Comparison between piles theoretical and actual settlements

Mohammad Mamon Hamdan

Abstract - **This paper compares the actual settlement of the pile foundation with the anticipated theoretical settlement computed using various methods. The piles under investigation were constructed to support a bridge structure and they are cast-in-situ piles. The bridge structure is supported by three groups of piles with pile lengths ranging from 11 m to 14 m and a diameter of 1.20 m. Detailed geotechnical investigations were performed to determine the soil's mechanical and chemical properties. Moreover, four piles were loaded statically to verify the viability of the design. kentledge method for testing was used, the concrete block was used as a counterweight and the main load was generated by the use of Hydraulic jacks, the settlement of piles recorded for each load increment. Four strain gauges were used to record the settlement of piles.**

The estimation of pile foundation theoretical settlement is performed by the use of various equations suggested by each method. The soil parameters incorporated in these equations are taken from the geotechnical report. Three boreholes were drilled at three different locations to collect soil samples, both disturb and un-disturb samples collected at various depths. Then all the samples were collected and tested to determine soil classification and the important parameters and properties of soil and rock such as unconfined compressive strength, particle size distribution, etc. Therefore, the parameters used for determining pile theoretical settlement are considerably precise, reliable, and represent the site condition.

1. Introduction

Foundations' main function is to transfer the structure loads into soil safely without excessive settlement. Selecting the proper type and size of foundation will guarantee the safety and stability of the structure. The magnitude of structure loads and soil type are the main factors in determining the size and type of the foundation. The settlement of the foundation should be considered carefully. Settlement of foundations should not cause excessive distortion or damage to the structure. This paper will compare the theoretical and actual settlement of four piles, constructed as a part of group piles in the gulf region-UAE in 2019. Precise estimation of pile foundation settlement is significantly important and it should not be ignored for any reason. This paper will include the following sections:

- Briefly describe the method used for soil exploration and the soil profile at the work zone
- Determining the bearing capacity for pile under-investigation
- Method of verifying piles capacity at the site
- Computing the immediate settlements for pile foundation by the use of four different methods and then comparing the results with actual results obtained from the pile static load test.

The piles were designed to carry the load of a bridge composed of two carriageways, each carriageway has four lanes. The pile capacity was determined for both frictional and end bearing resistance to verify the adequacy of the proposed pile length and diameter considering a factor of safety more than 2.5. The safety factor is essential to account for uncertainties in pile design that may arise due to discrepancies in soil properties, quality of pile material, construction method, and workmanship. Also, it is crucial to limit pile settlement and differential settlement to allowable limits. Moreover, a factor of safety should be increased if the soil parameters are unknown and no testing is done for the pile to verify their capacity.

The verifying of the adequacy of bearing capacity for investigated piles was based on structure loads, soil properties, pile settlement, and a minimum factor of safety. The result was two groups of piles with 11 m and 14 m in length and 1.20 m in diameter. Another method used for verifying the pile load capacity was conducting a load test for a trial pile before constructing the working piles. Testing a trial pile can be very helpful in scrutinizing the quality of pile design and even the construction procedure to enable design modification or changing the construction method in case of any deviation from the allowable settlements.

The pile settlement consists of three parts: side friction, base capacity, and shortening of the concrete shaft. Piles studied in this paper are subjected to loads that lesser than the side friction capacity. Therefore, the settlement of these piles will consist of two components side friction and shortening of the concrete shaft only. Four methods for calculating settlement have been utilized in this paper and all the results are presented in table no:8.

2. ***Geotechnical investigation and soil classification at the work zone***

A detailed geotechnical investigation has been carried out to provide a clear image of the soil and rock profile and properties of the pilling zone. The information provided by the geotechnical investigation assisted the engineer to provide a reliable, safe, and economic design for the structure foundation. Conducting soil investigation enable engineer to estimate the pile bearing capacity and settlement based on data retrieved from geotechnical investigation and tests conducted on collected samples. The rotary drilling method has been used for geotechnical investigation. A total number of three boreholes with a 25-meter depth were drilled, and the drilling tube has a diameter of 150 mm equipped with a double tube core barrels' sampler. The soil and rock samples were recovered at various depths, the collected soil or rock samples were labeled and preserved in a suitable plastic container to prevent moisture loss.

The collected soil and rock samples were tested at the laboratory for particle Size Distribution, uni-axial Compressive Strength (qu), moisture content, chloride Content (Cl) of Soil/Water, sulphate Content (SO3) of Soil/water, and pH Determination of Soil/Water. Moreover, a standard penetration test (SPT) was performed for the three boreholes, the value "N" which is the number of blows is indicative of the site relative density of soil. The soil exploration findings reveal the following subsurface geological layers:

- Depth of 0 m to 2.00 m: fine to medium sand (Medium dense).
- Depth of 2:00 m to 4:00 m: fine to medium sand (Very dense).
- Depth of 4:00 m to 12:00 m: Very Weak, fine to medium-grained sandstone.
- Depth of 12:00 m to 18:00 m: Very Weak, fine-grained Mudstone.
- Depth of 18:00 m to 25:00 m: Weak, crystalline gypsum.

The required soil parameters for the calculation of pile-bearing capacity and settlement are presented in table: 1. The values are given in table: 1 for each pile group are taken from the geotechnical investigation report.

Table 1

Pile no	qun-Mpa	Cu=0.5*qun	Rock socket-m
1	2.06	1.03	9.8
2	2.43	1.21	7.50
3	2.17	1.085	13.5
4	2.06	1.03	7.50

3. ***Pile-bearing capacity***

The pile's ultimate bearing capacity is reached when settlement increased with no further increase of loads or when the settlement increased at a higher rate than normal. The pile foundation transfers the loads by two mechanisms: side friction and end-bearing resistance. Side friction resistance is generated by the interaction between pile material and surrounding soil, therefore, it will depend on several factors such as soil properties, pile size, and length. The second mechanism transfers the loads from the pile end to beneath rock or soil. Therefore, pile-bearing capacity compose of two components side friction and end bearing.

The pile-side skin resistance can be estimated by the use of the following equation [6]:

$$Qs = \alpha * Cu * Asu$$

Where α is adhesion factor = 0.38 for bored piles, Cu is the undrained shear strength of soil and Asu is the surface area of the shaft. Using the information provided from the geotechnical investigation which is presented in table no:1. The side skin resistance for pile no:1 Qs=0.38*1.03*36926400=14452992 N =14453 Kn. Similarly, the skin resistance can be calculated for the remaining piles and the results are presented in table no:2. For pile end bearing resistance, the following equation can be used [6]:

$$Qb = Cu * Nc * Ap$$

Where Nc equals 9.0 as per Skempton and Ap is the cross-section area of the pile. For pile no:1, the end bearing capacity is Qb=1.03*9*1130400=10478808 N = 10479 Kn. The total bearing capacity for pile no:1 is the sum of skin friction resistance and end bearing resistance which is equal to 24932 Kn. All the results of skin resistance, end-bearing capacity, and total pile-bearing capacity are presented in table no:2.

Table 2

Pile no	As-mm2	Asu-mm2	Skin resistance-Kn	End bearing-Kn	Qtotal
1	1130400	36926400	14453	10479	24932 Kn
2	1130400	28260000	12994	12310	25304 Kn
3	1130400	50868000	20973	11038	32022 Kn
4	1130400	28260000	11060	10478	21538 Kn

The designer should always consider an appropriate factor of safety. The factor of safety is important to account for uncertainties in anticipated load, construction mistakes, and uncertainties in pile material and soil properties. The factor of safety is computed simply by the use of the following equation:

$$Factor\ of\ safety = \frac{Pile\ bearing\ capcity}{Pile\ working\ load}$$

The minimum recommended factor of safety is 2.5 [4] to produce a safe reliable design. Table no:3 present the pile's factor of safety. All the investigated piles have a factor of safety larger than required (2.50). The high value of the safety factor indicates that the expected settlement for these piles is small and within the allowable limit. Moreover, the high safety factor suggests that the pile is overdesigned and the length can be reduced slightly.

Table 3

Pile no	Testing Load-Kn	Qtotal	F.s
1	6200	24932 Kn	4.00
2	6200	25304 Kn	4.00
3	9300	32022 Kn	3.50
4	8200	21538 Kn	2.63

Load	Maximum time of holding load
25% DVL	30 minutes
50% DVL	30 minutes
75% DVL	30 minutes
100% DVL	6 hours
75% DVL	10 minutes
50% DVL	10 minutes
25% DVL	10 minutes
0	1 hour
100% DVL	1 hour
100% DVL + 25% SWL	1 hour
100% DVL + 50% SWL	6 hours
100% DVL + 25% SWL	10 minutes
100% DVL	10 minutes
75% DVL	10 minutes
50% DVL	10 minutes
25% DVL	10 minutes
0	1 hour

4. *Verification of pile design at the site (Pile load test)*

Another method that can be used to verify the pile bearing capacity is the pile load test. The maintained load test (ML) is the common testing method for piles at construction sites. In this method, the pile is loaded in increments and the load is maintained for a predetermined period or until the settlement rate is less than 0.25 mm/hr. Initially, a trial pile can be tested to verify the design before constructing structure piles (working piles). The test load for the trial pile is twice the working load while for working piles the test load is 1.5 for the working load. Sometimes the magnitude of the testing load varies for different countries and different local codes and specifications. Piles no:1, 2 &3 is a working pile while pile no:4 is a trial pile.

Table 4

Compression load tests conducted for piles no:1 to 4 were successful and all piles undergo minimal settlement of less than 1.0% of pile width (12.00 mm). The largest settlement of 2.58 mm was measured for pile no:04 and it is logical because the test load for this pile is larger than other piles of the same group (same length and diameter). The residual settlement after removing the load was low and approaching zero which is within the allowable range.

Table 5

Pile	Actual

Figure no:1 shows the arrangement for a pile load test. Simply, a hydraulic jack is needed to exert a specified load on the pile, a pressure gauge to measure the amount of load transferred to a pile, a counter-load such as a concrete block or a reaction system to hold the hydraulic jack in place, and strain gauge to measure the settlement of piles at different intervals. All equipment and tools should be calibrated for accurate results.

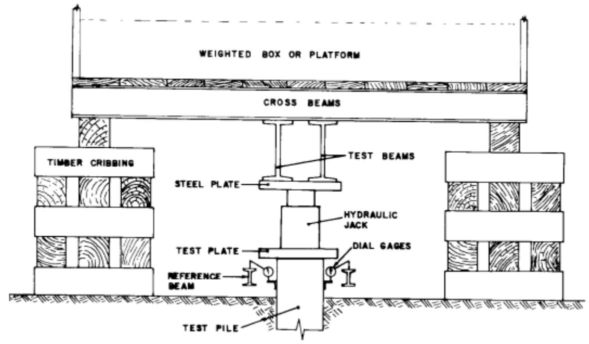

Figure 1 [1]

The pile is loaded on stages and each stage is held for a specific time. Table no:4 is an example of the loading sequence for a pile load test. In this table, DVL is the designated verification load and SWL is the service working load. The loading sequence can vary for different countries or even different states in the same country and it is not identical everywhere. Clear criteria should be available for the engineer to define the result of a pile load test. The engineer should be able to use these criteria to define whether the pile passes the test or fail. An important factor in defining the status of tested piles is the settlement. The settlement should not exceed 1% of the pile lateral dimension. Increasing settlement beyond this limit can cause severe distortion and damage to the structure. Also, the failure of reaching the test load which indicates a high rate of settlement is another reason for rejecting the tested pile. The residual settlement is the remaining settlement when the testing load is removed and it should not be more than 6.0 mm. These are some of the common conditions that can be used to define the status of the tested pile, but they can vary for different projects or even different structures.

no	settlement
1	1.68 mm
2	1.79 mm
3	2.19 mm
4	2.58 mm

5. *Theoretical settlement for piles*

The importance of the capability to estimate the settlement of piles arise from the problems associated with excessive or differential settlement and it is a negative impact on structures. Precise prediction of the settlement will result in reliable and durable structures and it can reduce the cost associated with load tests for piles. In this paper, the settlement is computed by four methods. The investigated piles subjected to a load are within the skin resistance of piles. therefore, the expected settlements are small and within the accepted range. The computed theoretical settlements are available in Table 8.

5.1. Settlement calculation by Bowles method

Bowls provide an equation to calculate the total settlement that consists of two components. The first term of the equation is to evaluate the axial elastic deformation of the shaft, while the second term is to estimate the settlement of the pile due transfer of the load by side friction and end bearing:

$$Stotal = \frac{P * \Delta L}{Ep * Ap} + \Delta q * D * \frac{1 - \mu^2}{Es} * mIs * IF * F1$$

Where P is the applied load, ΔL is the length of the pile socketed in rock, Δq is equal to (the input load/Ap), μ is the Poisson's ratio, Es is the stress-strain of soil below the pile tip, mIs is the shape factor=1.0, IF is the fox embedment factor (IF=0.55 if L/D<=5, IF=0.50 if L/D>5.0), F1 is a reduction factor (F1=0.25 if point load transfer Pp <=0, F1=0.50 if Pp>0).

For pile no:1, P=6300000 N, L=9800 mm, Ep=28800 Mpa, $\mathrm{mIs} = 1.0, \mathrm{D} = 1200\ \mathrm{mm}, \mu = 0.35, \Delta\mathrm{q} = \frac{\mathrm{P}}{\mathrm{A}} = \frac{6300000}{1130400} = 5.57\ \mathrm{Mpa}, \mathrm{Es\ for\ Mudstone} = 180\ \mathrm{Mpa}, \mathrm{IF} = 0.50\ \mathrm{because}\ \frac{\mathrm{L}}{\mathrm{D}} = 6.25 > 5.0, \mathrm{Fi} = 0.25$ because skin resistance reduce point load transfer to 0.0.
The total settlement for pile no:01 is equal to:

$$Stotal = \frac{P * \Delta L}{Ep * A} = \frac{6300000 * 9800}{28800 * 1130400} + 5.57 * 1200 * \frac{1 - 0.35^2}{180} * 1 * 0.50 * 0.25 = 5.96\ mm$$

The settlement for the remaining piles will be calculated by the use of the same procedure. The values of settlement for all piles are shown in table no:8.

5.2. Reese and O'Neill Method

In this method figure no: 2, and 3 are used to determine the settlement of a pile at specified loads. Figure no:2 can be used to determine the settlement due to loads within the side friction capacity of a pile, while figure no:3 will be used to estimate the settlement generated by loads larger than the side friction resistance of piles. To find the settlement for pile no:01 which has a load of 6300 Kn. By knowing that pile no:01 is subjected to a load lesser than the side friction resistance of the pile, figure no:2 were used to determine the settlement. The ratio of pile load to ultimate side friction is equal to:

$$Ratio = \frac{side\ load\ transfer}{ultimate\ side\ load\ transfer} = \frac{6300}{14453} = 0.44$$

To find the settlement of pile no:01, a horizontal line is drawn from the vertical axis at 0.44, and the value on the horizontal axis that corresponds to the point of intersection of the horizontal line and Trend line curve is determined. The value is 0.13 for the current case (Pile no:01) and the resulting settlement will be 0.13%*1200=1.56 mm.

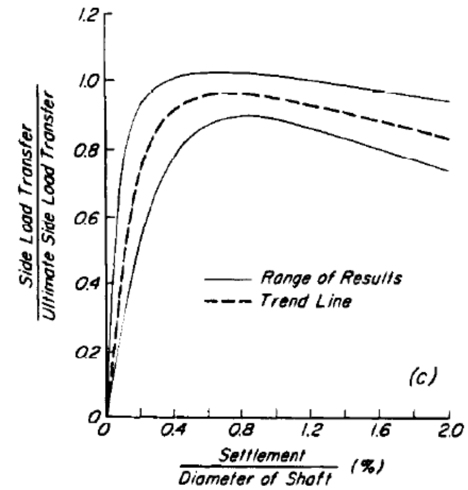

Figure 2 [4]

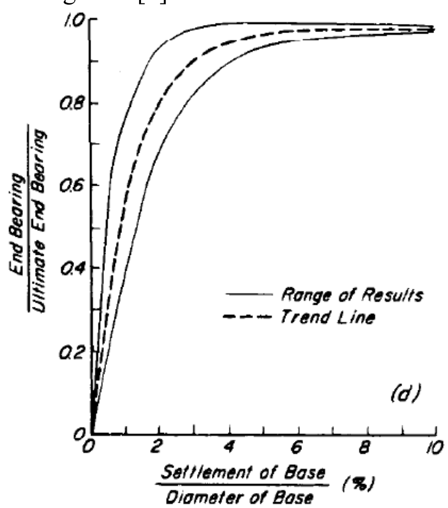

Figure 3 [4]

5.3. Pells and Turner method

Pells and turner provide the following equation to calculate the settlement for load transferred by side friction only.

Pells and Turner's equation includes a new factor, influence factors (Ip) and it can be determined from figure no:5.

$$Stotal = \frac{Q * Ip}{B * Ed}$$

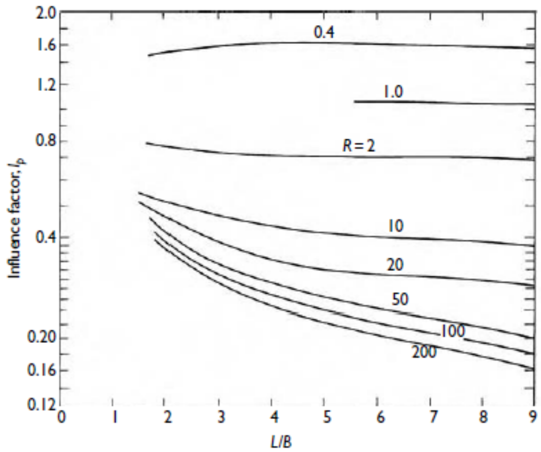

Figure 4 [6]

Ed is the deformation modulus and it can be determined using the following equation

$$Ed = j * Mr * qc$$

The settlement for pile no:01 by the use of the Pells and Turner equation:

To determine Ed, the following should be determined, J is the mass factor, from table no:6, j=0.70, Mr = 600 from figure no:5, Ip from figure no:4 (knowing that L/B=9800/1200=8.1, Ec/Ed=28800/865=33.2) is 0.26.

Table 6 [6]

RQD (%)	**Fracture frequency per meter**	**Mass factor j**
0-25	**15**	**0.2**
25-50	**15-8**	**0.2**
50-75	**8-5**	**0.2-0.5**
75-90	**5-1**	**0.5-0.8**
90-100	**1**	**0.8-1**

Ed=j*Mr*qc=0.7*600*2.06=865 Mpa

compression strength. BS 8004 gives the following values for M_r:

		Values for M_r
Group 1	Pure limestones and dolomites Carbonate sandstones of low porosity	600
Group 2	Igneous Oolitic and marly limestones Well-cemented sandstones Indurated carbonate mudstones Metamorphic rocks including slates and schists (flat cleavage/foliation)	300
Group 3	Very marly limestones Poorly cemented sandstones Cemented mudstones and shales Slates and schists (steep cleavage/foliation)	150
Group 4	Uncemented mudstones and shales	75

Figure 5 [6]

$$\text{settlement for pile no: 01} = \frac{630000 * 0.26}{1200 * 865} = 1.57 \text{ mm}$$

According to Pells and Turners, a reduction factor will be used to reduce the settlement in case a layer of weak soil lies on top of hard rock. The reduction factor can be determined from the curves given in figure no:6.

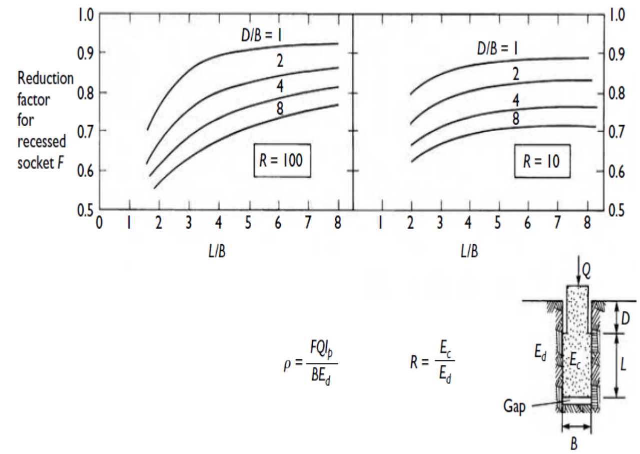

Figure 6 [6]

5.4. Vesic method

The fourth and final approach used in this paper for estimating pile foundation settlement is the Vesic method. Vesic proposed a semi-empirical equation for calculating the pile settlement. According to the Vesic method, the total settlement of a pile consists of three components: axial deformation of the pile shaft, settlement due to side load transfer, and settlement due to point load transfer (pile end bearing)

$$Total\ settlement = Ws + Wps + \square pp$$

Where,

$$Ws = \frac{\alpha s * Qs * L}{A * Ep}$$

$$Wps = \frac{Cs * Qs}{D * q}$$

$$Wpp = \frac{Cp * Qp}{B * q}$$

Where αs is a factor that depends on pile side friction distribution on the pile shaft estimated from figure no:7, Qs is the side resistance for the pile at the design load, D is the embedded pile length, B is the diameter or width of the pile, Qp is the point resistance for the pile at design load and q is the unit ultimate tip capacity of the pile.

For pile no:01, the settlement is calculated by determining Ws which is the axial deformation of the pile shaft, and Wps which is the settlement due to side load transfer

$$Ws = \frac{0.67 * 6300000 * 9800}{1130400 * 28800} = 1.27\ mm$$

The second component of settlement due to side load transfer:

$$Wps = \frac{Cs * Qs}{D * q}$$

Where,

$$Cs = \left(0.93 + 0.16\sqrt{\frac{D}{B}}\right) * Cb$$

Cb determined from table no:7, Cb=0.09 for sand, the value should be reduced by 51% if the rock is present at 1B from the pile tip, so Cb=0.49*0.09=0.044

$$Cs = \left(0.93 + 0.16 * \sqrt{\frac{9.8}{1.2}}\right) * 0.044 = 0.060$$

$$Wps = \frac{Cs * Qs}{D * q} = \frac{0.060 * 6300000}{98000 * 9.27} = 5.43\ mm$$

Table 7

Value of Cp		
Soil Type	**Driven piles**	**Bored Piles**
Sand (dense to loose)	**0.02 to 0.04**	**0.09 to 0.18**
Clay (Stiff to soft)	**0.02 to 0.03**	**0.03 to 0.06**
Silt (dense to loose)	**0.03 to 0.05**	**0.09 to 0.12**

The total settlement for pile no:01 is 6.70 mm. The settlement for all piles is presented in table no:8

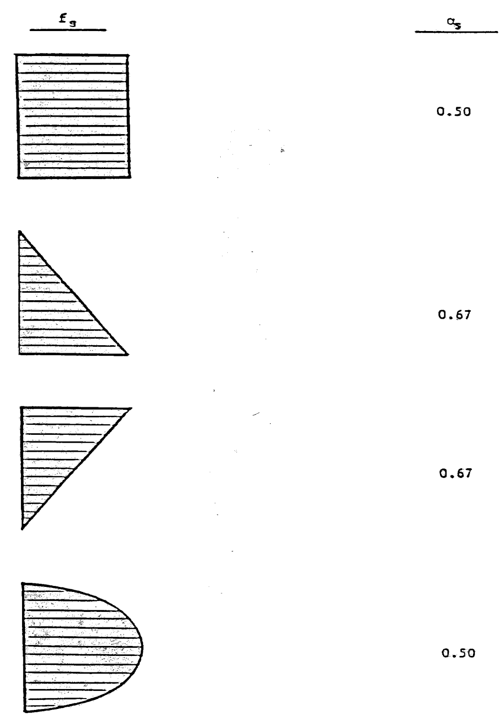

Figure 7

6. conclusion

Pile settlement is very important and it should be kept below the allowable limit. The impact of the high settlement of piles can be severe and it can affect structure stability and integrity. Therefore, it is important to precisely estimate the pile settlement theoretically to element any unforeseeable negative impact on structures. In this paper, the settlement estimated by the use of four methods and the results of four methods were not identical. Reese and O'Neill's method and Pells and Turner's method provide results that are close to actual settlement, while Bowles and Vesic provide results that are larger than settlements measured at the site. It may seem that some methods are more accurate than others, but the accuracy of these methods may vary for different loading cases, subsurface geology, pile type, construction method, and other factors.

A pile load test can be performed to verify pile bearing capacity and settle. It is recommended to conduct a load test on a trial pile. Testing a trial pile allows the engineer to assess the reliability of the pile design, estimated settlement, and compatibility of the construction method.

Table 8

Pile no	**Actual settlement**	**Bowles**	**Reese and O'Neill**	**Pells and Turner**	**Vesic**
1	**1.68 mm**	**5.96 mm**	**1.56 mm**	**1.58 mm**	**6.70 mm**
2	**1.79 mm**	**5.52 mm**	**1.32 mm**	**1.34 mm**	**5.57 mm**
3	**2.19 mm**	**8.85 mm**	**1.92 mm**	**2.21 mm**	**4.96 mm**
4	**2.58 mm**	**7.05 mm**	**2.28 mm**	**2.10 mm**	**7.66 mm**

The exhibited methods in this paper except Pell's and Turner's method can be used for calculating the settlements as a result of transferring loads due to side friction and end bearing. Assuming the load on pile no:1 is equal to 20,000 Kn which is larger than the side friction resistance, the estimated settlement for pile no:1 is exhibited in table no:09, the estimated settlement is larger than allowable settlements as expected for loads that exceed the side friction resistance of a pile. The settlement value varies largely for different methods as presented in table no:9.

Table 9

Pile no	**Pile capacity**	**Assumed load**	**Bowles**	**Reese and O'Neill**	**Vesic**
1	**25513**	**20,000 Kn**	**29.20 mm**	**18 mm**	**22.20 mm**

A. References:

1. ASTM Standards. (1981). Standard Test Method for Piles Under Static Axial Compressive Load. Retrieved 1994
2. Gedeon, G. (1991). *Design of Pile Foundations.* Stonewall Ct, Woodcliff Lake: Continuing Education and Development.

3. Joseph E. Bowles, P. S. (1997). *Foundation Analysis And Design.* New York: McGraw-Hill Companies.
4. Karl Terzaghi, R. B. (1996). *Soil Mechanics in Engineering Practice.* New York: A Wiley-Interscience Publication.
5. Lina Gabrielaitis, V. P. (2013). Estimation of Settlements of Bored Piles Foundation. *Science Direct*, 7.
6. Michael Tomlinson, J. W. (2008). *Pile Design and Construction Practice.* New York: Taylor & Francis e-library.

Mohammad Mamon Fayiz Hamdan
Civil/Structural Engineer
Bachelor degree in Civil Engineering from Birzeit university
Member of Society of Engineers/UAE
Vast Experience in construction and consultancy works for infrastructure project.