \cdot A_p} \tag{4}$$



Where; **C** is the reduction factor ($C \approx 0.5$ for most soil, and $C \approx 0.7$ for soft soil). The shortening settlement calculates only when ($E_p/E_s < 500$). The total elastic settlement can be shown in Eq. (5);

$$\rho_{ET} = \rho_{ES} + \rho_b + \rho_p \tag{5}$$

C- Pile group settlement calculations based on the settlement of single pile through a group the settlement factor **Rs**, as;

$$Rs = \frac{\text{settlement of group}}{\text{settlement of single pile at same average load}}$$

(Fleming, et al., 1985) given an empirical solution of **Rs**:

$$Rs = n^\phi$$

where : $\phi = (0.4 - 0.6)$, **n** = number of the pile in the group

D- Consolidation settlement under the pile group based on the pile group may be embedded in soft soil and transfer the load causes consolidation settlement, the full load design act at depth $2/3 L$ and the distribution according to the 2:1.

2- (DAS, 2011) explained that the total settlement of single pile caused by a vertical working load is:

$$S_{Est} = S_{E1} + S_{E2} + S_{E3}$$

Where: (**S_{E1}**) elastic settlement of the pile, (**S_{E2}**) settlement caused by the vertical load at the pile tip, (**S_{E3}**) settlement caused by the transmitted the load along the pile shaft. The total settlement can be represented in Eq. (6, 7 and 8):

$$S_{E1} = \frac{(Q_{wp} + \xi Q_{ws})L}{A_p \cdot E_p} \tag{6} \quad S_{E2} =$$

$$\frac{(Q_{wp} D)(1 - \mu_s^2) I_{wp}}{E_s} \tag{7}$$

$$S_{E3} = \frac{(Q_{ws} D)(1 - \mu_s^2) I_{ws}}{P \cdot L \cdot E_s} \tag{8}$$

Vesic, 1977, also, explained another semi-empirical solution to obtain the magnitude of the settlement as in Eq. (9&10).

$$S_{E2} = \frac{Q_{wp} \cdot C_p}{D \cdot q_p} \tag{9}$$

$$S_{E3} = \frac{Q_{ws} \cdot C_s}{L \cdot q_p} \tag{10}$$

Where: **Q_{wp}**: load carried at the pile point, **Q_{ws}**: load carried by frictional (skin) resistance, **A_p**: area of cross-section of pile, **L**: length of pile, **E_p**: modulus of elasticity of the pile material, **ξ**: The magnitude of varies between 0.5 and 0.67 and will depend on the nature of the distribution of the unit friction resistance along the pile shaft, **D**: diameter of pile, **Q_{wp}**: point load per unit area at the pile = Q_{wp}/A_p , **E_s**: modulus of elasticity of soil at or below the pile point, **μ_s**: Poisson's ratio of soil, **I_{wp}**: influence factor = 0.85, **q_p**: point resistance of the pile, **C_p**: empirical coefficient. Representative values for various soils are given below, **P**: perimeter of the pile, **L**: length of pile, **I_{ws}**: influence factor = $2 + 0.35 (L/D)^{0.5}$, **C_s**: an empirical constant = $(0.93 + 0.16(L/D)^{0.5})$. **C_p**: values (0.03-0.06) for bored pile. In general, a group pile elastic settlement at a similar working load on each pile increases with the width of the group

(B_g) and the center-to-center spacing of the piles (d). The simplest relation for the settlement of group piles was given by Vesic, Eq. (11) (Budhu, 2011):

$$S_e(G) = (B_g/d)^{0.5} \cdot S_e(\text{single pile}) \quad (11)$$

B_g : width of pile group.

The consolidation settlement of a group pile in clay can be estimated by using the 2:1 stress distribution method. The elastic pile settlement, E_p , is determined according to the cubic compressive strength F_c (for $F_c = 39\text{MPa}$, $E_p=27000\text{ MPa}$), the modulus of soil is equals ($E_s=9000$), Poisson ratio for soft clay soil, $\nu =0.5$.

6. PILE LOAD TEST RESULTS OF BORED PILE

The field method for pile settlement estimation is more reliable than estimates based on empirical methods because of the pile is being tested under the conditions which they are used, Thus the test results are a direct consequence of the soil-pile interaction. The field pile load test represented by three pile load tests for single and group were performed at the site. The procedure of test followed the Quick pile load test procedure presented in (ASTM-D1143, 2007). In performing a pile load test, two settlement dial gauges were used to record the vertical settlement of the pile. The dial gauges were connected to the references beam. The arrangement of the load reaction consisted of a platform of iron H-beam section, the end of platform rested over timber grabbing and then overreaction support, the applied load on the head of pile consist of a load of platform and a dead load of heavy material (a kentledge) were supplied by using a concrete blocks, Fig.6 .

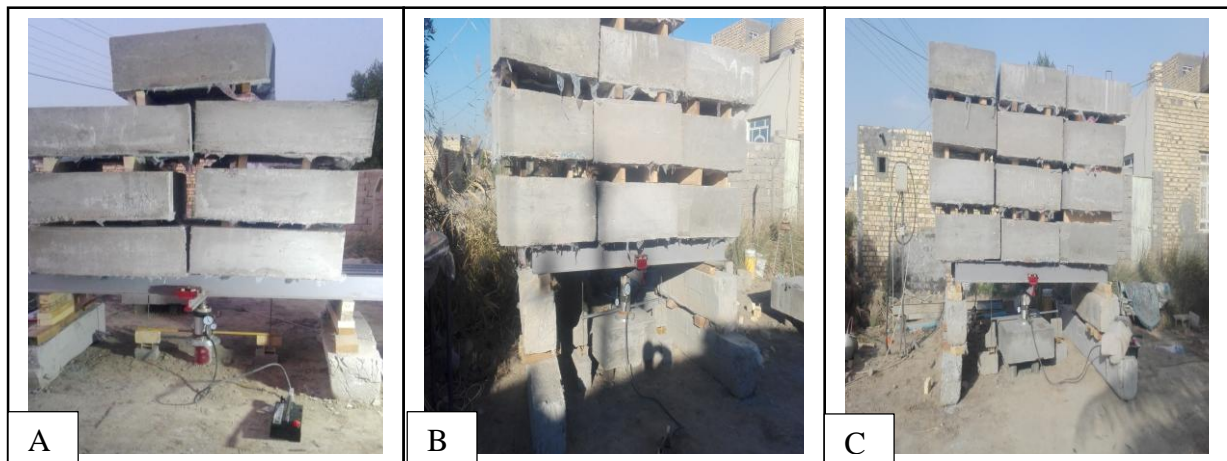


Figure 5. Pile load test for: A; single, B; Group (1*2) and C; Group (2*2) bored pile.

The results of the load-settlement curve of single and group bored pile can illustrate in Fig.7. The total settlement for each casing of the bored pile load - settlements relationships are listed in Table 5, A comparison was made between measured settlement and total settlement of single and group bored pile has lasted in Table 6 From Fig.7, it can be seen that the total head settlement increased with increasing the number of piles in the group.

- The total settlement values estimated by the interpretation estimation by Hansen's and Butler method had given closer value for single and group pile when compared with each other, while



Fuller and Hoy had given an overestimated value single and group pile when compared with to Hansen’s and Butler method.

- The total settlement values estimated by the interpretation estimation by Hansen’s and Butler method had given underestimation when compared with measured settlement by Poulos and Vesic for single and group pile.
- The measured settlement values based on the Poulos method had given acceptable values when compared with Vesic.

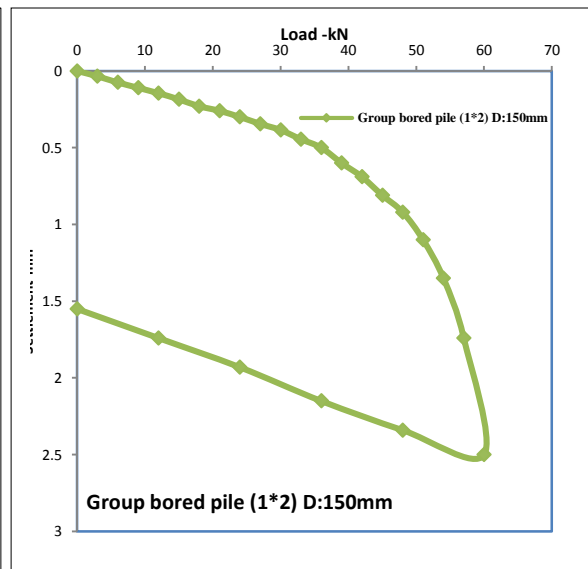
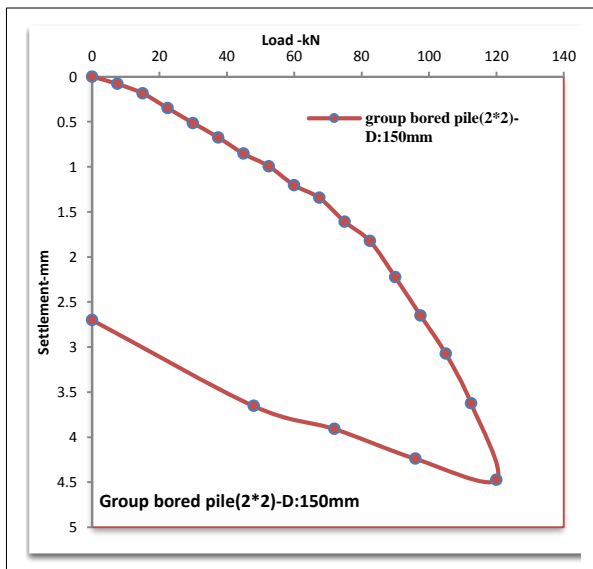
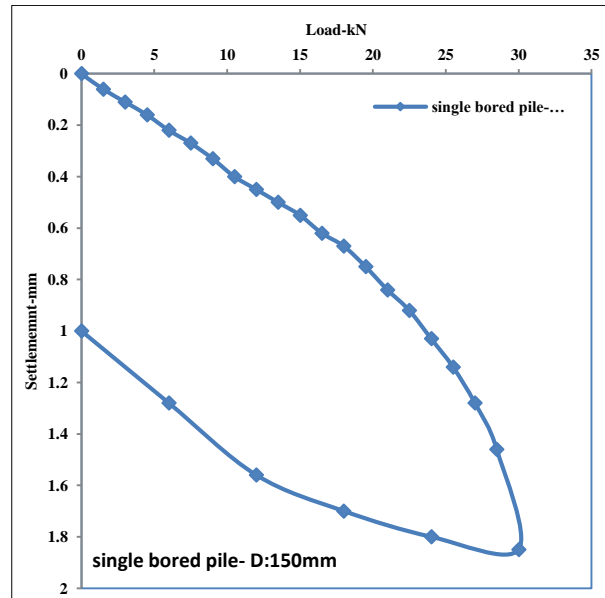


Figure 6. Load settlement curves of single and groups bored pile (S/D=3).



Table 5. Summary of total settlement of bored pile (d=150mm) from pile load test.

Single Bored Pile		
Interpretation of Pile Load Test	Ultimate pile Capacity-kN	Settlement (mm)
Hansen's 90% Method (1963)	21	0.84
Butler and Hoy's Method (1977)	25	0.9
Fuller and Hoy's Method (1970)	25.6	1.4
Group of Bored Pile (1*2)		
Interpretation of Pile Load Test	Ultimate pile Capacity-kN	Settlement (mm)
Hansen's 90% Method (1963)	48.6	1
Butler and Hoy's Method (1977)	49	1
Fuller and Hoy's Method (1970)	45	1.5
Group of Bored Pile (2*2)		
Interpretation of Pile Load Test	Ultimate pile Capacity-kN	Settlement (mm)
Hansen's 90% Method (1963)	81	2.2
Butler and Hoy's Method (1977)	91	1.9
Fuller and Hoy's Method (1970)	73	3.5

Table 6. Summary of Calculated Settlement and Measured Settlement of Bored Pile.

Pile references	Hansen's 90% Method (mm)	Butler and Hoy's (mm)	Fuller and Hoy's (mm)	Poulos (1989)		Das based on Vesic (1977, 1969)	
				Settlement-mm	Load-kN	Settlement-mm	Load-kN
Single Bored Pile	0.84	0.9	1.4	1.35	20	2.3	20
Group (1*2) Bored Pile	1	1	1.5	3.4	40	3.4	40
Group (2*2) Bored Pile	2.2	1.9	3.5	4.68	80	6.1	80

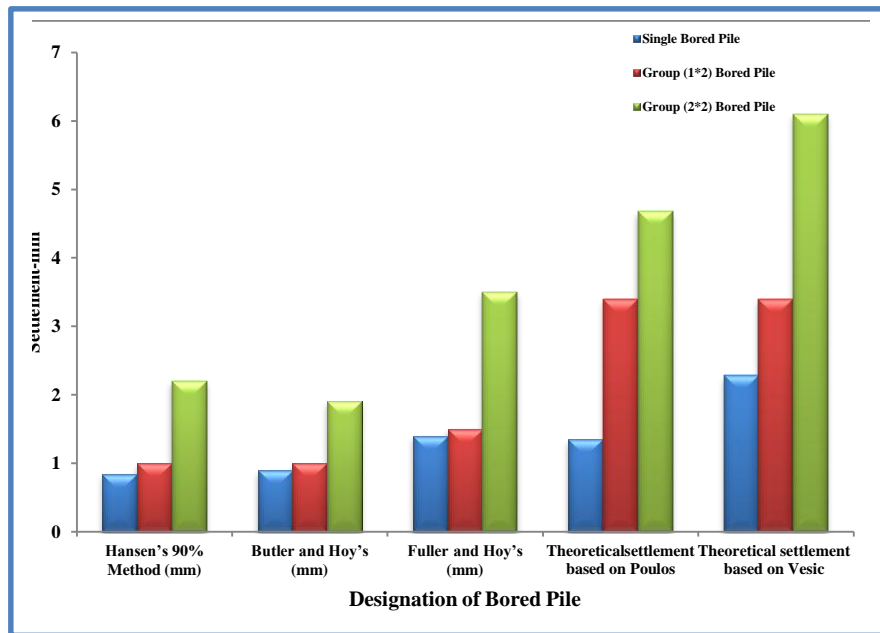


Figure 7. Comparison of field and theoretical settlement of bored pile.

7. COMPARISON OF INTERPRETED AND MEASURED SETTLEMENT

To compare the interpreted total settlement and measured settlement based on Poulos and Vesic, the ratio of interpreted total to measured settlement (S_t/S_m), expressed in percent, were plotted in histograms forms from **Fig.9** to **Fig.14** for single and group bored pile. The line 100% of Poulos and Vesic represents a basis for comparison, the value of (S_t/S_m) higher than 100% indicate to overestimation, whereas, lower than 100% indicates an underestimation of the total settlement, from the figures, it may be noted that:

- The settlement of a single bored pile estimation by Fuller and Hoy's Method had given closer value to measured value by Poulos about 104%, while the based Vesic method had given underestimation about 61%.
- The Hansen and Butler methods are given an underestimation of total settlement when compared with all measured values for single and group pile.
- The settlement of group (1*2) bored pile estimation by Fuller and Hoy's Method had given underestimation value to measure value by Poulos and Vesic about 44%.

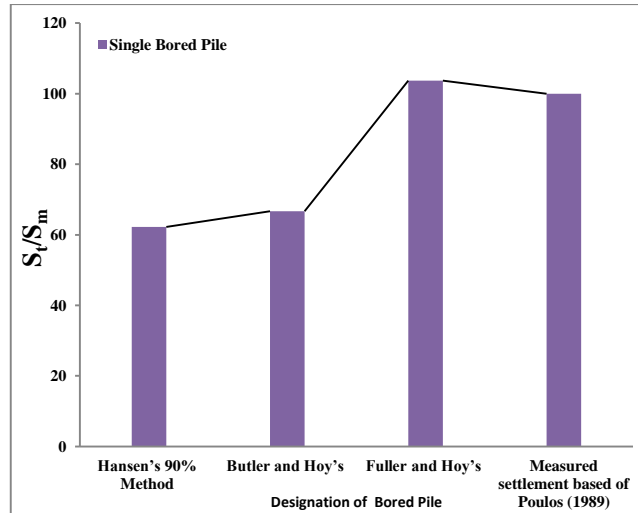


Figure 8. Percentage of S_t/S_m for comparison interpreted total and measured settlement based on Poulos (1989) for single Bored pile.

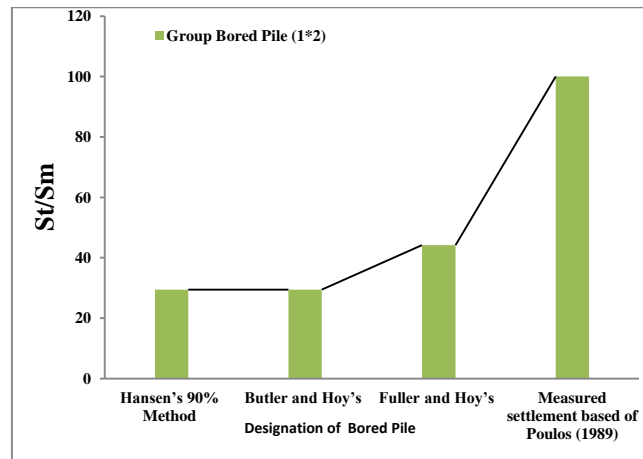


Figure 9. Percentage of S_t/S_m for comparison interpreted total and measured settlement based on Poulos, for the group (1*2) bored pile.

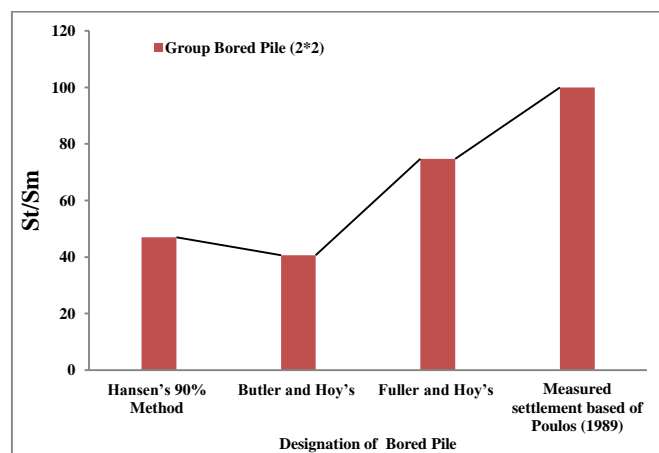


Figure 10. Percentage of S_t/S_m for comparison interpreted total and measured Settlement based on Poulos for (2*2) group Bored Pile

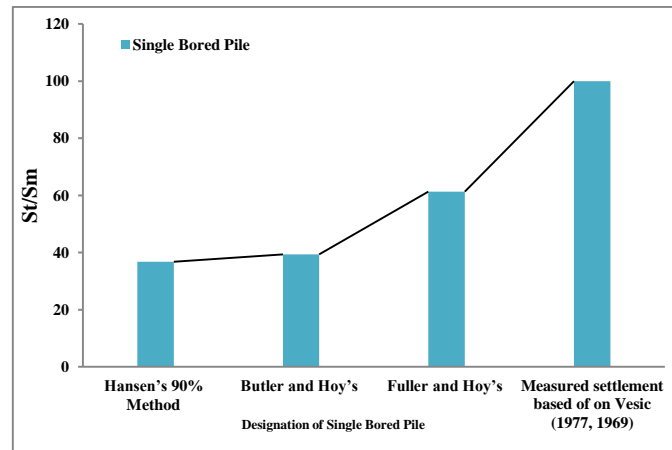


Figure 11. Percentage of S_t/S_m for comparison interpreted total and measured settlement based on Vesic (1977) for single Bored pile.

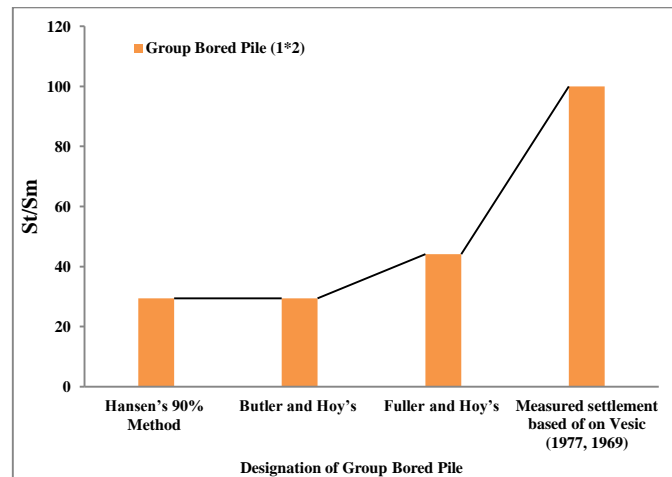


Figure 12. Percentage of S_t/S_m for comparison interpreted total and measured settlement based on Vesic (1977) for (1*2) group Bored pile.

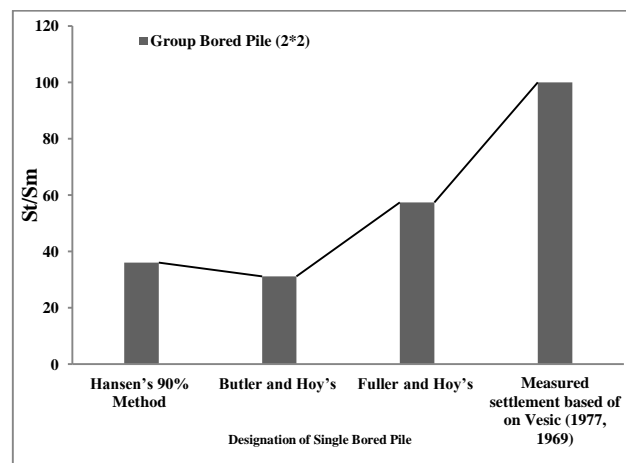


Figure 13. Percentage of S_t/S_m for comparison interpreted total and measured settlement based on Vesic for the group (2*2) Bored pile.



8. CONCLUSIONS

The analysis of deep foundation settlement was performed employing most widely used standards and approaches. To compare the results of the pile load test for bored Pile settlement, three selected interpretation methods such as Hansen's 90%, Butler and Hoy's and Fuller and Hoy's were chosen to examine their accuracy for calculating settlement. According to the pile load test analysis, it has been exposed that the bored pile settlement increase with increase in the number of piles. The comparative analysis results of methods indicate that the settlement values are similar for interpreted Hansen's 90% and Butler and Hoy's methods for the single and the group pile while the largest value of bored pile settlement was obtained based on the Vesic's theoretical methods. The reliable results of pile settlements were obtained from Fuller and Hoy's, and Poulos method of a single pile. At last, the best way for computation and prediction of bored pile settlement in soft clayey soils is a pile load test and use the average value of the settlement from the adequate interpretation methods.

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