LOAD-BEARING CAPACITY OF STEEL PIPE PILES IN CORAL GRAVELLY SAND CONSIDERING THE EFFECT OF HELICAL PLATE DISTANCE

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Abstract

Construction projects on geological grounds, particularly coral reefs, hold significant importance for national security, defense, and marine economic development. However, the application of new technologies and enhanced pile foundation structures in these projects has been limited. This study focuses on researching and evaluating the correlation between the load capacity of traditional steel pipe piles, which are supplemented with two helical plates, and the variations in the distance of these helical plates along the depth of the pile in coral gravelly sand using Mohr-Coulomb model by finite element method. The results of this study conclude that the load-bearing capacity of piles with two helical plates is 2.1 to 3.3 times higher than that of traditional plain round piles. In addition, a calculation function for the load-bearing capacity of the improved steel single-pipe pile in relation to the appropriate distance for the helical plates is proposed. This function is essential for projects built under the geological conditions of coral and the typical hydrological properties found in the offshore seas and islands of Vietnam.

***Keywords**: Steel pipe piles; helical plate; coral gravelly sand; Mohr-Coulomb model; finite element; correlation function; load-bearing capacity of pile.*

1. Introduction

The offshore islands under Vietnam's sovereignty also set requirements that require the proposal of new technological solutions in construction in general and in foundation engineering in particular in works to strengthen national security and defense and develop the marine economy. In particular, the improved pile structure of the pile foundation to increase resistance and economic efficiency is a solution that needs attention for berths, offshore drilling rig, maritime signal shipping, shore protection embankments, wind power towers. This is an area with coral bed geology, in which the coral sand and rock bed are distributed at different borehole depths on some typical islands [1].

The offshore islands under Vietnam's sovereignty present specific challenges that necessitate the proposal of innovative technological solutions in construction, particularly in foundation engineering, to bolster national security and defense, as well

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as to advance the marine economy. In particular, enhancing pile structures for foundations to increase both resistance and economic efficiency is a crucial solution for various applications, including berths, offshore drilling rigs, maritime signal stations, shore protection embankments, and wind power towers. This region features coral bed geology, where coral sand and rock beds are distributed at varying depths in boreholes across several typical islands.

Currently, in Vietnam, pile foundation design standards do not adequately address the performance of piles in coral gravelly sand, particularly for those featuring two reinforced helical plates designed to enhance resistance [2-4].

Studies conducted in Vietnam and in the world have demonstrated that traditional steel pipe piles, when reinforced with independent and intermittent helical plates and variable cross-sections along the pile body (such as screw piles and piles with helical plates), significantly enhance the transmission area of the pile into the surrounding foundation. This improvement greatly increases the resistance of the pile compared to conventional plain round piles, particularly in scenarios where the pile is subjected to uplift forces [5]. However, the study results have not determined the impact of the ratio between the distance of the plates and the length of the pile on the load capacity. Additionally, there is no established correlation function for the load capacity of the pile that accounts for variations in the distance of the helical plates in relation to different lengths of steel pipe piles [6, 7].

Coral gravelly sand is widely distributed in islands, archipelagos, and seas around the world, exhibiting varying thicknesses. In Vietnam, the coral gravelly sand found in offshore islands is characterized by significant thickness [1, 8].

The article establishes a correlation function between the load-bearing capacity of traditional steel pipe piles enhanced with two helical plates and the distance of those plates. This analysis focuses on the performance of piles in coral gravelly sand conditions, addressing a significant practical issue with considerable scientific value.

2. Theoretical basis of the research problem

The objective of this research is to investigate traditional steel pipe piles enhanced with two reinforced horizontal helical plates featuring variable spacing. To quantitatively evaluate the effect of these helical plates on the load-bearing capacity of the steel pipe piles, the authors also analyze plain round piles as comparative basis for assessment (Fig. 1).

Based on the model shown in Fig. 1, the load capacity of a plain round steel pipe pile subjected to axial compressive loads is determined using the following expression [9]:

$$[P_c] = Q_f + Q_p \tag{1}$$

in which

$Q_f = u_c \sum f_i \Delta z_i$ - lateral resistance (2)

$Q_p = q_p A_p$ - end bearing resistance (3)

u_c is body pile circumference, f_i is unit side resistance, Δz_i is the length of each pile segment which calculates the resistance on the side f_i unit, q_p is the unit end-bearing resistance, A_p is the horizontal section of the end-bearing pile, d and L_c are pile diameter and pile length.

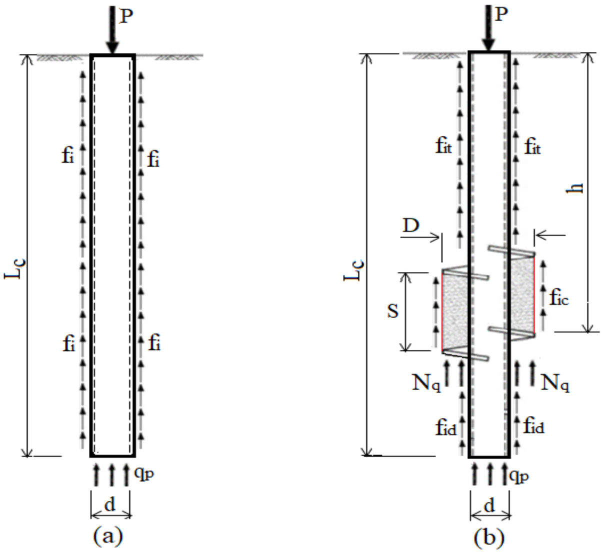

Fig. 1. Pile load capacity calculation model
a) Circular pile; b) Helical pile.

For a pile equipped with two helical plates positioned at an appropriate distance apart, the soil located between these helical plates functions similarly to a ground pillar pile (Fig. 1). Consequently, the section of the pile within these two helical plates can be treated as if it has a diameter equal to that of the helical plates. This approach has been suggested by authors such as B. W. Byrne and G. T. Houlsby [10]; H. A. Perko [11]; M. J. Nowkandeh and A. J. Choobbasti [12]; and M. Ali [13]. Under this model, the bearing capacity of the steel pile is determined using the following expression:

$$[P_c] = (Q_{ft} + Q_{fc} + Q_{fd}) + (Q_p + Q_c) \quad (4)$$

in which Q_{ft} is the lateral resistance of the upper pile segment of the helical plate;

$$Q_{ft} = u_1 \sum f_{it} \cdot \Delta z_{it} \quad (5)$$

Q_{fd} is the lateral resistance of the lower pile segment of the helical plate;

$$Q_{fd} = u_1 \sum f_{id} \cdot \Delta z_{id} \quad (6)$$

Q_{fc} is the lateral resistance of the pile section between two helical plates;

$$Q_{fc} = u_2 \sum f_{ic} \cdot \Delta z_{ic} \quad (7)$$

u_1 and u_2 - in turn, the circumference of the pile body corresponds to the diameter of the pile and the circumference of the section has two helical plates corresponding to the diameter of the helical plate; f_{it}, f_{id}, f_{ic} are the resistance on the unit side of the pile segment on the helical plate, the lower pile segment of the helical plate and the limit pile segment between 2 helical plates respectively; Δz_{it}, Δz_{id}, Δz_{ic} are the corresponding length of each pile segment on the helical plate, the lower pile segment of the helical plates and the limit pile segment between two helical plates respectively; Q_p, Q_c are the resistance of the tip of the pile and the resistance due to the counter force of the lower helical plate when the pile is subjected to compression respectively. Q_p is defined by equation (3) [9], and Q_c is defined by Eq. (8) [14]:

$$Q_c = 2 \cdot D \cdot \gamma (N_q - 1) A_c \tag{8}$$

D is helical plate diameter, N_q is the counter force coefficient of the helical plate when the pile is subject to compression; A_c is the area of the helical plates that has been reduced minus the cross-sectional area of the pile body; γ is the volumetric weight.

Given the extensive scope of the research, the aim is to develop a computational model using the finite element method. The author simulates three-dimensional interaction problems involving steel pipe piles with helical plates in coral sand and sandy conditions using PLAXIS 3D - Version 20.1.0.98. The modeling includes three-dimensional block elements for the coral sand and gravel bed, contact elements for the steel pipe pile, and virtual non-thickness elements for the coral sand and gravel bed. In the research, the steel pipe pile model can be represented as a beam element (Beam) combined with solid elements (Solid) [7], or alternatively, shell elements (Plate) can be used for the pile walls and helical plates [5].

The computational model is a continuous model, where different element forms of the overall structure are interconnected through node points. The placement of these nodes within the model is determined by the size of the elements and the type of elements chosen for the calculation.

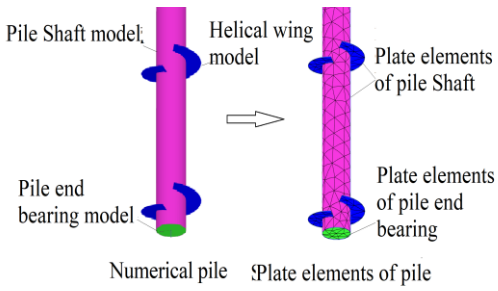

Fig. 2. Numerical model plate elements of pile.

Due to the characteristics of steel pipe piles with small thickness, hollow in the pile bed, the model according to the beam element method has difficulties when assuming the characteristic ratio of bending resistance and compression resistance, so there is often an error in the calculation.

3. Results and discussion

3.1. General pattern

Building on the aforementioned theory and numerical modeling approach, the author utilizes PLAXIS 3D-V2020 software to conduct numerical modeling, calculations, analyses, and evaluations of the research concerning steel pipe piles with two helical plates. This study focuses on the end-bearing behavior of the piles, with the distance between the helical plates varying proportionally to the length of the pile. The parameters of the numerical model, based on the general model, are as follows:

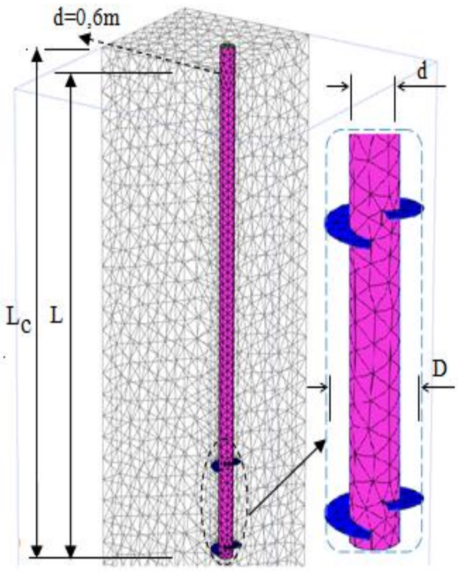

Fig. 3. Numerical model of steel pipe pile with two helical plates.

- Steel pipe piles have a diameter of d = 0.6 m; the pile lengths vary as L_c = 15 m; 12 m and 9 m. The piles are sealed at both the tip and the top (Table 1);

- The reinforced pile is equipped with two helical plates at the end bearing, with plate distances of S = 1.2 m; 1.8 m; 2.4 m and 3.0 m. The diameter of the plates is D = 2d = 1.2 m; plate step H = 0.3 m;

- The piles operate in the elastic stage, exhibiting linear deformation behavior. Their rigidity, geometric dimensions, horizontal cross-section, and specific gravity remain constant relative to the length of the pile, ensuring stability in a vertical orientation;

- Soil model: The model consists of a branch sand mixture with one isotropic homogeneous layer that is saturated, functioning according to the ideal flexible Mohr-Coulomb model.

The summary table of pile model parameters and coral gravelly sand of the survey problem is summarized in the following Table 1 and Table 2.

Table 1. Parameters of steel pipe piles with two helical plates

Model parameters	Value	Model parameters	Value
Elastic modulus *E* (kPa)	$2.00 \cdot 10^8$	Pile wall thickness δ_1 (m)	0.016
Sliding module *G* (kPa)	$7.69 \cdot 10^7$	Number of helical plates (n)	2
Specific gravity γ (kN/m^3)	78.0	Helical plate diameter *D* (m)	1.2
Pile length L_c (m)	15; 12; 9	Helical plate thickness δ_2 (m)	0.028
Pile depth *L* (m)	14; 11; 8	Helical plate step *H* (m)	0.3
Pile outer diameter *d* (m)	0.60	Helical plate distance *S* (m)	1.2; 1.8; 2.4; 3.0

Table 2. Parameters of coral gravelly sand [15, 16]

Expansion angle Ψ (°)	Friction angle φ' (°)	Apparent adhesion force c' (kPa)	Saturated volumetric weight γ_{sat} (kN/m³)
9.52	46.49	29.83	20.38
Poisson coefficient ν	Distortion module *E* (kPa)	Intensity attenuation coefficient, R_{inter}	Natural porosity coefficient e_{init}
0.34	30.86E+3	0.56	0.5

The interaction parameter between the coral gravelly sand and the steel pipe pile with helical plates involves simulating two materials with different behaviors through a contact element, which can be either thick or thicknessless. In this study, the authors employed PLAXIS 3D geotechnical analysis software to model the interaction between the coral gravelly sand with helical plate steel pipe piles, using a thicknessless contact element. This was done through the Rinter strength attenuation coefficient, which reflects the differences between the steel pile material model and the sand material with varying gradations. This coefficient was determined by the authors and their colleagues using experimental methods, and the average result of this parameter applied in the study is as follows: $R_{inter} = 0.56$ [15].

The force applied at the pile head is directed either to pull out or compress the pile along its axis. When subjected to load, the continuity condition of displacement is maintained at the contact surface between the substrates; however, relative slippage may occur between the pile and the substrate at the contact interface.

The width of the surveyed coral gravelly sand should be $B \geq 20d = 12$ m (where d is the outer diameter of the pile), choose $B = 12$ m. The height of the foundation block $H_n \geq L + 20d = 26$ m (L is the pile length in the foundation), select $H_n = 36$ m.

3.2. Survey results

Using the aforementioned model, the research team developed and analyzed 12 models of 15 m long piles, 12 models of 12 m long piles, and 12 models of 9 m long piles. The evaluation focused on the behavior of steel pipe piles with two helical plates by examining the correlation between the load-bearing capacity of the piles and the allowable displacement at the pile head, based on the extreme load capacity conditions for a single pile. The corresponding maximum displacement at the pile head is defined as $[U_c] = 0.1d = 60$ mm [9, 14]. This capacity is referred to as the load-bearing capacity of the pile, denoted $[P_c]$.

The calculation results from the models are synthesized and graphed as follows:

3.2.1. Evaluation of the load capacity of the pile

In order to evaluate the effectiveness of the load-bearing capacity of the pile, the author builds a graph of the correlation between the load and the displacement of the pile head, the results are shown in Fig. 4 and Fig. 5.

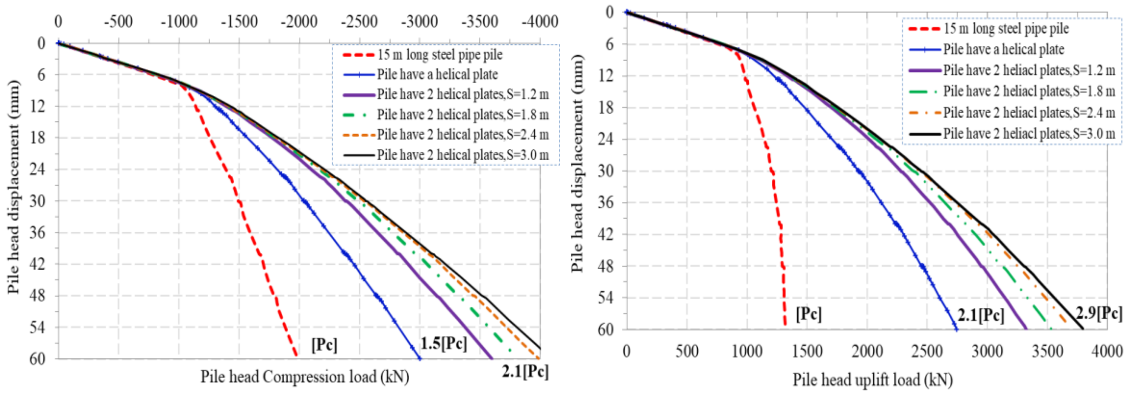

Fig. 4. Correlation pile head load with pile head displacement of 15 m long pile.

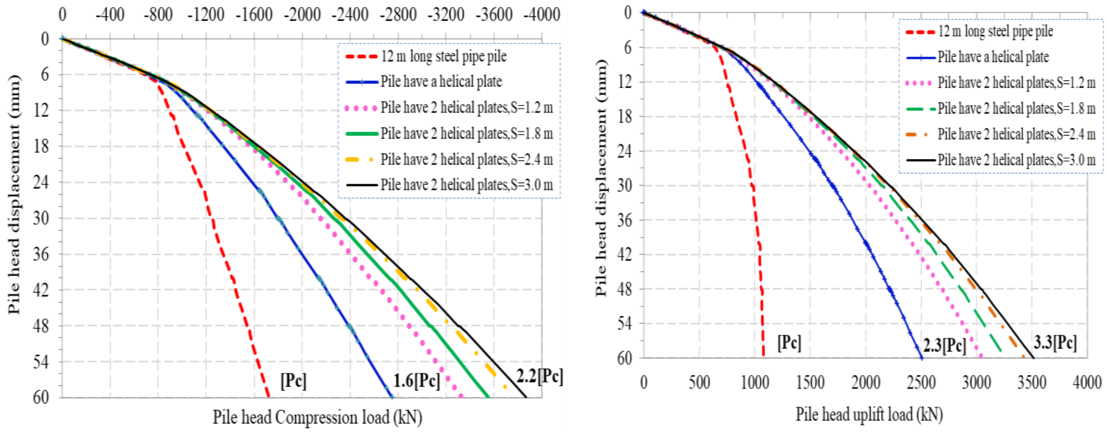

Fig. 5. Correlation pile head load with pile head displacement of 12 m long pile.

The results illustrated in the graph indicate that when the pile is subjected to compressive loads, the presence of the helical plates enhances the load capacity of the pile by a factor of 2.1 to 2.2 times compared to traditional plain round piles at extreme displacement. In cases of uplift, this difference is even more significant, increasing the load capacity by a factor of 2.9 to 3.3 times, respectively.

3.2.2. The correlation function load-bearing capacity with helical plate distance of pile

According to the condition of the extreme load capacity of a single pile, corresponding to the extreme displacement at the pile head is $[U_c] = 0.1d = 60$ mm. Therefore, in order to build the correlation function of the load-bearing capacity of the pile in the extreme state, the author synthesizes the results from the above numerical models and graphs the correlation between the load of the pile head and the ratio of the distance of the plates and the length of the pile, the results are shown on the graph of the following figures:

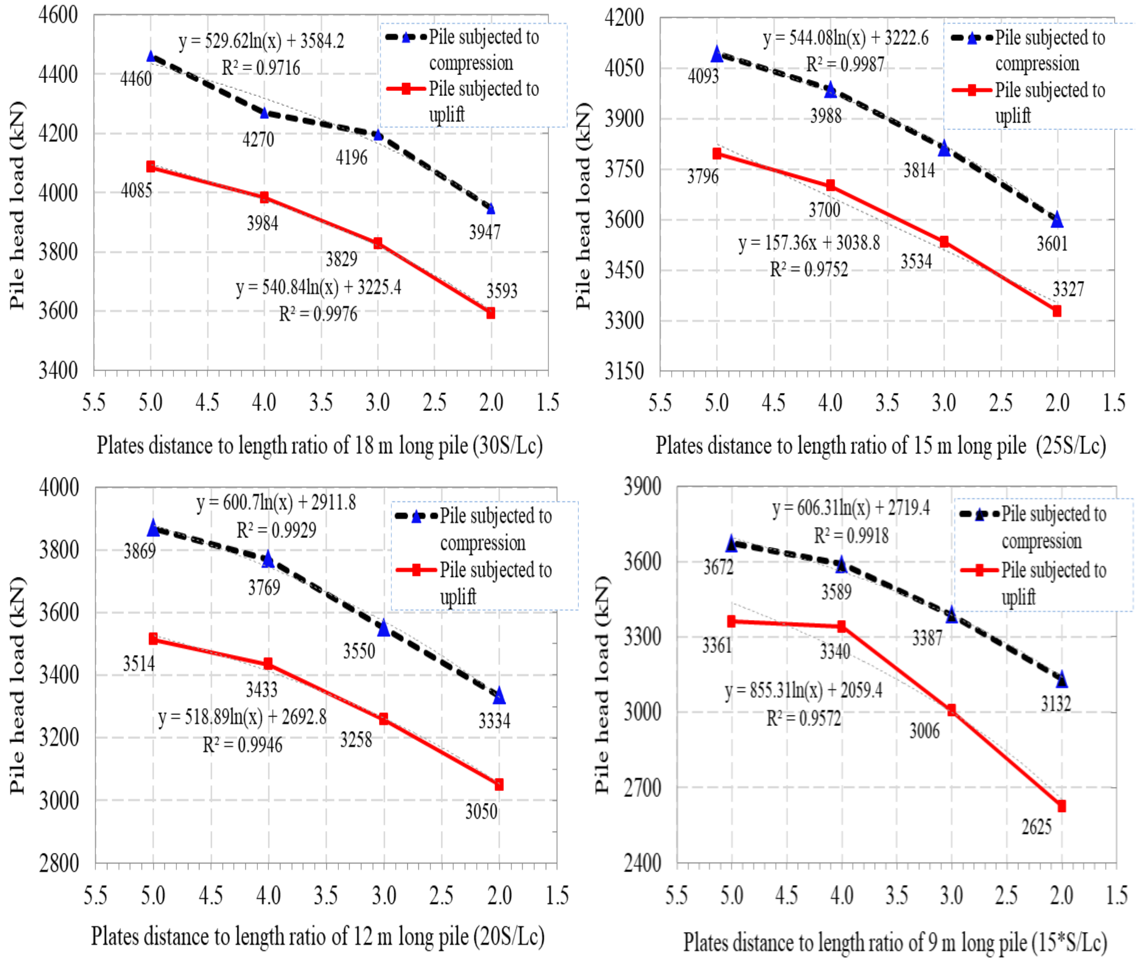

Fig. 6. Correlation of pile head load with of plates distance to length ratio of pile.

The results of the study shown in Fig. 6 have built a Logarithmic correlation function to calculate the load capacity of steel pipe piles with 2 helical plates when changing the distance of helical plate in the different load-bearing cases:

- 18 m long steel pipe pile:

+ Pile subjected to compression load:

$$[P_c^n] = 529.62\ln(30S/L) + 3584.2529.62\ln(30S/L) + 3584.2$$

+ Pile subjected to uplift load: $[P_c^k] = 540.84\ln(30S/L) + 3225.4$

- 15 m long steel pipe pile:

+ Pile subjected to compression load: $[P_c^n] = 544.08\ln(25S/L) + 3222.6$

+ Pile subjected to uplift load: $[P_c^k] = 157.36\ln(25S/L) + 3038.8$

- 12 m long steel pipe pile:

+ Pile subjected to compression load: $[P_c^n] = 600.7\ln(20S/L) + 2911.8$

+ Pile subjected to uplift load: $[P_c^k] = 518.89\ln(20S/L) + 2692.8$

- 9 m long steel pipe pile:

+ Pile subjected to compression load: $[P_c^n] = 606.31\ln(15S/L) + 2719.4$

+ Pile subjected to uplift load: $[P_c^k] = 855.31\ln(15S/L) + 2059.4$.

3.2.3. The correlation function load-bearing capacity of pile with the pile length

In the research results mentioned above, the author examines the impact of varying the spacing of the plates for piles of different lengths. To simultaneously consider the correlation with pile length, the author compiles the results from 36 models of piles measuring 15 m, 12 m, and 9 m, and additionally analyzes 8 numerical models of piles with a length of 18 m. The ratio of pile lengths is established relative to the shortest pile length (9 m), and a graph is created to illustrate the relationship between the load at the pile head and this length ratio. The results are displayed in the graphs in Fig. 7 and Fig. 8.

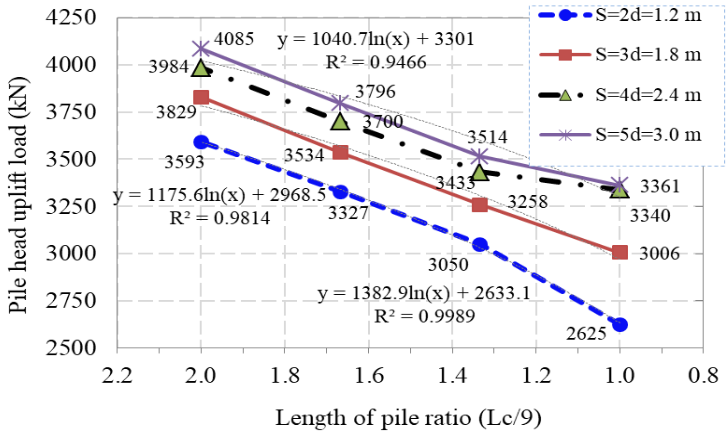

Fig. 7. Correlation of pile head uplift load with length ratio of pile.

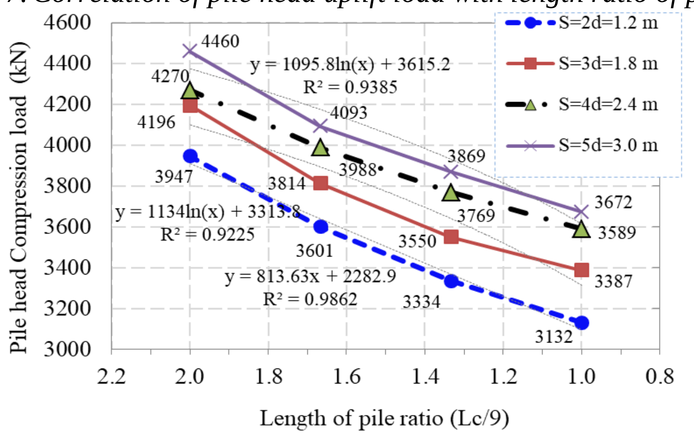

Fig. 8. Correlation of pile head compression load with length ratio of pile.

The research results presented in Fig. 7 and Fig. 8 illustrate eight logarithmic correlation functions that describe the relationship between the load at the head of a steel pipe pile with two helical plates and varying pile lengths. These functions account for changes in the distance between the helical plates on the pile body, considering both compression and independent uplift along the axis at the pile head.

4. Conclusion

The findings of this study, based on variable pile lengths of 15 m, 12 m, and 9 m, demonstrate that the load-bearing capacity of piles with two helical plates is 2.1 to 2.2 times higher than that of traditional plain round piles under compression conditions, and 2.9 to 3.3 times higher under uplift conditions.

Additionally, the spacing of the plates significantly impacts the performance of the piles. Consequently, the authors established correlation functions between the load-bearing capacity, the spacing of the plates, and the length of the steel pipe piles in coral gravelly sand. These functions are of great significance for practical design applications and suggest avenues for further research.

Piles used in the foundations of construction projects in coral gravelly sand on offshore islands are influenced by various factors. Therefore, the research results are of substantial importance for engineers involved in designing wharves, marine signal installations, wind power towers, and solar power poles in these regions. They offer valuable insights for selecting appropriate helical plates based on pile depth, in alignment with the geological characteristics of coral gravelly sand in Vietnam's offshore areas.

Furthermore, it is recommended to continue expanding research on optimizing the spacing of helical plates to evaluate and propose effective configurations that align with the operational needs of specific projects.

Acknowledgement

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NGHIÊN CỨU KHẢ NĂNG CHỊU TẢI CỦA CỌC ỐNG THÉP TRONG NỀN CÁT SẠN SAN HÔ XÉT ĐẾN ẢNH HƯỞNG KHOẢNG CÁCH CÁNH XOẮN

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Tóm tắt: Các công trình xây dựng trên nền địa chất, đặc biệt là san hô có ý nghĩa quan trọng về an ninh - quốc phòng và phát triển kinh tế biển. Tuy nhiên, đến nay việc áp dụng những công nghệ mới, kết cấu móng cọc cải tiến cho các công trình này còn hạn chế. Bài báo tập trung nghiên cứu đánh giá và xây dựng hàm tương quan giữa khả năng chịu tải của cọc ống thép truyền thống được bổ sung 2 cánh xoắn với sự thay đổi khoảng cách các cánh xoắn đó dọc theo chiều sâu của cọc trong nền cát sạn san hô, các tác giả sử dụng mô hình nền Mohr-Coulomb theo phương pháp phần tử hữu hạn. Kết quả nghiên cứu cho thấy, trong phạm vi nghiên cứu cọc ống thép có 2 cánh xoắn làm tăng khả năng chịu tải từ 2,1 đến 3,3 lần so với cọc tròn trơn truyền thống và kiến nghị khoảng cách cánh xoắn phù hợp cùng với hàm tính toán khả năng chịu tải của cọc đơn ống thép cải tiến trong móng công trình khi xây dựng trong điều kiện địa chất là nền san hô và tính chất thuỷ hải văn đặc trưng trên các vùng biển đảo xa bờ của Việt Nam.

Từ khoá: *Cọc ống thép; cánh xoắn; nền cát sạn san hô; mô hình Mohr-Coulomb; phần tử hữu hạn; hàm tương quan; khả năng chịu tải của cọc.*

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