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A STUDY ON THE EFFECT OF TOE-WING POSITION ON SCREW PILE PERFORMANCE IN COHESIONLESS SOIL

*****Ahmad Waheed Sahil[1], Taro Uchimura[1], Tadashi Maejima[2] and Md Raihanul Kabir[1]

[1]Department of Civil & Environmental Engineering, Saitama University, Japan; [2]Asahi Kasei Construction Materials Corporation, Tokyo, Japan

*Corresponding Author, Received: 17 June 2024, Revised: 12 August 2024, Accepted: 14 August 2024

ABSTRACT: Over the past 30 years, screw piles with diverse geometries have gained popularity over conventional piles for deep foundations. The behavior of toe-wing screw piles is not widely recognized on a global scale, and the effect of toe-wing plate position on the performance of screw piles has not been explored. Therefore, this paper investigated the impact of toe-wing position on screw pile performance embedded in the bearing layer. The toe-wing plates were embedded (Ew) in the bearing layer at a depth equal to the wing plate diameter, while the embedment depth (Ed) of the central shaft (pile tip) increased from 0 mm to 90 mm, which reflects the change in the toe-wing position. The model ground was prepared in the steel container with bearing layer densities of 55, 80, and 90 %, while the soil above the bearing layer was placed at a relative density of 45 %. The experimental results indicated that the installation load and torque non-linearly increased with the increase in embedment depth ratio (Ed/Ew). However, if checked at the same embedment depth (Ed), the normalized installation load increased to Ed/Ew = 1.2 and then decreased. In contrast, the normalized installation torque is non-linearly reduced with an increased embedment ratio (Ed/Ew). The normalized ultimate pile capacity increased non-linearly with the increase in embedment ratio (Ed/Ew). Regression equations based on the above trends are presented in this study to quantify the effect of Ed/Ew on installation load, torque, and bearing response.

Keywords: Toe -Wing Position, Embedment depth ratio (E_d/E_w), Installation Effort, Ultimate Pile Capacity

1. INTRODUCTION

Piles are relatively slender, structural foundation elements that transfer the load from a superstructure to the subsoil. Deep foundation technology has innovated significantly, developing and introducing many uniquely shaped piles [1,2]. Among these specifically shaped piles, screw piles have become more popular worldwide because of their high bearing capacity, rapid construction speed, ease of installation, and environmental friendliness [3].

Screw piles are steel piles with special helical plates that are welded at specific locations along the pile shaft. These plates facilitate the penetration of the pile into the ground during installation. The purpose of studying pile behavior is to determine the effects of various factors on the pile's load-bearing capacity, including pile geometry, site soil characteristics, groundwater conditions, implementation methods, pile material, soil displacement during installation, settling rate, and structural strength [4]. These dimensions have been carefully selected to maximize performance in different ground conditions. Screw piles provide structural support against tensile, compressive, and lateral forces, as well as against overturning moments [5]. In recent years, considerable progress has been made in improving the axial load-bearing capacity and installation methods of screw piles [6]. It is claimed that the loads exerted on the pile head are transferred to the surrounding soil, making the pile's load-bearing capacity dependent on the soil's strength properties [7]. The failure modes of screw piles can be broadly categorized into two types: individual bearing failure (IBF) and cylindrical shearing failure (CSF). Understanding these failure mechanisms is crucial for the design and optimization of screw pile foundations as it enables engineers to predict performance accurately and ensure the stability and safety of the structures they support [8]. The comparative study on the performance of a screw pile and a straight pipe pile indicated that screw pile performance is better than that of a straight pipe pile for similar shaft diameter and soil conditions. Moreover, the ultimate end-bearing capacity of small-scale screw piles with a single helix (closed-end) averaged 16.25% less than that of straight pipe piles under similar tip areas and ground conditions, regardless of increasing overburden pressure [9]. Composite foundations incorporating screw-shaft piles demonstrate a remarkable increase in load-carrying capacity of approximately 82% compared to foundations using straight piles [10]. An increase in the embedment ratio is known to enhance the bearing capacity of screw piles in both cohesive and cohesionless soils under both compressive and tensile loads. The increase in bearing capacity is generally more significant under tensile loads [11].

Previous studies have shown that the installation torque of helical piles with different geometric dimensions in the dry sand of varying densities is affected by various factors such as pitch, helix diameter, helix angle, central shaft diameter, sand friction angle, pile tip condition, pile material, and surface roughness [12,13]. The power consumed to install the screw pile increased non-linearly with the increase in sand relative density, with a 90 % contribution from torque and a 10 % contribution from installation force [14].

Research on toe-wing piles is extremely rare, and their use in engineering practice still needs improvement. Consequently, this innovative type of specially shaped pile offers excellent engineering performance but has yet to gain widespread attention among geotechnical engineers worldwide.

The existing research on toe-wing piles, mainly discussing the potential benefits of closed-end and open-end configurations in soft ground conditions, highlights their distinct behaviors and advantages [15]. Therefore, this study presents the results of the experimental evaluation of the toe-wing position on the performance of the screw pile. The screw piles having two semicircular plates (toe-wing) attached at the toe of the central shaft are also known as “Tsubasa Piles” [15]. These piles are typically installed using a drill by applying torque to the pile shaft. To ensure uniform penetration into the ground, an axial load is applied to the pile head, allowing progression corresponding to the rotation of the vane plates. The Tsubasa pile is one of the most used screw piles in Japan. Its advantages include low noise during installation, minimal vibration, no environmental pollution during construction, independence from groundwater levels, recyclability, high execution speed, and economic efficiency [16]. Also, the previous results indicated that Tsubasa piles require less torque for installation and can be loaded immediately after installation.

Moreover, it was also investigated that Tsubasa piles exhibit better performance in terms of bearing capacity when subjected to tension [17]. The two main variables influencing the toe-wing’s performance are the embedment depth ratio and the position of toe-wing plates along the shaft. These variables are investigated in detail in this study.

2. RESEARCH SIGNIFICANCE

There are limited available studies on the performance of toe-wing screw piles, and those primarily available focused on their benefits in terms of installation effort and bearing resistance concerning toe-wing diameter, pitch, and shaft end condition. The overall performance of such type of screw pile is strongly related to the toe-wings, and no previous study discussed the effect of toe-wing position on the installation effort and bearing resistance. Therefore, this study seeks to fill this critical gap by investigating the potential benefits of positioning toe-wing plates along the shaft and examining various embedment depths in the bearing layers, which significantly affect the design of piles due to their varying behaviors.

3. TESTING PROCEDURE

This section provides the physical properties of the sand, the experimental setup, and the testing procedure.

3.1 Model Container

A cylindrical steel container prepared the model ground for the pile load tests. Previous studies have shown that the zone affected by the load is typically 3 to 8 times the diameter of the pile tip [18]. The zone of influence around the pile ranged from 0.9 to 1.4 times the length of the pile [19]. Yang suggested that in clean sand, the zone of influence above the pile tip should be 1.5 to 2.5 times the diameter of the pile [20]. The proposed area for the zone of influence below the tip of the pile is 3.5 to 5.5 times the diameter of the pile [21]. In this study, the tank has a diameter of 1000 mm and a depth of 1130 mm, as shown in Fig.1. The spacing around the pile was (15 to 23 times the diameter of the pile tip). The clearance below the pile tip was 545 mm for a 65 mm diameter and 567 mm for a smaller 43 mm diameter (8 to 13 times the pile tip diameter). Thus, the container size was selected to be sufficiently large to eliminate boundary effects.

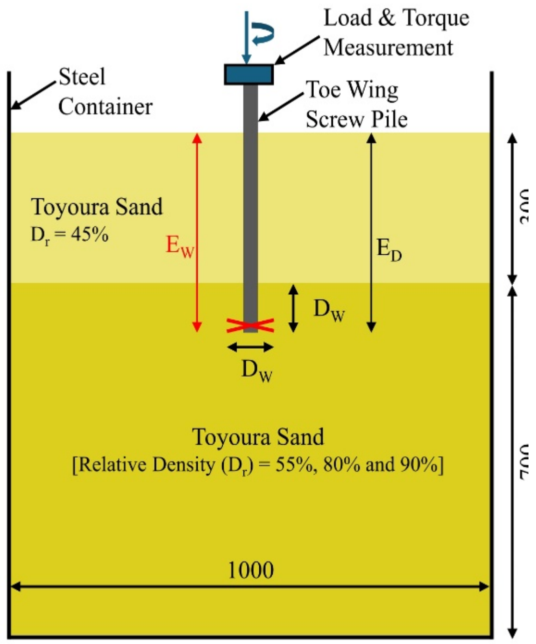


Fig.1 Model steel container (units in mm)

3.2 Model Screw Piles with Toe-Wing (Tsubasa Pile)

This study used toe-wing screw piles (Tsubasa

Piles) with smooth semicircular steel plates (toe-wing) attached at the central shaft to simulate actual piles; the toe-wing plates have a diameter of 2 to 3.0 times the diameter of the steel pipe, as shown in Fig.2. The physical specifications of these piles are listed in Table 1.

The shape of the end tips of these piles was kept close-fitting in all test programs. The toe-wing plates are attached to the pile shaft at three positions from the pile tip, i.e., W_p = 0, W_p = 50 mm, and W_p = 90 mm.

Table 1 Physical specifications of toe-wing piles

Pile Shaft		Toe Wing Details			
L_S [mm]	D_S [mm]	D_W [mm]	T_W [mm]	I_W [degree]	W_P [mm]
500	21.7	43	1.75	25	0, 50, 90
500	21.7	65	3.60	25	0, 50, 90

Notes: L_S = Pile shaft length, D_S = Pile shaft diameter, D_w = Toe-wing diameter, T_W = Toe-wing thickness, I_W = Toe-wing plates inclination, W_p = Toe-wing position from the pile tip.

(a)

(b)

Fig.2 Model toe-wing screw piles with varying toe-wing position from the pile tip (a) Toe wing diameter of 43 mm (b) Toe wing diameter of 65 mm

3.3 Testing Outline

The model ground was prepared with dry Toyoura sand having the following properties,

- Specific gravity 2.645
- D_{50} (mm) 0.19
- e_{max} 0.973
- e_{min} 0.609

According to Garnier et al. [22] and Rakotonindriana et al. [23], there is no scale effect on the tip resistance of the pile when the ratio of pile tip diameter to D_{50} is above 35. This study's D_w/D_{50} ratio was between 226 and 342.

The sand was compacted into ten layers to develop the model ground, with each layer compacted to a thickness of 100 mm for the desired relative density. The first seven layers were produced in a dense state with a relative density (D_r) of 55, 80 and 90 %. The top three layers were constructed in a loose state with a relative density (D_r) of 45 % during all tests. To ensure uniform relative density along the depth of the model ground, the known mass of sand concerning considered relative density and layer thickness (after compaction) was poured into the model container. After compaction to the targeted layer thickness (100 mm), the layer's height was checked at different locations, confirming the uniformity of the model ground. The settlements during the pile load test were measured with a displacement transducer. The axial load and torque on the pile head were measured using a load cell.

4. TEST RESULTS AND DISCUSSIONS

4.1 Pile Installation Response

The toe-wing screw piles are installed using a combination of pressing and rotation applied at the top of the pile head with an automatically controlled system for pushing and rotation rate. The pressing rate is adjusted so that during one complete rotation, the pile is inserted into the ground by one pitch of the toe-wing plates (28 mm/min for D_w=65mm pile, and 19 mm/min for D_w=43 pile). The rotation rate was set to 1 revolution per minute.

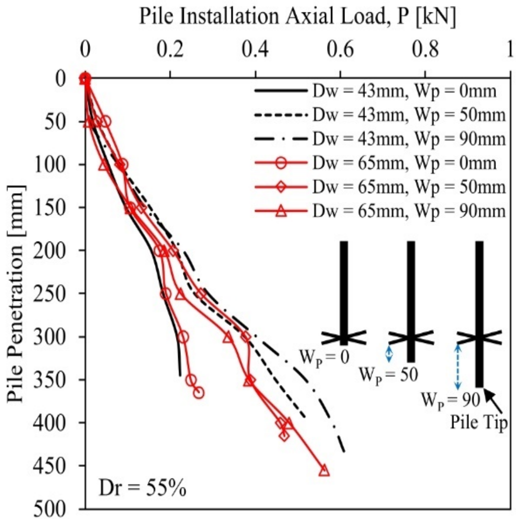
In this study, it was made sure that the embedment depth of the toe-wing (E_w) should be fixed and at one time the wing plate diameter (D_w) into the dense layer (based on [24]. In contrast, the embedment depth of the pile tip (E_d) increased from W_p = 0 mm to W_p = 90 mm.

Typical results of the pressing axial load (P) during the installation of the toe-wing screw piles for relative densities of the bearing layer of 55, 80, and 90 % are shown in Fig.3. The results indicated that the pressing load increased nonlinearly with the increase in penetration depth [25]. Moreover, the maximum installation load also increased with an increase in the toe-wing position from the pile tip (Wp = 0 to 90 mm) due to the rise in the embedment depth of the pile tip (central shaft).

The embedment depth of the pile tip (E_d) to toe-wing plate depth (E_w) ratio (E_d/E_w) against maximum installation load (P_{max}) normalized by installation load for screw pile with toe-wing attached at the pile tip, i.e., W_p = 0, is shown in Fig.4.

The normalized installation load ($P_{max}/P_{Wp=0}$) increased non-linearly with a gradually increasing trend in embedment ratio (E_d/E_w). This is due to the increase in stress level at the pile tip embedment depth (E_d). Moreover, with the Ed/Ew ratio increase, the toe-wing plates and pile tip may act independently, which may further increase the pressing load.

If the above relationship is checked at the same pile tip embedment depth, i.e., E_d = 300 mm, the normalized installation load ($P/P_{Wp=0}$) increased to E_W/E_d = 1.2 and then decreased, as shown in Fig.5. Moreover, a further decrease in E_w decreases the stress level at toe-wing plates, which further reduces the load contribution of toe-wing plates. In Figure 5, for D_w = 43 mm, the trend is not as high as in other cases, and that might be due to the localized ground change during pile installation.



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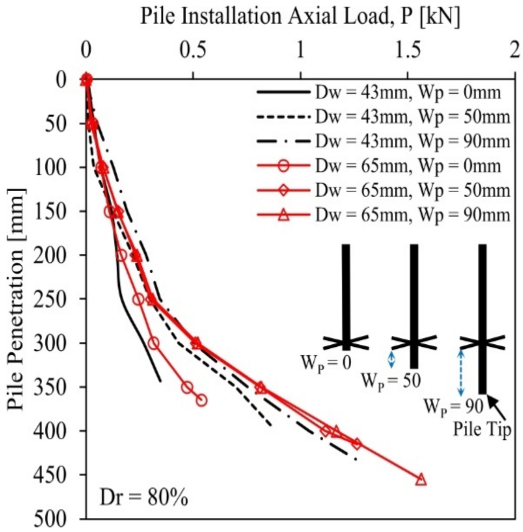

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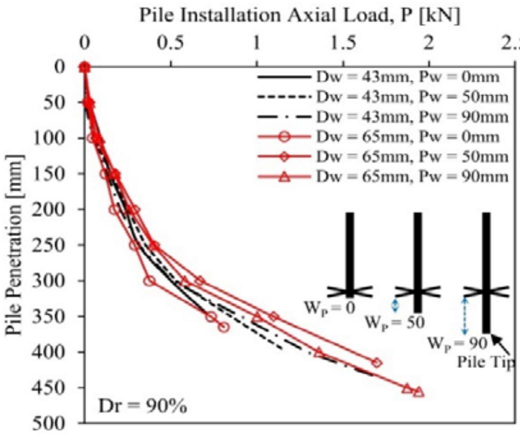


(c)

Fig.3 Installation pressing load at various positions of toe-wing plates (W_P) of screw pile (a) at relative density (D_r) = 55 %, (b) D_r = 80 % (c) 90 %

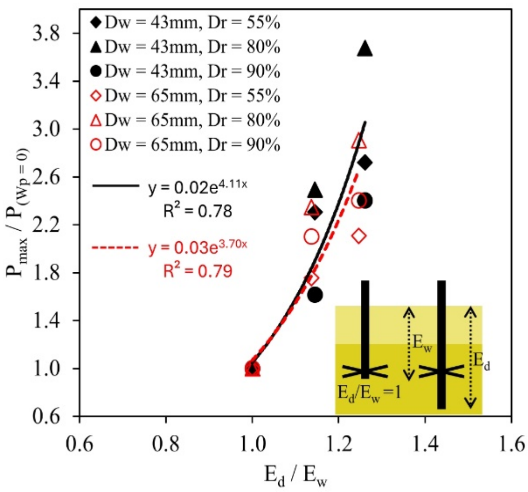


Fig.4 Embedment depth ratio against normalized installation load

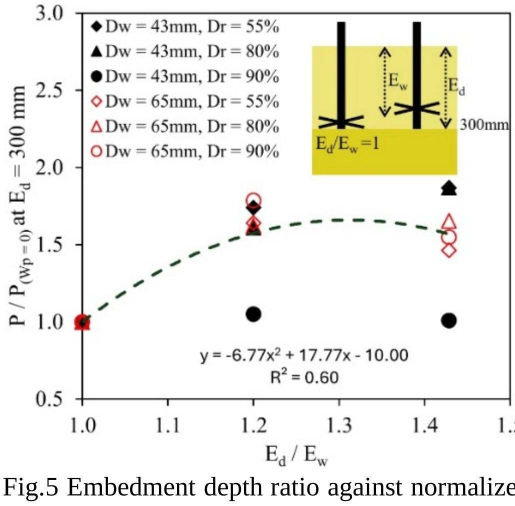
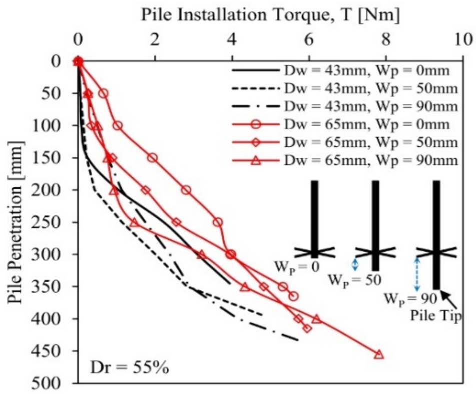


Fig.5 Embedment depth ratio against normalized installation load at embedment depth of 300 mm

The results of installation torque (T) during the installation of toe-wing screw piles for the relative densities of 55, 80, and 90 % are shown in Fig.6. Like installation load, the installation torque increased non-linearly with an increase in the penetration depth [25]. The installation torque at the final embedment depth increased with the rise in toe-wing position from the pile tip (W_p = 0 to 90 mm) due to the increase in the embedment depth of the pile tip (central shaft).

The embedment ratio (E_d/E_w) against maximum installation torque (T_{max}) normalized by installation torque for screw pile with toe-wing attached at the pile tip, i.e., W_P = 0, is shown in Fig.7. The normalized installation torque ($T_{max}/T_{Wp=0}$) increased non-linearly with a gradually increasing trend of embedment ratio (E_d/E_w), this is due to the increase in stress level at the pile tip embedment depth (E_d). Moreover, with the increase in the E_d/E_w ratio, the toe-wing plates and pile tip may act independently, which may further increase the torque.

If the above relationship is checked at the same pile tip embedment depth, i.e., E_d = 300 mm, the normalized installation torque ($T/T_{Wp=0}$) decreased non-linearly with the increase in embedment ratio (E_d/E_w), as shown in Fig.8. This reduction is due to the decrease in stress level as the wing plate position (W_P) increased from 0 mm to 90 mm, i.e., decreased in wing plate embedment depth (E_w).



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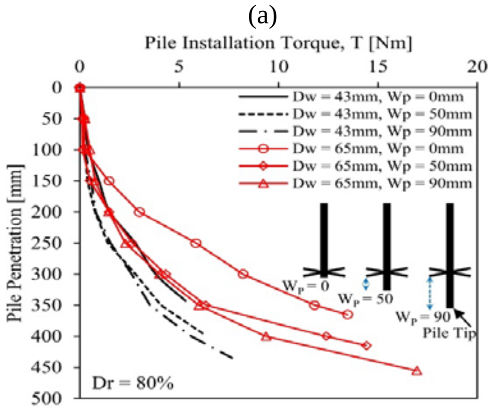

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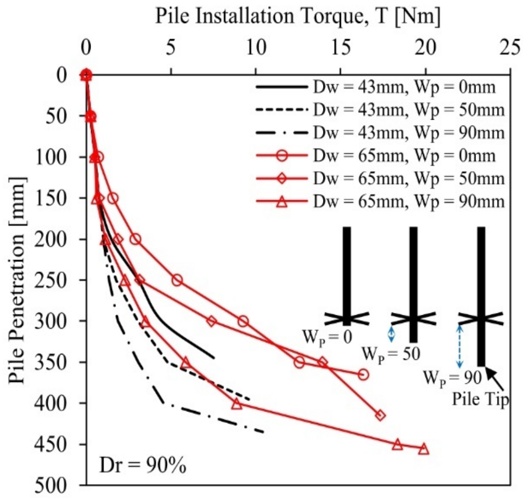


(c)

Fig.6 Installation torque at various positions of toe-wing plates (W_P) of screw pile (a) at relative density ($\boldsymbol{D_r}$) = 55 %, (b) $\boldsymbol{D_r}$ = 80 % (c) 90 %

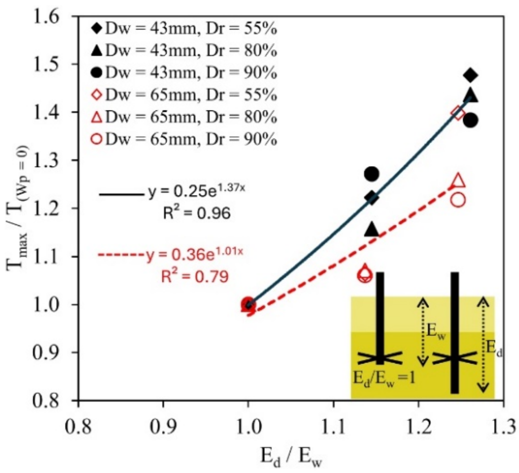


Fig.7 Embedment depth ratio against normalized installation torque for D_w = 43 mm and D_w = 65 mm at relative densities of 55,80, and 90 %

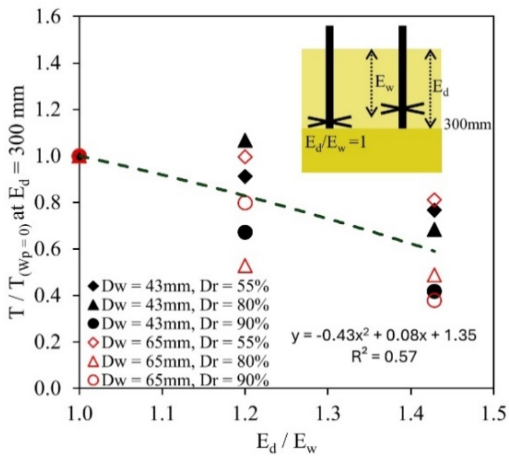
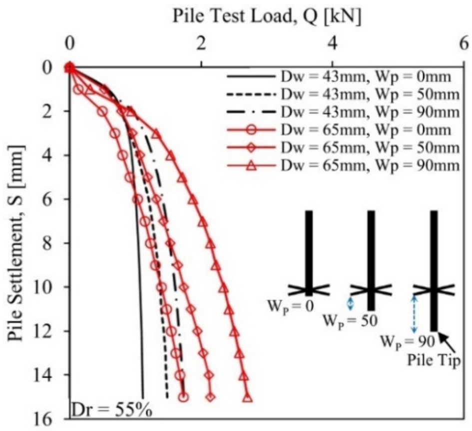


Fig.8 Embedment depth ratio against normalized installation torque at embedment depth of 300mm

4.2 Pile Bearing Resistance

After pile installation, pile load tests were performed approximately 30 minutes later on the toe-wing screw piles with varying wing plate positions (W_P) concerning pile tip embedment depth (E_d). Figure 9 shows the load settlement response of the toe-wing screw piles having wing plate diameters of 43 mm and 65 mm at bearing layer densities of 55, 80, and 90 %. The results indicated that the pile resistance increased with the increase in wing plate position (W_P) concerning the pile tip. Moreover, pile resistance increased with the increase in wing plate diameter.

The ultimate pile capacity was obtained from the load settlement curve at the plugging resistance state. The embedment ratio (E_d/E_w) against ultimate pile capacity (Q_u) normalized by ultimate pile capacity for screw pile with toe-wing attached at the pile tip, i.e., W_P = 0, is shown in Fig.10. The normalized ultimate pile capacity $\{Q_u/Q_{u(Wp=0)}\}$ increased non-linearly (gradually decreasing trend) with the increase in embedment ratio (E_d/E_w). This increase is due to the rise in the embedment depth of the pile tip (E_d), which reflects an increase in the stress level. Moreover, a further rise in E_d/E_w may separate the combined effect of the toe-wing and pile tip, which may reduce the bearing response.



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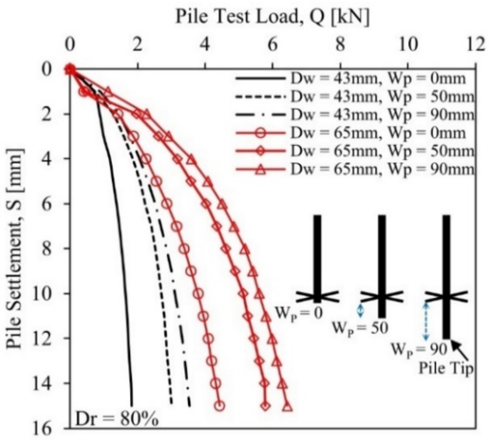

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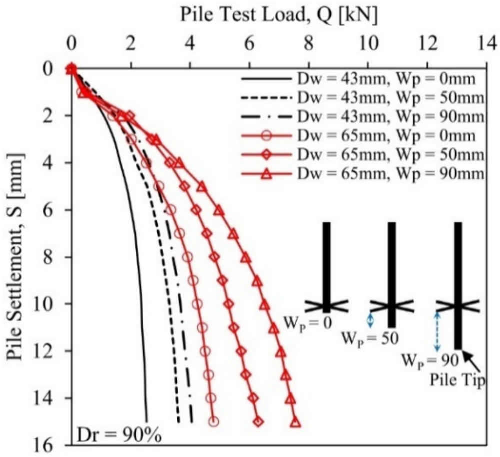

(c)

Fig.9 Load settlement response at various positions of toe-wing plates (W_P) of screw pile (a) at relative density (D_r) = 55 %, (b) D_r = 80 % (c) 90 %

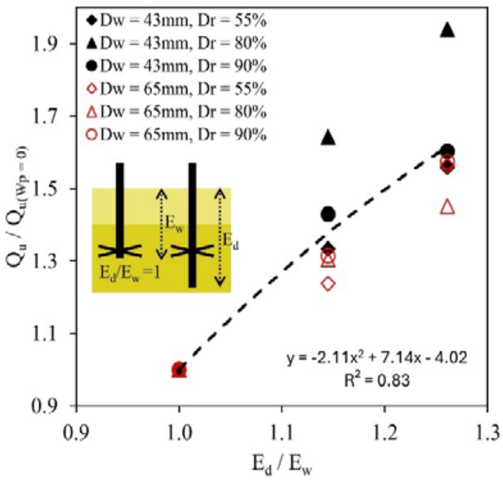

Fig. 10 Relationship of embedment depth ratio against normalized ultimate pile capacity at various bearing layer densities

It is presumed that ground disturbance in the dense bearing layer (loosening) occurred in all test scenarios, reducing the bearing resistance. However, the highest influence on bearing resistance was when the toe-wing plates were the pile tip (Wp = 0) because this disturbance directly affects the toe-wing contribution towards bearing response.

5. CONCLUSIONS AND RECOMMENDATIONS

This study investigated the effect of the toe-wing position on the installation effort and bearing response of the screw pile embedded in the dense bearing layer with relative densities of 55, 80, and 90 %. The ground above the bearing layer was at a relative density of 45 % in all experiments. The wing plate position (W_p) was kept at one time the wing plate diameter (D_w) into the bearing layer while the pile tip (central shaft) embedment depth (E_d) increased from 0 mm to 90 mm to reflect the position (W_p) effect of the wing plate. The experiments were conducted on a model scale, and piles were installed by pressing and rotation. The following are the primary outcomes of this study.

- The installation load and torque increased non-linearly with the increase in penetration depth. Moreover, with the rise in pile tip embedment depth (Ed) at maximum installation depth while keeping the toe-wing embedment depth (E_w) unchanged, installation load and torque increased.
- It is revealed that the normalized installation load ($P_{max}/P_{Wp=0}$) and torque ($T_{max}/T_{Wp=0}$) increased non-linearly with a gradually increasing trend in embedment ratio (E_d/E_w). This is due to increased stress levels as the embedment depth of the pile tip (central shaft) increased.
- At the same pile tip embedment depth (E_d), the normalized installation load ($P/P_{Wp=0}$) increased to E_w/E_d = 1.2 and then decreased. Meanwhile, the normalized installation torque ($T/T_{Wp=0}$) is non-linearly reduced with the increase in embedment ratio (E_d/E_w). This is due to the decrease in stress level at the wing plate position as the wing plate position (W_P) increased from 0 mm to 90 mm, i.e., decreased wing plate embedment depth (E_w).
- The normalized ultimate pile capacity $\{Q_u/Q_{u(Wp=0)}\}$ increased non-linearly with the increase in embedment ratio (E_d/E_w). This increase is due to the rise in the embedment depth of the pile tip (E_d), which reflects an increase in stress level.

The study on the effect of toe-wing position on screw pile performance in cohesionless soil is crucial for optimizing foundation design and construction. By determining the optimal positioning of toe-wing plates, the research can enhance load-bearing capacity, stability, minimum nearby ground disturbance by toe-wing plates, and effectiveness in installation efforts. This has direct implications for reducing construction costs and improving the safety and reliability of structures built on cohesionless soils. Moreover, results also motivate further researchers to consider other variables that significantly impact the behavior of screw piles, such as coarser materials, saturated soil, partially saturated soil, multiple helical blades, and geometrical shape.

This study's limitations are primarily restricted to the test results presented. The presented polynomial equations are valid within the considered E_d/E_w range and not recommended for extrapolation.

6. ACKNOWLEDGMENTS

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