

Shaft Resistance of Long (Flexible) Piles Considering Strength Degradation

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ABSTRACT

Soil-structure frictional resistance is an important parameter in the design of many foundation systems. The soil-structure interface area is responsible for load transferring from the structure to the surrounding soil. The mobilized shaft resistance of axially loaded, long slender pile embedded in dense, dry sand is experimentally and numerically analyzed when subjected to pullout force. Experimental setup including an instrumented model pile while the finite element method is used as a numerical analysis tool. The hypoplasticity model is used to model the soil adjacent to and surrounding the pile by using ABAQUS FEA (6.17.1). The soil-structure interface behavior depends on many factors, but mainly on the interface soil's tendency to contract or dilate under shearing conditions. To investigate this tendency, three piles with different surface roughness and under different confining pressures are used. A dilation behavior is observed in the relation of the average shaft resistance with the axial displacement for piles with rough and medium roughness surfaces, while contraction behavior is noticed when shearing piles with smooth surfaces. A large shear strength degradation of about (10%) reduction in the shaft resistance is observed under low confining pressure compared to a lesser reduction value of about (2%) under high confining pressure. Good agreement is obtained between the experimental and the numerical results.

Keywords: Shaft Resistance, Long Pile, Strength Degradation, Hypoplasticity.

مقاومة السطح لركيزة طويلة ومرنة مع الإخذ بنظر الاعتبار الانخفاض بالمقاومة

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الخلاصة

مقاومة الاحتكاك لمنطقة الالتقاء بين المنشأ بالتربة هي عامل مهم في تصميم الاسس المختلفة. حيث هذه المنطقة هي المسؤولة عن انتقال القوى من المنشأ الى التربة. في هذا البحث سيتم دراسة المقاومة المتولدة على السطح لركيزة طويلة ومرنة معرضة الى قوى سحب مختبريا ونظريا. العمل المختبري يشمل ركيزة مفردة مع متحسسات بينما طريقة العناصر المفردة ستستخدم في النموذج النظري وذلك باستخدام برنامج الاباكاس نسخة (6.17.1) وباستخدام موديل (hypoplasticity). تصريف منطقة الالتقاء

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يعتمد على عوامل عديدة لعل اهمها هي قابلية التربة للتمدد او التقلص تحت تأثير القصر. ولبحث هذا الموضوع تم استعمال ثلاث ركائز بخشونة سطح مختلفة وتحت تأثير ثلاث احمال مختلفة مسطرة على سطح التربة. تمددت التربة المجاورة لركيزة بسطح خشن بينما تقلصت التربة المجاورة لركيزة بسطح املس عندما تعرضنا الى القصر. انخفاض كبير في المقاومة بحوالي (10%) تمت ملاحظته للركائز المفحوصة تحت تأثير احمال قليلة بينما نسبة الانخفاض كانت حوالي (2%) تحت تأثير الاحمال العالية. تقاربا واضحا تمت ملاحظته بين النتائج المختبرية والنتائج النظرية.

الكلمات الرئيسية: مقاومة السطح، ركيزة طويلة، انخفاض المقاومة، الهايوبلاستيستي

1. INTRODUCTION

The load transferred from the pile to the surrounding soil by the shear stresses developed in the soil at horizontal and vertical planes with little change in the normal stress except near the pile's base. A series of concentric soil cylinders surround the pile in this theory. Each cylinder has its value of the shear stress, which is reduced inversely with the cylinder surface area. The stress variation in the soil is mostly of shear-type, which decreases inversely with distance away from the pile surface, leading to a concentration of the stress in the area adjacent to the pile surface, **Fig. 1**. Most piles show some shaft compression under working loads, which should be considered when estimating the pile deflection. The load applied at the pile top is not constant. It decreased with moving towards the pile tip as it shed to the surrounding soil leading to a very little load reaches the base of the long (flexible) piles. For such piles, the load settlement ratio is independent of the pile's length (**Fleming et al., 2008**).

Large relative movement between the pile shaft and the soil may reduce shear transferred from peak value of shaft friction to residual value, which is the famous phenomenon known as "shear softening" (**Loukidis and Salgado, 2008**).

Usually, the pile-soil interface does not show strain softening. However, in certain cases, the degradation of soil structure due to shearing (from pile loading or pile installation) causes shaft friction softening behavior at the interface of these two materials (**Tan et al., 2014**). From a theoretical perspective, the rough soil-structure interface tends to dilate while smooth surface suffers contraction in volume change response (**Lashkari, 2012**).

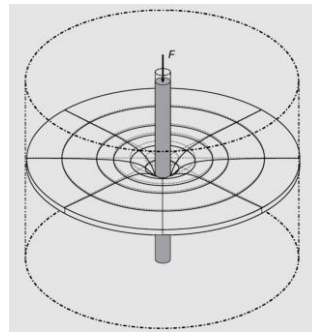


Figure 1. Simulation of the pile under axial load with a series of shear stress cylinders (**Loukidis and Salgado, 2008**).

The degradation of the strength resistance is getting much attention in the last years with much theoretical analysis are used to simulate. The shear strength degradation is a significant characteristic feature due to the interfacial interaction along the contact accompanied by an increase in the shear strain between the two materials in contact (**Yan and Gao, 2010**), **Fig. 2**.

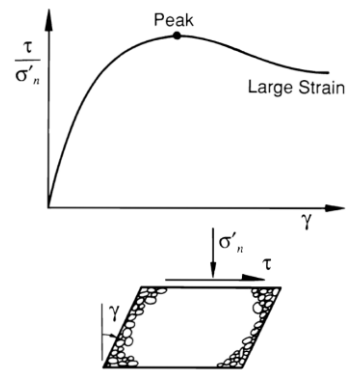


Figure 2. Typical shear stress-shear strain curve in the simple shear test (Houlsby, 2014).

For long flexible piles (the most common types of piles used in offshore foundation structures), the pile's skin friction plays a major role in the pile loading capacity. Two important features recognize the pile-interface zone: first, it is narrow (the width is about a few particles diameter). Second, the particles in this zone undergo large strain relative to the remaining soil. The friction angle values between the construction materials and soil (δ) depend on many factors. The friction mobilized at the interface depends on the type of construction material, its surface texture (smooth or rough), the soil particles' angularity, and to a lesser extent, on the normal stress applied at the shear plane (Rinne, 1985). The interface friction angle increased with the increase of surface roughness and angularity of particles. The effect of normal stress appears at high relative shear displacement (between the soil and the pile), where the upper bound of (δ) reaches faster at high stresses as compared to low stresses. The skin friction at the pile-soil interface is the highest for concrete, followed by wood and then steel (Tiwari and Al-Adhahd, 2014).

Accurate modeling of the soil-structure interface is very important to obtain a realistic and less conservative piles design since the interface area is considered a potential failure surface with highly non-linear behavior. Therefore an advanced model is required for better representation. In this study, the hypoplasticity model (which is a particular class of rate non-linear constitutive model at which the stress increment is represented as a tensorial function of strain increment, actual stress, and void ratio) is used to simulate the soil at the pile-soil interface area and the soil surrounding the pile.

2. SINGLE PILE MODEL TESTS

The soil used in this study is a coarse sandy soil obtained from Al-Basrah city, South of Iraq. This sand has an average diameter ($D_{50}=0.58$ mm), as obtained from the grain size distribution curve shown below according to ASTM D2487-06, and can be classified as SP (poorly graded sand) according to the USCS. The solution of the boundary value problems requires the determination of the material parameters and the state variables' initial values. The hypoplasticity model has eight material parameters (φ_c (critical friction angle), e_{c0} , e_{i0} , e_{d0} (critical, maximum and minimum void ratio respectively), h_s (stiffness parameter), n , α , β (model constants)), **Table 2**. Full details of the calibration of the model parameters used in this study are presented in (Subair and Aljorany, 2020).

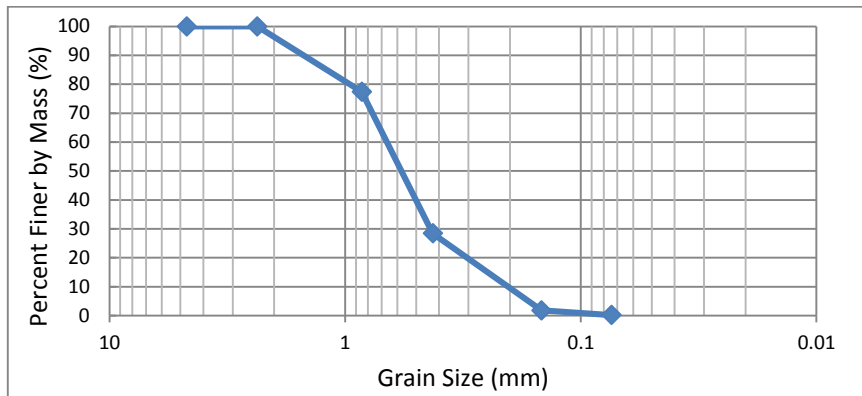


Figure 3. Grain size distribution curve.

Table 1. Soil Properties.

Specific Gravity (G.S)	γ_{dmax}	γ_{dmin}	γ_{dused}	R.D	Cu	Cc	ϕ	C
2.63	17.9 [kN/m ³]	16.3 [kN/m ³]	17.5 [kN/m ³]	76.7%	3.24	1.3	43.50	1 [kPa]
ASTM D854	ASTM D4253-00	ASTM D4254-00			ASTM D2487-06		ASTM D3040-04	

Table 2. Properties of the hypoplasticity model.

e_{d0}	e_{c0}	e_{i0}	α	β	n	h_s	ϕ_c
0.441	0.582	0.667	0.37	1	0.269	18.54 [Gpa]	31 ⁰

2.1 Experimental Work

The experimental work is implemented to study the shaft resistance of a single pile model. The results will be compared to the ABAQUS FEA's numerical results to test the performance of the hypoplasticity model. Pullout tests were emphasized as the evaluation of the shaft friction is the main purpose of the tests. The model consists of a steel box of (70×70 cm) in a plane, 60 cm depth, and (5mm) in thickness. A horizontal try (1m long and 20cm wide) is attached to the steel box supplied with a pulley and steel rope placed at the far end from the box used to supply the pile pullout force.

The displacement and the stress patterns in the sand are affected by the soil container boundaries. Also, the sand's vertical stress may be decreased by the friction developed between the sides of the container and the soil (Al-Mhaidib and Edil, 1998). That is why the dimensions of the steel box



together with the pile dimensions were chosen to eliminate such boundary effects by satisfying the following conditions:

- A distance of (10 pile diameter (d_p)) should be available around the pile to avoid the expected shear zone area (Beijer, 2012).
- Below the pile tip, a clearance distance of (8 dp) is required (Al-Mhaidib, 2006).
- For vertically loaded pile $\frac{d_p}{d_{10}} \geq 50$ (Al-Mhaidib and Edil, 1998).

Where $d_p = 1.58\text{cm}$.

An electrical motor together with a gearbox is fixed at the steel box's side above the horizontal tray. To control the speed at which the pile is pulled out from the soil, an AC-drive with a range (2-50 Hz) is attached to the electrical motor. Preliminary tests are performed to draw a relation between the speeds of pile pullout with the AC-drive readings, Fig. 4.

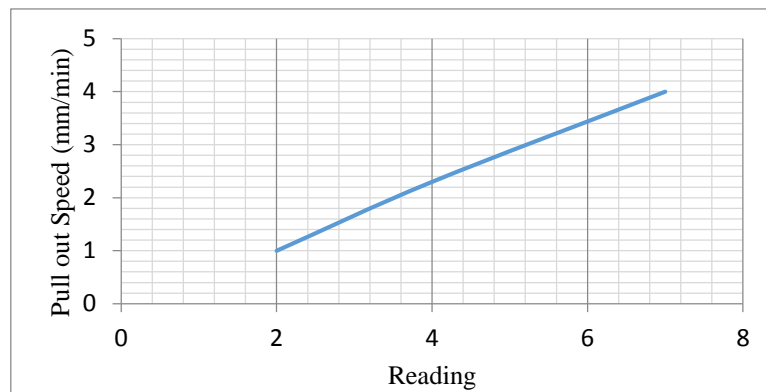


Figure 4. The relation between the AC-drive reading and the pull out speed rate.

The model pile used is an aluminum alloy of the hollow square section (1.4×1.4cm) and (2mm) thickness with an embedded length of (68cm) in all cases. The dimensions were chosen to ensure that the pile will behave as a long flexible pile. The instrumented pile with eight strain gauges at four locations in full-bridge connection is placed in a horizontal direction at the height of (28.5cm) from the box's base to provide the required confinement, Fig. 5. Two linear variable differential transformers (LVDT) of (25mm) in length and (0.01mm) inaccuracy used to measure the pullout displacement of the pile at the top and tip of the pile placed in these two positions by two magnetic holders, Fig. 5. A load cell (1000kg) S-beam (SS-300) type fixed at the pile head at one end is used to measure the applied load as the pile is pulled out of the soil. A steel rope attached to the other end of the load cell and fixed to a shaft operated by the electrical motor. All the above devices are linked to a data acquisition system for data recording by using the LabVIEW application. Preparation of the soil bed was performed by a traveling pluviation technique (raining), at which the specified amount of sand for each sand layer is poured from a specially designed frame to achieve the required relative density (77%).



Figure 5. The model set up.

After filling the metal box with soil three different confining pressures are placed at the top of the soil (9.7 (low), 16.2 (medium), and 21.6 kPa (high)). Three piles were used with three surface roughness values (rough R, medium M and smooth S) by covering the pile surface with sandpaper (P60, P220, and without sandpaper, respectively), **Fig. 6**. The sandpaper is used to provide the required roughness due to the rough particles' uniformity along the surface (**Sadrekarimi et al., 2009**). Sandpaper is classified according to the number of abrasive particles in the square inch the lower the number, the more coarse the grit (from 40 to 60) is graded as coarse, (from 80 to 120) considered as a medium (from 150 to 180) as a fine grade, and (from 220 to 240) as very fine, (**Liu, 2018**). Each type of sandpaper has a value of roughness factor (R) factor, **Fig. 7**.



Figure 6. The model set up.

2.2 Numerical Work

The hypoplasticity model is used to simulate the shaft resistance along with the pile by using the ABAQUS FEA, and since the hypoplasticity model is not a built-in model yet. A user-defined subroutine is required (**Masin, 2005**). A hypoplastic UMAT, a 3-D soil model available at (soilmodel.info project by Masin), is used to simulate the soil surrounding the pile in the model test. At the same time, the hypoplastic interface constitutive model developed by **Hans Stutz** is used to simulate the pile-soil interface by a FRIC subroutine also available at (soilmodel.info). This model is based on the hypoplasticity model by giving the interface soil the same characteristics as the rest of the continuum soil with two additional parameters for the surface roughness and the width of the shear zone, respectively (k_r and d_v^s) (**Stutz, 2016**). A hollow Aluminum pile is simulated as an elastic material with only two parameters ($E=68800$ MPa, and

$\nu=0.32$) (Jawad, 2018) with the boundary conditions shown in Fig. 8. All the points at the base of the soil are fixed in all degrees of freedom (x, y, and z), while the vertical edges of the soil are fixed in the (x and z-direction) and left free in the y-direction (Stutz, 2017).

Abrasive Grit Number	R_A (μinch)
500	4 - 10
320	6 - 15
240	8 - 20
180	25 - 40
120	45 - 60
60	140 - 180

Figure 7. Roughness factor for different sandpaper (Liu, 2018).

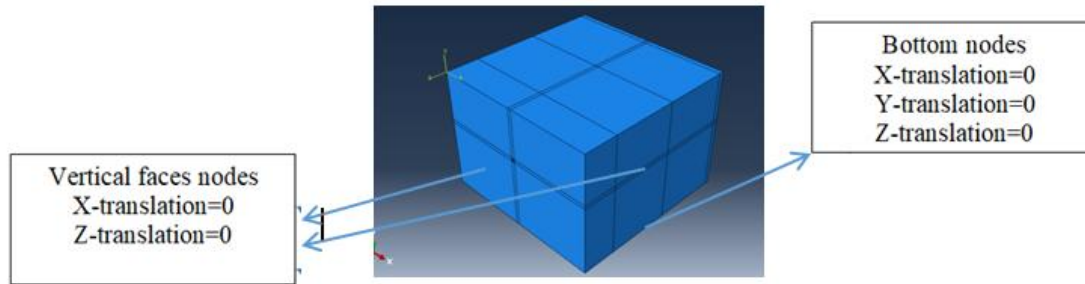


Figure 8. Simulation of the soil sample with the required boundary conditions.

Three steps are needed for this analysis (Ahmed and Al-Zaidee, 2020); the first is the "geostatic step" with a single increment at which a body force of (17.5kN/m³) is applied to the soil sample. The second step is the "loading step" which is also a single increment step at which a predefined pressure (the same used in the experimental work) is applied at the top surface of the soil in the triangular form to simulate the geostatic stress in both above steps a general static command is invoked since the soil is in a dry condition. The third step is the "shearing step" with a time increment of (1500 seconds) for 1mm/min strain rate used in the experimental tests, which is the same strain rate used in the direct shear test as stated by the ASTM D3040-04 for drained conditions. The shearing is presented as constant displacement control by applying (25 mm) displacement in the pile head's tension direction. Eight-node continuum three-dimensional brick element (C3D8R) with reduced integration available in ABAQUS was used to simulate the soil sample and the pile (Stutz et al., 2017).

3. PILE SHAFT RESISTANCE

The pile under tension load transmits the applied load only through its surface area by the shaft friction. The main aspect of all load transfer mechanisms is to define the mobilized resistance per unit pile shaft area as a function of the pile axial movement. In this model test, the unit skin friction at each pile segment (i) is calculated as done by (Fioravante, 2002), Fig. 9.:



$$\tau_i = \frac{F_{i-1} - F_i}{A_i} \tag{1}$$

Where $i=1, 2, 3$

F_i = Axial force measured by the strain gages along with the pile.

A_i = Shaft area of the segment (i).

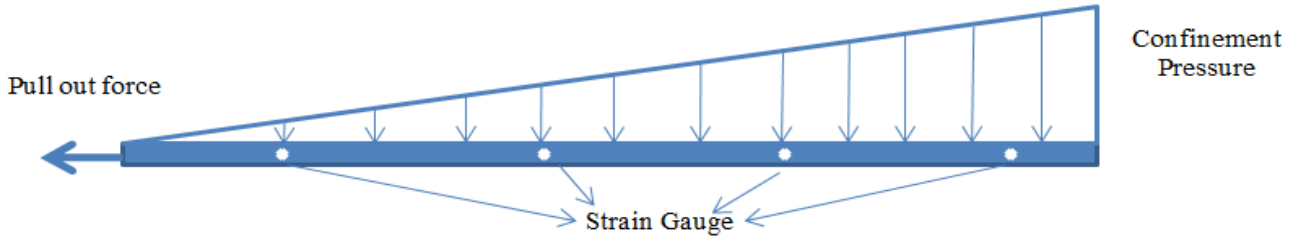
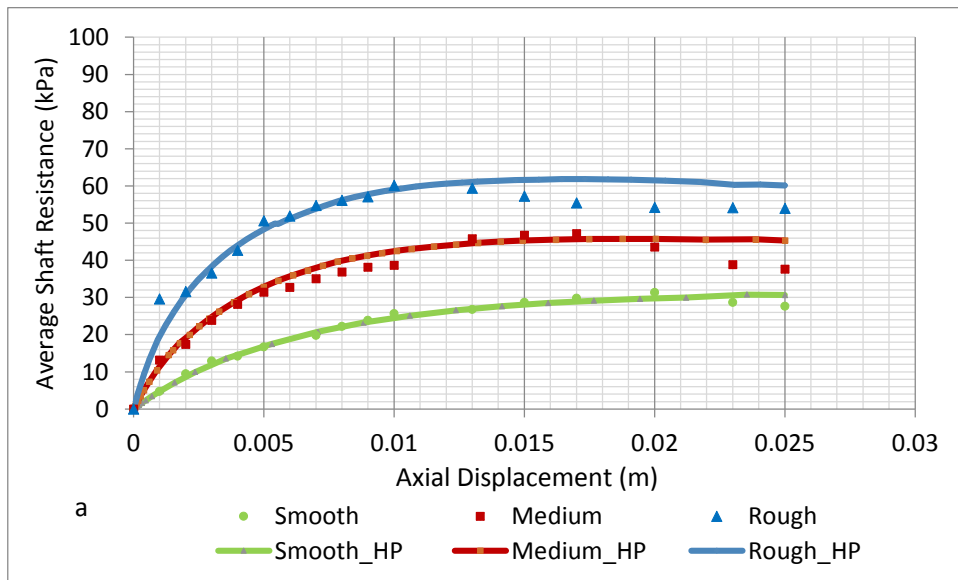


Figure 9. Distribution of the strain gauges along the pile surface.

The effect of surface roughness on the average shaft resistance along the pile is investigated. The results are shown in **Fig. 10**, which shows the results under a strain rate (1 mm/min) and different confining pressure (9.7,16.2, and 21.6 kPa), respectively.



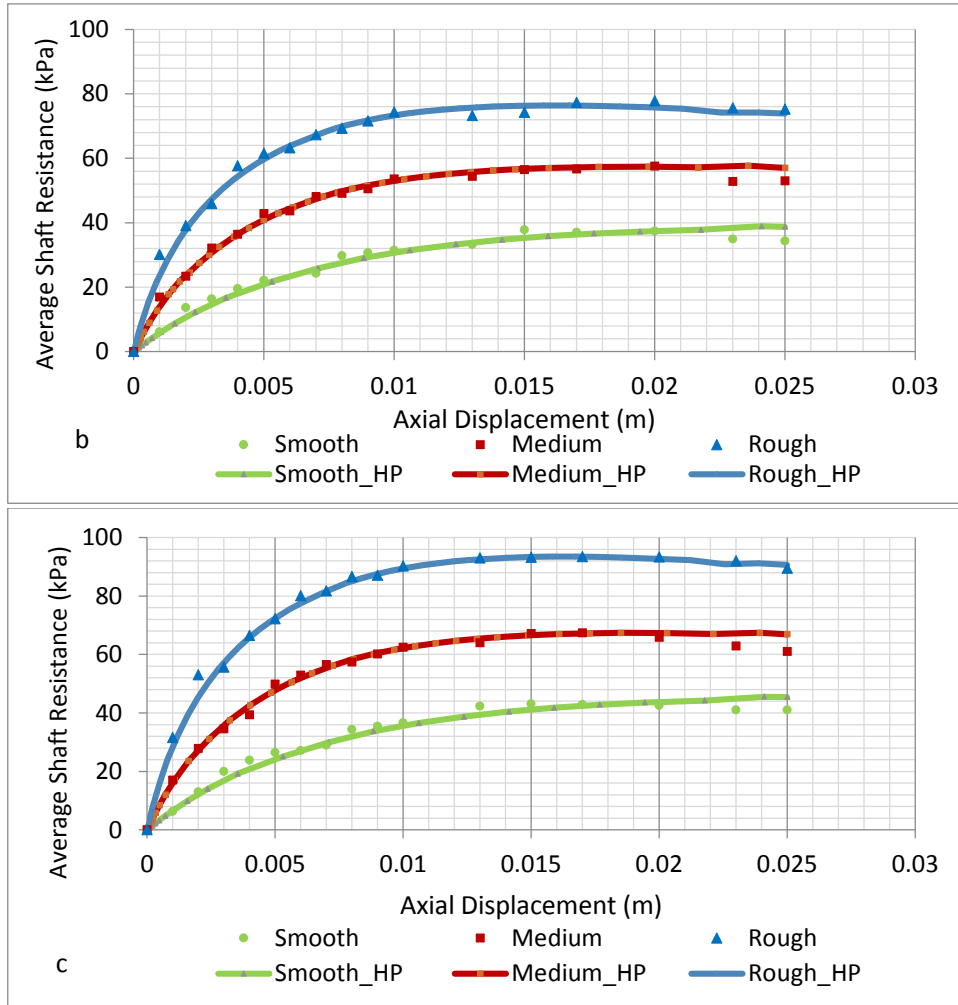
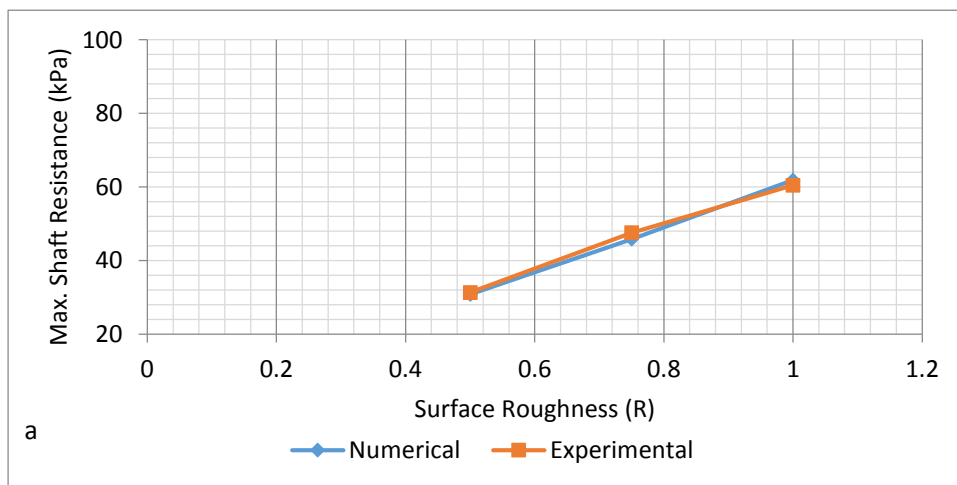


Figure 10. The effect of surface roughness on the average shaft resistance's experimental and numerical results under three confining pressure (a-9.7, b-16.2, and c-21.6 kPa), respectively.



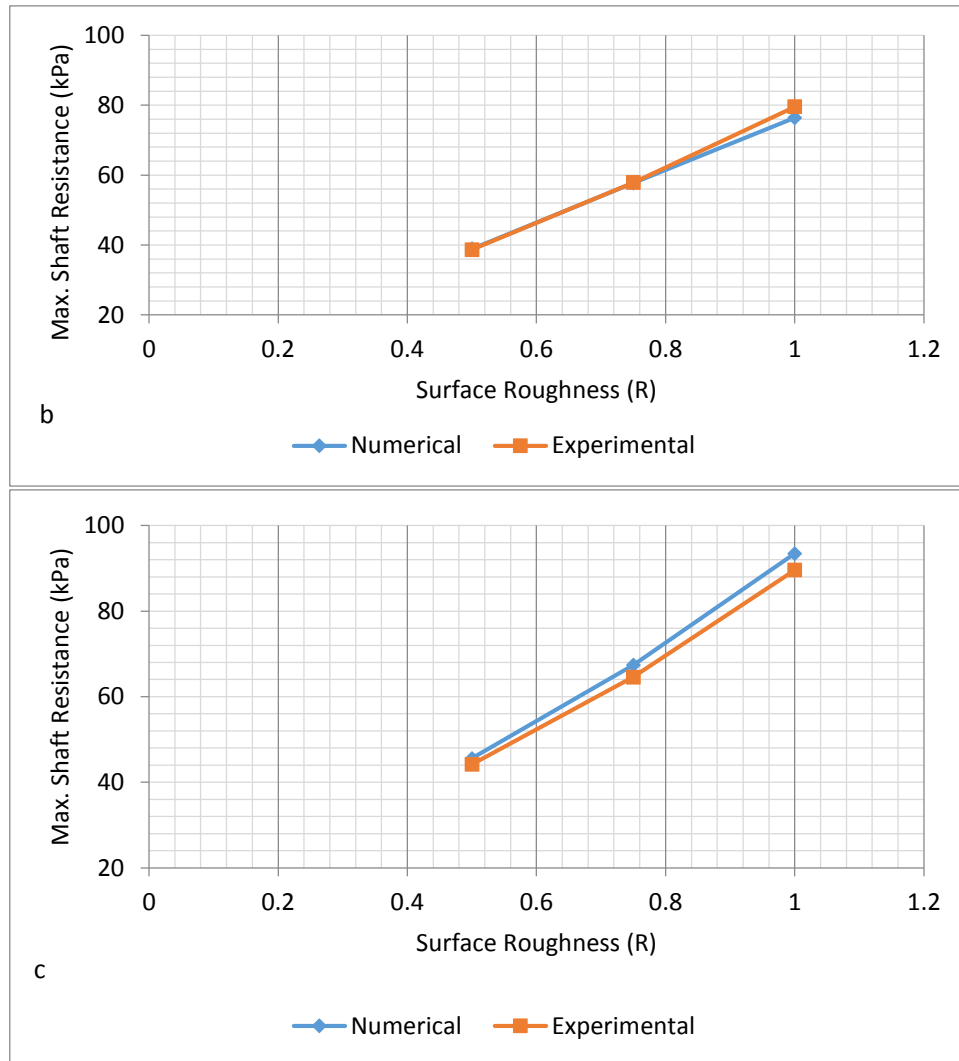


Figure 11. The relation between the ultimate shaft resistance and roughness factor (R) under three confining (a-9.7, b-16.2, and c-21.6 kPa), respectively.

When examining **Fig. 10**, the shear resistance increases with the increase in the surface roughness (from 22-59.4 kPa), (from 38-78 kPa), and (from 43 to 97 kPa) in **Fig. 10** (a, b, and c) respectively when changing the pile from smooth to a rough surface. A more pronounced post-peak softening is observed when shearing against rough surfaces. The rough surface interlocks with soil forcing the strain to occur away from the surface with a large magnitude. The effect of the surface roughness on the average shaft resistance along the pile is evident in the value of the shaft resistance and the relationship's shape relative to the pile axial displacement in all test conditions. (**Sadrekarami et al., 2009**) explained that the pile surface roughness enhances the pile's tendency to dilate during loading, which in turn increases the radial stress against the pile surface, leading to an increase in the pile shaft friction and partially due to the increase of the interface friction angle due to the increase in the surface roughness.

Similar results were obtained by (**Jin et al., in 2018**), where they stated that the peak interface efficiency increases linearly with the increase in the surface roughness factor, as seen in **Fig.11**.



The confinement pressure has a lesser effect on the average shaft resistance along the pile (compared to the shaft roughness), where the ultimate average shaft resistance increase (from 59.4 to 97 kPa), (from 40.5 to 61 kPa), and (from 22 to 43 kPa) for piles with (rough, medium roughness and rough surface respectively) when the confining pressure increased from (9.7 to 21.6 kPa) as seen in **Fig. 10**. These results are in agreement with the results obtained by **Zhang et al., 2007**. They stated that at the soil-solid (pile) interface, the higher the normal stress, the higher the interface strength, and the failure will always occur along the weaker surface, which is the pile surface in this case.

The pullout tests performed on rough piles give a clear strength degradation ranging from high values of about (10%) degradation from ultimate to residual values in tests with low confining pressures and lower values of about (2%) for tests under high confining pressure. The medium roughness piles also give a lower extent of strength degradation (compared with rough piles) when sheared under low confining pressures (5 %) and about (0.5%) under high confining pressures. No or negligible degradation in the shaft resistance is observed for tests with smooth piles.

Comparing the experimental results with the numerical ones shows a similar trend and close values in the relationship between the shaft resistance and the axial displacement. The peak in this relationship is more pronounced in the experimental results than the numerical.

4. CONCLUSIONS

The present study investigates using the numerical simulation the problem of the limit shaft resistance of long slender non-displacement pile installed in dense sand. The numerical simulation uses an advanced constitutive model (the hypoplasticity model) to predict the soil behavior under different surface roughness and confining pressure conditions. The shaft resistance behavior along the pile surface is non-linear and affected the most by the surface roughness. Its value increases by about (57%) when the pile changed from a smooth to a rough pile. The shaft resistance increased to a lesser extent with the increase in the confining pressure applied at the soil's top surface. The shaft resistance increased by about (40%) when the confining pressure increased from (9.7 to 21.6 kPa). The shaft resistance behavior along the pile surface is non-linear and affected the most by the surface roughness. Almost a linear relation is obtained when the maximum average shaft resistance is plotted against the roughness factor (R) and the confining pressure. A clear degradation is observed in the shaft resistance when plotted against the axial displacement in rough and medium roughness pile. The ultimate value is followed by a reduction in the shaft resistance (softening) both in the experimental and the numerical results, even if softening is more pronounced in the experimental results.

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