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Research on uplift mechanism of screw pile

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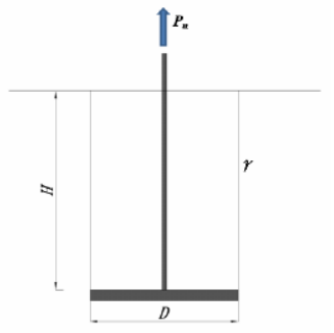
Abstract: This paper uses numerical simulation software to study the bearing characteristics of screw pile with pitch after installation. The selected soil is single layer sandy soil, and the blade is buried in deep burial mode. Based on the numerical simulation results, the vertical bearing characteristics of single spiral pile and ordinary bladeless pile are compared, and the excellent compression and pull-out characteristics of spiral pile are revealed. Then, the influences of different pitch sizes, blade diameters, tilt angles, blade numbers and blade spacing on spiral single pile were compared and analyzed. The results show that single screw pile has higher bearing capacity and bearing efficiency. The vertical bearing capacity of single inclined screw pile has no obvious improvement compared with that of straight pile.

Keywords: Screw pile; Numerical simulation; Lifting mechanism.

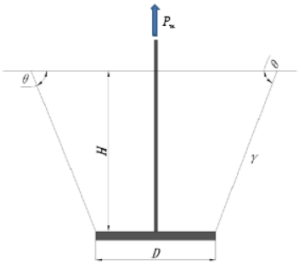
1. Introduction

Most scholars regard the pulling up of screw pile as the pulling up of circular anchor. The assumption of failure surface of soil is generally related to the ultimate puller capacity of foundation. Therefore, in the process of the research of foundation puller by many scholars at home and abroad, the mechanical research of foundation and foundation soil is always accompanied by the analysis of soil deformation and different assumption of failure surface of soil.

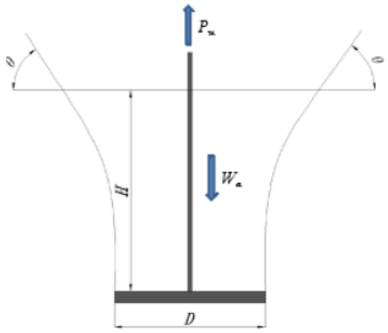
The uplift of flat anchor was studied earlier abroad. Caquot [1] and Kerise [2] were involved in the study of earth pressure in 1948 at the earliest. They believed that the slip surface of shallow buried anchor plate was developed to the soil surface, and that the slip surface of deep buried anchor plate was developed to a certain depth, which was determined by laboratory experimental observation. The classic failure mode of shallow buried anchor plate is shown in Fig 1, where Pu is the uplift bearing capacity, φ



(a)Cylinder failure mode [3]



(b)Slope failure mode [4]



(c)Surface failure mode [5]

Fig 1. Classic failure mode of shallow buried anchor plate

Is the internal friction Angle of the soil, D is the diameter of the anchor plate, θ is the Angle between the slip surface and the soil surface, H is the buried depth of the anchor plate, and Wa is the weight of the soil inside the slip surface. Majer [3] proposed the hypothesis of plane strain sliding surface of anchor plate in 1955, assuming that the sliding surface extends vertically along the edge of anchor plate to the surface, and the corresponding pulling capacity is equal to the sum of the soil weight inside the sliding surface and the friction resistance on the sliding surface. In 1959, Mors [4] proposed the inclined plane failure model, assuming that the ultimate pulling capacity of anchor plate was equal to the weight of soil in the sliding plane without considering the shear action of soil. Balla [5] proposed in 1962 that the circular sliding plane was a curved surface extending to the soil surface with an Angle of π/4-φ/4 with the soil. The pulling capacity of the corresponding anchor plate is equal to the sum of the weight of the soil inside the sliding surface, the weight of the foundation itself and the vertical component of the shear resistance generated on the sliding surface. Matsuo [6] proposed the logarithmic spiral sliding surface in 1967, which belongs to the improved shear mode method and is more in line with practice. In 1968, Meyerhof and Adams [7] used the semi-empirical method of passive earth pressure to study the significant differences between anchor plates under shallow and deep buried conditions, and proposed a formula to calculate the pulling capacity of anchor plates in sandy soil under different buried depths. In 1971, Vesic [8] proposed a

new method to calculate the ultimate pulling force based on the keyhole expansion theory, which was suitable for the anchor plate foundation under shallow burial. In 1978, Rowe [9] used the upper limit method of plastic limit to obtain the upper limit solution of ultimate bearing capacity of anchor plate of deep-buried strip foundation in homogeneous clay. In addition, many scholars [10-14] also studied the ultimate pulling capacity of anchor plate under different soil quality.

2. ABAQUS finite element numerical simulation

2.1. ABAQUS finite element numerical simulation

In this paper, ABAQUS finite element software is used to carry out three-dimensional finite element analysis of offshore wind turbine screw pile foundation in sandy soil, and the vertical bearing characteristics of screw pile under different working conditions and different forms are studied. As the text studies the influence of screw pile size parameters on bearing capacity, only two examples are taken in this chapter to illustrate the modeling process, one is single pile foundation and the other is group pile foundation.

The modeling of single pile foundation is divided into three parts, which are single straight screw pile, soil core inside pile and soil outside pile, as shown in Fig 2. Pile group foundation model modeling is divided into four parts, including four screw piles in a certain distance array, middle soil wrapped screw piles, soil core inside piles and soil outside piles, as shown in Fig 3.

The difficulty of modeling in this paper lies in the drawing of screw pile. The spiral line needs to be realized with the help of auto CAD, and the unique function of importing geometry parts with third-party software is used to model. In this process, screw piles with different pitch and blade diameters can be successfully built.

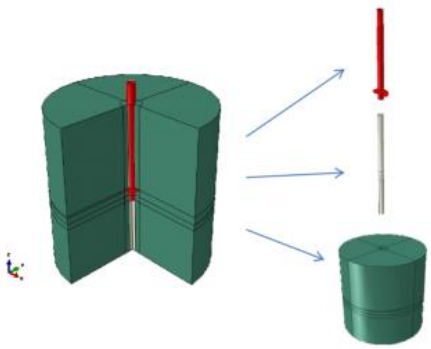


Fig. 2 Single screw pile foundation model

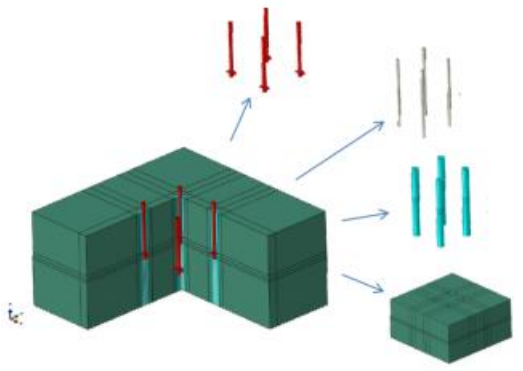


Fig. 3 Screw pile group foundation model

In single pile foundation, screw pile diameter is 2 m, screw blade diameter is 5 m, screw pitch is 2 m, blade buried depth is 25 m, pile wall thickness and blade thickness are 0.03 m. In order to eliminate boundary effect, cylindrical outer soil diameter is 40 m and height is 40 m. In pile group foundation, the parameters of a single screw pile are the same as those of a single pile foundation, and the pile spacing is 24 m. The middle soil is a hollow cylindrical sleeve with an inner diameter of 2 m and an outer diameter of 5 m, and the outer soil is a cuboid with a length of 100 m, a width of 100 m and a height of 50 m.

The stress-strain relationship of soil is very complicated. At present, no constitutive model can accurately and comprehensively express the constitutive characteristics of soil with various properties under any loading mode. According to experience, although some constitutive theories are well expressed, there are many parameters and their meanings are not clear, which is easy to cause large deviation of calculation results due to improper parameter values. While some constitutive models are simple in form, but the meaning of physical parameters is simple and clear, easy to determine, and the calculation results are relatively reasonable. In order to analyze the bearing characteristics of screw pile foundation, a more suitable Mohr-Coulomb constitutive model is selected for analysis.

The surface sandy soil of a coastal area in Anhui province was selected with a density of 1200 kg/m3. The elastic modulus of the soil was 18 MPa, Poisson's ratio was 0.3, the internal friction Angle was 34.4°, the dilatancy Angle was 0.1°, and the cohesion was 5 KPa. In addition, the density of spiral steel pile is 7850 kg/m3, the elastic modulus is 206 GPa and Poisson's ratio is 0.3.

2.2. Contact Settings and boundary conditions

In finite element analysis, there are generally two ways to deal with contact nonlinear problems [15]. The first is to establish a contact surface unit between two contact media, and simulate the mechanical properties of the interface by setting the special constitutive relationship of the contact surface unit. Currently, interface units are widely used, such as Goodman non-thickness contact surface unit and Desai thin layer unit. The other is to directly define the mechanical transfer characteristics of the contact surface between two media, establish the mechanical model of the contact surface force transfer and contact constraint conditions, and solve the contact constraint equation by Lagrange multiplier method or stiffness penalty method. ABAQUS uses a second algorithm to simulate the interaction between two media, called the Contact Pair algorithm.

When the pile-soil Contact is set, the screw pile wall with greater stiffness is selected as the main surface, and the contact surface between soil and pile body and blade is selected as the secondary surface. The normal interaction between the two is Hard Contact. When the two contact surfaces are pressed, the normal stress is transmitted to each other through the contact constraints established between the master and slave surfaces. When the tension stress between the contact surfaces is separated from each other and the gap is generated, the contact constraint and the corresponding friction effect between the contact surfaces do not exist, and the pressure transmitted during the contact is not limited. Through this setting, the nonlinear process of pile and soil separation can be simulated.

In this example, the face to face Contact algorithm of

master-slave face connection is selected, the normal friction of contact surface is Hard Contact, and the tangential friction function is adopted. According to experience, the friction coefficient between sand and screw pile is set as 0.3. In this paper, the difficulty of contact setting is to cut the soil. The first is the cutting of helix, which needs to be cut with the help of the spiral blade drawn in auto CAD, which is slightly larger than the size of the soil model. Otherwise, it will cause incomplete segmentation. Only when the soil is divided well can the corresponding contact surface be selected for setting contact. In addition, the quality of soil cutting will directly affect the layout and division of the grid. The quality of soil cutting includes the symmetry of the element, whether the boundary line is regular, and whether the edge of the geometric component is connected. R3=0), does not allow anisotropic displacement and rotation; Radial constraint ZASYMM (U1=U2=UR3=0) is applied on the soil side, and only vertical displacement and torsion are allowed. The upper part of the soil is the free end.

2.3. Meshing

In this paper, C3D8R solid element is used for soil and S4R shell element is used for screw pile. In the meshing process, the meshes near the inner foundation of sandy soil are dense, and the periphery is sparse. The joint of pile and blade is dense, and the farther away it is, the thinner it is. The upper and lower parts of the model correspond to each other, and the inner and outer grids should be consistent as far as possible to ensure the transitivity and accuracy of the calculation. The number of grids should range from 100,000 to 250,000. The concrete grid division is shown in Figure 4 for single pile foundation and Figure 5 for pile group foundation.

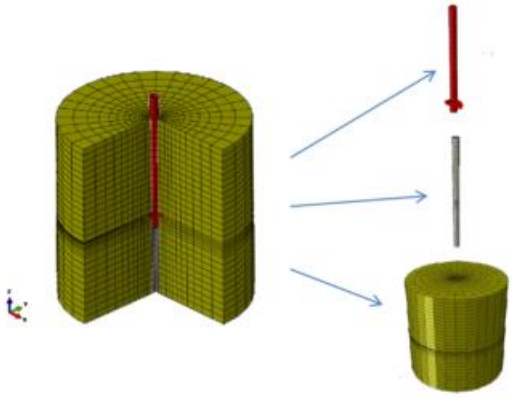


Fig. 4 Grid division of single pile foundation

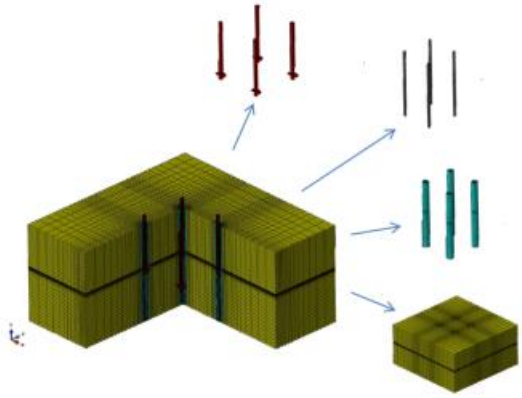


Fig. 5 Grid division of pile foundation group

2.4. Loading mode and failure criterion

In this paper, C3D8R solid element is used for soil and S4R shell element is used for screw pile. When ABAQUS finite element software is used to calculate the ultimate bearing capacity of foundation, there are generally two loading control methods: load control and displacement control. Comparatively speaking, the displacement-controlled loading mode often reflects the trend and correlation of load and displacement more clearly. In this paper, displacement control method is adopted to apply displacement. The displacement action point is coupled with the center of pile top on the soil surface, as shown in Figure 6, and then load-displacement curve is obtained.

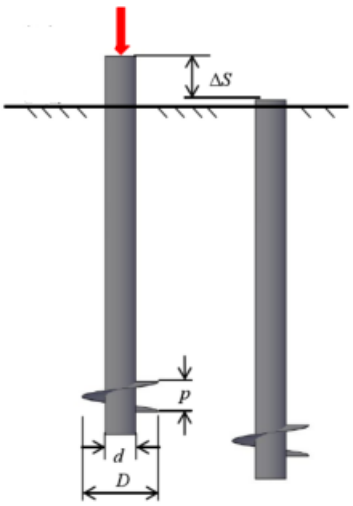


Fig. 6 Changes before and after displacement control loading of screw pile

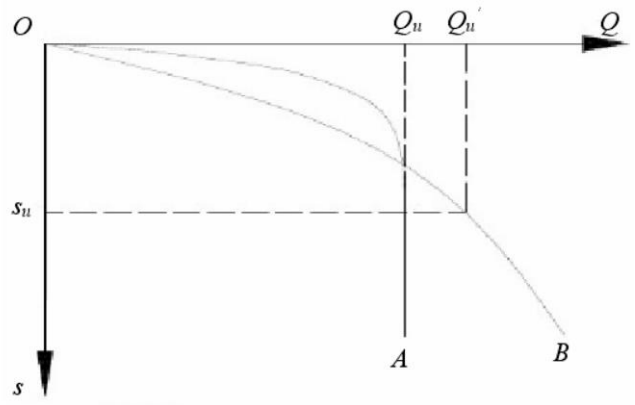


Fig. 7 Typical load-displacement curve

Curve A in Fig. 7 is a steep drop curve, belonging to "rapid failure". The failure characteristic point is obvious, the load exceeds the failure characteristic point, the pile settlement increases sharply, and the foundation loses the bearing capacity. Curve B in Fig. 7 is a slow curve, belonging to "progressive failure". If the initial and last sections of the load-displacement curve are straight lines, and the middle section is a curve, the connection point of the middle section curve and the end line can be taken as the failure point, and the corresponding load is the ultimate bearing capacity. If the load-displacement relationship is always a smooth and slowly changing curve without obvious failure characteristic points, it is necessary to determine the ultimate bearing capacity by various analytical methods [16].

For offshore structures, superstructures generally have very

strict requirements on the vertical deformation of foundation, so the ultimate bearing capacity of pile foundation is usually determined according to the normal limit state.

The offshore fan pile foundation structure studied in this paper bears large vertical load and has a high requirement for structural performance due to complex geological environment. In this paper, referring to relevant specifications and literature [17-19], the Angle of pile top of offshore fan foundation should be controlled within 0.005 radian and the vertical settlement should be controlled within 100 mm. Therefore, the load with vertical displacement of 0.1m is selected as the vertical ultimate bearing capacity in this paper.

3. Comparison of bearing capacity between single screw pile and ordinary pile in sandy soil

3.1. Finite element model and comparison condition

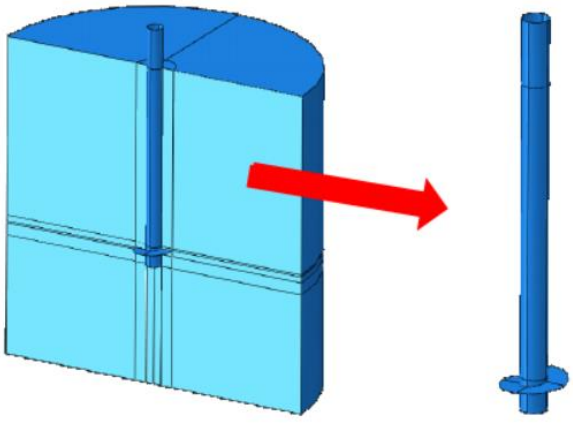
Comparing the displacement of screw pile and ordinary pile under load in homogeneous sandy soil, studying the influence of screw blade and the influence range of soil displacement is conducive to highlighting the unique bearing advantage of screw pile, which is more conducive to subsequent analysis.

Table 1 shows the specific parameters and dimensions of screw pile and ordinary pile. During comparison, the size of screw pile except blade is ensured to be consistent with that of ordinary pile, so that blade or not becomes the only variable, and the bearing capacity and displacement influence range of the two are compared.

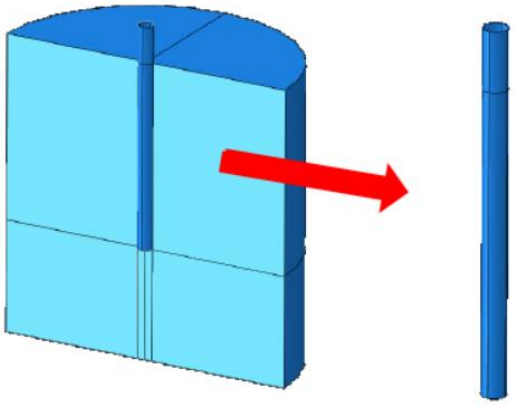
Table 1. Comparison Conditions of Pile Types

	Pile diameter/m	Pile length/m	Blade diameter/m	Number of blades
Spiral anchor	2	25	5	1
Ordinary pile	2	25	0	0

In the finite element analysis, the displacement control loading method is applied to the pile top coupled to the center point on the soil surface. Fig. 8 shows the finite element model of two working conditions.



(a) Screw pile

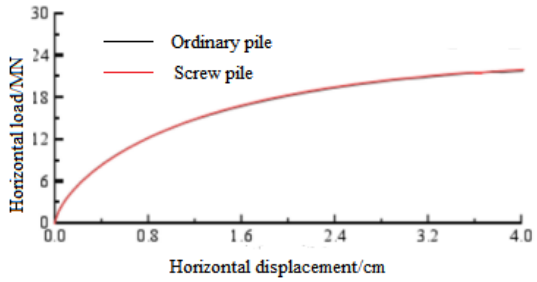


(b) Ordinary pile

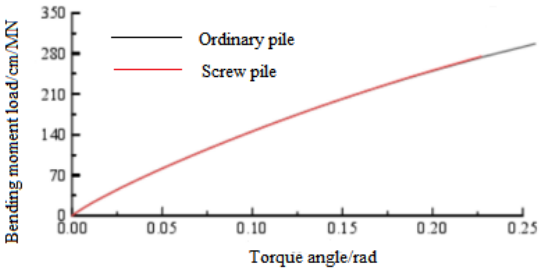
Fig. 8 Comparison model between screw pile and ordinary pile

3.2. Horizontal bearing capacity and moment bearing capacity

A displacement far larger than the expected bearing capacity is applied in the center of the top of the foundation pile to obtain the load-displacement curve of the pile foundation, and then the load change is studied to determine the load size and the displacement at the time of failure, so as to obtain the corresponding bearing capacity. Fig. 9 shows the load-displacement curve of ordinary pile and screw pile obtained after applying excessive horizontal displacement and Angle.



(a) horizontal bearing capacity



(b) bending moment bearing capacity

Fig. 9 Comparison of horizontal and bending moment bearing capacity of screw pile and ordinary pile

In Fig. 9, the horizontal bearing capacity and bending moment bearing capacity curves of spiral piles and ordinary piles are basically similar. This is because the spiral blades are buried deep and have little influence, and the upper horizontal bearing characteristics are basically the bearing mode of piles. Therefore, the latter part of this paper focuses on the comparison of the vertical bearing capacity and their bearing modes.

3.3. Compression bearing capacity

Fig. 10 shows the compression load displacement curve of ordinary pile and screw pile obtained after applying excessive vertical downward displacement.

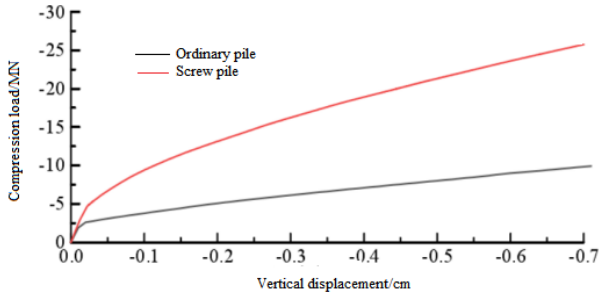
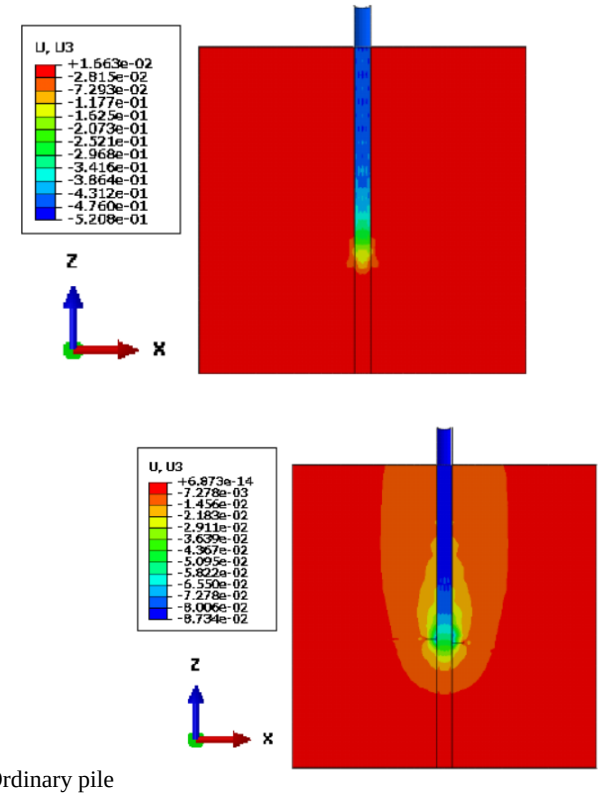


Fig. 10 Compressive load-displacement curve of screw pile and ordinary pile

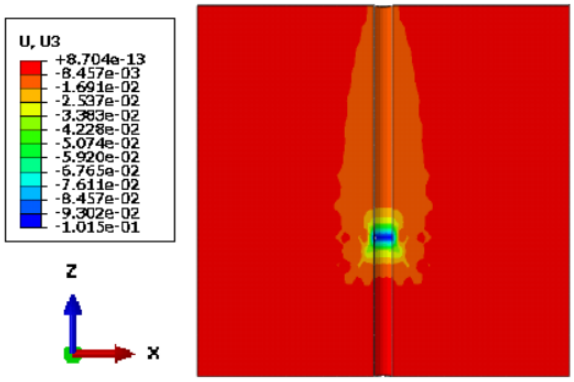
As shown in Fig 10, when the vertical displacement reaches 0.1m, that is, 0.05d, the compressive bearing capacity of the two kinds of pile foundation is 3.77MN for ordinary pile and 9.38MN for spiral pile, which increases the bearing capacity of spiral pile by 149 %. When the foundation is subjected to compression load, both of them first go through an elastic section with linear growth of the curve, and then the ordinary pile becomes gentle in the plastic section, while the screw pile still grows rapidly. In this process, the existence of spiral blades makes the pile show better bearing capacity. When the compressive load applied is 7 MN, the comparison of displacement nephogram between the two is shown in Fig 11. The cloud image after removing the soil core in the pile is shown in Fig12.



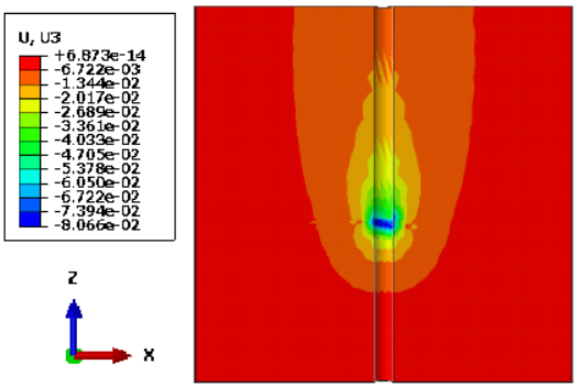
(a) Ordinary pile

(b) Screw pile

Fig. 11 Comparison model between screw pile and ordinary pile

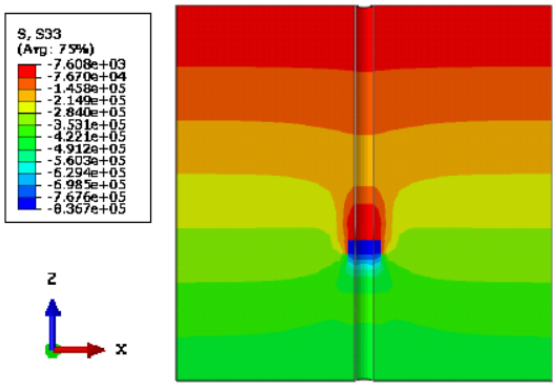


(a) Ordinary pile

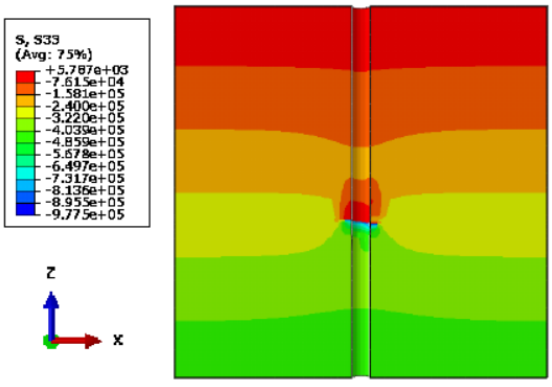


(b) Screw pile

Fig. 12 Displacement cloud image after removal of soil core



(a) Ordinary pile



(b) Screw pile

Fig. 13 Stress nephogram of soil outside pile

When the compression load is 7 MN, the vertical displacement of ordinary pile foundation is 0.39 m, and that of screw pile is 0.055 m, and the deformation of screw pile is

far less than that of ordinary pile. As shown in FIG. 11, soil inside piles has the maximum deformation in both cases, but the soil around piles can be seen to have a certain degree of displacement, while ordinary piles are small. The cloud Fig. 12 after removing the soil core shows that both piles have maximum displacement at the bottom and then develop around them. Due to the anchorage effect of spiral blades, the soil around the pile bears more load and has a certain pressure effect, while ordinary piles are mainly caused by the penetration of the pile end, that is, shear failure. The influence range of lateral soil displacement of screw pile is obviously greater than that of ordinary pile.

As shown in Fig. 13, the vertical stress nephogram of the two piles is slightly different at the pile end, and the stress abrupt change occurs at the pile end, which is more obvious for ordinary piles.

3.4. Pulling capacity

After applying excessive vertical upward displacement, the tensile load-displacement curves of ordinary pile and screw pile are obtained, as shown in Fig 14.

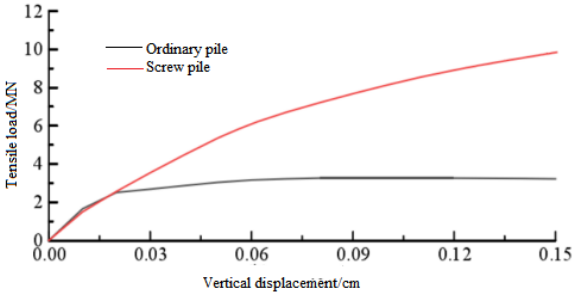
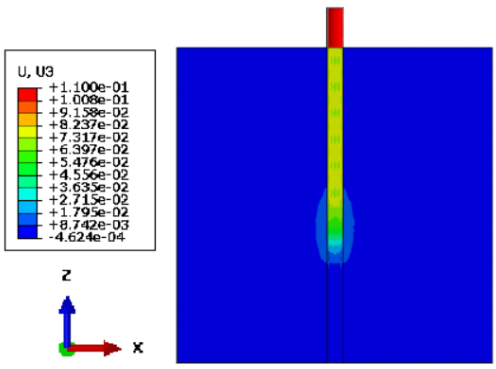
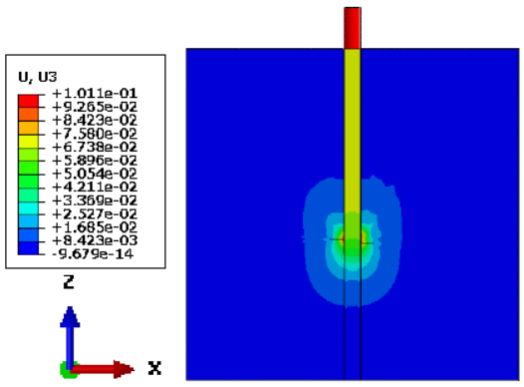


Fig. 14 Compressive load-displacement curve of screw pile and ordinary pile

In Fig. 14, when the pulling displacement is 0.1m, the pulling capacity is 3.27MN for ordinary pile and 8.13MN for spiral pile. It is obvious that the addition of spiral blades greatly increases the vertical bearing capacity. When the foundation bears the tensile load, the ordinary pile has reached the ultimate bearing capacity before the vertical displacement reaches 0.06 m, and the load basically remains stable with the increase of displacement. After this, the screw pile still has a substantial increase, and the uplift ability is significantly improved. When the pull-up displacement is 0.1m, the comparison of the two displacement nephogram is shown in FIG. 15. The cloud image after removing the soil core in the pile is shown in Fig 16.

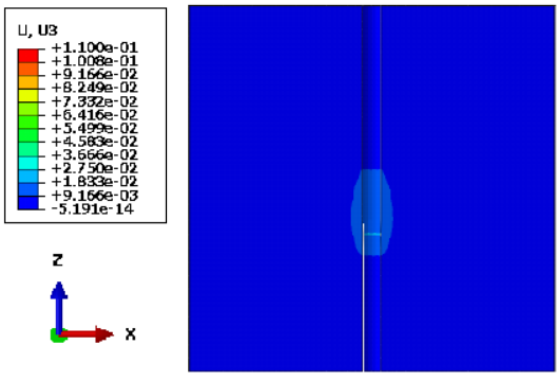


(a) Ordinary pile

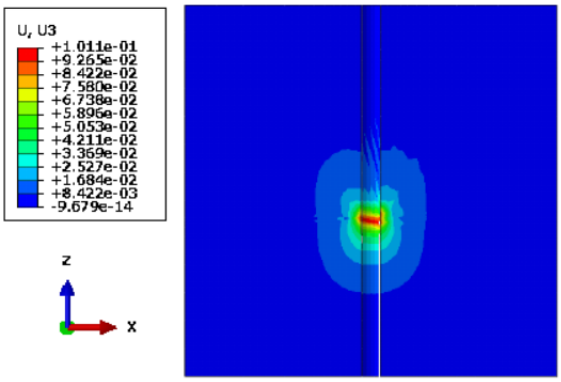


(b) Screw pile

Fig. 15 Displacement cloud image with the same pulling displacement



(a) Ordinary pile



(b) Screw pile

Fig. 16 Displacement cloud image after removal of soil core

When the displacement reaches 0.1m, that is, under the same displacement condition, the influence range of soil displacement around the pile is obviously larger, while the influence of soil around the pile and the displacement of soil outside the pile is small for the ordinary pile. This is because the spiral blade drives the soil around the pile to pull up, while the ordinary pile is only driven by the friction between the side wall and the tip of the pile. Compared with the compression load, the soil at the pile tip is radial under the action of uplift, while the cloud image is funnel-shaped under ballast. This is because when pressing down, the upper soil is more likely to be affected due to the unconstrained boundary, so it will drive the settlement of the upper soil. When pulling up, the soil below is equivalent to the fixed end constraint, so it is less affected. The deeper the depth, the more difficult to pull up.

4. Conclusion

In this paper, the bearing characteristics of screw pile and bladeless pile are analyzed, and the advantages of screw pile resisting vertical load are highlighted. When the pile length is long and the buried depth of the blade is large, the horizontal load-displacement curve and bending moment-angle curve of the ordinary pile almost coincide, and the horizontal force is still the bending deformation squeezing mode of the pile.

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