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Research Article

Modification of Peck Formula to Predict Ground Surface Settlement of Twin Tunnels in Low Permeability Soil

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Accurate prediction of surface settlement induced by tunnel excavation is significant for preventing damage to existing structures under complex geological conditions. The Peck formula is currently considered as an efficient solution for surface settlement prediction. This paper proposes a modified Peck formula considering geological conditions to improve the accuracy of surface settlement prediction of twin tunnels. The asynchronization of the sinking rate and stability of the vault settlement and surface settlement within the river-affected area may attribute to the groundwater drawdown caused by cofferdam construction on the river. A modified Peck formula is put forward with soil permeability and width-controlling parameters involved. There is a small settlement at the center of the twin tunnels, making the settlement trough upward buckling, which is like a "W" shape. This situation can be accurately predicted by the modified formula with a significantly increased adjusted R-square. The modified formula can accurately predict the surface settlement of tunnels excavated in low permeability soil layers with a permeability coefficient between 10^{-4} cm/s and 10^{-7} cm/s, especially in the groundwater drawdown environment. The reliability of the modified Peck formula is verified by other cases in Nanjing and Singapore.

1. Introduction

Due to the rapid development and expansion of coastal cities around the world, underground traffic construction has been widely adopted to alleviate traffic pressure. Inevitably, an increasing number of subway and road tunnels are planned and constructed through rivers or sea with prosperous business districts nearby, which are considered as complex geological conditions. In tunnel construction, surface settlement caused by excavation is one of the most critical issues as it may cause damage to existing structures near tunnels. Therefore, accurately predicting surface settlement in tunnel construction is of great importance.

To date, many studies on the prediction of surface settlement in tunnel construction have been carried out. Peck [1] considered the form of tunnel surface settlement as a normal distribution curve based on a large amount of measured data and first summarized an empirical formula to predict tunnel surface settlement under the assumption that the volume of the settlement trough is equal to the soil loss volume in undrained conditions. O'Reilly and New [2] proposed the empirical formula between settlement trough width and the tunnel depth for cohesive soil and sand. Liu and Hou [3] modified the Peck formula by considering the effect of pore pressure dissipation and tunnel depth. Many attentions have been paid to various influencing factors of surface settlement, e.g., space and time [4], the shape and depth of the tunnel [5–8], soil types and construction operation [9–13], reinforcement [14], and consolidation settlements [15, 16]. The prediction models in these studies greatly improve our understanding of tunnel settlement in different soils, whereas the utility of them cannot be extended to the tunnels in complex geological conditions, primarily owing to the ignorance of groundwater flow.

In general, groundwater seepage is recognized as a risk for tunnel construction and thus decelerates the speed of excavation. The occurrence of seepage in the rock massifs could also induce some difficulties [17, 18]. The impact of geological conditions on the surface settlement caused by tunnel excavation has been investigated by some scholars. Raposo et al. [19] employed a water balance model to quantitatively evaluate the hydrogeological impact subjected to tunnel construction. When tunneling in permeable strata, the groundwater flow may occur and consequently change the hydraulic head in soil layers, and nonlinear seepage flow equations were taken into account to predict the deformation of tunnels [20]. Chai et al. [21] addressed that the land subsidence was induced by the consolidation caused by pore pressure drawdown. Shen et al. [22] proposed that groundwater infiltration was responsible for the long-term settlement of tunnels. Yoo et al. [23] found that excessive surface settlement and large settlement affecting the zone were caused by groundwater drawdown. Shen and Xu [24] established a numerical model analyzing the relationships among land subsidence, groundwater withdrawal volume, and groundwater level to predict land subsidence due to groundwater withdrawal. Butscher et al. [25, 26] investigated the hydraulic effects of tunneling on groundwater flow and found that hydraulic conductivity and groundwater level of the aquifer were important indicators to estimate the swelling potential of clay sulfate rocks in tunneling. An artificial neural network analysis was then performed by Yoo [27] to qualitatively study the influence of soil stiffness within the groundwater seepage zone and the permeability coefficient of shotcrete lining on the tunnel surface settlement. Tang et al. [28] presented a case history of Shenzhen Metro in which groundwater seepage was found to be the main cause of the rapid increase in surface settlement.

Accurate prediction of surface settlement induced by tunnel excavation is significant for preventing damage to existing structures. To accurately predict the surface settlement, some modifications of the conventional Peck formula have been made based on on-site monitoring data [8, 14, 29–32]. The simulation of the surface settlement of twin tunnels could be divided into (1) "V" shape with downward convexity and wider settlement trough and (2) "W" shape with upward buckling and narrower settlement trough (see Figure 1) [9, 33]. For the simulation of the "V" shape, the width of the settlement trough i is high (i_{high}). The settlement of twin tunnels is seriously overestimated, and the settlement trough is much wider, which may lead to the waste of construction time and budget increase. For the simulation of the "W" shape, the width of the settlement trough is low (i_{low}). The settlement of twin tunnels is significantly underestimated, and the settlement trough is much narrower, which may cause construction accidents due to insufficient safety factors. The overfitting of the modified Peck formula for twin tunnels could also be seen in other researchers [11, 34]. However, few studies focus on the accurate shape simulation of the settlement trough of twin tunnels taking both the depth and width of the settlement trough into account.

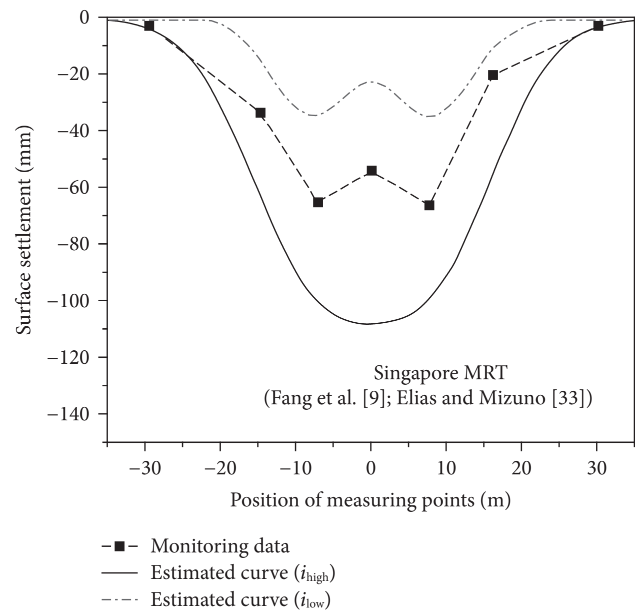

Figure 1: Monitoring data versus estimated curve of Singapore MRT.

This research presents a modification of the conventional Peck formula satisfying the "W" shape of twin tunnels' monitoring data with proper depth and width of the settlement trough. Considering the complex geological conditions such as groundwater drawdown and the permeability of soil layers, the formula proposed is especially suitable for twin tunnels under permeable strata with a low permeability coefficient. The verification of the presented formula is carried out by comparing the predicted settlement with in situ monitoring data of the Zizhi Tunnel Project and other previous cases of Nanjing Metro and Singapore MRT.

2. Modification of Peck Formula to Predict Ground Surface Settlement Presented in This Paper

2.1. Limitation of the Peck Formula. Based on the statistical analysis of a large amount of measured data, Peck [1] assumed that the volume of the settlement trough was equal to the volume loss of the soil in undrained condition and found that the shape of the settlement trough was similar to the normal distribution curve. For a single tunnel, the distribution of surface settlement is governed by

$$S_{(x)} = S_{\max} \cdot \exp\left(-\frac{x^2}{2i^2}\right), \tag{1}$$

where $S_{(x)}$ is the settlement at the offset distance x from the tunnel centerline, $S_{\max}$ is the maximum settlement above the tunnel centerline, and i is the width coefficient of the surface settlement trough.

To pursue a better understanding of the curve of twin tunnels, the superposition technique is used to describe the surface settlement troughs of twin tunnels. For twin tunnels, the additional settlement trough induced by the second tunnel, which is assumed to be relatively symmetric with respect to the second tunnel centerline, can be described by a Gaussian curve. The total settlement trough can be constructed by superimposing the additional curve on the settlement trough of the first tunnel by modifying the parameter i. The validity of the superposition of Gaussian functions has been verified in different tunnel projects in the situation of two or more tunnels excavated closely [11, 35]. For twin tunnels, the superimposed Peck formula could be written as

$$S_{(x)} = S_{\max 1} \cdot \exp\left(-\frac{(x-x_1)^2}{2i_{p1}^2}\right) + S_{\max 2} \cdot \exp\left(-\frac{(x-x_2)^2}{2i_{p2}^2}\right), \quad (2)$$

where x_1 and x_2 are the positions of the central axis of twin tunnels separately, $S_{\max 1}$ is the maximum settlement of left settlement trough of Peck formula, $S_{\max 2}$ is the maximum settlement of right settlement trough of Peck formula, i_{p1} is the width of left settlement trough of Peck formula, and i_{p2} is the width of right settlement trough of Peck formula.

A bunch of in situ monitoring data of Zizhi Tunnel is calculated and analyzed, indicating that a simple normal distribution curve of Peck is not accurate enough to simulate the settlement of the tunnel under the influence of groundwater (see Figure 2). The monitoring data shows that the shape of surface settlement is like "W," which is different from the "V" shape of Peck and other simulations reported by Fang et al. [9] and Zhang et al. [4]. Compared to the curve shape, the key monitoring points in the red circle in Figure 2 are not well fitted. Peck's prediction is not able to fit the upward buckling at the center of the two tunnel center axes. In addition, Peck's prediction is not accurate enough to cover the points far away from the tunnel axis, and it is related to the width of the settlement trough. The width of the settlement trough is defined by the important parameter i, which is the distance from the tunnel centerline to the point of inflection of the trough. In the nonlinear fitting analysis, the adjusted coefficient of determination (adjusted R-square) is used to show the accuracy of the regression equation. The adjusted R-square of the conventional Peck formula is only 0.40 calculated by nonlinear fitting analysis with the iteration algorithm of Levenberg Marquardt, which also verifies the inaccuracy of the simulation.

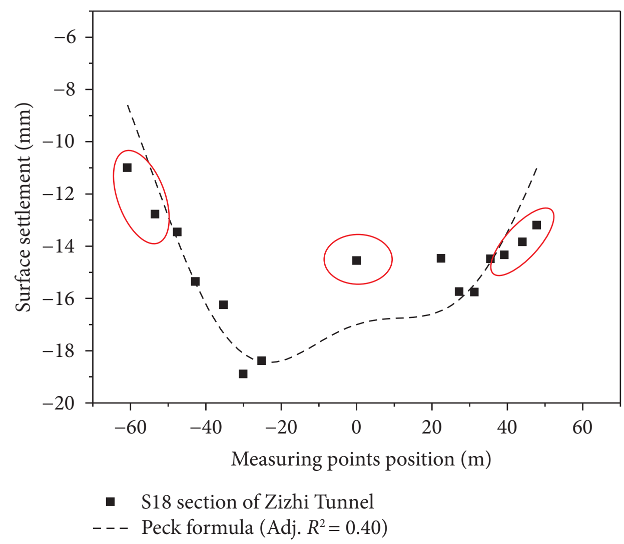

FIGURE 2: Surface settlement of $S18$ section by the Peck formula.

2.2. Form of the Width Modification of the Peck Formula. It can be found from the monitoring data that i under the influence of groundwater seepage has increased to a certain extent, which means that the width of the settlement trough needs to be corrected. Scholars proposed a modified Peck formula with the width controlling parameter to change the width of the settlement trough and get a better fitting effect [32, 36]. Vorster et al. [36] modified the Gaussian probability function by mathematical methods and introduced the shape function parameter controlling the width of the profile n and adjustment coefficient α to adjust the shape of the Peck formula curve, as follows:

$$S_{(x)} = \frac{n}{(n-1)+e^{\left[\alpha (x/i)^2\right]}} S_{\max}, \quad n = e^{\alpha}\frac{2\alpha-1}{2\alpha+1}+1. \quad (3)$$

From the above formula, it can be found that the use of the fractional function is a good method to control the coordinated deformation of the shape of the settlement trough. The influence of the permeability coefficient on the width of the settlement trough is evaluated by the relative permeability coefficient. The relative permeability coefficient is defined as k_s/k_0, where k_s is soil equivalent isotropic permeability and k_0 equals 10^{-4} cm/s in the present study. Since the magnitude of the permeability coefficient varies greatly in different soil layers, the logarithm of the permeability coefficient is used to reduce the magnitude of the impact. We divided log k_s by log k_0 to eliminate the influence of dimensions. It is noteworthy that when the tunnel construction process is affected by groundwater seepage, both the shape and width of the surface settlement trough may change at the same time. Therefore, the parameters b and k mentioned above are introduced to the Peck formula in the form of a fractional function considering the nonlinear and compatible deformation of twin tunnels' surface settlement.

The form of width modification of the Peck formula in this paper is proposed as follows:

$$S_{(x)} = S_w \cdot f(x) = S_w \frac{A}{A-1+\exp\left[\left(x^2/b_w(2i_w)^2\right)\right]}, \quad (4)$$

$$A = \frac{\log k_s}{\log k_0} \cdot \frac{2b_w-1}{2b_w+1}+1, \quad (5)$$

$$k_s = \frac{\sum H_m}{\sum (H_m/k_v)}, \quad (6)$$

where S_w is the maximum settlement of the tunnel, $f(x)$ is the function of the curve, x is the position of the central axis of the tunnel, A is the shape function parameter controlling the width of the profile, k_s is the soil equivalent isotropic permeability, $k_0 = 10^{-4}$ cm/s, b_w is the width controlling parameter, i_w is the width of settlement trough, H_m is the height of the m^{th} layer of soil, and k_v is the vertical permeability coefficient. Note that equation (5) becomes Gaussian distribution equation (1) when $b_w = 0.5$ and $A = 1$.

For twin tunnels, A is calculated with different width controlling parameters in the form of

$$A_j = \frac{\log k_s}{\log k_0} \cdot \frac{2b_{wj} - 1}{2b_{wj} + 1} + 1, \quad (j = 1, 2), \tag{7}$$

where b_{wj} is the width controlling parameter of the j^{th} line. Based on the superposition technique, by substituting equation (5) to (4), equation (4) can be written as

$$\begin{aligned} S_{(x)} &= \sum S_{wj} \cdot f(x_j) \\ &= \sum S_{wj} \frac{A_j}{A_j - 1 + \exp\left[\left(\left(x - x_j\right)^2 / b_{wj}\left(2i_{wj}\right)^2\right)\right]}, \quad (j = 1, 2), \end{aligned} \tag{8}$$

where x_j is the position of the central axis of twin tunnels separately, S_{wj} is the maximum settlement of the j^{th} line, $f(x_j)$ is the superposition function of the j^{th} line, and i_{wj} is the width of the j^{th} settlement trough.

Figure 3 shows the effect of shape function parameter A. When $A = 1$, the modified Peck formula becomes the superimposed Peck formula, and the curve is like a "V" shape. When $A < 1$, the small settlement in the center of twin tunnels is more obvious, which is like a "W" shape, and the settlement is narrower. When $A > 1$, the curve of the modified Peck formula is a "V" shape with a downward convexity and wider settlement trough. The physical meaning is divided into two parts: the fractional function is used to coordinate the deformation of the settlement trough, and the permeability coefficient is regarded as a logarithm and divided by k_0 to eliminate the influence of dimensions.

2.3. Determination of Parameters. The analysis of the modified formula is based on the nonlinear fitting analysis. Parameters used in the analysis are divided into two categories, one of which is obtained from the project geological information, and the other is obtained by a nonlinear fitting algorithm. Parameters obtained from the project geological information are as follows: S_w, x, and k_s. Parameters obtained by nonlinear fitting analysis are based on the iteration algorithm of Levenberg–Marquardt, including b_w and i_w.

The parameter values in the iterative procedure are adjusted by the Levenberg Marquardt (L-M) algorithm, which combines the Gauss-Newton method and the steepest descent method. The algorithm works well for most cases and becomes the standard of nonlinear least squares routines.

The adjusted R^2 value ($\overline{R}^2$) is used to evaluate the effect of the fitting, which is calculated as follows:

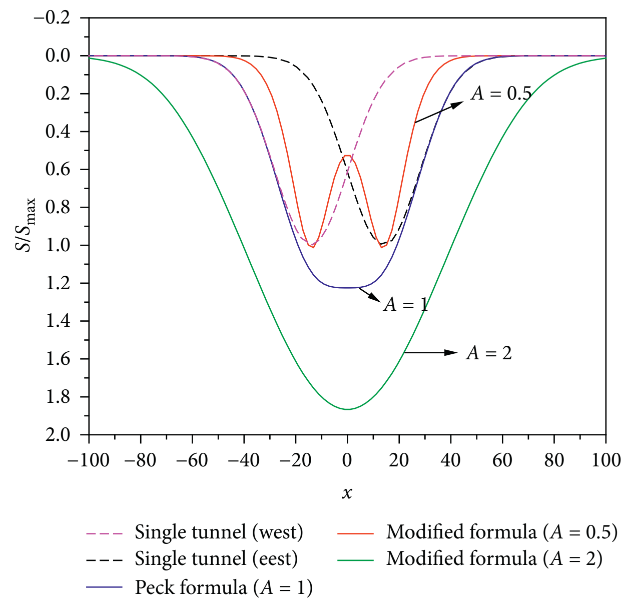

Figure 3: Influence of (A) on settlement trough of twin tunnels.

$$\overline{R}^2 = 1 - \frac{\mathrm{RSS}/\mathrm{d}f_{\mathrm{Error}}}{\mathrm{TSS}/\mathrm{d}f_{\mathrm{Total}}}, \tag{9}$$

where TSS is the total sum of the square, RSS is the residual sum of the square, and $\mathrm{d}f_{\mathrm{Error}}$ and $\mathrm{d}f_{\mathrm{Total}}$ are the degree of freedom of Error and Total separately.

3. Project Overview

3.1. Project Overview and Geological Conditions. Zizhi Tunnel Project, with a total length of 14.4 km, is located in the western area of Hangzhou, surrounded by dense residential blocks and commercial buildings. The selected research section is a part of the north tunnel section near the exit, including both the east and west lines. The east line starts from $K12 + 700$ to $K13 + 569$ with a length of 869.1 m, while the west line starts from $K12 + 710$ to $K13 + 587$ with a length of 877.1 m. Starting from the working well, the twin tunnels go along the Zijingang Road to the south along the Yanshan River and Tianmushan Road, which is under the influence of Yanshan River.

Figure 4 shows the typical longitudinal profile of the twin tunnels around the Yanshan River. The tunnel excavation mainly is laid in the silty clay mixed gravel layer, including miscellaneous fill, plain fill, mucky silty clay, and silty clay. The longitudinal slope of the tunnel is 2.98%, and the thickness of the overburden above the tunnel gradually varies from 9.5 m to 18 m.

Figure 5 shows a typical transverse profile at $K13 + 541.652$ (see in Figure 4) of the east line based on borehole data. Detailed geotechnical properties of each soil layer are obtained through laboratory soil tests. The soil properties are listed in Table 1. The groundwater in the construction section is mainly Quaternary pore phreatic water, replenished by atmospheric precipitation runoff and laterally replenished along the Yanshan River with a

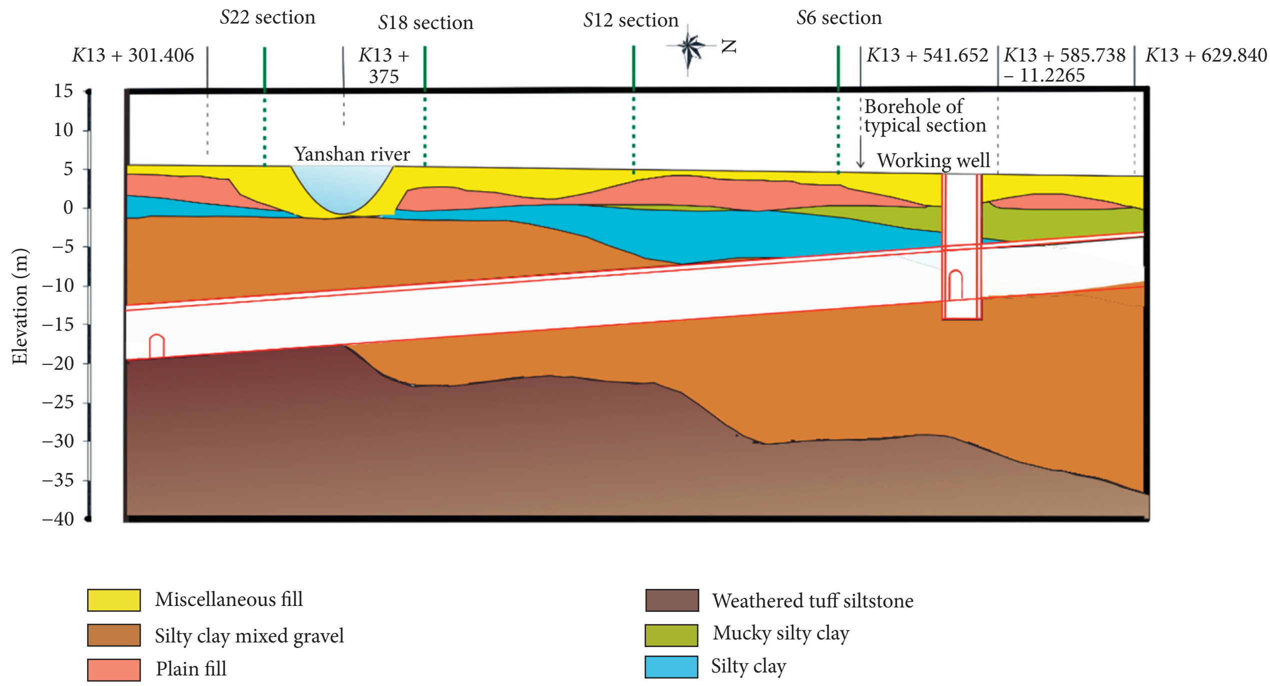

FIGURE 4: Typical longitudinal profile.

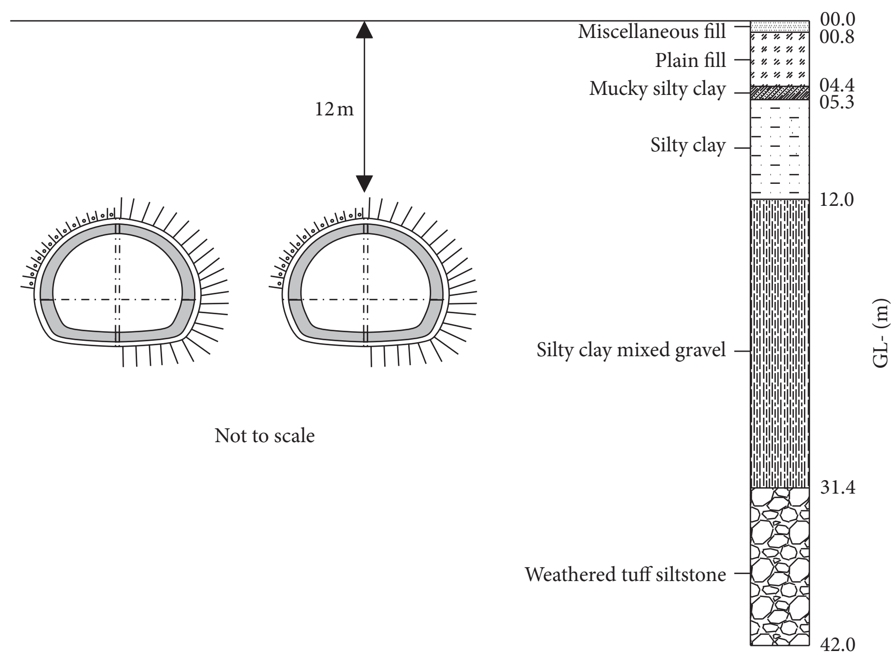

FIGURE 5: Typical transverse profile (not to scale).

relatively large content. The static water level is 0.6~3.5 m, and the annual variation range is 1~2 m.

3.2. Measurement of Project. To grasp the influence of tunnel excavation on the surrounding environment, surface settlement and vault settlement are carefully measured in the research region. More details of the instrument and accuracy are provided in Table 2. For a better study of the influence of the river on the monitoring data, the research region is divided into two parts: river-affected area and outside river-affected area, which takes 45 m from the river center as the boundary.

Figure 6(a) shows the layout of 28 surface settlement monitoring sections within 300 m of the northern section of Zizhi Tunnel. Outside the affected area of the river, a total of 18 monitoring sections (*S*1~*S*15, *S*26~*S*28) are arranged at a spacing of 10 m. Inside the affected area of the river, a total of

Table 1: Geotechnical properties of soil layers.

Soil type	γ (kN/m^3)	e	E_s (MPa)	υ	c (kPa)	φ (deg)	k_v (cm/s)	k_h (cm/s)
Miscellaneous fill	17.5	0.783	2.6	0.33	0	10.0	4×10^{-3}	5×10^{-3}
Plain fill	18.4	0.875	3.5	0.35	10	12.0	6.5×10^{-4}	8×10^{-4}
Mucky silty clay	17.6	1.245	2.5	0.45	11	9.5	4×10^{-7}	5×10^{-7}
Silty clay	19.4	0.721	6.0	0.41	35	16.0	2×10^{-7}	3×10^{-7}
Silty clay mixed gravel	19.8	0.601	10.0	0.38	45	17.0	6×10^{-6}	8×10^{-6}

Note. γ = unit weight, e = void ratio, E_s = modulus of compressibility, υ = Poisson's ratio, c = cohesion, φ = internal friction angle, k_v = vertical permeability coefficient, and k_h = horizontal permeability coefficient.

Table 2: Monitoring items and indexes.

No.	Item	Instrument	Accuracy (mm)	Frequency
1	Surface settlement	Levels	0.01	$L > 5\ S$, 1 time/week $L < 5\ S$, 1 time/2 days $L < 2\ S$, 1~2 times/day
2	Vault settlement	Levels steel rulers	0.01	After excavation 1~15 days, 1~2 times/day 15~30 days, 1 time/2 days 1~3 months, 1~2 times/week after 3 months, 1~3 times/month

Note. L = interval of excavation face and measurement section, S = tunnel span.

12 monitoring sections (S15~S26) are set at an interval of 5 m for S19~S23 and 10 m for others. The arrangement of measuring points is divided into two categories: one is only one measuring point directly above the central axis of the tunnel, and the other is a row of measuring points arranged at a spacing of 5 m directly above and on both sides of the central axis and the arching line of the tunnel. Figure 6(b) plots the placement of settlement points within a typical monitoring cross section. The vault settlement measurement points are set in the east and west lines every 10~15 m to monitor the tunnel deformation, which are installed as soon as possible after excavation.

Figures 7(a) and 7(b) compare the settlement development of the surface points above the central axis of the tunnel with that of the vault points in two different monitoring sections of S6 and S18 at $K13+417$ and $K13+537$, which are outside and within the river-affected area, respectively. The settlement data used in the analysis is the final settlement that does not change for a period of time observed at the settlement monitoring points after 120–160 days, of which the settlement has no correlation with time. In the figure, the ground settlement monitoring point directly above the tunnel (S6-6 and S18-6) and the vault settlement monitoring point at the corresponding position (V6-1, V6-2, V17-1, and V17-2) are selected for research. Two types of development laws on the surface settlement above the tunnel can be observed, possibly attributed to the construction of the Yanshan River cofferdam. In the initial stage of monitoring, the settlement rate of the vault is greater than that of the ground surface. As the distance between the tunnel face and the monitoring section is becoming larger, the decrease of the settlement rate of the vault is higher than that of the ground surface. As can be observed in Figure 7(a), outside the river-affected area (S6), the sinking rate of the vault is close to the surface settlement rate and tends to be stable at the same time. In the river-affected area (S18), the vault sinking is larger than the surface settlement. After the vault sinking is stable, surface settlement continues to develop (see Figure 7(b)). The vault sinks at the same rate inside and outside the river-affected area, which is caused by soil loss. The surface settlement develops slower inside the river-affected area. The asynchronization of the sinking rate and stability of vault settlement and surface settlement indicates that the continuous growth of surface settlement is primarily attributed to the groundwater drawdown caused by cofferdam construction on the river instead of the tunnel deformation after construction. From the two various development laws of settlement discussed above, the groundwater drawdown of the river has a significant impact on the surface settlement of the tunnel.

The surface settlement in the river-affected area develops slower than the vault settlement, continues to develop, and differs greatly from the vault settlement. This may be due to the existence of low permeability silty clay and mucky silty clay in the affected area. In the soil layer with a low permeability coefficient, the groundwater seepage will cause the pore pressure redistribution of the surrounding saturated silty clay mixed gravel layer, causing further consolidation and settlement of the overburden layer of the tunnel [21, 27, 28]. Meanwhile, the permeability coefficient will gradually decrease with the consolidation stress in the soft soil layer, leading to a slower consolidation process and increasing consolidation time [37, 38]. It is consistent with the slower convergence rate of surface settlement within the river-affected area in Figure 7(b).

From the above analysis, it can be seen that, under the influence of groundwater, the surface settlement law caused by tunnel excavation of soft soil will change due to the low permeability, including the slowdown of settlement convergence and further consolidation caused by groundwater seepage.

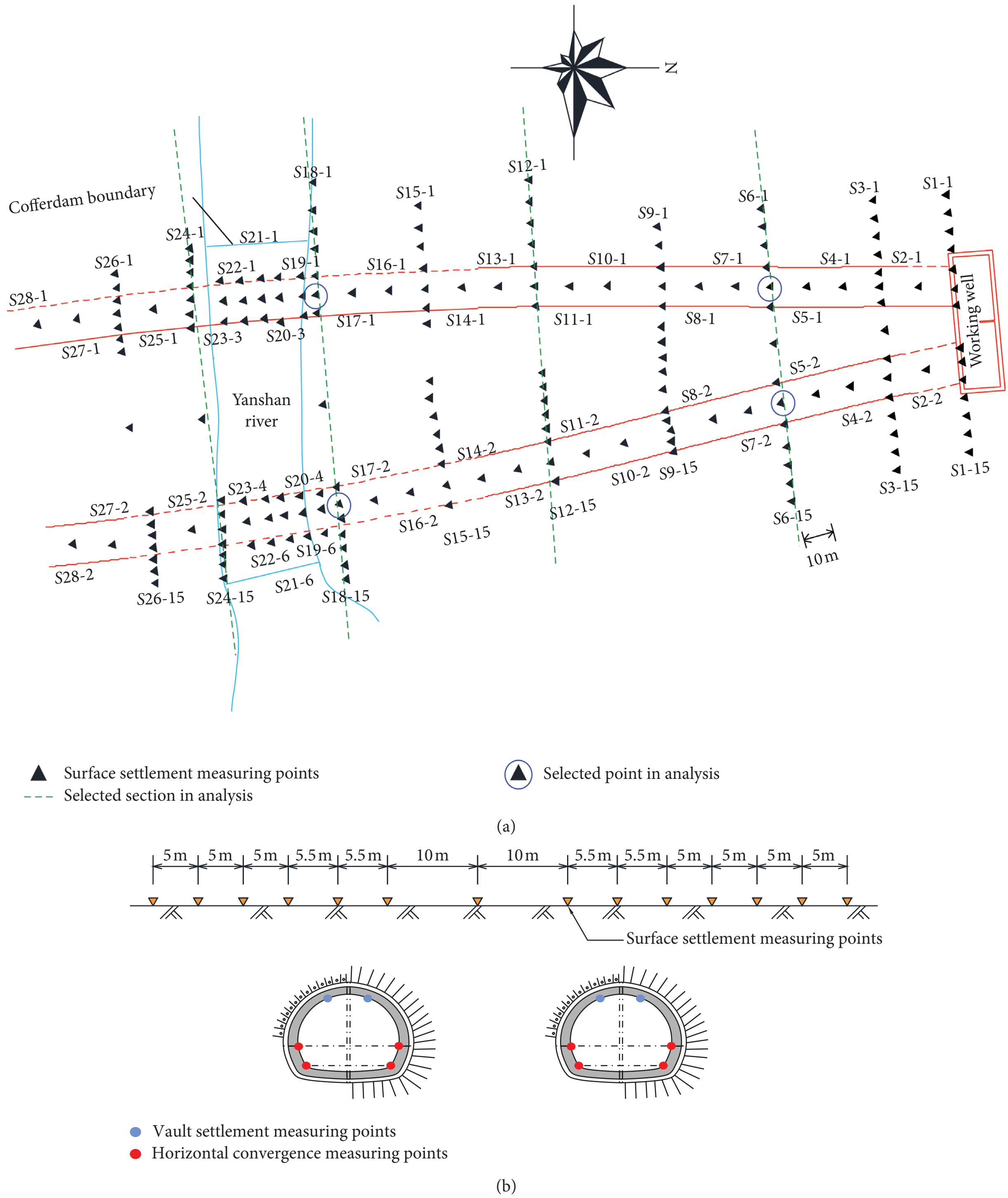

Figure 6: Arrangement of monitoring points. (a) Layout of monitoring points. (b) Typical cross section ($S6$) measuring points' arrangement.

4. Comparison of Predicted Value and Project-Measured Data

The research of surface settlement of Zizhi Tunnel is still carried out from two aspects: river-affected area and outside river-affected area. Four sections are selected as representative research objectives. $S6$ and $S12$ sections are outside the river-affected area, and $S18$ and $S26$ sections are within the river-affected area. The parameters of the simulation are shown in Table 3.

For $S6$ and $S12$ sections outside the river-affected area, Figures 8 and 9 show the shape of the predicted settlement of Peck and the modified Peck formula of sections $S6$ and $S12$. The proposed solution and Peck formula both predict the

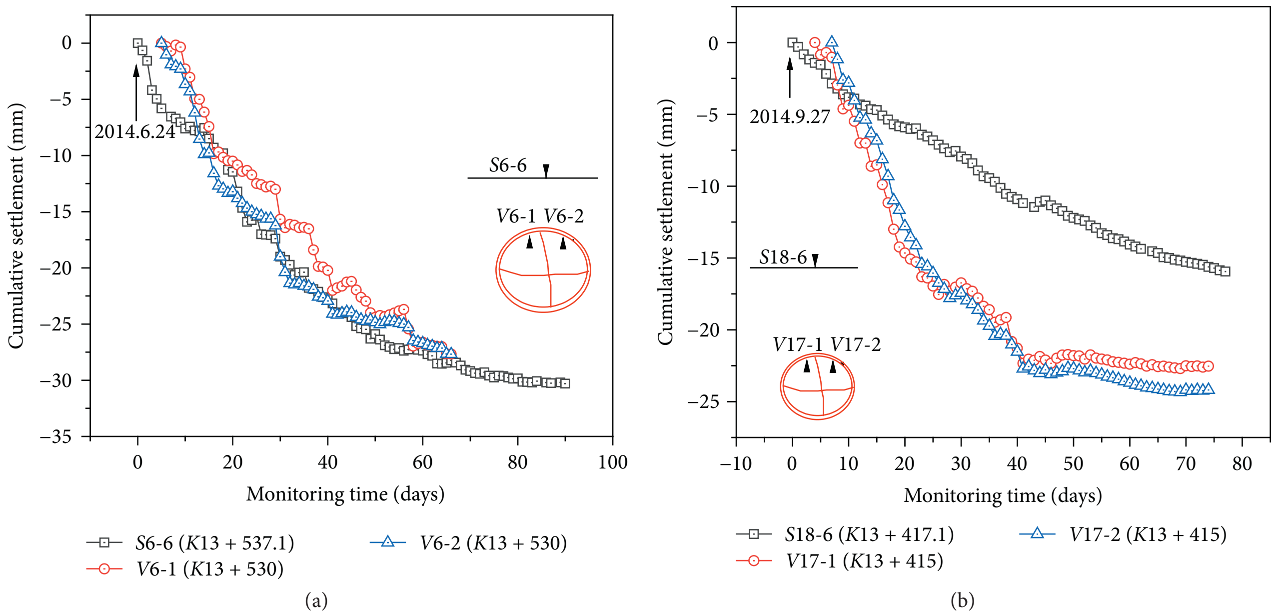

FIGURE 7: Comparison of surface settlement and vault settlement development. (a) Outside the river-affected area. (b) Inside the river-affected area.

TABLE 3: Parameters of the simulation in Zizhi Tunnel.

Project	k_s (cm/s)	$S_{\max 1}$ (mm)	$S_{\max 2}$ (mm)	S_{w1} (mm)	S_{w2} (mm)	i_{p1} (m)	i_{p2} (m)	i_{w1} (m)	i_{w2} (m)
S6 section	6×10^{-6}	−48.19	−52.62	−43.65	−53.43	17.18	28.22	11.33	119.39
S12 section	6×10^{-6}	−24.12	−23.87	−25.98	−24.12	16.60	21.22	20.01	33.80
S18 section	6×10^{-6}	−16.87	−14.47	−17.74	−15.09	26.32	26.13	10.89	60.67
S24 section	6×10^{-6}	−22.52	−20.74	−5.83	−23.02	44.65	10.52	45.87	90.32

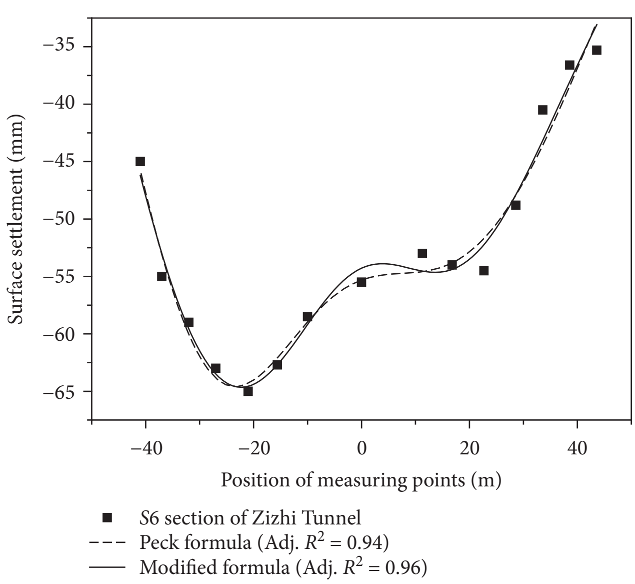

FIGURE 8: Surface settlement of S6 section outside the river-affected area.

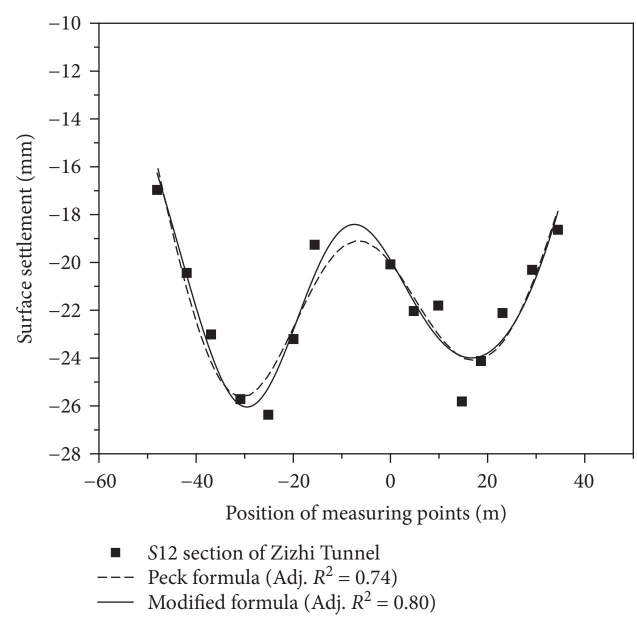

FIGURE 9: Surface settlement of S12 section outside the river-affected area.

settlement well with similar adjusted R-square (Adj. $R^2 = 0.94$ and 0.96 for S6 section, Adj. $R^2 = 0.74$ and 0.80 for S12 section). The modified formula can successfully predict the small settlement at the tunnel center. The settlement of the west line tunnel is larger than the east line, which is attributed to the advancement excavation of the west line over the east line. However, since the S6 and S12 sections of the Zizhi Tunnel are outside the river-affected area and less affected by the drawdown of the groundwater, the accuracy of the predicted settlement by the modified Peck formula is as Peck formula.

For the monitoring $S18$ and $S24$ sections which are within the river-affected area, the fitting curves of the modified formula compared with Peck's formula are shown in Figures 10 and 11. It can be seen from the fitting results that there is a significant improvement in the accuracy of the prediction, of which the adjusted R-square is increased from 0.40 to 0.89 for the $S18$ section and from 0.38 to 0.96 for the $S24$ section. As for the shape of the fitted curve, the curve can successfully fit the upward peak of the double tunnel center and a wider settlement trough. The "W" shape of the settlement curve is perfectly shown instead of the "V" shape of Peck's simulation. The center of the twin tunnels is more easily discernible, which improves from -16.8 mm to −12.8 mm for the $S18$ section. The central axis of the tunnel at the east and west lines has a large settlement, and then the trend of gradually decreasing toward both ends is more obvious. The parallel excavation trend of the twin tunnels is obvious, which is more in line with the actual situation. Both the predicted and measured values of Peck and modified Peck formula are plotted in Figures 12 and 13. Better correlation of the predicted and measured data is found for the modified Peck formula rather than the Peck formula. The Root Mean Squared Error (RMSE) of the $S18$ section decreases from 1.35 mm to 0.54 mm, and the RMSE of the $S24$ section decreases from 1.65 mm to 0.22 mm. Regardless of the accuracy of the data prediction or the shape of the settlement trough, the modified formula can be better presented.

From the above two monitoring sections, the modified Peck formula derived by the superposition method has good adaptability and accuracy in the settlement prediction of twin tunnels. In addition, the degree of fitting of the modified Peck formula to the surface settlement monitoring data of Zizhi Tunnel is good, which is better than the fitting of the Peck formula. The improvement of the $S18$ and $S24$ section fitting in the river-affected range is much better than that of the $S6$ and $S12$ sections outside the river-affected range, whose adjusted R-square is about doubled. The small settlement at the twin tunnels' center is more recognizable, and the settlement trough width is increased, which could be considered that the groundwater drawdown caused by the construction river has a great influence on the development of the surface settlement. The construction of the cofferdam on the river makes the groundwater drawdown, which leads to pore pressure redistribution and a slower consolidation process by the decreased permeability coefficient. In soft soils with a low permeability coefficient, the extension of the consolidation time is more likely to occur, and the soil layer is more susceptible to changes in groundwater. Permeability coefficient is an important index for evaluating soft soil properties. Therefore, the modified Peck formula is more suitable for the cases of low permeability soil with groundwater changes.

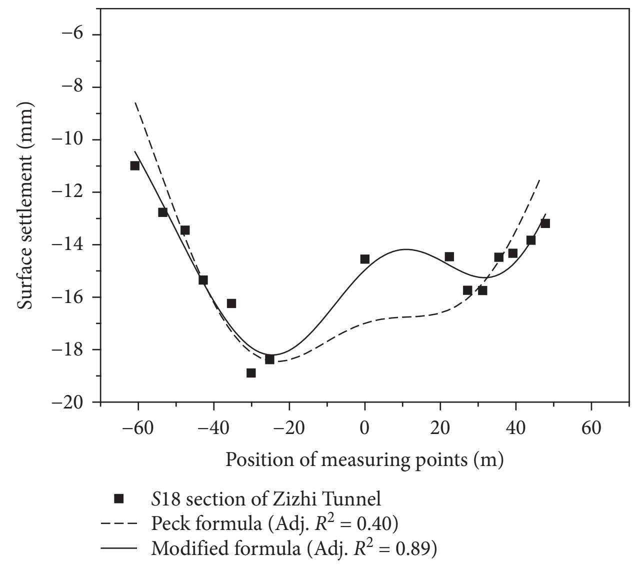

Figure 10: Surface settlement of $S18$ section inside the river-affected area.

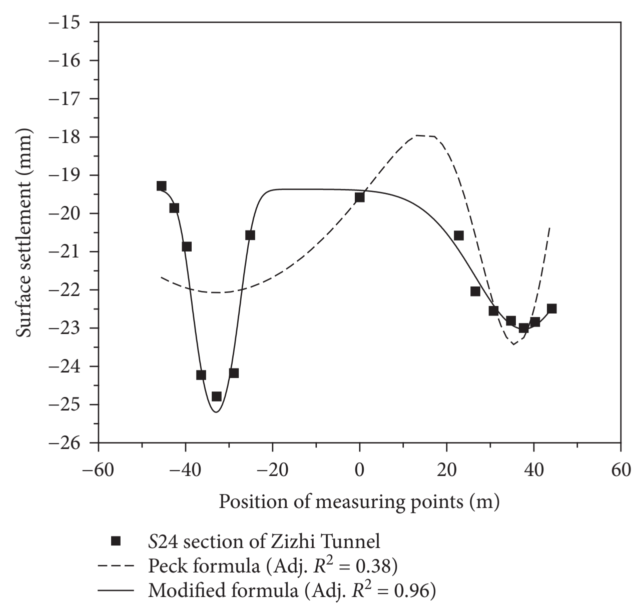

Figure 11: Surface settlement of $S24$ section inside the river-affected area.

5. Comparison of Predicted Value of Other Cases

The modified Peck formula for twin tunnels is compared with measured data from other scholars to improve the credibility of the proposed formula. The measured settlements of the Nanjing Metro twin tunnels [39] and Singapore MRT [9, 33] are selected for verification, of which the geological conditions are similar. Both Nanjing Metro and Singapore MRT analyzed in this paper are being constructed in soft soils, and the groundwater level is high [40–43]. The construction of tunnels inevitably disturbs the soil and tilts the balance of the original groundwater seepage field and

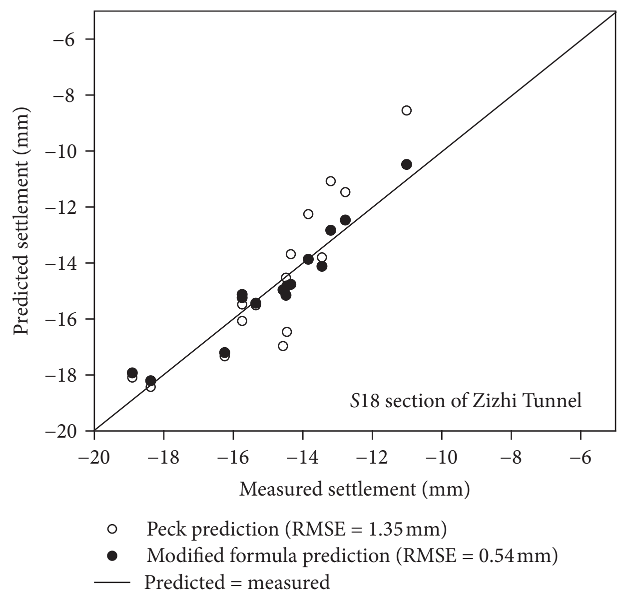

Figure 12: Comparison of predicted settlements for the $S18$ section inside the river-affected area.

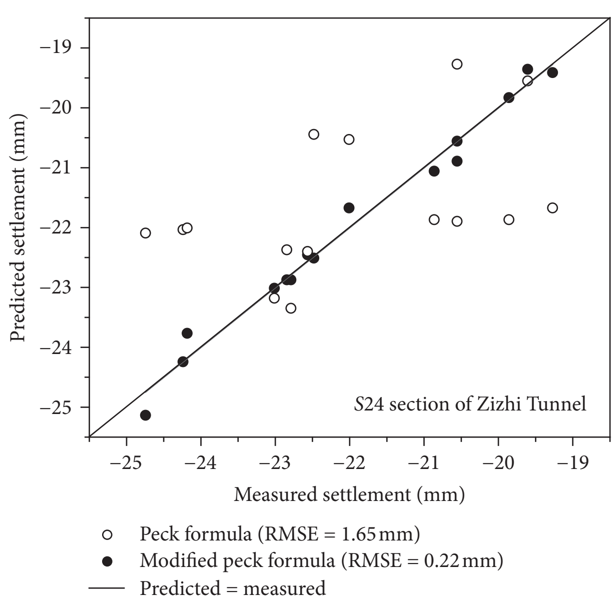

Figure 13: Comparison of predicted settlements for the $S24$ section inside the river-affected area.

stress field, causing surface deformation. Due to the low permeability of the overlying soil and the high groundwater level, the settlement caused by the construction of the Nanjing Metro and the Singapore MRT project is affected by groundwater seepage, which is inseparable from the influence of the permeability coefficient. The predicted result reflects the trend of twin tunnels under groundwater seepage in low permeable soil. The parameters of the simulation are shown in Table 4.

Figures 14 and 15 are the comparison results between the predicted value and the in situ measured value of Nanjing Metro twin tunnels [39] and Singapore MRT [9, 33], respectively. According to Figures 14 and 15, the prediction from the current solution is consistent with the measured data. The adjusted R^2 of Nanjing Metro improves from 0.60 to 0.88, and the value of Singapore MRT improves from 0.81 to 0.99, which proves that the modified Peck formula can accurately predict the settlement and the trend of twin tunnels under groundwater seepage. From Figure 16, it could be found that the RMSE of the modified Peck formula is much smaller with a reduced error of 9.83 mm. The predicted value of the Peck formula is more discrete than the modified Peck formula. With the modified Peck formula, the "W" shape at the center of the twin tunnels is more recognizable and the width of the settlement trough is larger.

The modified Peck formula could be used in other cases and accurately predict the trend of the settlement of twin tunnels. The improvement in Nanjing Metro and Singapore MRT is not as obvious as it on the Zizhi Tunnel, which may be caused by many factors. For the Nanjing Metro, it could be found that the permeability coefficient of Nanjing Metro (6×10^{-4} cm/s) is not as low as that in Zizhi Tunnel (6×10^{-6} cm/s). The higher permeability coefficient of Nanjing Metro makes the improvement of the modified model is not as good as that in Zizhi Tunnel. For the Singapore MRT, although the improvement is relatively limited, the adjusted R^2 of the revised model has reached 0.99, which is already very high. Although the improvement of the modified Peck formula is different in various cases worldwide, it still improves the accuracy of prediction of ground surface settlement caused by tunnel

Table 4: Parameters of the simulation in Nanjing Metro and Singapore MRT.

Project	k_s (cm/s)	$S_{\max 1}$ (mm)	$S_{\max 2}$ (mm)	S_{w1} (mm)	S_{w2} (mm)	i_{p1} (m)	i_{p2} (m)	i_{w1} (m)	i_{w2} (m)
Nanjing Metro	6×10^{-4}	−13.88	−13.44	−16.85	−17.54	6.73	6.35	10.12	47.22
Singapore MRT	7×10^{-7}	−39.44	−28.89	−58.08	−56.50	14.70	30.14	19.77	66.95

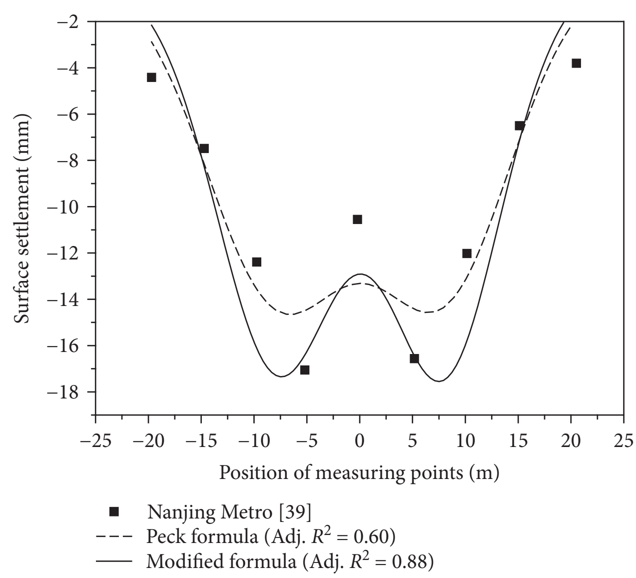

Figure 14: Surface settlement of Nanjing Metro.

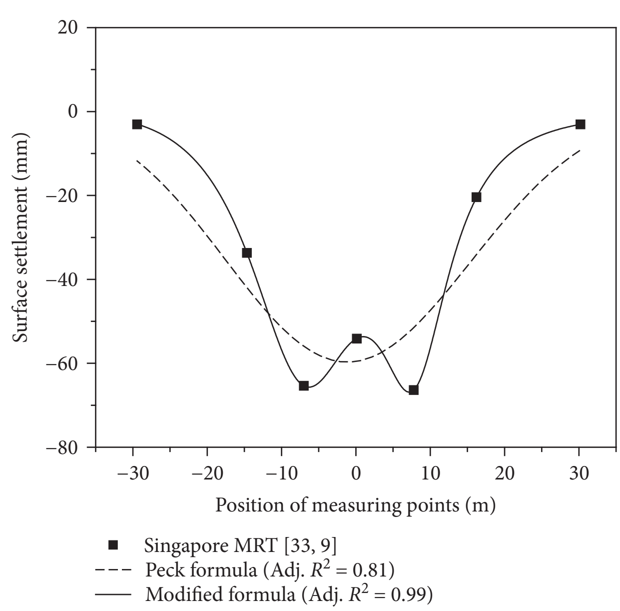

Figure 15: Surface settlement of Singapore MRT.

excavation in low permeability areas. It reflects how the ground surface settlement develops under the tunnel construction, which is useful to study the influence of surrounding structures and take methods to control the settlement in time.

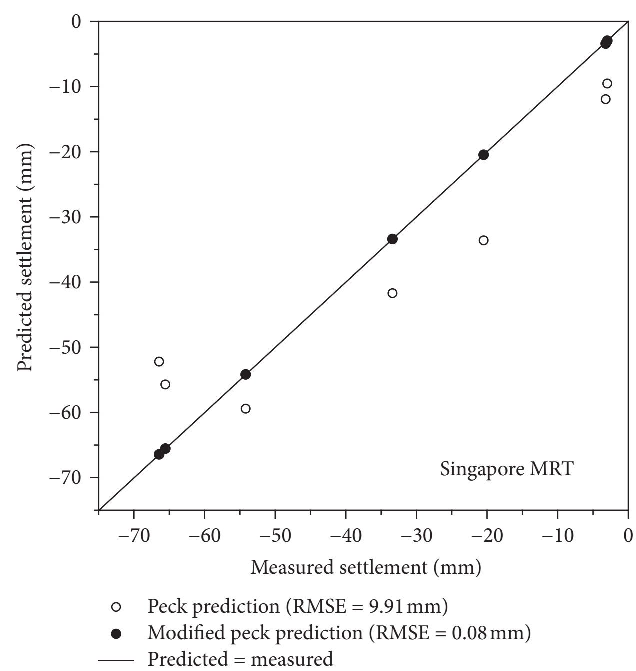

Figure 16: Comparison of predicted settlement for Singapore MRT.

6. Conclusions

This paper investigates the prediction of the surface settlement of single and twin tunnels using the nonlinear fitting analysis combined with in situ monitoring data of the Zizhi Tunnel. A modified Peck formula considering the low permeability of soft soil is put forward and is compared with measured data from other cases in Nanjing Metro and Singapore MRT. The predicted result reflects the "W" shape of the settlement trough with higher accuracy. The main findings are summarized as follows:

(1) The observation of the Zizhi Tunnel and Singapore MRT shows that there is a small settlement at the center of the twin tunnels, making the settlement trough upward buckling which is like a "W" shape. Peck formula is not able to simulate the small settlement at the center of twin tunnels with high accuracy in some situations. A modified Peck formula is proposed to improve the accuracy of the prediction for twin tunnels.

(2) The geological conditions have an impact on surface settlement development. The surface settlement and vault settlement develop differently within and outside the river-affected area. The asynchronization of the sinking rate and stability of vault settlements

and surface settlement within the river-affected area may attribute to groundwater drawdown caused by cofferdam construction on the river. A modified Peck formula is put forward with soil permeability and width controlling parameter involved, which is suitable for low permeability soil layers with permeability coefficient between 10^{-4} cm/s and 10^{-7} cm/s. The accuracy of the predicted value of surface settlement improves 30%–50% by the modified Peck formula.

(3) For twin tunnels, the modified Peck formula has a significant improvement over the Peck's curve, of which the applicability and credibility are verified by other cases in Nanjing Metro and Singapore MRT. With the application of the modified formula, the "W" shape at the center of twin tunnels is more recognizable with a significantly increased adjusted R-square, which represents the improvement in the accuracy of the prediction. The modified Peck formula is especially suitable for twin tunnels in soft soil layers with low permeability coefficients in complex geological conditions, where groundwater drawdown may occur.

Data Availability

All the data used to support the findings of this study are included within the article. the statement could be rephrased by the editor.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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