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Research Article

Semianalytical Solution and Parameters Sensitivity Analysis of Shallow Shield Tunneling-Induced Ground Settlement

Jifeng Liu[1,2] and Huizhi Zhang[1,2]

[1] *Key Laboratory of Materials Engineering & Structural Reinforcement, Sanming University and Fujian Province University, Fujian, China*
[2] *Department of Civil Engineering & Architecture, Sanming University, Fujian, China*

Correspondence should be addressed to Jifeng Liu; ph_dliujifeng@126.com

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The influence of boundary soil properties on tunneling-induced ground settlement is generally not considered in current analytic solutions, and the hypothesis of equal initial stress in vertical and horizontal makes the application of the above solutions limited. Based on the homogeneous half-plane hypothesis, by defining the boundary condition according to the ground loss pattern in shallow tunnel, and with the use of Mohr-Coulomb plastic yielding criteria and classic Lame and Kiersch elastic equations by separating the nonuniform stress field to uniform and single-direction stress field, a semiempirical solution for ground settlement induced by single shallow circular tunnel is presented and sensitivity to the ground parameters is analyzed. The methods of settlement control are offered by influence factors analysis of semiempirical solution. A case study in Beijing Metro tunnel shows that the semiempirical solution agrees well with the in situ measured results.

1. Introduction

With the rapid development of China's urban infrastructure construction, the shield tunneling is widely used as a safe and efficient tunnel construction method in urban subway, underground pipeline, and so on. At present, there are still a series of problems needing to be solved in the metro shield tunneling construction; one of the problems that should be urgently solved is the prediction and control of the shield tunneling construction induced ground surface settlement [1, 2]. The research methods of this problem include the observational method, numerical simulations, and analytical methods [3].

In recent years, a large number of analytical solutions for axisymmetric circular tunnels in strain plane state have been presented [3–11], but those analytic methods are seldom considering the influence of ground soil properties on shield tunnel induced ground settlement, and some methods are based on the assumption of homogeneous semi-infinite plane; the calculated results are suitable for the deep buried tunnel surface settlement calculation but are not fully applicable for most shallow-buried tunnel, which limits the use of those methods. Therefore, it is an urgent problem to find suitable methods to calculate shallow shield tunnel surface settlement.

2. Semianalytical Analysis of Shallow Single Tunnel

As shown in Figure 1, the assumption of shallow tunnel surrounding rock analytic analysis is as follows: (1) the rock is homogeneous and isotropic; (2) tunnel excavation is a plane strain axisymmetry problem; (3) the original stress affecting the surrounding rock is not equal in the vertical and the horizontal direction; the static earth pressure coefficient is 0.5. The other parameters are tunnel buried depth of H (m), average overburden soil weight γ (kN/m^3), excavation radius a (m), plastic radius R (m), and face support reaction stress σ_0 (kPa).

Equilibrium differential equation for axisymmetric problem is

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = 0. \tag{1}$$

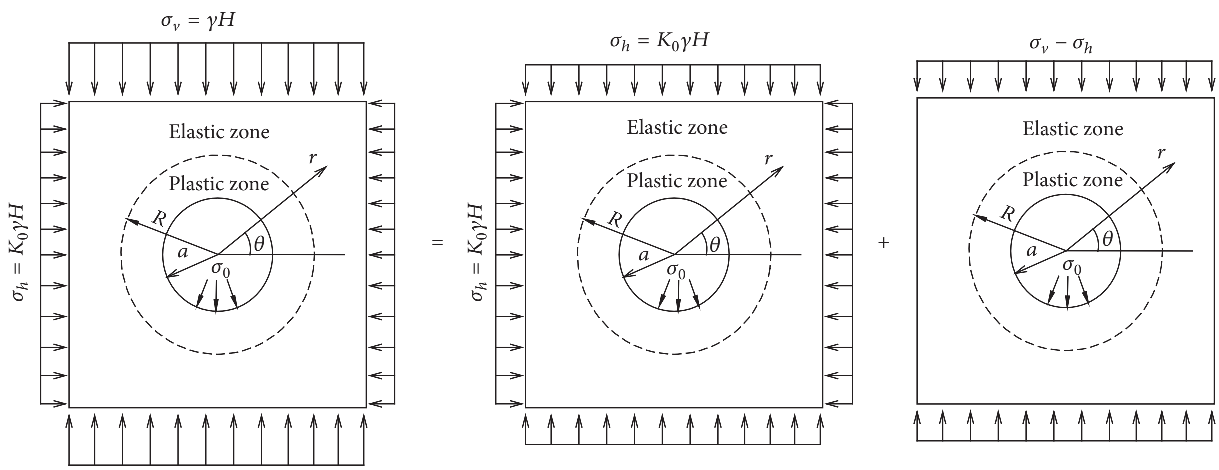

Figure 1: Initial stress field of shallow tunnel.

During the tunnel excavation, the soil deformation is elastic; then the expression of the stress-strain relationship of axisymmetric elasticity is

$$\varepsilon_r = \frac{1+\mu}{E}\left[(1-\mu)\sigma_r - \mu\sigma_\theta\right]$$
$$\varepsilon_\theta = \frac{1+\mu}{E}\left[(1-\mu)\sigma_\theta - \mu\sigma_r\right], \qquad (2)$$

where μ is the Poisson ratio of surrounding rock of tunnel and E is Young's modulus of surrounding rock of tunnel.

Two-way nonisobaric state could be divided into the external pressure as σ_h uniform stress field and the external pressure as $(\sigma_v - \sigma_h)$ one-way stress field. For uniform stress field and one-way stress field, the Lame and Kiersch formula is, respectively, used to calculate the stress field; the elastic zone can be obtained by summing the above calculated uniform stress field and one-way stress field of the surrounding rock:

$$\sigma_r = -\sigma_0\frac{R^2}{r^2} - \frac{1}{2}(1+K_0)\sigma_v\left(1-\frac{R^2}{r^2}\right) + \frac{1}{2}(1-K_0)\sigma_v\left(1-\frac{R^2}{r^2}\right)\left(1-2\frac{R^2}{r^2}\right)\cos 2\theta$$
$$\sigma_\theta = \sigma_0\frac{R^2}{r^2} - \frac{1}{2}(1+K_0)\sigma_v\left(1+\frac{R^2}{r^2}\right) + \frac{1}{2}(1-K_0)\sigma_v\left(1+\frac{3R^4}{r^4}\right)\cos 2\theta. \qquad (3)$$

By (2) and (3), and considering the boundary conditions and symmetry, the elastic zone displacement u can be obtained, and the tunnel excavation induced relative displacement can be obtained by subtracting the initial stress generated initial displacement from the calculated elastic zone displacement u, as shown in

$$u' = \frac{1}{2G}\frac{R^2}{r}\left\{\sigma_0 - \frac{1}{2}(1+K_0)\sigma_v - \frac{1}{2}(1-K_0) \times \sigma_v\left[\frac{R^2}{r^2} - 4(1-\mu)\right]\cos 2\theta\right\}, \qquad (4)$$

where G is shear modulus of soil.

The Mohr-Coulomb theory strength criterion is adopted to judge whether the soil is in plastic state. The yield condition is

$$\sigma_\theta - \sigma_r = \frac{2\sin\varphi}{1-\sin\varphi}\left(\sigma_r + c\cot\varphi\right), \qquad (5)$$

where c is soil cohesion, kPa, which can be obtained from the shear test and φ is soil internal friction angle, °, which can be obtained from the shear test.

The stress expression of the plastic zone can be obtained by (1) and (5), shown as

$$\sigma_r = \left(\sigma_0 + c\cot\varphi\right)\left(\frac{r}{a}\right)^{2\sin\varphi/(1-\sin\varphi)} - c\cot\varphi$$
$$\sigma_\theta = \frac{1+\sin\varphi}{1-\sin\varphi}\left(\sigma_0 + c\cot\varphi\right)\left(\frac{r}{a}\right)^{2\sin\varphi/(1-\sin\varphi)} - c\cot\varphi, \qquad (6)$$

where c is soil cohesion, kPa; φ is soil internal friction angle, °; a is tunnel excavating radius, m; σ_a is face supporting pressure, kPa; and r is the radius of the calculating stress point, m.

Along the boundary between the elastic and plastic zone, the stress boundary conditions should be met at the same time; that is, there is $\sigma_\theta^{\text{Plastic}}|_{r=R} = \sigma_\theta^{\text{Elastic}}|_{r=R}$ when the radius $r = R$; the plastic radius R is shown as follows:

$$R = a\left\{\frac{(1-\sin\varphi)\left[(1/2)(1+K_0)\sigma_v + (1-K_0)\sigma_v\cos 2\theta + c\cot\varphi\right]}{\sigma_0 + c\cot\varphi}\right\}^{2\sin\varphi/(1-\sin\varphi)}. \tag{7}$$

When $a \le r \le R$, the Mohr-Coulomb yield criterion nonassociative plastic flow method is used to solve the displacement [12]. The tunnel excavation is unloading process; (8) can be obtained by nonassociated flow rule.

$$\frac{\varepsilon_r}{\varepsilon_\theta} = -\frac{1+\sin\psi}{1-\sin\psi}, \tag{8}$$

where ψ is dilatancy angle of soil.

Substituting (2) and (3) into (8), (9) can be available.

$$\varepsilon_r + \frac{1+\sin\psi}{1-\sin\psi}\varepsilon_\theta = \frac{1}{m}\left[\left(1 - \frac{1+\sin\psi}{1-\sin\psi}\times\frac{\mu}{1-\mu}\right)\sigma_r + \left(\frac{1+\sin\psi}{1-\sin\psi} - \frac{\mu}{1-\mu}\right)\sigma_\theta\right], \tag{9}$$

where $m = E/(1-\mu^2)$.

For the soil or rock, the value of m is very large, the value to the right of (9) is very small, and then (9) can be simplified to (10) by assuming no deformation in the tunnel axis direction and neglecting the elastic strain in the plastic zone [6].

$$\varepsilon_r + \frac{1+\sin\psi}{1-\sin\psi}\varepsilon_\theta = 0. \tag{10}$$

From the geometric equation $\varepsilon_r = du'/dr$, $\varepsilon_\theta = u'/r$, and (10), the relative displacement of the plastic zone can be solved as follows:

$$u' = \frac{1}{2G}\frac{R^{2/(1-\sin\psi)}}{r^{(1+\sin\psi)/(1-\sin\psi)}}\left\{\sigma_0 - \frac{1}{2}(1+K_0)\sigma_v - \frac{1}{2}\times(1-K_0)\sigma_v(4\mu-3)\cos 2\theta\right\}\sin\varphi. \tag{11}$$

The deformation of (11) is radial uniform, which is different from the actual situation. Park [13] presented that the ground deformation model for shallow-buried tunnel displacement boundary conditions is adopted to modify (11) so that it can better predict the subsidence of shallow-buried tunnels. The displacement boundary expression of Park is shown as (12), where u_0 is the uniform radial deformation boundary, which is the value of (11) at the $r = a$ position; the meaning of θ is shown in Figure 1, $\sin\theta = -(z-H)/r$, $\cos\theta = x/r$, and z is the vertical distance of the forecast point to the ground surface. The deformation pattern of (12) is shown in Figure 2.

$$u_r\big|_{r=a} = -\frac{u_0}{4}\left(5 + 3\sin\theta - 3\cos^2\theta\right) \tag{12}$$

$$u' = \frac{R^{2/(1-\sin\psi)}}{r^{(1+\sin\psi)/(1-\sin\psi)}}\left\{\sigma_0 - \frac{1}{2}(1+K_0)\sigma_v - \frac{1}{2}\times(1-K_0)\sigma_v(4\mu-3)\cos 2\theta\right\}\times\frac{1}{8G}\sin\varphi\left(5 + 3\sin\theta - 3\cos^2\theta\right). \tag{13}$$

3. Parameters Sensitivity Analysis of Semianalytical Solution

For a given depth and radius of the tunnel, taking the soil horizontal pressure coefficient $K_0 = 0.5$, it is shown that the influence parameters of the ground deformation are K_0, Young's modulus E, Poisson's ratio μ, soil cohesion c, internal friction angle φ, and dilatancy ψ. The calculated results of (13) by Matlab software are shown as Figures 3–7. Figure 3 shows the influence of Young's modulus on the settlement when $c = 30$ kPa, $\psi = 5^\circ$, $\varphi = 20^\circ$, and $\mu = 0.2$; Young's modulus is inversely proportional to the maximum subsidence of the surface. Figure 4 shows the influence of Poisson's ratio on the ground settlement, which shows that the maximum settlement increases with increase of Poisson's ratio μ.

Figure 5 is the influence of soil internal friction angle φ on surface settlement when $E = 15.0$ MPa, $\psi = 5^\circ$, $c = 30$ kPa, and $\mu = 0.2$, Figure 6 is the influence of cohesion c on surface settlement when $E = 15.0$ MPa, $\psi = 5^\circ$, $\mu = 0.2$, and $\varphi = 20^\circ$, and Figure 7 is the influence of dilatancy ψ on surface settlement when $E = 15.0$ MPa, $c = 30$ kPa, $\mu = 0.2$, and $\varphi = 20^\circ$. Figures 5–7 show that the maximum surface settlement decreases with E and c increase and increases with ψ, μ, and φ increase. In comparison, the influence of E, μ, ψ, and φ on the maximum surface settlement is larger than c.

The above analysis for the influence of surrounding soil properties on the ground subsidence shows that there are two ways to control the shield tunnel induced ground settlement: one way is the active way, which is to reduce the surrounding soil properties weakening degree by optimizing the construction parameters of shield tunneling, such as choosing the rationale supporting face force and excavating speed or shield tail grouting reinforcement; the other way is the passive protection measures, which is to improve soil physical parameters by engineering methods to reduce the surface settlement of shield construction, the feasible methods including bolt reinforcement, partition wall, pile

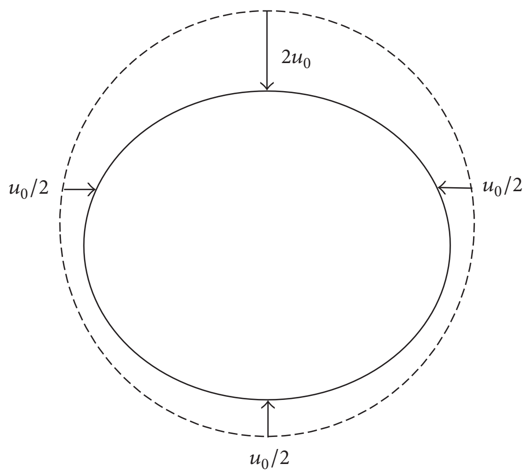

FIGURE 2: Boundary condition of displacement.

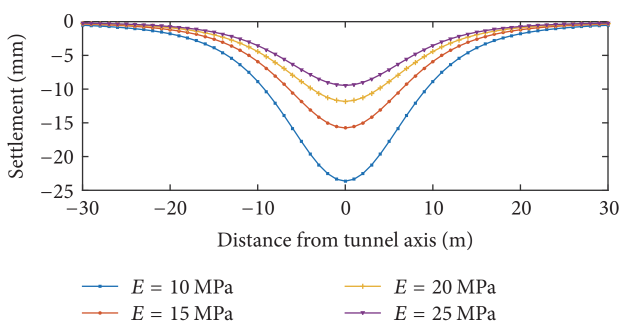

FIGURE 3: Influence of E to surface settlement.

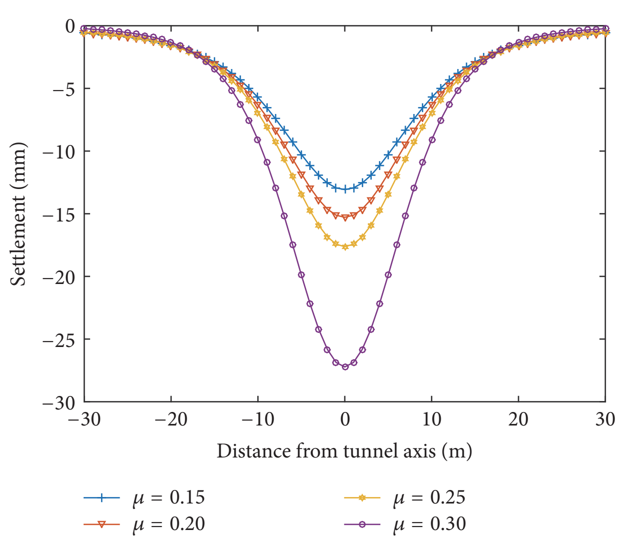

FIGURE 4: Influence of μ on surface settlement.

foundation underpinning, or the affected building body reinforcement [14].

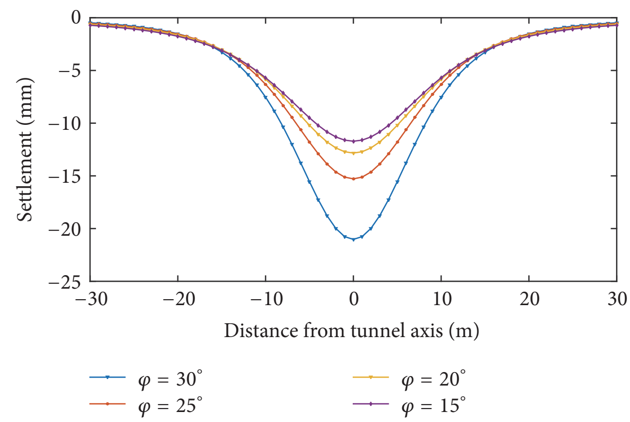

FIGURE 5: Influence of φ on surface settlement.

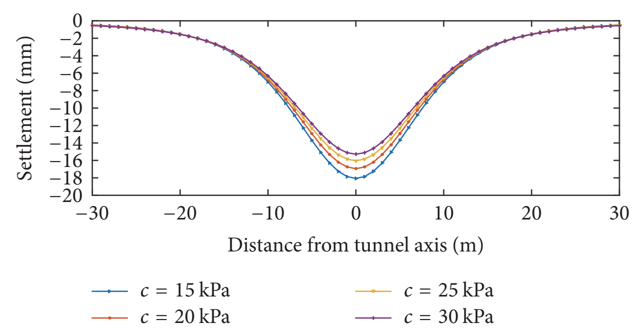

FIGURE 6: Influence of c on surface settlement.

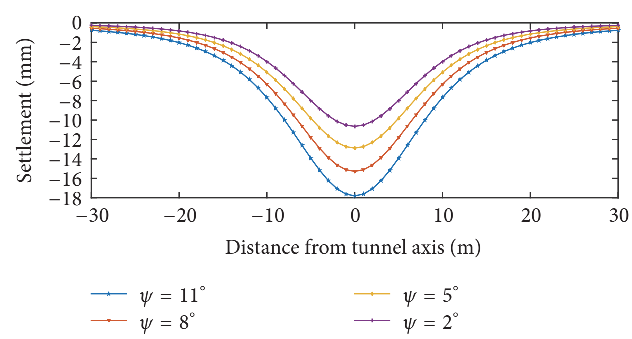

FIGURE 7: Influence of ψ on surface settlement.

4. Case Study

The 11th Project of Beijing Metro Line 10 is underground twin tunnels and is constructed by shield tunnel; the 6 m diameter tunnels are buried 16 m deep with nonsynchronous construction; the left tunnel is excavated more than 200 m ahead of the right tunnel. The ground elevation is 38.15 m. The shield tunnels are mainly through ⑤ the medium-coarse sand, ⑥ silty clay, $⑥_1$ clay, and $⑥_2$ silt. The perched groundwater is 2.74–3.58 m deep and the diving groundwater is 7.26–7.52 m deep. The layered and main mechanical parameters of foundation soil are found in Table 1.

As shown in Figure 8, the left shield tunnel machine is nearby underpassing the North Street 8# and South Street

Table 1: Physical and mechanical parameters of foundation soils.

Number	Name	Weight/kN/m^3	Sr	e	I_p	Standard penetration/N	Fast shear test Cohesion c/kPa	Fast shear test Internal friction angle/°	UU Cohesion c/kPa	UU Internal friction angle/°	Modulus E_s/MPa	Poisson's ratio μ	Layer height/m
①	Miscellaneous fill	16.6	/	/	/	/	10	8	10	5	/	/	2.4
③$_1$~③	Silt-silty clay	19.3	78.12–96.3	0.61–0.77	7.2–11.8	13–10	30.8	15.7	26.7	17.2	6.6–12.7	0.30	5.4
④	Silty clay	20.1	96.5	0.59	11.9	10	35	9	30	15	5.5–10	0.31	4.0
⑥	Silty clay	19.8	96.2	0.71	13.3	15	46	15	30	15	8.3–11.9	0.29	4.4
⑥	Silt	20.2	95.3	0.58	8.4	17	33	28	15	15	9.3–17.1	0.30	6.0
⑦$_1$~⑦	Silty sand	19.9				54–48	0	32.8			30–40	0.28	3.6
⑦	Rounded gravel	21.1					0	40			60	0.25	1.4
⑧	Silty clay	19.7	96.4	0.73	12.9	25	54	5			9.2–13.6	0.30	5.0
⑨	Silty fine sand	20.6				52	0	30			35	0.27	1.6
⑩	Silty clay	19.7					20	20			8.7–13.1	0.29	6.2

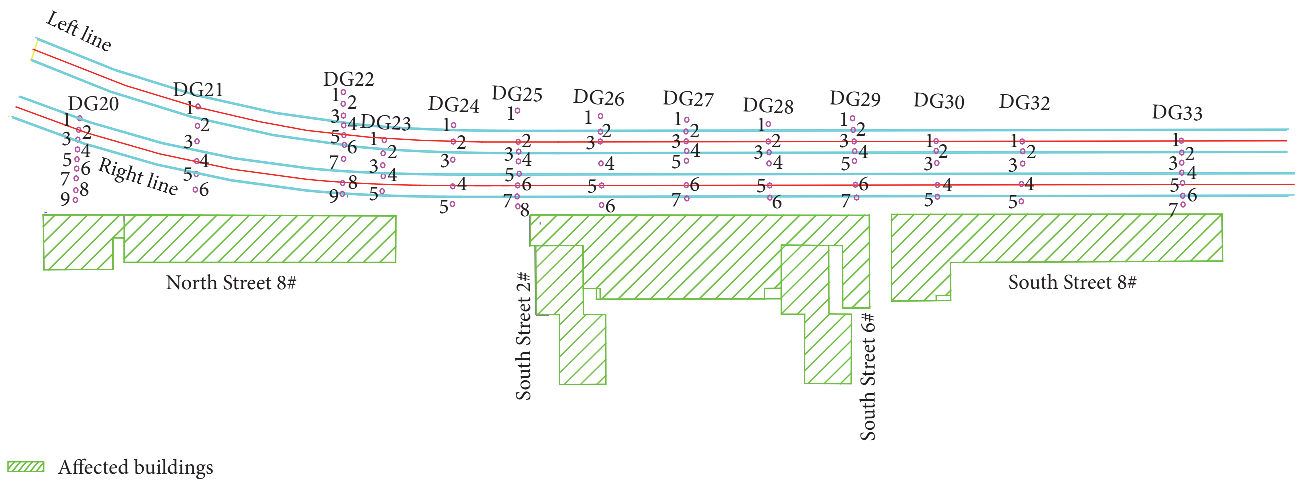

FIGURE 8: Plan of tunnel line, buildings, and layout of surveying points.

8# residential building; in this underpassing process, the shield machine is just in the transition from circular curve to straight line, and the two tunnels center distance is 11.15 m~15.28 m, which puts great challenge to the control of strata settlement caused by the shield construction. In order to carry out the information construction and to reasonably control the ground surface subsidence for ensuring the safety of the affected building group, the corresponding settlement measurement point is laid out before the construction.

According to the relevant provisions of the national code of "code for design of building foundation (GB50007-2011)," taking into account the importance, the longtime service, and the poor deformation coordination of the upper panel type structure of the tunnels excavation affected buildings, the foundation deformation limit should be more strict than the national code; the previous studies suggest that the whole building tilt value should be controlled within 0.002, but the building tilt value of North Street 8# and South Street 8# residential building should be controlled within 0.001 and the maximum settlement under the wall which is nearby the street should be less than 10 mm because those buildings have tiled about 0.001 [15]. In order to test the impact of shield construction on the settlement of buildings, according to the mechanical properties of various strata and construction parameters, and considering the shield tunneling straightening on the surrounding soil disturbance, the following parameters are used for analytical analysis of the shield tunnel induced ground surface settlement, that is, the tunnel buried depth $H = 16$ m, the static earth pressure coefficient $K_0 = 0.5$, excavation radius $a = 3$ m, weight of soil $\sigma_v = 310$ kPa, face support reaction stress $\sigma_0 = 120$ kPa, cohesion $c = 25$ kPa, internal friction angle $\varphi = 20^\circ$, Young's modulus $E = 15$ MPa, Poisson ratio $\mu = 0.24$, and dilatancy angle $\psi = 3^\circ$. After the shield tunnel straightened, the shield tunneling causing surrounding soil properties weakening is relatively small, so the above-mentioned parameters were adjusted to $c = 30$ kPa, $\varphi = 25^\circ$, $E = 20$ MPa, $\mu = 0.25$, and $\psi = 5^\circ$. The two sets of parameters are taken into (13), and the Matlab7.0 is used for programming; the calculated results are shown in Figure 9. The maximum ground surface settlement is 23.8 mm when shield tunnel is in straightening phase, and the maximum ground surface settlement is 16.4 mm after posture adjustment.

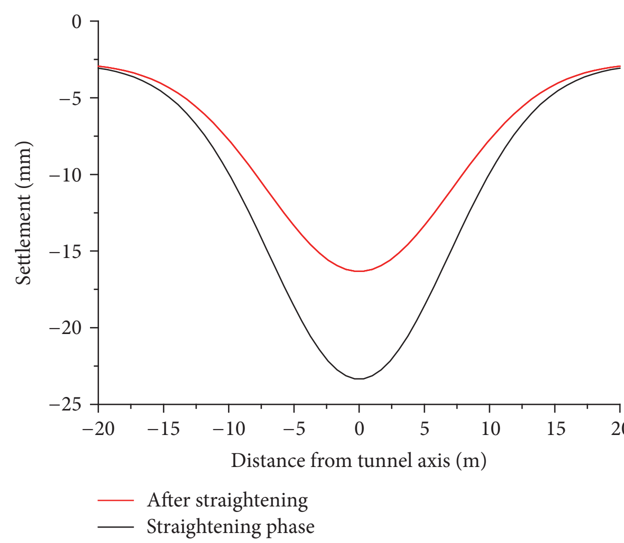

FIGURE 9: Surface settlement calculation curves.

Figure 9 shows that the maximum settlement of the foundation under the external wall nearby street will be more than 3 mm due to the left-line tunnel construction if the corresponding engineering measures are not taken. With the same construction technology and considering the influence of left tunnel excavation, the right tunnel construction induced maximum settlement of the foundation under the external wall nearby street will exceed 10 mm; it is difficult to ensure the safety of nearby buildings. So, the double-row high-pressure jet grouting cement piles were constructed between the external wall nearby street and the right tunnel; before the shield tunneling, the North Street 8# building pile diameter is 500 mm with 1000 mm center distance, and the South Street 8# building pile diameter is

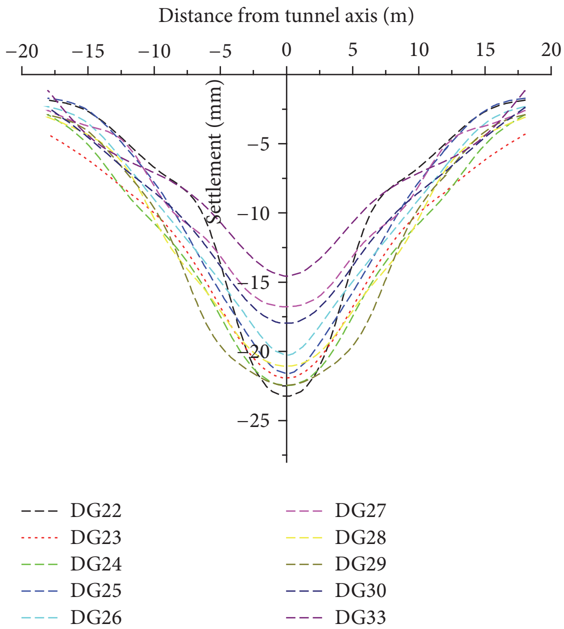

Figure 10: Surveying curves of some cross-sections.

450 mm with 950 mm center interval. Pile length is more than 1 m at the bottom of the shield tunnel, the water-cement ratio of pile is 0.8 ~1.2, the P.O.32.5 Portland cement is used, and the I20~I30 steel I-beam is inserted in piles. In the construction process, the inertia synchronous grouting slurry is replaced as hard synchronous grouting slurry, and the amount of cement is increased, the secondary grouting pressure is 0.3~0.4 MPa, and the grouting amount is 1.5 m^3 per liner segment.

Figure 10 is settlement monitoring results of some sections; it shows that the left tunnel excavation induced about 5 mm ground surface subsidence on the right tunnel axis which is 11 m away from left tunnel axis and induced about 2 mm ground surface subsidence on the building which is 18 m away from left tunnel axis; the measured results of shield tunneling causing ground surface settlement are accordant with the analytical calculation results. It is revealed that the foundation reinforcement and grouting slurry adjustment measures are reasonable. By adopting active and passive engineering measures, the twin tunnels successfully underpassed the adjacent buildings, the shield tunneling-induced ground settlement is in standard control, and the nearby buildings safety is ensured.

5. Conclusions

Based on the assumption of homogeneous semi-infinite space, the initial two-way nonisobaric stress field of shallow-buried shield tunnel is divided into the uniform stress field and the one-way stress field; the semiempirical solution for shallow tunnel surface subsidence prediction is presented by using the analytical mechanic theory and definition the surrounding rock displacement boundary conditions of shield tunnel. The Matlab7.0 is chosen for programming to analyze the influence of the surrounding rock and soil mass properties on the ground surface settlement, and the corresponding surface settlement control method is proposed. The results of this research are used in the 11th Project of Beijing Metro Line 10 to predict and control the settlement of adjacent residential buildings affected by shield tunneling; the results show that the semiempirical solution is in good agreement with the in situ measured results; it can be used in the control of shield tunnel induced ground subsidence.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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