Displacement analysis of open pipe piles sinking based on strain path method

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Abstract. The displacement field in the process of opening pipe piles sink has always been a hot issue in the study, especially in the area of pile, the soil body has produced a large strain, regardless of the large deformation effect of the soil, there will be a large calculation error. The strain path method can obtain the flow velocity of the soil because it does not rely on the constitutive relationship of the soil, which is a favorable theory for solving large strain problems. In this paper, the modified strain path method is used as the theoretical basis. The open pipe pile is equivalent to a closed pipe pile through the soil plug effect, and the sunk pile displacement of the open pipe pile is calculated to further reveal the soil plug effect and the soil squeeze effect of the open pipe pile mutual restraint and mutual influence, thus providing a theoretical basis for the pile displacement of open pipe piles.

1. Introduction

Many scholars have also paid close attention to the problem of pile compression of open pipe piles and its impact. Due to the complexity of this problem, people have so far focused on the squeezing effect and soil plugging effect of open pipe piles on sinking piles and their service periods. The impact is still not very clear. During the process of sinking piles, the soil displacement is mainly affected by four aspects: 1. The influence of surface displacement 2. The influence of soil plug displacement 3. The influence of pile side displacement 4. The influence of pile end displacement, as showed in Figure 1. In fact, during the process of sinking piles, large displacements and large strains occurred in the soil around a pile. Without considering the large deformation of the soil, large calculation errors will occur.

![Fig. 1 Soil displacement diagram](image)

At present, there have been some achievements in theoretical methods for solving large strains of soil. Butterfield, Randolph, and others[1] regarded the soil as an incompressible and isotropic ideal elastoplastic material. Under the condition of plane strain, the circular hole expansion method was utilized to solve the pile foundation sinking problem. Cao[2] solved the analytic solution of the radial displacement field of the soil around the pile when sinking by using the method of circular hole
expansion. However, the circular hole expansion theory treats the sinking pile process as a plane strain problem, neglecting the influence of the vertical soil mass, and cannot characterize the vertical displacement of the soil mass and the uplift phenomenon of the soil surface. Based on this, Li Yuejian[3] used source-theory and spherical hole expansion theory to modify the effect of vertical coordinates on the displacement field, but their theoretical derivation is based on the small strain assumption, which results in large errors in calculating the soil displacement at the pile-soil contact surface. In order to avoid the constraints of small strains caused by the constitutive relationship of the soil, Baligh[4] uses the strain path method to simulate the pile sinking process, but this method is suitable for deep foundations and ignores the existence of stress-free ground surfaces. Subsequently, Sagaseta[5] modified the strain path method using source-sink theory to simulate the stress free ground surface. So far, the modified strain path method can well simulate the sinking process. Huang Yuanxiong and Luo Zhanyou[6] derived the analytical solution of the displacement field of the soil around the single pile based on the small strain assumption and the large-strain assumption respectively. However, the research on the application of the strain path method to open piles and sunken piles is relatively rare, and the studies taking soil plugging effects into account are rare. At the same time, the great reason for studying the displacement field of piles and soils is to serve the bearing capacity of the piles, but the bearing of the piles is only closely related to the displacement of the soils in a limited range around it. During the process of sinking the pile, the soil has a large displacement within a limited range of pile side soil. Therefore, studying the theory of large strain sinking piles in open pipe piles can play a certain role in evaluating the bearing capacity of open pipe piles.

2. Basic principles of strain path method
The strain path method treats the sinking pile process as a point source sinking at a certain speed. By integrating the velocity of the soil particles along the streamline to calculate the displacement of the soil, this method can obtain a stress-strain field independent of the constitutive relationship.

However, the strain path method also has disadvantages: ① the flow field analysis is used to simulate the penetration of piles and soils, and the soil is treated as a non-viscous material similar to the fluid, and the plasticity, viscosity and dilatancy of the soil are ignored; The method adopts the assumption of infinite soil, which is only applicable to deep foundations; ③ The strain path method assumes that the soil is incompressible, which is not completely consistent with the actual situation.

3. Establishment of calculation model
In order to apply the strain path method to the sinking process of open pipe piles, two key issues need to be addressed: ① free ground surface stress correction; ② the impact of the formation and development of soil plugs on penetration.

Aiming at the problem ① is the common problem of the strain path method applied to the sinking pile process, which is generally solved by source-sink theory, as shown in the figure:
The strain path method is applicable to an isotropic infinite body, ignoring the existence of the ground surface. During the actual pile pressing process, the ground will have different degrees of uplift. The ground surface has no normal stress and shear stress. The facts do not match, so to solve the displacement field of piles, follow the steps below.

1. First ignore the existence of the free ground surface, and find the sum of the ground surface that the real source is displaced to a certain depth.
2. In order to eliminate the effects of normal and shear stresses on the ground surface. It is assumed that there is a virtual sink above the ground surface that is symmetrical with the real source. The movement direction of the virtual sink is opposite to that of the source. Surface radial displacement is 0, vertical displacement is doubled, normal stress is 0, and shear stress is doubled.
3. Set the shear stress equal to the source and sink at the ground surface, and correct the vertical displacement by a force in the opposite direction to obtain the vertical displacement in the sinking process under actual conditions.

In the same way, the radial displacement during the sinking process of the ground surface can be obtained by using the source theory.

Aiming at the problem (2), the formation and development of soil plugs are closely related to the squeezing effect in the process of sinking piles. The formation process of soil plugs is also the development process of open pipe piles from partially squeezed piles to fully squeezed piles. Therefore, it is necessary to combine the soil plug growth rate FIR and the strain path method that can represent the soil plug development law, so that the calculation process can reflect the influence of the soil plug evolution and development on the squeezing of the open pipe pile.

4. Theoretical solution
The velocity of the soil element at the location \( \rho(r,z) \) in Baligh's strain path method is

\[ v_{\rho} = \frac{V}{4\pi \rho^2}. \]

Converting it to a rectangular coordinate system breaks it down into radial and vertical velocities:

\[ v_r = \frac{V \sin \phi}{4\pi \rho^2}, \quad v_z = \frac{V \cos \phi}{4\pi \rho^2} \tag{1} \]

\( v_r \) is the radial velocity; \( v_z \) is the vertical velocity; \( \rho^2 = r^2 + z^2, r = \rho \sin \phi, r = \rho \cos \phi. \)

The assumption of incompressible soil during the penetration of the pile foundation can be obtained:

\[ R = \frac{\sqrt{V}}{\pi v_{\rho}} \tag{2} \]

For pipe piles, since the squeezing effect of open pipe piles has been changing during the sinking
process, parameters that can reflect the squeezing effect can be introduced. Strength of the squeezing effect. The parameters that describe the change in the height of the soil plug during the sinking process of the pipe pile are mainly the soil filling ratio (IFR) and the plug length ratio (IFR).

\[
IFR = \frac{dh}{dL}, \quad PLR = \frac{h}{L}
\]

\(dh\) is soil plug height increase; \(dL\) is sinking pile depth increase.

\[
R = R^2 - IFR r^2
\]

\(R\) is open pipe pile outer diameter, \(r\) is inside diameter of open pipe pile.

This formula shows that when the growth rate IFR of the soil plug is 0, the soil plug no longer grows. At this time, the penetration of the open pipe pile is equivalent to the closed diameter pile of the same diameter. When the soil plug growth rate IFR is 0–1, the soil plug is not occluded, and the squeezing effect at this time is equivalent to a reduced size closed pile. Therefore, this formula can describe the interaction between the soil squeezing effect and the soil plugging effect during the whole process of sinking piles.

Therefore, under the action of the source, the soil particle velocity can be obtained:

\[
\begin{align*}
    v_{p1} &= \frac{v_p R^2 r}{4} \frac{1}{r_1} \\
    v_{z1} &= \frac{v_p R^2 z - h}{4} \frac{1}{r_1}
\end{align*}
\]

Under the action of the converge, the soil particle velocity can be obtained:

\[
\begin{align*}
    v_{p2} &= \frac{v_p R^2 r}{4} \frac{1}{r_2} \\
    v_{z2} &= \frac{v_p R^2 z - h}{4} \frac{1}{r_2}
\end{align*}
\]

\(v_p\) is the penetration speed of the pile, \(r_1 = \sqrt{r^2 + (z + h)^2}\), \(r_2 = \sqrt{r^2 + (z - h)^2}\), \(r_1, r_2\) is the distance between the source and sink and the soil particles.

After the soil particle velocity is determined, the radial displacement and vertical displacement at any position can be obtained by integrating the time.

\[
\begin{align*}
    \{r(z)\} &= \{r_0(t)\} + \int_0^z \{v_p(r, z, h)\} dt \\
    \{z(h)\} &= \{z_0(t)\} + \int_0^z \{v_p(r, z, h)\} dt
\end{align*}
\]

Because it is a large deformation, it is assumed that the initial position of the soil changes after \(t\), and its initial value changes with time. Therefore, its integral can only be in the form of numerical integration. In addition, the value of IFR must be calculated based on the actual test value.
5. Results analysis

(a) horizontal displacement at 0.25m on pile side

(b) vertical displacement at 0.25m on pile side

Fig. 3. Soil displacement at 0.25m on pile side

By calculating the displacement field at 0.25m lateral to the pile, we can find that after the extreme value of horizontal displacement is reached, its displacement does not change, while the vertical displacement value reaches the extreme value with the sinking of the pile, it will further sink and shrink the pile. The reason is that when the pile end reaches a certain position, the stress reaches a maximum value, and the soil is strongly squeezed, resulting in a large displacement, but when the pile end reaches the next position, the stress state of the soil at the previous maximum displacement is restored, and its displacement is reduced accordingly. On the other hand, because it is a homogeneous soil body, as the pipe pile goes deeper, its squeezing effect increases, it can be seen from the figure that the deeper the sinking pile, the greater its vertical extreme value, until it reaches a stable value, achieving a similar effect to that of a closed pile.

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