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Load-settlement Behavior of Steel Piles in Different Sandy Soil Configurations

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ABSTRACT

In the case where a shallow foundation does not satisfy with design requirements alone, the addition of a pile may be suitable to improve the performance of the foundation design. The lack of in-situ data and the complexity of the issues caused by lagging in the research area of pile foundations are notable. In this study, different types of piles were used under the same geometric conditions to determine the load-settlement relationships with various sandy soil relative densities. The ultimate pile capacity for each selected pile is obtained from a modified California Bearing Ratio (CBR) machine to be suitable for axial pile loading. Based on the results, the values of Q_u for close-ended square pile were increased by 15.2, 19.3, and 9.1 % for different pile lengths of 100, 150, and 200 mm in comparison with the H-pile. At the same time, the open-ended square pile had a lower capacity in comparison with closed-ended square pile tested in medium sand. Also, in the dense sand, the values of Q_u for close-ended square pile were increased by 49.7, 47.8, and 69.6% for the same pile length in comparison with the H-pile. Notably, sand's density has a significant effect on the ultimate load capacity for different types of piles.

Keywords: Pile Bearing Capacity, Sand Density, H-pile, Square pile, Pile length.

سلوك الحمل-الهبوط لركائز الصلب في تكوينات التربة الرملية المختلفة

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الخلاصة

في حالة عدم تلبية الأساس الضحل لمتطلبات التصميم وحدها ، قد يكون من المناسب إضافة اساس ركيزة لتحسين أداء تصميم الأساس. إن الافتقار إلى البيانات في الموقع وتعقيد القضايا الناجمة عن التأخر في مجال الأبحاث الخاصة بأساسات الوبر ظاهرة

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ملحوظة. في هذه الدراسة ، تم استخدام أنواع مختلفة من الركائز تحت نفس الظروف الهندسية لتحديد علاقات تحميل-هبوط بالكثافة النسبية لتراب رملية مختلفة. السعة القصوى للخوازيق لكل ركيزة محددة تم الحصول عليها من آلة نسبة تحمل كاليفورنيا (CBR) المعدلة لتكون مناسبة للتحميل المحوري للركيزة. بناءً على النتائج، تمت زيادة قيم Qu للركائز المربعة المفتوحة النهايات 15.2 و 19.3 و 9.1% لأرتفاعات الركائز المختلفة 100 و 150 و 200 ملم بالمقارنة مع الركيزة من نوع H. في حين أن الركيزة المربعة المفتوحة النهايات لديها قدرة أقل بالمقارنة مع الركيزة المربعة المغلقة النهايات التي تم اختبارها في الرمال ذات الحبيبات المتوسطة الاحجام. بالإضافة، في الرمال كثيفة الحبيبات، زادت قيم Qu للركائز المربعة المغلقة النهايات بنسب 49.7 ، 47.8 ، و 69.6 % لنفس طول الركيزة مقارنة مع الركيزة من نوع H. والجدير بالذكر أن كثافة الرمال لها تأثير كبير على قدرة التحمل النهائية لأنواع مختلفة من الركائز.

الكلمات الرئيسية: قدرة تحمل الركيزة، كثافة الرمل، ركيزة H، الركيزة المربعة، ارتفاع الركيزة.

1. INTRODUCTION

The fast growth of high and heavy buildings in the developing cities globally led to an increase in the demand for a pile foundation. This results in an incorrect prediction of the pile's settlements, which becomes significant in weak soils. In most cases, the critical value to control pile design is a settlement. Hence, this led to the need to search for more advanced approaches (**Randolph et al., 1994**). The difficulty of the issue is caused by multiple factors related to geometrical and mechanical properties of piles, the mechanism of piles installation, and soil foundations. Considerably related studies have been carried out to discover the interaction mechanisms between piles and sandy soils during installations and loading process. This leads to the development of further reliable, scientific, and economical procedures for pile foundation design (**Jardine, 1996; Klotz and Coop, 2001; Randolph et al., 1994, Al-Busoda and Al-Rubaye, 2015; Alsaddi and Albusoda, 2017**). Nevertheless, the pile–sand interaction issues remain ambiguous. The problem in pile models testing utilizing a centrifuge test is to find the lowest adequate dimension of the testing device that can produce a reasonable condition of far-field ground (**Salgado et al., 1998**). For the last six decades, several methods have been used for piles' settlement calculation. Those methods can be categorized as (1) experimental or semi-experimental method (**Meyerhof, 1963; Vesic, 1977**), (2) equivalent pier or raft method (**Fellenius, 1991; Poulos, 1993; Terzaghi et al., 1996; Yamashita et al., 2015**), (3) interaction factor method (**Randolph and Wroth, 1979; Poulos and Davis, 1980**), and (4) mathematical analysis method (**Chow, 1986; Clancy and Randolph, 1996**). These methods have been described and examined properly (**Dung et al., 2010**). The study that reported a range of 50% in standard deviation for settlements was calculated by four different methods. The difference in those calculations indicates a considerable issue inaccuracy for pile settlements.

In addition to these methods, (**Shahin, 2014**) used recurrent neural networks adjusted with the cast in place real model of pile load tests to estimate pile settlements. Pile settlements can be affected by many factors. Importantly, one of those factors is the pile installation method (**Housel and Burkey, 1948; Cummings et al., 1950; Lo and Stermac, 1965; Orrje and Broms, 1967; Fellenius, 1971 and 2006**).

Recently, studies focused on rate-dependent model development, specially designed for weak soil. Those models are useful for demonstrating the pile installation effects (**Zhu and Yin, 2000; Grimstad et al., 2010; Karstunen et al., 2013; Ottolini and Dijkstra, 2014**). Centrifuge tests were used to confirm the results of the full-scale tests. Some studies showed that the void ratio was decreased by 5%, while a single pile bearing capacity increased by 2.5 times around a pile tip upon pile installation (**Wolffersdorff, 1996; Hamderi, 2018**). The majority of conducted studies on pile foundation have been dedicated to the behavior of load or bearing settlement. However, some studies focused on examining the effect of governing and by derivative parameters on the

interaction within the structures system, and consequently, on the load sharing mechanism (Tradigo et al., 2015; Zhu, 2017; Salih, 2017). This study aims to determine the ultimate capacity of three steel pile types, namely: H-pile, close-ended pile, and open-ended pile driven in loose, medium, and dense sand under the application of static load test.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1 Materials

In this study, the samples of sand were taken from Darbandixan city, Northern Iraq (longitude 45° 41' 43" E, and latitude 35° 6' 39" N). The poorly-graded sandy soil sample (SP) was classified according to USCS, as shown in Fig. 1. ASTM specifications were considered for the conduction of a series of laboratory tests to classify the selected sand. Three different densities were chosen to be used for modeling piles; loose, medium, and dense sand with varying angles of friction of 36°, 40°, and 48°, respectively. The relative densities used in the study for loose, medium, and dense sand are 15%, 50%, and 85%, respectively. The experimental results of the carried-out test are shown in Table 1. In this study, steel section piles (H-pile, close-ended pile, and open-ended pile) with the same cross-sectional area (78 mm²) are used with three various lengths of 100, 150, and 200 mm, as shown in Fig. 2. With the consideration of different relative densities, twenty-seven model tests were conducted.

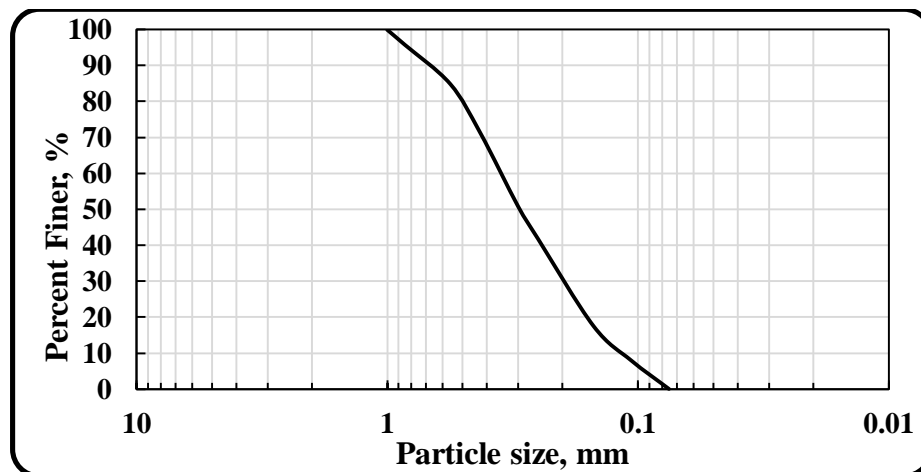


Figure 1. Grain size distribution for the used sand in this study.

Table 1. The physical properties of the selected sandy soil sample.

Index property	Value	Specification
D ₁₀ (mm)	0.12	ASTM D2487 -11
D ₃₀ (mm)	0.20	
D ₅₀ (mm)	0.30	
D ₆₀ (mm)	0.38	
Coefficient of uniformity (C _u)	2.22	
Coefficient of curvature (C _c)	1.25	
Soil classification (USCS)	SP	
Specific gravity (G _s)	2.66	ASTM C128 - 15



Maximum dry unit weight, $\gamma_{d_{max}}$ (kN/m ³)	18.96			ASTM D7382-08
Minimum dry unit weight, $\gamma_{d_{min}}$ (kN/m ³)	15.00			ASTM D4254 -14
Maximum void ratio, e_{max}	0.775			
Minimum void ratio, e_{min}	0.403			
Relative density, (RD) %	Loose, RD=15 %	Medium, RD=50%	Dense, RD=85%	
Dry unit weight, γ_d (kN/m ³)	15.18	16.43	17.90	
Angle of internal friction (ϕ)	36	40	48	ASTM D3080 -11
Void ratio, e	0.72	0.59	0.46	



Figure 2. Three types of steel piles used in this study.

2.2 Sand container and sample preparation

All tests on the pile's model were carried out on dry sand samples compacted inside a steel container with dimensions of 35 cm for diameter and 45 cm for depth, as shown in **Figure 3**. The sand densities were prepared by layers using a compaction method inside the steel container. According to the related literature, the inner sides of the used soil container effect on the stress and displacement modes for the sand modeling. Also, the vertical stress in the sand can be reduced with depth. This is because of the sandy soil grains and the internal container walls (**Al-Neami & Wasmi, 2018; Kraft Jr, 1991**). A disturbance occurs for the soil surrounding the pile during the pile installation process (loading process). The obtained soil disturbance may extend to the concerned zone, which depends on the relative density magnitude of the used soil, and the method of pile installation. The zone found to be ranging from 3D to 8D, D is the pile's diameter (**Robinsky et al., 1964**). Therefore, 8D (maximum) was selected and used; D_{max} is the maximum pile diameter used in this study. The required weight of the sand is predetermined for the soil modeling purpose via the three chosen relative densities, which are 15%, 50%, and 85%. This is done to prepare the loose, medium, and dense sand bed. Each of the added soil layers was compacted to the desired depth, which previously identified by lines drawn on the inner sides of the container.



Figure 3. The soil container used for pile modeling.

2.3 Details of pile models

After the completion of the bed preparation by sand inside the steel container, the pile model was vertically inserted using a modified California bearing ratio machine (CBR), as shown in Fig. 4. So, to ensure the correct vertical installation, the pile pressing system was modified by adding a subframe (pile holder) of the square hollow section (SHS) to the container with a dimension of 25mm × 25mm, length equal to 80 mm and 2 mm for the thickness. By using four screws, the pile vertically stabled, the SHS fixed with a container because of the two rods. The axial loading on the model was applied by hydraulic jack having a maximum loading capacity of 45 kN. A load cell with a maximum capacity of 45 kN was used and connected with a digital data log reader to record the applied load.





Figure 4. Soil container with loading frame (A) model tank, (B) loading frame, (C) detachable screwed frame

2.4 Testing program

To achieve the aims of this research, 27 soil samples were tested. A set of nine pile samples was used for each pile model with various shapes, namely H-pile, close-ended square pile, and open-ended square pile. Three different relative densities of sand, namely; loose, medium, and dense sand, were used to obtain the effect of amplitude load. The used pile holder was removed from the container after the completion of the process of pile-driving. With the controlled displacement of 1.0 mm/min, gradually, the static loading was applied via the hydraulic jack. Continuous load measurement was performed until the developed settlement exceeded 10% of the used pile's diameter. ASTM D1143-13 was considered for the piles testing procedure.

3. RESULTS AND DISCUSSION

3.1 Load-settlement relation for loose sand

Fig. 5 (A, B, and C) shows the load settlement curves for different pile lengths with different relative densities. The results are summarized in **Table 2**. The open-ended square pile showed more capacity compared with the closed-ended square pile. This is because of the open-ended pile can produce more external and internal skin friction, which led to higher capacity record. Also, for some tests conducted on loose sand, the H-pile had more lateral capacity compare to the obtained capacity by the close-ended square pile, as shown in **Fig. 6**. Notably, the pile's shape and length have influenced the behavior of steel piles, which are almost related to the exposed surface areas to the lateral forces and how they showed more resistance. Regardless of the selected shapes, the pile's height has a significant role in increasing the capacity (**Fig. 6**). This is related to the increase in the pile's vertical surfaces, which resulted in higher capacity values.

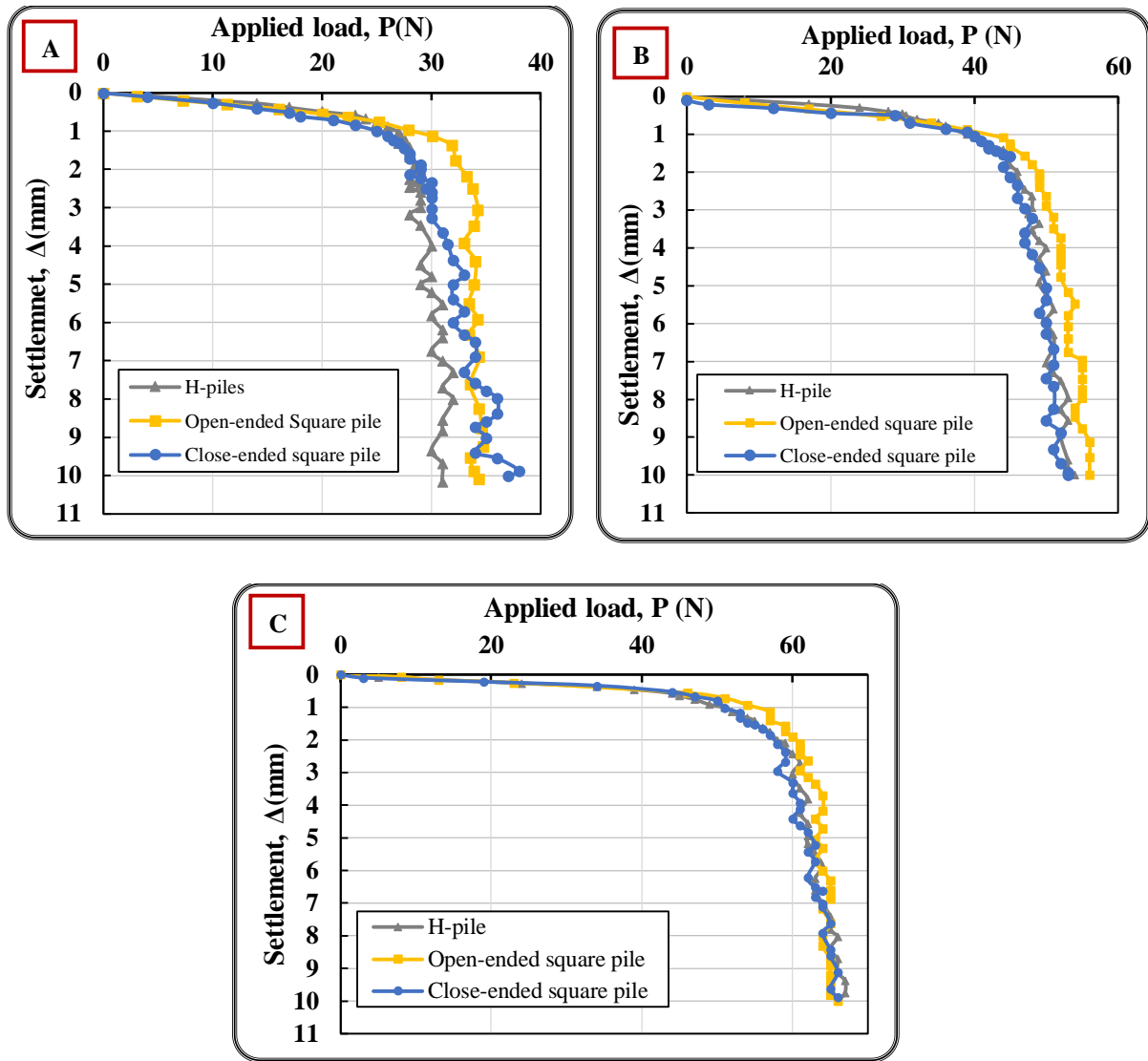


Figure 5. Load-settlement relationships for loose sand (RD=15%). A- Pile length = 100mm, B- pile length = 150mm, and C- pile length = 200mm.

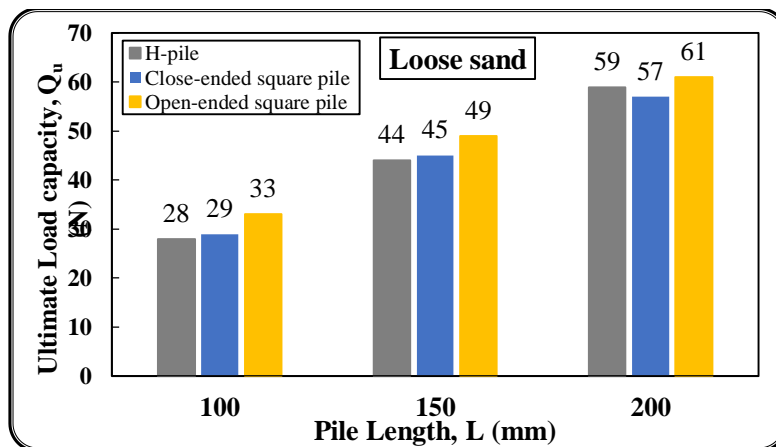


Figure 6. Comparison of the results of tested piles for loose sand.

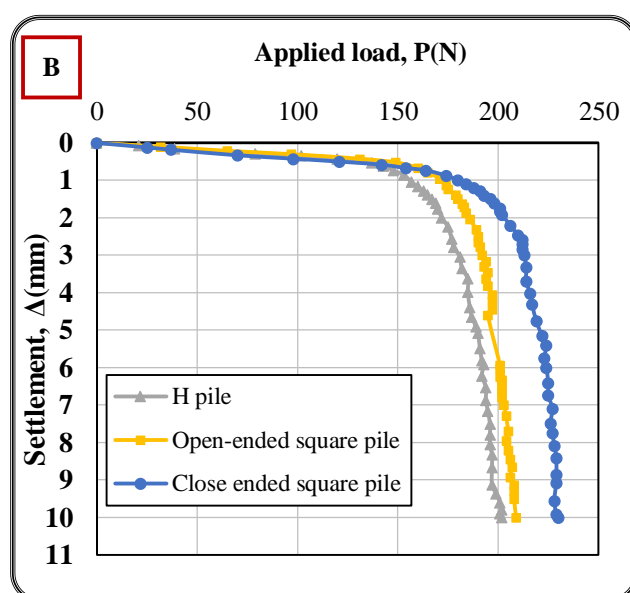
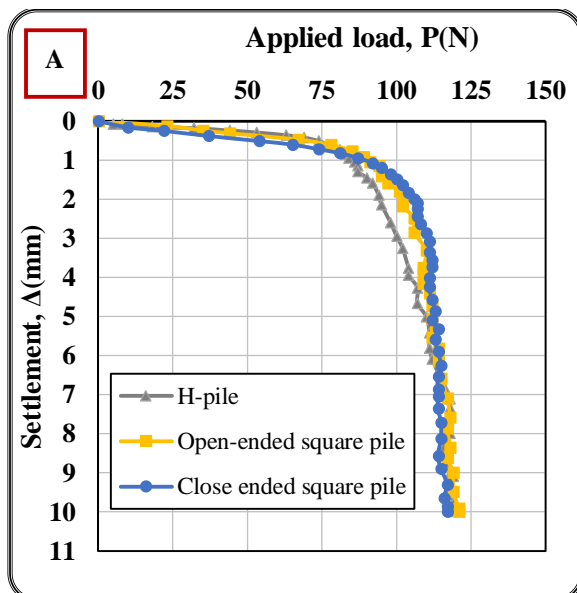


Table 2. The values of Q_u for loose sand.

Relative density, (RD) %	Length of the pile, L (mm)	H-pile, (N)	Close-ended Square pile, (N)	Open-ended square pile, (N)
15	100	28	29	33
	150	44	45	49
	200	59	57	61

3.2 Load-settlement relations for medium sand

For sand's density, medium sand, the values of Q_u were obtained from the static load test. In load testing of the pile's models, the static load test was performed to obtain the magnitude of load needed to reach the pile's ultimate load capacity. The load-settlement curves for all types of the pile are shown in **Fig. 7** (A, B, and C). So, the summary of the results is presented in **Table 3**. The values of Q_u for close-ended square pile were increased by 15.2, 19.3, and 9.1 % respectively for different lengths of piles (100, 150, and 200 mm), compared with the H-pile shape. This is because of the pile's tip cross-section area, which covered horizontally more sand particles and higher resistance obtained. While, the open-ended square pile showed a lower capacity compared with the closed-ended square pile, as shown in **Fig. 8**. A close-ended pile occupies a larger area below the tip compared with the open-ended pile. The close-ended pile showed higher values of the piles' capacities presented in **Fig. 8**. Physically, pile forces distribution is on the larger surface of the close-ended pile, which increased the tipping capacity due to higher resistance by the beneath medium sand. However, either in the case of H-pile shape or open-ended pile, the piles' bottoms has other shapes, specifically lines, contacting beneath sand particles. The pile's masses were distributed on smaller lines of contact with the medium sand particles. This led to less number of sand particles resisted the applied load and showed lower tip capacity.



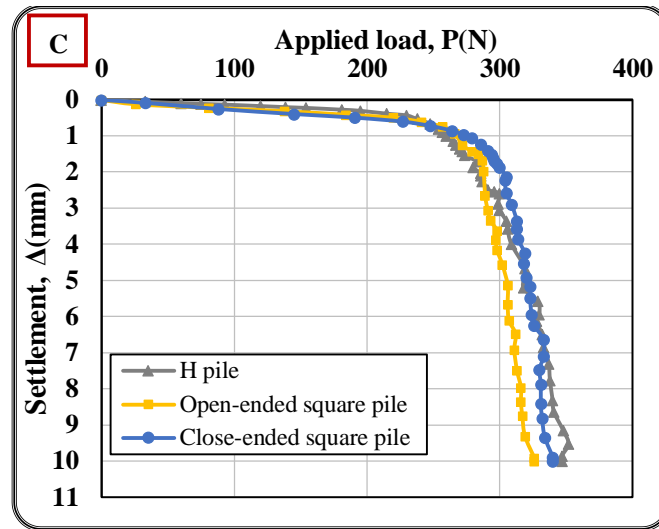


Figure 7. Load-settlement relationships for medium sand (RD = 50%). A-Pile length = 100mm, B-pile length = 150mm, and C- pile length = 200mm.

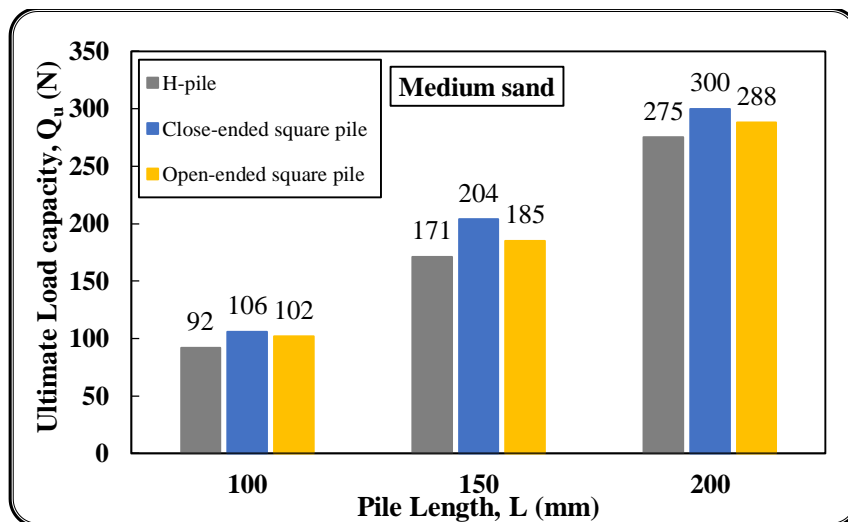


Figure 8. Comparison of the results of tested piles for medium sand.

Table 3. The values of Q_u for medium sand.

Relative density, (RD) %	Length of pile, L (mm)	H-pile, N	Close-ended Square pile, N	Open-ended square pile, N
50	100	92	106	102
	150	171	204	185
	200	275	300	288

3.3 Load-settlement relation for dense sand

The values of Q_u were obtained from the static load test. The load-settlement curves for all pile types are shown in Fig. 9 (A, B, and C), and the summary of the obtained results are presented in



Table 4. The values of Q_u for the close-ended square pile were increased by 49.7, 47.8, and 69.6% for different pile lengths (100, 150, and 200 mm) compared to the H-pile, as shown in **Fig. 10**. While, the values of Q_u for the open-ended square pile were reduced by 15.3, 11.2, and 16.9% for the same pile length, which compared with the close-ended square pile, as shown in **Fig. 10**. Because of the end bearing (tip) resistance, the close-ended pile recorded a higher capacity compared to that of the open-ended pile and H-pile. So, physically, the pile forces distributed on a larger surface for the close-ended pile, which increased the tipping capacity due to higher resistance by the beneath medium sand and resulted in higher load capacity. However, for both cases of H-pile shape and open-ended pile, the piles' bottoms have other shapes, specifically lines, contacting beneath sand particles. The pile's masses were distributed on smaller lines of contact with the dense sand particles. This led to less number of sand particles resisted the applied load and showed lower tip capacity.

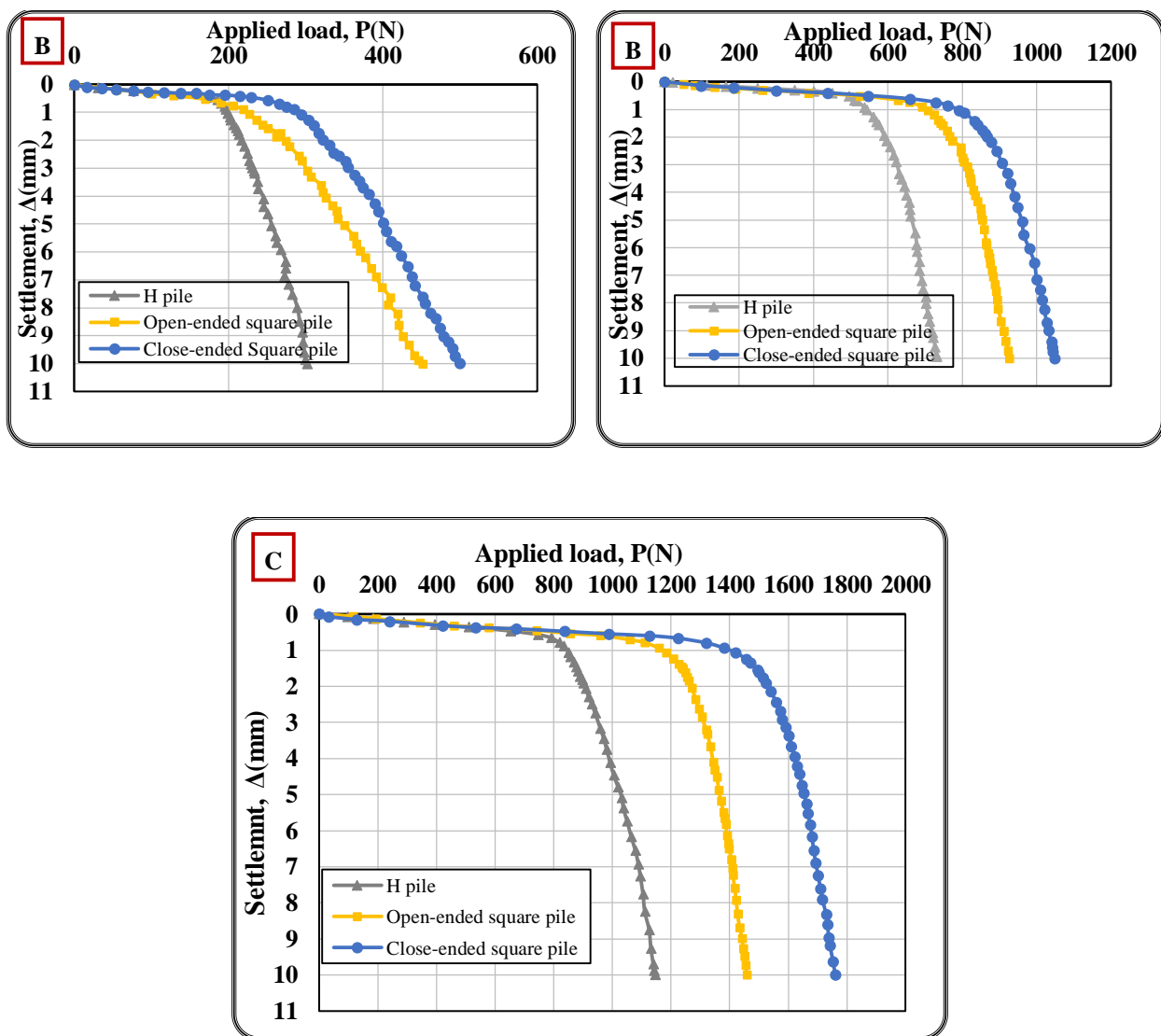


Figure 9. Load-settlement relationships for dense sand (RD=85%); A- Pile length=100mm, B- pile length=150mm and C- pile length=200mm.

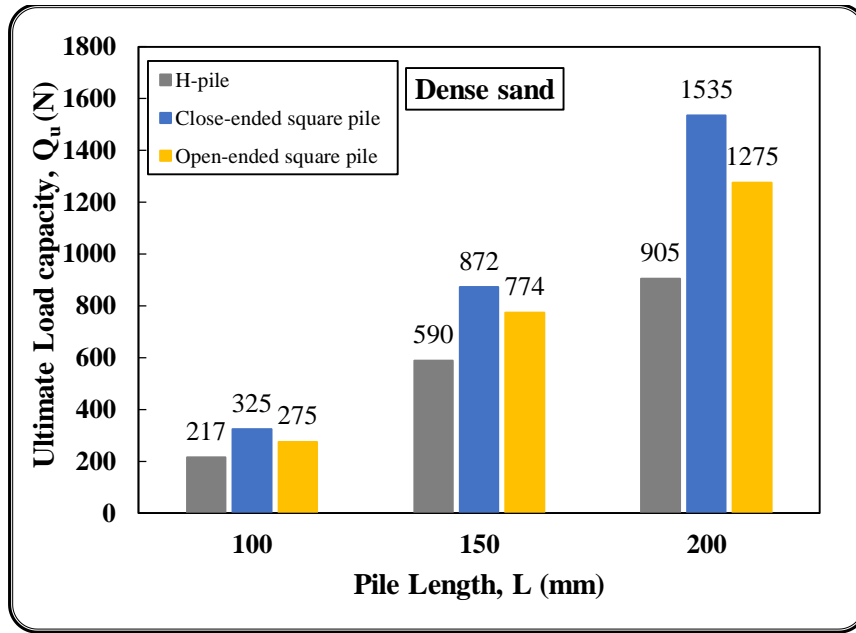


Figure 10. Comparison of the results of tested piles for dense sand.

Table 4. The values of Q_u for dense sand.

Relative density, (RD) %	Length of pile, L (mm)	H-pile, N	Close-ended Square pile, N	Open-ended square pile, N
85	100	217	325	275
	150	590	872	774
	200	905	1535	1275

4. CONCLUSIONS

The effects of different types of pile foundations under the same geometric conditions were investigated in this study. Based on load-settlement curves, the following conclusions were drawn:

- The open-ended square pile had a higher bearing capacity compared to the H-pile and close-ended square piles, which tested in loose sand.
- Sand density and pile geometric have a significant role in increasing the pile's bearing capacity.
- For the cases of dense and medium densities sand, the close-ended square pile had a higher bearing capacity compared to the open-ended square pile under the same geometric conditions.
- The values of Q_u for close-ended square pile were increased by 15.2, 19.3, and 9.1 % for different pile's lengths (100, 150, and 200 mm) that compared with the H-pile. In contrast, the open-ended square pile had a lower capacity compared to the closed-ended square pile, which was tested in medium sand.



- In the case of dense sand, the values of Q_u for the close-ended square pile were improved by 49.7, 47.8, and 69.6% for different piles lengths (100, 150, and 200 mm) compared to the H-pile.

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