Research Article

Theoretical Analysis on the Vertical Bearing Characteristics of Pile Foundations Containing Sediment Defects

Binhui Ma,1,2 Kai Cai,1 Jiale Guo,1 Zhuo Li,1 Zhiyong Hu,1 Qunan Chen,1,2 and Xiaocheng Huang1,2

1School of Civil Engineering, Hunan University of Science and Technology, Xiangtan 411201, China
2Hunan Provincial Key Laboratory of Geotechnical Engineering for Stability Control and Health Monitoring, Hunan University of Science and Technology, Xiangtan 411201, China

Correspondence should be addressed to Binhui Ma; mbh@hnust.edu.cn

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Aiming at the situation that the bottom of the pile foundation contains sediment defects, the theoretical analysis of the vertical bearing characteristics of the pile foundation is carried out. Based on the load transfer mechanism of the pile-soil system and based on the load transfer function of the elastoplasticity of the soil on the side of the pile and the weakening of the trifold line of the soil at the end of the pile, a load transfer calculation model for bored cast-in-place piles with slag defects under different conditions was established. The corresponding analytical formulas are deduced, and the accuracy and reliability of load transfer derivation are verified in combination with calculation examples, which are suitable for indoor and field tests. The influence coefficient of sedimentary defect in single pile is defined, and the parameters are analyzed. The law about the influence coefficient of length-diameter ratio, the thickness of sedimentary defect, and the modulus of elasticity of sedimentary defect in single pile are obtained: With the increase of the ratio of length and diameter, the defect coefficient of single piles gradually increases and tends to ease, and the bearing effect of pile foundations is more convergent. As the thickness of the sediment increases, the influence factor of the single pile defect gradually decreases, and the influence factor of the bearing capacity of pile foundation becomes more discrete. With the increase of the elastic modulus of sediment, the influence factor of single pile defect gradually increases, and the ultimate bearing capacity loss decreases. The vertical bearing characteristics of the pile foundation are evaluated in this way, which provides an important reference for further analysis of the bearing characteristics of pile foundations with slag defects.

1. Introduction

Pile foundation is an economical, practical, safe and effective, stable, and reliable foundation form, with good geological and topographic adaptability, so it is widely used in civil engineering [1], and some scholars have also carried out related theoretical research [2–5]. In actual engineering, due to various factors, pile foundations with different degrees of defects account for a large proportion. If they are not handled properly, it will seriously affect the performance of the superstructure and cause great safety hazards, endangering lives and property. At present, domestic and foreign scholars are still in the preliminary exploration stage for the research of defective pile foundations. The domestic scientific research team led by Professor Wang of Tianjin University [6] conducted field model tests on the basis of Poulos’ research. Through the use of finite element numerical simulation, the bearing behaviors of single piles with defects were analyzed. The corresponding load-bearing laws of single piles with defects were obtained [7], and the infinite element program was developed to simulate the vertical load-bearing behavior of defective piles such as sediment, broken piles, diameter-expanding pile, and shrinking-diameter piles in homogeneous soil [8, 9], compared the vertical bearing behavior of normal piles with that of normal piles, and obtained different understandings of the laws, which provides theoretical guidance for subsequent research on defective piles. Xu
et al. [10] conducted laboratory tests and numerical simulations on bored piles with loose deposits and excavation debris, and the axial load-settlement behavior of bored piles with debris is evaluated. Lin et al. [11] established a finite element numerical model of bored piles with pile-end sediments, using the thickness of pile-end sediments and the modulus of sediments as variables, and studied and analyzed the law of the bearing characteristics of bored piles affected by the sediments.

The above studies have not yet formed a complete and targeted theoretical analysis system, and there are relatively few studies on the bearing behavior of pile foundations with sediment defects and lack of theoretical support. During pile formation, the poured concrete and pile foundation sediments are easy to form a certain strength of sediment mixture. In the process of pile foundation inspection, the identification and treatment of pile foundations containing sediment defects can usually arouse the attention of engineers [12]. However, in the quantitative analysis of the bearing performance of defective pile foundations, it is easy to be overlooked by people. Therefore, most of them lack standard and reasonable theoretical basis and only use early experience for treatment and prevention. Therefore, it is of great significance to study the bearing properties of pile foundations with slag defects and the influence on the superstructure to propose a comprehensive and practical analysis method for the bearing characteristics of piles with slag defects.

2. Load Transfer Analysis

Seed and Reese [13] first proposed the method of load transfer analysis in 1955. Because of its clear logic, convenient formula derivation, and convenient operation calculation, it has been vigorously promoted in related engineering applications. In the mechanical analysis of the pile-soil system structure, only the load transfer function of the pile side and pile-end soil is determined, and then, the load-settlement relationship of a single pile can be calculated by mechanical and mathematical physical methods. At the same time, it can also calculate the distribution of the axial force of the pile and the settlement and displacement of the pile along the embedded depth, which can be verified by repeated static load simulation tests. The influence relationship between the parameters in the pile-soil system can be very intuitively displayed in the derivation process of the load transfer analysis method. However, the load transfer analysis method ignores the continuity of the soil and is only suitable for the analysis of a homogeneous and single pile-soil system. The transfer functions of pile-soil systems that are currently widely used are as follows: hyperbolic function model, ideal elastoplastic model, and threefold line model.

2.1. Load Transfer Model of Pile-Side Soil. The experimental research by Chen et al. [14] put forward that the double broken line model is more suitable for the performance of the shaft friction of the single pile bearing pile. Through the actual measurement data of the pile shaft friction of the partial static load test, the pile settlement is analyzed, and it is pointed out that the soil on the side of the pile will soften in some areas. However, overall, the trend of the pile shaft friction is more appropriate. Ideal elastoplastic model can be fitted more accurately. Therefore, in the analysis of the pile-soil system in this paper, the ideal elastoplastic double-line model of the pile-side soil is established as the pile-side transfer function, as shown in Figure 1. Use the following expression to describe:

\[
\begin{align*}
\tau_s &= \lambda_1 S, & S \leq S_u, \\
\tau_s &= \lambda_1 S_u + \lambda_2 (S - S_u), & S \geq S_u.
\end{align*}
\]

In the formula, \(\tau_s\) is the pile shaft friction resistance; \(S\) is the displacement of the soil node adjacent to the pile itself; \(\lambda_1\) and \(\lambda_2\) are the coefficients corresponding to the shear strength of the soil in the elastic and plastic stages, respectively; \(S_u\) is the displacement corresponding to the boundary point of the elastic and plastic phases.

2.2. Load Transfer Model of Pile-End Soil. A large number of literature studies have pointed out through experimental demonstration [15, 16] that the common pile-end load transfer function models are as follows: end resistance elastoplastic model and end resistance hardening model. However, relatively few end resistance threefold line weakening models, as shown in Figure 2, are more in line with the actual bearing capacity of pile foundations with sediment defects, because in the initial stage when the pile top load is applied, the area at the bottom of the pile foundation containing the sediment layer will be elastically deformed. With the gradual increase of the load on the pile top, the area of the lower part of the pile with sediment will appear compression failure, which will lead to a process of piercing and destruction of the pile. If you continue to load, the sediment layer at the bottom of the pile has only residual strength.

When Z. Zhang and Q. Zhang [17] carried out destructive tests on a single pile on site, according to the actual measurement data, they found that the effective curve of pile tip resistance-settlement conformed to the characteristics of weakening. With the gradual loading of the pile top load, the bearing layer after the piercing failure process occurs, and the pile tip force is fully exerted until it falls to the residual strength, which conforms to the weakened form of...
weakening and plastic stages of the pile end. Plastic phase (Pa/m); studies on the bearing performance of bored piles in different geological environments and summarized some laws by centrifugal test studies on the model piles and found the same rule through the analysis of the actual test data: as the soil depth increases, if the pile shaft friction resistance reaches the limit state, the pile itself needs the relative displacement of which will gradually increase to meet. Therefore, when analyzing the pile-soil system with the load transfer method, in order to ensure the accuracy of the analytical deduction process, the corresponding assumptions are first proposed:

1. The geological environment of the pile foundation is a homogeneous and single soil in all directions. In a heterogeneous single geological layer, a weighted average method will be used to process the foundation soil.
2. Each section of the pile itself is homogeneous and single in all directions, ignores the role of the steel frame, and continues to be in a linear elastic state during the bearing analysis process.
3. The slope of the curve corresponding to the load transfer function of the pile-side soil remains unchanged along the depth of the pile, that is, \( \lambda_1 \) remains unchanged along the depth, \( \lambda_2 = 0 \).
4. The low-strength section formed by the mixture of the sediment at the bottom of the pile foundation and the first poured concrete is regarded as the pile section with sediment defects.
5. Because the foundation soil itself has consolidation stress and other interference factors, it will cause the strength of the soil to increase to varying degrees with depth. Therefore, in the derivation process involved in this article, it is assumed that the ultimate friction of the soil at the side of the pile follows the pile. The extension of the foundation depth into the soil is presented in the form of linear increase:

   \[ \tau_u = \tau_0 + f\lambda z \]  

   \( \tau_u \) is the ultimate lateral friction resistance of the pile-side soil at a certain depth (Pa), and the distribution of \( \tau_u \) along the depth is shown in Figure 3; \( f \) is the strength coefficient of the soil along the pile side (Pa/m).

   According to the assumptions provided above, the relationship between the critical displacement at different depths along the pile itself, the ultimate friction resistance of the pile side, and the elastic modulus under shear can be obtained.

   \[ S_u(z) = \frac{\tau_0 + f\lambda z}{\lambda_1}, \]

   \[ S_u(0) = \frac{\tau_0}{\lambda_1}, \]

   \[ S_u(l) = \frac{\tau_0 + f\lambda l}{\lambda_1}. \]
4. Load Transfer Analysis of Single Pile with Sediment Defect

4.1. Basic Equations. As shown in Figure 4, the total design length of the entire pile is \( l \). The thickness of soil layer between the top of the pile and the top of the sediment defect section is \( l_2 \), which is also the normal length of the upper pile. The thickness of the soil layer in the section containing sediment defect is \( l_2 \), which is also the length of the section containing sediment defect. \( E_1 \) and \( A_1 \) represent the elastic modulus and cross-sectional area of normal pile section, and \( E_2 \) and \( A_2 \) represent the elastic modulus and cross-sectional area of the pile with sediment defects. Use \( P_0 \) and \( S_0 \) to denote the load and settlement of the pile top of the pile with a sediment defect \( P_2 \) and \( S_2 \) to denote the load and settlement of the pile top of the pile with a sediment defect.

The basic differential equation of load transfer is obtained from the force analysis of the microsegment element [1], when the load on the top of the pile is small, the soil on the side of the pile is completely in an elastic state, and the balance differential equation of the upper normal pile section is as follows:

\[
E_1 A_1 \frac{d^2 S}{dz^2} - \lambda_1 SU = 0. \tag{5}
\]

Continuous conditions of force and displacement of upper normal pile section are as follows:

\[
\begin{align*}
E_1 A_1 \frac{d^2 S}{dz^2} |_{z=l_1} &= -P_2, \\
S |_{z=l_1} &= S_2. \tag{6}
\end{align*}
\]

Equilibrium differential equation of pile section with sediment defect is as follows:

\[
E_2 A_2 \frac{d^2 S}{dz^2} - \lambda_1 SU = 0. \tag{7}
\]

Continuous conditions of force and displacement of piles with sediment defects are as follows:

\[
\begin{align*}
E_2 A_2 \frac{d^2 S}{dz^2} |_{z=l_1} &= -P_2, \\
S |_{z=l_1} &= S_2. \tag{8}
\end{align*}
\]

\[
b_1 = \sqrt{\frac{\lambda_1 U}{E_1 A_1}}, \quad b_2 = \sqrt{\frac{\lambda_1 U}{E_2 A_2}}, \quad E_1 > E_2, \quad \text{and} \quad A_1 = A_2 = \pi r^2.\]

Combining the abovementioned continuous conditional solution, the displacement equation of any section of the entire pile section (including the normal pile section and the pile section with sediment defects) can be obtained.

\[
\begin{align*}
S(z) &= \frac{b_1 S_2 - P_2/E_1 A_1}{2b_1} e^{b_1(z-l_1)} + \frac{b_1 S_2 + P_2/E_1 A_1}{2b_1} e^{-b_1(z-l_1)} \quad 0 \leq z \leq l_1, \\
S(z) &= \frac{b_2 S_2 - P_2/E_2 A_2}{2b_2} e^{b_2(z-l_2)} + \frac{b_2 S_2 + P_2/E_2 A_2}{2b_2} e^{-b_2(z-l_2)} \quad 0 \leq z \leq l. \tag{9}
\end{align*}
\]
4.2. The Process of Deriving Formulas. The model used in the analysis of a single pile with sediment defects and the soil at the side of the pile is an ideal elastoplastic model. According to the different stress states of the pile side and pile tip soil, the interaction mode of the pile-soil system is determined, and the hyperbolic function is used to derive it. There are six related expressions for the pile top load settlement.

4.2.1. Case 1: The Soil Is Elastic. Assuming that the load on the top of the pile causes the settlement of the top of the pile to reach $S_{11}$ and $S_{22}$, the settlement at the end of the corresponding pile is exactly the boundary displacement settlements $S_{bu1}$ and $S_{bu2}$ between the elastic phase, the weakening phase, and the plastic phase.

(1) When $0 \leq S_{0} \leq S_{11}$, the pile-side soil and the pile-end soil are both elastic

$$P_{2} = K_{21} \cdot S_{2} = E_{2}A_{2}b_{2}E_{2}A_{2}b_{2} \tanh (b_{1}l_{2}) + k_{1} \tanh (b_{1}l_{2}) \cdot S_{2}$$

(10)

where $K_{21} = E_{2}A_{2}b_{2}E_{2}A_{2}b_{2} tanh (b_{1}l_{2}) + k_{1}E_{2}A_{2}b_{2} + k_{1} tanh (b_{1}l_{2})$ is the rigidity of the pile top of the pile with sediment defects.

When $Z = 0$, the expressions of the pile top load $P_{0}$ and settlement $S_{0}$ of the whole pile can be obtained from the boundary conditions:

$$P_{0} = K_{15} \cdot S_{0} = E_{1}A_{1}b_{1}E_{1}A_{1}b_{1} \tanh (b_{1}l_{1}) + K_{21} \tanh (b_{1}l_{1}) \cdot S_{0},$$

(11)

where $K_{15} = E_{1}A_{1}b_{1}E_{1}A_{1}b_{1} tanh (b_{1}l_{1}) + K_{21}/E_{1}A_{1}b_{1} + K_{21} tanh (b_{1}l_{1})$ is the rigidity of the pile top of the pile with sediment defects. It is easy to see that it is a constant at this time, so at this stage, the curves of pile top load $P_{0}$ and settlement $S_{0}$ are straight lines.

(2) When $S_{11} \leq S_{0} \leq S_{12}$, the pile-side soil is in an elastic state, and the pile-end soil is in a weakened state

$$P_{2} = E_{2}A_{2}b_{2}E_{2}A_{2}b_{2} \tanh (b_{1}l_{2}) + k_{2} \tanh (b_{1}l_{2}) \cdot S_{2}$$

$$+ \frac{S_{bu1}(k_{1} - k_{2})E_{2}A_{2}b_{2}}{E_{2}A_{2}b_{2} \cosh (b_{1}l_{2}) + k_{2} \sinh (b_{1}l_{2})} \cdot D_{2}$$

(12)

Let $K_{22} = E_{2}A_{2}b_{2}E_{2}A_{2}b_{2} tanh (b_{1}l_{2}) + k_{2}E_{2}A_{2}b_{2} + k_{2} tanh (b_{1}l_{2})$ and $D = S_{bu1}(k_{1} - k_{2})E_{2}A_{2}b_{2} \cosh (b_{1}l_{2}) + k_{2} \sinh (b_{1}l_{2})$. Then, there is the following:

$$P_{2} = K_{22} \cdot S_{2} + D.$$  

(13)

When $Z = 0$, the same principle can be used to obtain the expressions of the pile top load $P_{0}$ and settlement $S_{0}$:

$$P_{0} = E_{1}A_{1}b_{1}E_{1}A_{1}b_{1} \tanh (b_{1}l_{1}) + K_{22} \tanh (b_{1}l_{1}) \cdot S_{0}$$

$$- \frac{E_{1}A_{1}b_{1} \sinh (b_{1}l_{1}) + \cosh (b_{1}l_{1})K_{22}}{\cosh (b_{1}l_{1})E_{1}A_{1}b_{1} + K_{22}} - \cosh (b_{1}l_{1}) \cdot D_{1}.$$  

(14)

Let $K_{16} = E_{1}A_{1}b_{1}E_{1}A_{1}b_{1} tanh (b_{1}l_{1}) + K_{22}/E_{1}A_{1}b_{1} + K_{22} tanh (b_{1}l_{1})$ be the rigidity of the pile top of the pile with sediment defects in the weakening stage. At this time, $K_{16}$ is a constant, and the curve about the pile top load $P_{0}$ and settlement $S_{0}$ is a straight line.

(3) When $S_{12} \leq S_{0} \leq S_{13}$, the pile-side soil is in an elastic state, and the pile-end soil is in a plastic state

$$P_{2} = E_{2}A_{2}b_{2} \tanh (b_{1}l_{2}) \cdot S_{2} + \frac{k_{1}S_{bu1} + k_{2}(S_{bu2} - S_{bu1})}{\cosh (b_{1}l_{2})}.$$  

(15)

Let $K_{23} = E_{2}A_{2}b_{2} tanh (b_{1}l_{2})$ and $D_{1} = k_{1}S_{bu1} + k_{2}(S_{bu2} - S_{bu1})/\cosh (b_{1}l_{2})$; then, there is

$$P_{0} = E_{1}A_{1}b_{1}E_{1}A_{1}b_{1} \tanh (b_{1}l_{1}) + K_{23} \tanh (b_{1}l_{1}) \cdot S_{0}$$

$$- \frac{E_{1}A_{1}b_{1} \sinh (b_{1}l_{1}) + \cosh (b_{1}l_{1})K_{23}}{\cosh (b_{1}l_{1})E_{1}A_{1}b_{1} + K_{23}} - \cosh (b_{1}l_{1}) \cdot D_{1}.$$  

(16)

Let $K_{17} = E_{1}A_{1}b_{1}E_{1}A_{1}b_{1} tanh (b_{1}l_{1}) + K_{23}/E_{1}A_{1}b_{1} + K_{23} tanh (b_{1}l_{1})$ be the rigidity of the whole pile top of the pile with sediment defects in the plastic stage. At this time, $K_{17}$ is a constant, and the curves for the pile top load $P_{0}$ and settlement $S_{0}$ are also straight lines.

4.2.2. Case 2: The Soil Is Partly Plastic. As shown in Figures 4 and 5, an assumption is made about the interface between the normal pile section and the pile section with slag defects, and this interface is the C section. Assume the interface between the elastic and plastic regions of the soil on the side of the pile. Let this interface be the D section, the depth is $z = l_{3}$, the settlement of the pile itself is $S_{D}$, and the axial force of the pile is $P_{D}$. Similarly, suppose that when the pile top settlement reaches $S_{13}$ and $S_{14}$, the corresponding pile tip settlement is just the critical settlements $S_{bu1}$ and $S_{bu2}$.

(1) When $S_{0} \leq S_{0} \leq S_{13}$, the pile-side soil above the D section of the pile is the plastic stage, below the D section is the elastic stage, and the pile-end soil is the elastic stage.
Figure 5: Load transfer of the pile-side soil in the plastic status.

(i) Section BC with sediment defect in elastic zone

\[ P_2 = K_{24} \cdot S_2 = E_2A_2b_2E_2A_2b_2 \tanh (b_1l_2) + k_3 \cdot S_2 \]

\[ K_{24} = E_2A_2b_2(E_2A_2b_2 \tanh (b_1l_2) + k_3/E_2A_2b_2 + k_1 \tanh (b_1l_2)) \] is the rigidity of the pile top of the pile with sediment defects at this stage.

(ii) DC section of normal pile in elastic zone

\[ P_D = K_D \cdot S_D = E_1A_1b_1E_1A_1b_1 \tanh [b_1(l_1 - l_3)] + K_{24} \cdot S_D \]

\[ K_{24} = E_2A_2b_2(E_2A_2b_2 \tanh (b_1l_2) + k_3/E_2A_2b_2 + k_1 \tanh (b_1l_2)) \] is the rigidity of the pile top of the pile with sediment defects at this stage.

(iii) OD section of normal pile in plastic zone

\[ P_0 = \frac{K_{D}E_1A_1}{E_1A_1 + l_3K_D} \cdot S_0 - \left[ \frac{l_3K_D}{2(E_1A_1 + l_3K_D)} - 1 \right] \cdot A_1S_0UL_3 \]

Let \( K_{18} = K_{D}E_1A_1/E_1A_1 + l_3K_D \). Because there is a variable value of \( l_3 \), in this state, the relationship between the pile top load \( P_0 \) and the settlement \( S_0 \) will appear in the form of a curve.

(2) When \( S_a \leq S_0 \leq S_{14} \), the pile-side soil above the D section of the pile is the plastic stage, below the D section is the elastic stage, and the pile-end soil is the weakening stage

(i) Section BC with sediment defect in the lower part of elastic zone

\[ P_2 = E_2A_2b_2E_2A_2b_2 \tanh (b_1l_2) + k_3 \cdot S_2 \]

\[ \frac{S_{\text{hol}}(k_1 - k_3)E_2A_2b_2}{E_2A_2b_2 \cosh (b_1l_2) + k_2 \sinh (b_1l_2)} \]

\[ = K_{25} \cdot S_2 + D \]

(ii) DC section of normal pile in elastic zone

\[ \begin{align*}
P_{D1} &= E_1A_1b_1 \sinh [b_1(l_1 - l_3)] \cdot S_2 + \cosh [b_1(l_1 - l_3)] \cdot P_2 \\
S_{D1} &= \cosh [b_1(l_1 - l_3)]S_2 + \frac{\sinh [b_1(l_1 - l_3)]}{E_1A_1b_1} \cdot P_2
\end{align*} \]

In the same way, the expression of load and displacement can be calculated:

\[ P_{D1} = E_1A_1b_1E_1A_1b_1 \tanh [b_1(l_1 - l_3)] + K_{25} \cdot S_{D1} \]

\[ - \left\{ E_1A_1b_1 \tanh [b_1(l_1 - l_3)] + K_{25} \right\} \sinh [b_1(l_1 - l_3)] \cdot D \]

\[ E_1A_1b_1 + \tanh [b_1(l_1 - l_3)]K_{25} \]

\[ + \cosh [b_1(l_1 - l_3)] \cdot D. \]

Let

\[ K_{D1} = E_1A_1b_1((E_1A_1b_1 \tanh [b_1(l_1 - l_3)] + K_{25})/(E_1A_1b_1 + \tanh [b_1(l_1 - l_3)]K_{25})) \]

(23)

and

\[ F_1 = \left\{ E_1A_1b_1 \tanh [b_1(l_1 - l_3)] + K_{25} \right\} \sinh [b_1(l_1 - l_3)] \cdot D \]

\[ //(E_1A_1b_1 + \tanh [b_1(l_1 - l_3)]K_{25}) \]

\[ - \cosh [b_1(l_1 - l_3)] \cdot D \]

(24)

Substituting \( F_1 \) into Equation (22), then

\[ P_{D1} = K_{D1} \cdot S_{D1} - F_1. \]

(25)

(iii) OD section of normal pile in plastic zone
In the same way, the expressions of load $P_0$ and displacement $S_0$ on the top of the pile on the D section load $P_{D1}$ and displacement $S_{D1}$ can be calculated:

$$
\begin{align*}
S_0 &= S_{D1} + \frac{l_3}{E_1 A_1} \cdot P_{D1} + \frac{\lambda_1 S_0 U l_0^2}{2E_1 A_1}, \\
P_0 &= P_{D1} + \lambda_1 S_0 U l_0.
\end{align*}
$$

Substituting Equation (25) into Equation (26), the curve expressions of pile top load $P_0$ and settlement $S_0$ can be obtained:

$$
P_0 = \frac{E_1 A_1 K_{D1}}{E_1 A_1 + l_3 K_{D1}} \cdot S_0 + \frac{(2l_3 F_1 - \lambda_1 S_0 U l_0^2)K_{D1}}{2(E_1 A_1 + l_3 K_{D1})} - F_1 + \lambda_1 S_0 U l_0.
$$

In the formula, $K_{19} = E_1 A_1 K_{D1}/E_1 A_1 + l_3 K_{D1}$, and there is a variable value of $l_3$ in the coefficient $K_{19}$. Therefore, the relationship between the load $P_0$ and the settlement $S_0$ of the pile top position will also appear in the form of a curve.

(3) When $S_a \leq S_{D1} \leq S_{D2} \leq S_0$, the pile-side soil above the D section of the pile is the plastic stage, below the D section is the elastic stage, and the pile-end soil is the plastic stage

(i) Section BC with sediment defect in elastic zone

$$
P_2 = E_2 A_2 b_2 \tan \left( b_2 l_2 \right) \cdot S_2 + \frac{k_1 S_{bu1} + k_2 (S_{bu2} - S_{bu1})}{\cosh \left( b_2 l_2 \right)}
$$

Let $K_{26} = E_2 A_2 b_2 \tan \left( b_2 l_2 \right)$ and $D_1 = k_1 S_{bu1} + k_2 (S_{bu2} - S_{bu1})/\cosh \left( b_2 l_2 \right)$. Then there is the following:

$$
P_2 = K_{26} \cdot S_2 + D_1.
$$

(ii) DC section of normal pile in elastic zone

In the same way, the expression of load $P_{D2}$ with respect to displacement $S_{D2}$ can be calculated:

$$
P_{D2} = \frac{E_1 A_1 b_1}{E_1 A_1 + K_{D2}} \cdot \tan \left[ b_1 (l_1 - l_0) \right] + K_{26} \cdot \frac{E_1 A_1 b_1}{E_1 A_1 + K_{D2}} \cdot \tan \left[ b_1 (l_1 - l_0) \right] \cdot S_{D2}
$$

$$
\left( \begin{array}{c}
\left\{ \frac{E_1 A_1 b_1 \sinh \left[ b_1 (l_1 - l_0) \right] \tan \left[ b_1 (l_1 - l_0) \right]}{E_1 A_1 b_1 + \tan \left[ b_1 (l_1 - l_0) \right]K_{26}} \\
+ \frac{E_1 A_1 b_1 + \tan \left[ b_1 (l_1 - l_0) \right]K_{26}}{E_1 A_1 + \tan \left[ b_1 (l_1 - l_0) \right]K_{26}} \\
- \cosh \left[ b_1 (l_1 - l_0) \right]
\end{array} \right) \cdot D_1.
\right.
$$

$$
\begin{align*}
K_{26} &= E_1 A_1 b_1 (E_1 A_1 b_1 \tan \left[ b_1 (l_1 - l_0) \right] \\
&+ K_{26})/(E_1 A_1 b_1 + K_{26} \cdot \tan h[b_1 (l_1 - l_0)])
\end{align*}
$$

and

$$
F_2 = \left\{ \left\{ \frac{E_1 A_1 b_1 \sinh \left[ b_1 (l_1 - l_3) \right] \tan \left[ b_1 (l_1 - l_3) \right]}{E_1 A_1 b_1 + \tan \left[ b_1 (l_1 - l_3) \right]K_{26}} \\
+ \frac{E_1 A_1 b_1 + \tan \left[ b_1 (l_1 - l_3) \right]K_{26}}{E_1 A_1 + \tan \left[ b_1 (l_1 - l_3) \right]K_{26}} \right) - \cosh \left[ b_1 (l_1 - l_3) \right] \right\} \cdot D_1.
$$

Substituting it into Equation (30), there is the following:

$$
P_{D2} = K_{D2} \cdot S_{D2} - F_2.
$$

(iii) OD section of normal pile in plastic zone

$$
P_0 = \frac{E_1 A_1 K_{D2}}{E_1 A_1 + l_3 K_{D2}} \cdot S_0 + \frac{(2l_3 F_2 - \lambda_1 S_0 U l_0^2)K_{D2}}{2(E_1 A_1 + l_3 K_{D2})} - F_2 + \lambda_1 S_0 U l_0.
$$

In the formula $K_{20} = E_1 A_1 K_{D2}/E_1 A_1 + l_3 K_{D2}$, there is available value of $l_3$, so in this state, the relationship between the pile top load $P_0$ and the settlement $S_0$ will appear in the form of a curve.

4.2.3. Method for Determination of the Length $l_1(l_3)$. According to the above-derived corresponding relational expressions, the length of the pile-side plastic stage $l_1(l_3)$ can be determined.

(1) When $S_b < S_a(l)$, it can be deduced by formula (4) and formula (21) to determine the following:

$$
S_c = \frac{\left( r_a + f_{l_1} \right)}{l_1} = \cosh \left[ r_a (l_1 - l_1) \right] S_b + \frac{\sinh \left[ r_a (l_1 - l_1) \right] P_b}{E_1 A_1 r_a}
$$

(2) When $S_b \geq S_a(l)$, $l_1 = l$

4.3. Defect Influence Coefficient. Defects containing sediment have a certain impact on the bearing characteristics of the pile foundation. Excessive thickness of the sediment will lead to a sharp drop in the ultimate bearing capacity of the pile foundation. Excessive displacement of the pile body is prone to piercing damage, causing uneven settlement of the upper structure and causing structural instability, seriously endangering the safety of life and property. According to the theoretical analysis of the abovementioned pile-soil system, in order to evaluate the impact of sediment defects on the bearing capacity of the pile foundation, the ratio of the ultimate bearing capacity of such defective piles to the ultimate bearing capacity of a normal single pile (or the pile top under the limit state displacement ratio) is defined as the influence coefficient of single pile defect, which provides
Table 1: Model pile state parameters.

| Stake | Pile length L/mm | Pile diameter D/mm | Elastic modulus of pile concrete/MPa | Poisson’s ratio v | Severe γ kN/m | Sediment thickness/mm |
|-------|-----------------|-------------------|--------------------------------------|-------------------|---------------|----------------------|
| P1    | 500             | 20                | 3 × 10^4                              | 0.2               | 25            | 0                    |
| P7    | 460             | 20                | 3 × 10^4                              | 0.2               | 25            | 40                   |

Table 2: Soil mechanical parameters.

| Stratigraphic lithology | Elastic modulus E MPa | γ kN/m² | Internal friction angle φ ° | Cohesion c kPa | Poisson’s ratio v | Permeability coefficient k/md⁻¹ |
|------------------------|-----------------------|--------|--------------------------|----------------|-----------------|---------------------------------|
| Surrounding soil        | 30                    | 18     | 37                       | 5              | 0.3             | 1                               |
| Sediment               | 5                     | 16     | 10                       | 2              | 0.2             | 0                               |

where ξ is the influence coefficient of single pile defect, \( P_{us} \) is the ultimate bearing capacity of single pile with sediment defect, \( P_{us}^d \) is the normal ultimate bearing capacity of single pile, \( S_{us}^d \) is the displacement of the pile top under the limit state of a single pile with a sediment defect, and \( S_{us}^s \) is the normal single pile top displacement in the ultimate state.

5. Example Study

5.1. Example 1. In order to verify the accuracy and reliability of the weakened load transfer method of pile-side soil double-fold line and pile tip soil threefold line proposed in this paper, the indoor test P1 and P7 model piles in the literature [20] are selected as examples. P1 and P7 models are known. The basic parameters of the pile and the soil around the pile are shown in Tables 1 and 2. The method in this paper is used to calculate the load-displacement curve of the pile top and compare it with the measured value in the test to verify its calculation accuracy and reliability.

To determine other parameters, through fitting and weighted average methods, the initial parameter information of the calculated model pile load-displacement curve is as follows: \( E_1 = 30 \) GPa, \( \lambda_1 = 7.02 \) kPa/mm, \( \lambda_2 = 0 \), \( \tau_u(0) = 0.7558 \) kPa, \( S_{su}(0) = 1.4 \) mm, and \( f = 1.12 \) kPa/m.

The load transfer parameters \( k_1, k_2, k_3, S_{bu1}, \) and \( S_{bu2} \) of the pile-end soil are fitted to the measured pile-end force-displacement curves according to the ideal elastoplastic double-line model and the threefold line weakening model: \( k_1 = 68.5 \) kN/mm, \( k_2 = 0 \), and \( S_{bu1} = 1.82 \) mm. In the actual measured pile tip force-displacement curve of the model pile that is weakened and fitted with a threefold line, the soil at the tip of the pile has not yet entered the plastic strength stage, so in the fitting process, it is assumed that the critical displacement point of the weakening stage and the plastic stage is 4 mm. The state can determine the load transfer parameter information of the pile-end soil: \( k_1 = 68.5 \) kN/mm, \( k_2 = -21.7 \) kN/mm, \( k_3 = 0 \), \( S_{bu1} = 1.82 \) mm, and \( S_{bu2} = 2.4 \) mm.

Combining the above parameter information and substituting the derived analytical formula for data processing, the pile top load \( P_0 \) and settlement \( S_u \) curves calculated by the indoor test P1 and P7 test piles can be obtained and compared with the measured pile top load-settlement curve for comparative analysis. It can be seen from Figure 6 that the ideal elastoplastic double-line model of the pile tip soil is calculated. When the load on the pile top is small, the calculated load-settlement curve is in good agreement with the measured curve; as the pile top load gradually increases, the displacement and settlement value of the pile top shows a larger deviation from the actual measured value and gradually increases. This phenomenon appears because the ideal elastoplastic bifold line model cannot objectively reflect the actual load transfer characteristics of the pile-end soil. The calculated load-settlement curve of the threefold line
weakening model of the pile-end soil is more consistent with the actual measured curve than the ideal elastoplastic bifold line model of the pile-end soil. Therefore, for the settlement calculation of defective piles containing sediment at the bottom of the pile, the trifold line weakened load transfer curve is more in line with the actual load transfer characteristics of the pile tip soil.

5.2. Example 2. In order to evaluate the actual stress analysis of a single pile with sediment defects, the single pile static compression test pile Z1 in the literature [21] is selected as an example. The basic parameters are shown in Tables 3 and 4. The load-displacement curve is compared with the measured value on site to verify the accuracy and reliability of its calculation.

For the determination of other parameters, the initial parameter information for calculating TS3 test pile load-displacement curve is obtained through fitting and weighted average methods as follows: \( E_1 = E_2 = 32.5 \text{GPa} \), \( \lambda_1 = 13.28 \text{kPa/mm} \), \( \lambda_2 = 0 \), \( \tau_1f(0) = 43.21 \text{kPa} \), \( S_{bu1}(0) = 3.68 \text{mm} \), and \( f = 2.79 \text{kPa/m} \). The load transfer parameters \( k_1 \), \( k_2 \), \( S_{bu1} \), and \( S_{bu2} \) of the pile-end soil are fitted to the measured pile-end force-displacement curves according to the ideal elastoplastic double-line model and the threefold line weakening model. Fitting the ideal elastoplastic double polyline is divided into two stages: elastic stage and plastic stage. The load transfer parameters of the pile tip soil in this state are obtained as follows: \( k_1 = 198.6 \text{kN/mm} \), \( k_2 = 0 \), and \( S_{bu1} = 15.25 \text{mm} \). In the actual measured pile tip force-displacement curve of the Z1 test pile using the threefold line weakening fit, the pile tip soil has not yet entered the plastic strength stage, so in the fitting process, it is assumed that the critical displacement point of the weakening stage and the plastic stage is 40 mm. This state can determine the load transfer parameter information of the pile-end soil: \( k_1 = 198.6 \text{kN/mm} \), \( k_2 = -24.8 \text{kN/mm} \), \( k_3 = 0 \), \( S_{bu1} = 15.25 \text{mm} \), and \( S_{bu2} = 40 \text{mm} \).

In the same way, combining the above parameter information and substituting the derived theoretical calculation formula for calculation and data processing, the pile top load \( P_0 \) and settlement \( S_0 \) curves calculated by the field test Z1 test pile can be obtained and compared with the actual measured pile top load-settlement curve analysis. It can be seen from Figure 7 that the load-settlement curve calculated by the threefold line weakening model of the pile tip soil for the test pile Z1 is close to the actual static load value of the single pile with sedimentation defects and the theoretical value of the normal single pile bearing theoretical value and the theoretical value of the single pile bearing defect. With the increase of the pile top load, when the pile shaft frictional resistance reaches its limit and the pile side gradually enters the plastic stage, the pile-end force performance is more obvious. The existence of sediment causes the pile top displacement to appear abrupt drop and sudden change. The load settlement of the pile is relatively gentle. The pile top load corresponding to the pile top displacement settlement of 40 mm is extracted, the theoretical value is 9256 kN, the measured value is 9715 kN, and the error is 4.72%. Combined with calculation Example 1, for the calculation of the load settlement of the defective pile with sediment at the bottom of the pile, the calculation method proposed in this
6. Parametric Analysis

In order to fully consider the impact of the pile bottom sediment on the bearing properties of the pile foundation, avoid other factors from interacting with it. Now, taking a certain engineering project in Tianjin involved in the literature [22] of the second chapter of calculation example as the background, assuming that the soil around the pile is a single homogeneous soil, extract the test pile Z1 and its geological conditions parameters and carry out various data. The weighted average processing pseudo-coefficients are combined, combined with the impact of single pile defects to analyze the bearing behavior of the pile foundation, and the parameters are analyzed from the aspects of length-diameter ratio \(\frac{L}{d}\), sediment thickness \(t_2\), and sediment elastic modulus \(E_2\).

6.1. Length-Diameter Ratio. The analysis of the influence coefficient of the length-diameter ratio on the defects of a single pile is to consider the two parameters of pile diameter and pile length in turn. When the pile length is 40 m, the pile diameters are 0.5 m, 0.8 m, 1.0 m, 1.5 m, and 2.0 m, and the ratio of length to diameter \(\frac{L}{d}\) is as follows: 0.5 m, 0.8 m, 1.0 m, 1.5 m, and 2.0 m, and the aspect ratio \(\frac{L}{d}\) is 80, 50, 40, 27, and 20, respectively. The load \(P_0\) and settlement \(S_0\) curves of the pile top are shown in Figure 8. The gradient change of the length-diameter ratio \(\frac{L}{d}\) caused by the pile diameter will directly affect the effect of the pile bottom sediment on the pile top load \(P_0\) and settlement \(S_0\). The thickness of the sediment remains the same. With the increase of the pile diameter and the decrease of the length-diameter ratio, the load \(P_0\) and settlement \(S_0\) curves of the normal single pile and the single pile with sediment defects tend to be discrete, indicating that as the pile diameter increases, the length-diameter ratio becomes smaller. The single pile load \(P_0\) and settlement \(S_0\) are less and less affected by the pile bottom sedimentation defects. Compared with normal single pile, the ultimate bearing capacity loss is smaller.

According to the load \(P_0\) and settlement \(S_0\) curves caused by the change of the length-diameter ratio under different pile diameter conditions, the pile top load corresponding to the pile top settlement of 40 mm is extracted as the ultimate bearing capacity of the single pile in this state [22], and the defect influence coefficient of single pile containing sediment defects under each pile diameter can be calculated with the method defined in this paper. As shown in Figure 9, it can be seen that with the increase of pile diameter, the ratio of length to diameter gradually decreases, and the influence coefficient of single pile defects gradually decreases. The influence coefficient of single pile defects can be used to evaluate the bearing state of single piles containing sediment defects. Combined with the analysis of load \(P_0\) and settlement \(S_0\) curves under different pile diameters, the larger the pile diameter, the smaller the length-diameter ratio of the pile. The load-settlement curve of a single pile with or without sediment gradually becomes discrete, and the ultimate bearing capacity loss is more obvious.

When the pile diameter is set at 0.8 m, the pile lengths are 20 m, 30 m, 40 m, 50 m, and 60 m, and the ratio of length to diameter \(\frac{L}{d}\) is 25, 30, 35, 40, and 45. The load \(P_0\) and settlement \(S_0\) curves under the vertical load on the pile top
The load-settlement curve of a single pile with or without sediment will gradually become tighter, and the ultimate bearing capacity loss will become smaller. It can be explained again that the larger the ratio of length to diameter, the larger the value of the influence coefficient of single pile defects, and the smaller the ultimate bearing capacity loss of the pile foundation. This parameter can be used as a reference index for evaluating the bearing behavior analysis of single piles with sediment defects.

6.2. Thickness of Sediment. The values of the influence coefficient analysis of the thickness of the sediment on the single pile defect are as follows: 60 mm, 82 mm, 100 mm, 120 mm, and 140 mm. Figure 12 is the load $P_0$ and settlement $S_0$ curves of different sediment thickness under the action of vertical load. It can be seen from the figure that the change of sediment thickness has a greater impact on the bearing performance of a single pile. In the initial stage of the implementation of the vertical load on the pile top, the settlement of the pile top did not fluctuate widely with the thickness of the sediment. This is because the initial loading range is not large, and the pile shaft friction gradually intervenes in the bearing of the pile foundation, resulting in the load transferred to the pile end. Relatively weak, the sediment-containing area is in an elastic state at this time, so the sediment does not significantly change the settlement of the pile foundation at this time. With the continuous increase of the pile top load, the feedback of the sediment on the settlement of the pile foundation gradually becomes significant. Under the same load condition, as the thickness of the sediment increases, the more sensitive the impact on the pile foundation becomes, so that the settlement amount on the pile top gradually increases. When the thickness of the sediment at the bottom of the pile is 140 mm, the settlement at the top of the pile has a leaps and bounds, because under this condition, with the increase in the load on the pile top, the shaft...
friction resistance of the pile gradually enters the limit state, and the load is gradually transferred. To the end of the pile, the strength of the sediment area is low and the bearing capacity is small, and it will tend to the limit state in a short time. At this time, the sediment will enter a plastic state, and the continuous increase of the pile top load will accelerate the settlement rate of the pile top. The greater the thickness, the more prominent the force performance of this pile. The pile top load value corresponding to the pile top settlement of 40 mm is extracted as the ultimate bearing capacity of the single pile in this state, and the single pile defect influence coefficient is calculated. Figure 13 shows the influence coefficient of sediment thickness corresponding to single pile defect.

6.3. Elastic Modulus of Sediment. The values of the influence coefficient analysis of the elastic modulus of sediment on the single pile defect are as follows: 1 MPa, 2 MPa, 3 MPa, 4 MPa, and 5 MPa. Figure 14 is the load P₀ and settlement S₀ curves of different sediment elastic modulus under vertical load. It can be seen from the figure that within the range of the sediment elastic modulus, the change in the sediment elastic modulus has an effect on the bearing behavior of a single pile. The effect of gradient changes. In the initial stage of the implementation of the vertical load on the pile top, the settlement of the pile top fluctuates in a small range with the change of the elastic modulus of the sediment. This is because the initial load range is not large, and the pile shaft friction gradually intervenes in the pile foundation bearing, resulting in the load transferred to the pile end. It is relatively small, so there is no obvious change in the settlement of the pile foundation at this time. With the continuous increase of the pile top load, the feedback of the sediment
7. Conclusions

The load transfer method is used to carry out theoretical analysis on the vertical bearing characteristics of pile foundations containing sediment defects, and the influence coefficient of pile foundation defects is proposed, which provides an important reference for further analysis of the bearing characteristics of pile foundations containing sediment defects. Now draw the following main conclusions:

(1) The theoretical calculation model of the single pile with slag defect was established by the load transfer method, and the corresponding analytical expressions under different conditions were obtained.

(2) The accuracy and reliability of the method of weakened load transfer between the double-folded line of the pile-side soil and the three-folded line of the soil at the end of the pile were verified, and it is suitable for indoor and field tests.

(3) The influence coefficient of the slag-containing defect is defined to analyze the bearing behavior of the pile foundation. The bearing capacity of the pile foundation is directly related to the pile diameter and the pile length. With the increase of the length-diameter ratio \((L/d)\), the single pile defects of the influence coefficient gradually increase and tend to ease, and the bearing influence of the pile foundation is more convergent; with the increase of the thickness of the sediment, the influence coefficient of the single pile defect gradually decreases, and the bearing influence of the pile foundation becomes more discrete. This verifies the “Code.” The thickness of the sediment of the friction pile is not more than 100 mm; with the increase of the elastic modulus of the sediment, the influence coefficient of the single pile defect gradually increases, and the ultimate bearing capacity loss is less.

(4) The load transfer method for defect pile calculation has the characteristics of clear logic and convenient calculation, which is convenient for engineering application. However, its calculation accuracy depends on the assumption of load transfer function of pile side and pile end and ignores the continuity of soil, so it is generally suitable for the analysis of homogeneous pile-soil system.

Data Availability

The [Data Type] data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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