Finite element study on the response of screw pile with open and closed shaft in dense sand

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ABSTRACT

The recent increase in the acceptability of displacement steel piles is due to their sustainable and environmentally friendly installation methods. The most used displacement steel piles are pipe piles and screw piles. In these piles, one of the important elements is their shaft end condition, i.e., open or closed, because it affects both installation effort (pressing load and torque) and bearing resistance. This study focused on the response of open and closed-end single helix screw piles in dense sand without considering the effect of installation to highlight only open and closed-end responses. The existing experimental data and validated numerical model (PLAXIS 3D) considering a single helix screw pile embedded in dense sand is used to conduct a parametric study to see the effect of in-pile plug length on the bearing response of the screw pile. An elastic, perfectly plastic model was used for interface material to represent soil-pile interaction. The numerical results indicated that the helix experiences more upward normal stresses in the case of a fully open-end screw pile than closed-end and open-end with 2.8 times shaft diameter (D_s) in-pile soil plug screw piles. The overall response of the open-end pile with 2.8D_s (1 x helix diameter) in-pile soil plug can produce sufficient resistance to exhibit a more or less similar response as the closed-end pile.

Keywords: *Screw Pile, Open-end, Closed-end, Soil Plug, Finite element analysis, Bearing response*

1. Introduction

The recent increase in the acceptability of displacement steel piles is due to their sustainable and environmentally friendly installation methods, such as press-in and rotary press-in. The most commonly used displacement piles that follow the above-mentioned installation methodologies are pipe piles and screw piles. In these piles, one of the important elements is their shaft end condition, i.e., open or closed, because it affects both installation effort (pressing load and torque) and bearing resistance. In the case of the closed-end pipe and screw piles, the shaft end condition, i.e., flat, cone, cutting-edge, also affects the installation effort and bearing resistance (Malik et al., 2021; Saleem et al., 2020). Moreover, the advancement ratio also affects the bearing response of screw piles (Annicchini et al., 2023; Malik et al., 2024). It is easier to install open-ended piles than closed-ended piles (Kido et al., 2022). However, the performance of open-ended piles is strongly related to plug formation, which is the movement of soil mass into the shaft (Li et al., 2021; Randolph et al., 1991). The degree of plugging differentiates the behaviour of open-ended piles from closed-ended piles (Gavin & Lehane, 2003). Moreover, the degree of plugging, i.e., unplugged, partially plugged, and fully plugged, is associated with the pile installation method, geometry, and ground conditions (Li et al., 2021; Henke & Bienen, 2013). At deeper penetration, the pile capacity of open-ended pipe piles is comparable with closed-ended pipe piles due to fully plugged conditions (Paik et al., 2003). Generally, piles are penetrated to the dense layer (bearing layer) if it is reachable. Kido et al. (2022) stated that the thickness of the bearing layer should be more than three times the diameter of the pipe pile (open or closed-end). Another study indicated that in the case of a screw pile, the embedment depth in the bearing layer should be at least one times the diameter of the helix to achieve high bearing performance (Ikeda et al., 2010).

In the case of screw piles, not many studies have been conducted that highlight the effect of open and closed ends of the central shaft on the bearing layer. The soil penetration into the central shaft does not increase uniformly with the increase in pile penetration (Saeki & Ohki, 2000). Another study indicated that screw piles with open-end showed a similar response to closed-end piles, and it is due to full plugged formation. However, when the open-end pile enters the bearing layer in a fully unplugged condition, then its performance is better than the closed-end pile, and it is due to the loosening of sand (Shahzad et al., 2022). Keeping in mind the above-mentioned outcome, this study focused on the response of open and closed-end single helix screw piles in dense sand (bearing layer) without considering the effect of installation. For this purpose, published experimental and numerical data (Ho et al., 2021; 2022) is used to investigate only the effect of open-end conditions with 2.8 times central shaft diameter (one times helix diameter) in-pile soil plug length.

2. Methodology

The published literature (Shahzad et al., 2022) highlighted that an open-end single helix screw pile bearing response is better than a closed-end screw pile installed and embedded in a dense bearing layer. A numerical study is conducted to investigate whether there is any contribution of in-pile plug length towards bearing response. The experimental data and validated numerical model (PLAXIS 3D) considering single helix screw pile embedded in dense sand by Ho et al. (2021; 2022) is used to conduct a parametric study to see the effect of in-pile plug length on the bearing response of screw pile. The in-pile plug length varied from 0 to 1 times the helix diameter (D_h) = 2.8D_s. This study does not consider the installation effect to highlight the contribution of in-pile plug length. Moreover, the helix is modelled as a flat surface (i.e., zero pitch), as helix pitch doesn't affect the bearing response once the pile is installed (Qu et al., 2023).

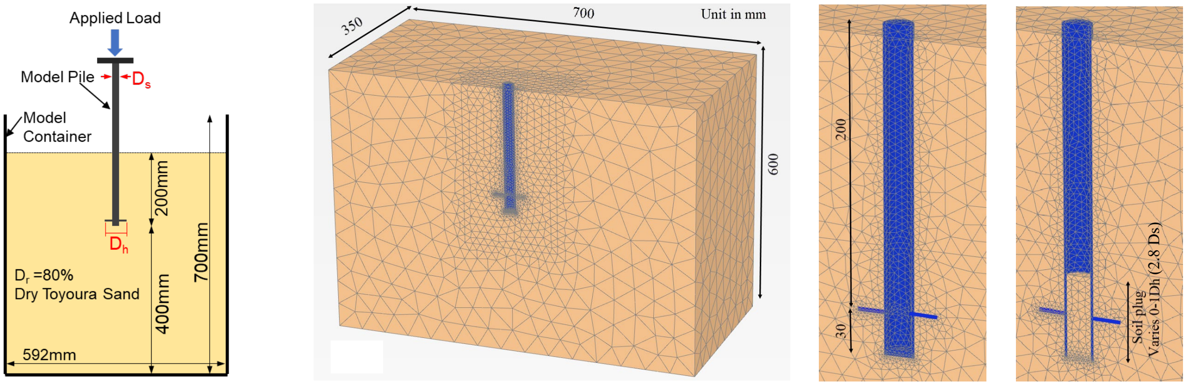
3. Experimental and Numerical Setups

3.1. Experimental Setup

The experimental setup consisted of a circular steel container with 592 mm diameter and 700 mm depth, as shown in Fig. 1(a). Toyoura sand was compacted in the model container at a relative density of 80 %. The screw pile with a single helix and closed-end was placed (wished-in-place) in the model container after compacting the model ground up to 400 mm. The surrounding soil was placed and compacted carefully to develop the embedment depth of 200 mm. After that, a pile load test was conducted (based on Ho et al. 2021; 2022).

3.2. Numerical Setup

The numerical model was created by using PLAXIS 3D (Bentley, 2020), and it is based on previous studies (Ho et al., 2021; 2022), as shown in Fig. 1(b, c, d). The screw pile (D_h = 60 mm) was modelled as a linear elastic model. Two screw piles with closed-end tips and open-end tips having 2.8D_s (1D_h) plug are shown in Fig. 1(c, d). The experimental ground was modelled as a Hardening soil model with small-strain stiffness (Benz, 2007). The soil parameters were back-calculated from Nakai & Hinokio's (2004) study, which used the same soil and relative density. The numerical model using soil parameters in Table 1 was validated with experimental data of the load-settlement curve of a single helix screw pile with a closed end. An elastic, perfectly plastic model was used for interface material to represent soil-pile interaction with the stiffness of 20,000 kN/m^2. The properties of the interface inside and outside of the shaft are the same. Since the real model is exactly symmetric, it is sufficient to model half of the 3D model in the numerical analysis. The numerical model size is width x length x depth = 350 x 700 x 600 mm.



(a) (b) (c) (d)

Fig. 1. Experimental and numerical setup a) Schematic illustration of test setup b) 3D PLAXIS model, c) Closed-end pile Plaxis model (d) Open-end pile Plaxis model with varying plug lengths.

Table 1 Soil (Toyoura Sand) model parameters based on Ho et al. (2021; 2022) studies.

Secant stiffness, E^{ref}_{50} [kPa]	29,000
Oedometer stiffness, E^{ref}_{oed} [kPa]	30,000
Unloading stiffness, E^{ref}_{ur} [kPa]	85,000
Stress dependency parameters, m	0.5
Poisson's ratio, v_{ur}	0.2
Internal friction angle,	38.79
Dilatancy angle,	15
Shear modulus at small strain, G^{ref}_0 [kPa]	260,000
Coefficient of friction between soil-pile	0.85

4. Results and Discussions

To investigate the effect of in-pile soil plug length on open-end screw pile bearing response, the following experimental and numerical cases are considered in this study (Table 2).

Table 2 Different experimental and numerical test cases

Test Case	**Mode**	**Shaft Dia., D_s [mm]**	**Helix Dia., D_h [mm]**	**Shaft End condition**
T-1	Exp.	21.7	60	Closed-end
T-2	NumV	Thickness of the Shaft is 1.9mm		Closed-end
T-3	NumP			Open-end
T-4	NumP			ISPL – 2.8 x D_s ($1xD_h$)

Notes: Exp. [Experimental data], NumV [Numerically validated data], NumP [Numerical parametric study], ISPL [In-pile soil plug length]

Compressive load is applied and recorded with the help of a pressure transducer on top of the pile, and pile settlement is recorded with the help of a displacement transducer. The pile penetrates the model ground until the ultimate state of the ground is achieved. Figure 2 represents the load-settlement curves obtained from experimental and numerical results, and it can be seen that both curves are quite close to each other, which reflects the validation of the numerical model.

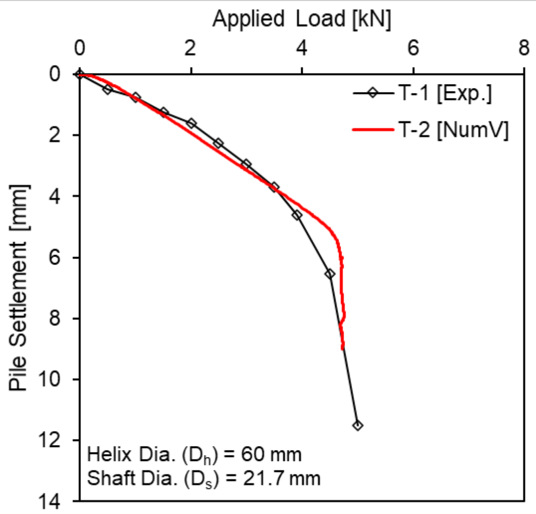
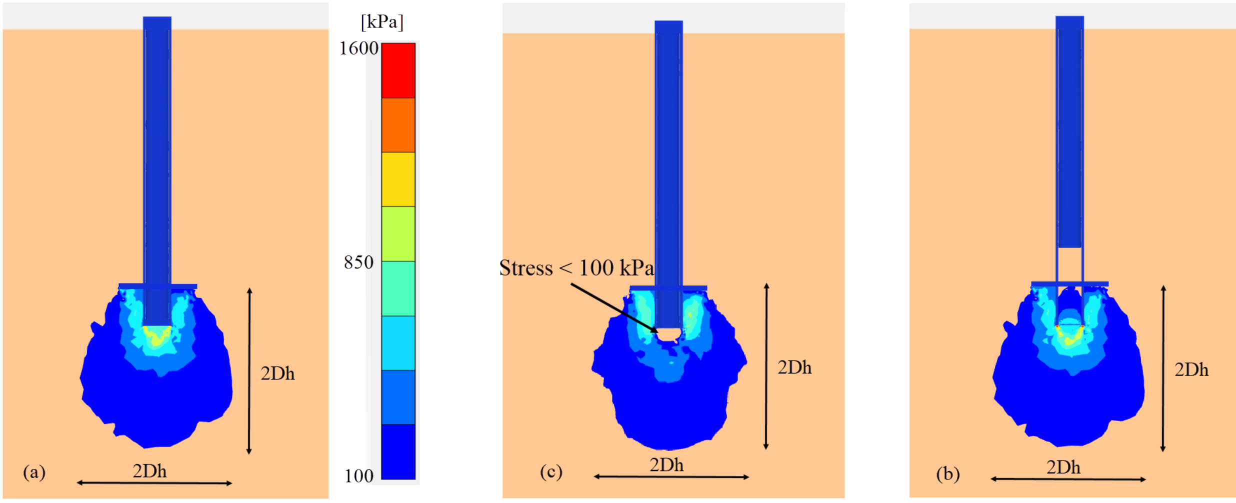


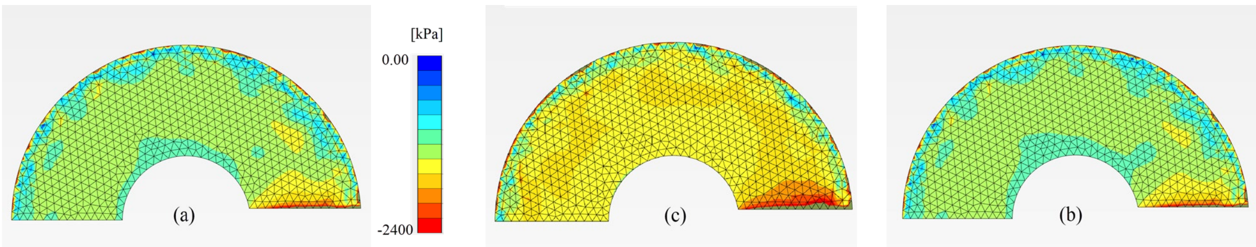
Fig. 2. Experimental and numerical load-settlement curves – validation of the model

After validating the Plaxis 3D model, a parametric study is conducted by changing the central shaft end condition, i.e., open-end with $2.8D_s$ ($1D_h$) soil plug in the shaft.



(a) (b) (c)

Fig. 3. Mobilized shear strength (at 9 mm of pile displacement) of (a) Closed-end pile (b) Open-end pile (c) Open-end pile with 2.8D_s (1D_h) in-pile plug



(a) (b) (c)

Fig. 4. Effective normal stress acting upward (at 9 mm of pile displacement) beneath helix (a) Closed-end pile (b) Open-end pile (c) Open-end pile with 2.8D_s (1D_h) in-pile soil plug

The mobilised shear strength (τ_m) of three piles is shown in Fig. 3. It indicates that the area zone of the τ_m greater than 100 kPa is quite similar in closed-end and 2.8D_s (1D_h) soil plug open-end piles, but it is seen large mobilised shear strength inside the shaft on the open-end pile due to soil moving up inside the pile. A little smaller zone is seen for the fully open-end pile and low shear mobilised strength (τ_m < 100 kPa) beneath this pile shaft. The effective stress acting upward beneath the helix is shown in Fig. 4. The stress distribution is quite similar for the first two piles (closed-end and open-end with soil plug), approximately 1100 kPa, while large stress, 1600 kPa, is seen for the fully open-end pile. This is due to the low stress beneath the fully open-end tip, which transfers more load to its helix.

The load settlement response of all cases (T2-4) are shown in Fig. 5, and it can be seen that both the closed-end screw pile and open-end screw pile with 2.8D_h (1D_h) in-pile soil plug showed a similar bearing response, whereas the fully open-end pile showed a lower bearing response than the other two. This difference can be magnified when the installation effect (Shahzad et al., 2022) and lower D_h/D_s ratios are considered. The reason for this difference is due to the development of an elastic cone under the central shaft for closed-end (Fig. 3a) and open-end with 2.8D_s (1D_h) in-pile soil plug length (Fig. 3c) screw piles which don't allow the soil to move in. The results also indicated that 2.8D_s (1 x D_h) in-pile soil plug length is sufficient to generate enough rigidity to create a similar response as a closed-end screw pile. It is also seen that the overall response of the open-end pile with 2.8D_s (1 x D_h) in-pile soil plug is more or less similar to that of the closed-end pile. A higher difference can be seen if the installation effect is incorporated (Shahzad et al., 2022).

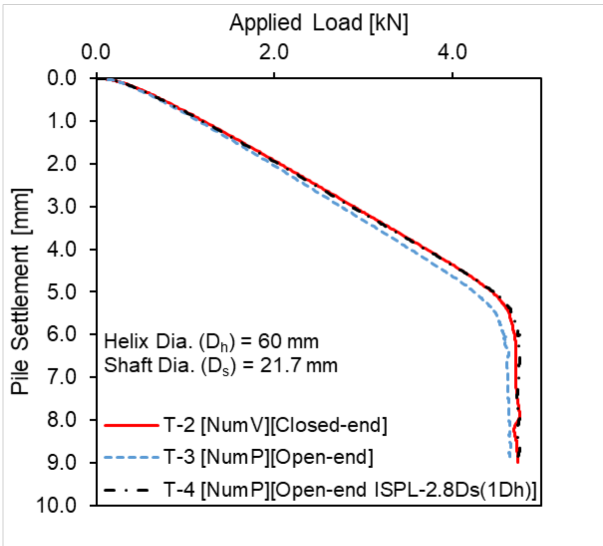


Fig. 5. Load-settlement curves for numerical test cases under parametric study.

5. Conclusions

This study highlights the response of single helix screw piles under different central shaft end conditions, i.e., closed-end, open-end, and open-end, with 2.8 x D_s (1xD_h) in-pile soil plug, through numerical study, which is validated with experimental data. The main outcome of this study is as follows.

- The open-end screw pile bearing response is lower than the closed-end screw pile, and it is due to the absence of an elastic cone under the central shaft, which developed under closed-end conditions. This condition can be achieved if an open-end screw pile is plugged with at least 2.8 x D_s (1 x D_h) in-pile soil length at embedment depth.

- The helix experiences more upward normal stresses in the case of a fully open-end screw pile than a closed-end and open-end with 2.8D_s (1 x D_h) in-pile soil plug screw piles.

- The overall response of the open-end pile with 2.8D_s (1 x D_h) in-pile soil plug is similar to that of the closed-end pile, and this is due to the generation of an elastic cone under the plugged central shaft. A higher difference can be seen if the installation effect is incorporated (Shahzad et al., 2022).

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