Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 2489711, 11 pages
https://doi.org/10.1155/2022/2489711

Research Article

Analytical Study on Surface Settlement Troughs Induced by the Sequential Excavation of Adjacent and Parallel Tunnels in Layered Soils

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Received 8 November 2021; Accepted 15 January 2022; Published 15 February 2022

Academic Editor: Ping Xiang

In this paper, the settlement troughs induced by the excavation of adjacent and parallel tunnels in layered soils were studied. Firstly, a trough width parameter calculation method in layered soils was established based on the propagation model of the plastic zone and unloading disturbance zone. Secondly, the mechanism of the superposition disturbance between parallel tunnels is analyzed, and a method for calculating additional settlement trough is proposed. Finally, the applicability of the proposed model was demonstrated with two case studies of the parallel tunnels. The following conclusions were obtained: the difference of soil properties in layered soils had a significant influence on the width parameter of surface settlement trough; a Gaussian curve can describe the additional settlement caused by superimposed disturbance; and finally, the relationship between the ground loss induced by superposition disturbance and the ground loss induced by the preceding tunnel was approximately linear. The model presented in this paper is highly effective and convenient for use in practice and extends the calculation method of surface settlement trough based on the Gaussian curve.

1. Introduction

The settlement of overlying soil above the tunnel is induced by the disturbance of tunnel construction on surrounding soil [1]. The settlement not only affects the stability of surface buildings [2–4], but also jeopardizes the normal use of underground pipelines [5, 6]. The complex structure environment puts forward higher settlement control requirements for tunnel engineering, especially in adjacent and parallel tunnels event. Therefore, the tunneling-induced surface settlement calculation has received extensive attention [7, 8].

Peck [9] proposed that the single tunneling-induced surface settlement trough could be distributed by a Gaussian curve as follows:

$$S(x) = S_{\max} \exp\left[-\frac{x^2}{2i^2}\right], \quad (1)$$

where $S(x)$ is ground settlement; $S_{\max}$ is the maximum surface settlement above the tunnel centerline; x is the horizontal distance from the tunnel centerline; and i is the distance from the tunnel centerline to the curve's inflection point, which is called trough width parameter, as shown in

Figure 1. The empirical methods based on the Gaussian curve have become a generally accepted research model on the surface settlement trough and the interaction of two adjacent and parallel tunnels.

Many measured data in engineering practice show that the surface settlement trough induced by the adjacent and parallel tunnels is asymmetrical [10–12]. It is because the following tunnel was excavated in a brown-field site (previously developed site) [13, 14].

Some scholars have proposed that the surface settlement trough above the following tunnel, which is affected by the preceding excavation, enlarges and shifts. The settlement trough above the following tunnel could be obtained by modifying and moving according to the settlement date of the preceding tunnel. This method is called the modification factor method [15]. Chapman and Hunt [16] proposed the modified function as follows:

$$S_2(x) = \left\{1 + \left[k\left(1 - \frac{|B + x|}{2.5 i_1 h}\right)\right]\right\} S_1(x), \tag{2}$$

where $S_1(x)$ is the surface settlement trough above the preceding tunnel (same as the single tunnel); $S_2(x)$ is the modified surface settlement trough; k is the value of maximum modification; i_1 is the trough width parameter of the preceding tunnel. Dong [15] proposed the deal of maximum modification k could be determined as follows:

$$k = -\frac{1.85B}{2h + D} + 1.002, \tag{3}$$

where B is the center-to-center spacing of tunnels. Wei and Wei [17] proposed a method of moving settlement trough.

Other scholars proposed that calibration of i and S_{max} is vital during the settlement trough calculation above the following tunnel. Ma et al. [18] converted the Gaussian curve into a linear form, and two numerical methods were used to estimate the settlement parameters induced by parallel tunnels. Zheng et al. [19] investigated the interaction between parallel tunnels by the physical model test, and the differences between the surface settlement troughs above two tunnels were described in terms of parameters.

Many scholars have studied the surface settlement trough induced by adjacent and parallel tunnels with various methods, but the reasons for the changes of surface settlement trough were rarely mentioned from the perspective of interactions. The consistent relationship between model parameters and excavation parameters remains unclear. This paper presents a method for calculating the trough width parameter of surface settlement trough in layered soils. Then, a new calculation method of surface settlement trough above the following tunnel is demonstrated by analyzing the mechanisms of superposition disturbance. Finally, two cases' study is presented to assess the rationale of the proposed model.

2. Calculation of Disturbance Zone and Surface Settlement Trough Induced by Tunnel Excavation in Layered Soils

In order to minimize the detrimental effect of tunneling on surrounding structures, it is necessary to calculate the disturbance zone induced by tunnel excavation accurately. In practical engineering, tunnels are primarily constructed in layered soils. The differences in geotechnical properties significantly affect the plastic zone, unloading disturbance zone, and surface settlement trough.

2.1. Basic Assumptions

(1) The tunnel is excavated in a stratum with a large thickness and covered with multiple soil layers. The surrounding soil is only defined as a standard elastomer.

(2) Instantaneous surface settlement occurs during tunnel excavation, and the ground will not continue to move after the excavation.

(3) The tunnel is excavated in a greenfield, and a Gaussian curve could distribute the settlement trough.

2.2. Plastic Zone and Unloading Disturbance Zone in Layered Soils. Assuming that there are n layers of soil overlying the tunnel and the tunnel was excavated in the nth layer of soil, h is the distance from the tunnel centerline to the ground surface. In layered soils, h_1 is the thickness of the first soil layer, and so on; h_n is the distance from the tunnel centerline to the interface of the $n-1$th layered soil (Figure 2). The plastic zone and the unloading disturbance zone are calculated by the layered accumulation method.

The tunnel excavation process can be seen as the unloading process of the column hole, and the plastic zone appears in the soil around the tunnel. For the sake of simplicity, the force around the tunnel is assumed to distribute symmetrically. The initial Earth stress and the support force of the tunnel can be calculated as follows:

$$\begin{aligned} \sigma_0 &= \sum_{i=1}^{n} h_i \gamma_i, \\ \sigma_a &= \sigma_0 \tan^2\left(45^\circ - \frac{\varphi_n}{2}\right) + 2c_n \tan\left(45^\circ - \frac{\varphi_n}{2}\right). \end{aligned} \tag{4}$$

According to the Fenner formula [20], the radius of the plastic zone caused by tunnel construction can be estimated by

$$a = \frac{D}{2}\left[(1 - \sin\varphi_n)\left(\frac{\sigma_0 + c_n \cot\varphi_n}{\sigma_a + c_n \cot\varphi_n}\right)\right]^{(1-\sin\varphi_n/2\sin\varphi_n)}, \tag{5}$$

where h_i is the thickness of the i soil layer; γ_i is the unit weight of soil of the ith layer; φ_n is the internal friction angle

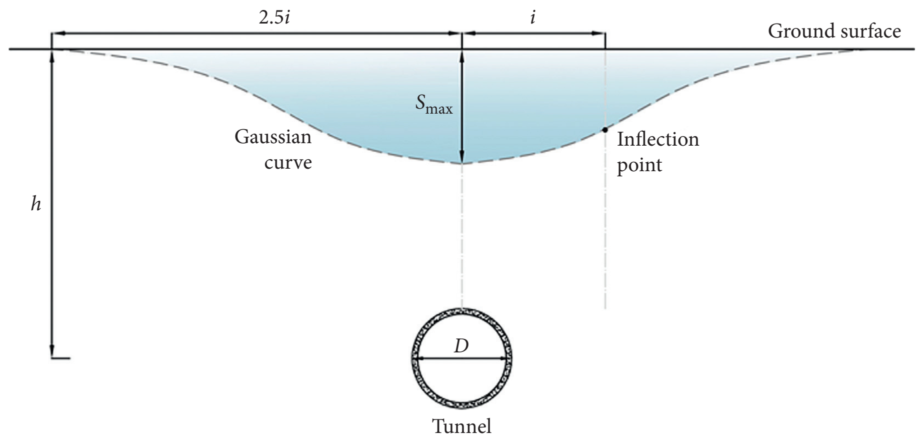


Figure 1: Ground settlement trough induced by a single tunnel.

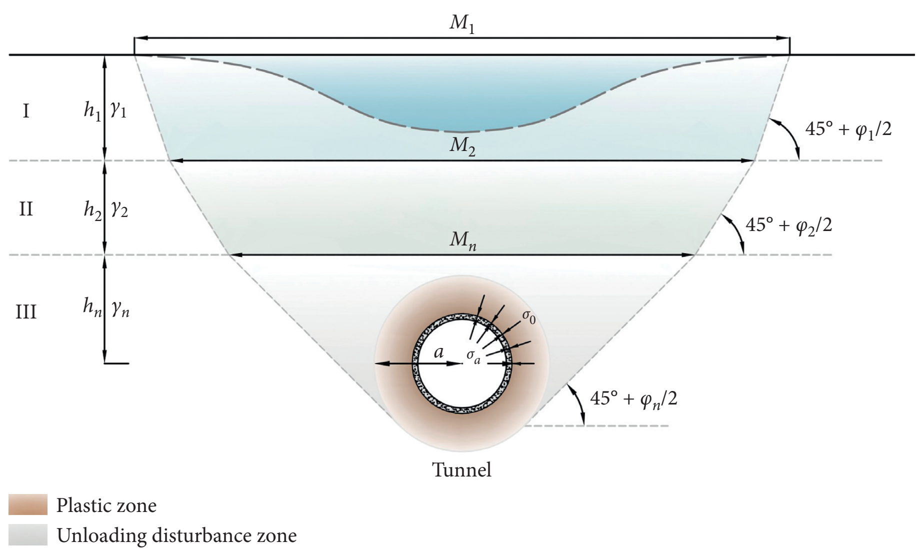


Figure 2: Plastic zone and unloading disturbance zone in layered soils.

of the soil layer where the tunnel is located; c_n is the cohesion of the soil layer where the tunnel is located.

The unloading disturbance zone is produced due to the stress release of the soil above the plastic deformation zone. The shear failure has taken place at the boundary of the unloading disturbance zone. The failure plane of the unloading disturbance zone is tangent to the shearing disturbance zone, which inclines by an angle $45^\circ + (\varphi/2)$ from the horizontal based on Rankine's Earth pressure theory [21, 22]. Because of the different properties of each soil in layered soils, the failure plane is deflected at the interface between the two soil layers [23, 24]. According to the geometric relationship as shown in Figure 2, the width of the unloading disturbance zone at the interface of the nth soil layer can be calculated as follows:

$$M_n = 2\left(\frac{h_n}{\tan\left(45^\circ + \varphi_n/2\right)} + \frac{a}{\sin\left(45^\circ + \varphi_n/2\right)}\right). \quad (6)$$

Hence, the width of the unloading disturbance zone on the ground is obtained as follows:

$$M_1 = M_n + 2\sum_{i=1}^{n-1} h_i \tan\left(45^\circ + \frac{\varphi_i}{2}\right). \quad (7)$$

2.3. Surface Settlement Trough and Ground Loss of Single Tunnel. According to the above analysis, it can be seen that the unloading disturbance zone and the settlement trough are equal in width. The trough width parameter in the Gaussian curve determines the width of the settlement trough, so there will be a corresponding relationship between the trough width parameter and the width of the settlement trough. Based on a review of a large number of measured data, Stallebrass and Taylor [25] found that the trough width parameter has a linear correlation with the width of settlement trough, as follows:

$$i_1 = \frac{M_1}{5}. \tag{8}$$

Another key parameter in the Gaussian curve is the maximum ground settlement just above the tunnel centerline, which determines the depth of the settlement trough and has an inevitable relationship with the ground loss induced by the tunnel excavation. Ground loss is defined as the volume of surface settlement trough per unit length of the tunnel. Although there are some calculation methods for ground loss, it is difficult to select parameters and consider factors that influence the ground loss. Attewell and Farme [21] proposed that the calculation formula of ground loss can be obtained by integrating the Gaussian curve as follows:

$$V_{\text{loss}} = \int_{-\infty}^{+\infty} S_{\max} \exp\left(-\frac{x^2}{2i^2}\right) dx = \sqrt{2\pi} i S_{\max}, \tag{9}$$

where V_{loss} is the ground loss induced by tunnel excavation.

2.4. Surface Settlement Trough above Parallel Tunnels. Through the statistical analysis of the surface settlement in published case history, it is found that the settlement trough above the parallel tunnels is difficult to describe by a single Gaussian curve. Therefore, Suwansawat and Einstein [12] proposed a superposition calculation method to describe the surface settlement trough above a parallel tunnel. According to the method, the surface settlement trough caused by the excavation of adjacent and parallel tunnels would consist of two components: the surface settlement troughs of the preceding tunnel and the following tunnel. Both troughs caused can be described by Gaussian curve. The first component equals the surface settlement trough induced by the single tunnel. However, the calculation of the second component (i.e., surface settlement trough above the following tunnel) would be the critical point of this method.

3. Calculation of Surface Settlement Trough above the following Tunnel Based on Superposition Technique

The existing calculation models have complex calculation processes and narrow application scope. Therefore, a calculation model of surface settlement trough above the following tunnel with broad applicability is established by analyzing the interaction mechanism between adjacent and parallel tunnels.

3.1. Overlapping Disturbance of Adjacent and Parallel Tunnel. The soil stability changes in the unloading disturbance area above the preceding tunnel due to the excavation disturbance. The soil in the overlapping zone has been disturbed so that the surface settlement trough above the following tunnel will be larger than the preceding tunnel. In the overlapping zone, the increase of settlement is called additional settlement.

Considering the influence of the overlapping disturbance, it is reasonable that the surface settlement trough above the following tunnel could divide into two components for calculation. The first component is the surface settlement trough caused by tunnel excavation without considering the interaction and would be equal to the surface settlement trough of a single tunnel. The second component is the asymmetric settlement resulting from the overlapping disturbance in the overlapping zone, as shown in Figure 3. The calculation of asymmetric settlement is the critical point of this method.

3.2. Additional Surface Settlement Trough Induced by Overlapping Disturbance. The mechanism of soil disturbance in the process of overlapping disturbance is complex, and the additional settlement is the result of various disturbances in the excavation process. It is hard to calculate the surface settlement accurately. As shown in Figure 4, through the analysis of multiple groups of measured data, it could be found that the additional settlement trough caused by the overlapping disturbance also appears as a Gaussian curve, and the settlement characteristics can be described by a Gaussian curve as follows:

$$S'(x) = S'_{\max} \exp\left(\frac{-x'^2}{2i'^2}\right), \tag{10}$$

where x' is the horizontal distance to the surface; $S'(x)$ is additional surface settlement; i' is the width parameter of additional settlement trough, $S'_{\max}$ is the maximum additional settlement. The surface additional settlement trough and soil loss caused by overlapping disturbance are two key points of research.

In order to describe the surface additional settlement trough caused by superposition disturbance, it is necessary to determine the width parameter i' and the maximum additional settlement $S'_{\max}$. As shown in Figure 3, according to the definition and model of overlapping disturbance, the width of surface overlap disturbance is obtained as follows:

$$L = M_1 - B. \tag{11}$$

And the width parameter of additional settlement trough is obtained based on (8), as follows:

$$i' = \frac{L}{5}. \tag{12}$$

The maximum additional settlement is closely related to the ground loss in the overlapped disturbance zone.

3.3. Ground Loss Induced by Overlapping Disturbance. The analysis of additional settlement found that it is difficult to establish a simple corresponding relationship between two adjacent and parallel tunnels in terms of the maximum surface settlement. Considering that the stratum conditions and the construction parameters of the primary and overlapping disturbance zone are similar, a simple correlation between the two adjacent and parallel tunnels can be established through the ground loss. However, the mechanism of soil loss caused by overlapping disturbance is

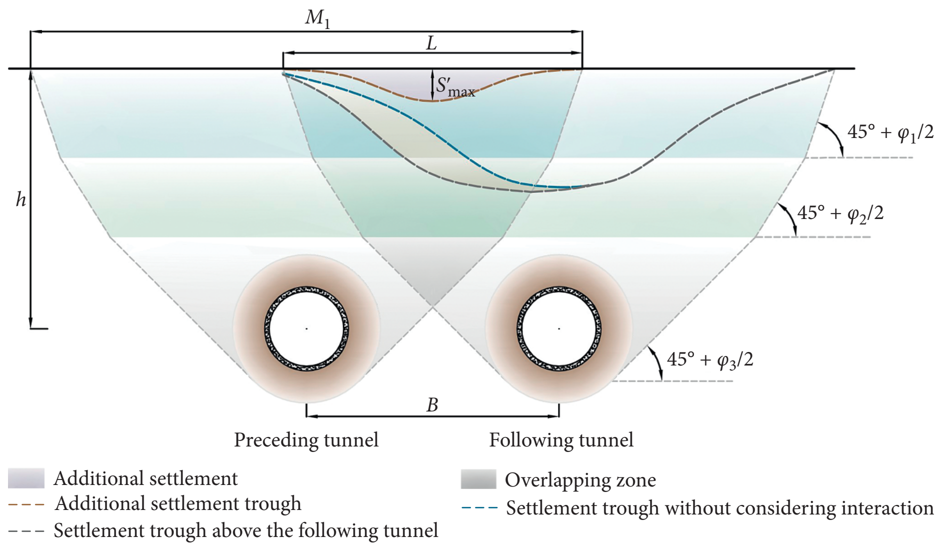


FIGURE 3: Calculation diagram of calculation method based on superposition theory.

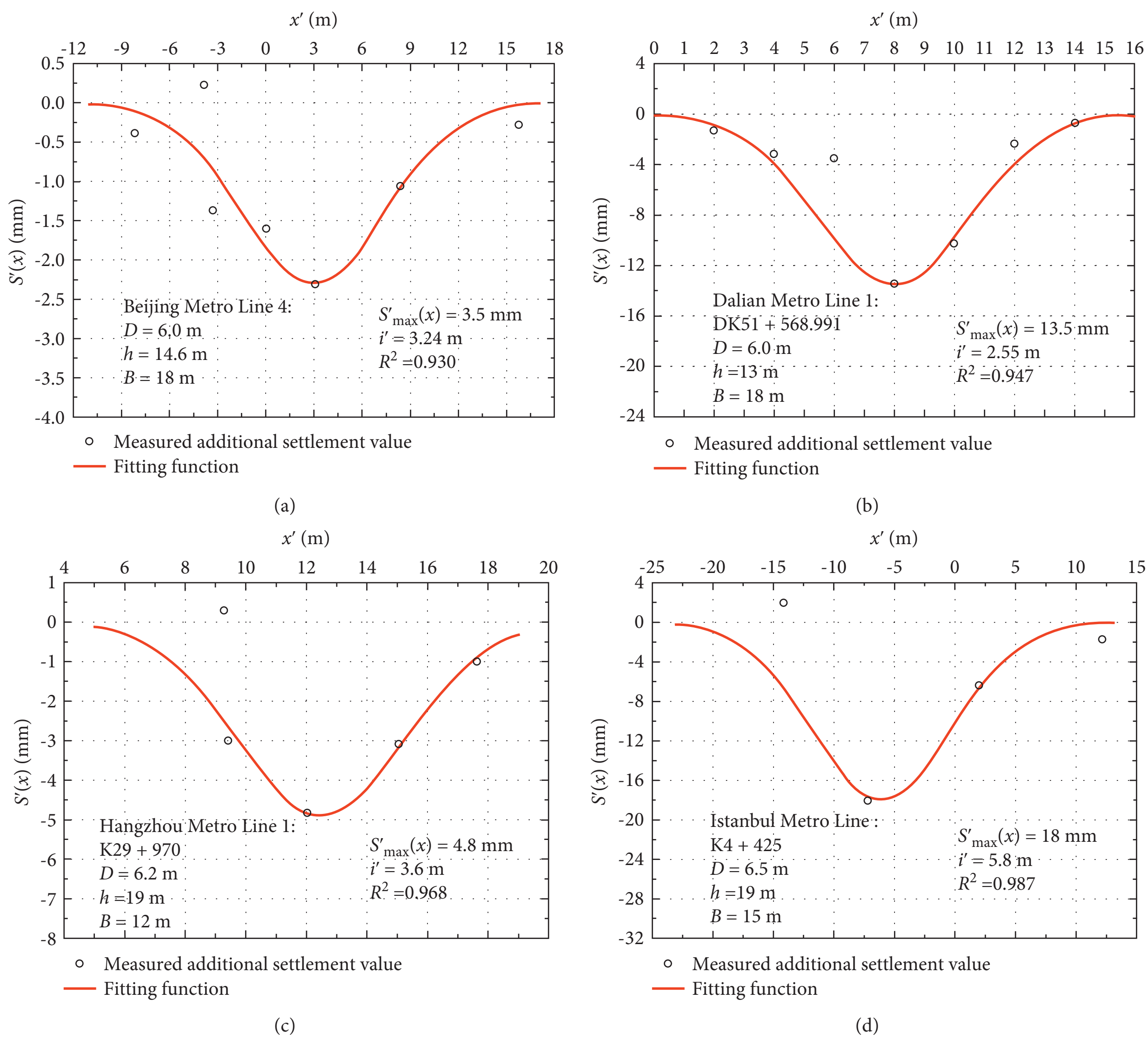


FIGURE 4: Comparison between the measured data of additional settlement and the fitting curves. (a) [26]. (b) [27]. (c) [28]. (d) [29].

complex, and it is difficult to monitor accurately. Therefore, the ground loss induced by overlapping disturbance can only be explored based on the existing measured settlement data. The additional settlement data can be obtained according to the following procedure:

(1) Translate the settlement trough of the post-constructed tunnel to the proconstructed tunnel so that the positions of the two tunnels are overlapped.
(2) Subtract the preceding tunnel's settlement from the following tunnel's settlement to obtain an additional surface settlement caused by superposition disturbance.
(3) The additional settlement value caused by the superposition disturbance is fitted and integrated by the gauss formula. And then, the soil loss caused by superposition disturbance is calculated.

3.4. Back Analysis of Ground Loss Induced by Overlapping Disturbance. A total of 14 tunnel excavation cases are collected in Tables 1 and 2 to study the distribution of ground loss caused by overlapping disturbance. All cases are parallel tunnels excavated by the EPB shield machine. Table 1 summarizes the details of each tunnel project, and Table 2 summarizes the surface settlement data from the measured and calculated data. In Table 2, V'_{loss} is the ground loss caused by superposition disturbance and V_{loss1} is the ground loss caused by the preceding tunnel.

For convenience, the least-squares principle is used to carry out linear fitting of V'_{loss} in the overlapping disturbance area. All calculated V'_{loss} for cases 1–14 from the back analysis are plotted as a function of V_{loss1} in Figure 5. The approximate relationship of $V'_{\text{loss}} \sim V_{\text{loss1}}$ can be expressed as

$$V'_{\text{loss}} = 0.0249 + 0.2845V_{\text{loss}}. \tag{13}$$

The coefficient of determination (R^2) was used to compare the goodness of fitting. 72% of the data show a good fitting result ($R^2 = 0.7146$), which indicates that V'_{loss} has a significant linear positive correlation with V_{loss1}. It can be concluded that the ground loss caused by the overlapping disturbance can be obtained through the ground loss of the following tunnel.

3.5. Calculation Process of Settlement Trough for the following Tunnel. The settlement trough calculation procedure is shown in Figure 6. Firstly, $S_1(x)$ and V_{loss1} are monitored by the measured data after the preceding tunnel excavated. Secondly, $S'(x)$ is determined by i' and V'_{loss}, which are calculated by (12) and (13). Finally, based on superposition technique, $S_2(x)$ is predicted by superimposing $S'(x)$ on $S_1(x)$.

4. Field Project Cases Validation

A total of 2 sets of data are investigated from 2 field tunnel projects to validate the calculation model for the trough width parameter and the settlement troughs above the parallel tunnels. Parameters and known quantities are listed in Table 3.

4.1. Changsha Metro Line 2 Project. Changsha Metro Line 2 project included two tunnels constructed using an EBP shield with a diameter of 6.00 m. Field settlements were obtained from section DK16 + 265. The depth of each tunnel axis is approximately 18 m, and the spacing between the center of two adjacent tunnels is 13 m. The soil profile at the instrumented site comprises miscellaneous fill, silty clay, sand, and argillaceous siltstone. The tunnel is located in argillaceous siltstone.

4.2. Shenyang Utility Tunnel Project. Shenyang utility tunnel project, which involved two tunnels, was built in Shenhe District of Shenyang City. Two tunnels were excavated using an EBP shield with a diameter of 6.00 m. Field settlements were obtained from section K8 + 577. The depth of each tunnel axis is approximately 18 m, and the spacing between the center of two adjacent tunnels is 12 m. The soil profile at the instrumented site comprises miscellaneous fill, round gravel, medium-coarse sand, and gravelly sand. The tunnel is located in gravelly sand.

4.3. The Trough Width Parameter. The proposed formula for i (i.e., (8)) is validated in two cases. Comparison between measured data and the i calculated results is shown in Table 4. In the first case, the relative error of i calculated by the proposed formula is 9.1%, and in the second case, the relative error is 1.4%.

It can be seen that different soil properties in the layered soils affect the trough width parameters induced by the tunnel, and it must be considered in the calculation. The proposed formulas for i could accurately calculate the trough width parameters in the field project.

4.4. The Settlement Troughs above the Parallel Tunnels. In two cases, the Gaussian curve is used to describe the surface settlement troughs above the parallel tunnels. The calculation results of the modification factor method are shown in Figures 7(a) and 8(a), and the calculation results of the proposed method based on the superposition technique are also presented in Figures 7(b) and 8(b), respectively.

A comparison between the calculated settlement troughs and the data points is shown in Figures 7 and 8. In the first case, only 50% of the data using the modification factor method show a good fitting result ($R^2 = 0.645$), while 80% of the data using the calculation method based on the superposition technique show a good fitting result ($R^2 = 0.852$). But in the second case, 75% of the data using the modification factor method show a good fitting result ($R^2 = 0.928$), and 83% of the data using the calculation method based on superposition technique show a good fitting result ($R^2 = 0.952$). The comparison demonstrates that the proposed method based on the superposition technique reasonably describes the feature of surface settlement trough above the following tunnel.

Table 1: Engineering details.

Case NO.	Project name	Ground conditions	D (m)	Reference
1	Bangkok MRTA project	Soft clay, hard clay	6.45	Suwansawat and Einstein [12]
2	The new Milan metro line 5	Gravelly sand	6.7	Fargnoli et al. [7]
3	Wuhan Yangtze river tunnel	Miscellaneous fill, silty clay, Mucky soil, silty clay, silt, silty clay, fine sand	12.6	Ma [30]
4	Nanjing metro line 1	Silt, mucky silt clay	6.4	Li [31]

Table 2: Data obtained from measurement and fitting.

Case NO.	Monitoring section	h (m)	B (m)	L (m)	i' (m)	S'_{max} (mm)	V'_{loss} (m^3/m)	i_1 (m)	S_{max1} (mm)	V_{loss1} (m^3/m)
1	CS-8D	20.1	15	19.26	3.85	3.4	0.033	9	6.5	0.147
2	SS-5T-52E-S	22.2	20	16.45	3.29	4.3	0.035	13	15.4	0.501
3	S19	15	15	10.42	2.08	1.9	0.010	7	8.8	0.154
4	S35	15	16.5	8.72	1.74	1.8	0.007	6	8.8	0.131
5	HS-2	17.4	20	17.46	3.49	27.0	0.236	8	43.7	0.873
6	HS-3	18.4	20	20.98	4.19	19.1	0.201	7	29.9	0.523
7	HS-5	35.6	20	39.91	7.98	7.7	0.155	15	22.6	0.733
8	HS-6	37.6	20	42.15	8.43	7.0	0.148	15	12.8	0.482
9	HS-7	44	20	49.26	9.85	3.3	0.083	22	6.4	0.352
10	HS-8	46.5	20	51.9	10.38	4.1	0.116	23	6.0	0.347
11	H1	11	13	12.09	2.42	4.4	0.026	6	19.0	0.285
12	H6	16.4	13	20.08	4.02	6.6	0.067	8	15.8	0.316
13	H7	17	13	21.20	4.24	4.3	0.046	9	17.8	0.401
14	H15	14	13	16.77	3.35	5.7	0.048	7	13.9	0.243

Note: Cases 1-2 are from Project 1, Cases 3-4 are from Project 2, Cases 3–10 are from Project 3, and Cases 11–14 are from Project 4.

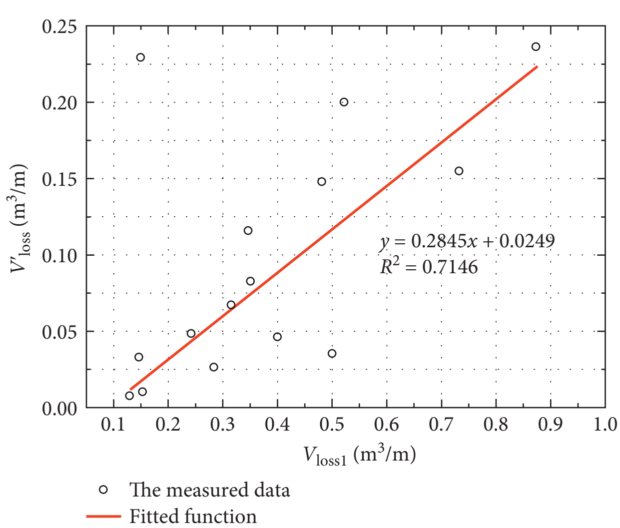


Figure 5: Fitting results.

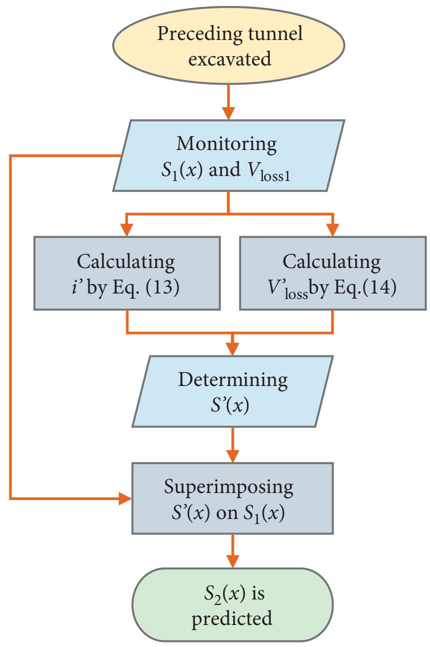


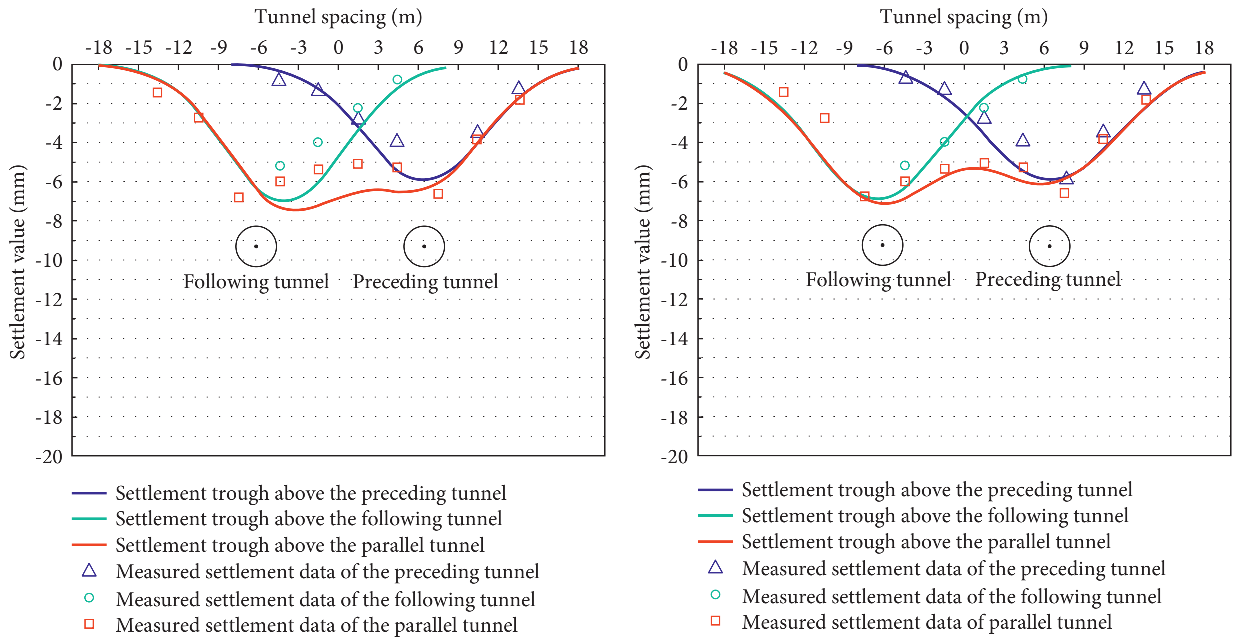
Figure 6: Flowchart of the calculation procedure.

Table 3: Information of the investigated tunnel cases.

Case no.	Soil profile	h (m)	γ (kN/m^3)	c (kPa)	φ (°)	References
1	Miscellaneous fill	3.1	19.4	16.2	50	Huang [32]
	Silty clay	4.3	19.8	59	15.3	
	Sand	3.1	19			
	Argillaceous siltstone	10.5	20.5	125	32	
2	Miscellaneous fill	4	18	15	10	Li [33]
	Round gravel	6	19.8	25.9	31	
	Medium-coarse sand	4.5	20.3	27	29.5	
	Gravelly sand	9.4	20.2	29	30	

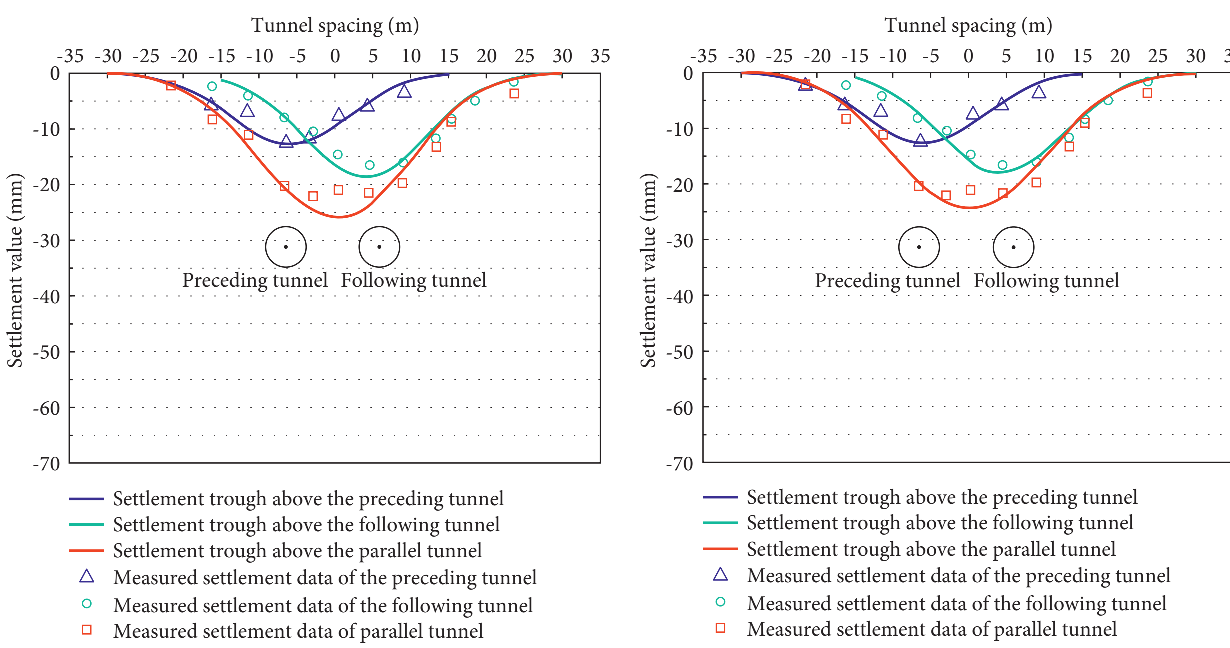
Table 4: Calculation results of trough width parameters.

Case NO.	Monitoring section	Field data (m)	Calculation result (m)
1	DK16 + 265	5.5	6.0
2	K8+577	6.8	6.7



(a) (b)

Figure 7: Comparison between the measured data and the calculated curves in case 1.



(a) (b)

Figure 8: Comparison between the measured data and the calculated curves in case 2.

5. Conclusion

This paper establishes a new calculation method of surface settlement trough induced by the parallel tunnels in layered soils. The primary aim was to address the problem that settlement trough above the following tunnel was affected by the preceding tunnel in adjacent and parallel tunnels event.

The following conclusions can be obtained based on the results of the work:

(1) The difference of soil properties in layered soils significantly affects the width parameter of surface settlement trough. In the calculation, the plastic zone and unloading disturbance zone are firstly

determined in layered soils. And then, according to the linear relationship between the width parameter and the width of the unloading disturbance zone, the width parameter is calculated by the linear formula.

(2) Based on the superposition technique of tunnel settlement, the surface settlement above the following tunnel can be divided into the single tunneling-induced surface settlement and additional settlement induced by overlapping disturbance. The Gaussian curve can approximate the additional settlement trough according to the fitting results.

(3) Through extensive data exploration, the method for calculating the ground loss V'_{loss} induced by overlapping disturbance is proposed. With the increase of V_{loss1}, the value of V'_{loss} is gradually increased. The approximate relationship of $V'_{\mathrm{loss}} \sim V_{\mathrm{loss1}}$ can be expressed as

$$V'_{\mathrm{loss}} = 0.0249 + 0.2845V_{\mathrm{loss}}, \quad (14)$$

(4) The calculated and measured settlement troughs above the parallel tunnels are in good agreement for the case study. Generally, the proposed model is effective and convenient for use in practice.

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by a grant from the National Natural Science Foundation of China (Grant no. 51804006).

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