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Study on Optimization of Design Parameters for Precast Pipe Pile Treatment of Soft Soil Subgrade on the Jianghan Plain

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Abstract

The soft soil in the Jianghan Plain is characterized by a high water content, liquid limit, sensitivity, porosity ratio, and organic matter content and low strength and is commonly known as “five highs and one low” soft soil. Thus, the construction of expressways in this area is likely to cause subgrade settlement. The manuscript investigated the influence of the design parameters of precast pipe piles on the soft ground treatment in the Jianghan Plain based on the case of the soft soil subgrade project of the Xiaogan south section of the Wuhan city ring expressway, China. Midas GTS NX 2019 finite element software was used to analyse the settlement pattern of the subgrade under the variations in pile length, pile spacing and pile diameter. The results show that precast pipe piles are effective in reducing the settlement of soft soil subgrades with a high compressibility and water content; the soft foundation settlement decreases with increasing pile length and pile diameter and decreasing pile spacing. As the pile tip is embedded in the bearing stratum, the settlement of the soft foundation is greatly affected by the variations in pile length and pile spacing while slightly influenced by the variation in pile diameter; in combination with the curve fitting obtained from the real-time monitoring data, the analysis concludes that the soft foundation treatment plan with a pile length of 15 m, pile spacing of 1.2 m to 1.5 m and pile diameter of 0.6 m can better contain the soft soil subgrade settlement in this section.

Keywords

Expressway, Weak Soil Roadbed, Prefabricated Tubular Pile, Numerical Simulation, Settlement Calculation

1. Introduction

As China's transportation infrastructure develops rapidly, the construction of highways continues [1] [2]. Currently, major issues limiting social development and the increase in human activities and traffic trips include the scale and condition of current roadways, since many roads have long been in a dilapidated condition and can no longer meet people's travel needs, posing enormous challenges to the carrying capacity of public roads [3] [4] [5]. To ease the strained road environment and improve urban capacity, China has prioritized building city ring expressways in its major central and southern regions. The south-central region of Hubei Province, in the Jianghan Plain, hosts many soft clay soils with river- and lake-derived silt. With flat and low-lying terrain and long ditches, it is characterized by "five highs and one low" soft soils with a high water content, liquid limit, sensitivity, porosity ratio, and organic matter content and low strength and thus has poor engineering properties [6] [7]. The Wuhan city ring road in central China is a national construction area, and most of its western line is located in the Jianghan Plain, on which the stability of the subgrade is easily affected by the construction of the expressway. Especially under long operational lifespans, uneven settlement and other problems easily occur, affecting the safety of traffic. Therefore, how to control the settlement of soft soil subgrade in this area is a pressing engineering technical problem to be solved [8] [9].

To solve the soft soil subgrade settlement problem, engineering scholars at home and abroad have proposed to study the settlement and deformation of subgrade by using indoor tests, spot monitoring, theoretical analysis, finite element numerical simulation and other methods, achieving many notable results [10] [11] [12]. For instance [13], based on the Hang-Ningbo Expressway project, studied the differences in the settlement of embankments in the preconstruction and postconstruction phases by adopting a theoretical analysis method and establishing a theoretical model. [14] explored the variation in the boundary constraints and pore water pressure influencing the settlement of unsaturated soft clay soils by studying the one-dimensional consolidation theory of unsaturated soft soils and establishing a physical model using FLAC3D software. [15] researched the pavement stress distribution and differential settlement of subgrade after embankment expansion using field monitoring, theoretical analysis, finite element modelling and other methods. Through analysing the real-time monitoring data of soft foundation settlement, [16] summarized a set of results based on the stages of soft foundation settlement, namely, the occurrence, development, stability, and limitation stages, and put forwards the S-shaped curve prediction method for soft foundation settlement. Although China has made some strides in managing and containing soft soil subgrade, there are fewer studies on precast pipe piles for the treatment of soft soil in river and lake facies in the Jianghan Plain area.

Precast pipe piles, as an effective soft foundation treatment measure, are characterized by high pile formation quality and convenient construction. Compared to cement mixing piles and GFC piles, precast pipe piles have obvious advantages and have been widely used over recent years. Soft foundation treatment generally involves a wide range of measures, while precast pipe piles have a high production budget, so this pile foundation design has a greater impact on costs [17] [18]. Hence, it is particularly important to constrain the design parameters of precast pipe piles under the premise of guaranteeing stable subgrade, better settlement and reasonable costs. By using Midas GTS NX 2019 finite element software to develop a numerical model, this paper refers to the soft soil filling embankment of the Xiaogan south section of the Wuhan city ring expressway, studies the optimization of three key parameters of pipe pile length, pile spacing and pile diameter on the basis of the existing management engineering measures, and analyses the reinforcement effect under different schemes to obtain the optimal management design parameters. This study aims to provide a reference for soft foundation treatment projects on the Jianghan Plain.

2. Information on This Project

2.1. An Introduction to This Project

The Wuhan city ring expressway is an indispensable section of "nine vertical, five lateral and three circular" expressway networks in Hubei Province, of which the Xiaogan southern section project is a vital part. The section in the hinterland of the Jianghan Plain contains a large area of soft soil subgrade. With a 26 m subgrade and a south-north direction, this section has four lanes of traffic, adopts the standard construction of first-class highways and has a speed limit of 100 km/h. The subgrade plan is shown in **Figure 1**.

2.2. Engineering Geology Overview

The upper part of the subgrade is revealed to be the Holocene alluvial, lacustrine clay, silty clay, silty soil and fine sand layer. The parent material of the soil formation mainly consists of fill soil and modern fluvial/alluvial and lacustrine soil. It is described as follows:

1) Plain fill soil ($Q4^{ml}$): yellow brown, plastic, mainly clay, silty clay, with a small amount of fine sand and gravel, gravel particle size of 1 - 33 cm. According to the borehole exposure, the thickness of the layer is 1.0 - 2.7 m, the basic allowable foundation bearing capacity [fa0] is 100 kPa, and the pile side friction qik is 30 kPa.

2) Silty soil ($Q4^{al+l}$): grey brown, viscoplastic, containing a small amount of humus, moderate dry strength and toughness, locally containing a thin layer of silt lens, with silt in between. According to the drilling exposure, the layer thickness of this section is 3.5 - 6.6 m, and the basic allowable foundation bearing capacity [fa0] is100 kPa.

3) Clay and silty clay ($Q4^{al+l}$): yellow brown, mainly plastic, local hard plastic, mainly clay, containing a small amount of humus and grey kaolin; according to

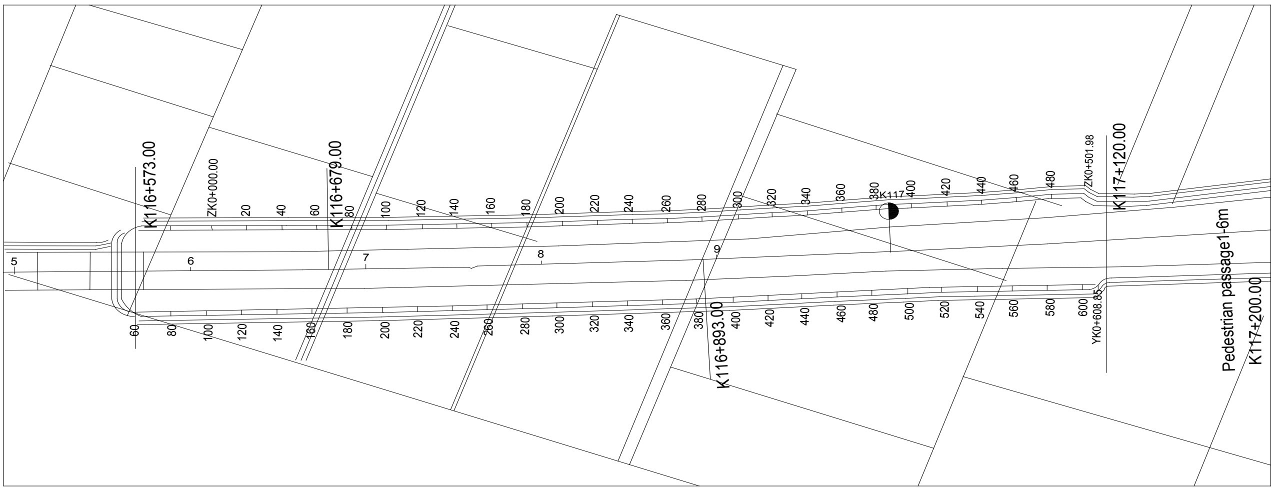

Figure 1. Subgrade plan.

the drilling exposure, the layer thickness of this section is 10.9 - 12.8 m, the basic allowable foundation bearing capacity [fa0] is 150 kPa, and pile side friction qik is 50 kPa.

4) Fine sand ($Q4^{al+l}$): bluish grey, dense, mainly composed of quartz, mica, feldspar, uniform particles, and a local layer of silt. According to the basic allowable value of the foundation bearing capacity revealed by the drilling hole [fa0] = 300 kPa, the pile side friction qik is 60 kPa.

The engineering geological profile of the left line of the K116+561.5 - K117+120 section is shown in **Figure 2**. Plain fill soil ($Q4^{ml}$) in the shallow surface layer is basically cultivated soil affected by the agricultural activities of the residents and has a loose structure. Due to the flat and low-lying terrain in this area, the soil in this layer is basically viscoplastic. The underlying silty soil ($Q4^{al+l}$) is alluvial and lacustrine soft soil, which is viscoplastic (mainly plastic), with a high compressibility, porosity ratio, water content, sensitivity, organic matter content, low bearing capacity, etc., and thus has poor engineering properties.

2.3. Soft Foundation Treatment Scheme

The original design was that this section was sand-filled subgrade. The subgrade was filled with fill and sand, and the foundation soil was mainly composed of plain fill, sludge, cohesive soil and fine sandy soil. The height of the fill varied from 5.658 m to 7.639 m, its thickness increased gradually from south to north, and a wrapping layer of soil was used on the sides of the subgrade for the edge cladding. A dry jet mixing pile in the soft soil below the subgrade was originally used for foundation treatment; however, this treatment could not be achieved because the soft soil of the superficial surface in this section tended to be viscoplastic, and the pile foundation after being embedded in soil shortly broke and fell apart.

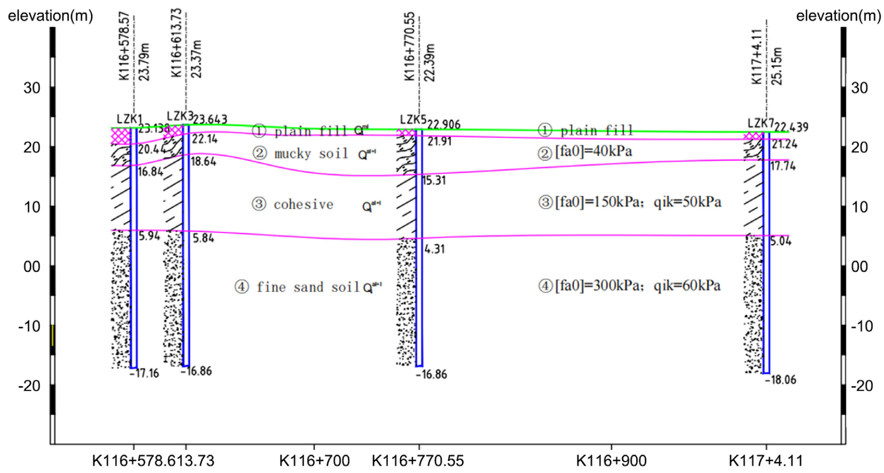

Figure 2. Longitudinal section of roadbed.

According to the engineering geological conditions of the road section, the principle of subgrade reinforcement and the nearby regional engineering experience, it is not proper to employ tap densification, dynamic consolidation, compaction piles and other methods to achieve reinforcement for large areas of saturated soft soil, and deep treatments are needed; thus, the pile foundation method can be applied for reinforcement treatment. However, the cement soil mixing pile is used in the early construction stage of this section for reinforcement, resulting in excessive settlement of the subgrade, failing to achieve the effect of reinforcement. Therefore, a precast pipe pile is used to strengthen the soft soil in this section.

A precast pipe pile with a PTC cap is used in the soft soil area for deep reinforcement treatment. With a plum-shaped arrangement, the prestressed pipe pile is 400 - 800 mm in diameter, 70 mm in wall thickness, 9.0 m to 17.0 m in pile length, and 0.9 to 2.1 m in pile spacing. In addition, a 50 cm thick reinforced concrete pile cap is poured, a 50 cm thick sand-gravel cushion is laid along the pile cap, and two 30 cm thick steel grid cushions are laid on top of the sand-gravel cushion. Finally, fill is used to achieve back pressure on top. The treatment scheme is shown in Figure 3.

3. Analysis of the Calculation Model of the Soft Soil Subgrade

3.1. Model Assumptions

To simplify the calculation process, the following assumptions are made during the finite element numerical simulation:

1) There is a complete continuous contact and no relative motion between the subgrade soil and the foundation soil.

2) The Mohr-Coulomb elastic-plastic model is used for both the subgrade soil and the foundation soil.

3) The elastic model is used for the sand-gravel cushion, steel grid cushion and pipe foundation.

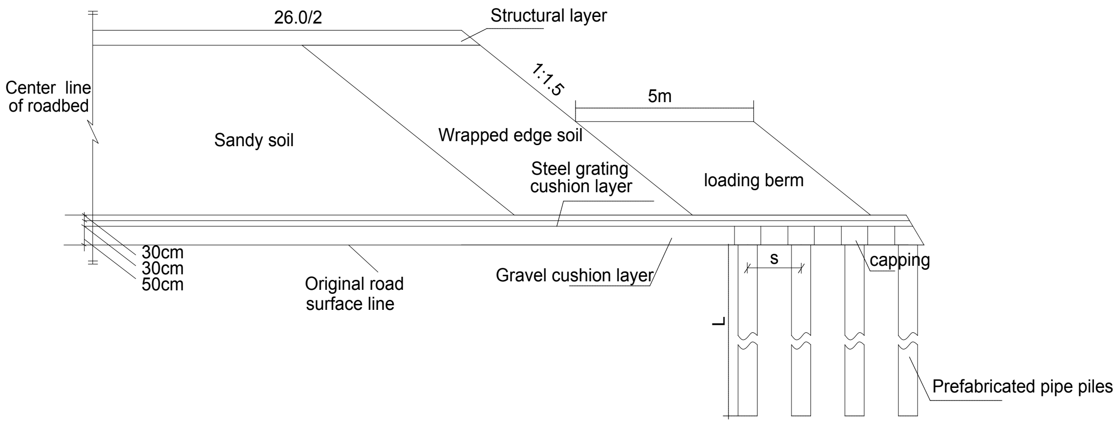

Figure 3. Soft foundation treatment scheme diagram.

4) Other units are unconstrained except for the grid units with specified drainage conditions and unconsolidated conditions.

3.2. Drainage and Consolidated Conditions

In the soft soil subgrade model of Midas GTS, each grid unit is entitled with one degree of freedom (DOF) of pore water pressure, and there is translational DOF at the nodes. For material bodies without drainage consolidation behaviour, the drainage and unconsolidated conditions are defined in this paper in accordance with general cells.

1) The pile foundation of the precast pipe pile, pile bottom, and cohesive soil layer in the original foundation soil is allowed to drain; the sand-gravel cushion and steel grid cushion in the subgrade soil layer are also allowed to drain.

2) The unconsolidated condition is given to the plain fill layer in the original foundation soil and the sand-filled subgrade in the subgrade soil layer.

3.3. Boundary Constraint Conditions

To make the finite element numerical simulation more realistic and accurate, this paper sets constraints on the four boundaries around the model.

At the left and right boundaries of the model, displacement constraints in the x-direction are applied to avoid horizontal deformation; in the lower boundary of the model, displacement constraints in the x- and y-directions are set to ensure that no deformation can occur in either the horizontal or vertical direction.

3.4. Calculation Parameters

By spot survey data and indoor test data, in combination with the Concrete Structure Design Norm [19], the parameter values of each foundation soil are obtained (Table 1).

3.5. Calculation Model

When using Midas GTS to establish the finite element model for the soft foundation of roads, this paper establishes a two-dimensional plane model for analysing the subgrade section in light of the plane strain characteristics of roads. The K116+573 section of the Xiaogan south section of the Wuhan city circle expressway subgrade is chosen for model building, which has a model size of 1:1, a width of 48 m, and a height of 48 m. Midas GTS automatically divides the grid units and adjusts the grid density. The calculation model and grid division of the subgrade section are shown in Figure 4.

4. Optimization Analysis of the Design Parameters of the Precast Pipe Pile

To better understand the treatment effect of precast pipe piles on soft soil subgrade sections of the Jianghan Plain, the first task is to compare the settlement conditions 15 years after the completion of subgrade filling with and without piles. Subsequently, the settlement deformation response of the subgrade is observed by the variation in the pile length, pile spacing and pile diameter. Then, a comprehensive analysis is performed to select the best parameter scheme for the treatment and design.

Table 1. Table of foundation soil parameters.

Stratum number	Geotechnical name	Thickness (m)	Elastic modulus (kN/m^2)	Volumetric weight (kN/m^3)	Cohesive force (kPa)	Internal friction angle φ (˚)
1	plain fill	1.3	4000	19.8	10	21
2	sludge	5.8	1418	17.5	4.65	3.76
3	cohesive soil	9.8	5831	18	30.49	12.31
4	fine sandy soil	26.0	53827	18.5	5.41	33

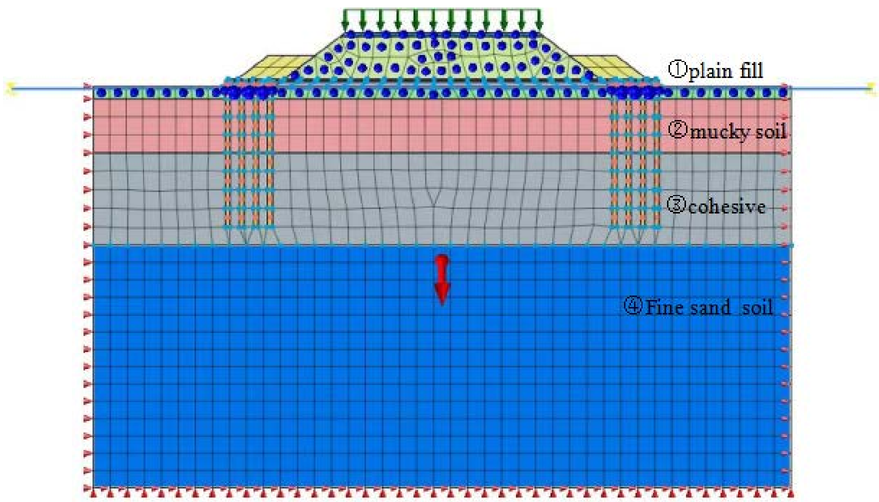

Figure 4. Calculation model and grid division diagram.

4.1. Comparison of the Settlement of the Subgrade with or without Piles

The K116 + 573 section is chosen for analysis. First, this paper compares the settlement variation in the subgrade without piles with the settlement variation in the subgrade with piles. This section has a 13 m pile embedment length, 1.5 m pile spacing, and 0.6 m pile diameter. As the model boundary conditions and geotechnical parameters are unchanged, the paper takes 15 years after completion as the time point for further analysis and chooses the centre of the subgrade pavement as a monitoring point. The variation curves of the cumulative settlement of the subgrade are shown in Figures 5-7.

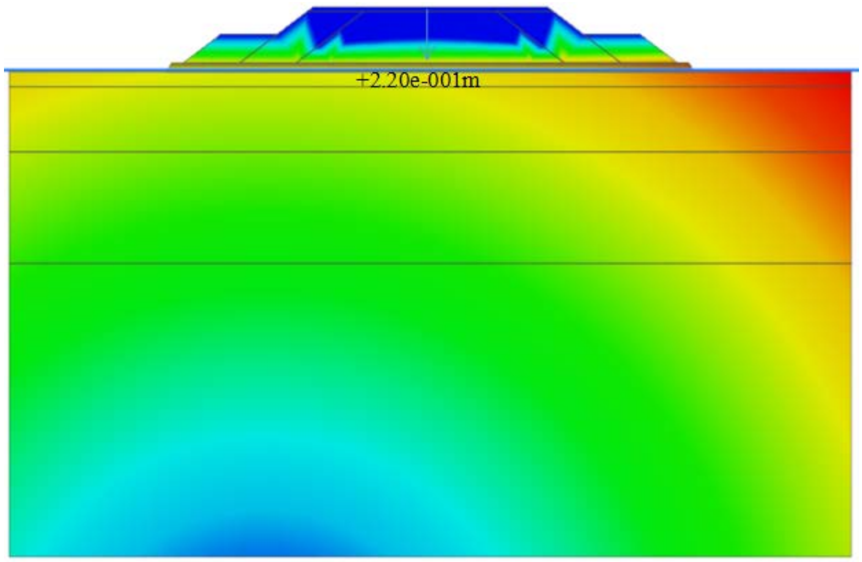

Figure 5. Settlement diagram of the pileless body at 15 years.

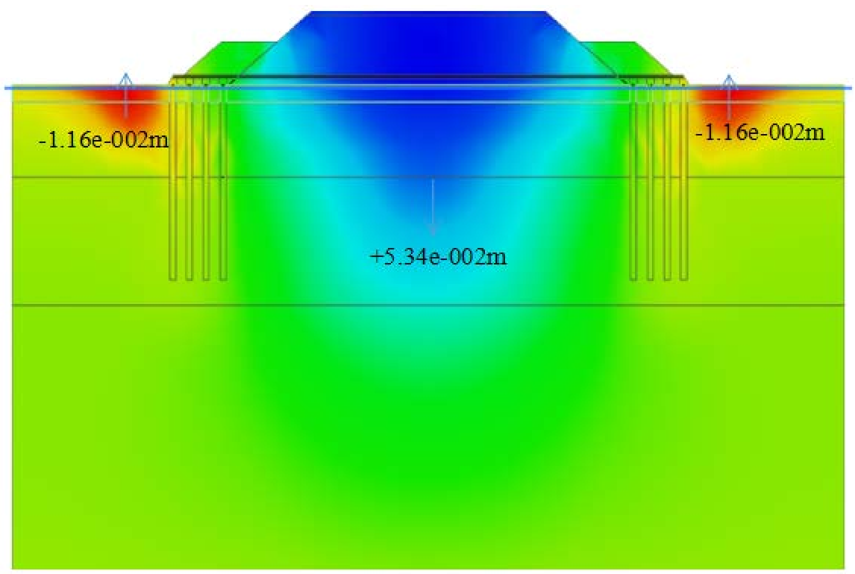

Figure 6. Settlement diagram of adding piles at 15 years.

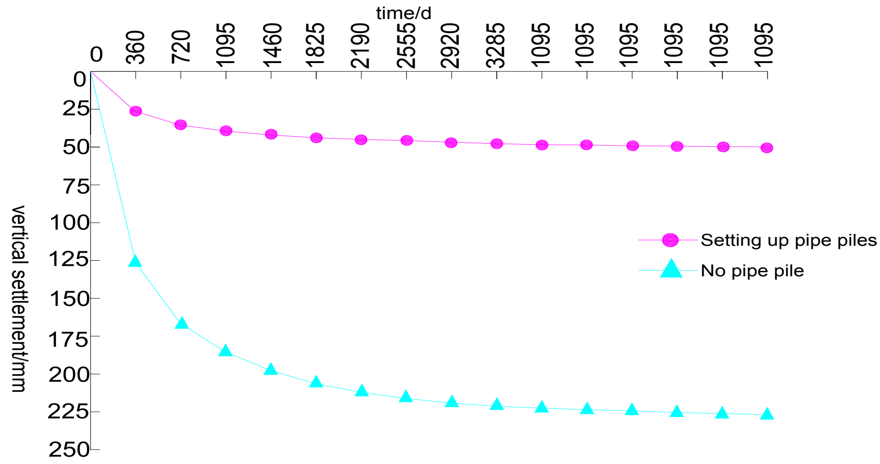

Figure 7. Comparison diagram of the accumulated settlements of the subgrade with and without piles.

From **Figures 5-7**, it can be obtained that the subgrade in its natural state, without setting the precast pipe pile, has a larger settlement; the settlement of the embankment load reaches 125 mm in one year and then gradually slows, finally reaching 220 mm. According to the design, the maximum allowable settlement of this road project should not exceed 100 mm from the completion of construction to 15 years of operation; however, the final settlement of the subgrade reaches 220 mm through simulation. This means that this figure obviously does not meet the project's requirements. For the soft soil subgrade with an additional precast pipe pile, the settlement in the first year is 25 mm, and the maximum settlement in 15 years of loading is 53 mm, satisfying the project's requirement. In addition, the corresponding settlement curve tends to level off in the 10th year, indicating that there is a good effect on settlement control.

There is a considerable difference between the settlement variation curve of the subgrade without a pile and that with an additional pile, both of which show nonlinear variation with continuous loading. **Figure 5** and **Figure 6** show that the stability of the soft soil roadbed treated with prefabricated pipe piles significantly improves. Under the action of the overlying load, the settlement depth of the roadbed soil with added pipe piles is significantly reduced; that is, the consolidation settlement process is completed above the soft soil layer, while the foundation soil layer without pipe piles still experiences diffusion settlement below the soft soil layer. After the addition of pipe piles, there is a small amount of local uplift on the outer side of the anti-pressure protective channel at the foot of the embankment slope. However, due to the effect of the anti-pressure protective channel body and pipe piles, the impact is relatively small, and the accumulated settlement meets the engineering requirements. Under the integration of the sand and gravel and the steel grid, the pile and soil share the overlying load, between which the lateral friction resistance further deters the subgrade deformation so that the settlement does not change significantly. This shows that the precast pipe pile has a good effect on stabilizing the soil and containing the settlement in the process of treating the settlement of the soft soil subgrade.

4.2. The Effects of Pile Length Variation on the Settlement of the Subgrade

After the soft foundation treatment effect of the precast pipe pile is verified, the soft foundation is fitted separately with the variation in the pile parameters. With respect to the actual situation of the project, this paper sets the pile length as a single variable to analyse the settlement of the soft soil subgrade when the pile length is changed. Based on the original model data, the pile spacing is 1.5 m, the pile diameter is 0.6 m, and the length of the pile is set to 5 different pile lengths of 9 m, 11 m, 13 m, 15 m, and 17 m, respectively. In addition, the time point of 15 years after completion is taken for analysis, and the centre of the subgrade pavement is selected as the monitoring point to obtain the construction settlement and postconstruction settlement of the subgrade after 15 years. The settlement variation curve is shown in Figure 8.

From Figure 8, the settlement of the top surface of the soft soil subgrade gradually decreases with increasing pile length. When the pile length is short, the pile only influences the soil within the embedment depth, so the amount of settlement is larger; as the pile length increases and the pile has a greater range, the foundation has a better bearing capacity. When the pile length reaches 15 m, the declining trend of soft soil subgrade settlement decreases gradually, and the settlement of soft subgrade changes little with the increase in pile length at this time. Due to pipe pile construction technology, the pile length is generally longer, the pile body is long enough to be embedded into the clay soil bearing layer, and the strength of the pile foundation is higher. The pile tip and pile side friction resistance can provide sufficient bearing capacity to the soft foundation within the effective pile length to increase the pile length and reduce the settlement of the soft foundation.

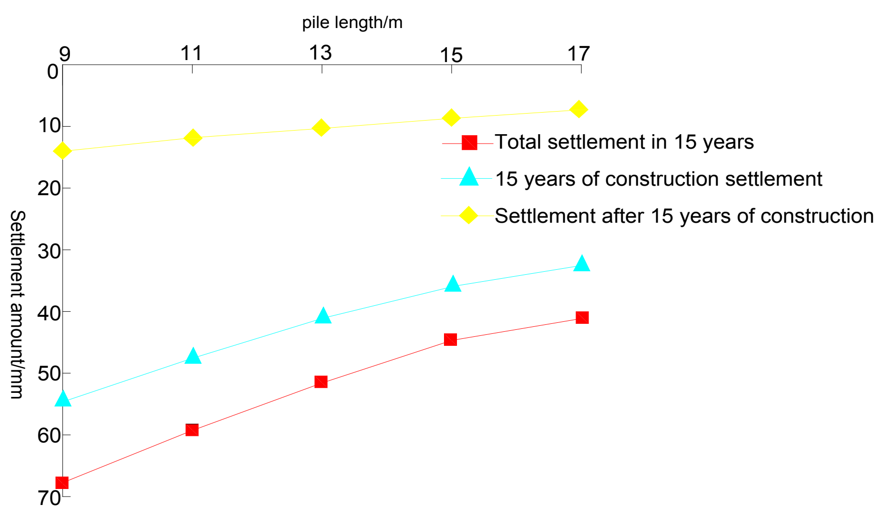

Figure 8. Settlement curve of the subgrade under different pile lengths.

Figure 8 shows that as the pile length increases by 2 m, the settlement of the soft soil subgrade decreases by 22.8% during construction and 24.9% after construction; according to the engineering geological data, the depth of soft soil in the Jianghan Plain is generally approximately 15 m. By reducing the settlement of the subgrade after construction, the precast pipe pile has the best effect in controlling settlement when it is embedded less than 15 m. Therefore, under the comprehensive consideration of economic, treatment, and environmental conditions, setting the length of the pipe pile to approximately 15 m and applying it in actual construction are increasingly economical and reasonable, helping to shorten the construction period.

4.3. The Effects of Pile Spacing Variation on the Settlement of the Subgrade

The difference in pile spacing in soft highway foundations also causes variations in subgrade settlement. In this simulation, a pipe pile with a 13 m pile length and 0.6 m pile diameter is selected, and by changing the pile spacing to 0.9 m, 1.2 m, 1.5 m, 1.8 m and 2.1 m, the settlement variation in the soft soil subgrade is calculated under different pile spacings. The analysis is performed 15 years after the completion of the project, and the centre of the subgrade and pavement is selected as the monitoring point; the settlement variation curves of the subgrade obtained during and after construction are shown in Figure 9.

Figure 9 shows that the variation in pile spacing significantly affects the settlement of the soft soil subgrade, and the amount of soft foundation settlement gradually increases with increasing pile spacing. Specifically, as the pile spacing increases by 0.3 m, the total settlement of the soft soil subgrade increases by 19.9%, and the settlement during construction and after construction increases

Figure 9. Vertical settlement curve of the subgrade under different pile spacings.

by 23.5% and 26.6%, respectively. Moreover, when the pile spacing exceeds 1.5 m, the increase in the settlement at the top surface of the subgrade tends to increase greatly. As the variation in lateral friction resistance in the pile changes the soil bearing capacity within its action range, the compactness between the pile and soil decreases, and the bearing capacity of the soil decreases when the pile spacing increases, resulting in an increase in settlement during construction and after construction. When there is a smaller pile spacing, the settlement of the soft soil subgrade is smaller, and the bearing capacity improves. Therefore, when a precast pipe pile is used, the pile spacing should not be larger than 1.5 m, and a sufficient number of piles should be used; otherwise, the bearing capacity of the foundation changes unevenly, and the soil undergoes differential settlement.

4.4. The Effects of Pile Diameter Variation on the Settlement of the Subgrade

To analyse the impact of pile diameter on the settlement of soft foundations, in accordance with the principle of a single variable, this paper considers the existing model data, keeps the 13 m pile length and 1.5 m pile spacing, and selects pile diameters of 0.4 m, 0.5 m, 0.6 m, 0.7 m, and 0.8 m. The aim of this analysis is to calculate the settlement variation of the soft subgrade. The analysis is performed 15 years after the completion of the project, and the centre of the subgrade and pavement is selected as the monitoring point; the settlement variation curves of the subgrade obtained during and after construction are shown in **Figure 10**.

It can be seen from the data analysis in **Figure 10** that although the pile diameter under the five schemes changes little, it has a certain influence on soft foundation settlement, and the settlement at the top surface of the subgrade gradually decreases with increasing pile diameter. When the pile diameter is between 0.4 m and 0.7 m, the total settlement of the soft foundation decreases from 61 mm to 48 mm, and the amount of settlement changes little. However, when the pile diameter increases from 0.7 m to 0.8 m, the settlement of the soft foundation during construction increases significantly, leading to a sharp decrease in settlement after construction. This is because the contact area between the pile and soil increases with increasing pile diameter. When the pile diameter is too large, the soft soil around it sinks drastically under the influence of the overlying load and its own gravity, resulting in increased settlement of the soft foundation during construction and reduced settlement after construction.

Generally, as the pile diameter increases by 0.1 m, the total settlement decreases by approximately 4 - 5 mm, with little variation relative to the pile length and pile spacing. Although the settlement of the soft foundation decreases with increasing pile diameter and its bearing capacity increases with increasing pile diameter, a larger pile diameter is not always better. Considering the actual situation and deformation trend of soft foundation settlement, the analysis shows that it is increasingly reasonable to set the pile diameter to 0.6 m.

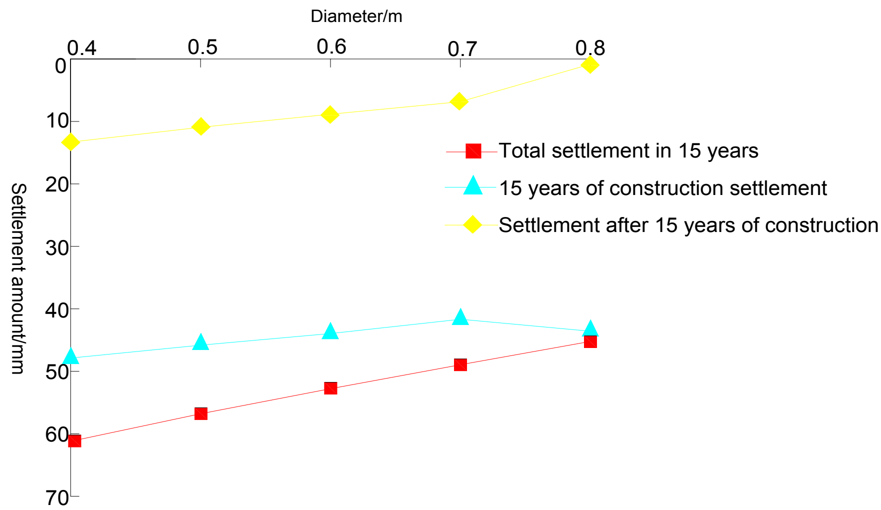

Figure 10. Settlement of the subgrade under different pile diameters.

5. Comparative Analysis Based on the Curve-Fitting Method

5.1. Real-Time Measurement of the Settlement of the Section

The numerical simulation results show that when precast pipe pile is used to treat soft soil subgrade on the Jianghan Plain, it is more appropriate to set pipe pile with a pile length of approximately 15 m 5 m, pile spacing less than 1.5 m and pile diameter of approximately 0.6 m. To verify the settlement effect under different pile layouts, in combination with the actual conditions of the project, four sections from two test phases of K116+610, K116+880, K117+120 and K117+720 in the Xiaogan south section are selected for monitoring, as shown in Table 2.

Figures 11-14 denote the filling height-time-settlement relation curve of each section.

Figures 11-14 show that the subgrade settlement increases with increasing filling height. In the early stage of construction, the settlement of the four sections changes rapidly, mainly because the soil quality is relatively soft in this period and the soil is not compacted. With the advance of preloading, the soil reaches a certain strength, the settlement begins to level off, and the subgrade becomes stable.

5.2. The Fitted Analysis of the Settlement of the Subgrade

The methods mainly used for subgrade settlement prediction include numerical calculation methods, traditional theoretical prediction methods, and curve prediction methods based on real-time measured data.

This time, the hyperbolic method of curve prediction is selected for the post-construction settlement prediction of the project. Its main idea is to simulate real-time measured data with the settlement data obtained based on the hyperbolic method, draw a certain curve via curve fitting, and predict the postconstruction settlement. The basic expression is:

Table 2. Layout of monitored sections.

Monitoring section	Foundation treatment method	Height of fill/m	Monitoring interval/d	Pile length/m	Pile spacing/m	Pile diameter/m
K116+610	Precast pipe pile	7.457	500	15	1.2	0.6
K116+880	Precast pipe pile	7.417	500	15	1.5	0.6
K117+120	Precast pipe pile	6.917	500	13	1.2	0.6
K117+720	Precast pipe pile	6.797	500	13	1.5	0.6

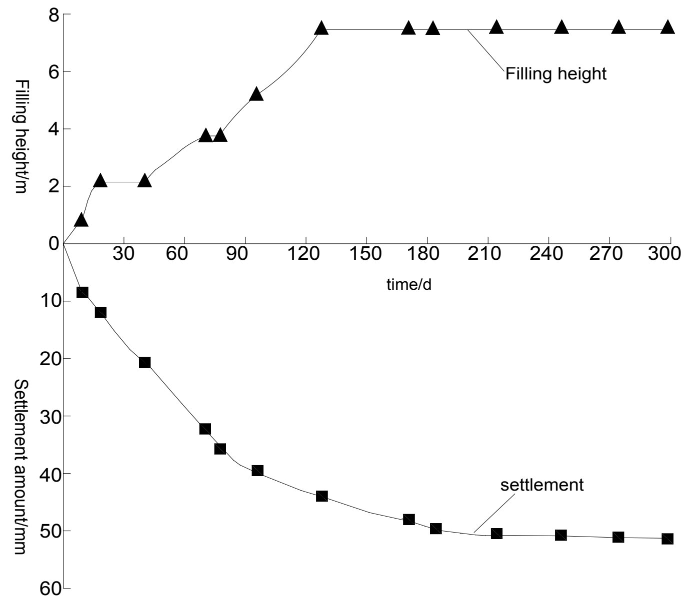

Figure 11. Settlement curve of the K116+610 section.

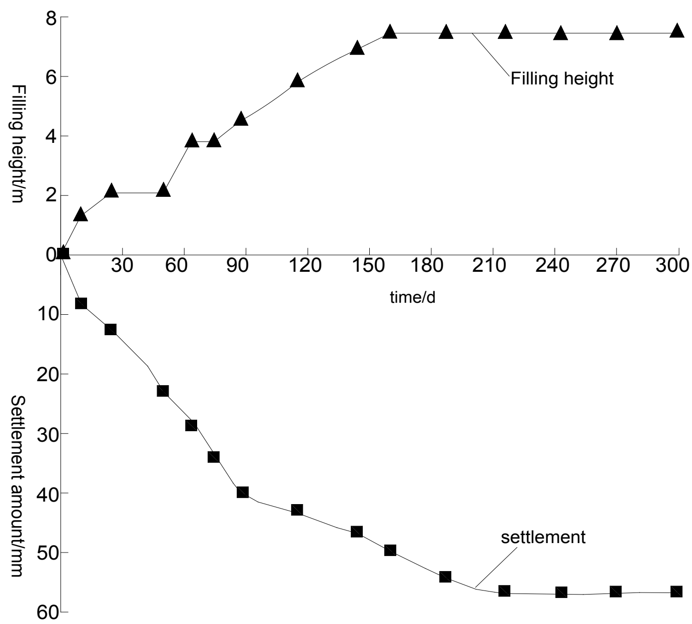

Figure 12. Settlement curve of the K116+880 section.

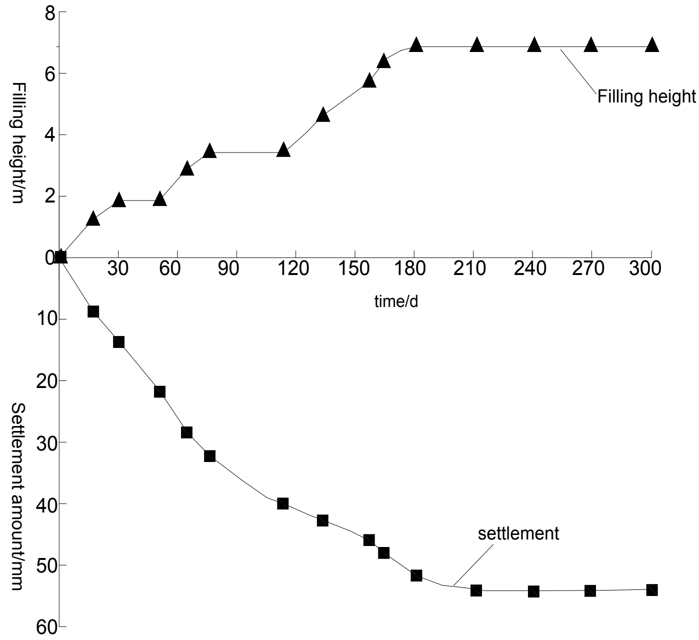

Figure 13. Settlement curve of the K117+120 section.

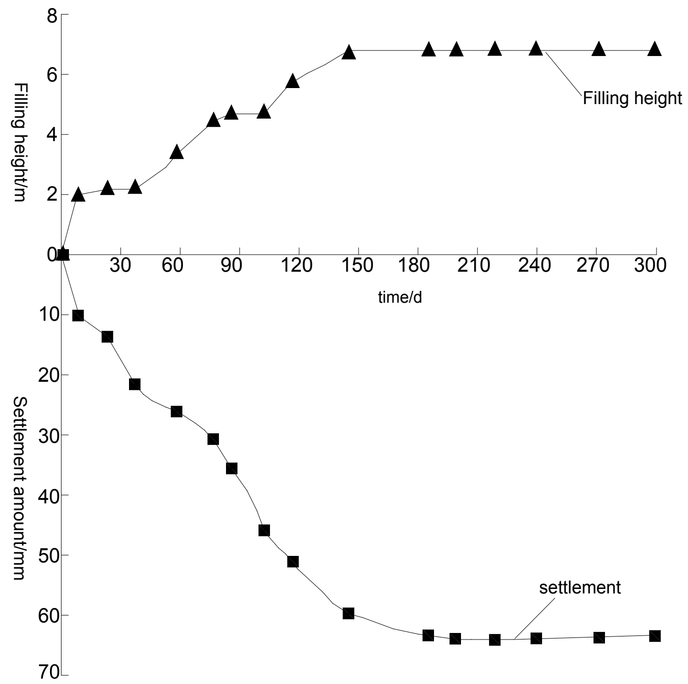

Figure 14. Settlement curve of the K117+720 section.

$$S_t = S_0 + \frac{t - t_0}{\alpha + \beta\left(t - t_0\right)} \tag{1}$$

where S_t is the settlement amount at time t; S_0 and t_0 are the selected initial points corresponding to the settlement and time; and α and β are two undetermined parameters.

The measured data are substituted into Equation (1) to obtain the slope β and intercept α of the curve fitting, and by substituting the obtained parameters back into the original equation, the settlement S_t at any time and the final settlement S_∞ can be acquired. The formula is:

$$S_\infty = S_0 + \frac{1}{\beta} \quad (2)$$

Then, the predicted postconstruction settlement ΔS is $\Delta S = S_\infty - S_t$.

By substituting the measured data of each section into the equation, the results of the postconstruction settlement prediction are acquired, as shown in Table 3. The specific curve fittings are denoted in Figures 15-18.

Table 3. Predicted settlement of each section.

Monitoring section	Intercept α	Slope β	Correlation coefficient R^2	S_∞/mm	ΔS/mm
K116+610	1.0575	0.0158	0.9823	115.29	63.29
K116+880	1.2109	0.0139	0.9706	124.94	71.94
K117+120	1.5834	0.0123	0.9325	136.30	81.30
K117+720	1.0790	0.0126	0.9196	140.37	79.37

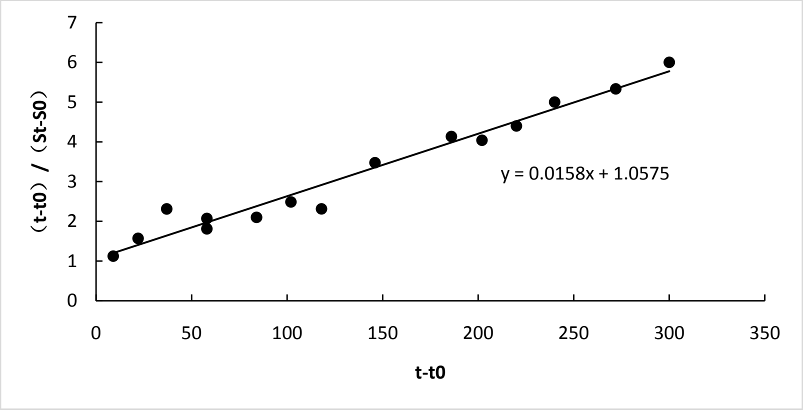

Figure 15. Curve fitting of the K116+610 section.

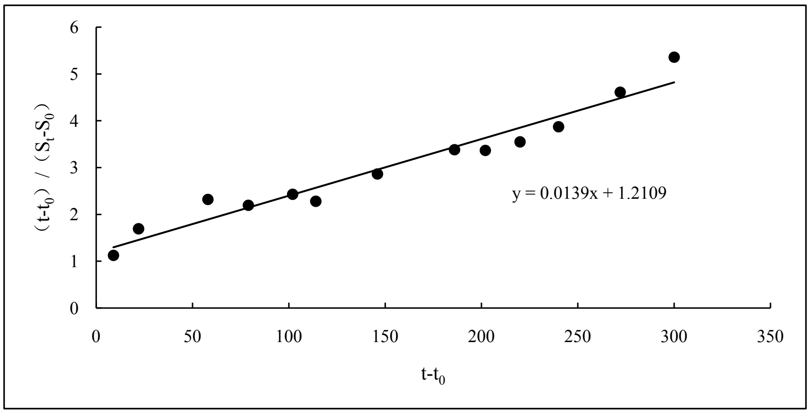

Figure 16. Curve fitting of the K116+880 section.

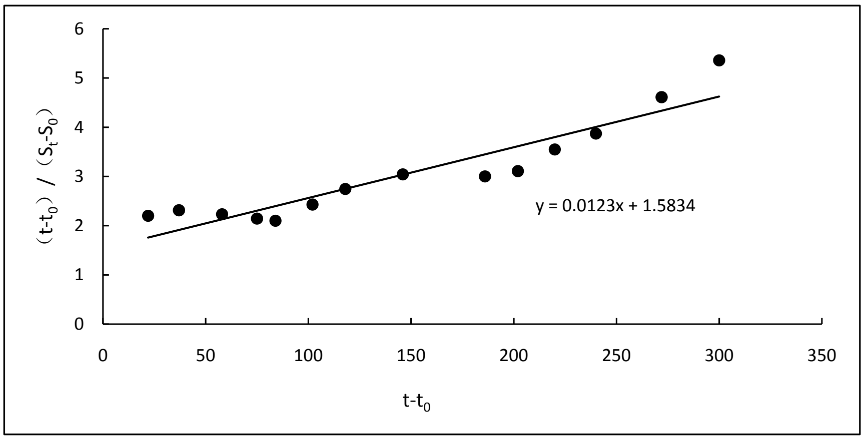

Figure 17. Curve fitting of the K117+120 section.

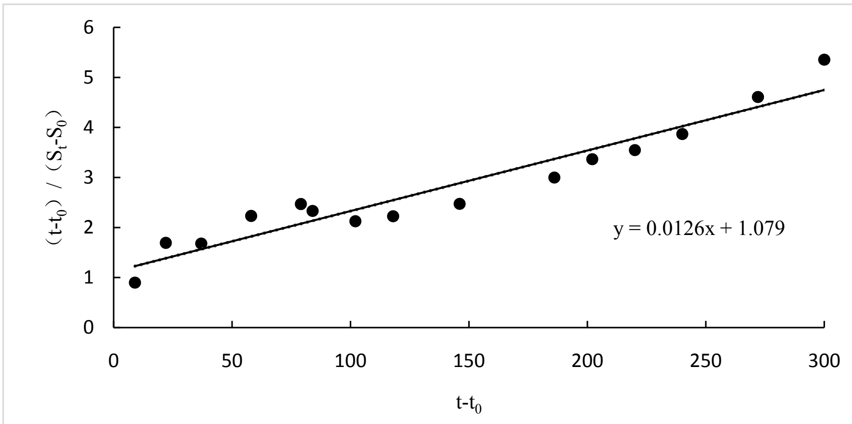

Figure 18. Curve fitting of the K117+720 section.

Figures 15-18 show that the settlement value predicted by the hyperbolic method approaches the actual monitored settlement values and that the variation trends of settlement are basically consistent. The better fitted conditions under the four schemes prove that the hyperbolic method of predicting settlement is feasible.

Among the fitted conditions, the K116+610 section has the highest curve fitted correlation coefficient, the best fitted effect, and a significant effect in containing settlement. Therefore, the soft foundation optimization scheme with a pile length of 15 m, pile spacing from 1.2 m to 1.5 m, and pile diameter of 0.6 m meets the requirements of the project best under the consideration of the treatment effect, economic cost and other factors.

6. Conclusions

This paper, based on the soft soil subgrade of the Xiaogan south section of the Wuhan city ring expressway, uses Midas GTS NX 2019 finite element software to analyze the factors influencing settlement deformation under the variations in pile length, pile spacing and pile diameter, and draws the following conclusions:

1) The precast pipe pile is effective in treating the settlement of the soft soil subgrade in the Jianghan Plain, and its pile length and pile spacing are the key factors affecting the settlement and deformation of the soft foundation. The settlement is significantly affected by the variation in pile length, followed by that in pile spacing, and is least affected by the variation in pile diameter.

2) Increasing the pile length can effectively reduce the settlement of soft foundations. It is more appropriate to set the pile length below 15 m because the decreasing trend of settlement weakens when the pile length exceeds 15 m. The settlement of the soft foundation decreases with decreasing pile diameter. When the pile spacing is between 1.2 m and 1.5 m, there are better results in containing the settlement of the soft foundation and reducing the economic cost. With increasing pile diameter, the soft foundation settlement gradually decreases, but when the pile diameter exceeds 0.7 m, it accelerates settlement during construction. Considering that pile diameter variation has less of effect on the settlement and results in a higher production cost of a single pile than other parameter variations do, this paper proposes that it is more reasonable to set the pile diameter to 0.6 m.

3) The curve fitted results under four optimization schemes are obtained through the hyperbolic method used to verify and predict the postconstruction settlement of soft foundations. In combination with the geological characteristics of the soft soil subgrade in the Jianghan Plain and the construction technology of precast pipe piles, this paper suggests that the optimization scheme of a pile length of 15 m, pile spacing between 1.2 m and 1.5 m and pile diameter of 0.6 m should be applied to achieve the settlement effect.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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