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Comparison of Different Calculation Methods of Soil Plug Effect

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Abstract

Soil plug effect is common in underground geotechnical engineering construction. In order to clarify the calculation method of soil plug effect and better guide engineering practice. Using the method of literature investigation and summary, the relevant theories of soil plug effect are divided into three parts: the mechanism of soil plug, the judgment of soil plug blocking degree and the ultimate bearing capacity of pile bottom foundation. The results show that the formation of soil plug is actually a cyclic process of continuous formation and failure of soil arch at the bottom of pile; The Yamahara method and the improved Yamahara method are the most reasonable to analyze the soil plug effect, but the ultimate bearing capacity of the pile bottom needs to be obtained before calculating the blocking rate; The soil plug effect of large-diameter steel pipe pile, the influence of layered soil on soil plug effect, the calculation of reasonable soil plug height of dynamic change, and the dynamic evolution law of the interaction between soil plug and the inner side of pipe pile are all directions worthy of further study.

Keywords

Soil Plug Effect; Calculation Method; Generation Mechanism; Degree of Occlusion; Ultimate Bearing Capacity.

1. Introduction

The static pressure construction or piling construction of open tubular pile [1], the settlement of bucket foundation [2], the penetration of suction anchor [3], the settlement of open caisson [4], and the propulsion of variable pitch screw conveyor [5] all face the problem of soil plug effect. How to reasonably calculate the soil plug effect obviously has important practical significance for engineering design and construction. At present, scholars at home and abroad have done a lot of research on the soil plug effect. The research work mainly focuses on three aspects: the generation mechanism of soil plug [6], the judgment of the blocking degree of soil plug [7-10] and the calculation of bearing capacity at the end of soil plug.

For a specific project, scholars at home and abroad mostly use the finite element method to calculate the soil plug effect. However, the finite element method has high requirements for users' theoretical foundation and operation skills. In many cases, even for the same engineering example, the results calculated by different finite element users may be quite different, resulting in a great reduction in the applicability of the finite element method in the calculation of soil plug effect. Analytical or semi analytical methods are preferred in engineering. Although many methods have been proposed at home and abroad to calculate and analyze the soil plug effect and related problems, the effectiveness and scope of application of each method need to be further clarified in order to better guide the

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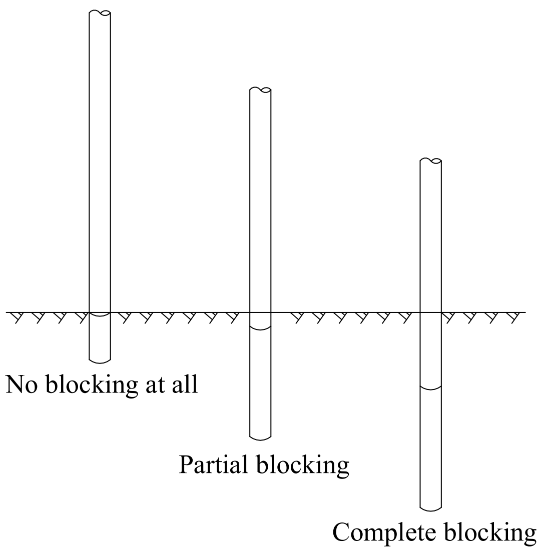
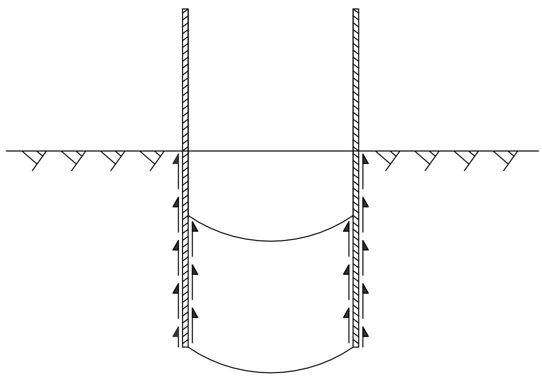
engineering practice. Therefore, this paper uses the comprehensive comparison method to compare and analyze several classical soil plug effect calculation methods, defines their respective application scope, and points out the shortcomings of each method and further research direction.

2. Mechanism of Soil Plug

As shown in Figure 1 (a), when a pipe pile is pressed into the soil, part of the extrusion effect acts on the soil outside the pipe and part of the extrusion effect acts on the soil inside the pipe. As shown in Figure 1 (b), through the stress analysis of the pipe pile, it can be seen that it is subject to the vertical side friction of the soil outside the pipe and the vertical side friction of the soil inside the pipe. As for the soil column in the pipe, as shown in Figure 1 (c), it is subject to the vertical downward friction provided by the inner wall of the pipe pile, which plays a certain compression role on the soil column in the pipe. With the continuous pressing of the pipe pile, the height of the soil column in the pipe will continue to increase, the friction between the inner wall of the pipe pile and the soil column in the pipe will continue to increase, and the closure effect will occur at the pipe end, that is, the soil plug will be formed.



(a) Pipe pile press in



(b) Stress of pipe pile

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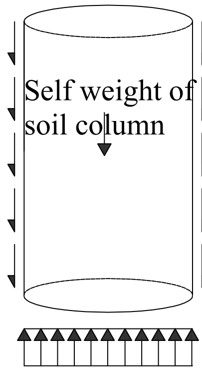

(c) Soil plug stress

Figure 1. Schematic diagram of soil plug generation mechanism

The classical theory to explain the cause of soil plug is dynamic arch theory [6]. The core assumption of this theory is that the formation of soil plug is due to the formation and failure of soil arch at the bottom of pile, and then the process of continuous circulation. With the continuous driving of the pile, the stress adjustment of the soil in the pipe will produce the soil arch effect. When the external load exceeds the ultimate bearing capacity of the soil arch, the soil arch will be damaged, and then the soil outside the pipe will flow into the pipe, so as to establish a new soil arch.

3. Judgment of Blocking Degree of Soil Plug

With the continuous pressing of the pipe pile, the height of the soil column in the pipe changes continuously. The blocking state of the corresponding soil plug can be divided into: (1) the complete non blocking state in the initial stage of pile pressing. At the initial stage of pile pressing, the mud surface inside and outside the pipe is generally flat, and the compression effect of the soil column in the pipe is not strong, resulting in the soil plug effect is not obvious. (2) Partial blocking state in the middle stage of pile pressing. In the middle stage of pile pressing, the soil surface in the pipe is significantly lower than that outside the pipe, the compression effect of soil column in the pipe is obvious, and the height of soil plug slows down with the increase of pile pressing. (3) Complete blocking state in the later stage of pile pressing. At this time, the height of soil plug in the pipe will no longer change with the progress of pile pressing, and the working behavior of open pile is similar to that of closed pile. As shown in Figure 1 (c), it is obvious that in the complete non blocking state and partial blocking state, the ultimate bearing capacity of the soil foundation under the pipe is greater than the sum of the gravity and lateral resistance of the soil plug. At this time, the soil at the pile end can enter the pipe, and the corresponding stress failure occurs between the soil plug and the inner wall of the pile. In the completely blocked state, the ultimate bearing capacity of the soil foundation under the pipe is equal to the sum of the gravity and lateral resistance of the soil plug. At this time, the soil at the pile end cannot enter the pipe, and the corresponding stress failure occurs between the pile end and the soil foundation.

3.1 Soil Plug Length Ratio and Incremental Filling Ratio

The soil plug length ratio PLR can be used to describe the soil plug effect, while the incremental filling ratio IFR can be used to describe the change of soil plug height [7], and the specific expression is:

$$PLR = \frac{h}{L} \tag{1a}$$

And:

$$IFR = \frac{\mathrm{d}h}{\mathrm{d}L} \tag{1b}$$

Where, h and L respectively represent the height of soil column in the cylinder and the depth of pile into the soil. Obviously, the values of incremental filling ratio corresponding to complete non blocking state, partial blocking state and complete blocking state are $IFR = 1$, $0 < IFR < 1$ and $IFR = 0$ respectively.

Although the indexes PLR and IFR describing soil plug effect and soil plug change have been established by geometric method, in practical engineering, engineers and technicians and designers are more used to analyzing soil plug effect from the perspective of mechanical mechanism. At present, the theoretical methods of analyzing soil plug effect by mechanical methods mainly include Randolph method [8], Tadao method, Koizumi method, Yamahara method [9], improved Yamahara method [10], etc.

3.2 Randolph Method

Considering that the reaction force at the bottom of the soil plug is transmitted from bottom to top, and the soil plug is affected by gravity, the upper part of the soil plug may not bear the load at the bottom of the soil plug, so Randolph method divides the soil plug height h into the effective height l of the lower part and the non effective height h - l of the upper part. Part of the soil plug at non effective height does not provide side resistance, which is regarded as overload analysis. When the sum of gravity plus internal friction of the plug is the same as the end resistance of the plug, the plug reaches static equilibrium and meets the requirements at this time:

$$\frac{\mathrm{d}\sigma_v}{\mathrm{d}z} = \gamma_w + \gamma' + \frac{2}{R_i}\tau \tag{2}$$

where, σ_v is the total vertical stress in the soil plug at the distance z from the dividing point of non effective height and effective height, kPa; γ_w is the gravity of water, kN/m3; γ' is the effective gravity of soil mass, kN/m3; R_i is the inner radius of the pipe pile, m; τ is the side friction resistance between the soil plug and the inner wall of the pile, kPa, specifically:

$$\tau = \beta\gamma'\left(h - l + z\right) \tag{3}$$

where, β is the proportional coefficient of horizontal stress and vertical stress of soil plug in the pipe, which depends on the contact performance of pile-soil interface.

For the layered soil in the actual project, the distribution of vertical stress σ_v in the soil plug along the depth z can be obtained by piecewise integration of equation (2). However, in practical engineering application, it is very difficult to determine the non effective height of the upper part of the soil plug, which directly limits the application of this method in engineering.

3.3 Tadashima Method

By comparing the stress mechanism of open pile and closed pile, combined with the assumptions that the gravity of soil is ignored, the friction between soil plug and the inner side of pile is directly proportional to the relative displacement, and the settlement of pile end is directly proportional to the

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foundation reaction in the limit state, the blocking rate α is obtained through certain derivation, as follows:

$$\alpha=\frac{1}{1+K_v\sqrt{\dfrac{R_i}{2GE\tanh\beta}}} \tag{4}$$

where, $\beta=h\sqrt{\dfrac{2G}{R_iE}}$, G refers to the friction displacement coefficient between the soil plug and the inner side of the pile, kN/m3; E represents the bulk compression modulus of soil, kPa; K_v represents the reaction coefficient of pile end foundation, kN/m3. As can be seen from equation (4), the larger G and E, smaller K_v and R_i, the better the blocking effect. However, the blocking rate obtained from equation (4) is always less than 1, which is obviously inconsistent with the engineering practice.

3.4 Koizumi Method

Koizumi method converts the effective area considering the blocking effect into the sealing area of the pile end, then considers the influence of the wall thickness of the pipe pile t, and considers that the internal friction increases with the increase of the pile pouring depth, and obtains the calculation formula of the closing ratio:

$$\alpha=1-\left(\frac{B_1}{D_o}\right)^2 \tag{5}$$

where, $B_1=D_o-2\left(1+\dfrac{H}{D_o}\right)t$, D_o refers to the outer diameter of pipe pile, m; H indicates the depth of the pipe pile into the bearing stratum, m. Obviously, according to Koizumi's formula (5), the closure rate α has nothing to do with the nature of soil layer, and the closure rate α is always less than 1, which is obviously inconsistent with the engineering practice.

3.5 Yamahara Method

In this method, the occlusion rate α can be defined as follows:

$$\alpha=\frac{P_L}{R_U} \tag{6}$$

where, P_L refers to the sum of self weight and lateral resistance of soil plug; R_U represents the ultimate bearing capacity of pile end foundation.

Soil plug static equilibrium equation:

$$\frac{\mathrm{d}\sigma_v}{\mathrm{d}z}=\gamma+\frac{2}{R_i}(\tau+c) \tag{7}$$

where, $\tau=\gamma' z\tan\varphi$, γ refers to the gravity of soil mass, kN/m3; c Indicates cohesion of soil mass, kPa; φ represents the internal friction angle of soil mass. Considering the boundary conditions

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$\sigma_v|_{z=0}=0$, for the layered soil, the variation of the total vertical stress in the soil plug with depth σ_v can be obtained by piecewise integration of equation (7), so as to obtain the sum of the dead weight and lateral resistance of the soil plug $P_L=\sigma_v|_{z=h}$.

It can be seen from equation (7) that the yamahara method does not consider the lateral compression effect of the pile on the side of the soil plug, which may lead to the underestimation of the side resistance of the soil plug.

3.6 Improved Koizumi Method

The original mountain formula (7) does not consider the influence of pile circumference size effect and pile end size effect. On the basis of the original mountain formula (7), considering the influence of pile circumference size effect and pile end size effect, the static balance equation of soil plug is established:

$$\frac{\mathrm{d}\sigma_v}{\mathrm{d}z}=\gamma+\frac{2}{R_i}\left(\psi_s\tau+c\right) \tag{8}$$

Where, ψ_s is the size effect coefficient around the pile. Accordingly, the sum of the dead weight and side resistance of the soil plug is $P_L=\psi_L\left(\sigma_v|_{z=h}\right)$, where, ψ_L represents the size effect coefficient of the pile end.

Theoretically, the improved Yamahara formula (8) is more reasonable than the original Yamahara formula (7). However, the determination of size effect coefficient often depends on engineering experience, which causes great inconvenience to practical engineering application.

4. Calculation of Bearing Capacity of Soil Plug End

Randolph's formula (2), Yamahara's formula (7) and improved Yamahara's formula (8) can calculate the sum of the dead weight and lateral resistance of the soil plug. To calculate the blocking rate of the soil plug according to formula (6), the ultimate bearing capacity of the foundation at the pile end must be calculated first. At present, scholars at home and abroad have put forward many calculation methods of foundation ultimate bearing capacity, but the more common ones include API code method, standard penetration test method and Terzaghi method.

4.1 API Code Method

The calculation formula of ultimate bearing capacity of foundation given by API code method is:

$$R_U=\begin{cases} 9Ac & \text{clay} \\ N_q q_0' A & \text{sand} \end{cases} \tag{9}$$

Where, A refers to the cross-sectional area of pile end, m2; q_0' indicates the effective overburden earth pressure of soil at the pile end, kPa; N_q represents the bearing capacity factor.

This method cannot consider the influence of side load effect on the improvement of bearing capacity. The ultimate bearing capacity obtained according to formula (9) is too small, resulting in the calculated soil plug blocking rate is too large.

4.2 Standard Penetration Test Method

The formula for calculating the ultimate bearing capacity of the foundation is:

$$R_U=\Omega NA \tag{10}$$

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where, Ω refers to the conversion coefficient, which is taken according to the engineering experience; N indicates standard penetration blow count.

4.3 Terzaghi Method

Assuming that the base is rough and the friction between the base and the soil prevents the shear displacement of the base, according to the static equilibrium condition of the soil under the base, it can be deduced that the ultimate bearing capacity of the circular foundation in case of overall shear failure is:

$$R_U = (1.2cN_c + \gamma h N_q + 0.6\gamma R_i N_\gamma)A \tag{11}$$

Where, N_c , N_q and N_γ are adjustment factors of bearing capacity. In particular, for soft clay and loose sand, local shear failure often occurs, and the shear strength index needs to be adjusted.

$$c' = \frac{2}{3}c \tag{12}$$

$$\varphi' = \arctan\left(\frac{2}{3}\tan\varphi\right) \tag{13}$$

Considering that Terzaghi method can consider the side load effect, its applicability should be stronger.

5. Directions and Suggestions for Further Research

(1) At present, the research on soil plug effect mostly focuses on small and medium-sized steel pipe piles, and there is less research on soil plug effect of large-diameter and super large-diameter steel pipe piles. Considering the influence of size effect, it is suggested that the soil plug effect of large-diameter and super large-diameter steel pipe piles can be studied by means of field measurement and finite element method [11].

(2) Considering that the soil layer in engineering practice is mostly layered soil, and may also encounter special soil layers such as soft and hard phases [12], how to establish the calculation method of soil plug effect considering the interaction between soil layers is also a direction worthy of research.

(3) In fact, during the construction of steel casing cast-in-place pile, the height of soil plug in the casing is different. It is of great engineering practical value to establish the calculation formula of the disturbance effect of steel casing pressing construction on the surrounding stratum under different height of soil plug.

(4) In the process of concrete steel casing pressing down, when the soil plug in the casing is too high, it is easy to form complete occlusion. At this time, the continuous pressing down of the casing will cause the uplift of the surrounding stratum; When the soil plug in the cylinder is too low, the soil outside the cylinder tends to flow around the cylinder, resulting in the settlement of surrounding strata. Therefore, the establishment of a reasonable calculation method of soil plug height which changes dynamically with the downward pressure of pile casing also has strong engineering application value.

(5) The dynamic evolution law of the interaction between the soil plug and the inner side of the pipe pile will directly affect the establishment of the soil plug balance equation and how to affect the calculation of the blocking rate of the soil plug. Therefore, it is very necessary to deeply study the corresponding dynamic evolution law.

6. Conclusion

Literature collection and theoretical analysis are used to compare different calculation methods of soil plug effect, so as to better guide engineering practice. The results show that:

(1) The formation of soil plug is actually a cyclic process of continuous formation and failure of soil arch at the bottom of pile.

(2) The theoretical methods of analyzing soil plug effect by mechanical methods mainly include Randolph method, Tadashima method, Koizumi method, Yamahara method, improved Yamahara method and so on. Among them, Yamahara method and improved Yamahara method are the most reasonable, but the ultimate bearing capacity of pile bottom needs to be obtained before calculating the blocking rate.

(3) The soil plug effect of large-diameter steel pipe pile, the influence of layered soil on soil plug effect, the calculation of reasonable soil plug height of dynamic change, and the dynamic evolution law of the interaction between soil plug and the inner side of pipe pile are all directions worthy of further study.

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