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SIMULATION BETWEEN IN-SITU PILE LOAD TEST AND NUMERICAL ANALYSIS OF LARGE DIAMETER BORED PILE IN PORT SAID EAST PORT-EGYPT

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ABSTRACT:
At the end of 2015, Suez Canal Authority and Ministry of defense planned the construction of a new container terminal at east of Port Said port. The project comprises the construction of approximately 2.5 KM of new quay wall fully equipped to accommodate large container vessels. large diameter bored piles (~72 m in length and 1.20 m in diameter) were used to transmit the load to the soil safely. According to several international codes and foundation design standards, field loading tests are the most effective way to evaluate the pile's bearing load capacity. However, loading until failure is hard to achieve. In this paper, numerical analysis using (PLAXIS 2D, V8.2) was carrying out to simulate load-displacement curve of load test for large diameter bored piles at the location of Port Said East Port, Egypt, as well as, (All Pile, V.6) which is relied on (p-y) analysis curve. Avery good match was observed between numerical analysis using PLAXIS and the pile load tests in loading-unloading cycles along the pile shaft and the percentage of compatibility is about 95%. In contrast to PLAXIS, there are a significant difference between the results of All pile program and pile load test and the percentage of match is approximately 75%.

KEYWORDS: **Load-Displacement Curve, Large pile diameter, Bored Piles, 2D-Plaxis program, All Pile program.**

محاكاة بين اختبارات التحميل في الموقع والتحليل للعددي للخوازيق ذات الأقطار الكبيرة في شرق ميناء بورسعيد

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الملخص:
في نهاية عام ٢٠١٥، عزمت هيئه قناة السويس و وزاه الدفاع علي إنشاء محطة حاويات جديدة في ميناء شرق بورسعيد. يتكون المشروع من بناء ما يقرب علي ٢.٥ كيلو متر من الجدار الجديد لرصيف مجهز بالكامل لاستيعاب سفن الحاويات الكبيرة. لذلك تم استخدام خوازيق ذات أقطار كبيره (القطر ١.٢ متر ،الطول حوالي ٧٢ متر) لنقل الأحمال الي التربة بأمان. وفقا للعديد من المواصفات ومعايير التصميم الدولية، فان اختبار التحميل الحقلي هو الطريقة الأكثر فاعليه لحساب قدره تحمل الخازوق ومع ذلك فانه من الصعب الوصول لمرحله الانهيار في هذا النوع من الخوازيق. في هذا البحث تم إجراء التحليلات العددية لمحاكاة منحني الحمل-الازاحه في اختبار التحميل للخوازيق ذات الأقطار الكبيرة التي تم إجراؤها

في ميناء شرق بورسعيد باستخدام البرنامج العددي بلاكسيسز للتحقق من معاملات نموذج الحدود اللا متناهية التى تتحكم فى سلوك منحنى الحمل والهبوط للخازوق. اظهر هذا البحث وجود تتطابق جيد جدا بين التحليلات العدديه باستخدام برنامج ال بلاكسيسز واختبارات التحميل في الموقع وهذه النسبة وصلت لحوالي ٩٥% . ولكن هذه النسبة انخفضت الي ٧٥% عند استخدام برنامج أول بايل. ومن خلال هذه النسب نستطيع ربط نتايج اختبارات التحميل للخوازيق بطريقـــــه الحـــدود اللا متناهيه.

الكلمات المفتاحيه: منحني الحمل-الازاحه، الأقطار الكبيرة، خوازيق الحفر، برنامج التحليل العددي، برنامج البلاكسيز، برنامج أول بايل.

1. INTRODUCTION

Large diameter bored piles are qualified to be the most powerful element of deep foundations implemented in many types of heavy loaded structures such as the high-rise buildings, offshore ports, wind power mills, storage silos. They are employed most frequently both to support heavy loads and to minimize settlement (O'Neill and Reese, 1999), (Eid et al, 2019) .The in-situ full scale pile loading test is the most recommended methodology in several international geotechnical codes and foundation design standards ((ECP 202/4, 2005), (DIN 4014, 1990) and (AASHTO, 1998)) to evaluate the ultimate carrying capacity of large diameter bored piles in spite of its high cost as well as time consumption. The Egyptian code of practice (ECP 202/4, 2005), recommends to use the in-situ pile loading test for evaluating the ultimate capacity of large diameter bored pile. However, loading of large diameter bored piles, till achieving apparent failure is practically hard to achieve. This may be the reason why the measured pile load-settlement curves for large diameter bored piles usually do not show an apparent failure point.

Recently, finite element calculations and numerical analyses have risen in geotechnical problems for design foundation. In this paper, finite element model is used to simulate results of in-situ large diameter pile load test under loading-unloading cycles.

2. SITE UNDER INVESTIGATION

Port Said is located on the Egyptian Mediterranean north eastern cost of the Nile Delta approximately 70 km of Damietta port. The project comprises the construction of approximately 2.5 km of new quay wall fully equipped to accommodate large container vessels. The study area consists of two zones 4 and 5 as shown in **Figure (1).** Fortunately, all piles have the same length and diameter 72 m and 1.2 m respectively according to stratification of soil in boreholes.

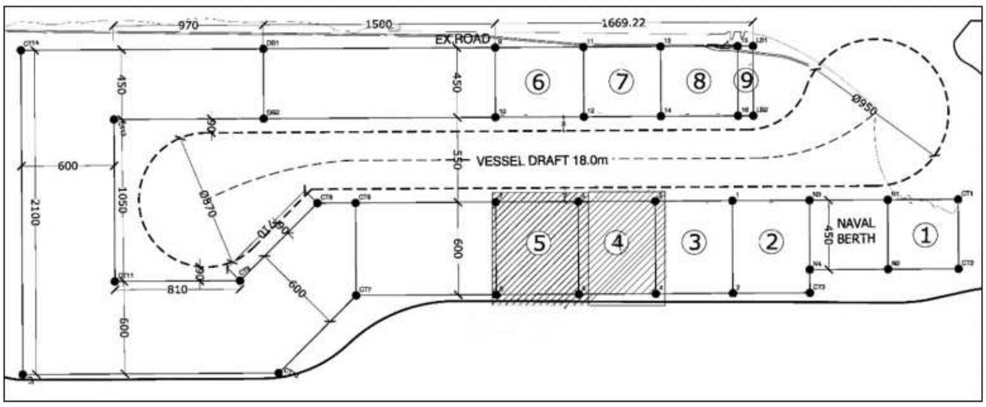

Fig (1) location of zones 4 and 5 under study.

3. SOIL PROFILES AT LOCATIONS OF BOREHOLES

In order to provide preliminary information of the soil layers, geotechnical investigation was carried out. Several boreholes were extended down to 100 m deep till reaching a layer that could support the applied load properly. **Figure (2)**, demonstrates the soil profile classification for boreholes under study (B.H: 2, 3, 4, 6, 7, 9 and 10).

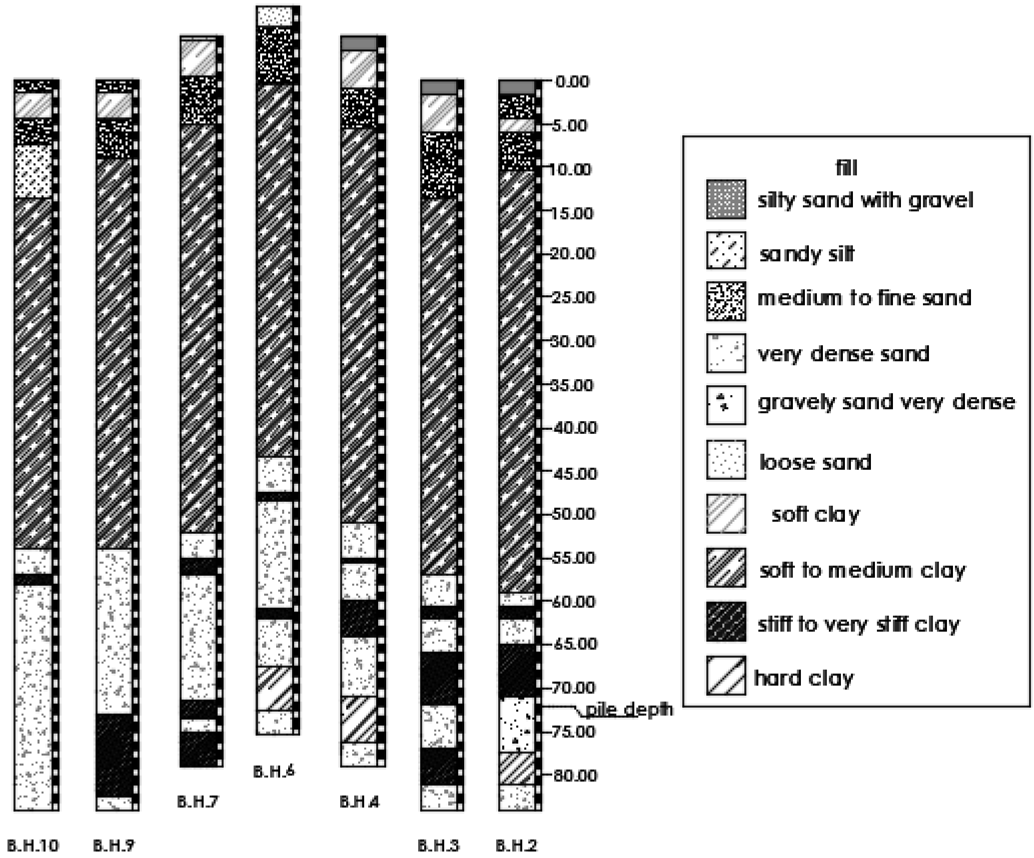

Fig (2) Soil stratigraphy for boreholes.

4. ESTIMATION OF ULTIMATE BEARING CAPACITY OF BORED PILE

Due to the importance of pile foundation in transferring the structural load to the bearing ground located deep below ground surface, various methods are used to determine the ultimate bearing capacity (Q_{ult}) of a single vertical pile either field method or theoretical equations such as:

- Field load tests (pile load test at the site).
- Dynamic method (pile driving formulae).
- Correlation use of SPT and CPT values.
- The use of static bearing capacity equations.

To ascertain the field performance and evaluate the load carrying capacity, in-situ pile load tests are commonly used reliably.

In situ pile load test:

The tests loads are applied using a hydraulic jack which pushes on a reaction frame, with sufficient reaction capacity to perform tests, as shown in **Figure (3)**.

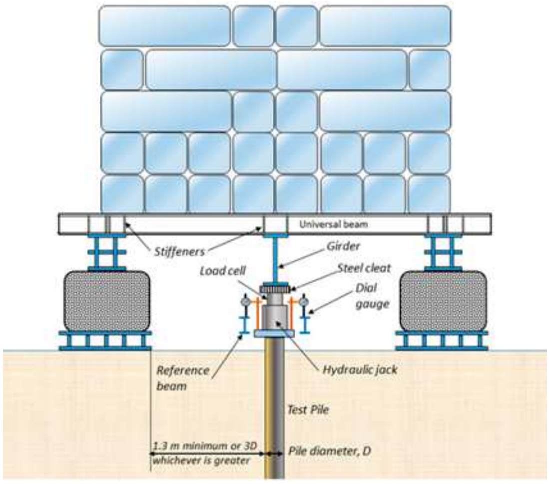

Fig (3) Device instruments for pile load test (Moayedi, 2019)

The tested pre-construction piles were loaded up to 26000 kN, representing 200% of the specified allowable pile load which is 13000 kN. The timing of loading and unloading stages, and corresponding time duration are according to (ASTM-D1143).

5. NUMERICAL MODELING

Numerical analysis was used to study the load-settlement behavior and failure load for large diameter bored pile under vertical loads is applied at the pile head using the commercial software (PLAXIS 2D-V8.2) (Brinkgreve and Broere, 2004) as well as, (All pile V.6) program which is relied on (p-y) analysis curve.

5.1 PLAXIS model

5.1.1 Geometry and boundary conditions

Two-dimensional axisymmetric finite element method was constructed using "PLAXIS 2D " after several trials to ensure all soil conditions are taken into account. The model height was 140 m and the model width was 70 m, as shown in **Figure (4)**. The external boundary conditions of the model were generated according to the following rules:

- The right and left edge were fixed in horizontal direction and free to move in the vertical ($U_X = 0$).
- The bottom boundary was fixed in two directions, ($U_X = U_Y = 0$).
- The top boundary was free in both directions.

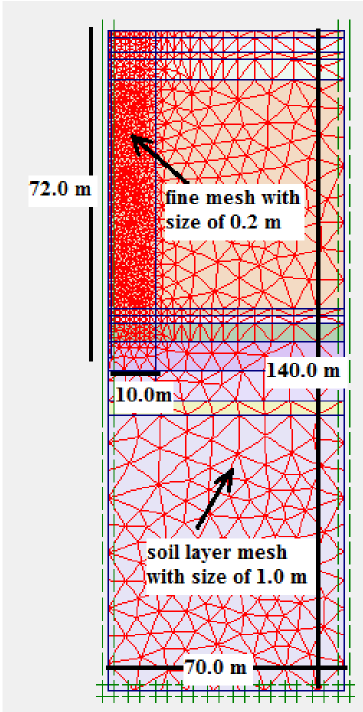

Fig.4: Geometry dimensions and boundary conditions of finite element model.

5.1.2 Properties of the Pile Model

Two-dimensional triangular elements "15 nodes" were selected to model the pile shaft. The material model used was Linear elastic model following Hooke's Law of isotropic linear elasticity. For accurate base resistance, the model needs at least two or three elements at the pile tip to get rid of the mesh dependency (Wehnert and Vermeer, 2004). Characteristic compressive strength (f_{cu}) of 350 kg/cm^2 was obtained in field after 28 curing days. According to this value, Young's modulus of elasticity could be determined according to Egyptian code of practice (ECP 202/4, 2005) from this relation refer to Eq. 1

$$E = 14000\sqrt{f_{cu}} \quad kg/cm^2 \qquad (1)$$

Summary of the pile properties are shown in **Table 1**.

Table 1: Structural parameters of large diameter bored pile.

Parameters of piles	Values
Pile diameter (D)	1.2 m
Pile length (L)	72 m
Young's modulus ($E_{elastic}$)	26 $*10^6$ kN/m^2
Poisson's ratio (υ)	0.2
Unit weight (γ)	25 kN /m^3

5.1.3 Properties of the Soil Model

The soil was modeled using (15-noded) Triangular elements. Different sizes were used to investigate the sensitivity of the soil mesh refinement and its effect on the results. Good progress was observed in stress and settlement results when fine mesh (with size of less than 0.2m) was used. However, analysis time significantly increased. As a compromise, the zone of very fine mesh with size of 0.2m was considered around and below the pile (10m x 77m). Gradually, soil mesh size is increased to be 1.0 m at boundaries locations.
Hardening-soil model is an advanced model for simulation the soil behavior; the soil stiffness is described by three types of elasticity moduli: the oedometer loading stiffness E_{oed}, triaxial

loading stiffness E_{50} and triaxial unloading stiffness E_{ur}. Almost practical cases consider that, E_{ur} is equal three times of E_{50} while E_{oed} value is equal to E_{50} (Teshome and Ismail, 2011). The dilatancy angle(ψ) is usually estimated when the internal angle of friction(φ) is more than 30^o, from the relation $\psi = \varphi - 30^o$. The coefficient of lateral earth pressure (k_o) is the most important and difficult parameter to determine (Kulhawy, 1991). A simplified relationship to calculate k_o based on soil the friction angle (φ) and the over consolidation ratio (OCR) is given by Eq. 2 (Kulhawy and Mayne, 1991):

$$k_o = (1\text{-}\sin\varphi)\ OCR^{\sin\varphi} \qquad (2)$$

Based on geologic and construction history at site location, OCR=1 is suitable value to be used in the equation. Drained condition was used to represent sand soil with no excess pore pressures are generated and undrained condition for clay soil with a full development of excess pore pressures.

Table 2, illustrates mechanical properties of soil layers according to Egyptian code of practice (ECP 202/3, 2005) for both sand (related to N value for SPT test) and clay. Young modulus E_s for sand is usually calculated according to the following specific formulas and recommended correlations by the Egyptian code (ECP 202/3, 2005):

- For silty sand soil, Es = 4 N kg/cm^2
- For medium to fine sand soil, Es = 7 N kg/cm^2 (3)
- For dense sand soil, Es = 10 N kg/cm^2

Table 2: Mechanical properties of soil layers.

soil layers	Unit weight "γ"	Cohesion "c"	Friction angle "Φ"	Poisson's ratio (υ)	Modulus of Elasticity "E_{oed}"	Modulus of Elasticity "E_{50}"	Modulus of Elasticity "E_{ur}"	k_o
Units	kN/m^3	kN/m^2	o	----	MN/m^2	MN/m^2	MN/m^2	----
Medium - Stiff clay	18.1-20.6	50-80	-----	0.35-0.4	12-18	12- 18	36- 54	1
Stiff - Hard clay	20.6-21	80-200	-----	0.3 - 0.35	18- 40	18 - 40	54 - 120	
Medium sand	17.5-18.5	1	25-30	0.3	25- 30	25 - 30	75 - 90	.5-.57
Dense sand	18.5-19.5	1	36-40	0.25- 0.3	3- 60	30 - 60	90 - 180	.43-.5

5.1.4 Parameters for Interface Elements

An elastic-plastic model is used to describe the behaviour of interfaces for the modeling of soil-structure interaction. When the interface is elastic then both slipping (relative movement parallel to the interface) and gapping or overlapping (relative displacement perpendicular to the interface) could be expected to occur. The displacement magnitudes are illustrated in equations "(4)" and "(5)" (**PLAXIS 2D-V8.2**):

$$\text{gap displacement} = \frac{\sigma \cdot ti}{Eoedi} \qquad (4)$$

$$\text{slip displacement} = \frac{\tau \cdot t_i}{G_i} \qquad (5)$$

where,

σ: the strength of the soil (ultimate shear stress) [kN/m^2].
G_i: Shear modulus of interface [kN/m^2].
E_{oedi}: Compression modulus of interface [kN/m^2].
t_i: virtual thickness of the interface factor (Ranges between 0.01 to 0.1).
The Coulomb criterion is used to distinguish between elastic behavior, where small displacements can occur within the interface, and plastic interface behavior when permanent slip may occur. Moreover, shear strength parameters of the interface elements are linked to the strength of the adjacent layers of soil through a strength reduction factor (R). as represented by equation (6):

$$C_i = R^* C_{soil} \qquad (6)$$

$$\tan \varphi_i = R^* \tan \varphi_{soil}$$

$$\Psi_i = 0^o \text{ for } R<1, \text{ otherwise } \Psi_i = \Psi_{soil}$$

Where,

φ_i: Angle of friction for the interface. [°]
C_i: Effective adhesion for the interface. [kN/m^2]
Ψ_i: Angle of dilatancy for the interface .[°]
In this research, a sensitivity analysis was performed for the parameter R based on the comparison between the settlement in pile load tests and finite element results. The best comparison was observed when the reduction factor of shear strength (R) was (1.0).

5.2 All Pile Program Model

All Pile program analyzes all types of pile load capacity efficiently and accurately. Additionally, define new pile types and input customized parameters based on local practices and experience.
This program capable of preforming the calculation of vertical load and settlement by using two method of analysis: Vesic method and Reese method.
Reese method is the method used to calculate settlement of the pile and corrected N value for SPT test was used to input the parameter of soil. Tables 4, 5 and 6 show the parameters are needed in All pile program for the pile and the soil:

Table 3: Soil properties for clay soils in All Pile program.

Soil classification	Unit weight "γ" kN/m^3	Cohesion "C" kN/m^2
Soft	16.3 - 18	8 - 12
Medium- stiff	18.1 - 20.6	25 - 30
stiff - very stiff	20.6 - 21	80 - 120

Table 4: Soil properties for sand soils in All Pile program.

Soil classification	N1 value for SPT	Unit weight " γ " kN/m^3	Friction angle Φ
Loose sand	3.0 - 10.0	16.4-17.5	20 - 25
Medium	10.0 - 25	17.5 - 18.5	25 - 30
Dense	26 - 50	18.5 - 20	36- 40

Table 5: pile specifications in All Pile program.

pile type	Drilled shaft D > 60 cm
pile length " L"	72 m
pile diameter "D"	1.20 m
total area "A_t"	1.13 m^2
modulus of elasticity "E"	$26*10^3$ MN/m^2
Inertia "I"	$10.18*10^6$ cm^4

6. RESULTS AND ANALYSIS:

By using numerical model and static load test, the performance of the pile for loading-unloading cycles and the ultimate bearing capacity as well as maximum deflection were predicted seven boreholes and loading tests for Port Said East Port were chosen for the comparison of the results. According to Egyptian code of deep foundation (ECP 202/4, 2005), if in-situ pile loading test results did not show apparent failure values, the ultimate load of the piles can be estimated as the average values that are obtained from Brinch Hansen 's 90 percent criterion (1963and Modified Chin 's method (1970). Table 6 illustrates the results of in-situ pile loading tests as well as the required details of each pile such as lengths, diameters, design loads and ground water table level.

Table 6: Results of Static load tests.

Test No	Model "No"	Pile length L (m)	Pile diameter D (m)	Pile load test Q (kN)	Ground water level G (m)	Predicted ultimate load		
						Brinch Hansen (kN)	modified chin (kN)	*Average load (kN)
1	2	72	1.20	7500	2.10	15667.40	14685.70	15175.50
2	3	72	1.20	7500	2.80	13596.50	12746.70	13171.60
3	4	72	1.20	10000	1.75	15788.20	14808.40	15298.30
4	6	72	1.20	7500	1.00	12138.40	11379.00	11758.70
5	7	72	1.20	10000	2.00	25823.20	24209.00	25016.10
6	9	72	1.20	7500	3.00	18767.20	17594.30	18180.75
7	10	72	1.20	7500	3.50	31784.00	29797.50	30790.75

The following Figures show the load-settlement results of the field static load test, along with the extrapolation of the results using Brinch-Hansen method recommended by the ECP. Model number 4 and 7 were loaded up to 10000 kN (2 Q_{design}) but anther models were loaded up to 7500 kN (1.5 Q_{design}) according to the field data. The figures also show the results of the numerical simulation for PLAXIS and All pile programs for the same pile. The figures show excellent comparison between measured and numerically predicted results using PLAXIS but, there is a big difference between All pile predictions and field loading tests.

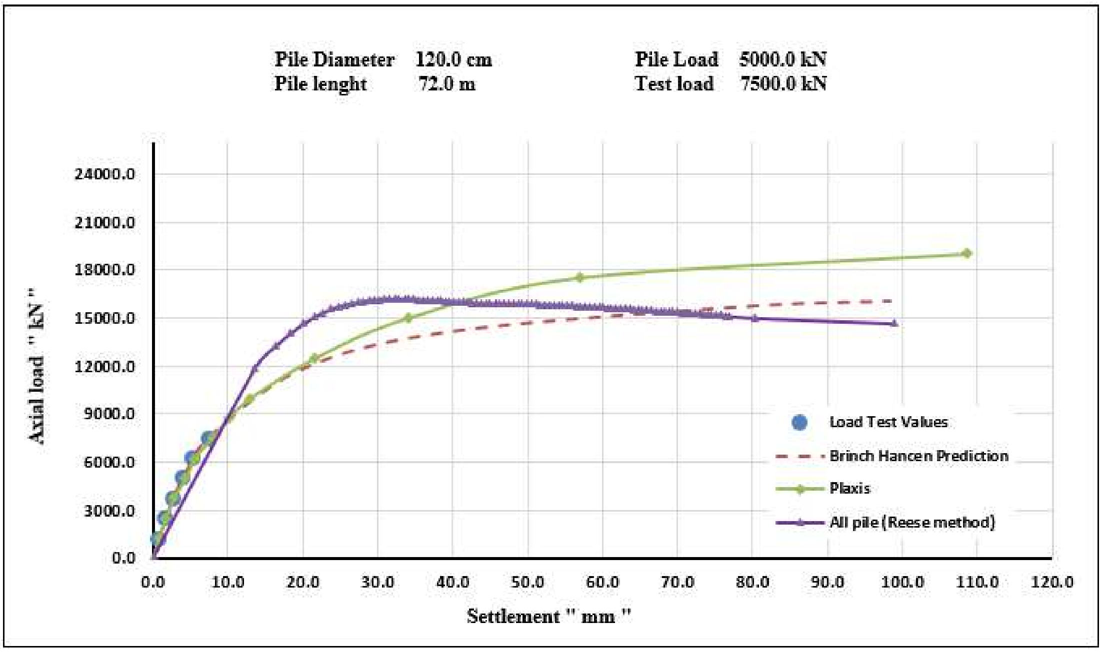

Fig. 4: Comparison between field test and finite element analysis in loading cycle for model No 1

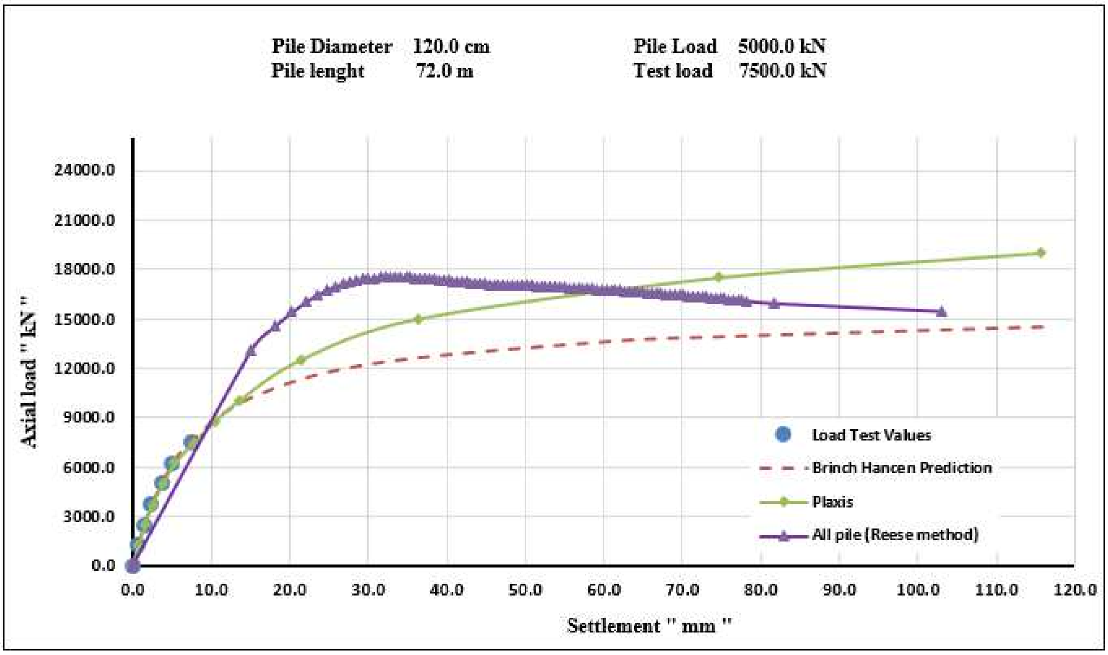

Fig. 5: Comparison between field test and finite element analysis in loading cycle for model No 2

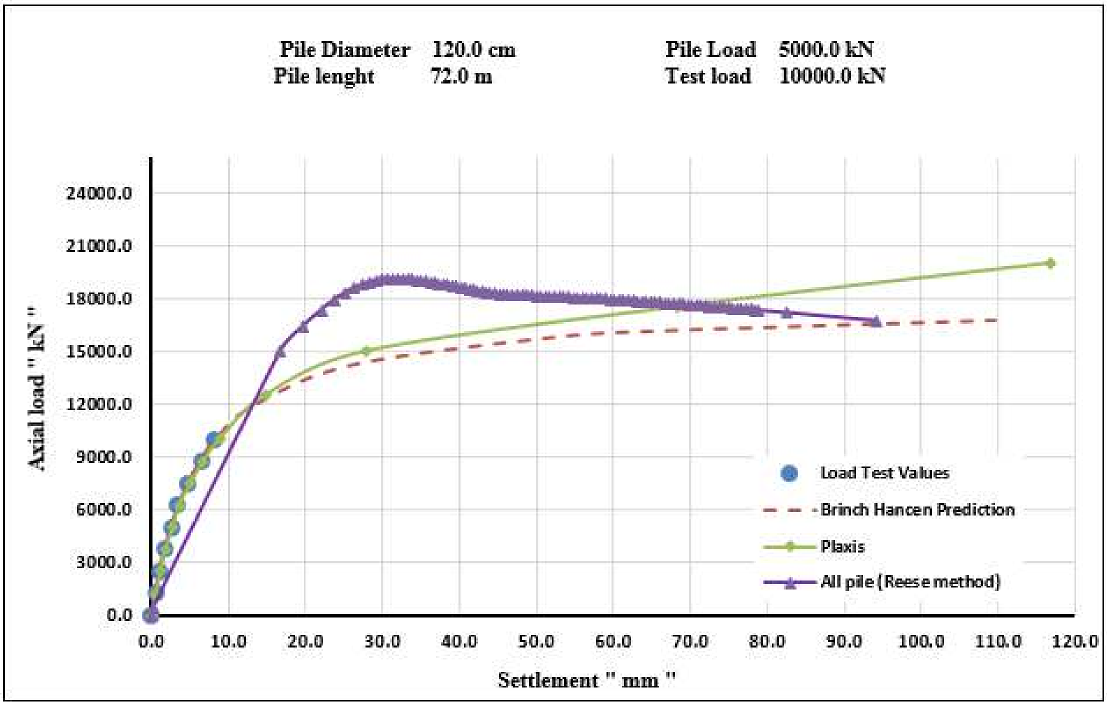

Fig. 6: Comparison between field test and finite element analysis in loading cycle for model No 3

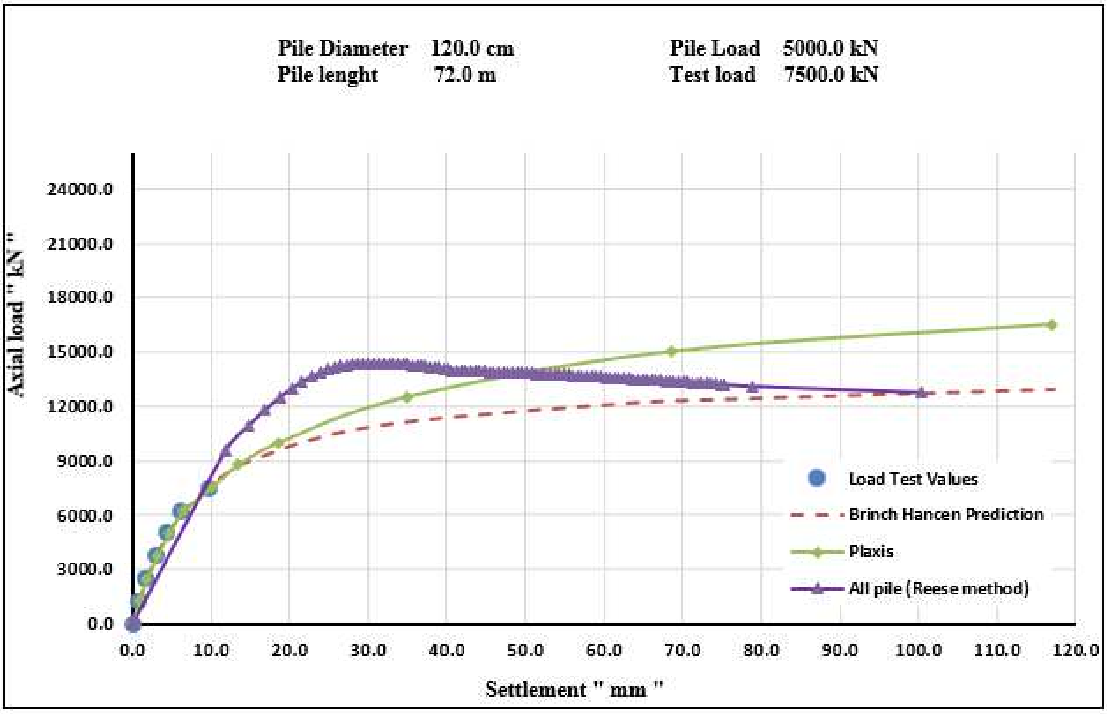

Fig. 7: Comparison between field test and finite element analysis in loading cycle for model No 4

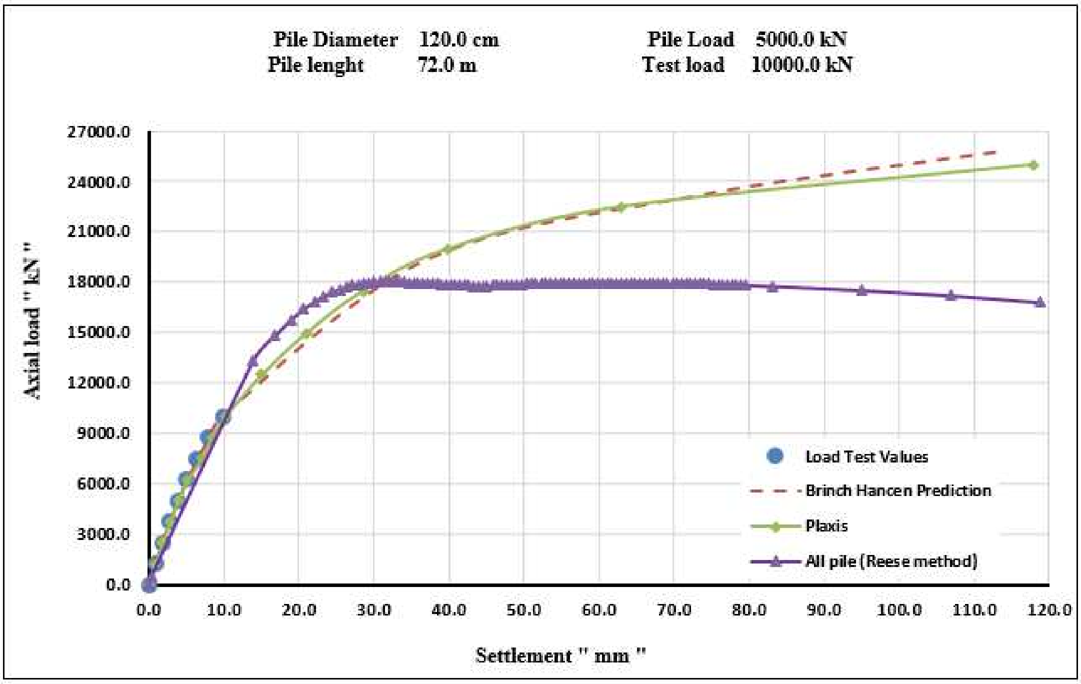

Fig. 8: Comparison between field test and finite element analysis in loading cycle for model No 5

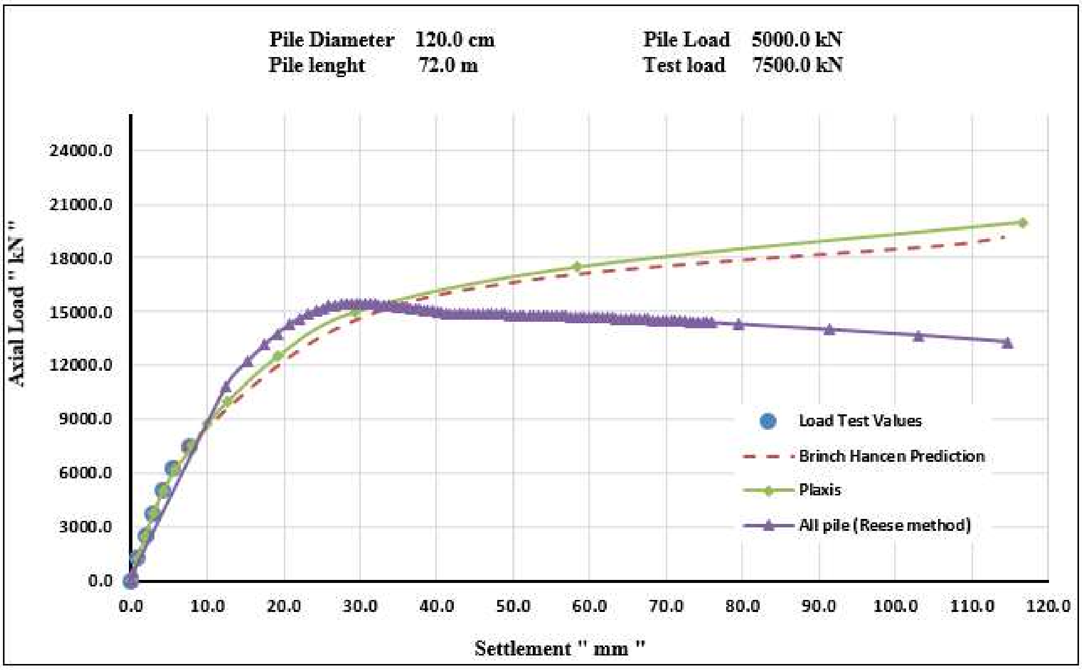

Fig. 9: Comparison between field test and finite element analysis in loading cycle for model No 6

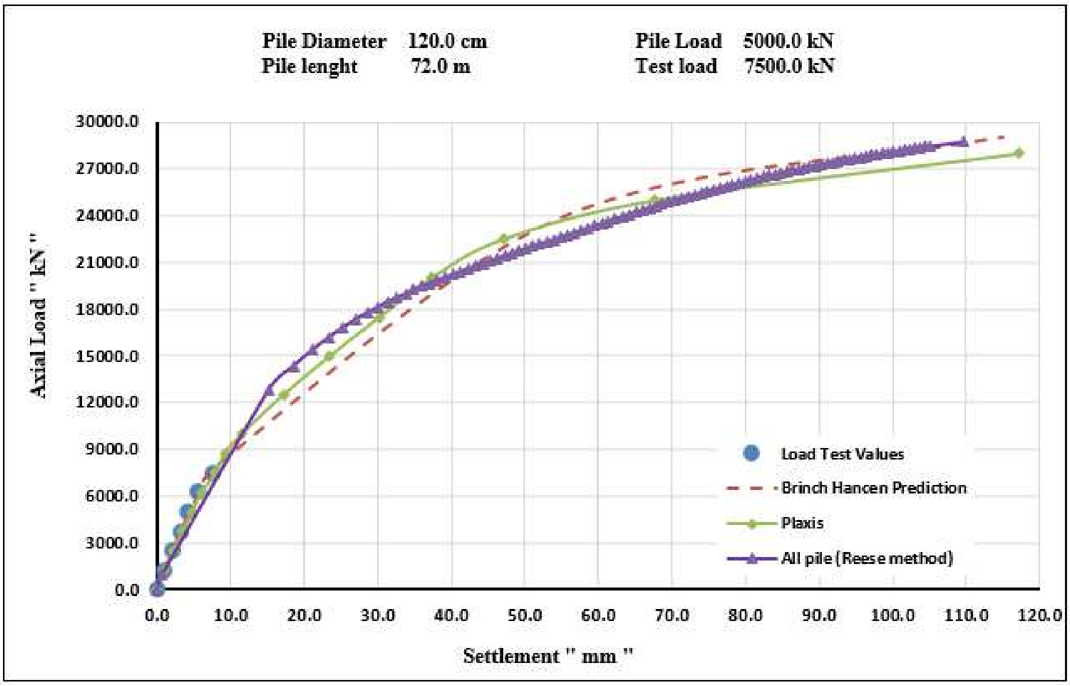

Fig. 10: Comparison between field test and finite element analysis in loading cycle for model No 7

Next figures show for the same tests the comparison between the loading-unloading curves of the experiment versus numerical prediction. Again, the figures show very good comparisons and give confidence on the reliability of the developed numerical models for future prediction.

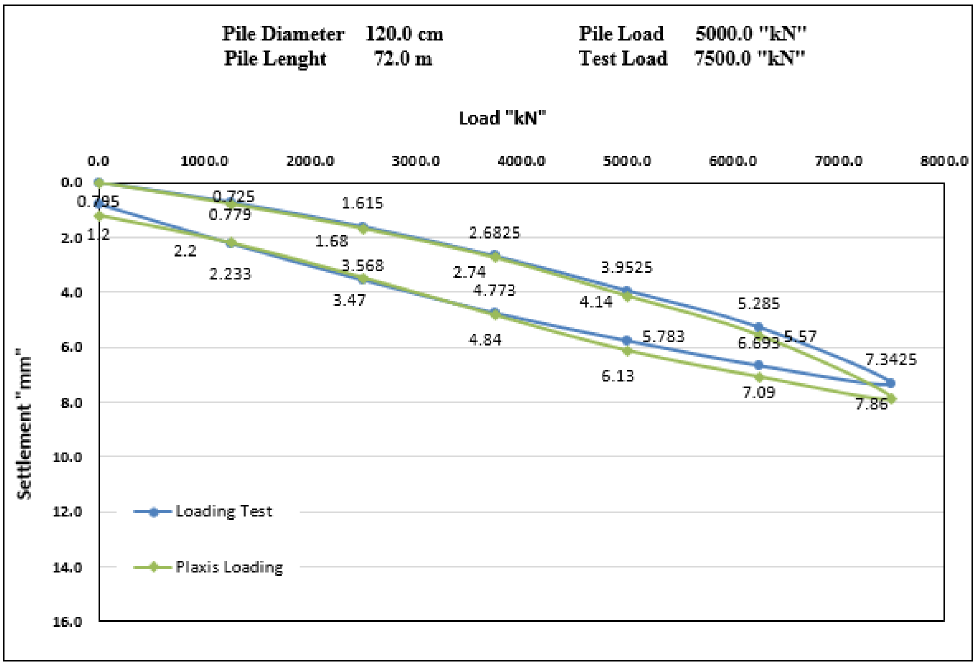

Fig.11. Comparison between field test and finite element analysis in loading-unloading cycle for model No 1

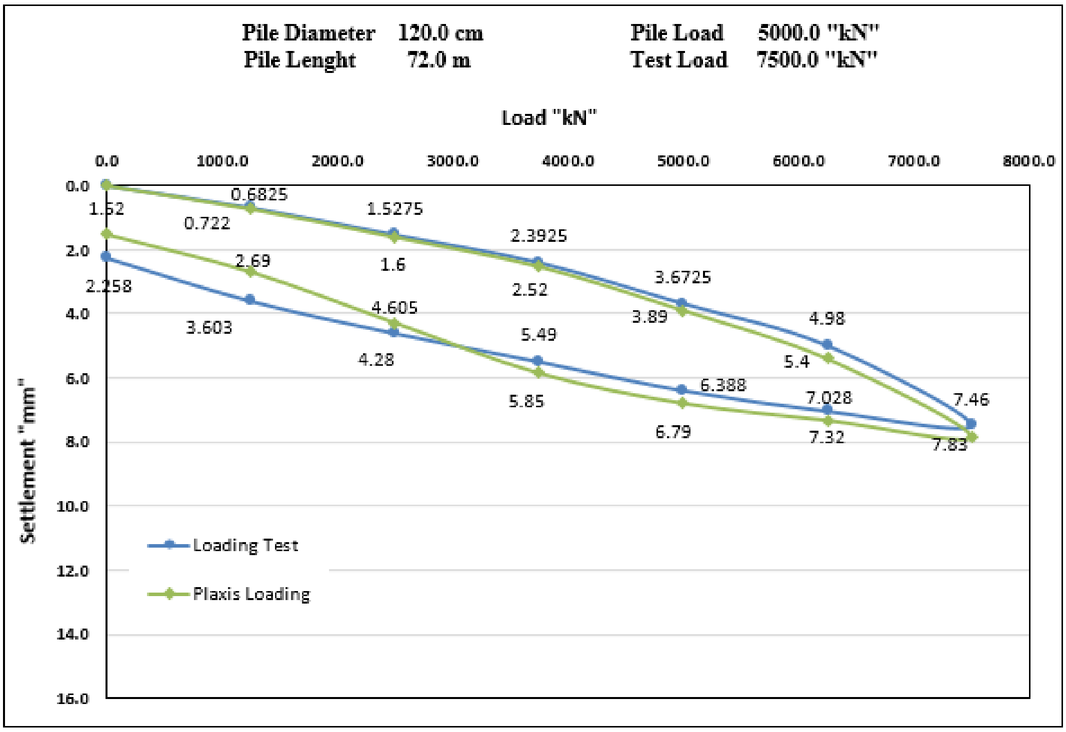

Fig.12. Comparison between field test and finite element analysis in loading-unloading cycle for model No 2

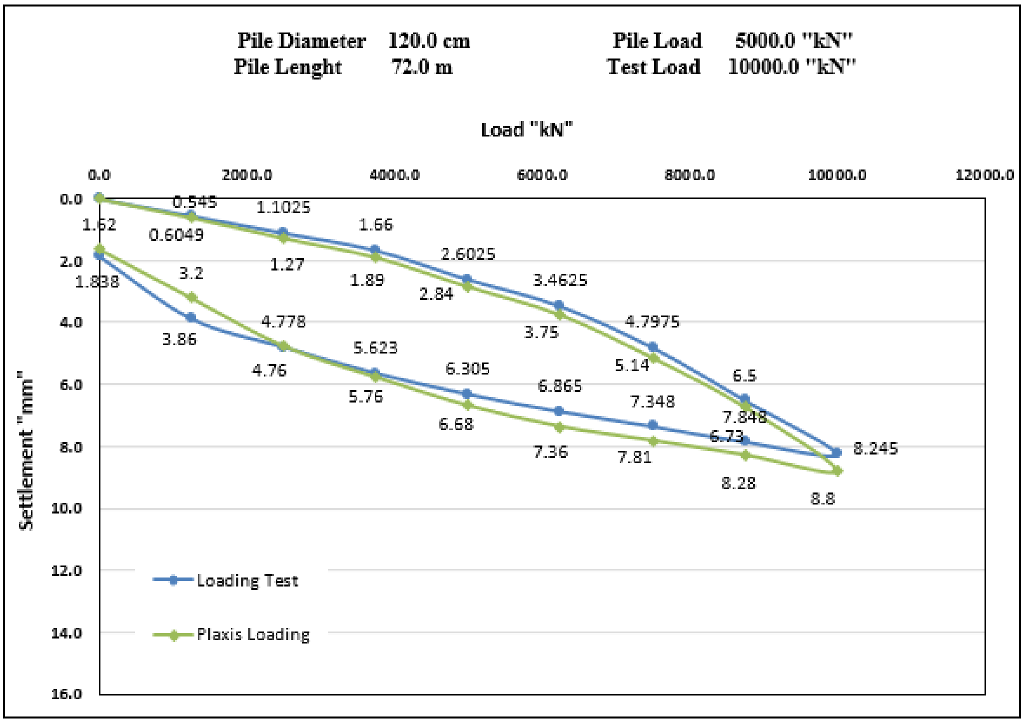

Fig.13. Comparison between field test and finite element analysis in loading-unloading cycle for model No 3

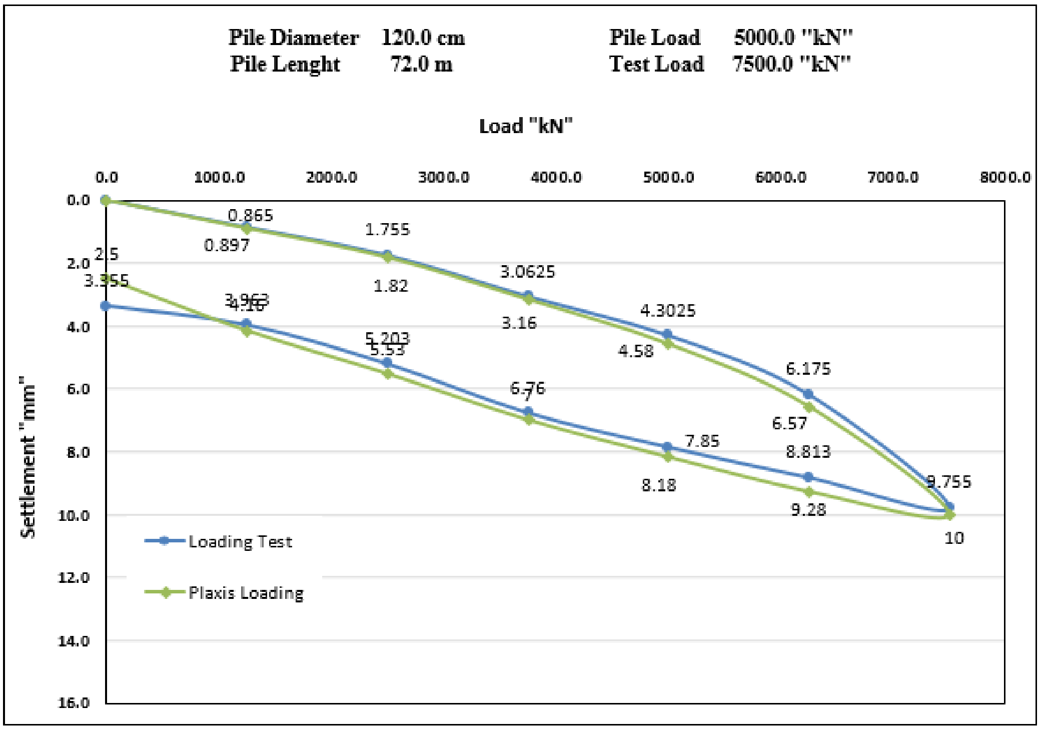

Fig.14. Comparison between field test and finite element analysis in loading-unloading cycle for model No 4

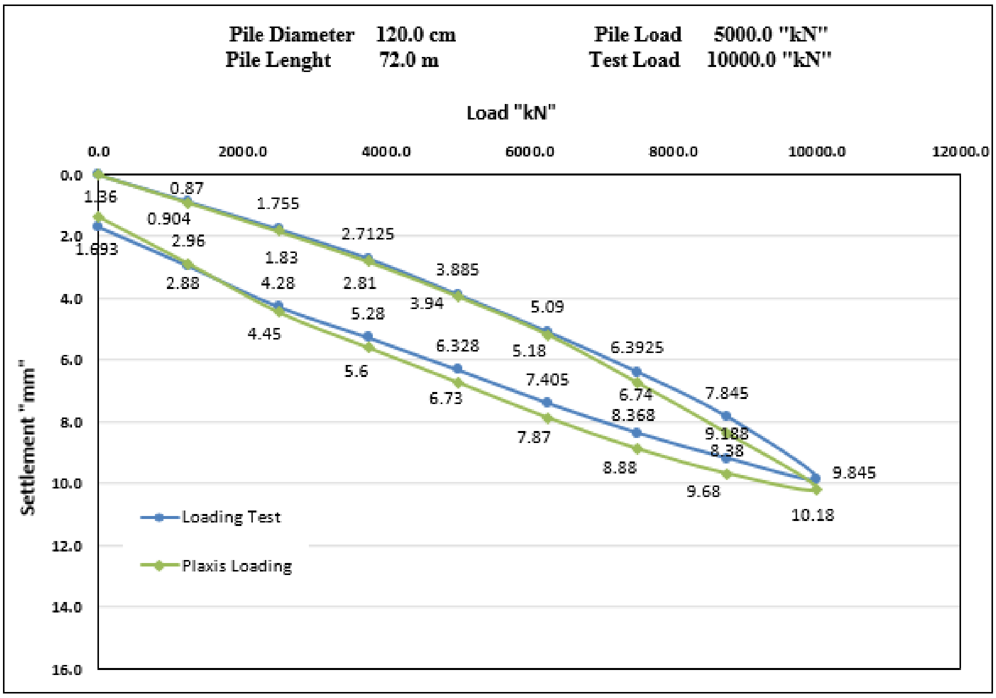

Fig.15. Comparison between field test and finite element analysis n loading-unloading cycle for model No 5

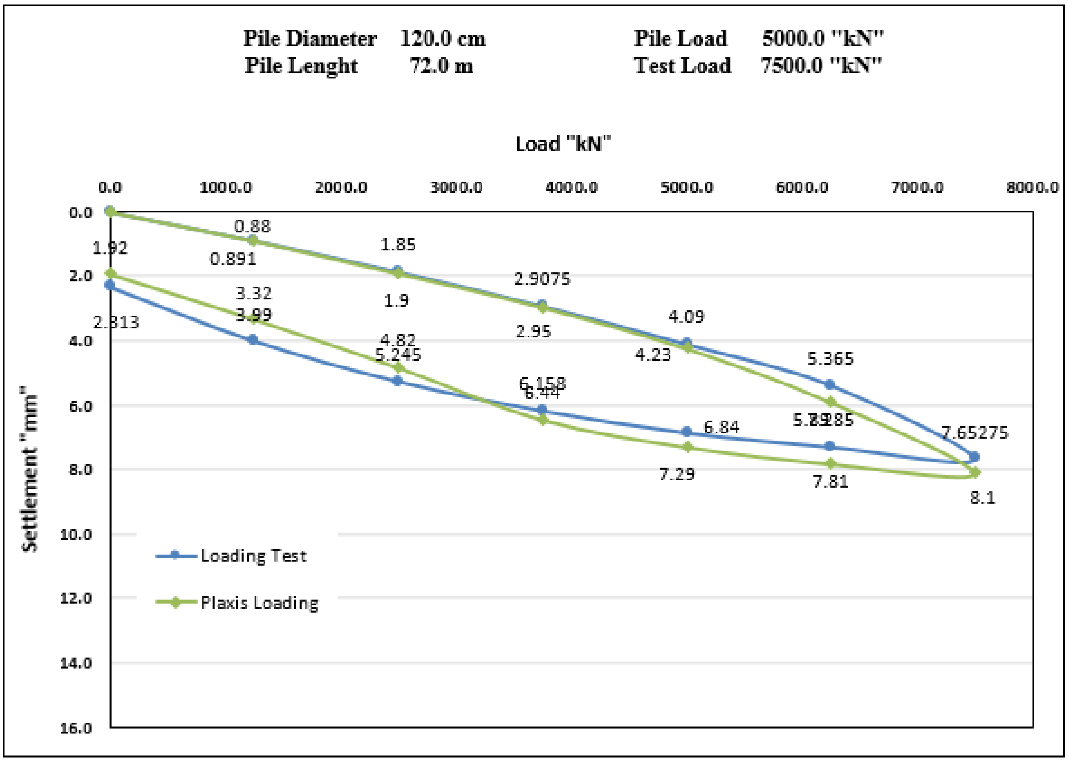

Fig.16. Comparison between field test and finite element analysis in loading-unloading cycle for model No 6

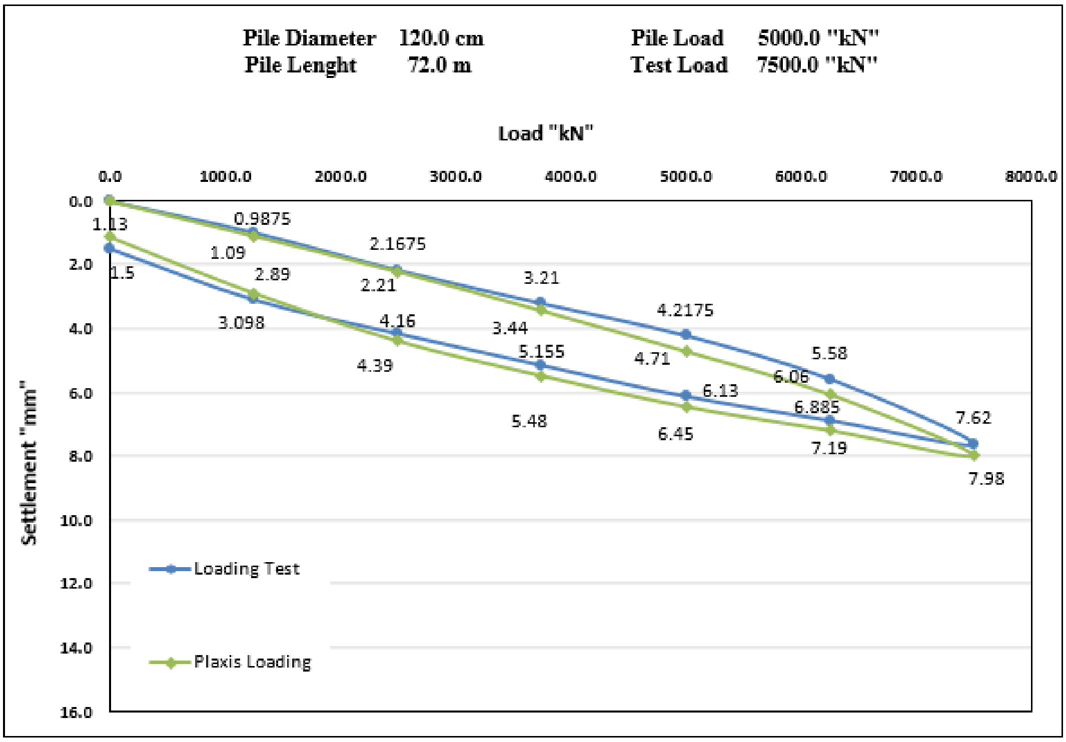

Fig.17. Comparison between field test and finite element analysis in loading-unloading cycle for model No 7

As shown in the previous figures, it can be seen that good agreement is obtained between field measurements and numerical analysis at all stages of the loading-unloading cycles through loading stage; especially from the first stage until achieved to test load (10000 KN).

Table 5, shows settlement comparison between static load test, All pile and PLAXIS at three loading stages: the design load Q, one and half of the design load 1.5 Q and twice the design load 2Q for the loading-unloading cycles.

Table 5: results of settlement for loading tests and numerical analyses

Test No	Model No	Loading cycle								
		Design load "Q"			Test load "1.5 Q"			Test load "2 Q"		
		Settlement in load test	Settlement in PLAXIS	Settlement in All pile	Settlement in load test	Settlement in PLAXIS	Settlement in All pile	Settlement in load test	Settlement in PLAXIS	Settlement in All pile
	units	mm	mm	mm	mm	mm	mm	mm	mm	mm
1	2	3.95	4.14	5.73	7.34	7.86	8.7	----	----	----
2	3	3.67	3.89	5.78	7.46	7.83	8.8	----	----	----
3	4	2.60	2.84	5.52	4.79	5.14	8.50	8.24	8.80	12.10
4	6	4.30	4.74	6.19	9.75	9.84	9.55	----	----	----
5	7	3.88	3.94	5.13	6.39	6.74	7.85	9.84	10.18	10.72
6	9	4.09	4.23	5.61	7.65	8.10	8.55	----	----	----
7	10	4.22	4.71	5.67	7.62	7.98	8.8	----	----	----

Table 6: results of settlement for unloading tests and numerical analyses

test No	Model No	Unloading cycle			
		Design load "Q"		Test load "1.5 Q"	
		Settlement in load test	Settlement in PLAXIS	Settlement in load test	Settlement in PLAXIS
	units	mm	mm	mm	mm
1	2	5.78	6.13	7.34	7.86
2	3	6.38	6.79	7.46	7.83
3	4	6.30	6.68	7.35	7.81
4	6	7.85	7.97	9.75	9.84
5	7	6.33	6.73	8.37	8.88
6	9	6.84	7.29	7.65	8.1
7	10	6.13	6.45	7.62	7.98

Table 7: Summary of compared settlement percentages between software program and results of field loading tests.

	$\frac{\Delta\, field}{\Delta\, program}\%$	At pile design load "Q"	At pile test load "150% Q"	At pile test load "200% Q"
Loading cycle	PLAXIS	(89.5-98.5) %	(93.2-99) %	(93.6-96.6) %
	All pile	(74.5-75.6) %	(56.4-89.5) %	(68.1-91.8) %
Un loading cycle	PLAXIS	(93.9-98.5) %	(93.2-99) %	(93.6-96.6) %

7. CONCLUSIONS

The paper calibrates commonly used software (PLAXIS) and (All pile) programs using seven in-situ pile loading tests. Based on the research work presented in the study, the following conclusions were observed:

- Very good agreement was obtained between numerical simulation using PLAXIS and in-situ pile load test for loading and unloading cycles.
- The percentage of compatibility is about 95% between numerical analyses using PLAXIS and field load tests. But this ratio reduced to 75% when using All pile program.
- The load- settlement curves of bored pile in all tests using All Pile program is so far in comparison with loading tests.
- Predicting the apparent failure in the felid loading tests of large diameter bored pile is very difficult due to the large loads carried by these piles.

- Ultimate load capacity for piles, determined by numerical model is in good agreement with the average load estimated from Chin (1970) and Hansen (1963) methods.

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