Research Article **SRR (2021) 14:121**

Scientific Research and Reviews
(ISSN:2638-3500)

Improved soil plug height calculation formula

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ABSTRACT

This paper analyzes the soil plugging effect of the open pipe pile during the pile sinking process. The soil in the pipe pile is regarded as a continuous and uninterrupted multiple units, and the force analysis is carried out in the vertical direction, and the vertical balance equation of the soil in the pile is obtained. By establishing an equation, the expression of the plug height of the pipe pile during the pile sinking process is obtained. Comparing the theoretical calculation results with the actual project, it is concluded that the theoretical calculation results can reflect the overall change in the height of the soil plug. Therefore, the pile plug height obtained by calculation has certain guiding significance for the project.

Keywords: Open pipe pile; Soil plug height; Theoretical calculation; Balance equation

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How to cite this article:
Sashuang Gao. Improved soil plug height calculation formula. Scientific Research and Reviews, 2021; 14:121

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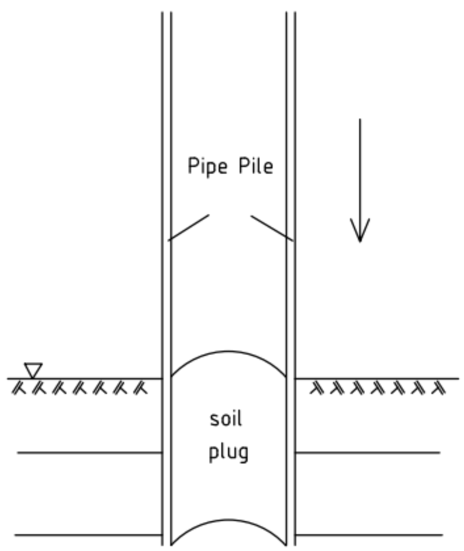
Website: http://escipub.com/

1. Introduction

Prestressed high-strength concrete pipe piles have been widely used in engineering in recent years because of their high single pile bearing capacity, low cost, strong pile quality controllability, good adaptability, fast construction speed and good seismic performance. During the pile sinking of the open pipe pile,, the pile end portion of the soil is pushed to the peripheral portion of the inner tube forms the influx of "soil plug. "Many experts and scholars at home and abroad have conducted in-depth studies on the soil plugging effect of pipe piles. PAIKOWSKY [1] studied the influence of soil plug on the bearing capacity and dynamic characteristics of pipe piles. Liu Yu-hua [2] applied the theory of circular hole column expansion to analyze the force of the soil in the precast pipe piles. The horizontal squeezing effect of the soil was considered. The change in the horizontal direction caused the soil to change in the vertical direction. Through numerical simulation, Wang Teng [3] analyzed the evolution of soil plug and the formation mechanism of soil plug, and simulated the formation process of soil plug during the entire pile sinking process. Yan Shuwang [4] proposed a method for judging soil blockage by studying the offshore oil production platform. Judge the degree of occlusion of the soil in the pile by the size of the bearing capacity and friction resistance of the foundation; Through experiments, Xie Yongjian [5] compared the influence of different soil layer structures on the effect of soil plugging, and summarized the changes in the soil plugging incremental filling rate of a specific soil layer. Zhu Hehua [6] considers that the open pipe pile is affected by the confined water during the pressure-bearing process. When the pipe piles are driven into the water layer, the water will generate greater water pressure on the soil plug. The water pressure is not good for the soil plug and will cause the height of the soil plug to increase. In summary, most of the research on the effect of soil plugging is based on field test data, and there is still a lack of calculation methods for determining the height of soil plugging. This article will establish an equation to analyze the force of the soil plug and determine the calculation formula for the height of the pipe pile plug.

2. Soil plug model



Simplified model of soil plug

As the pile sinks, the steady state of the soil inside the pipe pile is continuously broken, forming a new steady state. The friction force on the pipe wall and the ultimate bearing capacity of the pile end continue to change, which causes the influx of soil to change continuously. The soil in the pipe wall is switched between a fully occluded state and an incompletely occluded state. The degree of occlusion directly affects the end resistance performance and failure behavior and the bearing capacity of the pile. The physical and mechanical properties of soil plug directly affect the transfer of force between it and the pipe wall, but there are relatively few studies on the soil plug part, so there is a good prospect to study the soil plug effect of pipe piles.

3.Theoretical calculation of soil plug height

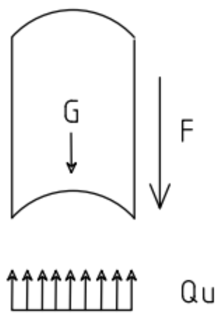
For simple calculation, a one-dimensional balance equation is established. It is considered that the soil in the force-bearing part is only affected by the force in the vertical direction, while the horizontal direction is considered to be symmetrical. Because of the symmetry, all horizontal forces are canceled. That is, the force analysis is performed on the part of the soil plug, and only the vertical coordinate axis is established for the force analysis, and the vertical downward direction is taken as the positive direction. At the same time, the internal soil core is regarded as a continuous and uninterrupted multiple units, and there is no void in the soil during the entire pile driving process. The force analysis of the influx of soil in the pipe piles is performed and the one-dimensional static balance equation is listed as follows:

$$G + F = Q_u \qquad (1)$$

G------the gravity on the part of the soil plug;

F------the effective height of the side friction resistance of the soil to provide;

Qu -------the ultimate bearing capacity provided by the foundation soil under the soil plug;



The force of the soil plug

Obviously, the expression of easy-to-get gravity is as follows:

$$G = \gamma h A \qquad (2)$$

h------soil plug height;

A------Cross-sectional area of pipe pile;

Where γ is the natural weight of the soil in the pipe pile, Since the soil poured into the pipe pile is usually the first layer of soil, the soil under the stratum structure may have been blocked during the process of driving the pile, and it is difficult for the lower layer of soil to enter the open pipe pile again. Or because it is in an unplugged state, but the influence of the soil on the pipe pile is relatively slight, in most cases, the value of γ only needs to take the natural weight of the first layer of soil. After calculating the height of the soil plug in the pipe pile, the value of γ needs to be checked. If the height of the soil plug poured into the pipe pile is less than or equal to the thickness of the first layer of soil, the natural weight of the first layer of soil is directly selected as the natural weight of the soil in the pipe pile. If the height of the soil plug poured into the pipe pile is greater than the thickness of the first layer of soil, the average natural weight should be used as the natural weight of the soil.

$$\bar{\gamma} = \frac{\gamma_1 x_1 + \gamma_2 x_2 + \ldots\ldots + \gamma_n x_n}{x_1 + x_2 \ldots\ldots + x_n} \quad (3)$$

γ_1-------the density of the first layer of soil from top to bottom, m;

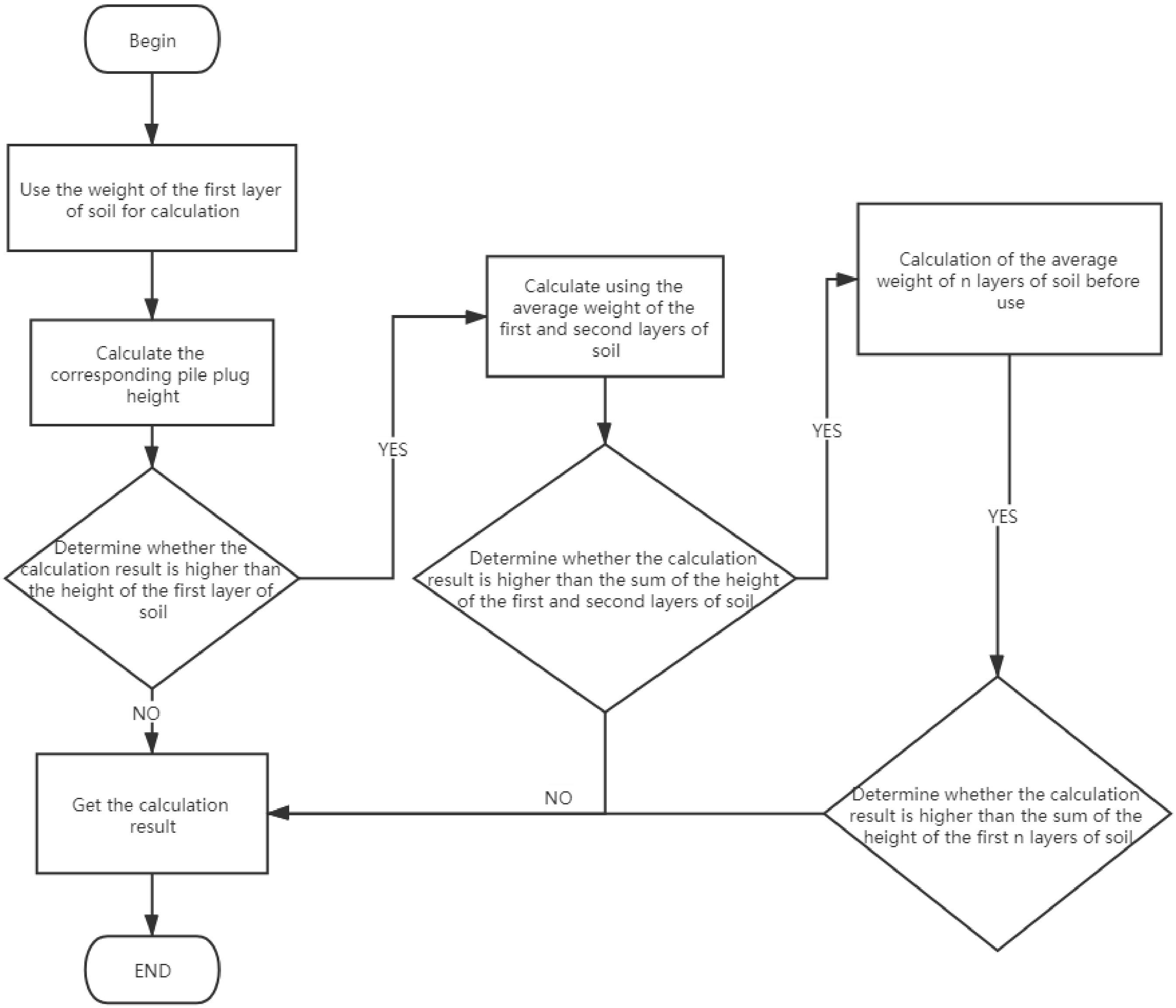
γ_2----the density of the second layer of soil from top to bottom, m;

γ_n-------the density of the nth layer of soil from top to bottom, m;

X_1--------the thickness of the first layer of soil from top to bottom, m;

X_2----the thickness of the second layer of soil from top to bottom, m;

X_n -----the thickness of the nth layer of soil from top to bottom, m;



Choose γ calculation flow chart

F------the side friction resistance provided by the effective height of the soil is determined by the following formula:

$$F = L\int_{h-h_0}^{h} \tau_z dz \quad (4)$$

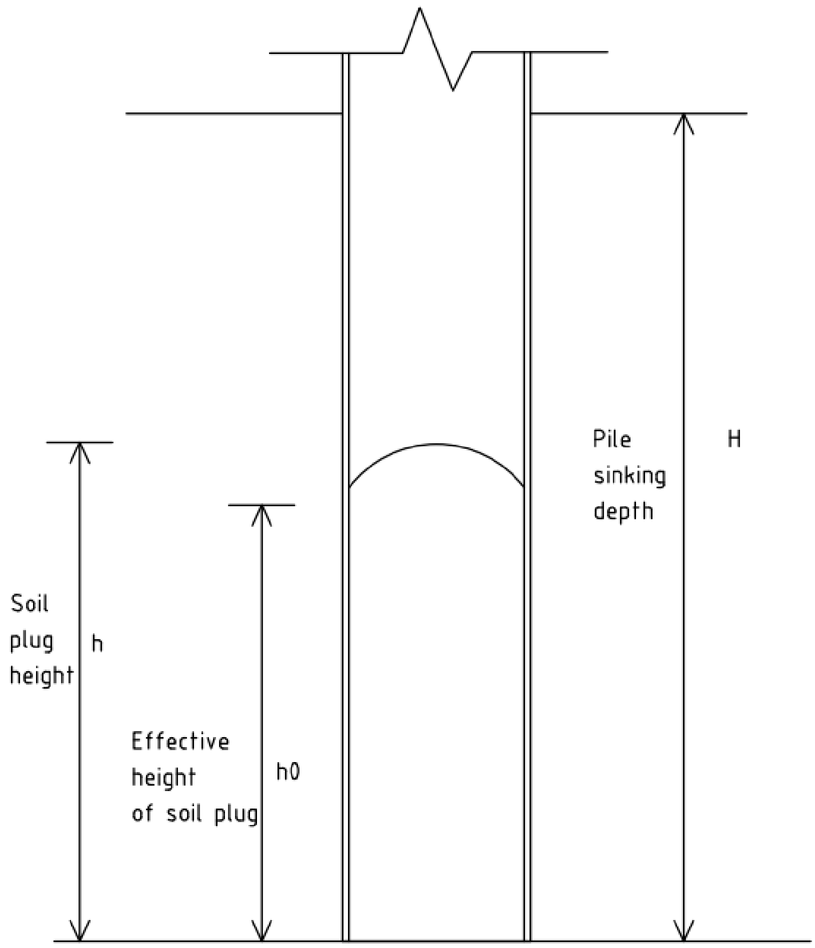
τ_z--------- the unit friction force of the pipe wall at the depth z of the soil plug inside the open pipe pile.

$$\tau_z = \eta \sigma_v \quad (5)$$

η-----the depth of the soil plug in the open pipe pile is the ratio of the unit friction force of the pipe wall to the vertical stress at z，Its magnitude depends on the ratio of the stress value in the vertical direction to the horizontal direction

It is assumed that the ratio of the height of the soil plug to the effective height of the soil plug isξ.

$$h_0 = \xi h \quad (6)$$



Combining all the previous equations, we can get the equation about h.

$$\frac{1}{2} L\eta\gamma(2\xi - \xi^2)h^2 + \gamma A h - Q_u A = 0 \quad (7)$$

Transform the formula to get a new formula：

$$h = \frac{-\gamma A \pm \sqrt{\gamma^2 A^2 + 2L\eta\gamma(2\xi - \xi^2)Q_u A}}{L\eta\gamma(2\xi - \xi^2)} \quad (8)$$

For the effective height ratio ξ, the ratio of pipe piles in sandy soil is between 0.69 and 0.78. The value of η is between 0.15 and 0.23.Q_u can be calculated according to Terzaghi bearing capacity formula or other empirical formulas. Measure the inner diameter of the pipe pile in advance, and sample the soil on site in advance to obtain relevant data about the soil below. Therefore, we calculated the approximate value of the plug height of the soil in the pipe pile at different pile driving depths to guide the construction of the project.

4. Standard

Internationally, the degree of soil occlusion is usually measured by IFR and PLR values. Both can reflect the degree of occlusion of open pipe piles. Under normal circumstances, the IFR value and PLR value are between 1.0 and 0 .The IFR value can see the change trend of the soil plug part, and the PLR value can be more intuitive to see the height change of the soil plug part. When the IFR value is equal to 0, it means that the soil in the pile was completely occluded state. As the pile driving progresses, the surrounding soil will no longer flow into the pipe pile, and the soil plug will not continue to grow. When the IFR value is equal to 1, it means that the soil in the pile is completely inoccluded state, the soil pours into the pipe pile freely to form a soil plug of corresponding height. The depth of the pile driving is equal to the height of the pipe pile soil plug formed by the soil in the pile, and the soil plug part no longer grows. When the value of IFR is between 0 and 1.0, it means that the soil in the pile is in a partially occluded state. The soil can be poured into the pile, but the soil will be restricted during this process, and the degree of occlusion is between the completely occluded state and the incompletely occluded state. When the PLR value is equal to 0, it means that there is no soil plugging in the pipe pile. When the value of PLR is equal to 1, it means that the pipe pile is filled with soil. In special cases, the value of IFR and PLR may be less than 0. When the value of IFR or PLR is less than 0, the height of the soil plug in the pipe pile is negative at this time. The soil in the pipe pile does not have a plugging effect, but a soil squeezing effect. The soil around the pipe pile did not enter the pipe pile to form an occlusion, but the pile driving caused the soil to gush out. This phenomenon is just the opposite of the soil plugging effect. The soil squeezing phenomenon often exists in closed pipe piles, but generally does not happen to open pipe piles.

$$IFR = \frac{\Delta \mathrm{h}}{\Delta \mathrm{H}} \times 100\%$$

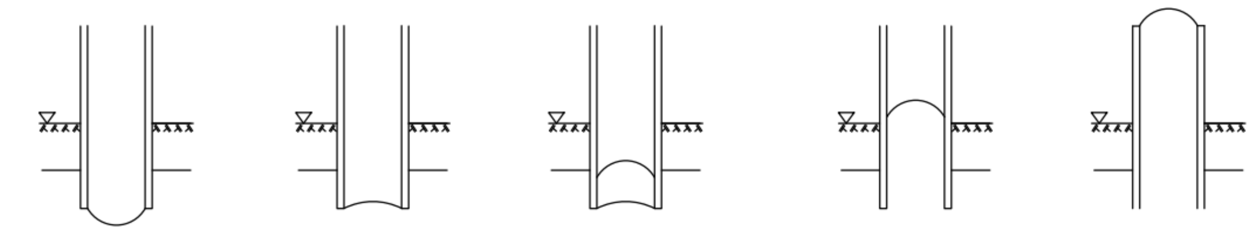
$$PLR = \frac{\mathrm{h}}{\mathrm{H}} \times 100\%$$

H------the driving depth of the pipe pile at a certain moment.

h------the height of the soil plug in the pile at a certain time.

ΔH------the increment of the pile driving depth of the pipe pile at a certain time.

Δh------the increment of the height of the soil plug of the pipe pile at a certain time.



Different IFR values

5. Calculation Result Analysis

To verify the accuracy of the calculation method in this article, the experiments in the literature are cited [7]. Calculate the soil plug height of the open pipe pile during the pile driving process. And draw the result into a line graph with IFR value and PLR value. There are two test sites in Xiasha and Xiaoshan for PHC pipe pile driving tests. The main purpose is to study the experimental study of soil plug pile height. In this test, the soil plug height in the pipe pile is measured every time the pile sinks about 1.8m, so as to study the dynamic relationship between the growth rate of soil plug and the pile driving depth.

5.1 Xiasha test sites

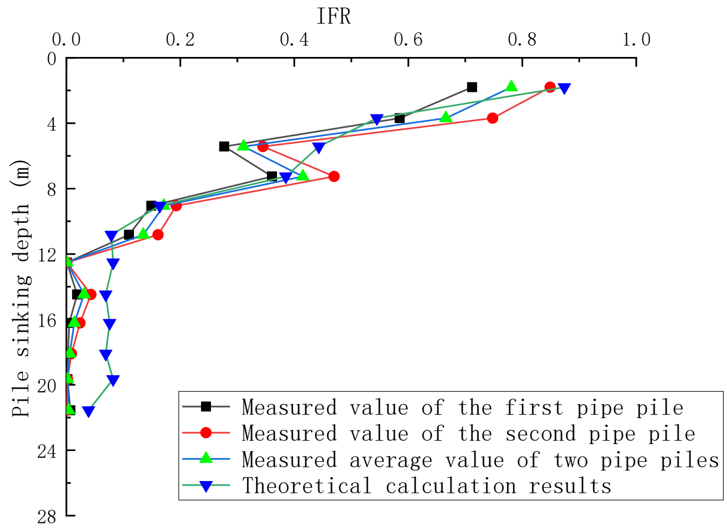
Physical and mechanical indexes of Xiasha test site

Soil layer	Soil thickness/m	Water content w/%	Density/(kN/m^3)	Void ratio e	Internal friction angle Φ/ (°)	Cohesion c/kPa	Compression modulus E_S/MPa
1	3.2	29.1	18.50	0.882	29.5	16.0	16.0
2	15.8	26.9	18.81	0.820	30.2	12.2	12.0
3	6.0	29.6	18.60	0.887	29.3	11.5	9.4
4	12.5	31.7	18.10	0.977	16.9	16.9	8.7

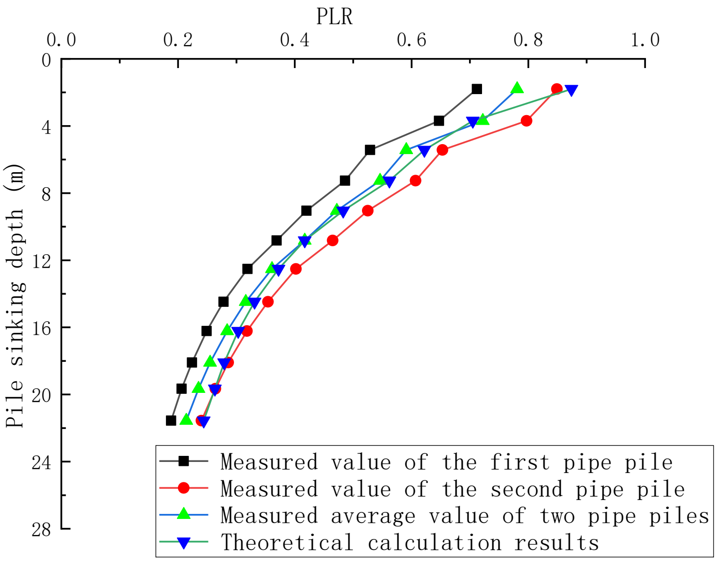
The soil layer distribution of Xiasha site is mainly composed of silt soil. The soil layer distribution and physical indicators are shown in the table. The pipe pile adopts PHC-500 (110) prestressed concrete pipe pile. The pile length is 22m, and the pile is driven by static pressure construction.

Calculation results of soil plug height in Xiasha test site

Pile driving depth	Measured value of the first pipe pile	Measured value of the second pipe pile	Measured average value of two pipe piles	Theoretical calculation results
1.802	1.283	1.530	1.406	1.574
3.695	2.390	2.945	2.668	2.606
5.424	2.869	3.541	3.205	3.373
7.261	3.531	4.405	3.968	4.080
9.048	3.797	4.749	4.273	4.373
10.825	3.993	5.035	4.514	4.514
12.518	3.994	5.037	4.515	4.653
14.476	4.031	5.121	4.576	4.788
16.219	4.039	5.163	4.601	4.920
18.097	4.045	5.180	4.613	5.051
19.655	4.048	5.183	4.615	5.178
21.562	4.061	5.185	4.623	5.253



The IFR value of PHC-500 test results and calculated results at Xiasha site



The PLR value of PHC-500 test results and calculated results at Xiasha site

For the entire test, the height of the soil plug in the first pipe pile and the second pipe pile is the actual measured value on site. It can be seen from the figure that although the stratum structure is the same, the pipe piles are the same, and other conditional variables such as loading conditions are the same, the height of the soil plug generated in the two pipe piles is different, indicating that soil plugging is a very complicated process. There are many factors that affect the soil plug. However, the IFR value of the two pipe piles is not much different from the PLR value. Through the comparison of the two pipe piles, the law of the change of the height of the soil plug can be found. The average value of the actual measured soil plug height of the two pipe piles is taken as the actual measured value of the field test. Compared with the theoretical calculation results, it is found that the PLR value fits well. The trend and interval of the theoretical calculation curve are between the actual measured values on site, indicating that the calculated total soil plug height is not much different from the measured soil plug height on site. The IFR value is basically between the actual measured values on site. It shows that the calculation method of the height of the soil plug has certain feasibility, and the method of theoretical calculation can be used for reference. It has certain guiding significance when it is necessary to determine the height of the soil plug during the pile driving process. Judging from the test results of the Xiasha site, the calculation process still has room for improvement. First of all, it can be seen from the IFR value that there is a sudden change in the IFR value at about 5.424m.According to the above normal pile driving trend, the IFR value of pipe piles will gradually decrease and will not increase suddenly. In the process of pile driving, as the pile driving depth increases, the soil in the pipe pile tends to become completely blocked, and the soil entering the pipe pile gradually decreases. The theoretical calculation result conforms to this rule, but in actual engineering, the IFR value becomes slightly larger. As the pile driving depth increases, the IFR value of the pipe pile tested in the field at the pile driving depth of 12.518m is 0.The soil in the pile becomes completely occluded in the pipe pile. At this time, the gravity of the soil, the bearing capacity of the foundation and the frictional resistance of the pile side begin to form a stable state, and the soil basically no longer flows into the pipe pile. Secondly, the calculation of the bearing capacity of the foundation tends to be conservative, which makes the calculated height of the pipe pile soil plug higher. After the pile driving depth of 14.476m, the pipe piles on site have been driven to a completely occluded state, but the calculation result has not reached a completely occluded state, and is still in a partially occluded state. According to the calculation of the equation, although it is small, the soil will still enter the pipe pile. This mainly involves the calculation of the pile side friction side, by a simple multiplication coefficient flawed, further improvement is required.

5.2 Xiaoshan test sites

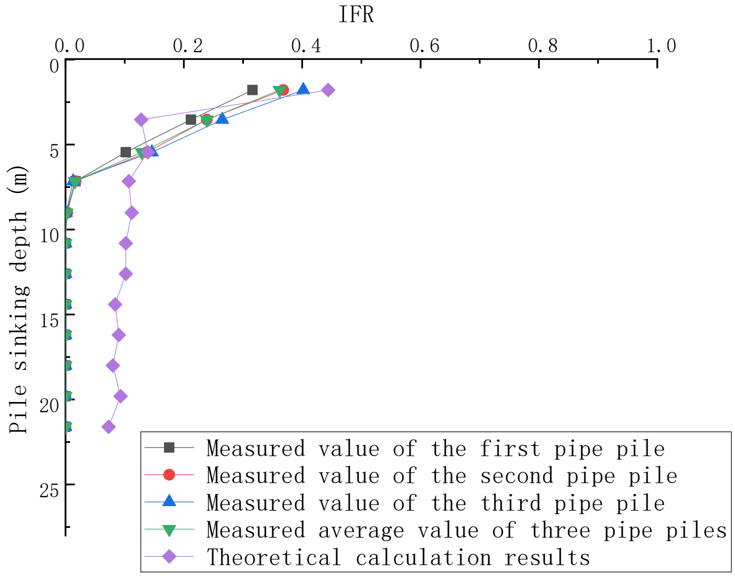
Physical and mechanical indexes of xiaoshan test site

Soil layer	Soil thickness /m	Water content w/%	Density /(kN/m^3)	Void ratio e	Internal friction angle Φ/(°)	Cohesion c/kPa	Compression modulus E_S/MPa
1	1.3	32.2	18.29	0.965	15.4	18.9	4.8
2	1.2	32.4	18.47	0.943	26.1	10.7	9.0
3	0.5	47.3	17.25	1.341	12.1	16.2	2.1
4	0.7	32.0	18.48	0.937	27.4	10.3	8.6
5	15.0	46.4	17.29	1.327	11.8	15.7	2.0
6	4.8	38.2	17.71	1.134	13.6	16.9	2.5
7	0.9	30.5	18.51	0.918	15.9	21.8	5.4

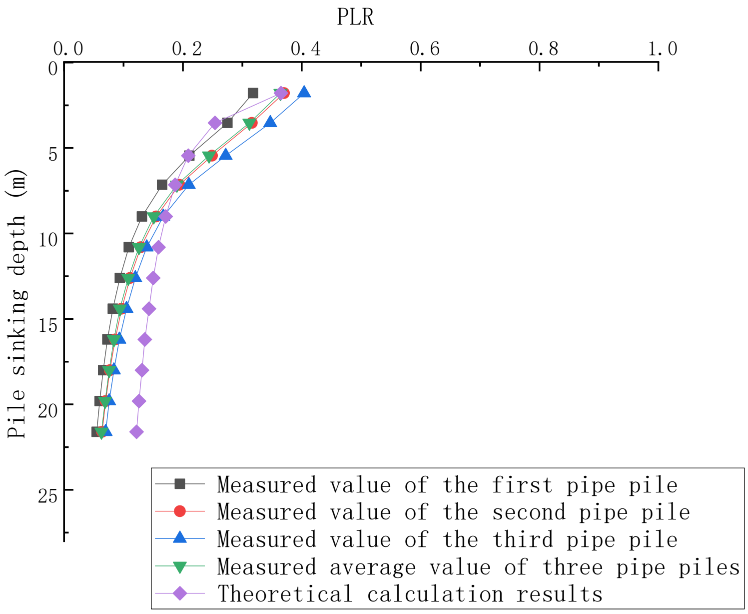
The soil layer distribution of Xiaoshan site is the interactive soil formed by silty soft soil. The soil layer distribution and physical indicators are shown in the table.The pipe piles adopt PHC-400 (60) and PHC-500 (65) two types of prestressed concrete pipe piles, 3 each, the pile length is 26m, and the static pressure construction method is adopted for pile driving.

Calculation Results of PHC-400 Soil Plug Height in Xiaoshan Test Site

Pile driving depth	Measured value of the first pipe pile	Measured value of the second pipe pile	Measured value of the third pipe pile	Measured average value of three pipe piles	Theoretical calculation results
1.792	0.507	0.664	0.724	0.653	0.801
3.536	0.971	1.117	1.227	1.105	1.030
5.448	1.148	1.356	1.479	1.328	1.259
7.153	1.179	1.387	1.504	1.357	1.448
9.005	1.181	1.393	1.507	1.360	1.640
10.805	1.181	1.393	1.507	1.360	1.674
12.605	1.181	1.393	1.507	1.360	1.708
14.405	1.181	1.393	1.507	1.360	1.741
16.605	1.181	1.393	1.507	1.360	1.774
18.005	1.181	1.393	1.507	1.360	1.806
19.805	1.181	1.393	1.507	1.360	1.838
21.605	1.181	1.393	1.507	1.360	1.870



The IFR value of PHC-400 test results and calculated results at Xiaoshan site



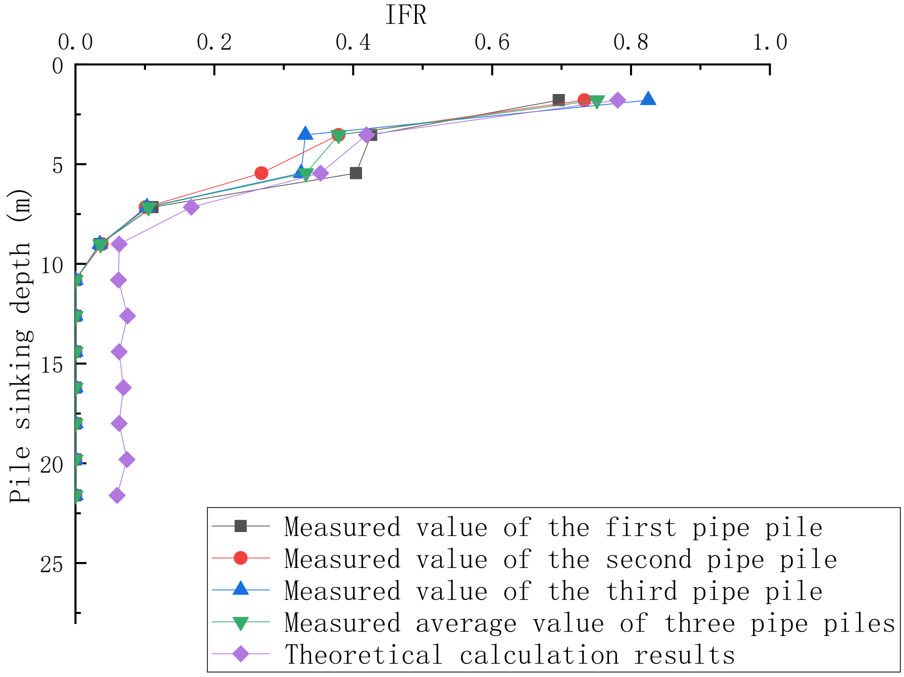
The PLR value of PHC-400 test results and calculated results at Xiaoshan site

Judging from the test results of Xiaoshan PHC-400, the IFR values and PLR values of the three field test pipe piles are different, which further illustrates that soil plugging is a complicated process.From the analysis of the PLR value, the theoretical calculation result is greater than the actual measurement result, and the calculated PLR value is relatively close to the actual PLR value measured on site, and the fit is better.However, the FLR value obtained from the calculation result did not become 0 at the pile driving depth of 9.005m, but continued to increase at a rate of almost 0.1.The main reason is that the soil structure of the Xiaoshan production area is silty soil and the geology is relatively soft. The theoretically calculated foundation bearing capacity is greater than the on-site foundation bearing capacity.The soil in the pipe pile becomes completely occluded at the pile driving depth of 9.005m, and the height of the soil plug will not change during the subsequent pile driving process.Compared with the IFR value of

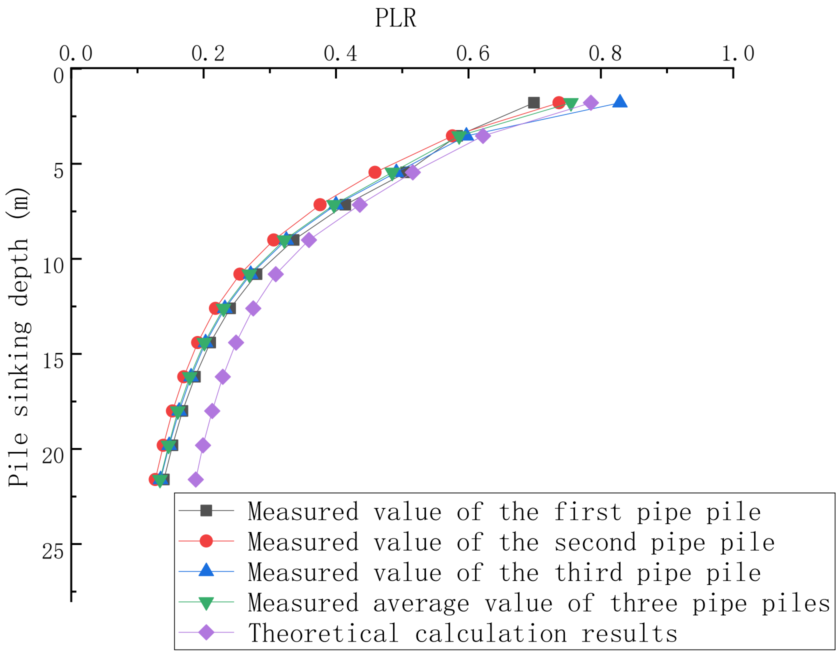
PHC-500 on the same site, the fitting degree of PHC-400 is a little lower, indicating that the calculation of the height of soil plug of PHC-400 is not ideal for the calculation of soil plug height of PHC-500.If the pipe diameter is too small, it will affect the convergence of the IFR value and the PLR value. It may be because the pipe piles with small diameters have greater radial pressure in the soil after they are squeezed into the soil, making the ratio of horizontal and vertical stresses μ should be bigger. The increase of μ will make the height of the soil plug smaller and it will be more convergence. Therefore, the IFR value of the Xiasha site is more convergent than the IFR value of the Xiaoshan site. From the results of the PLR value, the theoretical calculation results basically fit the field test results.

Calculation Results of PHC-500 Soil Plug Height in Xiaoshan Test Site

Pile driving depth	Measured value of the first pipe pile	Measured value of the second pipe pile	Measured value of the third pipe pile	Measured average value of three pipe piles	Theoretical calculation results
1.792	1.254	1.320	1.486	1.353	1.408
3.536	2.060	2.038	2.112	2.070	2.201
5.448	2.759	2.501	2.674	2.645	2.811
7.153	2.962	2.687	2.864	2.838	3.117
9.005	3.025	2.754	2.927	2.902	3.230
10.805	3.025	2.754	2.927	2.902	3.340
12.605	3.025	2.754	2.927	2.902	3.467
14.405	3.025	2.754	2.927	2.902	3.590
16.605	3.025	2.754	2.927	2.902	3.711
18.005	3.025	2.754	2.927	2.902	3.830
19.805	3.025	2.754	2.927	2.902	3.946
21.605	3.025	2.754	2.927	2.902	4.059



The IFR value of PHC-500 test results and calculated results at Xiaoshan site



The PLR value of PHC-500 test results and calculated results at Xiaoshan site

Compared with the PHC-400 pipe pile under the same geological conditions, the calculated IFR value of PHC-500 is more in line with the test results. The test pipe pile becomes completely occluded at the the pile driving depth of 10.805m. As the pile driving progresses, soil no longer flows into the pipe pile. The final IFR value of the calculated result converges to less than 0.1.The IFR value of the Xiaoshan site does not converge to the IFR value of the Xiasha site. The main reason is that the distribution of the soil layers of the Xiasha site is dominated by silt soil, and the physical properties of the soil layers, such as natural moisture content, internal friction angle, cohesion, and void ratio, are relatively close. However, the Xiaoshan site has obvious stratification, and the soil structure alternates with several layers of silty soil.

6. Conclusion

1. To study the soil plugging effect of pipe piles is basically to study the degree of occlusion of the soil in the pile. A lot of research data show that after the pipe pile is driven to a certain height, it is basically in a completely closed state, and the soil in the pile basically no longer enters the pipe pile.1. Exploring the state where the IFR value is 0 is to study when the soil in the pile will be in a completely occluded state.

2. Theoretical calculation of the height of soil plug has a certain bias against the smaller diameter opening pile. The main reason is the side friction resistance of the small diameter pipe pile. It may be because after the small-diameter pipe pile enters the soil, the radial pressure of the soil inside the pipe pile is greater, so that the ratio of horizontal to vertical stress μ should be greater. The increase of μ will make the height of the soil plug smaller, and it will be more convergent.

3. Theoretical calculations and field test results further illustrate the influx pile of soil is not flat cylinder, but a soil arch structure is similar. There is no sudden change in the size of IFR where the physical properties of the formation change.

4. There is still a lot of room to improve the

experimental and theoretical calculation results. For the test, the pile driving test should be carried out at a small interval, and the height of the soil plug should be measured more carefully. The height of the pipe pile soil plug calculated by the theoretical calculation results can only be used as a reference now, and the calculation results are only instructive for the project. Regarding the determination of the coefficients, a better functional relationship needs to be established, and more experiments and more accumulation are required to obtain the func- tional relationship.

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