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Review Article

Analysis and Prediction of the Factors Influencing Postconstruction Surface Deformation of Pipe-Jacking Tunnel in Soft Clay Strata in China

Guo-jing Cui,[1,2,3] **Jiang-sheng Xie**,[4] **Yin-hao Sun**,[5] **and Yong-ji Gao**[5]

[1]*School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China*
[2]*Shaanxi Provincial Key Laboratory of Geotechnical and Underground Space Engineering, Xi'an 710055, China*
[3]*Shaanxi Construction Investment Group Co, Ltd., Xi'an 710016, China*
[4]*China Railway 20th Bureau Group Corporation Limited, Xi'an 710016, China*
[5]*No. 1 Engineering Corporation Limited of CR20G, Suzhou 215151, China*

Correspondence should be addressed to Guo-jing Cui; 420487644@qq.com

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During the postconstruction operation period, the engineering structure and operation safety of a pipe-jacking tunnel are more likely to be threatened by the surrounding environment and groundwater when it is located in a soft clay stratum. Surface settlement data related to the construction of 24 rectangular pipe-jacking tunnels in a soft clay stratum in China were collected and analyzed to determine the effect of pipe-jacking tunnel engineering on its deformation based on factors such as structural section form, geotechnical condition, groundwater condition, and buried depth. The postmaximum surface settlement and postformation loss rate were obtained, the correlation coefficients between the postsurface deformation of soft clay strata and various influencing factors were calculated using a software for correlation analysis, and the variation rules for each influencing factor were explored in depth. Subsequently, multiple linear regression methods were used to predict the maximum surface deformation of the pipe-jacking tunnel project in soft clay strata during the postoperation period, and actual engineering cases were verified and analyzed. The results show that the relative buried depth of the pipe-jacking tunnel in soft clay stratum has the greatest influence on the postmaximum ground settlement, followed by the section area of the pipe-jacking tunnel, and the relative height coefficient of groundwater level has the least influence. Under the reduction coefficient of 0.937 – 0.846, a new prediction formula for surface settlement deformation after the construction of the soft clay layer was derived. The error between the formula and the measured data was 9.05%, which can be used as a reference for controlling design parameters to predict the settlement after construction of pipe-jacking engineering.

1. Introduction

During the operation period of a pipe-jacking tunnel project, soil deformation is caused by the surrounding environment, groundwater, and other factors. Meanwhile, the structure of the pipe-jacking tunnel project is affected to a certain extent, and the safety of people's lives and property is threatened. Soft soil layers are widely distributed in China, and the selection of urban pipe-jacking tunnel routes needs to comprehensively consider the political and economic surrounding environment and other factors; thus, it is inevitable that soft clay strata with poor engineering properties will be passed through. Compared with other strata, soft clay stratum has the characteristics of low bearing capacity, slow strength growth, easy deformation, uneven deformation after loading, and significant changes in stress and strain with time. Studying and predicting the soil deformation law of soft clay strata during the postoperation period of pipe-jacking tunnel projects is important for ensuring the safety of project operation.

At present, the prediction methods for surface deformation of pipe-jacking tunnel mainly include empirical and data modeling methods. The empirical method involves using hyperbolic and logarithmic curve formulas for reference, combined with a large number of long-term measured settlement data, to predict the final settlement amount. This method requires long-term collection of data, and the observation data are based on different engineering processes, geologies, and conditions, making prediction work challenging and leading to large errors. The data modeling methods mainly include artificial intelligence techniques using neural networks and time series analyses. Neural network methods have a strong adaptability and fault tolerance, which is especially suitable for dealing with various nonlinear problems but requires more sample data. Time series analysis is a type of data processing method that uses parameter modeling to analyze and process the observed ordered data.

In recent years, studying the change law of surface settlement according to a large number of measured data of stratum deformation of existing tunnels has been one of the important research methods for deformation prediction in tubular tunnel engineering, which has important engineering reference values [1–3]. Moreover, many experts and scholars have studied the law of tunnel settlement deformation considering multifactor influence on the measured data. Zhang and Li [4] considered the Shanghai Metro Line 1 as the background, established a three-dimensional model using the finite difference software FLAC3D, simulated the train vibration load through the excitation force function, considered whether there were two working conditions of groundwater, calculated the long-term settlement of the tunnel combined with the empirical model fitting, and summarized the influence law of train load on the long-term settlement of soft soil. Han et al. [5] analyzed over 30 sets of measured data of the land surface settlement in eight regions of China and obtained the characteristic parameters of land surface settlement in different regions and their variation rules. Wu and Zhu [6] collected the measured data of the maximum ground settlement of a shield tunnel in China, obtained the value of the formation loss rate through backward calculation of the Peck formula, and studied the distribution law and main influencing factors of the formation loss rate of shield tunnels with large ($D > 10\,\mathrm{m}$) and small diameters. Wei [7] combined the soil loss rates caused by shield tunnel construction in Beijing, Shanghai, Nanjing, Guangzhou, Wuhan, Tianjin, and Shenzhen in China, statistically analyzed 71 measured datasets, and studied the change law of soil loss rate with the construction level, soil condition, and tunnel axis depth. The soil loss rate decreases with increasing tunnel axis burial depth, and the trend is more obvious when the burial depth exceeds 25 m. The relationship between the two can be approximated by power function fitting. Zhu and Li [8] systematically summarized the value method for the characteristic parameters of surface settlement troughs. Based on the measured data of surface settlement of subway projects in over 20 cities in China, the Peck formula inversion analysis method was adopted. The variation rules of tunnel parameters such as maximum surface settlement $S_{\max}$, settlement trough width k, and formation loss rate $V1$ were obtained under different relative buried depths H/D, formation conditions, and construction methods. Wu et al. [9] statistically analyzed the data from 58 subway lines, 126 sections, and 964 surface transverse settlement troughs in 22 cities in China and studied the surface transverse deformation rule of a double-line shield section tunnel. Niu et al. [10], aiming at the problem of surface settlement caused by pipe-jacking in no. 6 subway in Kunming, analyzed the formation deformation caused by additional stress and friction force on the excavation surface during pipe-jacking process by Mindlin's displacement solution, and the formation deformation caused by soil loss by random medium theory. Many research results provide scientific references for ground settlement prediction and construction control of similar tunnel projects in relevant areas.

Although some studies have been conducted on the prediction of the formation deformation law by analyzing actual engineering data, the following problems still exist:

(1) Most current research studies are on settlement deformation analysis of shield tunnels, and the deformation law of urban pipe-jacking tunnels is mostly based on shield tunnels. Further, the deformation law of urban shallow-buried pipe-jacking tunnels has rarely been studied.

(2) At present, the characteristics of soil are mostly studied, and the available data on soil quality in soft clay areas are limited.

(3) At present, only a few studies have been conducted on the evaluation system of the comprehensive influence law of groundwater recovery and other complex conditions during the postoperation period, and little attention has been paid to the deformation warning of pipe-jacking tunnel projects during the postoperation period. Studying the influence mechanism of various factors on the surface deformation of soft clay tunnels has a certain guiding and reference significance for the prediction of postconstruction settlement by controlling the preliminary design parameters of pipe-jacking tunnels.

2. Research Idea

To quantitatively analyze the influence degree of various factors on soil deformation after the construction of a pipe-jacking tunnel, this study considers the surface settlement data obtained from the construction of 24 rectangular pipe-jacking tunnels in soft soil layers in China as the research background and adopts the Peck formula back analysis method to obtain the maximum surface settlement and maximum formation loss rate after construction. Considering the influencing factors, such as the structure section of the shallow-buried pipe-jacking tunnel after construction, geological condition of rock and soil mass, groundwater condition, and pipe-jacking depth, statistical product and service solutions (SPSS) data software was used to conduct the correlation analysis, calculate the correlation coefficient between surface deformation and each influencing factor, and explore the change rule of each influencing factor in depth. Subsequently, the multiple linear regression method was used to predict the maximum surface deformation after the construction of a pipe-jacking tunnel, and the monitoring data of actual engineering cases were verified and analyzed, which provided a technical reference for soil deformation early warning of pipe-jacking tunnel engineering in soft clay strata.

2.1. Establishment of Evaluation System. To quantitatively study the deformation law of soil mass induced by various factors in pipe-jacking tunnel engineering, representative engineering parameters should be selected as the evaluation indices. Various studies have focused on practical projects in China [11–13]. The postmaximum surface settlement value during the construction of pipe-jacking tunnel projects was selected as the dependent variable for correlation analysis, and the influence of four factors was mainly analyzed: pipe-jacking area, pipe-jacking buried depth, soil geological condition, and groundwater rebound. To further avoid the problems of inaccurate quantitative analysis, large sample dispersion, and low sample statistical value caused by differences in various factors in different regions [7], the postmaximum index of surface settlement was selected as the absolute dependent variable and the soil loss rate as the relative dependent variable to perform a comparative study; this is also one of the current scientific research methods.

In this study, the fact that soil consolidation of the pipe-jacking tunnel would produce postconstruction consolidation settlement after the completion of the jacking construction was considered. Gang et al. [14] obtained the maximum surface settlement $S1 = 20$ mm during the construction period and calculated the final maximum surface consolidation settlement $S2 = 35.45$ mm after the construction, and the total final maximum surface settlement $S = 55.45$ mm was obtained by the superposition of these two settlements. The postconstruction consolidation settlement accounts for 63.9% of the total settlement, which cannot be ignored. Ma [15] combined data during and after construction and observed that the maximum surface settlement during tunnel construction was 3.5 cm and the post-construction settlement was 5.4 cm. The postconstruction settlement accounted for approximately 60.7% of the total cumulative postconstruction settlement. In this study, the maximum settlement amount during the construction of a pipe-jacking tunnel was obtained. Based on this study, the maximum settlement amount during construction was assumed to account for 40% of the total settlement amount after construction, and the soil loss rate was subsequently calculated using the inverse calculation method from the total settlement amount after construction. According to relevant research results, the rise of groundwater levels has an obvious influence on the surface deformation performance of underground structures.

Owing to different groundwater conditions in different regions, simply comparing the height of the groundwater level in each project case is not feasible. Therefore, three water level conditions were designed after a comparative analysis of groundwater level recovery and the pipe-jacking structure's height (see Figure 1), and the relative height coefficient of groundwater level was proposed as an evaluation index of the impact of groundwater recovery.

$$\xi = \frac{h_w}{h_f}, \tag{1}$$

where ξ is the relative height coefficient of groundwater table, h_w is the height of the water table (m), h_f is the covering thickness (m), and h is the height of pipe-jacking structure (m). According to the analysis of the working condition diagram shown in Figure 1, the position relationship between the groundwater level and the height of the pipe-jacking structure is mainly presented in three ways: in working condition 1, the water level is lower than the bottom of the pipe-jacking structure; in working condition 2, the water level is in the middle of the pipe-jacking structure; in working condition 3, the water level exceeds the top of the pipe-jacking structure; the relative height coefficient of the groundwater level corresponds to the first two working conditions $\xi > 1$and relative height coefficient of groundwater level in working condition 3. Table 1 lists the value range of the relative height coefficient of the groundwater table and the impact on structural safety, which can be seen when $\xi > 1$. The pipe-jacking tunnel structure is in a relatively safe state, and the larger the value, the lower the groundwater level and the greater the distance from the bottom of the pipe-jacking structure. The surface deformation of the pipe-jacking tunnel is less affected by the rising groundwater level. When $\xi < 1$, that is, when the underground water level exceeds the upper part of the pipe-jacking structure, the pipe-jacking tunnel structure is in the most unfavorable safety state with the lowest safety factor. The parameters of other evaluation indicators are defined in Table 2.

2.2. Calculation of the Soil Loss Rate of Rectangular Pipe-Jacking. The construction of a rectangular pipe-jacking tunnel will inevitably cause a change in the soil stress state and stratum loss, which will cause ground deformation. Ground deformation caused by rectangular pipe-jacking is generally predicted using calculation methods of the soil deformation caused by circular pipe-jacking or shield construction [16–22]. Soil loss rate is mainly related to engineering geology, hydrogeology, tunnel construction method, construction technology level, project management experience, and other factors, and the value of this parameter also depends on regional experience [23–30]. The Peck inverse analysis method based on measured data is used to evaluate the soil loss rate. It is assumed that soil movement caused by stratum loss after tunnel jacking excavation takes the form of a nonuniform convergence process. The convergence model of the rectangular pipe-jacking excavation face is shown in Figure 2.

The area equivalent method is adopted; assuming that the rectangular pipe-jacking area is equivalent to the circular pipe-jacking area, then the two areas are equal as follows:

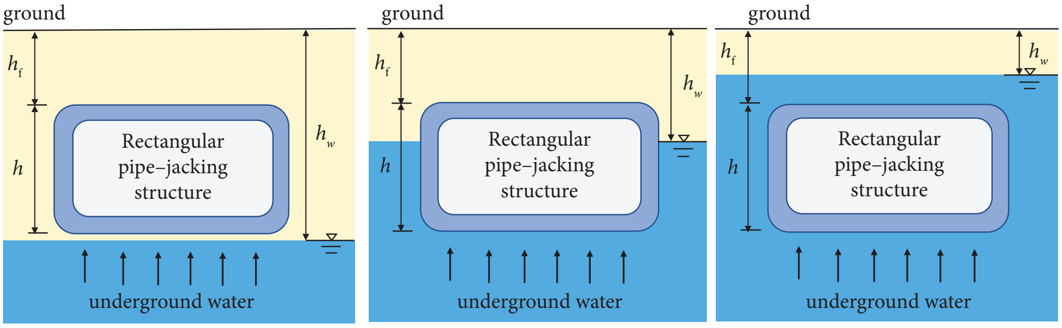

Figure 1: Schematic of the working condition.

Table 1: Value of the groundwater level relative to the height coefficient.

Groundwater level	ξ	Relationship between underground water level and structure height	Security coefficient	Diagram form
$h_w > h_f + h$	$\xi > 1$	Water level lower than the bottom of the jacking structure	High	Operational state 1
$h_f \leq h_w \leq h_f + h$	$\xi > 1$	Water level at middle of pipe-jacking structure	Medium	Operational state 2
$h_w < h_f$	$\xi < 1$	Water level exceeds the top of the pipe-jacking structure	Low	Operational state 3

Table 2: Parameter definition of each evaluation index.

Research program	Evaluation index	Surrogate parameter
Soil deformation	Maximum settlement	$S^*_{\max}$
	Rate of soil loss	η^*
Pipe-jacking construction	Structural area	$M = B \times h$
Soil depth	Relative depth ratio	h_f/h
Geological condition	Internal friction angle of soil	φ
Groundwater condition	Coefficient of the relative height of the groundwater table	ξ

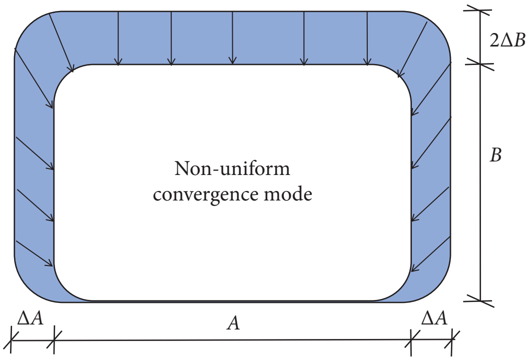

Figure 2: Schematic of the nonuniform convergence model of the excavation face of a pipe-jacking tunnel.

$$(A + 2\Delta A)(B + 2\Delta B) = \pi R^2, \tag{2}$$

$$\frac{S_{\max}}{S^*_{\max}} = 40\%. \tag{3}$$

Based on the Peck formula, the formation loss rate of circular pipe-jacking construction was calculated for the derivation. Combined with the construction settlement and postconstruction operation settlement hypotheses, the soil loss rate in postconstruction operation of a rectangular pipe-jacking tunnel is obtained as follows:

$$\eta^* = S^*_{\max} i \frac{\sqrt{2\pi}}{M}, \tag{4}$$

where $S^*_{\max}$ is the maximum ground settlement in the postconstruction operation period (mm), η^* is the maximum soil loss rate in the postconstruction operation period (%), h is the section height of the pipe-jacking tunnel (m), and $M = B \times h$ is the section area of the pipe-jacking tunnel (m^2).

2.3. Value of the Width of the Settling Trough. The width of the settling trough i is mainly relative to the tunnel axial depth H, tunnel size, and friction angle in the stratum. To better describe the width of the surface settling trough, the width coefficient of the settling trough is calculated as $k = i/H$. Based on previous studies [5, 19], this study selected $k = 0.5(H/D)^{1-n}$ and $n = 0.8 - 1.0$. It is applicable to all types of soil conditions, and combined with equation (4), the soil loss rate of the rectangular pipe-jacking tunnel after construction can be obtained as follows:

$$\eta^* = \frac{S_{\max}(H/D)^{1-n} H\sqrt{2\pi}}{2M}, n = 0.8 - 1.0. \quad (5)$$

2.4. Collection of Measured Data. According to the characteristics of urban strata in China and reference to literature, the strata through which the pipe-jacking tunnel passes can be divided into five categories: soft soil layer (mainly silt and silty soil), viscous soil layer (mainly silt and clay soil), sandy pebble layer (mainly sand, gravel, and pebble), weathered rock and soil layer (mainly rock weathering layer), and loess layer (mainly aeolian loess) [31]. In this study, the surface settlement data of large rectangular pipe-jacking tunnel projects in Shanghai, Guangzhou, Shenzhen, Kunming, Suzhou, Zhengzhou, and other provinces were comprehensively and systematically collected. The surface settlement trough data of 24 projects in 10 provinces, 14 cities, and 10 provinces were collected. The statistical data of the characteristic parameters of sedimentation trough are listed in Table 3. The maximum postconstruction settlement and maximum postconstruction soil loss rate of the pipe-jacking tunnel are calculated using equations (4) and (5). Figures 3 and 4, respectively, show the distribution histograms of the maximum postconstruction settlement and soil loss rate, which are used to estimate the reliability of statistical analysis of data.

According to the data presented in Table 3 and the statistical distribution of the maximum ground settlement and soil loss rate in the engineering cases of soft clay strata in China shown in Figures 3 and 4, the maximum ground settlement is mainly in the range of 20–50 mm, accounting for 91.67% of the total. The variation range of the soil loss rate in the settlement deformation of the pipe-jacking tunnel with soft clay stratum is 0.11%–1.81%. The samples with soil loss rates ranging from 1% to 1.5% accounted for 95.83% of the total, indicating that the numerical range of soil loss rate was a small dispersion; this was suitable for statistical analysis.

3. Correlation Analysis of Influencing Factors of Surface Deformation in the Pipe-Jacking Tunnel

3.1. Correlation Analysis Description. Correlation analysis is a statistical analysis method that examines the linear relationship between two or more variable elements (a description of the correlation analysis method is given in the Supplementary Materials (available here)). To accurately explore the correlation between variables through data mining, the maximum settlement and soil loss rate are considered as the dependent variables of correlation analysis, whereas the relative depth ratio, section area, soil internal friction angle, and groundwater level relative height coefficient are assumed as the independent variables. A quantitative investigation was performed through hypothesis testing and calculation of the correlation coefficient. In addition, to realize the reliability of sample data more systematically and accurately, the highest and lowest values of each influence parameter are summarized, which is more conducive to the comprehensive judgment of the data. After SPSS software analysis, the correlation of each factor in the statistical data is listed in Table 4 (the specific calculation theory is given in the Supplementary Materials (available here)). The general correlation analysis in Table 4 indicates that the significant coefficient between postsoil loss rate η^* and the postmaximum ground settlement value $S^*_{\max}$ is 0.019, which is less than 0.05, indicating that there is a significant correlation between the two. It can be seen from the Pearson phase relationship value of 0.476 that there is a positive correlation between the two; that is, with an increase in the soil loss rate η^*, the postmaximum ground settlement value $S^*_{\max}$ also increases.

In soft clay strata, the significant coefficient between the postmaximum ground settlement $S^*_{\max}$ and the relative buried depth ratio h_f/h is 0.01–0.014, which is less than 0.05, indicating a significant correlation between the two. It can be seen from the Pearson correlation values of −0.516 to −0.494 that a negative correlation exists between the two. The significant coefficient between the maximum ground settlement $S^*_{\max}$ and the section area $M = B \times h$ is 0.032, which is less than 0.05, indicating a significant correlation between the two. The Pearson correlation value of 0.439 suggests a positive correlation between the two. The significance coefficients of the maximum ground settlement $S^*_{\max}$ with the soil internal friction angle φ are 0.082–0.554, and the significance coefficients of the maximum ground settlement $S^*_{\max}$ with the relative height coefficient of groundwater level are 0.236–0.282, respectively, all greater than 0.05, indicating that the friction angle and groundwater level ξ have no significant correlation with the postmaximum ground settlement value.

3.2. Correlation Analysis between the Maximum Ground Settlement and Formation Loss Rate during Postconstruction Operation. Figure 5 shows the variation in the maximum ground settlement $S^*_{\max}$ with soil loss rate η^* in different pipe-jacking projects in soft clay strata during the postconstruction period. The figure demonstrates that the maximum ground settlement increases with the increase in soil loss rate during the postconstruction operation period. The relationship between the two is linear, which is consistent with the change law of traditional cognition and further explains the reliability of data statistics. The relatively dispersed data may be caused by the differences in collected engineering data from different external environments, management levels, and construction experiences.

4. Analysis of Influencing Factors of Surface Deformation during Postconstruction Operation

4.1. Simple Correlation Analysis between Maximum Ground Settlement, Soil Loss Rate, and Relative Buried Depth Ratio. Since the surface deformation of the pipe-jacking tunnel will change with its buried depth, this study adopted the relative buried depth ratio to analyze its influence on the maximum

TABLE 3: Statistical table of characteristic parameters of settlement troughs in some engineering cases of soft clay strata in China.

Serial numbers	Regions/provinces	Crossing formation feature	$S^*_{\max}$ (mm)	η^* (%)	h	M	h_f	h_f/h	φ	ξ
1	Shanghai	Gray silty soil, silty clay layer	16.67	0.73	4.2	28.98	5.1	1.10–1.21	12.00	1.09
2	Wen [32], Feng [33], and Zhu [34]	Silty sandy soil, silty clay	40.83	0.88	6.3	61.74	12.0	1.84–1.90	11.50–30.50	0.03–0.13
3	Jiangsu Zhou et al. [35], Zhou et al. [36], Ma et al. [37], Guo et al. [38], Chen [39], and Jin et al. [40]	Silt with silt	33.33	0.88	5.5	50.05	9.0	1.64	31.40–33.40	0.11–0.22
4		Silt with silt	26.67	1.25	4.2	28.98	9.2	2.07–2.19	16.80–33.40	0.23–0.34
5		Clay	40.18	1.43	5.0	34.50	4.0	0.80	5.00–35.00	0.25–0.50
6		Silt with silt	30.00	0.79	5.5	50.05	9.0	1.64	22.70–31.40	0.06–0.28
7		Silt with silt	16.02	0.57	5.0	35.00	4.4	0.75–0.87	15.00–19.00	0.53–2.26
8		Silt with silt	4.47	0.17	4.9	33.81	5.6	0.33–1.14	20.00	0.38–1.13
9	Henan Hu [41], Wang et al. [42], Guo [43], and Huang [44]	Silty soil, silty clay	35.83	0.57	7.3	73.73	4.0	0.44–0.55	20.00	2.66
10		Silty clay	13.00	0.54	4.2	32.76	10.0	2.38	3.00–7.00	1.10–1.17
11		Silt, clay	33.33	0.52	7.5	78.00	5.4	0.68–0.72	23.50–24.00	1.20
12		Silty clay	47.72	0.13	12.7	370.84	1.2	0.09	8.90–46.00	12.50–16.67
13	Tianjin [45]	Silty clay	42.17	0.67	7.6	79.04	8.2	1.08	9.00	0.31
14	Hubei [46]	Mucky silty clay	3.33	0.25	2.7	18.90	8.8	3.26	12.00	0.34–0.45
15	Zhejiang	Silty clay, sandy silt	50.00	0.43	9.4	139.12	6.5	0.60–0.70	10.50–27.50	0.09–0.74
16	Liu et al. [47] and Wu et al. [48]	Silty clay, silt	8.33	0.33	4.3	32.25	5.5	1.27	23.80–24.70	0.39
17	Fujian Chen [49] and Huang et al. [50]	Silt, medium sand	70.00	1.00	9.3	83.70	6.0	0.27–0.65	5.40–20.00	1.00
18	Yunnan [51]	Silty clay interbedded	46.67	1.81	4.9	33.81	7.5	1.12–1.53	18.50–31.00	0.45–1.02
19	Guangxi [52]	Silty clay	30.00	1.11	4.9	33.81	5.0	1.02	13.00–15.00	1.00
20	Guangdong Lin [53], Xin et al. [54], Shang [55], Duan et al. [56], Zhao [57], and Wei et al. [58]	Silty fine sand and silty clay	28.67	1.42	4.3	25.80	5.2	1.19–1.21	10.00–16.00	0.15–0.36
21		Sandy soil Clayey soil	15.83	0.60	4.5	34.65	7.0	1.56	12.00–30.00	0.07–0.69
22		Medium sand	37.50	1.34	4.9	33.81	3.5	0.71	22.00–28.00	1.23
23		Gravel cohesive soil, plain fill soil	20.00	0.38	6.6	67.32	8.4	1.27	15.00–20.00	0.24–0.95
24		Silty clay	3.33	0.11	5.5	41.25	8.0	1.45	8.00–23.50	0.69

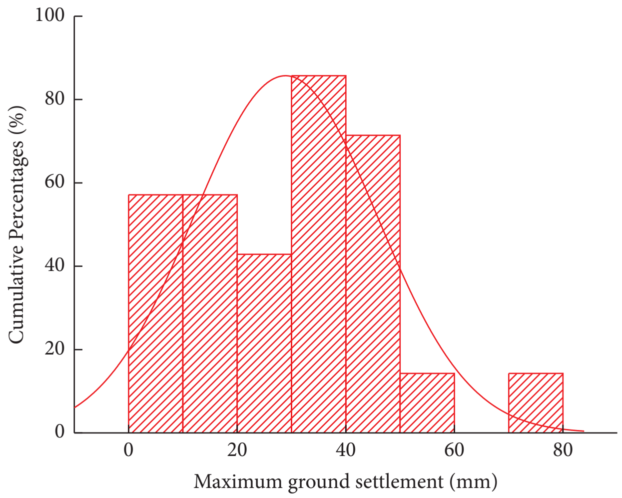

Figure 3: Histogram of distribution frequency of maximum ground settlement.

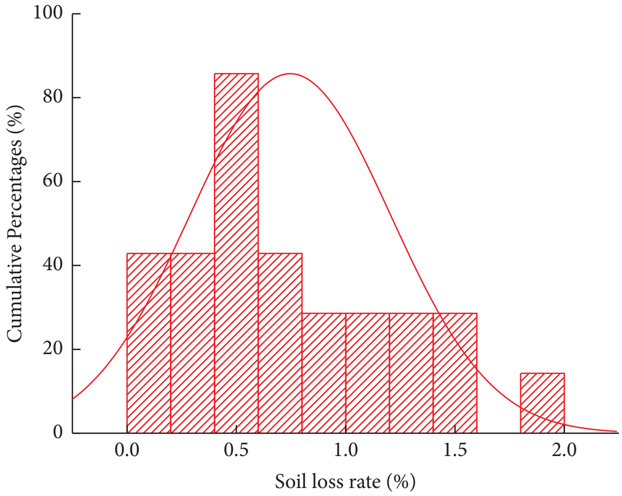

Figure 4: Histogram of distribution frequency of soil loss rate.

ground settlement. The analysis in Figure 6 shows that (1) under different relative burial depths, the land subsidence is mainly concentrated in the range of 20–50 mm, and the average value of the maximum ground subsidence is 28.91 mm, which meets the standard requirements of 30.0 mm specified in the relevant domestic maximum ground subsidence control; (2) with an increase in the relative buried depth ratio of pipe-jacking tunnels, the maximum ground settlement gradually decreases, and the relationship between the two becomes an approximate logarithmic function. When the relative buried depth is greater than 2.0, the average value of the maximum surface settlement is less than 30 mm. The trends of the fitting relationship show that when the relative buried depth is greater than 3.0, the influence of deep-buried tunnel construction on stratum movement is smaller or even negligible. This is because with an increase in the relative buried depth of the pipe-jacking tunnel, the thicker the soil covering the pipe-jacking tunnel, the more fully the "bearing arch" effect of the tunnel stratum can be brought into play, and the weaker will be the surface movement effect. Moreover, the impact of the postconstruction state after the disturbance of pipe-jacking construction on the surface will be small; thus, the maximum ground settlement will also decrease. This is consistent with the analysis results of the significant negative correlation between the maximum ground settlement value and the relative buried depth ratio in Table 4, and the research conclusion is also consistent with that of Zhu and Li [8] and other researchers.

It can be seen from the analysis in Figure 7 that the soil loss rate of soft clay stratum ranges from 0 to 1.5%, and the relative buried depth ratio of the pipe-jacking tunnel ranges from 0.5 to 2.0. When the relative burial depth ratio is less than 0.5, the soil loss rate is relatively small in the case of ultra-shallow burial. When the relative buried depth ratio is $0.5 < h_f/h < 2.0$, the soil loss rate is relatively concentrated in the range of 0%–1.5%. This section demonstrates that the soil loss rate increases with an increase in the relative depth ratio, exhibiting an approximately linear positive correlation. When $h_f/h > 2.0$, the overall soil loss rate shows a decreasing trend. This is because when the relative buried depth ratio exceeds a certain limit, the soil jacking becomes thicker, the "bearing arch" effect of tunnel stratum comes into play, and the surface movement effect becomes weaker. Consequently, the influence of soil jacking construction on stratum decreases, sensitivity becomes worse, and the soil loss rate shows a decreasing trend. This conclusion is similar to those in the literature [6, 9].

4.2. Simple Correlation Analysis of the Maximum Ground Settlement, Soil Loss Rate, and Sectional Area. The graphs in Figures 8 and 9 indicate that because of the statistical reasons of the sample data in this study, the sectional area of pipe-jacking in China is mainly within 100 m^2, the maximum settlement of soil mass during postconstruction operation is within the range of 0–50 mm, and the soil mass loss rate is mainly within the range of 0%–1.5%. The graphs in Figures 8 and 9 indicate an approximate linear relationship between the size of the pipe-jacking section and the maximum ground settlement and soil loss rate during construction within a certain range. The pipe-jacking area in China is mainly concentrated within 100 m^2, and the maximum ground settlement is controlled within the range during construction. The soil loss rate is mainly in the range of 0%–1.5%. When $M < 25\,\mathrm{m}^2$, the postmaximum ground settlement is small. When $25\,\mathrm{m}^2 < M < 100\,\mathrm{m}^2$, the section area increases, the maximum ground settlement also increases gradually, and the two have an approximately positive correlation. Based on the trend analysis of the fitting curve, it is estimated that when the pipe-jacking section area $M \geq 100\,\mathrm{m}^2$, the ground settlement of pipe-jacking will increase and exceed the 30 mm range stipulated in China's domestic standard. As shown in Figure 9, the soil loss rate of the pipe-jacking tunnel after construction tends to decrease linearly with the increase in the section area, and when $25\,\mathrm{m}^2 < M < 100\,\mathrm{m}^2$, the soil loss rate is mainly within the range of 0.5%–1.0%, and compared with the increase in the maximum ground settlement, the soil loss rate decreases only slightly. This is because with the increase

Table 4: General correlation analysis table of the parameters of the settling trough after operation.

Parameters of settling tank after operation		Maximum sedimentation	Rate of soil loss	Buried depth ratio		Sectional area	Boundary of the friction angle		Coefficient of the relative height of the water table	
				High limit	Lower limit		High limit	Lower limit	High limit	Lower limit
Maximum sedimentation	Pearson correlation	1	0.476*	−0.516**	−0.494*	0.439*	−0.362	0.127	−0.229	−0.251
	Significance (bilateral)		0.019	0.010	0.014	0.032	0.082	0.554	0.282	0.236
	N	24	24	24	24	24	24	24	24	24
Rate of soil loss	Pearson correlation	0.476*	1	−0.017	−0.023	−0.345	0.153	0.034	−0.307	−0.291
	Significance (bilateral)	0.019		0.938	0.913	0.098	0.475	0.874	0.145	0.167
	N	24	24	24	24	24	24	24	24	24

*Significant correlation at the 0.05 level (bilateral). **Significant correlation was found at 0.01 level (bilateral).

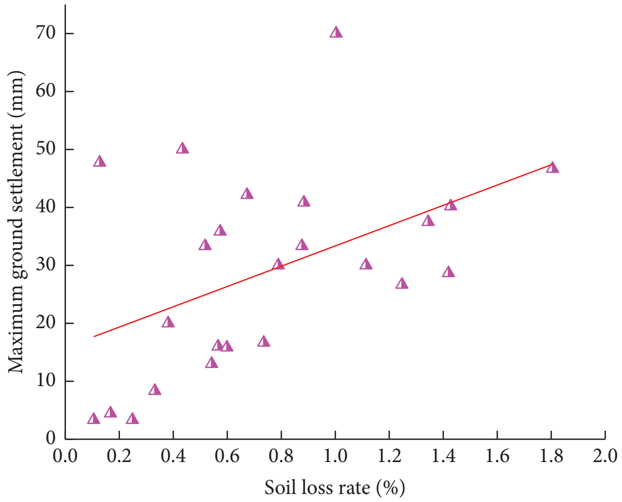

Figure 5: Correlation analysis diagram between the maximum settlement after construction and the soil loss rate of soft clay strata.

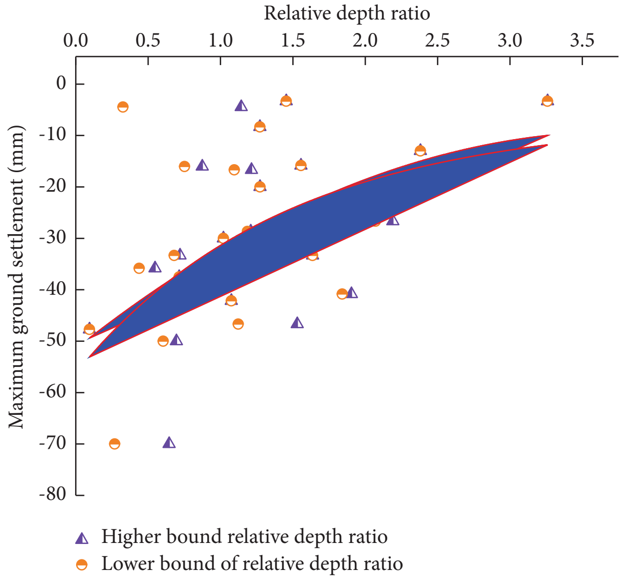

Figure 6: Correlation analysis diagram of the relative buried depth ratio of soft clay stratum and maximum ground settlement.

in the pipe-jacking section area, the disturbance to the soil mass caused by pipe-jacking tunnel construction increases, and the corresponding soil loss also increases, which is manifested as an increase in ground settlement. However, the soil loss rate is generally represented by the rate of soil settlement in a unit area. The larger the pipe-jacking area, the smaller the soil loss rate. The settlement control is particularly important in the construction and postconstruction operation processes of pipe-jacking tunnels.

4.3. Simple Correlation Analysis between Maximum Ground Settlement, Soil Loss Rate, and Formation Characteristics. The internal friction angle of soil reflects the frictional characteristics of soil and is an important parameter to evaluate the strength of rock (soil). The greater the internal

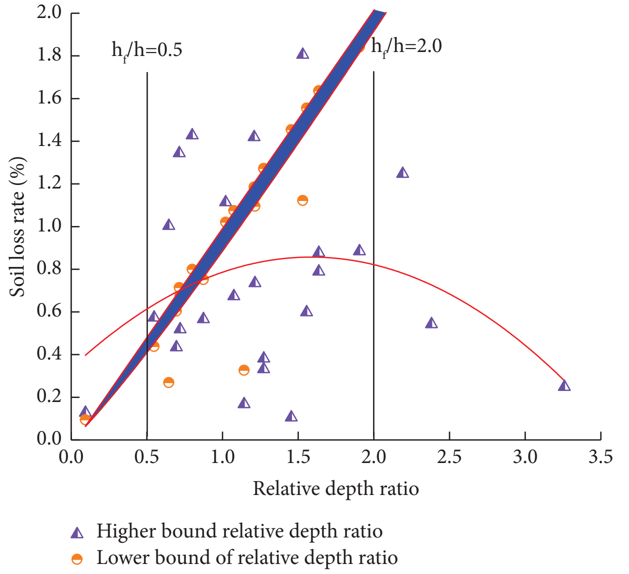

Figure 7: Correlation analysis diagram of the relative buried depth ratio of soft clay stratum and soil loss rate.

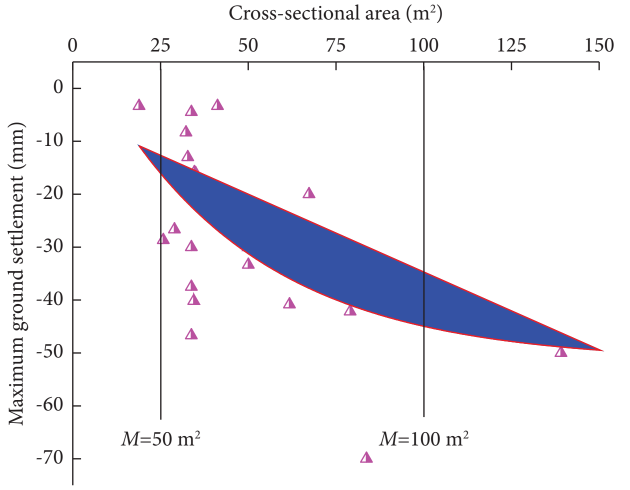

Figure 8: Correlation analysis diagram between the sectional area of soft clay strata and the maximum ground settlement.

friction angle of the soil, the more stable the formation characteristics. As can be seen from Figure 10, the internal friction angle through the soil layer in the pipe-jacking tunnel project is within the range of $\phi = 5^\circ - 35^\circ$, and the data are relatively centralized. The data fitting curve shows that in the same soft clay stratum when all other conditions are the same, the maximum ground settlement first decreases and then increases with the increase in the soil internal friction angle. When the internal friction angle of soil is at $\phi = 15^\circ - 25^\circ$, the maximum ground settlement is less than 30 mm. When the soil internal friction angle is $\varphi < 15^o$ or $\varphi > 25^o$, the maximum ground settlement increases and decreases, respectively, and the settlement is within the range of 30 to 40 mm, indicating that the soil internal friction angle is too large or too small and the ground settlement will increase. This is because when the internal

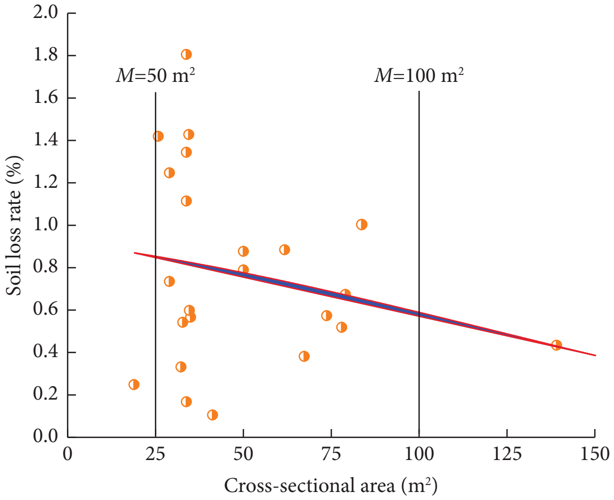

Figure 9: Correlation analysis diagram between section area and soil loss rate of soft clay stratum.

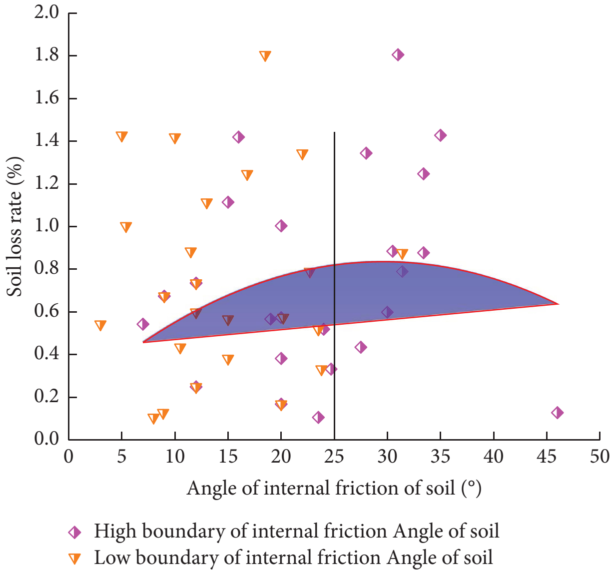

Figure 11: Relation between the internal friction angle and soil loss rate in soft clay stratum.

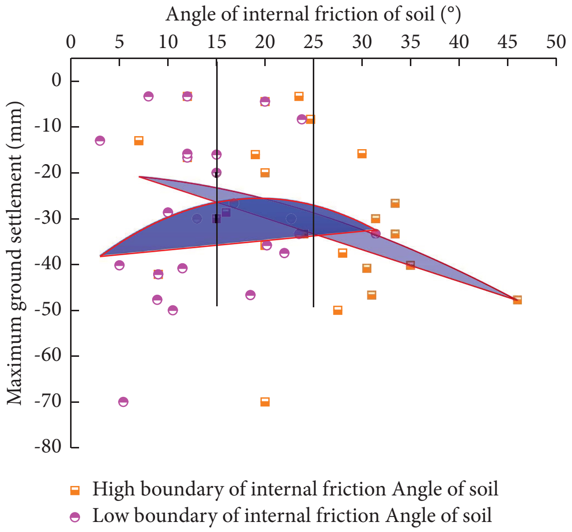

Figure 10: Relation between the internal friction angle and the maximum ground settlement in soft clay stratum.

friction angle of the soil is too small, the soil quality is relatively loose, the compactness of the soil is poor, and soil deformation is affected by disturbance during the construction. When the internal friction angle of the soil is larger than 25°, the power of the mechanical equipment used in construction will increase accordingly because the soil is dense and hard, thereby causing considerable disturbance to the stratum and a trend of relatively increasing ground deformation.

The relationship between the soil internal friction angle and the soil loss rate in Figure 11 is analyzed, and according to the data fitting curve, the soil loss rate first increases and then decreases with an increase in the internal friction angle of soil. When $15^\circ < \phi < 35^\circ$, the soil loss rate ranges from 0.4% to 0.8% and increases gradually with an increase in the friction angle. When $\phi > 35^\circ$, the soil loss rate decreases gradually. Compared with Figure 10, the soil loss rate changes along with the soil internal friction angle, and the maximum ground settlement change trend remains the same. This is because when the internal friction angle of the soil mass is large, the soil is more stable and harder, and the ground deformation and soil loss rate caused by construction also increase; thus, the soil characteristics have a crucial influence on ground deformation. This result is consistent with those of Wu et al. [9].

4.4. Simple Correlation Analysis of the Maximum Ground Settlement, Soil Loss Rate, and Groundwater Level Relative Height Coefficient. As can be seen from the analysis in Figure 12, with the statistical data of selected engineering cases, the relative height coefficient of groundwater level ξ in soft clay strata is in a concentrated range of 1.0–4.0, and with an increase in the relative height coefficient of groundwater level ξ, the land settlement increases slowly and tends to be stable after reaching a certain settlement amount. This is because the higher the relative height coefficient of the groundwater table, the deeper the groundwater table, and the greater the distance from the bottom of the pipe-jacking structure, the less the impact of the rising groundwater table on the surface deformation of the pipe-jacking tunnel and the smaller the settlement deformation of the surface soil.

According to the trend of the fitting curve, when the value of ξ is less than 1, the soil deformation will be positive and the soil will be uplifted. This is because after the groundwater level exceeds the top of the pipe-jacking structure, the buoyancy effect of the groundwater on the main pipe-jacking structure is far greater than the sum of gravity and other additional effects of the pipe-jacking structure, leading to surface uplift and deformation. When the value of ξ is greater than four, the settlement value tends to be stable; that is, when the distance between the groundwater level and the bottom of the pipe-jacking structure is large enough, the influence of groundwater

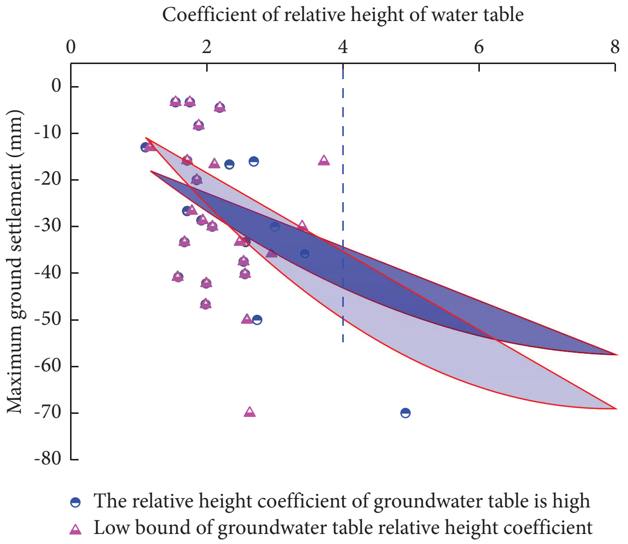

Figure 12: Relation between the relative groundwater level height coefficient of soft clay stratum and the maximum ground settlement.

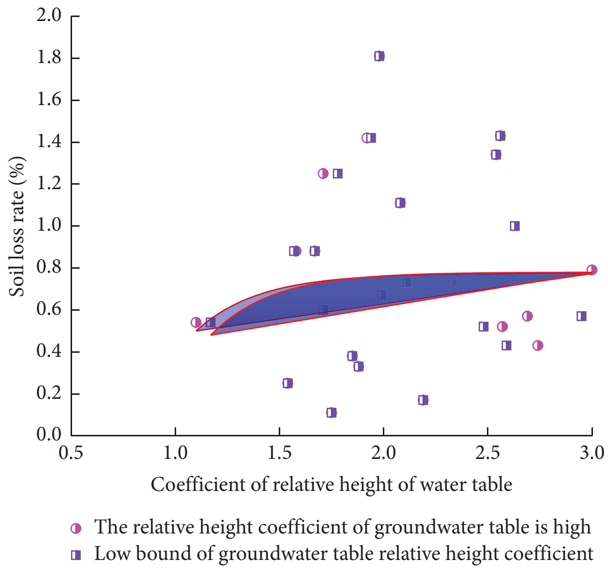

Figure 13: Relation between the relative height coefficient of groundwater level and soil loss rate in soft clay stratum.

rebound on the pipe-jacking structure and soil deformation becomes almost negligible, and the soil settlement deformation tends to become stable. It is very important to monitor and give early warnings regarding the rise of groundwater level during pipe-jacking construction and operation.

As shown in Figure 13, when the soil loss rate is mainly concentrated in the range of 0%–1.0%, the relative height coefficient of groundwater level ξ is mainly concentrated in the range of 1.0–3.0. Meanwhile, a comparative analysis of Figures 12 and 13 shows that with an increase in the relative height coefficient of groundwater level ξ, the maximum ground settlement tends to gradually increase, and the soil loss rate also tends to gradually increase, but the change range of the maximum ground settlement is greater than that of the soil loss rate. The relationship between the maximum ground settlement and the soil loss rate is further explained; that is, with an increase in ground settlement, the soil loss rate also increases. As can be seen from the figure, when $\xi > 2.0$, the soil loss rate tends to be stable, and the value remains in the range of 0.6%–0.8%.

5. Prediction and Analysis of Surface Subsidence during Postconstruction Operation

In this study, quantitative and qualitative methods are used to analyze the variation law of the maximum surface settlement and soil loss rate of an urban shallow-buried pipe tunnel under the comprehensive influence of various factors during the postconstruction operation of soft clay strata. Combined with the above studies, multiple linear regression calculations were performed for each factor. The general form of the multiple linear regression model is as follows:

$$y = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots\cdots \beta_n x_{in} + \varepsilon, \qquad (6)$$

where $\beta_0, \beta_1, \cdots, \beta_{\mathrm{n}}$ is called the population regression parameter, $i = 1, 2, \cdots, n, \varepsilon$ is the random error, and $E(\varepsilon) = 0$. The correlation regression formula is obtained as follows:

$$S^*_{\max} = \frac{8.5828 h_f}{h} - 0.1577M + 0.2169\phi + 5.2138\xi - 27.6963R^2 = 0.7192, \qquad (7)$$

$$\eta^* = -\frac{0.1507 h_f}{h} - 0.0039M - 0.004\phi + 0.027\xi + 1.197R_0^2 = 0.1669. \qquad (8)$$

In equations (7) and (8), $S^*_{\max}$ is the maximum ground settlement during postconstruction operation period (mm); η^* is the maximum soil loss rate during the postoperation period (%); h is the section height of the pipe-jacking tunnel (m)); M is the section area of pipe-jacking tunnel (m^2); h_f is the soil covering depth (m); the relative depth ratio is h_f/h; friction angle through formation is φ; and the coefficient of relative height of the water table is $\xi = h_w/h_f$. Compared with $R_0^2 < R^2$, the value R^2 is closer to 1, and equation (7) is more reliable and can be used as a prediction formula for the maximum ground surface settlement of a shallow-buried rectangular pipe-jacking tunnel during the postoperation period.

5.1. Verification Analysis of Practical Engineering Cases

5.1.1. Actual Engineering Cases. Based on the above prediction of the maximum surface settlement during the postconstruction operation period, a case study of the inclined shallow-buried pipe tunnel through the Longhai Railway line in Xi'an was selected, and the actual engineering diagram is shown in Figure 14. The overpass adopts the reinforced concrete structure of $(4.5 + 5 + 15.5 + 15 + 4.5)$ m, the pipe section width B is 50.5 m, the height h is 10.30 m, and the soil covering depth is 1 m. The groundwater is, the buried depth of the water table is approximately 9.80–13.50 m, the excavation depth of the pipe-jacking foundation pit is 14.2 m, and the water table is 0.5 m below the bottom of the pipe-jacking structure during the construction. The pipe-jacking through the soil layer is the silty clay layer, and the average internal friction angle of the soil is $\phi = 20^\circ - 25^\circ$.

The monitoring radius of the pipe-jacking tunnel section is set to be no less than 60 m according to the requirements of the monitoring specifications, and the monitoring range along the forward direction of the pipe-jacking is 52 m from the top distance of pipe-jacking. Monitoring of pipe jacking starts from the initial section of the pipe-jacking and is distributed between the initial well and the receiving well. Five sections (CJ1, CJ2, CJ3, CJ4, and CJ5) are set, and each section has 21 measuring points. The distance of each monitoring point is 2–5 m according to the requirements, and a distance of 4 m is selected. The settlement point code of the pipe-jacking tunnel is the monitoring section + the serial number. For example, CJ1 + 1 is measuring point 1 on the upper side of the CJ1 section. Specifically, they are CJ1 − 1–CJ1 − 10, CJ1 + 0, CJ1 + 1–CJ1 + 10, which are symmetrical with the pipe-jacking axis. There are 105 measuring points in total, and the measuring points are arranged as shown in Figure 15. The settlement amount of the monitoring section is mainly monitored before, during, and after the arrival of the rectangular pipe-jacking, and the surface deformation law of the surface measuring point of the rectangular pipe jacking is analyzed and examined.

6. Analysis of Surface Subsidence Monitoring Data

6.1. Analysis of the Variation of the Settlement of Each Monitored Section with the Topflight. According to the construction field measurement results, the No. 0 measuring point of the five monitoring sections (CJ1 + 0, CJ2 + 0, CJ3 + 0, CJ4 + 0, CJ5 + 0) is considered as the representative, and the development trend curve of its settlement with the change of the top height is drawn.

Period 1: In the early stage of jacking construction of the pipe-jacking tunnel, surface uplift occurs and the pipe-jacking structure floats up.

Period 2: Pipe-jacking construction enters a stable period, and the daily settlement fluctuates, but the overall trend is stable.

Figure 14: Xi'an Jingjiu road pipe-jacking tunnel engineering test site.

Period 3: Pipe-jacking tunnel construction is completed, and it enters the postconstruction operation stage.

Figure 16 shows that each section presents the same variation rule with the settlement of each measuring point in the construction of the pipe-jacking tunnel:

(1) Sections 1 and 2 are close to the initiation area of pipe-jacking, and the soil settlement is large. As the monitored section is far away from the initiation area, the soil settlement generally decreases. The maximum settlement of each section during construction is −22.60 mm, −18.48 mm, −10.77 mm, −9.81 mm, and −15.65 mm. The reason was that the settlement rate exceeded the warning value after crossing Sections 1 and 2 during pipe-jacking construction. Measures such as increasing the grouting amount, grouting pressure, and secondary grouting were immediately recorded on-site, and the thixotropic mud was continuously pressed into the surrounding area of the pipe joint under the two sections, which had a good effect of supporting the stratum and reducing the subsequent settlement.

(2) Before the pipe-jacking reaches each fault, the soil mass presents a certain degree of uplift. The uplift at the measuring points from Sections 1 to 5 is 1.83 mm, 2.02 mm, 1.92 mm, 2.11 mm, and 2.21 mm, respectively. The soil mass deformation at this stage is small and has little influence on the overall deformation trend.

(3) After pipe-jacking through the section, owing to the disturbance of pipe-jacking to the soil and the formation loss caused by the construction, the settlement of each measuring point begins to appear at a high rate. As the jacking construction continues to move forward and the grouting construction technology measures are adopted, the settlement of each measuring point at the section gradually becomes stable.

6.2. Analysis of the Variation Law of Construction Settlement and Postconstruction Settlement. The pipe-jacking construction gradually stopped after passing the last monitoring section (Section 5), and then monitoring of site data was continued. Figure 17 shows the measured settlement curve of monitoring Section 5 and the measured monitoring data

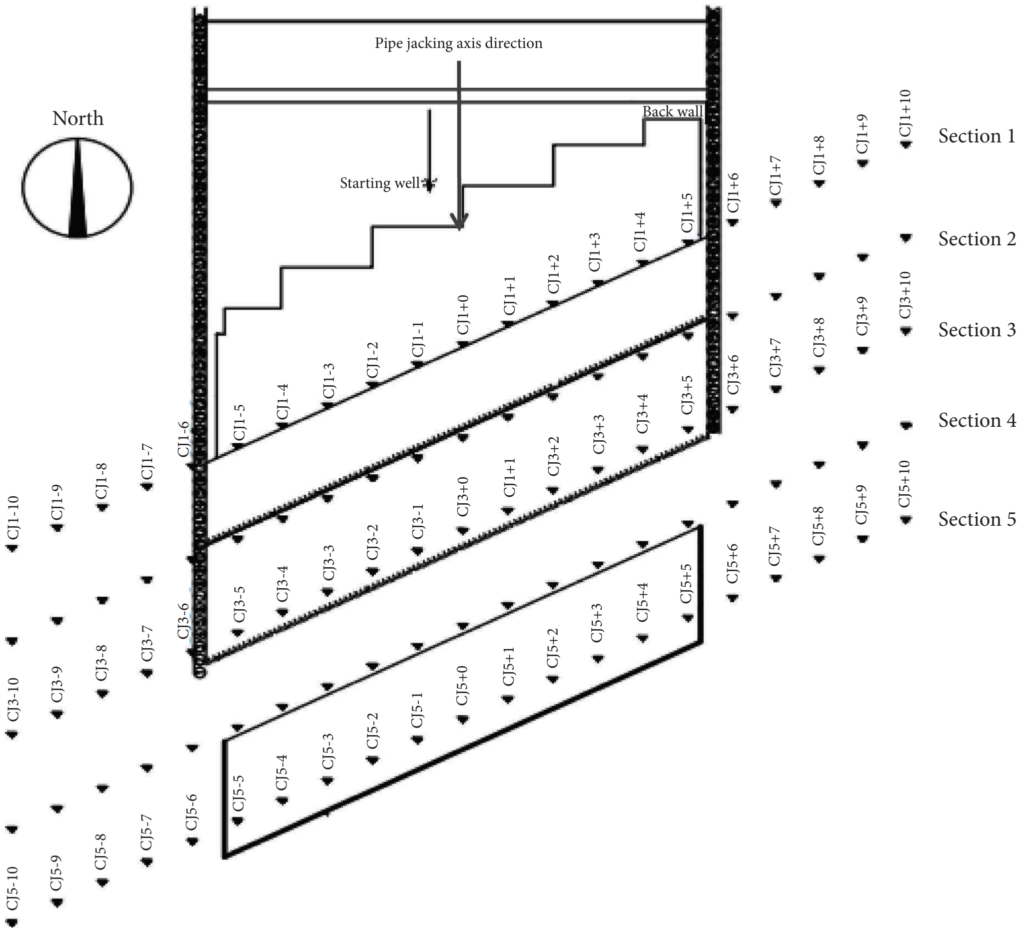

Figure 15: Layout of surface settlement monitoring points for pipe-jacking.

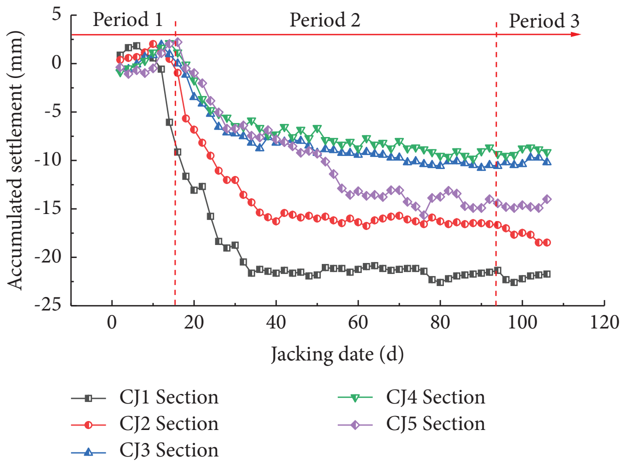

Figure 16: Variation curve of the settlement of each monitored section with the topflight.

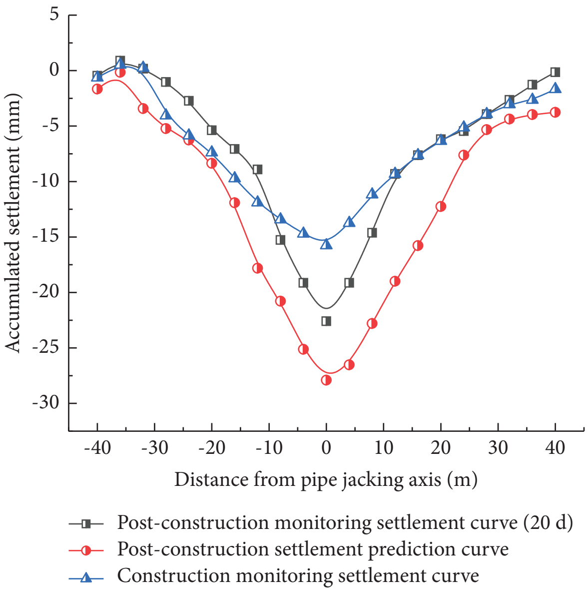

Figure 17: Construction process and postconstruction settlement curve comparison.

20 days after the completion of construction, which was used to analyze the variation rule of settlement in the construction and postconstruction operation stages. Combined with Figure 16, the maximum settlement during jacking construction of the pipe-jacking tunnel was 15.65 mm, and the maximum consolidation settlement after 20 days of construction was 23.59 mm, where the construction remained stable without elimination. By comparison, the maximum settlement during the construction period of the pipe-pushing tunnel accounts for 66.3% of the maximum

postconstruction consolidation settlement, which is consistent with the previous research hypothesis and further proves the reliability of data monitoring. The actual engineering case parameters in Section 6.1 are imported into equations (6) and (7) for calculation, and the predicted maximum ground settlement during operation after construction is as follows: $S^*_{\max} = -27.91mm$. The deviation rate between the measured data and the predicted value reached 15.4%. Combined with the Peck formula settlement trough theory, the maximum settlement point was located above the jacking axis, and the predicted change curve of surface settlement was drawn using the back analysis method, as shown in Figure 17. The reduction coefficient method was adopted to further optimize the fitting of the prediction formula. The reduction coefficient was 0.937–0.846, and a new prediction was obtained as follows:

$$S^*_{\max} = \frac{8.042h_f}{h} - 0.148M + 0.205\phi + 4.885\xi - 25.951. \tag{9}$$

It has been verified that the predicted settlement value was 25.938 mm, and the error from the measured value was 9.05%, which indicates a relatively accurate range and can be used as the prediction formula for postconstruction settlement.

7. Conclusions

In this study, various influencing factors of shallow-buried pipe tunnel engineering in soft clay stratum are selected, an evaluation index system of deformation influence is established, correlation quantitative comparative analysis is performed on each factor, and the deformation rule under the comprehensive influence of all factors is obtained. Multiple linear regressions are used to quantify the prediction formula of the maximum surface settlement during the postconstruction operation, and the results are combined with the actual project analysis and verification. The following conclusions are drawn:

(1) There is a strong correlation between the relative buried depth of pipe-jacking, the sectional area of the soft clay stratum, and the maximum ground settlement value; the maximum ground settlement value decreases with an increase in the relative buried depth of the pipe-jacking tunnel, and the maximum ground settlement value increases with an increase in the sectional area. The soil internal friction angle and relative influence height coefficient of groundwater level have a significant correlation with the maximum ground settlement value.

(2) From the perspective of influence degree, the relative buried depth of the pipe-jacking tunnel has the greatest influence on the maximum ground settlement, followed by the section area of the pipe-jacking tunnel, and the relative height coefficient of groundwater level has the least influence.

(3) Combined with the statistical results of 24 engineering cases of soft soil layer, the multiple regression analysis method was used to fit and form the prediction formula of maximum surface settlement during the postconstruction operation period, and the results were verified and analyzed with the actual engineering settlement monitoring data. The prediction formula for the maximum surface settlement deformation during the postconstruction operation period was formed with the error rate controlled at 15.4%. The new prediction formula was obtained by considering the reduction coefficient of 0.937 – 0.846, and the error was 9.05% compared to the actual measurement, which has certain guidance and reference significance for practical engineering.

When selecting the deformation data of pipe-jacking tunnel projects in this paper, considering the error factors such as regional differences, construction technology differences, and differences in data collection, the relative value is used for analysis when possible, which has a certain reference value. However, in the follow-up research, it is necessary to conduct a quantitative study on the deformation law under the comprehensive influence of various factors during the operation of a single project in a single area. Combined with the measured data, the settlement prediction is studied by machine learning.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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Supplementary Materials

Correlation analysis principle. (*Supplementary Materials*)

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