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Prediction of Settlement for Large Diameter Monopiles under Axial Loading

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ABSTRACT: The design of large diameter monopiles depends on determining the value of the failure load and its corresponding settlement. In-situ pile loading tests are the most reliable method to evaluate the behavior of piles (ECP). Also, numerical analysis is another way to plot the load-settlement (Q-S) curve and determine the plastic points of soil. In this paper, an equation is proposed to determine the settlement for piles under axial loading using the plasticity theory and the results of numerical analysis by Plaxis 3D. The proposed equation is compared with five historical case studies. A reliable agreement is obtained from the application of the proposed equation with the measurement in-situ loading test results.

KEYWORDS: Monopiles, large diameter pile, pile settlement.

1 INTRODUCTION

Large-diameter piles are used to support heavy loads and to achieve low settlement values for structures. Numerous studies have investigated their behavior through in-situ load testing. Also, in many cases, the test did not reach the failure load. Design calculations typically provide the failure load and its corresponding settlement. However, knowing the behavior of the pile under working loads up to the ultimate load is important in terms of load values and corresponding settlement values. As stated in earlier, the elastic settlement of pile head was estimated numerically under axial loading (Yoshichika, 1964) by assuming that the pile and the soil are the elastic materials. Fleming (1992) presented a method to predict the monopile settlement under axial loading using a hyperbolic function to evaluate the shaft and the base settlement. Also, Farzaneh et. al. (2014) presented a simple regression to predict the settlement using a finite element model and homogeneous elastic soil. Chong Jiang et. al. (2020) proposed a calculation method for the settlement of a vertically loaded single pile in sloping ground based on the hyperbolic curve tangent modulus method.

In this research, the load-settlement curve of piles is analyzed using numerical modeling to calculate the settlement values of the pile for various loads up to value of the yield load.

1.1 *Background of stresses and displacements*

The stresses on a soil mass due to applied loading result in deformation of the soil. The soil deformation is a displacement relative to two axis of soil mass, and the strain is a displacement per unit length in a given direction (Figure 1).

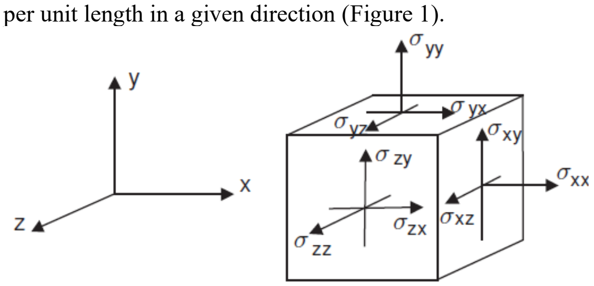


Figure 1. Principal stresses on soil mass in three dimensions.

As shown in Figure 2, the ratio between a stress (σ) and the corresponding strain (ε) for homogeneous and isotropic soil is carried out using the followed equation (Terzaghi 1943);

$$\frac{\sigma}{\varepsilon} = E \tag{1}$$

Which E is modulus of elasticity, and the both of vertical strain (ε) and horizontal strain (εl) can be expressed as;

$$\varepsilon = \frac{\Delta H}{H}\ , \quad \varepsilon l = \frac{\Delta d}{d} \tag{2}$$

Also, the analysis of soil stress-strain curve is depended on Hooke's law as shown;

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}, \quad \varepsilon = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix} \tag{3}$$

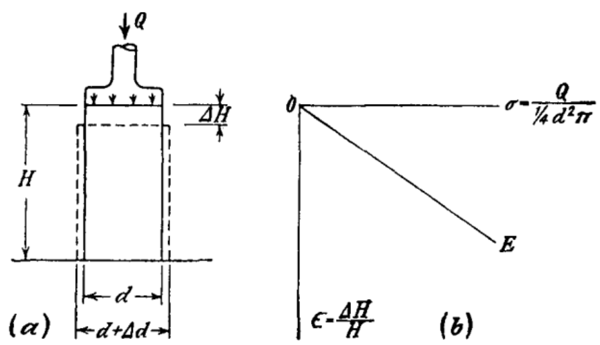
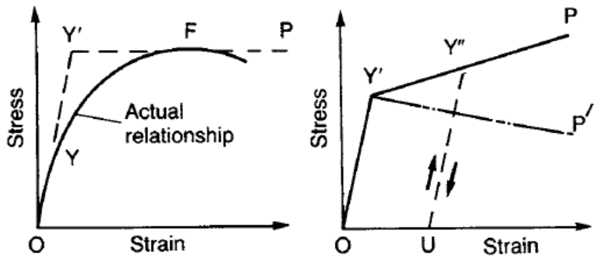


Figure 2. (a) The stresses on cylindrical soil mass, (b) test results (After Terzaghi 1943).

According to the case histories of pile load test, the most idealization of the stress-strain relationship are typical stress–strain and elastic–strain hardening model as shown in Figure 3 (a) and (b) respectively.



(a) (b)

Figure 3. (a) Typical stress-strain relationship (b) elastic–strain hardening model (After R.F. Craig 2004).

Which the Y' is assumed as the yield point, Y" is the yield point at a stress level higher than that at Y', and P is the failure load.

Van Impe (1993) analyzed the test results of 12 piles and the yield load was equal to 0.63 times the collapse load.

2 PARAMETRIC STUDY

2.1 *Numerical models*

The aim of this research is to predict the load-settlement curve of large-diameter monopiles under axial loading up to yield load. To achieve the aim of this research, numerical models were done to change the diameter and length of the pile in sandy soils. The diameters of the pile (D) range from 1.2 m to 3.6 m, and the lengths of the pile (L) vary between from 12 m to 60 m (Table 1).

Table 1. The pile lengths and diameters.

D (m)	1.2	2.4	3.6	L (m)	12	24	36	48	60

The initial model and its verification with full-scale pile load test are explained and illustrated by Baset et. al. (2024). However, numerical modeling was carried out for five types of sandy soil. As shown in Table 2, the characteristics of sandy soils were determined from the Egyptian Code and literature review.

Table 2. Soil description and selected parameters.

Sand description	γ	φ	Es	E_o	υ	ψ
V. loose	15	28	10	0.8	0.25	0
Loose	16	30	20	0.7	0.3	0
Medium	17	34	50	0.6	0.3	4
Dense	18	38	100	0.5	0.4	8
V. dense	20	42	200	0.4	0.4	12

Where γ is density (KN/m^3), φ is friction angle, E_s is elastic modulus (MN/m^2), e_o is void ratio, υ is Poisson ratio, and ψ is dilatancy angle.

The soil material is a hardening model, and the undrained type is considered. An elastic behavior of embedded beam and linear axial skin resistance are used to simulate the monopile. The pile properties are E_s = 30E6 MN/m^2 and γ = 24 KN/m^3. Also, the soil-pile interface is modeled as linear skin resistance, in which the shear force $t_s < (\sigma \tan\varphi)\ \pi D$ to remain elastic behavior, and σ is normal stress.

2.2 *Methodology*

The results of numerical models are plotted as load-settlement curves for all cases of numerical models. Then, the yield point for each case is selected, and a fitted line from the first load to the yield load is drawn as shown in Figure 4.

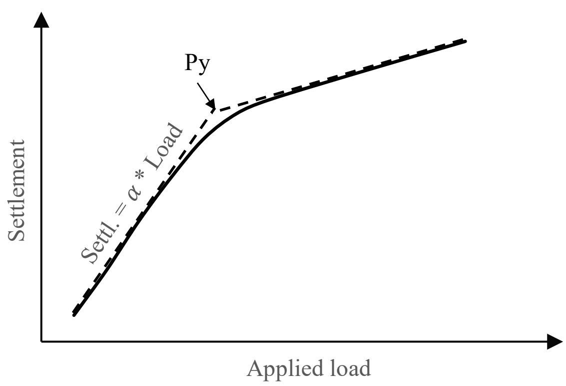


Figure 4. Typical load-settlement relationship.

The equation of the fitted line is a first-order linear and can be expressed as;

$$S_P = \alpha\ P_o \quad (4)$$

Where S_p is the pile head settlement, P_o is axial applied load, and α is the slop of load-settlement line up to yield load (p_y).

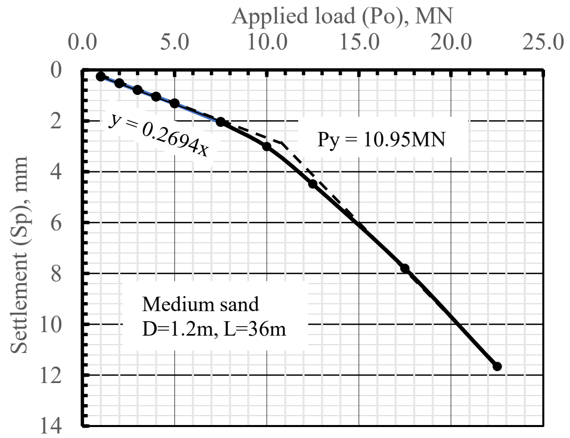
The slop of line (α) is analyzed as a function of the pile length (L), the pile diameter (D), and the elastic modulus of soil (E_s). Also, the values of yield load are analyzed to predict the load that limit of the equation.

While the numerical models of soil are one layer, the effect of multi soil layer are assessed based on history cases to evaluate the effect of soil layers on embedded pile and settlement.

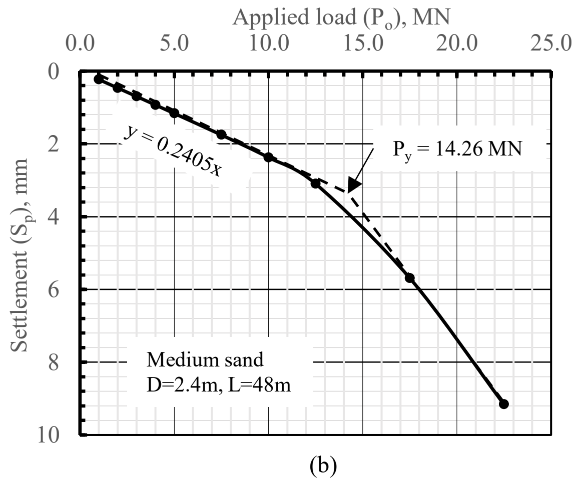
3 RESULTS AND ANALYSIS

The results of numerical models of 75 cases are analyzed, in which the slop of load-settlement line and yield load are determined graphically.

For example, Figure 5 (a) and (b) show the results of two case studies of pile embedded in medium sand of pile diameter 2.4m, and the pile lengths are and 36m and 48m respectively. It seen that the solid line is the pile behavior under axial loading and the two dash lines are tangents to load-settlement curve before and after the yield point. The slop of line (α) up to yield point equal 0.2694 and 0.2405, and the yield load (P_y) equal 10.95 and 14.26MN as shown in Figure 5 (a) and (b) respectively.



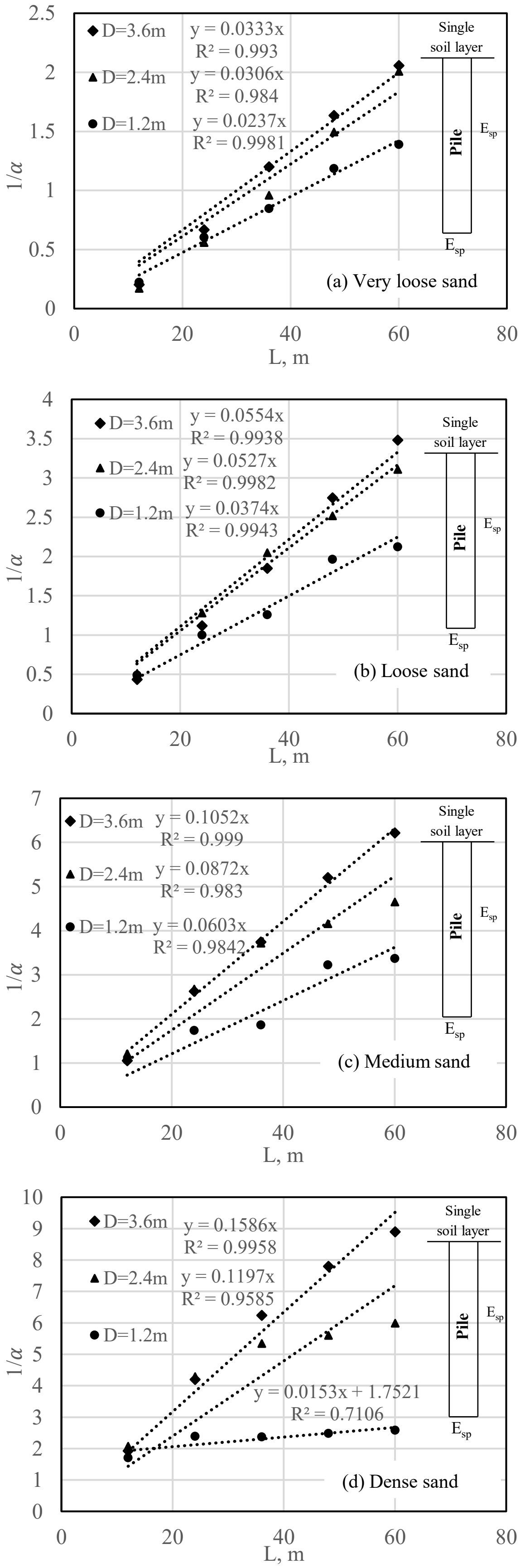
(a)



(b)

Figure 5. Analysis of load-settlement relationship for pile embedded in medium sand for (a) D=2.4, L=36m (b) D=2.4, L=48m.

The analysis revealed that the coefficient (α) exhibits a linear inverse relationship with pile length in different types of sandy soils.



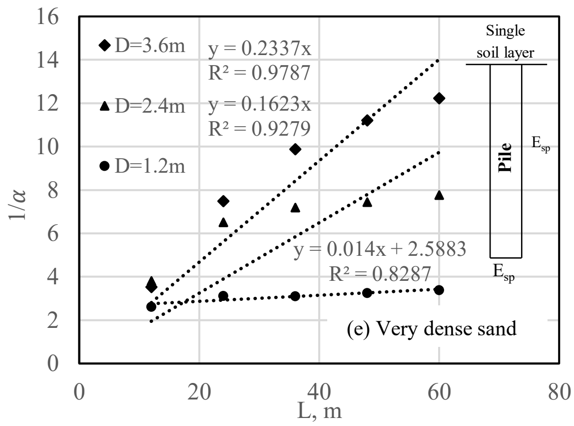


Figure 6. Constant (α) - pile length relationship at different pile diameter and sandy soil types.

It seen from Figure 6 that the parameter (α) decreases as pile length, pile diameter, and soil strength increase.

3.1 *Prediction of pile settlement equation*

The aim of this research is to find an equation to calculate the settlement of large-diameter piles. Therefore, the equations shown in the Figure 6 are analyzed. Since the equations are a linear relationship between the inverse of a constant and the pile length at different pile diameters and soil types, the equation for this relationship can be formulated as follows:

$$\frac{1}{\alpha} = \bar{\alpha}\, L \qquad (5)$$

Where $\bar{\alpha}$ is a value that function in pile diameter. The values of $\bar{\alpha}$ are plotted as relationship with pile diameter as shown in Figure 7. There were two of the results are non-consensual with other cases, namely case of dense and very dense sand of pile diameter 1.2m.

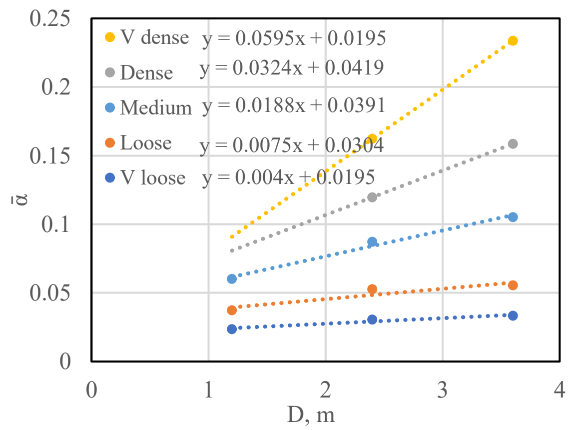


Figure 7. Constant ($\bar{\alpha}$) - pile diameter relationship at different sandy soil types.

As shown in Figure 7, the equations are two terms, in which first term is function of soil dtrength, and second term has average of 0.03. The equation for $\bar{\alpha}$- pile diameter relationship can be formulated as follows:

$$\bar{\alpha} = \beta\, D + 0.03 \qquad (6)$$

According to Equation (1), the elastic modulus of soil (E_s) is the main parameter that an effect on displacement. Therefore, the values of β are plotted as relationship with elastic modulus of soil (E_{sp}) as shown in Figure 8, and the values of elastic modulus are shown in Table 2.

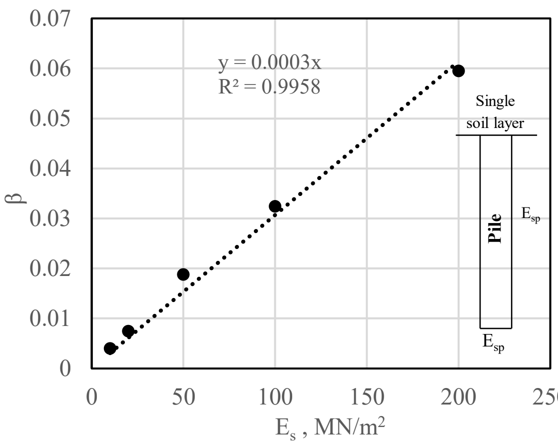


Figure 8. Constant (β) – soil elastic modulus relationship.

Then, the value of can be expressed as;

$$\beta = 0.0003\, E_{sp} \tag{7}$$

By substituting Equations (6) and (7) into Equation (5), the slop of load-settlement line (α) is:

$$\alpha = \frac{1}{\left(0.0003\, E_{sp}\, D + 0.03\right)L} \tag{8}$$

Then, the Equation (4) can be expressed for pile head settlement as;

$$S_p = \frac{P_o}{\left(0.0003\, E_{sp}\, D + 0.03\right)L} \tag{9}$$

3.2 *Effect of multi-soil layers*

Theoretically, the head settlement of rigid pile is a component of shaft and base settlements (Chandra et. al., 2008). Also, the results of the numerical models analyzed in the previous section based on one-layer soil. Therefore, when applying Equation (9) to full-scale loading test, multi soil layers have an effect on pile settlement. However, the pile settlement can be formelted as:

$$S_o = S_p + S_m \tag{10}$$

Where S_o is a total pile settlement, S_p is a pile settlement due to axial loading (P_o) for single soil layer, and S_m is the settlement due to multi soil layers around the embedded pile.

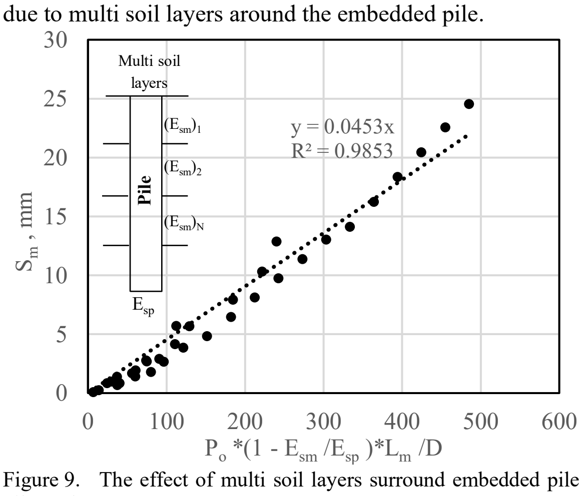


Figure 9. The effect of multi soil layers surround embedded pile on pile settlement.

While the shaft settlement influence factors determined for monopiles are a function of the elastic modulus normalization of soil surround embedded pile to bearing soil, and the normalization of soil layer thickness to pile diameter (Hisham T. Eid, 2013), so that, S_m can be formulated as follows:

$$S_m \propto P_o\,, \frac{E_{sm}}{E_{sp}}\,, \frac{L_{mi}}{D}$$

$$S_m = C * P_o * \left(1 - \frac{E_{sm}}{E_{sp}}\right) * \frac{L_m}{D} \tag{11}$$

Where P_o is applied load, C is the equation constant, E_{sm} and L_m are the elastic modulus and thickness of soil layers around embedded pile respectively, E_{sp} is elastic modulus of soil at pile base, and D is the pile diameter. Also, the term of $(1-E_{sm}/E_{sp})$ for ignore the soil layer at pile base on the settlement of embedded pile.

As shown in Figure 9, the S_m is calculated form the case histories (i.e. $S_m = S_o - S_p$), and the constant (C) equal 0.045. Therefore, the equation of S_m can be expressed as;

$$S_m = \sum_{i=1}^{i=N_{soil}} 0.045 * P_o * \left(1 - \frac{(E_{sm})_i}{E_{sp}}\right) * \frac{(L_m)_i}{D} \tag{12}$$

Where N_{soil} is the number of soil layers.

By substituting Equations (9) and (11) into Equation (10), the total pile settlement is:

$$S_o = \frac{P_o}{\left(0.0003\, E_{sp}\, D + 0.03\right)L} + \sum_{i=1}^{i=N_{soil}} 0.045 * P_o * \left(1 - \frac{(E_{sm})_i}{E_{sp}}\right) * \frac{(L_m)_i}{D} \tag{13}$$

3.3 *Determination of yield load*

The yield load is the applied load that transfers a material from the elastic behavior to the plastic behavior. The yield loads (P_y) are determined graphically for the results of numerical models. As shown in Figure 10, the yield loads for each pile diameter are collected and plotted as a relationship with pile length (L).

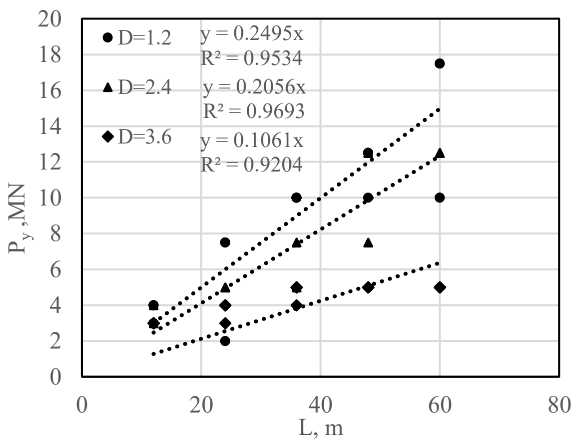


Figure 10. Yield load – pile length relationship at different pile diameter.

The yield load can be formelted as:

$$P_y = \delta * L \tag{14}$$

Where δ is a constant that function of the pile diameter. Figure 11 shows a linear relationship between δ and the pile diameter (D), and the equation of δ can be expressed as;

$$\delta = 0.33 - 0.06\, D \tag{15}$$

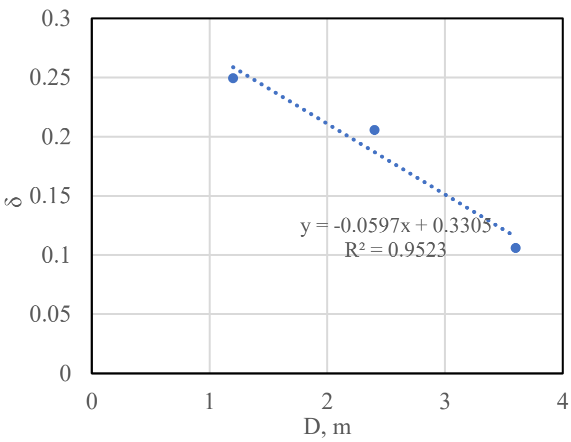


Figure 11. Constant (δ) – pile diameter relationship.

By substituting Equation (15) into Equation (14), the yield load (P_y) is:

$$P_y = (0.33 - 0.06\,D) * L \qquad (16)$$

4 APPLICATIONS OF THE PROPOSED SETTLEMENT EQUATION

4.1 *Case histories under consideration*

Full details of 5 large diameter pile loading tests and the surrounding soil were considered in this research in terms of comparing the results with them. The first three cases were from (Peisen W. et al. 2020), where the piles were embedded in dense sand. The pile diameters were 1.5 and 1.8 m, and the lengths ranged from 52 to 83 m. The fourth case of (Xiaoyu Bai et al. 2020) is a pile embedded in very dense sand, and the diameter and length of the pile are 0.8 and 25 m, respectively. The last pile in the Cairo Monorail project, in which the pile diameter and length are 2.0 m and 18 m respectively.

4.2 *Settlement equation and case histories comparison*

The cases of in-situ pile load test that explained in Section 1.2 are plotted as load-settlement curves and compared with the settlement (S_o) that estimated from Equation (13). Since the Equation (13) is limited to the yield load (P_y), the yield load is determined by Equation (16).

For each historical case, the settlement of soil base layer (S_p) is calculated. Also, the effect of soil layers around embedded pile on pile settlement (S_m) are calculated. Then, the total settlement (S_o) is evaluated. By knowing applied loads (P_o) from in-situ test, the suggested load-settlement curve is plotted to compare with in-situ curve.

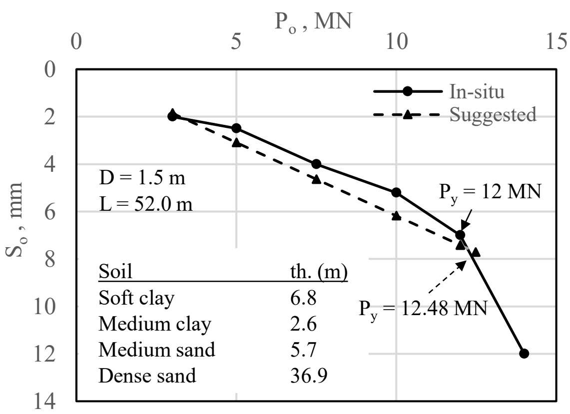


Figure 12. In-situ and suggested method comparison (case No.1).

For example, Figure 12 shows the description and thickness of soil layers for case No.1. The following four steps illustrate the suggested method to calculate the pile settlement under axial loading.

1. Determination of load-settlement slop line (α).

$$\alpha = \frac{1}{(0.0003\,E_{sp}\,D + 0.03)L} = \frac{1}{(0.0003 * 100 * 1.5 + 0.03) * 52} = 0.256 \qquad (17)$$

2. Calculations of sum effect of soil layers around embedded pile (N_{soil}).

Table 3. Calculations of sum N_{soil}.

	(1)	(2)	
N_{soil}	$1 - E_{sm}/E_{sp}$	L_m/D	(1) * (2)
1	1 – 1.5/100 = 0.985	6.8/1.5 = 4.53	4.462
2	1 – 3.5/100 = 0.965	2.6/1.5 = 1.73	1.67
3	1 – 50/100 = 0.5	5.7/1.5 = 3.8	1.9
4	1 – 100/100 = 0.0	36.9/1.5 = 24.6	0.0
		Summation	8.032

3. Calculations of total pile settlement (S_o) for applied loads.

Table 4. Calculations of S_o.

P_o	$S_p = \alpha * P_o$	$S_m = 0.045 * P_o *$ sum N_{soil}	$S_o = S_p + S_m$
3	= 0.256 * 3 = 0.768	=0.045*3*8.03=1.08	1.848
5	= 0.256 * 5 = 1.28	=0.045*5*8.03=1.81	3.09
7.5	= 0.256 * 7.5 = 1.92	=0.045*7.5*8.03=2.71	4.63
10	= 0.256 * 10 = 2.56	=0.045*10*8.03=3.61	6.17
12	= 0.256 * 12 = 3.07	=0.045*12*8.03=4.34	7.41
14	= 0.256 * 14 = 3.58	=0.045*14*8.03=5.06	8.64
16	= 0.256 * 16 =4.096	=0.045*16*8.03=5.78	9.876

4. Calculations of yield load (P_y).

$$P_y = (0.33 - 0.06\,D) * L = (0.33 - 0.06 * 1.5) * 52 = 12.48\ \text{MN} \qquad (18)$$

As shown in Figure 12, the results of in-situ test and suggested method are plotted as solid line and dotted line respectively. As explained previously, this method is limited by yield load, in which the settlement of pile that is elastic behavior.

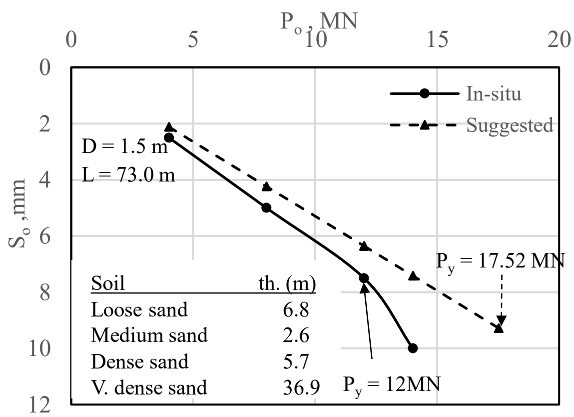


Figure 13. In-situ and suggested method comparison (case No.2).

Also, the steps of the previous example (Case No.1) were applied to the remaining historical cases (Section 4.1). The following figures compare the proposed method for calculating pile settlement with the in-situ load tests. The results demonstrate that the settlement equation and the behavior of the pile in-situ are close as summarized in table (5).

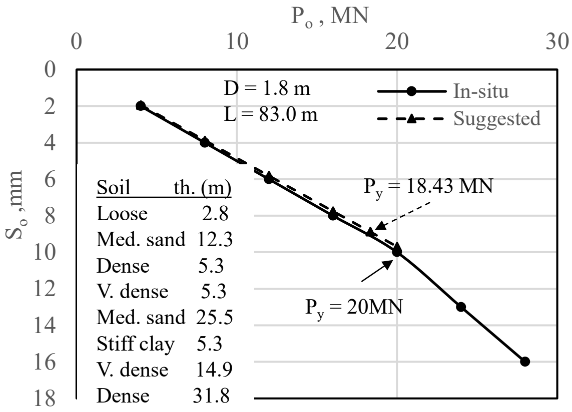


Figure 14. In-situ and suggested method comparison (case No.3).

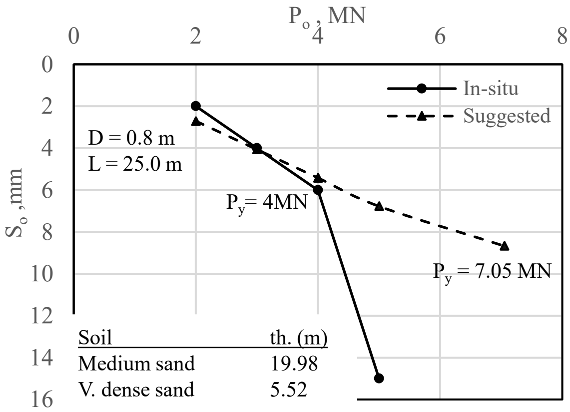


Figure 15. In-situ and suggested method comparison (case No.4).

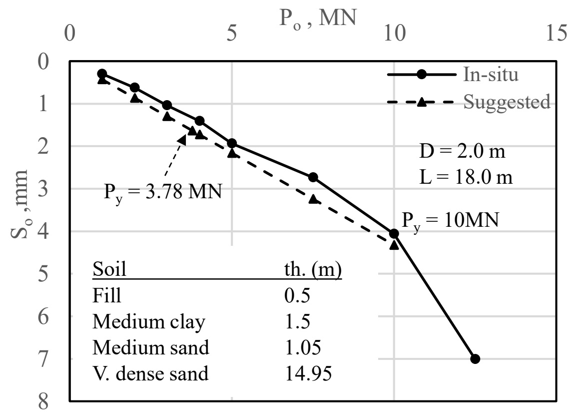


Figure 16. In-situ and suggested method comparison (case No.5).

Table 5 shows the summary of the pile settlements and yield loads of measured in-situ data and suggested equation results.

Table 5. In-situ and suggested equation results of S_o and P_y of.

Case No.	In-situ		Suggested Eq.		ΔP_y %	ΔS_o %
	P_y, MN	S_o, mm	P_y, MN	S_o, mm		
1	12	7	12.48	7.71	-4.0	-10.1
2	12	7.5	17.52	9.28	-46.0	-23.7
3	20	10	18.426	8.89	7.9	11.1
4	4	6	7.05	8.67	76.3	-44.5
5	10	4.1	3.78	1.64	62.2	60.0

Applying the suggested equation for calculating yield load and corresponding settlement generally shows fair agreement with the measured values, except in the case of piles resting on very dense sand. This discrepancy can be attributed to the influence of relative density, which significantly affects the behaviour of very dense sand and leads to deviations from the measured results.

5 CONCLUSIONS

A series of 75 numerical model pile load tests were analyzed in sandy soil. Pile diameters and lengths ranged from 1.2 to 3.6 m and from 12 to 60 m, respectively. The variables affecting pile behavior under axial loading were determined using elasticity theories, namely pile diameter, pile length, soil elasticity modulus, and yield point. These variables were analyzed, and an equation was developed to calculate head pile settlement for use in practical design for large-diameter monopiles. Load-settlement curves were also analyzed graphically to determine the yield load.

The suggested settlement equation consists of two parts. The first part calculates the slope of the settlement line under axial loading up to the yield load. The second part calculates the effect of soil layers around the embedded pile on settlement. Finally, the suggested equations were compared with the results of five in-situ pile load tests, and the results were in fair agreement.

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