STUDY OF THE BEHAVIOUR OF OPEN ENDED STEEL PILES USING PHYSICAL AND NUMERICAL MODELLING

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Abstract— Open-ended steel pipe piles are widely used in marine construction, coastal engineering, port, and offshore structures. The behavior of open-ended piles is complex because its response is generally intermediate between that of non-displacement and displacement piles. Meanwhile, when an open-ended pile is driven into the soil, a soil column (or soil plug) is formed inside the pile. This soil plug affects the ultimate pile capacity and end-bearing resistance. This research aims to introduce a three-dimensional Finite Element (FE) model capable of simulating the performance and estimating the ultimate pile load of open-ended pipe pile. Three-dimensional FE models based on the commercial software ABAQUS 6.17 has been developed for simulating the behavior of steel pipe pile. Moreover, a comparison is then performed between the results of the FE model and the experimentally obtained results. It has been demonstrated that the three-dimensional numerical model results match the experimental results.

Index Terms—Finite element method, Mohr-Coulomb model, steel tubular pile, numerical simulation.

1. Introduction

Steel hollow tubular pile with open-ends represents a kind of pile that is usually driven into the soil by a suitable hammer. However, a plug of soil may be formed during driving and the length of this plug may be equal to or less than the pile-driving depth. If they are equal, the pile has been driven in a fully coring or unplugged mode throughout. However, if driving takes place in a partially or fully plugged mode, at least during part of the way, the length of the soil plug within the pile will be less than that of the pile. It is possible to observe all three driving modes (fully coring, partially plugged, or fully plugged) during the driving of a single pile [1]. So, the three dimensional (3D) FE models used to simulate the behavior of the open-ended pipe pile are presented in this paper. Employed 3D finite element models are based on the commercial software ABAQUS 6.17. These models are used to simulate the behavior of a steel pipe pile of diameter D and embedded length L. The following section presents the salient publications in this field followed by a discussion of the modeling procedure adopted in this study to create the 3D finite element models using ABAQUS 6.17. Then, verification for the results of the numerical models has been compared with the experimental results.

2. Literature

Steel pipe piles have been used increasingly as deep foundations for offshore and onshore structures. For example, more than 5,000 steel pipe piles were used in the construction

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Of the Hangzhou Bay Bridge in China, the then-longest cross Sea Bridge in the world.

Steel pipe piles are usually open-ended and in most situations are driven to the foundation on competent strata such as dense sand. Determination of the base capacity of open-ended pipe piles is a difficult problem involving great uncertainty. The difficulty can be largely attributed to the complicated behavior of soil plugging. A column of soil tends to form as soil enters the pile from the pile tip during pile installation. Most of the earlier design methods did not differentiate between open- and closed-ended piles. Given the increasing demand for large diameter open-ended pipe piles in offshore engineering, a considerable effort has been made in recent years to investigate the loading behavior and bearing capacity of pipe piles in sandy soil leading to an improved understanding and availability of design methods. Nevertheless, current design methods remain largely empirical [2], relying heavily on the correlations derived from pile load tests and in situ penetration tests, particularly, on cone penetration tests (CPTs). More recently, the American Petroleum Institute (API) issued an updated edition of practice for fixed offshore platforms [3], Therein, four CPT-based design methods were included in the commentary, namely: the Fugro, Imperial College pile (ICP), Norwegian Geotechnical Institute (NGI), and the University of Western Australia (UWA) methods. Evaluation of the four methods has been documented in various forms in [4], showing that the UWA method [5] and the ICP method have more advantages than the NGI method [6] and the Fugro method [7]. The ICP and UWA methods consider the capability of accounting for the effect of soil plugging on pile base capacity, a key issue in the design of open-ended pipe piles is the need for further improvement. An improved approach introduced by the work entitled Hong Kong University (HKU) method, is then presented along with the theoretical considerations and experimental observations behind it. The new method, which is also CPT based has the advantage of the vast use of CPT data in pile foundation design and takes into consideration several important factors that have been largely ignored in current methods. The predictive performance of the new method is carefully assessed using well-documented field tests and through comparisons with the two major methods. This study is aimed at removing, to some extent, the heavy empiricism embedded in the current methods. While at the same time, incorporating factors that can help capture the involved mechanisms properly. It represents one of the steps toward developing more cost-effective and rational methods for design of open-ended steel pipe piles.

If the plugging response of the pile is not correctly assessed, the result is that either an excessive or costly additional power is used in hammering due to the high driving resistance, i.e. the soil plugs [8]. The mechanisms required for plugging soil in piles with open ends have been shown in [1] which require arching in cohesionless soil, and lead to important internal skin resistance and affect the capacity of the interior soil column. Plugging with soil is therefore not fully assessed through drivability characteristics. However, it is also influenced by the method of driving, as illustrated by [10]. The influence of different installation methods (piling, vibrating, and pressing) was described by [11], which concluded that compressed piles can achieve a greater carrying capacity than identical piled piles in the same soil conditions. Using numerical modeling and solving for the situation that occurs when plugs develop in an open pipe pile, similar conclusions can be drawn in [10]. Therein, a study has been carried out on piles with diameters of 61 cm in densely packed sand with installation through piling, pressing, and vibrating. A total number of 60 model pile tests were carried out by [12] to investigate the effect of plugs on pile bearing capacity and the effects of the removal of soil plugs. Several parameters were investigated, including pile diameter to length ratio and types of construction in sands of different densities. Although plug removal to three levels (50%, 75%, and 100%) was investigated in accordance with plug length, the changes in the length of soil plug and incremental filling ratio (IFR) with the depth of pile penetration during driving; illustrated that piles with open ends are plugged partially due to the pile driving outset. The pile reached a fully plugged state for pressed piles in loose and medium sand and partially plugged (IFR = 10%) in dense sand. For driven piles, the IFR is about 30% in loose sand, 20% in medium sand, and 30% in dense sand. The pile load capacity increases with rises in the length of the plug length ratio (PLR).

3. Experimental Work

The experimental tests contain 3 tests performed on single pipe piles. All tubular piles were tested using the well-graded sand. The sand was prepared at medium relative density using a raining technique. Different piles of diameters are considered in this study.

3.1 Soil properties

Graded clean sand was already employed in this study as a natural soil, most particles of the used sand are rounded. The sandy soil is sieved to obtain medium sand according to the physical soil properties as presented in Table 1.

3.2 Model Pipe Piles

Fig. 1. Illustrates the three steel open-ended pipe piles with different in diameters were used to achieve the objective of this study as shown in Table 2.

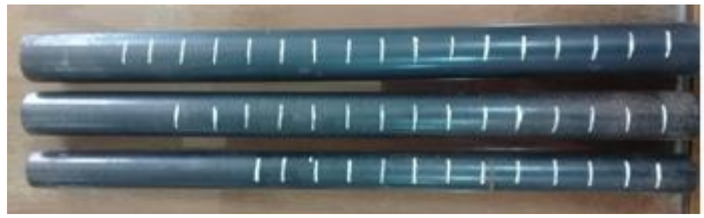

Fig. 1. Steel pipe pile models.

Table I: Physical properties of the used soil

Parameters	Symbol	Medium Sand
Effective size (mm)	D_{10}	0.194
Coefficient of curvature,	C_c	2.410
Coefficient of uniformity	C_u	0.884
Specific gravity	Gs	2.62
Dry Unit weight (kN/m^3)	γ_{dry}	16.50
Maximum Dry Unit weight (kN/m^3)	$\gamma_{d\ max}$	18.80
Minimum Dry Unit weight (kN/m^3)	$\gamma_{d\ min}$	14.30
Modulus of elasticity (kN/m^2)	E	63000
Relative density %	D_r	55
Friction angle	φ	34.80

Table 2: Model pipe piles dimensions and properties used in the tests

Test Designation	Soil conditions	Pile Outside Diameter D(mm)	Embedded length of pile L(mm)	The thickness of pile t(mm)
P-1	Dry State	32	320	1.5
P-2		38	380	1.5
P-3		42	420	1.5

3.3 Model Preparation and Testing Program

The apparatus was designed and manufactured to achieve the objective of this study. The apparatus consists of a steel loading frame with axial loading system, steel tamping hammer, steel container, digital weighing, indicator dial gauges, load cell, and pipe pile holder mm as presented in Fig. 2.

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The experiment tests were conducted in a cubic steel container of internal dimensions of (600 × 600 ×700). The sandy soil was poured into the test container in six layers to maintain a uniform condition. Depending on the dimensions of each lift, and with the knowledge the value of the dry unit weight corresponding to the required relative density of 55% which is used in this research. the weight of the dry soil placed in each lift can determine. A steel tamping hammer was used for compacting the soil lifts by uniformly distributed blows to get the required relative density.

For each pile model, four-pipe piles models were installed using a driving hammer to achieve the required penetration length into the soil as presented in Fig. 3. This procedure has been implemented to get all components of pile capacity, viz. shaft friction due to inner and outer friction, pile thickness resistance, and soil plug resistance. A constant driving rate has been adopted in the insertion of pipe piles models. A steel measuring tube of 10mm diameter was used to measure the plug length inside the pipe piles at each (25 mm) intervals during pile installation. Applying the test load at a constant rate. The test was continued until the recorded settlement exceeded 15% of the pile diameter. The displacement of the pile was measured by taking a rate of dial gauges.

Frist pile model test was performed to determine a total load of pipe pile capacity, the second pile model test was performed to get the annulus resistance. Since the pile thickness at the pile tip equal to zero. Nevertheless, the total pile load equal to the load from the test (1) minus the load from the test (2). The third pile model test was performed to get the load due to the external friction. Since the soil inside the pipe pile has been removed by using by a device manufactured due to the soil column entrapped inside the pipe piles during installations. Moreover, the pile subjected to tension load, to get the external friction. The fourth pile model test was performed in a special technique to get the internal friction. Finally, the plug resistance equal to (a total load of pipe pile) minus (the unit shaft friction + annulus resistance).

Fig. 2. Test model components.

Fig. 3. Pile models after installation.

3.4 Results and Discussion of Experimental work

Fig. 4. Presented the effect of pile diameter on the total pile load and the soil plug under pipe model piles with various diameters. Table 3 demonstrates the total pile capacity increased regularly with increasing pile diameters. Nevertheless, it is clear that when the pile diameter increased by 18.75% the total pile capacity increased by 71%. Moreover, when the pile diameter increased by 31.25% the total pile capacity increased by 109%. It can be noted that when the pile diameter increasing by the same percentage of diameter. The rate of increase of the total pile capacity decreases, this is due to the effect of soil plug inside the pipe pile is decrease.

Fig. 5. Shows the ultimate pile capacity and its components, e.g. inner friction, outer friction, annulus resistance, and soil plug resistance at the pile base for various piles models. It can be noted that the soil plug resistance decreases with the pile diameter increase. Also, the effect of pile thickness on the total pile load is very small compared to the effect of pile diameter. Moreover, the inner friction is less than the outer friction and usually equal to (50%-60%) from the outer friction.

Table 2: The ultimate pile capacities for pipe pile at different pile diameter.

Pile	The ultimate pile capacity (N)
pile diameter (mm.)	pile thickness (mm.)
	1.5
32	550
38	940
42	1150

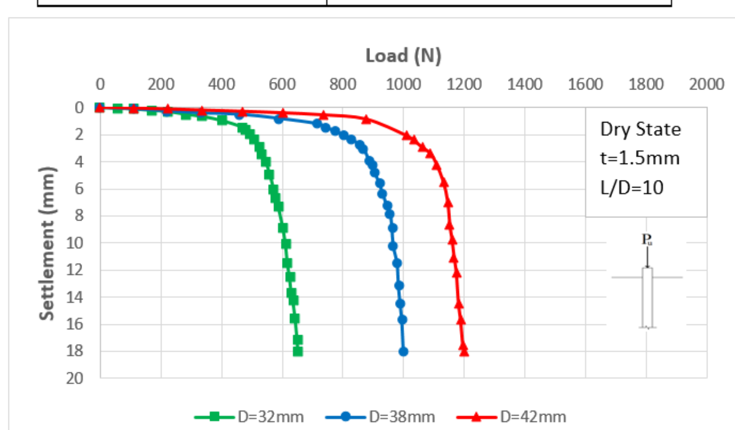

Fig. 4. Load-settlement curves for pipe pile of various diameters.

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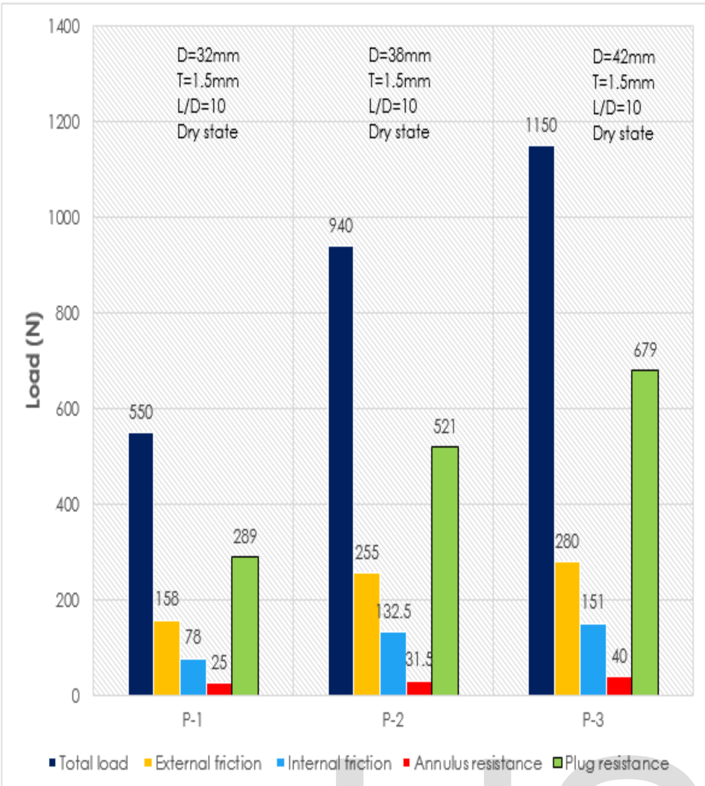

Fig. 5. The total pile load with both components.

4. FINITE ELEMENT MODELS

In this section, the 3D finite element models and the modeling procedure based on ABAQUS 6.17 are explained.

4.1 Geometry and Boundary Conditions

Three dimensional FE models are used in this paper to simulate the behavior of ordinary open-ended pile. The ordinary open-ended pile model consists of three parts, namely: steel open pipe pile, the soil around the open-ended pile, and soil-plug inside the open-ended pile. To study the effects of soil plugs formed by the driving of the open-ended pile, a model has been established as shown in Fig. 1. These three types of pile size categories have been simulated numerically for steel pipe pile with the geometric properties as mentioned in Table 1. The vertical load is applied at the top of the pile. It should be noticed that due to the symmetry of dimensions and loads, only one half of the FEM is considered in the analysis. This assumption reduces the computation time dramatically. Moreover, boundary conditions are fixed translation in X, Y, and Z directions and applied at the bottom boundary of FEM. Fixed translation in both X and Y directions were applied at the vertical boundaries on the soil external surfaces.

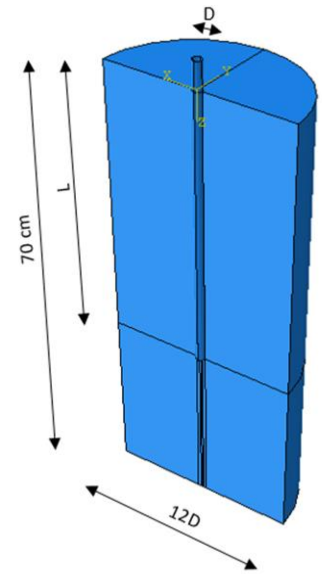

Fig. 1. Schematic diagram of the FEMs boundary conditions.

4.2 Material Modeling

This section presents the material modeling and the finite element mesh used to discretize the FEM. The behavior of open-ended pile is modeled using an isotropic linear elastic model. The input parameters are the elastic modulus (E) and the Poisson's ratio (υ). However, the soil was assumed to follow Mohr-Coulomb constitutive model for which the input parameters are the internal friction angle (φ), the elastic modulus (E), Poisson's ratio (υ) and the soil density (γ), while the steel pipe of piles is assumed as elastic materials. The soil, pipe piles properties are listed in Table 3 and Table 4.

Table 3: Soil properties input for the ABAQUS program

Parameters	Symbol	Medium Sand
Material model	model	Mohr-Coulomb constitutive model
Type of behavior	type	Drained
Dry Unit weight (kN/m³)	γ_{dry}	16.50
Modulus of elasticity (kN/m²)	E	63000
Power for stress dependent stiffness	m	0.5
Poisson's ratio	ν_{ur}	0.2
Cohesion (kN/m2)	c	0.1
Friction angle	φ	34.80
Dilatancy angle	Ψ	4.80
Reference shear modulus (kN/m2)	G_o^{ref}	75000
Reduction interaction factor	R_{inter}	0.8

Table 4: Pipe piles properties input for the ABAQUS program

Parameters	Symbol	Steel pipe
Material model	model	Linear elastic
Type of behavior	type	Non porous
Unit weight (kN/m^3)	γ_{Steel}	78.5
Modulus of elasticity (kN/m^2)	E	2 x 10^8
Poisson's ratio	ν_{ur}	0.3

Concerning the FE mesh, preliminary analyses were performed to optimize the mesh size. A mesh sensitivity analysis indicated that it is important to use a finer mesh to assess the accuracy of the obtained results. However, the computational time increases significantly. Thus, the mesh density for soil and pipe pile is shown in Fig. 2 and Fig. 3, respectively. Obtained results can be considered sufficiently accurate. The element type is chosen from the ABAQUS library.

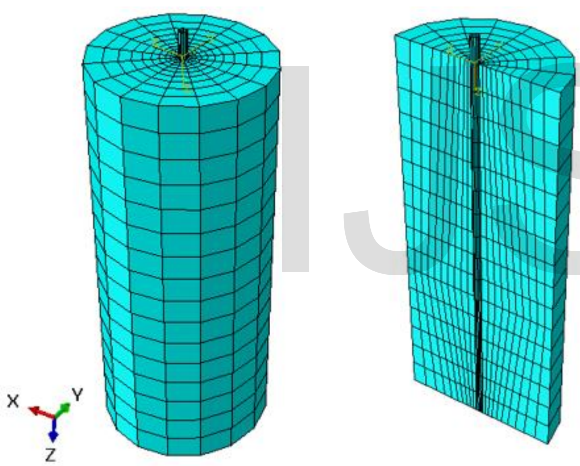

Fig. 2. Finite element mesh for the 3D model.

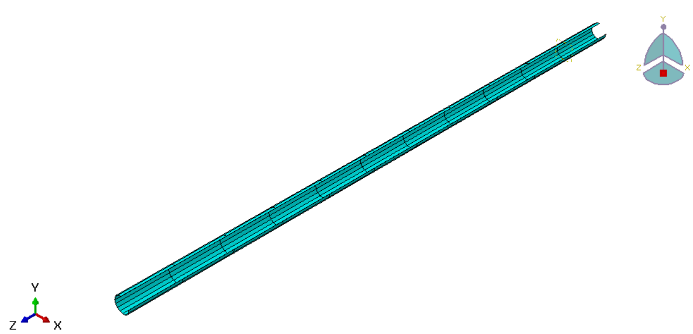

Fig. 3. Finite element mesh for the pipe pile.

4.3 Pile-Soil Interface

Interaction surfaces were applied at the interfaces between the elements representing the pile and adjacent soil layers that allow pile slippage and separation, which can properly simulate the tangential and normal behavior. The contact between soil and pipe pile is modeled using surface-to-surface master-slave contact pair concept with contact coefficient (μ) equals two-thirds of the soil internal friction angle (φ). Due to its high rigidity concerning the soil, the pipe pile is considered as the master surface.

4.4 Analysis Procedure

The finite element analyses were performed stepwise. At the first step, geostatic stresses were calculated by applying the gravity loading to the soil elements to generate the stresses developed in the soil due to the soil weight. In this step, the lateral earth pressure coefficient at rest (K_0) is taken equal to 1-sin (φ). In the second step, the pipe pile is created and is placed in its position in the soil domain and the model is brought to a steady-state of static equilibrium. This step aims to calculate the stresses and strains in the soil-structure system due to the pipe pile weight. Then, the vertical load which represents the own weight of the superstructure system is applied.

5. Verification Models

In this section, the accuracy of the modeling procedure adopted in this study has been verified. This verification has been achieved by comparing the finite element results with experimental results. The three models of pipe pile have been simulated and compared with their experimental counterparts under the same soil properties and conditions. This model can be described as presented in Table 2.

6. Results of the Experimental Tests and Numerical Analysis

Fig. 4, Fig. 5, and Fig. 6 illustrate the results of the open-ended pipe pile. Fig. 4, presented the relation between load and settlement for model pile (P-1) and shows the variation of results between the numerical model using the FE model and the experimental results. Nevertheless, it was concluded that the variation value is 12.73%. Fig. 5 shows the relation between load and settlement for model pile (P-2) and illustrates the variation of results between the numerical model using ABAQUS and the experimental results Nevertheless, it has been found the variation value is 2.13%. Finally, Fig. 6 presents the relation between load and settlement for model pile (P-3) and shows the variation of the results between the numerical model and the experimental results. Nevertheless, it has been founded that the variation value is 4.35%.

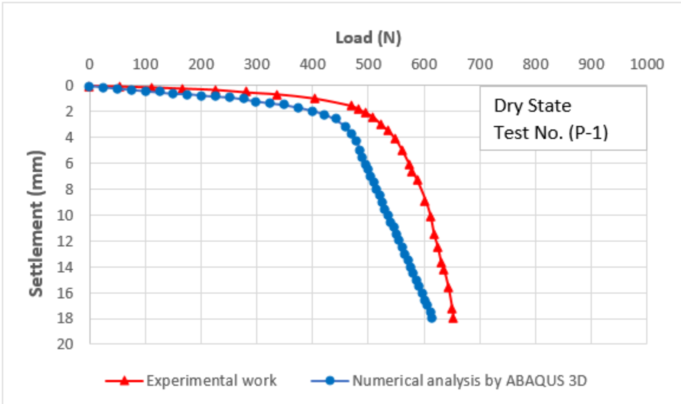

Fig. 4. Comparison of load-displacement curves For pile mode (P-1).

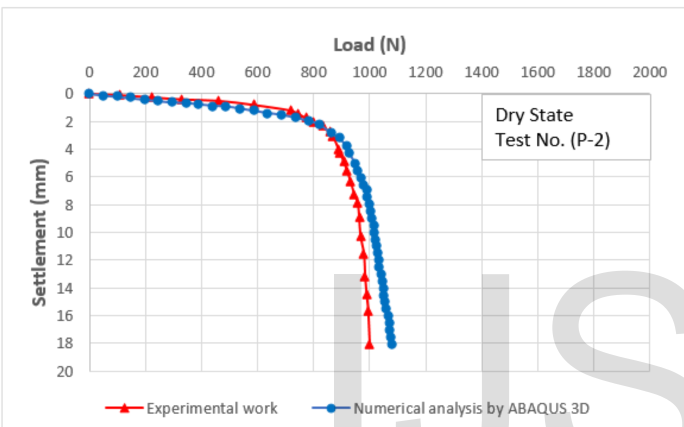

Fig. 5. Comparison of load-displacement curves For pile mode (P-2).

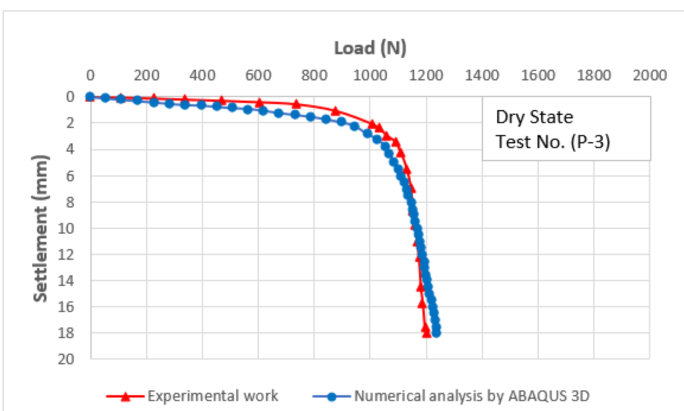

Fig. 6. Comparison of load-displacement curves For pile mode (P-3).

7. THE COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

The results of the numerical model using ABAQUS are in good agreement with the experimental results. Firstly, the variation of results between the 3D model and the experimental tests ranges between 2.13% and 12.73% as presented in Table 3. Moreover, the 3D model highly predicted the behavior of the relationship between load and settlement. It seems also that the ABAQUS 3D model is accurate than analytical methods as the results were more closely to the experimental results. 3D modeling (FEM) has been employed for the accurate prediction of overall soil behavior. Additionally, Fig. 7, represents the comparison and the variation between the experimental results and numerical results.

Table 3: The variation between experimental results and numerical results

Test designation	Pile load capacity (N)		The variation (%)
	Experimental results (N)	Numerical results (N)	
P-1	550	480	12.73
P-2	940	960	2.13
P-3	1150	1100	4.35

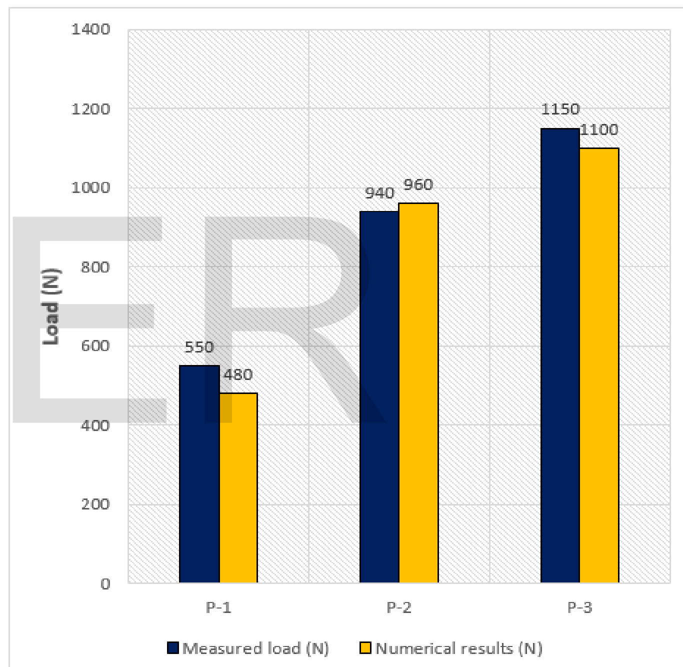

Fig. 7. A comparison between the experimental results and numerical results.

8. CONCLUSIONS

The research findings are summarized as follows:

1) It was found that the total load capacity of open-ended piles increased with increasing pile diameters.
2) The results showed that the soil plug resistance decreases with increasing pile diameter, this is due to the arching mechanism inside the pipe is decreased. Also, the effect of pile thickness on the total pile load is very small compared to the effect of pile diameter.
3) The value of interior unit shaft resistance in the open-ended steel pipe pile is typically on the order of 0.50 to 0.55 of the exterior unit shaft resistance. This is due to the soil plug length inside the pipe pile is less than the penetration pile depth into the ground.

4) Three-dimensional finite element modeling (3D FEM) using the ABAQUS program can accurately describe the behavior of the open-ended pipe pile. Moreover, the 3D model highly predicted the behavior of the relationship between load and settlement.
5) The results showed that the 3D FEM can highly predict the ultimate pipe pile capacity and it found that the ABAQUS 3D model is more closely to the experimental results. Furthermore, the results showed that the variation between the numerical results and the experimental results is nearly 13%.

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