Numerical simulation of pile load test

Simulation numérique de l'essai de chargement de pieux

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ABSTRACT

The current paper presents a back analysis of field pile load-settlement relationships using commercial finite element program ''PLAXIS''. Five driven piles, two continuous flight auger piles of diameters 0.40 m and 0.60 m and two bored piles of diameters 1.00 m, 1.80 m were used in the analysis. The study aims to investigate finite element parameters which control the load - settlement relationship for small diameter piles (Diameter 600 mm) and large diameter piles (Diameter > 600 mm) and to search for the matching values to test results. It is shown that the value of the interface factor (R_i) between pile and soil affects the load-settlement relationship for small diameter piles. For larger diameter piles results confirmed that the value of the lateral pressure coefficient (K) and the value of soil compressibility modulus (E_s) have strong effect on the pile load-settlement behaviour.

RÉSUMÉ

Le présent document présente une analyse de retour sur le terrain des relations de charge-tassement du pieu à l'aide du programme d'éléments finis "PLAXIS". Cinq pieux battus, deux pieux à la tarière continue de diamètres de 0,40 m et 0,60 m et deux pieux forés de diamètre 1 m, 1.80 m ont été utilisés dans l'analyse. Le Code de pratique égyptienne (ECP) a défini le gros tas de diamètre dépasse 0,60 m, sinon c'est un tas de petit diamètre. L'étude vise à étudier les paramètres des éléments finis qui contrôle la relation charge - tassement pour des pieux de diamètre petits et grands ainsi que pour rechercher les valeurs optimales en fonction des résultats d'essai. Il est démontré que la valeur du facteur de l'interface (R_i) entre la pile et le sol affecte le comportement relation charge de règlement pour les pieux de petit diamètre. Pour de plus grand diamètre résultats piles a confirmé que la valeur du coefficient de pression latérale (K) et la valeur du module de compressibilité du sol (E_s) ont un effet marqué sur le comportement relation de chargement de pieu de règlement.

Keywords: numerical simulation, pile load test, back analysis, small diameter piles, large diameter piles

1 INTRODUCTION

The pile test load-settlement curve is the best method to estimate the ultimate pile capacity and to investigate soil pile interaction behaviour. The variation of soil parameters around pile; compressibility modulus, lateral pressure coefficient and the interaction between pile and soil due to different pile installation methods are strongly affect and control the pile settlement. Researches based on simulation concept have been performed such as Baars and Niekrek (1998) determined the ultimate bearing capacity of tension piles by using (PLAXIS) program. This numerical model assessed the actual pile bearing capacity more closely than analytical models based on empirical calculation rules. Results were successively compared with actual test results which were measured during pile tests. Lawler (2003) introduced an assessment of the ability of hardening soil model to predict the behaviour of an instrumented continuous flight auger (CFA) pile in stiff clay. Livneh and EL Naggar (2008) encompassed 19 full scale load tests of helical piles in different soils and numerical modeling using finite element analysis to investigate the axial performance of helical piles and explored the relationship between the installation effort (torque) and pile capacity. Henke and Grabe (2006) introduced a three dimensional finite element model to simulate the pile installation process methods and made a comparison with a pile jacking analysis to examine the effects of these methods on the soil parameters around pile.

2 NUMERICAL MODELING OF THE PILE

The total settlement of a pile under vertical working load consists mainly of three components; elastic compression of the pile, settlement caused by the load transfered at the pile's tip and settlement caused by load transmitted to the soil along the pile shaft. In small pile displacement (about 1% of pile diameter) the ultimate skin friction of the pile is mobilized as such the load settlement behaviour of the pile depends strongly on the friction resistance between the pile and the soil. Pile is assembled as a beam element (plate) of an axi-symmetric mesh in a pile radius distance from the axis as shown in Fig 1. This procedure has two advantages compared to modeling the pile with elastic soil elements (concrete material). First, the plate is restrained to move horizontally which allows studying only vertical deformation of the pile. Second, the plate is made of a non - deformable material relative to the soil which leads to focus on soil deformation behaviour surrounding the pile rather than deformation in the pile itself.

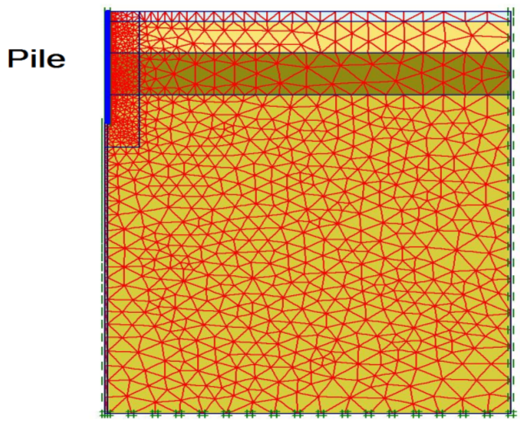

Fig 1 pile model and finite element mesh

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3 SMALL DIAMETER PILES

The load transfer from pile surface to the adjacent soil is a function of stiffness difference between soil and pile material. In the model, the stiffness of surrounding soil has been reduced by a % age R_i (interface value) to reduce load transferring from pile to soil, and thus, simulates loss of load transfer by skin friction. The value of R_i reflects failure mode which for smooth interface is elastic plastic where soil particles slip along the interface. To capture the actual interface factor value (R_i interface) numbers of iterations were performed to match the simulated load-settlement relationship with field pile load test as explained below.

Five driven piles and two Continuous Flight Auger (CFA) piles are examined. Results of the tests are listed in Tables 1 and 2 respectively. Δ is the pile displacement and D is the pile diameter.

Table 1. Details of driven piles and test loads

Model	Length (m)	Diameter (m)	Test Load (KN)	Displacement at maximum load Δ (mm)	Δ/D $*10^{-2}$
P01	20.5	0.4	1350	4.95	1.24
P02	20.8	0.4	1590	6.47	1.62
P03	20.3	0.4	1590	4.93	1.23
P04	21.4	0.4	1400	3.64	0.91
P05	20.1	0.4	1620	5.87	1.47

Table 2. Details of CFA piles and test loads

Model	Length (m)	Diameter (m)	Test Load (KN)	Displacement at maximum load Δ (mm)	Δ/D $*10^{-2}$
P06	16	0.6	900	2.27	0.38
P07	16	0.6	900	2.69	0.45

The ground profile and soil properties are shown in Tables 3 and 4, respectively.

Table 3. Soil design parameters for driven piles simulation

Layer	Fill1	Fill2	Salt	Soft clay	Med clay	Stiff clay	Sand
Thick (m)	1.5	1.5	2	5	2	5	8
γ (KN/m^3)	16	14	15	16	16	17	18
C_u (KN/m^2)	-	-	-	23	40	72	-
Φ degree	32	31	22	-	-	-	35
E_s (MPa)	25	15	10	1.15	2.80	3.30	56
ν	0.30	0.30	0.30	0.35	0.35	0.35	0.30

The water table is at 1.4 m below ground level.

Where

E_s	Soil Compressibility Modulus,
γ	Bulk density of soil,
ν	Soil Poisson ratio, and
Cu	Undrained soil cohesion

Table 4. Soil design parameters for CFA piles simulation

Layer	Fill	Sand	Silty clay	Sand cemented
Thick (m)	1.5	4.5	6	12
γ (KN/m^3)	15	15	15	17
Cu (KN/m^2)	-	-	15	-
Φ (degree)	28	32	-	36
E_s (MPa)	8	21	7.5	40
ν	0.30	0.30	0.35	0.30

The water table is at 1 m below ground level.

For all models, Mohr Couloumb model criterion is used for soil material behaviour in undrained condition

4 RESULTS AND DISCUSSION

The load-settlement relationship generated through numerical analysis is plotted on the same chart with the field load settlement curve for different values of the interface factor as shown in Figures 2 through 8.

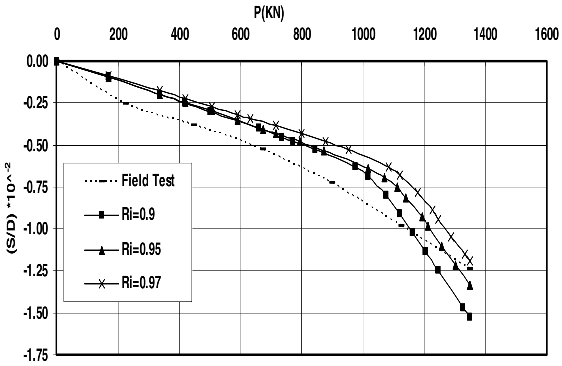


Figure 2. Simulation of P01 at different values of (R_i)

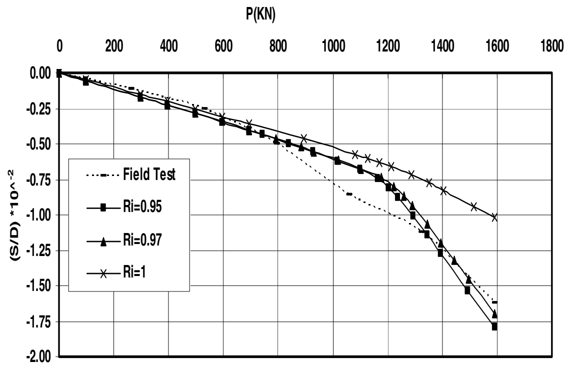


Figure 3. Simulation of P02 at different values of (R_i)

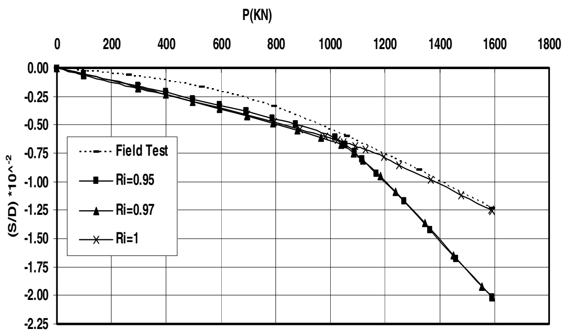


Figure 4. Simulation of P03 at different values of (R_i)

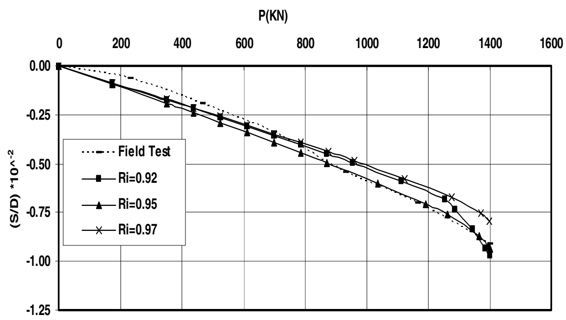


Figure 5. Simulation of P04 at different values of (R_i)

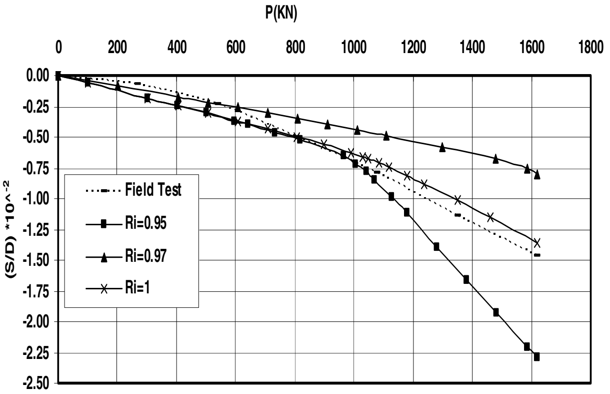


Figure 6. Simulation of P05 at different values of (R_i)

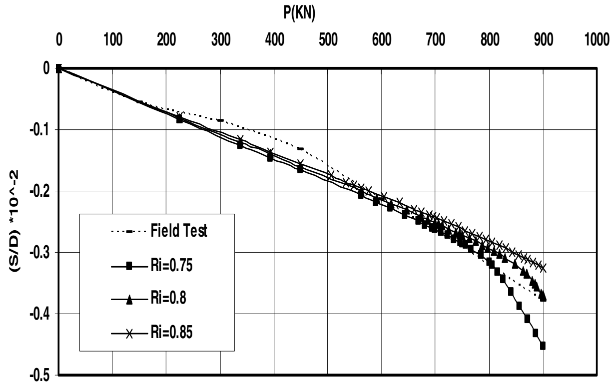


Figure 7. Simulation of P06 at different values of (R_i)

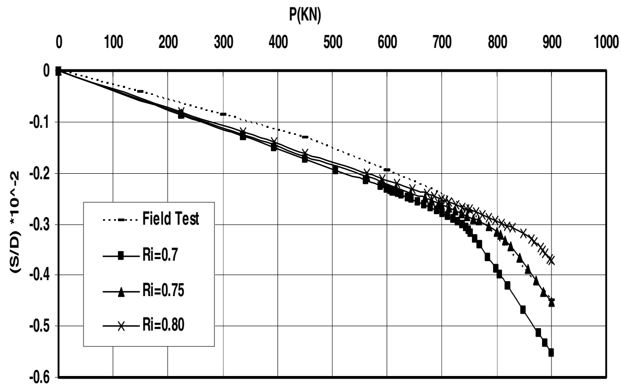


Figure 8. Simulation of P07 at different values of (R_i)

The interface factor relates pile - soil adhesion (Ca) and interface friction angle (Φ_i) to soil undrained cohesion (C) and angle of internal friction (Φ) according to Equation 1.

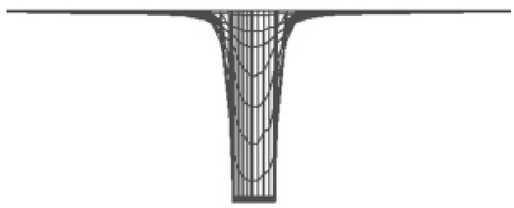
$$R_i = \frac{\tan \Phi i}{\tan \Phi} \text{ for sand, } = \frac{Ca}{C} \text{ for clay} \qquad (1)$$

The best matched values of the interface factor for the tested pile models are shown in Table 5.

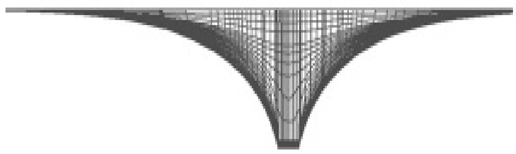
Table 5. The best matched values of the interface factor for Driven and CFA piles

Model	P01	P02	P03	P04	P05	P06	P07
R_i	0.97	0.97	1.00	0.95	1.00	0.80	0.75

As shown, below working load, the change of interface factor has no effect on the load-settlement relationship. However, for loads exceed the working load the interface factor has a major influence on the load-settlement relationship. This phenomenon might be attributed to that at higher loads plastic deformation of soil controls the settlement behaviour of the pile. Plastic deformations are concentrated in a narrow zone surrounding the pile shaft, outside this zone the soil behaviour remains mainly elastic as shown in Fig 9. Below working load, the plastic deformation zone is wider and much larger soil volume contributes to pile movement which cannot be digested to a single factor at pile soil interface.



a) Deformation under high load levels



b) Deformation under low load levels

Figure 9. Plastic deformation area around pile

5 LARGE DIAMETER PILES

According to ECP, for pile executed through boring the soil adhesion is 40% of the soil cohesion and the angle of friction between pile and soil is 75 % of the soil angle of friction.

The value of interface factor (R_i) will be assumed here to be 0.75 for sand soil and 0.4 for clay soil according to Equation 1.

When using a long steel caisson during the installation process, the interface factor is assumed a unity along the caisson length.

For large diameter piles, the lateral pressure coefficient (K) has strong influence on the load - settlement curve and the interface factor becomes less effective. Numbers of iterations on (K) for sand and rock soil were performed to match the simulated load-settlement curve with field pile load test.

The two pile load tests P08 and P09 data are presented in Table 6.

Table 6 Details of large diameter piles and test loads

Model	Length (m)	Diameter (m)	Test Load (KN)	Displacement at maximum load Δ (mm)	Δ/D $*10^{-2}$
P08	25	1.00	7500	10.23	1.02
P09	17.5	1.80	24050	4.35	0.24

For P09 a long caisson with 6 m length is used for installation, 0.5 m above ground level and 5.5 m below ground level, (R_i) is assumed to be 1 along caisson length.

The ground profile and soil properties are shown in Tables 7 and 8.

Table 7 Soil design parameters for P08

Layer	Fill	clay	sand	clay	sand	clay
Thick (m)	1.4	9.1	9.5	4.5	3.5	9
γ (KN/m^3)	16	18	18.5	18.5	19	18.5
Cu (KN/m^2)	-	125	-	135	-	125
Φ (degree)	32	-	36	-	38	-
E_s (MPa)	20	87.5	75	10.3	112	87.5
ν	0.30	0.35	0.30	0.35	0.30	0.35

The water table is at 3 m below the ground level.

Table 8 Soil design parameters for P09

Layer	Cemented sand	Calcareous sandstone	gypsiferous sandstone
Thick (m)	5.5	16.2	23.3
γ (KN/m^3)	19	20	20
Cu (KN/m^2)	5	60	80
Φ (degree)	36	39	39
E_s (MPa)	70	190	210
ν	0.30	0.25	0.25

The water table is at 6.5 m below the ground level.

During the installation of P09, four vibration wire strain gauges were installed at six different levels along the pile shaft. These strain gauges are used to investigate soil compressibility modulus for each layer. Compressibility modulus for soil along pile length for each layer is estimated from the slope of the local shear stress versus local displacement curves as assessed from the strain gauges and settlement readings. The measured values of soil compressibility modulus are shown in Table 9.

Table 9 Field measured values of soil compressibility modulus

Layer	Field Measured soil Compressibility modulus (MPa)
Cemented sand	250
Calcareous sandstone	1450

6 RESULTS AND DISCUSSIONS

The Load-settlement relationship generated from numerical analysis was plotted on the same graph with field load-settlement for different values of lateral coefficient pressure and soil compressibility modulus in Figures 10 through 12.

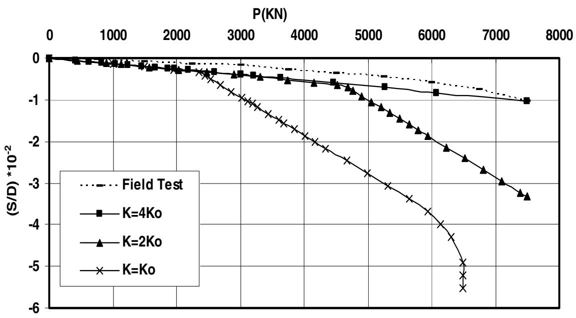


Figure10. Simulation of P08 at different values of lateral pressure coefficient

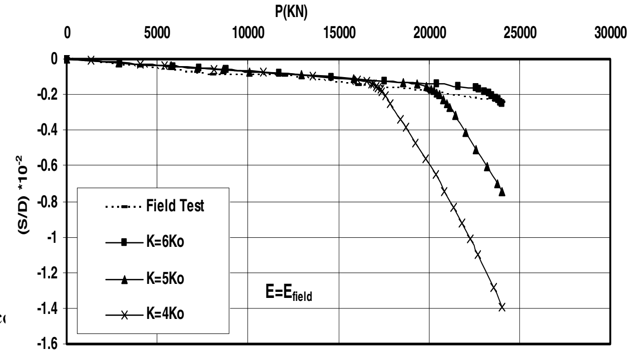


Figure 11. Simulation of P09 at different values of lateral pressure coefficient

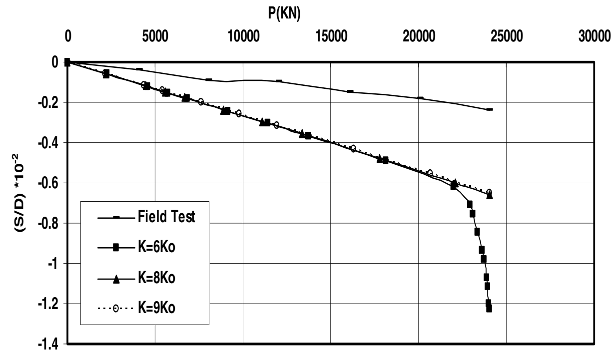


Figure 12 Simulation of P09 at different values of lateral pressure coefficient using field measured soil compressibility modulus values

As shown in Figure 10, the best matched results for P08 are for lateral pressure coefficient (K) of 4 times the value of lateral pressure coefficient at rest (K_o).

Fig 11 shows that the number of iterations on the value of lateral pressure coefficient was not enough to reach the best simulation, as the working load of P09 is very high. In these calculations the soil compressibility modulus was calculated based on soil design parameters. Cycles showed in Figure 12 are for different values of K and soil actual field measurement coefficient of compressibility. The best matched results are at K= 6 K_o and with using the field measured values of soil compressibility modulus.

7 CONCLUSIONS

7.1 Small diameter piles

1) For load values exceed the working load, the value of the interface factor (R_i), which reflects the interaction between pile and soil, has a strong effect on the simulated load-settlement relationship. However, it has no effect at load values below the working load.
2) The best matched values of the interface factor are found to vary between 0.95 and 1 for driven piles and between 0.75 and 0.80 for bored piles. These values relate pile - soil adhesion (Ca) and interface friction angle (Φ_i) to soil undrained cohesion (C) and angle of internal friction(Φ).

7.2 Large diameter piles

1) The value of the lateral pressure coefficient (K) is the major parameter controls the simulated load-settlement behaviour for large diameter piles.
2) The best matched values of the lateral pressure coefficient (K) were found to be 4 times and 6 times of the lateral pressure coefficient at rest (K_o) for sand soil and rock soil respectively. These values are applicable for small level loads of value less than 10000 KN according to the reference case study.
3) At higher pile load levels exceed 10000 KN according to the reference case study, the value of the soil compressibility modulus (E_s) controls the simulated load-settlement relationship.
4) It is highly recommended to use soil compressibility modulus in numerical simulation as estimated from field test results.

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