Analysis of Influence of Sand Parameters on Seismic Performance of PHC Piles

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Abstract. In order to study the effect of sand parameters on the seismic behavior of prestressed high-strength concrete (PHC) pipe piles, using the general finite element software ABAQUS6.12, by applying horizontal reciprocating load on the top of the pile, the influence of sand parameters on the seismic behavior of PHC piles under horizontal load is studied. The results show that increasing the relative density of sand increases the degree of hysteresis of PHC pipe pile hysteresis curve and reduces the cumulative hysteresis energy of PHC pipe piles; Increasing the internal friction angle of the sand increases the hysteresis loop area of the PHC pipe pile, and the cumulative hysteresis energy consumption increases; Increasing the initial modulus of sand soil resistance makes the PHC pipe pile stagnation loop shrinkage, and the cumulative hysteresis energy consumption decreases slightly. Increasing the relative density of sand, internal friction angle and initial modulus of soil resistance can increase the overall stiffness of the pile-soil system, increase the horizontal ultimate bearing capacity of PHC piles and reduce the ultimate displacement of PHC piles.

1. Introduction
As a kind of prestressed high-strength structural member, prestressed high-strength concrete (PHC) pipe pile has high vertical bearing capacity, but it has brittle failure mode when subjected to horizontal load and subjected to horizontal load. In order to improve the horizontal bearing capacity of PHC pipe piles and its seismic performance under earthquake action, domestic and foreign scholars have carried out related research [1-3], however, most of the research is currently focused on the structural parameters of the PHC pipe pile. In addition, due to the limitation of manpower and material resources, the experimental research on the seismic performance of PHC pipe piles in actual sand sites is rarely reported. The influence of sand-related parameters on the seismic performance of PHC pipe piles is still poorly understood. Therefore, this paper studies the influence of sand parameters on the seismic behavior of PHC pipe piles under horizontal load, and uses the finite element software ABAQUS 6.12 for numerical analysis, the effects of relative density of sand, internal friction angle and initial modulus of soil resistance on seismic behavior of PHC pipe piles are studied, which provides reference for seismic design and popularization of PHC pipe piles.

2. Finite element model

2.1. Pipe pile solid model
The research object of this paper is A-type PHC pipe pile with a diameter of 1200mm in 10G409 "Prestressed Concrete Pipe Pile" [4], the length is 30m, the relevant parameters are shown in Table 1.
Table 1. PHC pipe pile parameters

| Parameter | Value |
|-----------|-------|
| Diameter | 1200 mm |
| Wall thickness | 150 mm |
| Stirrup spacing | 80 mm |
| Stirrup diameter | 6 mm |
| Prestressed steel reinforcement | 30 A |
| Reinforcement ratio | 10.7% |
| Prestressed steel distribution circle diameter | 0.55 mm |
| Effective prestressing stress of concrete | 1060 MPa |
| | 4.73 MPa |

In this paper, the finite element software ABAQUS 6.12 is used to analyze the seismic performance of PHC pipe piles. The pipe pile concrete is selected from C3D8R unit. The steel bar is selected from the T3D2 unit, and the steel bar is inserted by the Embed command, and the initial tensile stress is applied by the cooling method. The concrete constitutive structure adopts the concrete plastic damage model of ABAQUS, and the relevant parameters are calculated according to the literature [5]. The reinforced steel constitutive structure uses the USTEEL01 model in the PQ-Fiber subroutine compiled by Tsinghua University.

2.2. Simulation of pile-soil interaction

Ultimate horizontal resistance of sand unit pile length \( p_u \) can be calculated by the following formula:

\[
\begin{align*}
\text{When } z &< z_t, \quad p_u' = (C_1z + C_2d)\gamma z \\
\text{When } z &\geq z_t, \quad p_u' = C_3d\gamma z
\end{align*}
\]

In the formula, \( p_u' \) is the ultimate horizontal soil resistance standard value (kN/m) of the unit pile length in the depth of the mud surface; \( c_1, c_2, c_3 \) are coefficients, it is related to the internal friction angle \( \phi' \) of the sand.

Solving the equations (1) and (2) simultaneously, the boundary depth \( z_s \) of the shallow soil and the deep soil can be obtained.

The \( p-y \) curve of the pile in the sand can be calculated according to the following formula:

\[
p = \Psi p_u' \tanh \left( \frac{kz}{\Psi p_u'} \right)
\]

\[
\Psi = \left\{ 3.0 - 0.8 \frac{z}{d} \right\} \geq 0.9
\]

In the formula, \( p \) is the horizontal soil resistance standard value (kN/m) acting on the pile at the \( z \) depth below the mud surface; \( \Psi \) is the calculation coefficient; \( k \) is the initial modulus of soil resistance (kN/m²).

In this paper, the depth of the PHC pipe pile is 28m, and the \( p-y \) soil spring is used to simulate the horizontal-soil interaction. The connector spring unit of ABAQUS6.12 is used to realize the function of soil spring. A soil spring is arranged every 1m below the mud surface. One end of the soil spring is connected to the pile body and the other end is fixed. In addition, the horizontal and vertical degrees of freedom of the pile bottom are limited, and a horizontal reciprocating load is applied to the top of the pile to simulate horizontal seismic action. Model is shown in Fig. 1.
3. Quasi-static analysis of seismic behaviour of pipe piles

3.1. Calculation parameters and working conditions
In order to study the effects of sand relative density, internal friction angle and initial modulus of soil resistance on the seismic behaviour of PHC pipe piles, the calculation conditions shown in Table 2 were selected.

| Working condition | Relative density/ (%) | Internal friction angle/(°) | Soil resistance initial modulus/(kN/m³) |
|-------------------|-----------------------|-----------------------------|---------------------------------------|
| 1                 | 20                    | 35                          | 80000                                 |
| 2                 | 40                    | 35                          | 80000                                 |
| 3                 | 60                    | 35                          | 80000                                 |
| 4                 | 80                    | 35                          | 80000                                 |
| 5                 | 60                    | 25                          | 80000                                 |
| 6                 | 60                    | 30                          | 80000                                 |
| 7                 | 60                    | 35                          | 40000                                 |
| 8                 | 60                    | 35                          | 60000                                 |

3.2. Loading mode
The force-displacement hybrid control is used for loading. The specific loading scheme is: Staged loading before yielding with 10%, 30%, 50%, 70% and 90% of the pile yield load, after yielding, the grading loading is performed at an integral multiple of the yield displacement, and the load cycle is three times per stage. When the horizontal bearing capacity of the pile top under a certain displacement loading is less than 85% of the ultimate bearing capacity of the pile top, the loading is stopped.

3.3. Analysis of results

3.3.1. Hysteresis curve
In the process of reciprocating loading, the horizontal bearing capacity-horizontal displacement curve of the pile top is the hysteresis curve. According to its shape and fullness, the seismic performance of the pile can be studied. The effect of different sand parameters on the hysteresis curve of PHC pipe pile is shown in Fig. 2.
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(a) Influence of relative density on hysteresis curve
(b) Influence of internal friction angle on hysteresis curve
(c) Influence of initial modulus of soil resistance on hysteresis curve

Fig. 2 Effect of different sand parameters on hysteresis curve of PHC pipe pile

It can be seen from Fig. 2(a) that as the relative density of sand increases gradually, the ultimate displacement of PHC pipe piles gradually decreases, the hysteresis curve pinch phenomenon becomes more and more obvious, the hysteresis loop shrinks, the energy consumption capacity decreases, and the seismic performance decreases. Fig. 2(b) shows that increasing the internal friction angle can increase the ultimate bearing capacity of the PHC pipe pile and reduce the ultimate displacement. The surrounding area of the hysteresis loop is gradually increased, and the seismic performance of the pipe pile is improved. It can be seen from Fig. 2(c) that as the initial modulus of sand soil resistance increases, the ultimate bearing capacity of PHC pipe piles increases, while the ultimate displacement decreases, the hysteresis loop shrinks, the shape becomes steeper, and the energy consumption capacity decreases.

3.3.2. Skeleton curve

The peak point of the first loading of each cycle of the hysteresis curve is the skeleton curve, as shown in Figure 3.

(a) The effect of relative density on the skeleton curve
(b) Influence of internal friction angle on skeleton curve
(c) Influence of initial modulus of soil resistance on skeleton curve

Figure 3. Effect of different sand parameters on the skeleton curve of PHC piles

The load displacement is linear in the initial stage of loading, and the pile-soil system is in the elastic stage with high rigidity. With the increase of the displacement amplitude, the pile-soil system gradually enters the yield, the pile-soil is separated, the stiffness is gradually reduced, the displacement amplitude is further increased, and the system stiffness is greatly reduced. The skeleton curve of the pile-soil system can be divided into three stages: elasticity, elastoplasticity and ultimate failure. It can be seen from Fig. 3(b)-(c) that increasing the internal friction angle or the initial modulus of soil resistance can increase the initial stiffness and ultimate bearing capacity of the PHC pipe pile and reduce the ultimate displacement, making the descending section of the skeleton curve more obvious. This is because the increase of the internal friction angle or the initial modulus of the soil resistance increases the constraint of the soil on the pile and limits the slight rotation of the pile in
the soil, so the ultimate bearing capacity of the pile is increased and the ultimate displacement is reduced.

3.3.3. Cumulative hysteretic energy consumption

The energy consumption capacity of PHC pipe piles can be described by cumulative hysteresis energy consumption. The greater the cumulative hysteresis energy consumption is, the stronger the dissipative ability of the component in the earthquake and the better the seismic performance. The effect of different sand parameters on the cumulative hysteretic energy of PHC pipe piles is shown in Fig. 4.

![Graphs](image)

Figure 4. Effect of different sand parameters on the cumulative hysteretic energy of PHC pipe piles

According to Fig. 4(a), the cumulative hysteresis energy of the pile decreases with the increase of the relative density of the sand. For the case where the internal friction angle of sand is 35° and the initial modulus of soil resistance is 80,000kN/m3, the cumulative hysteresis energy of PHC pipe pile decreases by 52.41% when the relative density of sand increases from 20% to 80%. It can be seen from Fig. 4(b) that the cumulative hysteresis energy of the PHC pipe pile increases as the internal friction angle increases. It can be seen from Fig. 4(c) that the cumulative hysteretic energy of PHC pipe piles decreases slightly with the increase of the initial modulus of soil resistance. When the relative density and internal friction angle of sand are 60% and 35°, respectively, when the initial modulus of soil resistance increases from 20000kN/m3 to 80000kN/m3, the cumulative hysteretic energy of PHC pipe pile decreases from 623.90kNm to 609.91kNm, a decrease of 2.24%.

4. Conclusion

Increasing the relative density of sand increases the degree of hysteresis of the hysteresis curve of the PHC pipe pile, and reduces the cumulative hysteresis energy of the PHC pipe pile; With the increase of the internal friction angle of the sand, the hysteresis loop area of the PHC pipe pile gradually increases, and the cumulative hysteresis energy consumption increases. With the increase of the initial modulus of sand soil resistance, the PHC pipe pile hysteresis loop shrinkage, and the cumulative hysteresis energy consumption decreases slightly.

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