Analysis of instantaneous surface settlement during tunnel construction in composite stratum

Guanfeng Tian[1,*], Jing Wu[2] and Xinmeng Yu[1]

[1] School of Environment and Civil Engineering, Dongguan University of Technology, Dongguan, China

[2] School of Mechanical Engineering, Dongguan University of Technology, Dongguan, China

*Corresponding author e-mail: tiangf126@126.com

Abstract. It is important for shield tunnelling safety to predict and control the instantaneous surface settlement. Particularly, the complex geological condition can make accurate prediction more difficult. To adapt to the stratum distribution, a semi-analytical method is established by introducing the finite layer method into tunnel mechanical analysis. Firstly, based on the elastic solution of the finite layer method, the horizontal flexibility coefficient of tunnelling and the surface settlement are obtained by applying effective thrust to the excavation face. Secondly, two influencing factors are analyzed, including the penetration of shield tunnelling and the Poisson ratio of geotechnical parameter. The relationship formula between the measured value and the theoretical value of the maximum settlement is derived through data fitting. Finally, the settlement prediction method of tunnelling is proved to be practical, which provide a new ideal for the mechanical analysis of tunnels in composite strata.

Keywords: Composite stratum; semi-analytical method, instantaneous surface settlement, penetration; poisson ratio.

1. Introduction

Nowadays it is more convenient for people to travel by subway. As a widely used technology for subway construction, shield tunneling changes the original stress field of the stratum to cause surface settlement. Especially in the composite geological environment, the settlement change caused by tunneling will increase greatly, which will endanger aboveground buildings and underground workers. Therefore, it is necessary to predict the settlement effectively before tunneling to ensure the smooth progress of tunnel construction.

Engineering practice shows that surface settlement caused by tunneling is a result of multiple factors, including the geological and hydrological environment, the stratum properties, and the shield tunneling parameters, with the complex correlation among them. In the past 50 years the empirical formula method is commonly used. Peck formula is widely used (Peck (1969)), which could be used to better describe the settlement trough of a single tunnel in simple stratum. Until now, it has been continuously revised and used by follow-up researchers according to new conditions. The size and range of surface settlement value of shield tunnel were estimated by empirical methods based on normal distribution function (Fang et al. (2014)). However, it is difficult to determine the empirical parameters for complicated geological conditions so that this method is limited in promotion and application.

The analytical method of surface settlement caused by tunnel excavation had a more rigorous theoretical foundation. Many research achievements were based on the homogeneous elastic half-space foundation models (Verruijt and Booker (1996)). The settlement prediction formula (Deng et al. (2022)) for curved tunnels is derived from Mindlin solution. However, for complex heterogeneous stratum problems, it is difficult to obtain a complete solution using the analytical method. In addition, shield construction factors have not been considered in these studies.

With the development of computer technology and algorithm science, more and more numerical analysis methods are increasingly applied to calculate the settlement caused by tunneling. The geometric feature of tunnels, geotechnical properties and tunneling parameters are all considered in the models to show a strong advantage of universality of numerical methods. For example, the finite element method can be used to simulate the creep and seepage of soil in the settlement study of the tunnel (Wang et al. (2012)). However, because the numbers of parameters and elements for finite element analysis of tunnel space is huge, only a more actual simulation for the coupling treatment of soil and tunnel structure interface can ensure the calculation results be reliable.

In recent years, new methods such as machine learning and depth learning algorithm have been introduced into the settlement research of tunnel construction with the rapid development of artificial intelligence. The artificial neural network is initially used to predict the maximum surface settlement caused by tunneling. The feasibility of this method is demonstrated by using the ANN to connect the tunneling parameters and geotechnical parameters with surface settlement (Qiao et al. (2010)), and applying it to practical engineering projects. There are many optimization algorithm such as multilayer back-propagation neural networks (Khatami (2013)), ANN optimized based on genetic algorithms (Ahangari et al. (2015)). By comparing the applicability and reliability of these artificial intelligence methods it is showed that different data sets suit different prediction methods. The advantage of an algorithm is that it can analyze the nonlinear relationship between the known high-dimensional parameters and the predicted settlement. The sufficient source data set used to train the calculation models allows the more accurate model prediction results. Therefore, computing performance depends heavily on the authenticity and reliability of a large number of source data.

It is well known the maximum surface settlement is a key warning factor for shield construction safety. Every research method has its own characteristics and application scope, with advantages and limitations respectively. Composite stratum is very common in the subway tunnels in South China. In this paper, the surface settlement prediction method of shield tunneling in composite strata is studied based on the Guangzhou Metro Project. First of all, the elastic finite layer method is used to analyze the composite strata, which is a semi-analytical method including the advantages of numerical method. It can not only simulate the contact relationship between stratum units, but also adapt to the diversified characteristics of soil layers, which can solve the difficulty in analyzing composite stratum. At the same time, the effective thrust of shield is applied to the tunnel excavation face as an active load, and the finite layer method elastic solution with horizontal forces is used to analyze surface settlement at the moment of tunneling. Secondly, the influencing factors of the differences between the measured value of surface settlement and the theoretical calculation value of the finite layer method are studied with consideration of the tunneling parameters and geotechnical parameters. Finally, the relation formula between the field-measured value and the theoretically calculated value of the maximum surface settlement is established by fitting the data of an engineering case, according to which the instantaneous surface settlement could be predicted.

2. The finite layer method of tunnel stratum analysis

The reliability of the mechanical analysis of shield tunneling is mainly dependent on the accuracy of the simulation analysis of the natural stratum. Especially composite stratum may easily cause complex interaction between the stratum and the shield cutterhead at the tunnel excavation face. The finite layer method was used to settle the mechanical analysis of uneven ground (Tian et al. (2016); Tian and Tang (2017)). So, this method will be used to study the relationship between the effective thrust and surface settlement when shield tunneling in the following.

2.1. Model of tunnel composite stratum

The finite layer method, a semi-analytical method, is suited for solving problems of layered ground better than other methods. Based on its basic principle, the mechanical model is shown in Figure 1.

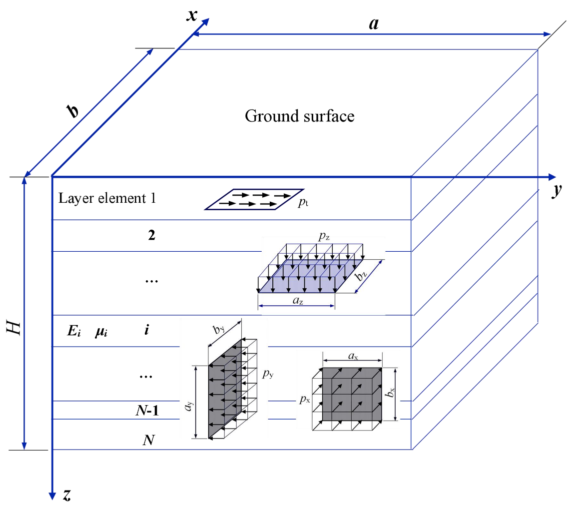
Semi-infinite layered tunnel space is simulated by adopting a sufficiently large area $a \times b \times H$, dividing into N layers by depth, and getting the elastic material parameters of each layer element i including the deformation modulus Ei and Poisson ratio μi , i = 1, 2, ..., n. The loads from different directions like normal forces px, py, pz and tangential forces pt , are imposed inside the area. In this way, the extended finite layer method (Tian et al. (2016)) is possible to work out the stress field and displacement field of the composite stratum.

2.2. Load model of shield tunneling

The loads transferred from the construction state of shield tunneling, as well as the ground weight, can be calculated by existing empirical formulas and soil mechanics formulas. All loads are converted into the equivalent load of the layer element where the loads are located.

The forces on the composite stratum of shield tunneling are shown in Figure 2. The excavation face of a circular shield with outer diameter De is simplified to an internal square face, which is tentatively taken as the equivalent acting face of the tunnel force section. The imposed load qe at the tunnel excavation face is the effective thrust of the shield machine. Meanwhile, there are imposed loads including the shell support pressure qf , the shell frictional resistance τf, and the lining support pressure qs along the longitudinal direction of the tunnel, among which, the stress-strain state generated by the joint action of the three imposed loads is basically the same as the state before the excavation.

Therefore, the relationship between the effective thrust and surface settlement can be identified with the finite layer method only if the effective thrust within the equivalent acting face is applied at the excavation face. The distribution of surface settlement along the longitudinal direction of the tunnel will be mainly focused to study the correlation between the maximum surface settlement and the tunneling parameters and soil parameters of the composite stratum.



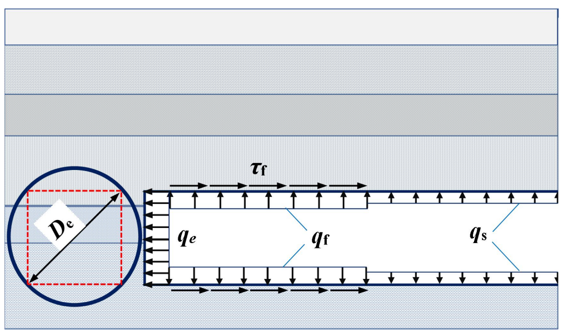


Figure 1. Mechanical model of composite stratum Figure 2. Force diagram of shield tunneling

3. Overview of the shield tunnel project

3.1. Overview

The project example is from the left line of the shield section between the Yuzhu and Xiangjingling of Guangzhou Metro Line 13, with a total length of 1,831 m. The tunneling is carried out by an earth pressure balance shield machine whose shield shell had an outer diameter De of 6.26 m.

3.2. Tunnel stratigraphic section

The strata crossed by the tunnel excavation face includes silt soft clay layer, plastic and hard plastic sandy clay lay-er, completely weathered migmatitic granite, strongly weathered migmatitic granite, moderately weathered migmatitic rock, migmatitic granite mixed with slightly weathered migmatitic rock, and migmatitic granite. The stratigraphic distribution changes are significant along the tunnel, the homogeneous stratigraphic section only accounted for 23% of the line while the double-layer or multi-layer composite stratigraphic section for 77%. Therefore, it is necessary to con-duct the qualitative and quantitative analysis on the composite characteristics of the stratum.

To allow for the qualitative description of the different stratigraphic characteristics in the tunnel section, the excavation strata are divided 8 groups along the longitudinal direction of the line. The stratigraphic distribution of every group is illustrated in Figure 3, where the numbers ①, ②, and ③ denote the geological layer, and A1, A2, and A3 are the distribution areas in corresponding layers. The physical mechanics parameters of the strata groups are shown in Table 1, where the weights of the weighted mean of the deformation modulus and Poisson ratio are on behalf of the area ratios within the tunnel excavation face. The layer thickness Bi corresponding to the equivalent quadrangular tunnel section can be calculated by the area ratio, and then the layer thickness hi in Figure 1 is obtained.

Table 1. Classification of strata groups and its physical mechanics parameters

Strata group number	Geometric feature	Area ratio of soil layer	Weighted mean of deformation modulus /MPa	Weighted mean of Poisson ratio
Gt-1	①Silt soft clay	1	20	0.42
Gt-2	①Silt soft clay ②Sandy clay layer	0.272:0.728	33	0.39
Gt-3	①Sandy clay layer	1	40	0.37
Gt-4	①Sandy clay layer ②Completely weathered migmatitic granite	0.564:0.436	63	0.34
Gt-5	①Completely weathered migmatitic granite	1	80	0.33
Gt-6	①Sandy clay layer ②Completely weathered migmatitic granite ③ Strongly weathered migmatitic granite	0.065:0.721:0.214	82	0.32
Gt-7	①Completely weathered migmatitic granite ②Strongly weathered migmatitic granite	0.481:0.519	90	0.31
Gt-8	①Strongly weathered migmatitic granite ②Moderately weathered migmatitic rock ③Slightly weathered migmatitic rock	0.292:0.668:0.04	2098	0.26

3.3. Soil layers covering on the top of tunnel cavity

The depth of the tunnel H is 9 to 16 m. The soil layers covering on the top of the tunnel cavity consists of silt clay, soft soil layer mixed with partial mucky clay, plastic and hard plastic sandy clay layer with partial silt. The main stratum is the alternative marine and land facies sedimentary layers while the fourth system stratum has rich and shallow groundwater. The height of the groundwater level from the tunnel roof is 6.5 to 13 m.

3.4. Surface settlement monitoring

According to the shield tunneling experience, when the shield machine tunneled into a strata group Gt, the maximum daily value of surface settlement w0r is measured within 50 meters from the front to the rear of the excavation face along the tunnel line, which is used as the instantaneous surface settlement for tunneling in the strata group Gt. The data sets related to the above tunnel strata groups, soil parameters, tunneling parameters such as total thrust and penetration of shield construction, and surface settlement monitoring values are randomly divided into analysis data sets and test data sets according to the ratio of 4:1.

4. Instantaneous surface settlement caused by shield tunnelling

4.1. Theoretical calculation of surface settlement by the tunnel finite layer method

(1) Calculation of effective thrust of shield tunnelling

According shield construction mechanics, the effective thrust of tunnelling Fe can be got by following,

$$Fe = Ft - F1 - F2 \quad (1)$$

Where, Ft is the total thrust of tunnelling parameter, F1 is the frictional resistance between the shield shell and the stratum, F2 is the frictional resistance between the prefabricate segment and the shield tail.

Take Gt-3 as an example, the frictional resistance F1 is calculated as,

$$F1 = \mu 1 \cdot \pi DeL \cdot p \quad (2)$$

Where, μ1 is the frictional coefficient between the stratum and the steel plate, the values of residual soil and completely weathered rock are 0.2, strongly to moderately weathered rocks 0.3 and slightly weathered rock 0.35.

De, the external diameter of the shield shell, is 6.26 m.

L, the length of the shield shell, is 8.77 m.

p, the average soil pressure, is 207.8kPa according to the static soil pressure at the excavation face.

Therefore, $F1 = \mu 1 \cdot \pi De\ L \cdot p = 0.2 \times 3.142 \times 6.26 \times 8.77 \times 207.8 = 7165$ kN.

Frictional resistance F2 is calculated as

$$F2 = n1 \cdot WS \cdot \mu 2 \quad (3)$$

Where n1, the number of prefabricate segments in the shield tail, is 2.

WS, the self weight of a single prefabricate segment, WS = [π (Dse2 - Dsi 2)/4]ts γG. The outer diameter of the prefabricate segments Dse is set as 6.0 m, the inner diameter D si as 5.4 m, the width ts as 1.5 m and the weight γG as 24.5 kN/m3.

μ2, the coefficient of frictional resistance between the prefabricate segments and steel plate, is 0.3.

Then, $F2 = 2 \times [(3.1416/4) \times (62 - 5.42) \times 1.5 \times 24.5] \times 0.3 = 119$ kN.

According to the source data of shield tunnelling parameters, the average total thrust of the strata group Gt-3 under normal working condition is 15325 kN, thus the actual effective thrust Fe is 8041 kN.

The effective thrust corresponding to the total thrust can be calculated for each strata group by the same method.

(2) Theoretical value of maximum instantaneous surface settlement

Based on the finite layer model of the tunnel strata, the effective thrust is converted to an equivalent square load pe to apply to the tunnel excavation face. By using the finite layer method of ground, the average horizontal displacement of the excavation face u0, and the maximum surface settlement w0c, which can be taken as the theoretical value of instantaneous surface settlement. The distributions of settlement along the tunnel line in different strata groups, are shown in Figure 4.

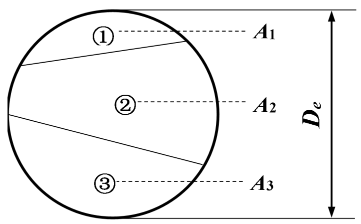


Figure 3. Stratigraphic distribution of tunnel section

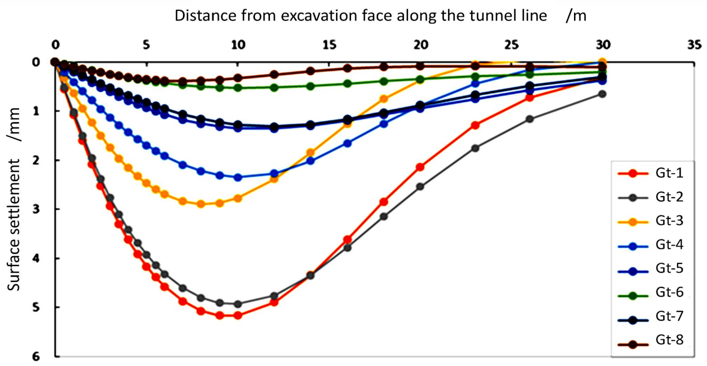


Figure 4. The distributions of settlement along the tunnel line in different strata groups

To characterize the horizontal displacement of tunnelling, the flexibility coefficient of tunnelling δu = u0 /Fe is defined as the horizontal displacement of the stratum at the excavation face when the unit effective thrust is applied. Furthermore, in order to discover the relationship between the horizontal displacement of the stratum and the vertical surface settlement, Poisson ratio ν of the soil mechanics parameter is introduced. Based on the definition that ν is the ratio of horizontal strain to vertical strain, it can be presumed that δu/ν is proportional to the vertical flexibility coefficient w0c /Fe.

4.2. The penetration of influencing factor

The penetration h of shield tunnelling parameter, which is the horizontal tunnelling size of the shield when the cutterhead rotates once, is numerically equal to the ratio of tunnelling speed to cutterhead rotational speed. There are two sets of force effects on the excavation face acted by the shield cutterhead. The effective thrust of reflecting compression effect, which generates the horizontal pressure stress by the vertical plane of the cutterhead, can cause compressive deformation of the layers at the excavation face. Meanwhile, the cutterhead torque of reflecting rotational effect, which generates the shear stress applied to the excavation layers, can cause shear deformation. The two sets of forces act together on the stratum, whose comprehensive effects should be considered in the analysis of surface settlement.

In the above, the settlement w0c caused by the effective thrust is calculated by using the ground finite layer method only, so the effect of cutterhead torque on the surface settlement can be added by considering the penetration h. The relationship of horizontal tunnelling flexibility coefficient δu and the penetration h obtained by the effective thrusts of different strata groups is shown in Figure 5. Therefore, a parameter combination h/δu is constructed to represent the effect of the cutterhead torsional action on the strata displacement, which refers to the growth multiple of the horizontal tunnelling size of the cutter head when it rotates for one circle relative to the horizontal displacement generated under the unit effective thrust. Similarly, h/δu is also used for settlement analysis based on superposition principle of force action.

4.3. Measured value of instantaneous surface settlement in tunnelling

The maximum value of surface settlement near the excavation face at the instant of tunnelling is defined as the measured value of instantaneous surface settlement w0r, which is a result of the combined action of the shield cutterhead in horizontal thrust and torque rotation. Therefore, (w0r /Fe)/ (w0c /Fe) = w0r/w0c is proportional to h/δu for its representative meaning.

Based on the above analysis, h, δu, ν, w0c, w0r followed the formula:

$$\frac{\delta_u}{\nu h} \propto \frac{w_{0c}}{w_{0r}} \tag{4}$$

By analyzing the 84 records of the data set, the relation curve is obtained in Figure 6, and the empirical formula is obtained by fitting as follows:

$$\frac{w_{0c}}{w_{0r}} = 5.7742\frac{\delta_u}{\nu h} - 0.0306 \tag{5}$$

The correlation coefficient R^2 is 0.8363, indicating a strong linear correlation between δu/νh and w0c/w0r .

5. Prediction of instantaneous surface settlement

On the basis of 21 records in the test data set by applying the fitting formula (5), in which the theoretical value of surface settlement w_{0c} is obtained based on the tunnel finite layer method and δu/νh is substituted.

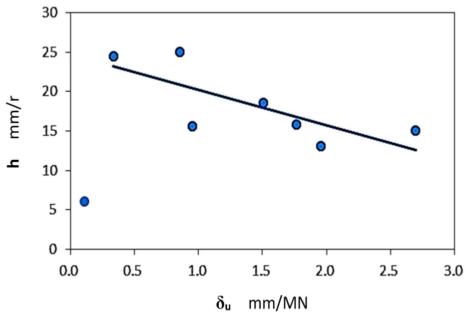


Figure 5. The relation between δu and h

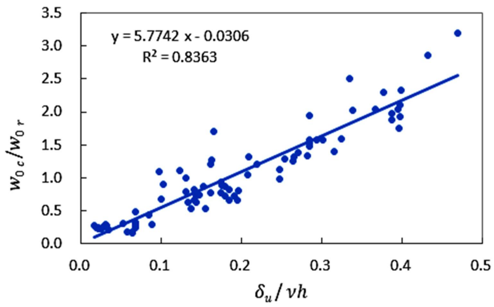


Figure 6. The relation curve of δu/νh and

The predicted value of instantaneous surface settlement w_{0p} can be calculated as follows,

$$w_{0p} = \frac{w_{0c}}{5.7742\frac{\delta_u}{\nu h} - 0.0306} \tag{6}$$

The comparison of the predicted value w_{0p} and the measured value w_{0r} is shown in Figure 7.

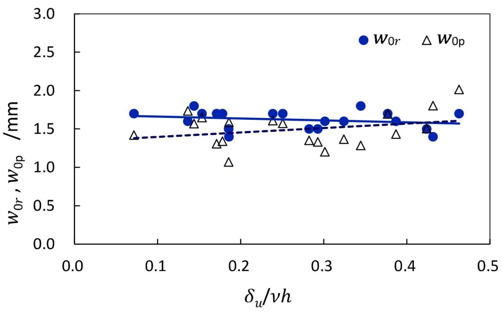


Figure 7. The relation curve of δu/νh and w0r ,w0p

Small δu means commonly that the tunnel geological layers are too hard to excavate. Under such circumstances, the original structures of the hard rock and soil layers are damaged by the shearing effect of cutterhead torque, resulting in the measured value of surface settlement greater than the predicted value. As δu increases, the softer the layers, the more elasticplastic deformation occurs. In this way, the shearing effect of the cutterhead torque is not significant in the enhancement of surface settlement for the soft layer, which leads to a greater theoretical predicted value by fitting formula than the measured value.

The formula for calculating the standard error of the prediction value is:

(6) $$\sigma = \sqrt{\frac{\varepsilon_1^2 + \varepsilon_2^2 + \cdots + \varepsilon_n^2}{n}} \tag{7}$$

Where,

$$\varepsilon_i = \frac{|w_{0c,i} - w_{0p,i}|}{w_{0c,i}}, \quad i = 1, 2, \dots, n \tag{8}$$

Finally, the standard error of the predicted value w_{0p} and the measured value w_{0r} is calculated, σ_0 = 16.89% < 20%, which can be considered as meeting the accuracy requirements of engineering projects.

6. Conclusion

In this paper, the application of the finite layer method is extended to the prediction analysis of instantaneous surface settlement for shield tunnels with composite strata, which is not only feasible but also effective. Its advantages are obvious.

First, it is beneficial to solve the simulation difficulty in the theoretical analysis of tunnel with composite strata. The finite layer method, as a semi-analytical method, has the advantage on analyzing non-homogeneous stratum compared to the traditional analytical methods. And it is able to simulate the layer element boundary more effectively than the finite element method to make the results more reliable.

Second, the theoretical values of the surface settlement of shield tunnelling can be calculated on the basis of the elastic solution of the finite layer method of tunnel, with consideration of the torsional effect of the cutterhead with the penetration study and the anisotropy of the rock and soil layers with Poisson ratio. The prediction formula proposed by data fitting can be used to obtain the instantaneous surface settlement to control the safety near the zone of shield tunnelling.

Acknowledgments

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