Construction Settlement Prediction of Shield Tunnel in Soft-soil Area

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ABSTRACT

The aim of this paper is to analyze and predict the construction settlement of shield tunnel in soft-soil area. Using the shield tunnel excavation gap parameters, by introducing the width correction coefficient *b* of the settlement trough, the analytical solution of shield tunnel construction settlement was obtained based on the Peck formula. Different buried depth ratios, unified focus spacing *d* and correction coefficient *b* were selected to analyze the ground settlement of tunnel construction. The results show that for shallow buried tunnel, the maximum settlement at different depths of the stratum shows a linear increase trend. For deep buried tunnel, with the deepening of depth, the maximum stratum settlement increases firstly linearly and then decreases gradually. Under the same buried depth, with the increase of the focus spacing ratio d/D_m, the settlement of the stratum increases gradually for strata with different hardnesses. Combined with engineering examples, the reliability of the proposed settlement prediction method is verified by the maximum ground settlement $S_{max}(z)$ and the settlement curve $S(x,z)$.

KEYWORDS: Shield tunnel, Construction settlement, Parameter analysis, Maximum ground settlement, Ground settlement curve.

INTRODUCTION

With the rapid progress of China's economic and social development and the acceleration of China's urbanization process, the municipal railway tunnel has become one of the important means to mitigate urban traffic pressure or solve urban traffic congestion. The disturbance caused by shield tunnel construction of municipal railway will inevitably lead to settlement of surrounding soil strata, which in turn causes unsafety to the surrounding buildings or the neighboring structures. Therefore, it is of important theoretical significance to predict the settlement of shield tunnel construction using scientific methods for the design and construction of shield tunnels.

Received on 12/7/2021.
Accepted for Publication on 31/3/2022.

Domestic and foreign scholars have carried out a lot of research on the construction settlement analysis of shield tunnels. Peck (1969) analyzed the surface settlement of tunnel construction based on a large number of engineering measured data, indicating that the shape of ground subsidence groove of tunnel construction in both non-cohesive soil and cohesive soil presented the form of error function or normal distribution curve. Gao et al. (2014) used a numerical method to simulate the construction process of shield tunnel and compared the longitudinal and transverse settlement data obtained by fitting with an empirical formula, such as Peck formula. The results showed that the empirical formula (such as Peck forumula) can be used to predict the surface settlement caused by shield tunnel construction. Lu et al. (2019) used MIDAS/GTS software to simulate the construction process of double-hole single-line tunnel in upper soft and lower hard strata. The simulation results and field measured data were compared with the Peck correction formula, indicating that the Peck correction formula could be used to predict the surface settlement of similar double-hole single-line tunnels. Lu et al. (2020), combined with an actual project, used numerical simulation and field monitoring data to study the shield construction settlement of upper soft and lower hard composite strata. It was concluded that with the decrease of the height ratio of soft and hard rock (soft rock height/hard rock height), the ground subsidence value decreased and the settlement trough became shallower. For soft ground with high compressibility, Hadri et al. (2021) studied the behavior of stone columns under loads by numerical simulation, where the numerical results of settlements were in good agreement with the field measurements collected from the case history.

Scholars also used the method of stratum loss gap parameters to study the stratum settlement caused by shield tunnel construction. Scholars (Rowe and Kack, 1983; Lee et al.,1992; Row and Lee, 2011) used stratum loss gap parameters to predict formation loss and further derived analytical solutions for tunnel surface settlement. Based on the influence of grouting pressure and thrust force on the working surface, Wang et al. (2013) proposed a ground settlement calculation formula considering the influence of grouting pressure and propulsion force on the working surface based on stratum loss gap parameters. They compared the measured data of practical engineering to prove the rationality of this correction method. Based on the Sagussetta solution, An et al. (2017) revised it considering the influence of construction time parameters and analyzed the influence of construction parameters on surface settlement during construction. The correctness of this correction method was verified by practical engineering. At present, regarding the study of ground settlement in shield tunnel construction, the prediction results of scholars at home and abroad can only reflect the settlement after shield construction and cannot reflect the disturbance of shield propulsion process to soil strata. The theoretical solution is derived under the condition of simplification as a single stratum. The stratum deformation has regional characteristics and the existing theory cannot be consistent with the settlement of strata of Oujiang shield tunnel, which needs further investigation.

Therefore, in this paper, combined with an actual project, shield tunnel excavation gap parameters are used by introducing the width correction coefficient b of the settlement trough, where the analytical solution of shield tunnel construction settlement was obtained based on the Peck formula. Different buried depth ratios C/D_m, unified focus spacing d and correction coefficient b were selected to analyze the ground settlement of shield tunnel construction and the reliability of the proposed settlement prediction method was verified by combining with practical engineering examples. It is expected that the findings of the current study will provide a theoretical reference for the design and construction of similar shield-tunnel projects.

THEORETICAL ANALYSIS OF SHIELD TUNNEL CONSTRUCTION SETTLEMENT

Ground Loss Rate

The uneven distribution gap ground loss model (Sagaseta, 1987; Lee, 1992) is used to analyze and calculate the ground loss. Rowe and Kack (1983) proposed the theory of gap parameters for the first time. The calculation formula of the gap parameter g* of shield tunneling in soft clay stratum without drainage is as follows:

$$g^* = G_p + u_{3D}^* + \omega \tag{1}$$

Where G_P is the shield tail gap; that is the difference between the tunnel outer diameter D and the shield outer diameter D_m. u^*_{3D} is the three-dimensional equivalent radial elastoplastic deformation of the tunnel excavation surface and ω is the stratum loss caused by tunnel construction.

The volume of the formation loss on the unit length is:

$$V_{los} = \pi g^* \left(a - \frac{g^*}{4}\right) = \pi g^* \left(\frac{D_m}{2} - \frac{g^*}{4}\right) \tag{2}$$

Where a is the grouting quality coefficient, representing the influence of grouting quality on shield tail gap.

In order to simplify the calculation and expression, the concept of volume loss rate V_l is introduced, which is the ratio of the loss volume to the volume of excavation section per unit length of the tunnel.

$$V_1 = \frac{V_{los}}{\pi D_m^2/4} = \frac{g^*}{D_m}\left(2 - \frac{g^*}{D_m}\right) \tag{3}$$

Stratum Settlement Mode of Shield Tunnel Construction

The stratum settlement of shield tunnel construction at a certain depth is described by a Gaussian curve,

$$\begin{cases} s(x,z) = s_{max}(z)\exp(-\frac{x^2}{2i(z)^2}) \\ s_{max}(z) = \frac{\sqrt{\pi}D_m^2V_1}{4\sqrt{2}i(z)} \end{cases} \quad (4)$$

Where *x* and *z* are the horizontal distance from the center line of the tunnel and the vertical distance from the ground surface, respectively. $S_{max}(z)$ represents the maximum settlement at depth *z*. *i(z)* represents the vertical distance from the center line of the tunnel to the inflection point of the Gaussian curve at depth *z*.

In order to calculate the maximum settlement $S_{max}(z)$ at the buried depth z below the surface, referring to a large number of actual engineering and model test data (Lu et al., 2020; Zymnis et al., 2013; Moh et al., 1996; Zhang et al., 2002; Romo, 1997; Li, 2004; Yi, 1999; Chen et al.,2011; Wang et al., 2009; Pan, 2015), it is considered that the maximum settlement at the buried depth z below the surface has the following characteristics.

(1) At the top of the tunnel, $z=z_0$, $z = z_0, \frac{s_{max}(z)}{s_{max}(z_0)} = 1$

(2) At the surface of the ground, $z=0$, $z = 0, \frac{s_{max}(z)}{s_{max}(z_0)} = \frac{s_{max}(0)}{s_{max}(z_0)}$

(3) When the buried depth *z* increases from 0 to z_0, the corresponding settlement $S_{max}(z)$ is gradually increasing.

Based on the above characteristics, combined with the law of actual data, the following power function is used to describe the relationship between the maximum settlement at the depth z below the surface and z.

$$\frac{s_{max}(z)}{s_{max}(z_0)} = (\frac{s_{max}(0)}{s_{max}(z_0)} - 1)(1 - \frac{z}{z_0})^{\frac{1}{n}} + 1 \quad (5)$$

Where *n* is a positive stratum parameter, which comprehensively reflects the influence of stratum condition and tunnel geometry on the maximum ground settlement.

Lu et al. (2020) summed up a large number of engineering measured data and obtained the value of ground parameter *n*. For strata composed of clay layer or soft soil ground, parameter n could be estimated according to the following expression:

$$n = (s_{max}(0)/s_{max}(z_0))^{-0.97} \quad (6)$$

Referring to the calculation method of maximum ground settlement of the unified soil movement model proposed by Wei (2007), it is considered that the surrounding rock around the tunnel will converge to a focus and the soil above the focus will converge downward, while the soil below the focus will converge upward. Because the mechanism is symmetrical, the focus moves in the plane of the tunnel axis.

Assuming that the soil is undrained, the expression of the maximum surface settlement $S_{max}(0)$ can be derived by using the source-sink method and the unified soil movement model.

$$s_{max}(0) = \frac{2D_m(D_m+2z_0+2d)}{D_m+2d} - 2D_m\sqrt{\frac{(D_m+2z_0+2d)^2}{(D_m+2d)^2} - V_1} \quad (7)$$

The value range of the distance d between the focus and the tunnel center point is 0–$D_m/2$. For saturated muddy soft soil, *d* is 0–0.1D_m. For cohesive soil, *d is* 0.1D_m–0.4D_m. For hard soil, *d is* 0.4D_m–0.5D_m. For the shield tunnel, $S_{max}(z_0)$ is equal to the gap parameter g* and can also be solved by knowing the ground loss.

$$s_{max}(z_0) = \begin{cases} g^* \\ D_m(1 - \sqrt{1 - V_1}) \end{cases} \quad (8)$$

From Eq. (4),

$$i(z) = \frac{\pi D_m^2 V_1}{4\sqrt{2\pi}s_{max}(z)} = \frac{\sqrt{\pi}D_m^2V_1}{4\sqrt{2}s_{max}(z_0)\left[(\frac{s_{max}(0)}{s_{max}(z_0)} - 1)(1 - \frac{z}{z_0})^{\frac{1}{n}} + 1\right]} \quad (9)$$

The correction coefficient b is introduced to correct the width of settlement trough in soft-soil area. The inflection point distance *i(z)* of stratum deformation after correction is:

$$i(z)=\frac{\sqrt{\pi}bD_m^2V_1}{4\sqrt{2}s_{max}(z_0)\left[(\frac{s_{max}(0)}{s_{max}(z_0)}-1)(1-\frac{z}{z_0})^{\frac{1}{n}}+1\right]} \quad (10)$$

Analytical Solution of Shield Tunnel Construction Settlement

Eq. (5) and Eq. (10) are taken into Eq. (4) to obtain the analytical formula of stratum deformation:

$$s(x,z)=s_{max}(z)\exp\left(-\frac{4xs_{max}(z_0)}{\sqrt{\pi}bD_m^2V_1}\left[(\frac{s_{max}(0)}{s_{max}(z_0)}-1)(1-\frac{z}{z_0})^{\frac{1}{n}}+1\right]\right)^2 \quad (11)$$

The solution of $S_{max}(0)$ and $S_{max}(z_0)$ can be referred to as in Eq.(7) and Eq.(8).

PARAMETER ANALYSIS OF GROUND SETTLEMENT

When predicting the ground settlement caused by shield construction, the factors influencing ground settlement are mainly as follows: the buried depth of the tunnel, the hardness of strata and the correction coefficient *b*. The parameters of buried depth ratio C/D_m and unified focus spacing *d* of different tunnels are selected to analyze the effect on ground settlement of the tunnel. Taking the Oujiang North Entrance Shield Tunnel engineering parameters as an example, in the clay layer, the diameter *D* of the tunnel is 14.5m and the diameter D_m of the tunnel excavation is 14.9m. Assuming that the stratum loss is certain, it is 1%. The buried depth *C* of the tunnel is $0.5D_m$-$4D_m$ and the unified focus spacing *d* is 0-$0.5D_m$.

Stratum Maximum Settlement $S_{max}(z)$

The influence of the buried depth ratio C/D_m of the tunnel on the maximum stratum settlement is analyzed. The values of other parameters are as shown in Fig.1. When the buried depth ratios are 1.0, 2.0, 3.0 and 4.0, the comparative analysis curves are as shown in Fig.1. It can be seen from Fig. 1 that for the same stratum, with the increase of buried depth, the maximum settlement at the surface plane gradually decreases. For shallow buried condition, the maximum settlement at different depths of the stratum shows a linear increasing trend. For deep buried condition, with the deepening of the buried depth, the maximum settlement of the stratum increases linearly at first and then decreases gradually until it is stable. The maximum settlement of the stratum increases gradually in the range of 0-$0.8z_0$ from the surface. When the depth is greater than $0.8z_0$, the maximum settlement of the stratum is basically unchanged, indicating that the greater the depth of the tunnel, the greater the value of the stratum parameter *n*. The settlement of the upper stratum of the tunnel is concentrated on the vault. This situation occurs because of the soil arch effect. For deep buried tunnel, the deformation influence range of the general stratum appears in the plastic zone of the vault, while the excess range is constrained by the soil arch effect and the deformation is mainly an elastic deformation.

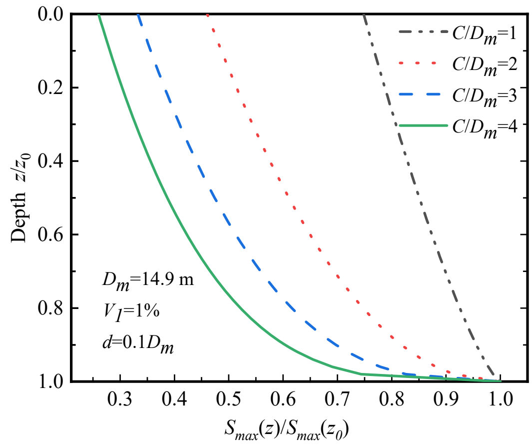
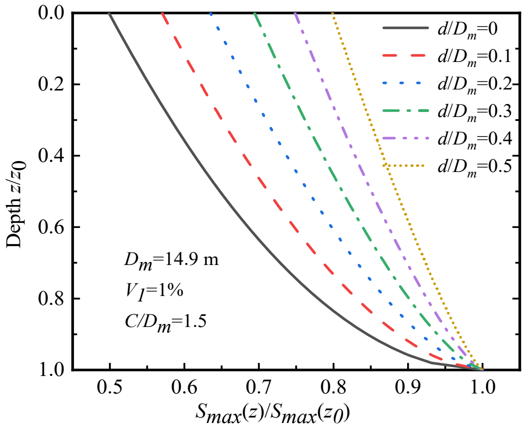
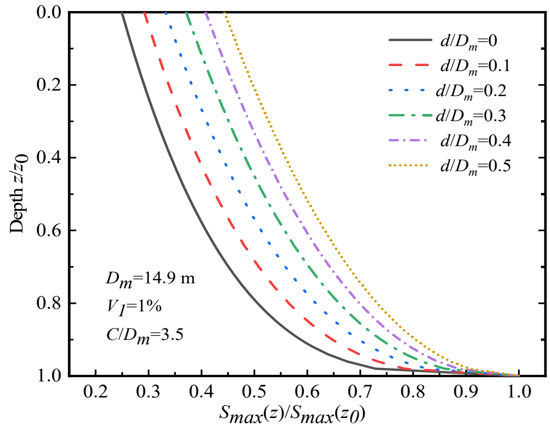


Figure (1): Influence curve of stratum maximum settlement (different buried depths)

The values of other parameters are are shown in Fig.2. For different strata with soft and hard conditions, shallow buried (buried depth ratio C/D_m=1.5) and deep buried (buried depth ratio C/D_m=3.5) conditions are discussed, respectively. When the focus spacing ratio d/D_m of the unified loss model is 0, 0.1, 0.2, 0.3, 0.4 and 0.5, respectively, the comparative analysis curves are as shown in Fig. 2. According to Fig.2, it can be seen that under the same buried depth, with the increase of the focus spacing ratio d/D_m, the settlement of the stratum is gradually increased. That is the greater the hardness of the stratum, the settlement of the stratum, which is due to that the greater the hardness of the stratum, the greater the force between the particles in the soil layer, resulting in that the deformation of the soil layer is smaller, in addition to that the change trend is slower.



(a) Buried depth ratio C/D$_m$=1.5



(b) Buried depth ratio C/D$_m$=3.5

Figure (2): Influence curve of maximum settlement of strata (different soft and hard strata)

PRACTICAL ENGINEERING EXAMPLE

The applicability of the proposed method is discussed. The numerical simulation data and the measured data of similar projects are used to verify and analyze the method proposed in the current study. The comparative analysis data of similar projects is selected as shown in Table 1.

Table 1. Measured values of engineering example deformation

No.	Project	Soil	Construction method	Buried depth C (m)	D_m/D (m)	Depth Z (m)	$S_{max}(z)$ (mm)	V_1/%	Remark
1	Oujiang North Tunnel	Soft clay	SPB	20.0	14.9/ 14.5	0	11.0	0.267	Numerical simulation
						1	11.1		
						2	11.2		
						3	11.4		
						4	11.5		
						5	11.6		
						6	11.8		
						8	12.1		
						10	12.3		
						12	12.7		
						14	13.3		
						16	14.3		
						18	16.5		
						20	19.9		
2	Taipei Rapid Traffic System Project	Clay	EPB	15.5	6.05/ 6.0	0.0	20.3	1.3	Document (Moh et al., 1996)
						6.0	22.9		
						9.5	26.0		
						14.5	36.0		
						15.5	39.5		

3	Guangzhou Metro Line 2	Clay	Shield	23	6.28/ 6.0	0	4	0.63	Document (Wang et al., 2002)
						1.2	4.6		
						4.3	5.7		
						6.5	6.6		
						7.1	8.6		
						12.6	7.7		
						14.5	7.7		
						15.1	10.6		
						18.3	11.7		
						20.5	13.7		
						21.7	17.6		
						23	19		
4	Heathrow Airport Tunnel	Lond on clay	Shield	16.8	8.5/ 8.5	0	27	1.27	Document (Deane, 1995)
						3	29		
						7	32		
						11	37		
						16.8	54		

Comparative Analysis of Maximum Settlement $S_{max}(Z)$

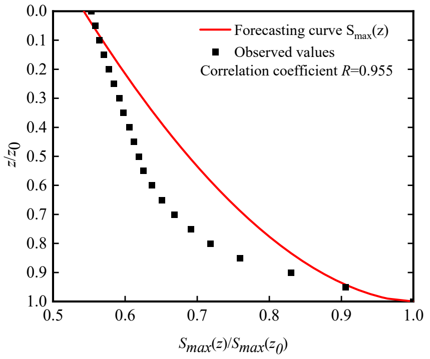
The method of formation loss is used to determine the maximum displacement $S_{max}(0)$ and $S_{max}(z_0)$ of the ground deformation curves at z=0 and $z=c$. In order to verify the accuracy of $S_{max}(0)$ and $S_{max}(z_0)$ obtained by theoretical calculation, the comparative analysis results are shown in Table 2. It can be seen from Table 2 that the measured value of the maximum settlement $S_{max}(z_0)$ at $z=c$ can be in good agreement with the theoretical value, where the error is within 5%. The maximum settlement of the stratum at $z=0$ can be obtained by reasonably selecting the parameter d according to the physical properties of the soil layer. The maximum error between the measured value and the theoretical value of the three engineering examples is 15.84%, but the measured value and the theoretical value can match each other. The measured value can be included in the range of theoretical calculation value when the parameter d is reasonably selected. Therefore, it is feasible to determine $S_{max}(0)$ and $S_{max}(0)$ by Eq. (7) and Eq. (8), which can be used to predict the deformation of soil.

Table 2. Measured values and theoretical values of $S_{max}(0)$ and $S_{max}(z_0)$

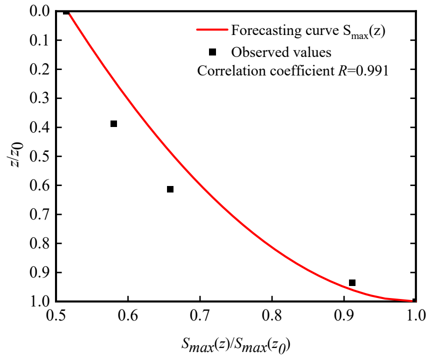
Project	$S_{max}(0)$ comparison			$S_{max}(z_0)$ comparison		
	Measured value	Theoretical value	Error	Measured value	Theoretical value	Error
Case1	11.0	10.80 (d=0)	1.8%	19.9	19.9	0
Case2	20.3	20.35 (d=0.4D_m)	0.24%	39.5	39.45	0.13%
Case3	4.0	4.75（d=0）	15.84%	19	19.81	4.10%
Case4	27	26.72 (d=0.15D_m)	1%	54.15	54	0.27%

The theoretical calculation results of the maximum settlement $S_{max}(0)$ and $S_{max}(z_0)$ of the ground deformation curves at $z=0$ and $z=c$ can be matched with the measured results. In order to clarify the influence on the maximum stratum deformation, the prediction error of the maximum settlement $S_{max}(z)$ curve is analyzed, as shown in Fig. 3.

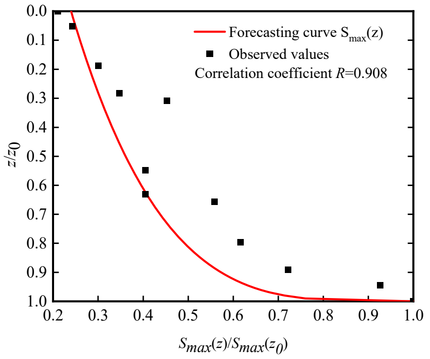
It can be seen from Fig. 3 that the prediction results of the maximum settlement $S_{max}(z)$ obtained by the method mentioned in this paper are compared with the actual monitoring results. The correlation coefficient R between the two is basically between 0.9 and 1.0, indicating that there is a high correlation between the two. The method can be used to predict the maximum settlement $S_{max}(z)$.



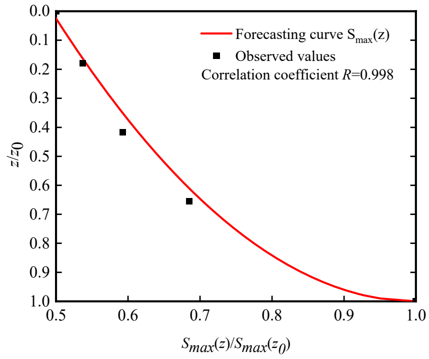
(a) Case 1



(b) Case 2



(c) Case 3



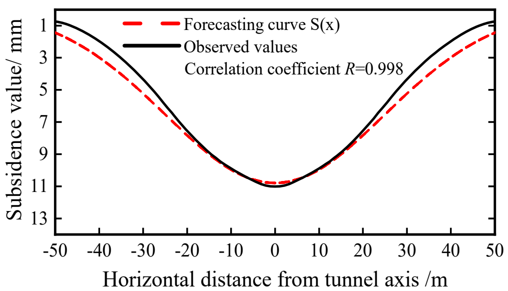
(d) Case 4

Figure (3): Correlation coefficient R is shown in each figure, which can reflect the correlation and the error between the predicted value and the observed value

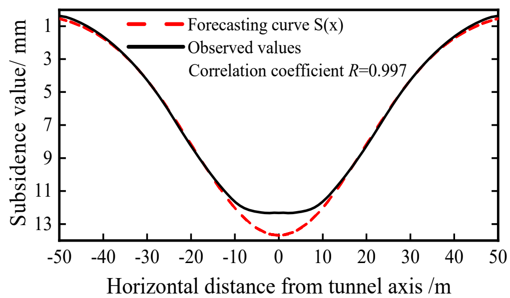
Comparative Analysis of Stratum Settlement Curve S (X, Z)

Case 1 and Case 4 are selected to analyze the error between the predicted settlement curve *S(x,z)* and the actual monitoring results, as shown in Fig. 4 and Fig.5.

From Fig. 4 and Fig. 5, it can be seen that the predicted settlement curve of the stratum at the depth *z* plane of the tunnel is consistent with the monitoring value of the stratum. The correlation coefficient *R* between the two is basically between 0.9 and 1.0, meaning a high correlation. This method can be used to predict the formation settlement *S(x,z)*.

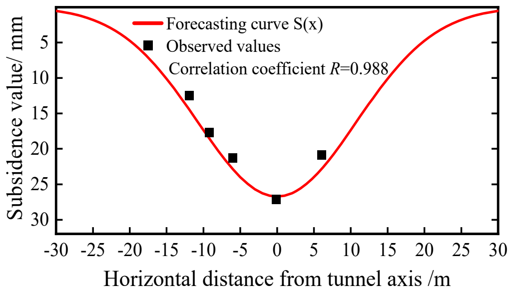


(a) Stratum depth z = 0 m

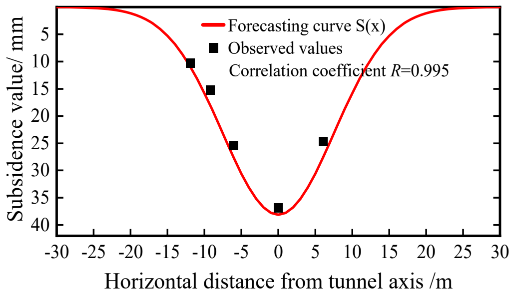


(b) Stratum depth z = 10 m

Figure (4): Error analysis of the deformation curve of the strata S(x,z) (Case 1: b=1.45)



(c) Stratum depth z=0 m



(d) Stratum depth z =11m

Figure (5): Error analysis of the deformation curve of the strata S(x,z) (Case 4 :b=1)

CONCLUSIONS

For the same stratum, with the increase of buried depth, the maximum settlement at the surface plane gradually decreases. For shallow buried tunnel, the maximum settlement $S_{max}(z)$ at different depths of the stratum shows a linear increase trend. For deep buried tunnel, with the increase of depth, the maximum settlement of the ground increases first linearly and then decreases gradually until it is stable.

Under the same buried depth, with the increase of the focus spacing ratio d/D_m, the settlement of the stratum decreases gradually.

The analytical solution of shield tunnel construction settlement is proposed and the reliability of the proposed prediction method of the stratum settlement curve is analyzed based on the simulation data of practical engineering examples and the monitoring data of similar projects. The results show that the proposed method is close to the actual results and the rationality of the prediction method is verified.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Data Availability Statement

Model parameters as well as model calculation results that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

This research is supported in part by the National Natural Science Foundation of China (Grant number: 51968045) and the Science and Technology Planning Project of Zhejiang Traffic Quality Supervision Industry (Grant number: ZJ201906).

REFERENCES

An, J.Y., Xiang, Y.Y., An, F.J. et al. (2017). “Simplified analytic calculation of the influence of shallow tunnel construction on ground deformation.” Journal of Underground Space and Engineering, 13 (1), 184-189.

Chen, R.P., Zhu, J., Liu W. et al. (2011). “Ground movement induced by parallel EPB tunnels in silty soils.” Tunneling and Underground Space Technology, 26 (1), 163-171.

Deane, A.P. (1995). “The Heathrow express trial tunnel.” International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts, 32 (8), 411A-411A.

Gao, L.X., Yang, X.J., and Qin, L.K. (2014). “Finite element analysis of the surface settlement induced by shield tunnel construction”. Applied Mechanics and Materials, 2974, 111-114.

Hadri, S., Messast, S., and Bekkouche, S.R. (2021). “Numerical analysis of the performance of stone columns used for ground improvement.” Jordan Journal of Civil Engineering, 15 (2), 253-265.

Lee, K.M., Rowe, R.K., and Lo, K.Y. (1992). “Subsidence owing to tunneling. I. Estimating the gap parameter.” Canadian Geotechnical Journal, 29 (6), 929-940.

Li, Y. (2004). “3D FEM simulation and experimental research on ground deformation by shield-driven construction”. PhD Thesis. Tianjin University (in Chinese).

Lu, J., Yao, A.J., Zheng, X. et al. (2019). "Study on the law and computational method of ground-surface settlement induced by double-line tunnel excavation." Chinese Journal of Rock Mechanics and Engineering, 38 (S2), 3735-3747.

Lu, J.B., Li, X.L., Fu, H.L. et al. (2020). "Influence of shield-tunnel construction on ground surface settlement under the condition of upper-soft and lower-hard composite strata." Journal of Vibroengineering, 22 (5), 1126-1144.

Moh, Z.C., Ju, D.H., and Hwang, R.N. (1996). "Ground movements around tunnels in soft ground." Proceedings of the International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground. London, UK, 725-730.

Pan, Z.G. (2015). "Study on the ground deformation of soil tunnel excavation." PhD Thesis, Beijing University of Technology (in Chinese).

Peck, R.B. (1969). "Deep excavations and tunneling in soft ground". In: the 7th ICSMFE, Mexico, 311-375.

Romo, M.P. (1997). "Soil movements induced by slurry shield tunneling." Proc. of 14th International Conference on Soil Mechanics and Foundation Engineering, Hamburg, Germany.

Row, R.K., and Lee, K.M. (2011). "Subsidence owing to tunneling. II. Evaluation of a prediction technique." Canadian Geotechnical Journal, 29 (6), 941-954.

Rowe, R.K., and Kack, G.J. (1983). "A theoretical examination of settlements induced by tunneling: Four case histories." Canadian Geotechnical Journal, 20 (2), 299-314.

Sagaseta, C. (1987). "Analysis of undrained soil deformation due to ground loss." Géotechnique, 38 (7), 301-320.

Wang, F., Miao, L.C., and Li, C.L. (2013). "Numerical analysis of shield-tunnel settlement considering the construction process." Chinese Journal of Rock Mechanics and Engineering, 32 (S1), 2907-2914.

Wang, Z.S., Wang, M.S., and Zhang, M. (2009). "Methods for estimating subsurface ground movements induced by shield tunneling." Rock and Soil Mechanics, 30 (6), 1699-1703.

Wei, G. (2007). "Establishment of a uniform ground-movement model for shield tunnels." Chinese Journal of Geotechnical Engineering, 29(4), 554-559.

Yi, H.W. (1999). "Research on the disturbance of soil and ground movements induced by shield tunneling." PhD Thesis, Tongji University (in Chinese).

Zhang, Y., Yin, Z.Z., and Xu, Y.F. (2002). "Analysis of three-dimensional ground-surface deformations due to shield tunneling". Chinese Journal of Rock Mechanics and Engineering, 21 (3), 388-392

Zymnis, D.M., Chatzigiannellis, Y., and Whittle, A.J. (2013). "Effect of anisotropy in ground movements caused by tunneling." Géotechnique, 63 (13), 1083-1102.