Stress Analysis of Screw-Bored Compaction Cast-in-Place Piles

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Abstract. Based on the current research status of screw-bored compaction cast-in-place piles (screw piles for short) and using ANSYS finite element software, in this research, a simulation analysis of the pile axial force and the side friction was conducted for three types of screw piles with different screw length ratios under vertical loading. The modeling analysis results were compared with the engineering data from a practical project in Anyang City, Henan Province, and the finite element model was validated. This research determined the effects of the screw length ratios on the pile axial force and the side friction and provided a theoretical foundation for the engineering design of a screw pile.

1. Introduction
Screw-bored compaction cast-in-place piles (screw piles for short) are a new type of irregular-shaped pile with a straight upper column and a lower screw portion. This new type of pile applies the common notion that a screw is more secure than a nail in piling construction and it achieves a more secure pile. Except for using with caution in all silted soil, a screw pile has a strong applicability [1]. In China, the theoretical research on the bearing capacity of a screw pile has received increasing attention from professionals in civil engineering, but overall, the theoretical research still lags far behind the practical engineering needs.

The pile parameters of a screw pile usually include the pitch of the screw, the length of the straight section, the length of the screw section, and geometric parameter of the blades, as shown in figure 1. Gavin et al. [2] conclude that the numerical simulation of the pile response in tension, using the strength and stiffness properties obtained in tri-axial compression tests, over-predicted the uplift resistance. In this case, the installation effect of the helical piles was not taken into account. For this Discussion, a parametric study was performed to investigate the effect of pile installation on the properties of the soil above the helix. A numerical simulation of the uplift behaviour of a helical pile in dense sand was adjusted using the result of a pull-out test on a pile model performed in a centrifuge. The contours of the numerical simulation considering the installation effect on the pile uplift response demonstrate that the failure surface is developed in the interface between the disturbed cylindrical volume of soil (penetrated during installation) and the surrounding undisturbed soil mass. Peng [3] created the pile-soil model of a single three-dimensional screw pile with the numerical simulation software ANSYS and provided the corresponding pile parameters to ensure the optimal bearing capacity of the screw pile. Three dimensional discrete element methods, with a particle refinement method to enhance computation efficiency, are used to study the driven behaviors of screw piles to compare with the laboratory mini screw pile test results achieved by Shi et al. [4].
Figure 1. Schematic of the screw pile parameters. (Where, D—the length of the screw section (external diameter of the blade); D1—the internal diameter of the screw section (not including the height of the blade); L1—the length of the screw rod; L2—the length of the screw; L—the total length of the screw pile; Ls—the pitch of the screw pile; B—the bottom width of the blade; B1—the top width of the blade.)

For this research, experiments and theoretical analysis were conducted by changing the length of the pile, the pitch of the screw, and the length ratio of the straight section to the screw section, while the blade parameters were not considered. The effect of the geometric parameters of the screw pile on the changes in the pile stress and lateral resistance was further discussed. This research provided a theoretical foundation for the design optimization of the pile type.

2. Screw Pile Experiment

According to a geotechnical investigation contract, a static pressure pipe pile is to be used in a high-rise building to be constructed in Anyang. Considering the fact that the seventh and eighth layers of the site are rich in cementitious sandstone blocks, which have locally formed cemented sandstone thin layers, it is difficult for a static pressure pipe pile to pass through. Therefore, it has been suggested in the engineering report that a bored cast-in-place pile or a screw pile be used. Because the buried depth of the foundation of the project is designed to be 5.50 m below ground and the ninth layer of silty clay will be used as the pile tip bearing stratum, screw pile will be used in this project. The physical properties of the foundation soil for this project are shown in table 1. The effective pile length is 20.0 m, the pile diameter is 0.5 m, the pile spacing is 1.8 m, and the cross-section schematic of the screw pile is presented in figure 2. One engineering test pile was used for the vertical compressive static load test of individual piles. In the test, the surcharge loading method was adopted, and an oil pressure jack was used for step-by-step loading. The reaction platform was constructed with I-steel and cast-iron blocks and the concrete blocks were stacked above the platform to provide the reaction force. The pressure was directly tested by the stress ring placed on the pressure jack, and the settlement of the test pile was measured by a dial gauge. To study the load transfer mechanism of the screw pile, a rebar stress gauge needed to be pre-inserted in the pile body. Accordingly, a rebar cage with a 4ø20 (mm) reinforcement was made and placed on the anti-compression pile body in the manner of a rear pressure cage. When the rebar cage was made, the rebar stress meter was welded to the main bar; one end of the connecting rod for the rebar stress meter was fully welded to the rebar, and the other end was free. When welding the rebar cage, placing reinforcement cage, and pouring concrete, special attention was paid to protecting the signal-shielded conductor of the rebar stress meter.
Table 1. Physical properties of the foundation soil.

| Name of stratum | Thickness of stratum (m) | Internal friction angle (°) | Cohesive force (Pa) | Deformation modulus (Pa) | Density (kN/m³) | Poisson's ratio |
|-----------------|--------------------------|-----------------------------|---------------------|--------------------------|-----------------|----------------|
| 4               | 2                        | 22                          | 2.8×10⁴             | 16×10⁶                   | 20              | 0.2            |
| 5               | 2                        | 20                          | 5×10⁴               | 13.6×10⁶                 | 20.9            | 0.25           |
| 6               | 3.6                      | 22                          | 7×10⁴               | 19.2×10⁶                 | 20.4            | 0.3            |
| 7               | 3.3                      | 28                          | 4×10⁴               | 24×10⁶                   | 20.5            | 0.2            |
| 8               | 6.3                      | 25                          | 5×10⁴               | 22.1×10⁶                 | 20.4            | 0.2            |
| 9               | 2.8                      | 27                          | 4×10⁴               | 25.9×10⁶                 | 20.7            | 0.3            |

(a) Cross-section schematic of the screw pile

(b) Heaping platform device

Figure 2. Test of the screw pile.

The static load test adopted the slow load maintenance method to load systematically until the pile reached the failure load or the pile body material reached failure. To study the load-settlement characteristics of the screw pile and analyze the sharing ratio of the pile side friction and pile end resistance, the test results were analyzed, and the relationship curves between the settlement displacement and the pile top load in different loading stages were plotted as shown in figure 3.

Figure 3. Load-pile top settlement curve of the pile.

According to the Technical Specification for Building Pile Foundation (JGJ 94—2008), and in combination with the s-lgt curve, it was concluded that the ultimate bearing capacity of the test pile was 2,800 kN, and the corresponding settlement of the pile top was 14.0392 mm.
3. ANSYS Finite Element Analysis

3.1. Establishment of the Model

Because the pile was a symmetrical structure, a ¼ pile-soil model could be selected for stress analysis. The selected ¼-scale pile-soil model had to have constraints applied to the lateral side of the pile soil and screw piles to equalize the original constraints and prevent the pile from having an eccentric load. The ANSYS soil model established in this research had a length of 10 times the pile diameter in both the X and Y directions, and a depth of three times the pile diameter in the Z direction. Both the pile and the soil adopt tetrahedron ten-node solid 92 elements, and the constraint around the pile soil was vertical release constraint [5–7]. To investigate the effect of the length ratio of the straight section to the screw section on the stress and lateral resistance of the pile, the piles were numbered Z1 (19 m), Z2 (20 m) and Z3 (23 m) for calculation. These three piles all had a 0.5 m diameter for the straight section and a 0.4 m diameter for the screw section. The other pile parameters are presented in table 2. The basic model was derived from ANSYS as follows. The pile-soil finite element division of the screw pile is shown in figure 4(a), the ¼-scale pile-soil model of the screw pile is shown in figure 4(b), the displacement nephogram with added constraints for the screw pile is shown in figure 4(c), and the ¼-scale pile model is shown in figure 4(d).

| Pile number | Length of straight section (m) | Length of screw section (m) | Screw pitch (m) | Width of blade (m) | Bottom width of blade (m) | Top width of blade (m) |
|-------------|-------------------------------|----------------------------|-----------------|-------------------|--------------------------|-----------------------|
| 1           | 19                            | 9.6                        | 8.4             | 0.45              | 0.05                     | 0.1                   |
| 2           | 20                            | 9.6                        | 10.4            | 0.45              | 0.05                     | 0.1                   |
| 3           | 23                            | 9.6                        | 12.4            | 0.45              | 0.05                     | 0.1                   |

**Figure 4.** Pile-soil finite element division model of the screw pile. (a) Network division model of the pile element (b) Model of the pile-soil element (c) Displacement nephogram post constraint (d) Model of ¼-scale of the pile.
3.2. ISON of the Calculation Results
Figure 5 presents the $S$-log $P$ curve calculated for a 20 m long screw pile. It was concluded from figure 5 that the ultimate capacity for the SZ2(20) pile was 2,944.2 kN and the pile top displacement was 14.8 mm. The results were close to the ultimate capacity for the Anyang Project, which had a measured ultimate capacity of 2,859 kN and pile top displacement of 15.1 mm. The error was approximately 3%. This means that the ANSYS finite element model could accurately analyze an actual engineering project.

![Figure 5. Pile top curve of the screw pile.](image)

3.3. RCE Transfer Mechanism and Optimization Analysis of the Screw Pile
The axial force of the pile shaft refers to the internal force generated by a pile body when the pile top is loaded. The study of the distribution of the axial force of the pile shaft was an important part of the study of the loading mechanism for the screw pile, and it was an important method for investigating the characteristics of the screw pile. The ANSYS finite element software was used to analyze the axial force of each section of the pile, calculate the axial force for a specific section, and plot the distribution curve of the axial force along the pile to intuitively understand the internal force transfer inside the pile. Through analysis of the data in table 1, the axial force of each part of the pile could be found, and the status of the side friction on the pile could be derived. The blade position schematic and the corresponding nephogram are shown in figure 6 and figure 7, respectively.

![Figure 6. Schematic of the slice position.](image)

![Figure 7. Stress nephogram of the slice.](image)

Through the ANSYS working plane slicing method, the axial force at each location of the pile could be determined for Z1, Z2, and Z3, as shown in figure 8(a). Through the above-mentioned axial force at each location of the pile, the corresponding side friction at various locations and under various
loads could be determined. The results are represented in figure 8(b). The side friction of various sections could be calculated through the following equation:

\[ q_s = \frac{\Delta p_s}{\Delta s} \]  

(1)

where \( q_s \) is the average side friction of various sections of the pile (kN/m²), \( \Delta p_s \) is the axial force difference between the adjacent sections (kN); and \( \Delta s \) is the lateral side area between the adjacent sections of the pile (m²).

**Figure 8.** Axial force and lateral resistance diagram for various locations of the pile under different loadings (a1 and b1 for Z1; a2 and b2 for Z2; a3 and b3 for Z3).
The following can be seen from the axial force graph and the pile side resistance graph of the above three piles:

1. Under application of various levels of loading on the pile top, the axial force applied to various sections of the pile was transferred from the top of the pile to the bottom of the pile. With the step-by-step increase in the pile top loading, the change in the axial force in the upper half of the pile was more severe than that in the lower half. When external load was applied, the upper half of the pile primarily transferred the load. At the interface between the straight section and the screw section of the pile, when the load was 800 kN, piles Z1, Z2, and Z3 accomplished 45%, 44.5%, and 44.7% of the load transfer, respectively. When the load was 2,400 kN, the three piles accomplished 45%, 40%, and 39% of the load transfer. When the load was small, the length ratio had minimal impact on the load transfer. With the increase of the load, the length ratio exerted an impact on the load transfer, and the screw section bore more lateral resistance. When the length ratio was greater than 50%, the screw section no longer had a large impact.

2. When the pile top was loaded to 2,200 kN and 2,400 kN, it was not difficult to find that there would be a steep rise in the side friction near the end of the pile, which presented a significant increase compared with the application of a small load. This meant that the lateral resistance in the screw pile exhibited a strengthening effect, and with an increase in the length ratio, a steep rise was more apparent.

4. Conclusion

In this research the parameters provided by an actual engineering project in Anyang City were entered in the finite element analysis software ANSYS, and the results were compared with the measured data. The outcomes of this research could provide a reference for the engineering design and actual construction of screw piles. The major conclusions are as follows:

When the load was small, the length ratio of the screw had minimal impact on the load transfer. With an increase in the load, the length ratio exhibited an impact on load transfer, and the screw section bore more lateral resistance. When the length ratio was greater than 50%, it no longer had a large impact.

When the load was large, there was a steep rise in the lateral friction near the end of the pile; and with an increase in the length ratio, this steep rise was more apparent.

Reference

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