Journal of Innovation and Development
ISSN: 2958-4752 | Vol. 3, No. 1, 2023

Research on Pile Parameters of Screw Pile based on Horizontal Bearing Capacity

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Abstract: This paper studies the horizontal bearing capacity of screw pile under the limit state of normal use in silty sand soil, simulates the horizontal loading process of screw pile by ABAQUS software, introduces the creation process of the model of screw pile, material attribute selection and finite element mesh division, etc. The influencing factors and variation rules of horizontal bearing capacity, plastic zone of soil mass, failure mode of soil mass and pile deformation mode of screw pile are studied, and a more comprehensive parameter basis is provided for the establishment of prediction formula of horizontal bearing capacity of screw pile. The parameters of screw pile diameter, screw blade diameter and screw blade buried depth are analyzed. It provides some support for the theoretical analysis and engineering practice application of screw pile.

Keywords: Screw Pile; Horizontal Bearing Capacity; Finite Element; Parameter Analysis.

1. Introduction

Screw pile foundation is considered by many scholars as one of the best foundation forms for future fans due to its advantages of convenient construction, environmental protection, no noise and long-term bearing capacity [1-3]. Scholars at home and abroad have carried out extensive studies on its bearing performance. Under the influence of wind, wave and current environmental loads, the horizontal load borne by screw pile foundation is about 70%-150% of the axial load [4,5]. The horizontal bearing capacity is the key technical parameter in the design and application of screw pile as the foundation of offshore fan. Therefore, the research on the horizontal bearing capacity of screw pile is of great engineering application value. According to the variation of deflection of horizontal piles under load, piles under load can be divided into rigid piles, rigid flexible piles and flexible piles [7-12].

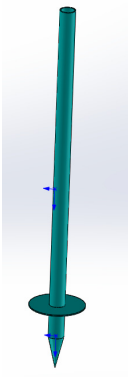
Rigid piles are usually set with a large diameter, shallow burial depth and close to the surface, and pile body almost does not bend and deform. Therefore, rigid piles tend to rotate rigidly as a whole under horizontal load, resulting in an obvious "kicking" phenomenon in the pile base [6], and the soil in contact with the pile is considered to reach the yield state as a condition for determining the failure of rigid pile bearing performance. Compared with rigid pile, the horizontal load flexible pile has a larger burial depth, and the soil surrounding the flexible pile, especially the soil at the bottom of the pile, will exert a strong constraint on the pile deformation, so that the part of the pile near the pile foundation has a small deformation or even no deformation, while the soil near the surface of the ground shows a small control on the pile deformation. Therefore, the deformation of flexible pile is mainly in shallow soil near the surface. At this time, plastic hinge is used as the judgment condition for the failure of flexible pile foundation.

In the initial application stage of screw pile, water depth is 40-50 m, and the ratio of length to diameter of screw pile is preliminarily estimated to be 5-25 m, which belongs to the range of rigid pile and rigid flexible pile. Therefore, the research on horizontal bearing capacity of rigid and rigid flexible screw pile is the main focus of this paper. Based on the geological condition of fine sand, the horizontal bearing capacity of rigid flexible screw pile is studied in this paper.

2. Finite Element Model of Screw Pile

2.1. Model Establishment

The finite element model in this chapter mainly includes two parts: rigid flexible screw pile and soil. The finite element model is half model. The soil type of rigid flexible screw pile is the same as that of rigid screw pile. The material properties of screw pile are shown in Table 1.



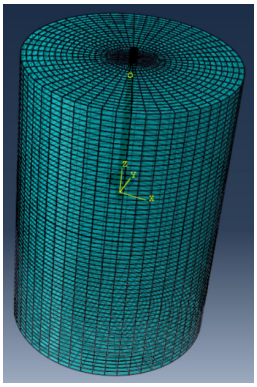


Fig 1. Simplified screw anchor **Fig 2.** Finite element model

The spiral blade is simplified into a flat blade, and the simplified spiral pile is shown in Figure 1. Constitutive model and contact type are the same as rigid screw pile. The side of the soil model is fixed along the horizontal direction, and the base boundary is completely fixed. The pile top is loaded by the horizontal displacement method, and the displacement size is 0.2 anchor disk diameter.

Table 1. Material properties of screw pile

material	Poisson's ratio	Modulus of elasticity / GPa
Q355	0.3	210

2.2. Grid Division

Because the accuracy and convergence of the finite element calculation results are easily affected by the mesh size, in order to determine the ideal mesh size, the sensitivity of the mesh will avoid large errors in the finite element calculation results. The process of grid division from dense to coarse: (1) the connection of anchor disk and anchor rod; (2) the contact point between the bolt and the soil; (3) the connection between anchor plate and soil; (4) the contact between the end and the soil; (5) soil near the screw pile side; (6) Keep away from the soil of the screw pile side. The soil and screw pile model grid are a linear hexahedral element with eight nodes (C3D8). The soil modeling external diameter is 3 times the blade diameter, the mesh size is 0.04m, and the radial mesh size outside the circular area is 0.1-15 times the anchor disk diameter. Figure 2 shows the finite element overall model grid.

3. Parameter Analysis

The research object of this section is the horizontal loading rigid flexible screw pile with fine sand under normal use limit state. In order to better understand and reveal the influence factors and change rules of the horizontal bearing capacity, plastic zone of soil, soil failure mode and pile deformation mode of rigid flexible screw pile, and to provide a more comprehensive parameter basis for the establishment of the prediction formula of horizontal bearing capacity of rigid flexible screw pile, the pile diameter, screw blade diameter and screw blade buried depth were analyzed. According to the different Settings of pile diameter, spiral blade buried depth and spiral blade diameter of rigid flexible screw pile, three groups of models were set, A1, A2 and A3, with a total of 12 calculation working conditions. Specific working conditions are shown in Table 2. Pile diameter d is set as 0.6m to 0.9m; The buried depth of blade is arranged in four different depths successively along the buried depth of screw pile: 1.7m, 3.8m, 5.8m and 8.8m. Spiral blade size is set to 2-5*d*.

Table 2. Numerical simulation of screw pile conditions

	No.	Pile diameterd /mm	Blade diameter D/mm	Blade depth /m	Eccentricity /e	Depth /m	Blade thickness /mm
A1	R1	600	5d	3.8	1.3	12	30
	R2	700	5d	3.8	1.3	12	30
	R3	800	5d	3.8	1.3	12	30
	R4	900	5d	3.8	1.3	12	30
B1	R5	700	2d	3.8	1.3	12	30
	R6	700	3d	3.8	1.3	12	30
	R7	700	4d	3.8	1.3	12	30
	R8	700	5d	3.8	1.3	12	30
C1	R9	700	5d	1.7	1.3	12	30
	R10	700	5d	3.8	1.3	12	30
	R11	700	5d	5.8	1.3	12	30
	R12	700	5d	8.0	1.3	12	30

3.1. Pile Diameter Influence

In order to quantify the influence of pile diameter on the horizontal bearing capacity of rigid flexible screw pile, the load-displacement curve at the mud surface was normalized. The pile body at the mud surface was normalized as the horizontal coordinate, and the horizontal bearing capacity was normalized as the vertical coordinate. The load-displacement diagram at the mud surface after normalization was shown in Figure 3. The load-displacement curves corresponding to pile diameter 0.6m, 0.7m, 0.8m and 0.9m at the normalized mud surface are described. The horizontal bearing capacity of rigid flexible screw piles with different pile diametries has the same variation trend, which shows that the horizontal bearing capacity of screw piles increases with the increase of pile deformation value at the mud surface.

In order to analyze the influence of pile diameter on the horizontal bearing capacity corresponding to the rigid flexible screw pile when it reaches the limit state of normal service, the relationship diagram between the horizontal bearing capacity corresponding to the rigid flexible screw pile when it reaches the limit state of normal service is drawn, as shown in FIG. 3. The vertical coordinate is the horizontal bearing capacity corresponding to the rigid flexible screw pile when it reaches the limit state of normal service, and the horizontal coordinate is different pile diameter. As can be seen from Figure 3, there is a linear relationship between the horizontal bearing capacity and pile diameter when the rigid flexible screw pile reaches the normal limit state, and the horizontal bearing capacity increases linearly with the increase of pile diameter.

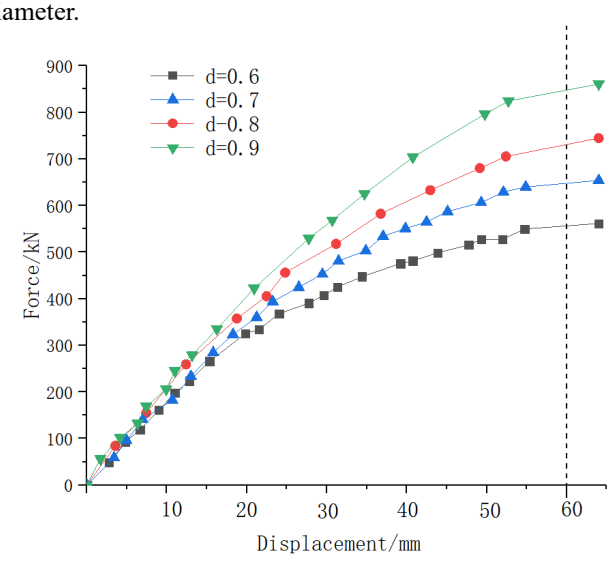


Fig 3. Load-displacement curves of different pile diametries

The intersection points of different curves in Figure 3 and 60mm reference lines are drawn in Table 3 (6). The horizontal bearing capacity growth rate of screw pile R2, screw pile R3 and screw pile R4 compared with screw pile R1 is denoted as ΔH_n, n=2, 3, 4, and calculated according to Equation (1).

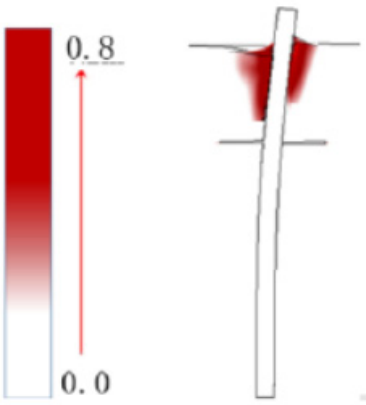
$$\Delta H_n=(H_n-H_1)/H_1 \quad (1)$$

It can be seen from the growth rate of ΔHn of the horizontal bearing capacity of the rigid flexible screw pile in Table 3 that the horizontal bearing capacity improvement of the rigid flexible screw pile is different. The growth rate of the horizontal bearing capacity of the rigid flexible screw pile in R4 calculation scheme is the largest, which is 53.6%, and the growth rate of the horizontal bearing capacity of the rigid flexible screw pile in R2 calculation scheme is the minimum, which is 16.3%.

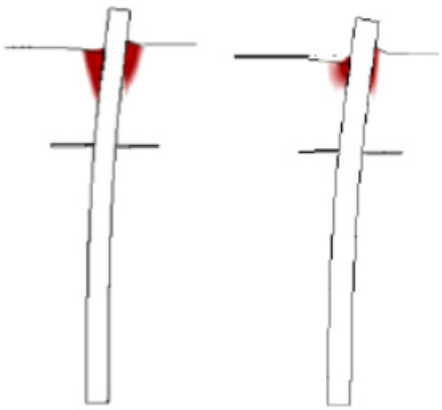
Table 3. Horizontal bearing capacity of different pile diameters

	NO.	Pile diameter/mm	Blade diameter/mm	Blade depth/m	Bearing capacity/kN	Growth rate/ΔH_n
A1	R1	600	5d	3.8	552	
	R2	700	5d	3.8	642	16.3%
	R3	800	5d	3.8	735	33.2%
	R4	900	5d	3.8	848	53.6%

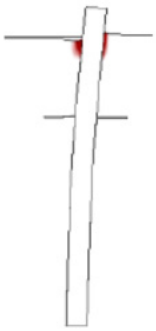
Fig. 4 shows the soil plastic strain nephogram corresponding to the rigid flexible screw piles with different diamediametions. It can be seen from Fig 4 that, under the influence of pile diameter changes, the plastic failure zone of soil mass of rigid flexible screw pile is mainly distributed on both sides of the pile body above the blade. When the pile diameter d= 0.6m expands to d= 0.9m, the plastic failure zone of soil mass around the pile gradually decreases, and the plastic failure zone of soil mass distributed on both sides of the pile body in the shape of "inverted triangle" almost disappears at last. No soil plastic failure zone develops around the blade and the base.



(a)Plastic strain (b)d=0.6



(c)d=0.7 (d)d=0.8

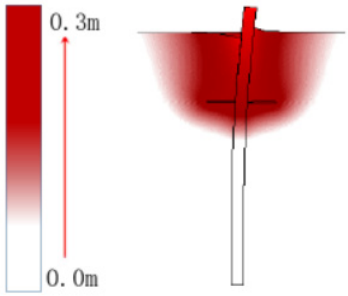


(e)d=0.9

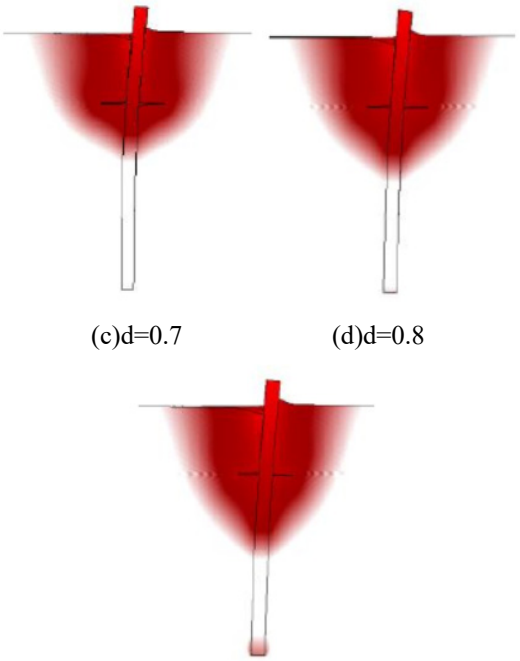
Fig 4. Plastic strain nephogram of soil mass corresponding to rigid flexible screw piles with different diamediametions

It can be seen from the above that when the rigid flexible screw pile reaches the normal service limit state, the plastic failure zone of soil around the rigid flexible screw pile is controlled by the pile diameter, which shows an inverse law that the plastic failure zone decreases with the increase of the pile diameter. The main plastic failure zone of soil is located on both sides of pile body above the spiral blade. The plastic failure zone of soil body at the bottom of spiral pile foundation and around the two wings of blade does not develop.

Fig. 5 is the cloud map of soil displacement change when the rigid flexible screw pile reaches the normal use state. As can be seen from Fig. 5, the overall soil displacement distribution range around the pile increases with the increase of the pile diameter. The development trend of soil displacement around the pile is that it keeps rising along the direction of longitudinal pile depth, but the soil displacement distribution range along both sides of the pile remains unchanged.



(a)Displacement (b)d=0.6



(c)d=0.7 (d)d=0.8

(e)d=0.9

Fig 5. Nephogram of soil displacement corresponding to rigid flexible screw piles with different diamediametions

It can be seen from the above that the failure mode of soil around the pile in the normal service limit state corresponding to the rigid flexible screw pile with different pile diametries is symmetrical distribution of the central axis of the rigid flexible screw pile. With the increase of the pile diameter, the displacement of soil around the pile gradually increases to the lower part of the blade. In general, as the pile diameter increases, the soil displacement area around the blade increases, which enables the upper and lower surfaces of the blade to squeeze the soil to form a resistance moment, and thus increases the horizontal bearing capacity of the rigid flexible screw pile. Therefore, the larger the blade diameter, the larger the horizontal bearing capacity of the rigid flexible screw pile.

3.2. Helical Blade Effect

Fig. 6 describes the corresponding normalized load-displacement curve at the mud surface when the spiral blade diameter is 2*d*, 3*d*, 4*d*, and 5*d*. The normalized treatment method is the same as that when the pile diameter is used as the parameter analysis method. The horizontal bearing capacity of rigid flexible screw pile increases with the increase of pile deformation at the mud surface.

As the increase of blade diameter increases the compressed surface area of soil mass and the greater the surface friction of soil mass, the horizontal resistance along the opposite direction of load on pile body increases. Meanwhile, the increase of blade diameter increases the rotational moment arm of blade and the resistance moment provided by blade. In conclusion, with the increase of blade diameter, the horizontal resistance of pile along the opposite direction of load increases, and the resistance moment provided by blade increases, thus increasing the horizontal bearing capacity of rigid flexible screw pile.

The intersection points of different curves in Fig. 6 and 60mm reference line is drawn in Table 4. The growth rate of horizontal bearing capacity of screw pile R6, screw pile R7 and screw pile R8 compared with screw pile R5 is denoted as ΔHn, n=6, 7, 8, and calculated according to Equation (2)

$$\Delta Hn=(H_n-H_5)/H_5 \quad (2)$$

According to the growth rate (ΔH_n) of the horizontal bearing capacity of the rigid flexible screw pile in Table 4, the improvement of the horizontal bearing capacity of the rigid flexible screw pile varies. The growth rate of the horizontal bearing capacity of the rigid flexible screw pile in R8 calculation scheme is the maximum 31.0%, and the growth rate of the horizontal bearing capacity of the rigid flexible screw pile in H6 calculation scheme is the minimum 11.2%. The maximum growth rate of the horizontal bearing capacity caused by the change of blade diameter is 31.0%, and the pile diameter has a greater influence on the horizontal bearing capacity of the rigid flexible screw pile. In the design process of the rigid flexible screw pile, the method can be used to increase the horizontal bearing capacity of the rigid flexible screw pile by simultaneously expanding the diameter of the pile and the diameter of the spiral blade.

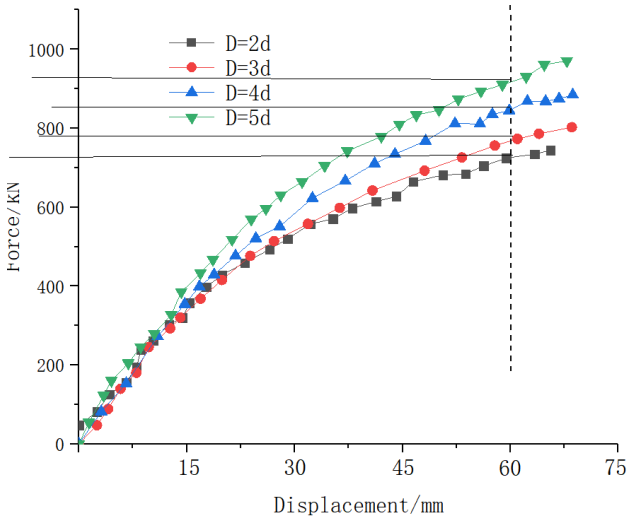


Fig 6. Load-displacement curves of different blade diameters

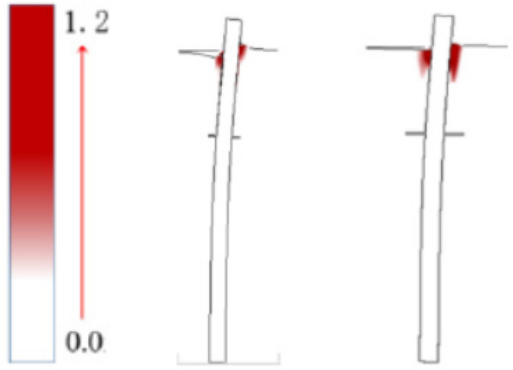
Table 4. Horizontal bearing capacity of different blade diameters

	NO.	Pile diameter/mm	Blade diameter/mm	Blade depth/m	Bearing capacity/kN	Growth rate/ΔH_n
A2	R5	700	2d	3.8	710	
	R6	700	3d	3.8	790	11.2%
	R7	700	4d	3.8	820	15.5%
	R8	700	5d	3.8	930	31.0%

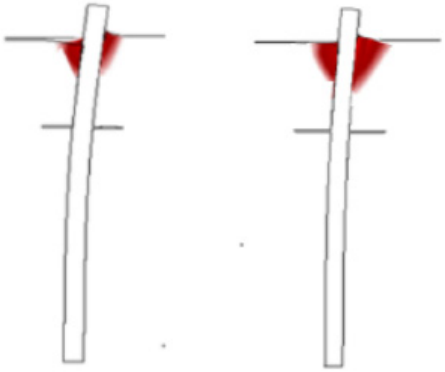
Fig. 7 shows the soil plastic strain nebulogram of rigid flexible screw piles with different screw blade diameters. As can be seen from Fig. 7, in the process of blade diameter expanding from 2*d* to 5*d*, the plastic failure zone of the soil mass of rigid flexible screw pile is mainly distributed on both sides of the pile body above the blade, the plastic failure zone

range of the soil mass around the pile increases with the increase of blade diameter, and the distribution pattern of the soil plastic failure zone gradually develops into an "inverted triangle" distribution pattern with the increase of blade diameter. No soil plastic failure zone develops around the blade and the base.

It can be seen from the above that the plastic failure zone of soil around the rigid flexible screw pile is controlled by the diameter of the screw pile blade, showing a general rule that the plastic failure zone increases with the increase of the blade diameter. When the rigid flexible screw pile reaches the normal service limit state, the plastic failure zone of soil is mainly located on both sides of the pile body above the spiral blade, and the axis of the pile body is symmetrically distributed. There is no plastic failure zone around the base and blade.

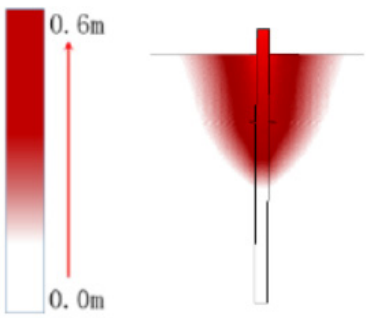


(a)Plastic strain (b)D=2d (c)D=3d

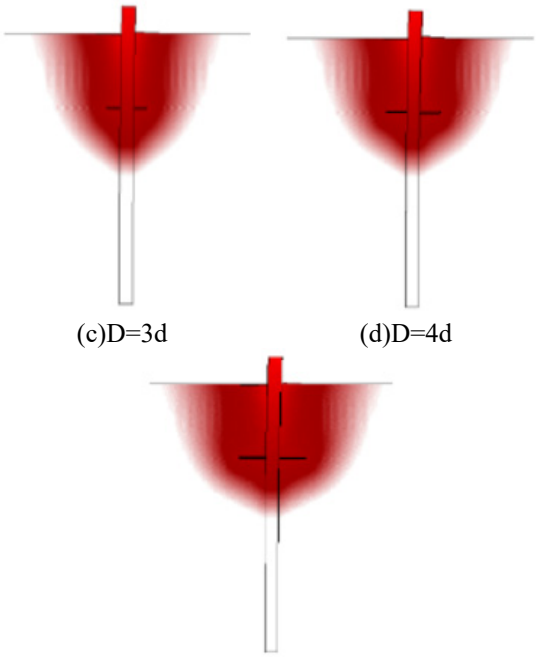


(d)D=4d (e)D=5d

Fig 7. Plastic strain nephogram of soil for rigid flexible screw piles with different diametries



(a)Displacement (b)D=2d



(c)D=3d (d)D=4d

(e)D=5d

Fig 8. Cloud map of soil displacement variation of rigid flexible screw piles with different screw blade diameters

Fig. 8 shows the cloud map of soil displacement changes when rigid flexible screw piles with different spiral blade diameters reach normal use. According to FIG. 8, the failure modes of soil around the pile under the normal service limit state corresponding to different spiral blade diameters are similar, and the central axis of rigid flexible spiral pile is approximately symmetrical, but the soil displacement distribution is different. As the blade diameter increases, the soil displacement under the blade decreases gradually. The soil displacement on both sides of the pile body above the blade expands to both sides of the pile body, and the soil displacement at the bottom of the rigid flexible screw pile foundation is always zero. The larger the diameter of spiral blade, the larger the contact area between blade and soil, so the larger the displacement range of soil formed around spiral pile.

3.3. Screw Blade Buried Depth Influence

Fig. 9 describes the normalized load-displacement curve at the mud surface when the embedded depth of spiral blades is 2.1m, 4.2m, 6.2m and 8.4m. The horizontal bearing capacity of rigid flexible screw piles with different buried depth of blades changes in the same trend, and the horizontal bearing capacity of rigid flexible screw piles increases with the increase of pile deformation at the mud surface.

The intersection points of different curves in Fig. 9 and 60mm reference lines are plotted in Table 5. The horizontal bearing capacity growth rate of screw pile R10, screw pile R11 and screw pile R12 compared with screw pile R9 is denoted as ΔH_n, n=10, 11, 12, and calculated according to Formula (3).

$$\Delta H_n=(Hn-H_1)/H_{J1} \quad (3)$$

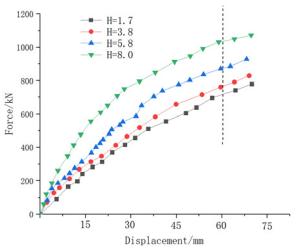


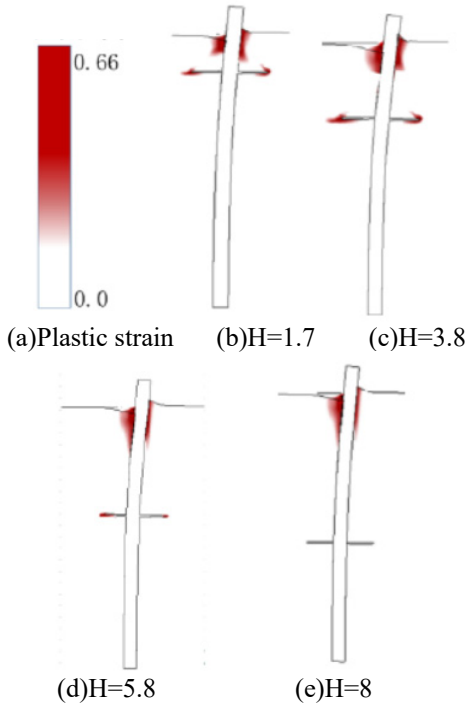
Fig 9. Load-displacement curves of different blade buried depths

It can be seen from the growth rate of the horizontal bearing capacity of the rigid flexible screw pile in Table 5 that the horizontal bearing capacity of the rigid flexible screw pile increases differently. The growth rate of the horizontal bearing capacity of the rigid flexible screw pile in the H10 calculation scheme is the maximum 50%, while the horizontal bearing capacity of the rigid flexible screw pile in the H12 calculation scheme is the minimum, which is 10.9%.

Table 5. Horizontal bearing capacity of different blade diameters

	NO.	Pile diameter/mm	Blade diameter/mm	Blade depth/m	Bearing capacity/kN	Growth rate/ΔHn
	R9	700	2d	1.7	640	
	R10	700	3d	3.8	710	10.9%
A2	R11	700	4d	5.8	890	39.0%
	R12	700	5d	8.0	960	50.0%

Fig. 10 shows the soil plastic strain nebulogram of rigid flexible screw piles with different helical blade buried depths. It can be seen from the figure that when the depth of spiral blade buried is 1.7m, there is no plastic failure zone at the bottom of rigid flexible spiral pile foundation, and there is an obvious plastic failure zone of soil on both wings of the blade. The plastic failure zone on both sides of the pile body above the spiral blade is symmetrically distributed with respect to the central axis of the pile body. When the blade depth is 3.8 m, there is no plastic failure zone at the bottom of rigid flexible pile foundation, and the plastic failure zone of soil on both sides of the pile body and the two blades of the blade remains approximately unchanged.



(a)Plastic strain (b)H=1.7 (c)H=3.8

(d)H=5.8 (e)H=8

Fig 10. Plastic strain nebulogram of soil mass corresponding to rigid flexible screw piles with different diameter

When the blade buried depth is 5.8 m, there is no plastic failure zone at the bottom of rigid flexible pile foundation, the plastic failure zone of soil on both sides of the blade decreases significantly, and the plastic failure zone on both sides of the pile body above the blade shrinks. When the blade buried depth is 8.0 m, there is still no plastic failure zone at the bottom of rigid flexible pile foundation, and the plastic failure zone of both blades completely disappears.

In conclusion, when the rigid flexible screw pile reaches the normal service limit state, the plastic failure zone of soil around the rigid flexible screw pile is controlled by blade depth. The plastic failure zone of soil around the pile generally decreases with the increase of blade depth. The main plastic failure zone of soil is located on both sides of the pile above the spiral blade, and a small amount of soil failure zone is located on both sides of the blade. There is no plastic failure area of soil in the basement.

4. Conclusion

In this paper, ABAQUS software is used to simulate the horizontal loading process of rigid flexible screw pile under normal use in fine sand. Firstly, the creation process and analysis content of the horizontal loading model are introduced, and parameters of screw pile are analyzed. Specific conclusions are as follows:

(1) The horizontal bearing capacity of rigid flexible screw pile increases with the increase of pile diameter, and the bearing capacity increases faster and faster. In the design process of rigid flexible screw pile, the horizontal bearing capacity of rigid flexible screw pile can be improved by expanding the diameter of rigid flexible screw pile and screw blade at the same time.

(2) The plastic failure zone of soil around the rigid flexible screw pile is controlled by the diameter of the screw pile blade, showing a general rule that the plastic failure zone increases with the increase of the blade diameter. When the rigid flexible screw pile reaches the normal service limit state, the plastic failure zone of soil is mainly located on both sides of the pile body above the spiral blade, and the axis of the pile body is symmetrical. There is no plastic failure zone around the base and blade.

(3) When the rigid flexible screw pile reaches the normal limit state, the plastic failure zone of soil around the rigid flexible screw pile is controlled by the buried depth of blade, and the plastic failure zone of soil around the pile decreases with the increase of buried depth of blade.

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