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Research Article

The Influence of Small Clear-Distance Tunnel Construction on Adjacent High-Voltage Transmission Tower Foundation

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The new tunnel construction will inevitably cause the change of the stress field and displacement field of the stratum where the adjacent existing structures are located, which poses a great threat to the safe and stable operation of the existing structures. Reasonable selection and optimization of construction sequence and construction method of double tunnels with small clear distance are of great significance to the safe and stable operation of existing structures. In this present study, taking the Xiaohan municipal double-arch highway tunnel near the high-voltage transmission tower as the engineering background, the ABQUS finite element numerical simulation method is used to analyze the influence of tunnel construction on the existing high voltage tower foundation. The accuracy of the numerical method is verified compared with the theoretical solution of induced stress at the bottom of the tower foundation caused by the excavation of circular cavity. Then, the influence law of tunnel position on induced stress field is discussed by parameter analysis. On this basis, the construction sequence which has the least influence on the tower foundation is selected by comparing the numerical simulation results of different construction schemes. That is, the left tunnel shall be excavated after the construction of the right tunnel is completed. Finally, the change of the settlement of the existing tower foundation, the stress of the base, and the inclination degree during the CD method excavation is analyzed. The results show that simultaneous excavation of new tunnels has the greatest influence on the settlement and stress increment of the existing tower foundation. It provides suggestions to construct the double tunnels step by step from far side to near side in similar projects.

1. Introduction

The high voltage transmission line is an important link in the power system, and the transmission tower is the main load-bearing component in the transmission line. Due to the limitation of regional characteristics and corridor conditions, the high-voltage transmission lines often cross or are parallel with highway and railway tunnels, so the high-voltage transmission tower is usually located above or near the tunnel. As a tall space structure, the high voltage transmission tower is sensitive to foundation settlement difference. During the underground construction near the existing high-voltage transmission tower, the stratum displacement caused by underground excavation is easy to lead to the uneven settlement of the tower foundation, which can cause the tower collapse in serious cases. Therefore, the construction should be strictly controlled to minimize the impact on the tower.

At present, a lot of research has been done on the ground movement caused by tunnel excavation. The traditional method is to fit a series of empirical formulas of ground subsidence caused by tunnel construction according to a lot of engineering monitoring data [1–3]. In addition to field monitoring tests, many researchers studied the ground deformation under different depths of tunnel position through model tests and centrifugal model tests2 and had a more in-depth understanding of the variation law of surface settlement with tunnel excavation depth [4–6]. With the rapid development of computers, the numerical analysis method is more and more favored by researchers in analyzing the ground deformation law caused by tunnel construction, in order to avoid the drawbacks of high cost and long-time of the test method [7–10]. In recent years, relevant research studies have gradually simulated the actual engineering situation more accurately. For example, Hamid et al.

[11] used FLAC3D to simulate and study the ground settlement characteristics caused by the excavation of a new tunnel near the existing tunnel in combination with the ground settlement distribution measured by the soil pressure balancer method (EPBM) in the actual project. Ramasamy and Karthigeyan [12] used PLAXIS3D software to carry out a series of numerical analysis on the ground settlement caused by the tunnel construction in sandy soil. In their analysis, the mechanical behavior of soil was set as nonlinear elastoplastic Mohr–Coulomb, and the calculation results were closer to the actual situation. These studies have fully demonstrated that various common geotechnical numerical methods (such as finite element method ABQUAS and finite difference method FLAC/3D) are accurate and effective in the analysis of ground deformation caused by tunnel excavation and also provide a reference for the study of settlement under complex working conditions.

In the process of tunnel excavation, the ground deformation will be caused and the adjacent structures will be affected. The unloading stress during tunnel excavation will change the additional pressure on the base of overlying soil or adjacent structures and then produce uneven settlement. In severe cases, it can lead to the toppling or destruction of structures. With the continuous construction of infrastructure, more and more new tunnels need to be built close to the existing structures, and the corresponding research studies on the impact of tunnel construction on the surface structure is also increasing. The research methods can be divided into two categories as follows: one is not considering the interaction between the strata and the surface structure, the other is considering the interaction between the strata and the surface structure of the tunnel [13]. For example, Lee analyzed the influence law of tunnel excavation on the ground pile foundation [14]. Based on the shield tunnel project of Suzhou metro Line 1, Zhao and Guoxing [15] used the finite element software PLAXIS3D tunnel to conduct three-dimensional finite element simulation of shield tunnel construction process and studied the response of pile foundation with different stiffness. Yang et al. [16] used three-dimensional finite element to study the influence of tunnel excavation on pile foundation settlement. Considering the small-strain stiffness hardened soil model, Dai et al. [17] analyzed the influence of tunnel excavation on the deformation of the structure and horizontal support plate in the upper foundation pit through three-dimensional finite element simulation. Liu et al. [18] took a subway shield tunneling under the existing tunnel in Zhengzhou as the research object, used the finite difference software to simulate the surrounding soil settlement caused by shield tunneling, and analyzed the internal force changes of the existing upgoing subway tunnel caused by shield tunneling. Wu et al. [19] used Plaxis numerical software to simulate and analyze the law of ground settlement caused by tunnel excavation and its influence on adjacent buildings. In the research, the accuracy of the numerical method was verified by comparing some numerical results with those of model tests.

As the high voltage transmission tower is a type of high-rise structure, it is very sensitive to the foundation deformation and easy to be inclined or even overturned by the deformation of the foundation or the uneven settlement. Therefore, in recent years, more attention has been paid to the study of tower stability in view of geological environment changes or engineering disturbances. For example, Itam et al. [20] analyzed the change of stress of high voltage tower structure in coal mine goaf by using the finite element method. In view of the development of soil caves, Zhou et al. [21] analyzed the influence of soil caves adjacent to or beneath the tower foundation on the stability of the tower foundation through numerical simulation and proposed the safety influence line of the top of the tunnel. Due to the great risk of tunneling construction near the high voltage transmission tower, the selection of lines is usually far away from the tower to avoid the risk. If the construction distance is relatively close, the numerical simulation method must be used for predictive analysis, and certain actual monitoring should be equipped in the construction process to guide the construction through settlement feedback. For example, Zhang et al. [22] used numerical simulation to analyze the impact of tunnel location on the stability of adjacent towers. Xiao et al. [23] used FLAC3D to analyze the influence of tunnel excavation and blasting on the ground high-voltage tower foundation and gave suggestions on the reinforcement of ground iron tower foundation.

From the previous part, it can be seen that there are many studies on the ground deformation caused by tunnel construction and its impact on adjacent buildings, but there are few studies on the influence of tunnel excavation on high-voltage transmission towers which are very sensitive to settlement. In addition, most of the existing engineering examples on the impact assessment of high-voltage transmission towers caused by tunnel excavation are for the situation that the tunnel excavation section is not large and the horizontal and vertical distance from the tower is large, and few involves the excavation of double-hole tunnel with large section. In view of this, based on the actual excavation project of a double-hole highway tunnel with a small clear distance in Loess area, in this present study, the ABQUAS numerical simulation method is used to study the influence of tunnel excavation on adjacent high-voltage tower. The research results can provide references for similar projects.

2. Engineering Background

Xiaohan Highway Tunnel is located in Sanmenxia City, Henan Province. Its geomorphic unit belongs to Class III terrace of the Yellow River. The soil layer is mainly lousier-like silt and silty clay, with silty sand in some parts. The loess soil is collapsible and homogeneous. The upper topsoil layer is mostly loose due to human disturbance, with low bearing capacity. The tunnel is a separated combined tunnel with small clear distance. The buried depth of the tunnel top is about 28 m, and the clear distance between the two lines is 23 m. The left line starts at ZK1 + 664-ZK2 + 164, with a length of 500 m. The right track starts at K1 + 663-K2 + 160 and is 497 m long. The tunnel is designed as a two-way six-lane tunnel, with large excavation section and shallow burial depth, and adjacent to the high-voltage transmission lines in normal operation on the top surface. The closest horizontal distance between the tunnel arch and the tower leg is only 21 meters, and the farthest distance is 38 meters. Figure 1 shows the schematic diagram of the position relationship between the tunnel and the upper high-voltage tower.

The high voltage line adjacent to the tunnel excavation area belongs to the 500 kV Lingbao-Shanzhou I loop line under the jurisdiction of Shanzhou Substation of Sanmenxia Power Supply Company, which is a high-level important line and hub connecting the northwest and central China power grids. As shown in Figure 1, the towers adjacent to the tunnel construction section include 74#–77# towers of the line. Taking 76# transmission tower with the nearest distance from the tunnel as the object, according to the local meteorological conditions, the load borne by the transmission tower foundation under normal operation (including maximum wind speed, ice cover) and line broken conditions is shown in Figure 2(a), where a and b are the tower leg foot distances and Φ is the angle between the main material on the side and the ground. Other symbols are load symbols calculated under normal operation, including gravity, wind pressure, etc. As shown in Figure 1, the instability of the tower caused by tunnel excavation mainly occurs in the x-O-z plane, so the analysis in this paper can be simplified as only considering the load on the tower in the x-O-z plane, as shown in Figure 2(b). The 76# tower is 30 m high, and the measured foundation forces are about $N = 960$ kN, $X_N = 350$ kN, $T = 370$ kN, $X_T = 180$ kN. According to the as-built drawing data, the foundation type of the tower leg is the stepped foundation, with the designed buried depth of 3.4 m and the actual outcrop of 0.2 m. The base is $2.2 \times 2.2 \times 0.4$ m reinforced concrete slab, the bottom is distributed according to two layers of steps, and the upper part is the foundation main pile with a diameter of 0.6 m. The specific size is shown in Figure 2(c).

In order to prevent the influence of tunnel excavation on the tower foundation, the CD method is selected for construction based on various factors and expert review opinions. The CD method construction process of the new tunnel is shown in Figure 3. However, it is still uncertain whether to adopt simultaneous excavation of double tunnels or step-by-step excavation of single tunnel. The excavation sequence that can be predicted includes three schemes, namely, first excavation of left tunnel (short distance tunnel), first excavation of right tunnel (far distance tunnel), and simultaneous excavation of double tunnels. Because the induced stress field of tower foundation is different due to the excavation process of caverns at different distances from the tower, the influence of three excavation sequence construction schemes on the stability of adjacent tower foundation is necessarily different. Therefore, it is necessary to adopt numerical simulation method to calculate and obtain the construction scheme with minimum influence before construction.

3. Numerical Model

In order to study the influence of the construction process of the new tunnel on the safety of the upper high-voltage tower, ABAQUS software is used for numerical simulation. According to Saint–Venant's principle, the boundary of the model should be selected at a location 3–5 times the hole diameter from the tunnel excavation contour [24]. Therefore, in order to eliminate the influence of boundary constraints, the horizontal direction of the model is taken as 3 times the tunnel excavation width, the upper part is taken to the ground surface, and the lower part is taken as 3 times the tunnel excavation height. In addition, to ensure the calculation efficiency, only the section of the nearest distance between tower # 76 and tunnel is taken for analysis. If the grid of the model is too dense, the calculation efficiency will be greatly reduced, and it is difficult to ensure the calculation accuracy under the condition of sparse grid. Therefore, the grid settings near the tunnels are dense, while those far away from the tunnels are sparse. The maximum mesh size is 0.8 m and the minimum mesh size is 0.5 m.

The numerical model is shown in Figure 4. In order to facilitate modeling, the tower foundation is set as a rectangular column with equal section, and the ladder shape enlargement of the foundation with depth is not considered. The width of the foundation is set as 2.2 m, and the burial depth is 3.4 m. C30 concrete is used for transmission tower foundation.

Since the tunnel is located on one side of the tower, in order to simplify the analysis, the tower is set as two tower legs, as shown in Figure 2(b), which are, respectively, applied to the two tower legs in the most unfavorable load state. As described in Section 1, the tower foundation load acts on the top of the tower foundation. Normal displacement constraints are applied to the boundary around the model, and three-direction displacement constraints are applied to the bottom surface, while the upper surface is a free boundary.

In numerical simulation, C3D8R element is used to simulate soil and tunnel lining structure. The Mohr–Coulomb constitutive model is used for soil, and the linear elastic constitutive model is used for tunnel lining structure. Binding contact is adopted between the lining and surrounding rock. The element passivation and activation in ABAQUS are used to simulate the soil excavation and lining structure support, respectively, during construction. In order to simplify the reinforcement of small conduit grouting, the surrounding rock reinforced by small conduit grouting is regarded as a reinforcement layer in the simulation process, and the reinforcement layer of surrounding rock is simulated by improving the cohesion and friction angle of rock mass [25]. According to the engineering geological survey report, the soil layer is divided into four layers, namely, miscellaneous fill, loess soil, silt, and silty clay. The parameters of soil mass, lining structure, and tower foundation are shown in Table 1.

In the process of simulation, when comparing and selecting the construction schemes, only the influence of the construction schemes on the tower foundation is considered, and the uneven settlement and inclination of the foundation are taken as the judgment basis. Therefore, the upper tower structure can be ignored, and the analysis can be carried out according to the most unfavorable plane. The location relationship between the newly-built tunnel and the existing tower foundation is shown in Figure 5. The figure

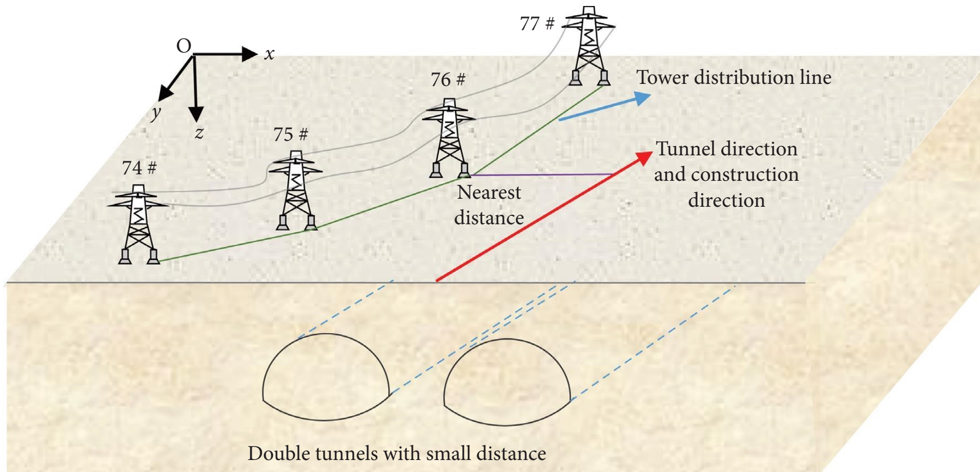


Figure 1: Schematic diagram of the position relationship between the tunnel and the upper high-voltage tower.

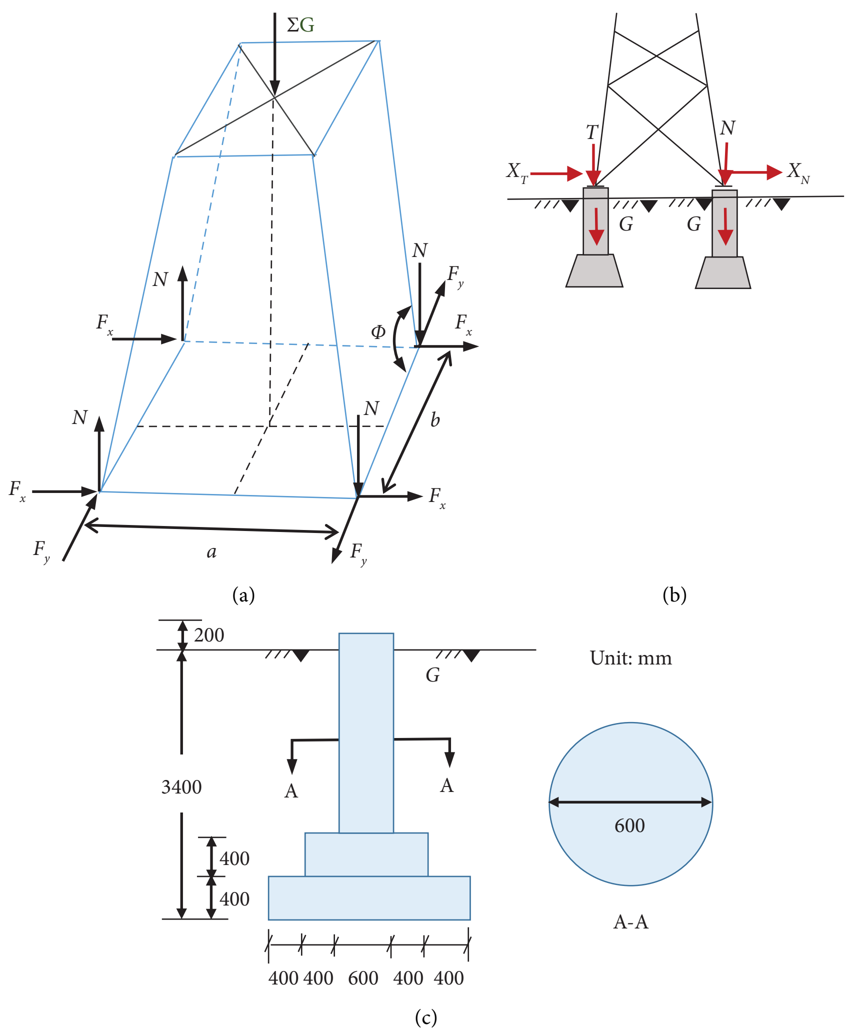


Figure 2: The loads and foundation of the 76 # tower. (a) The load on the tower. (b) The load condition of tower foundation in plane. (c) The dimensions of the tower foundation.

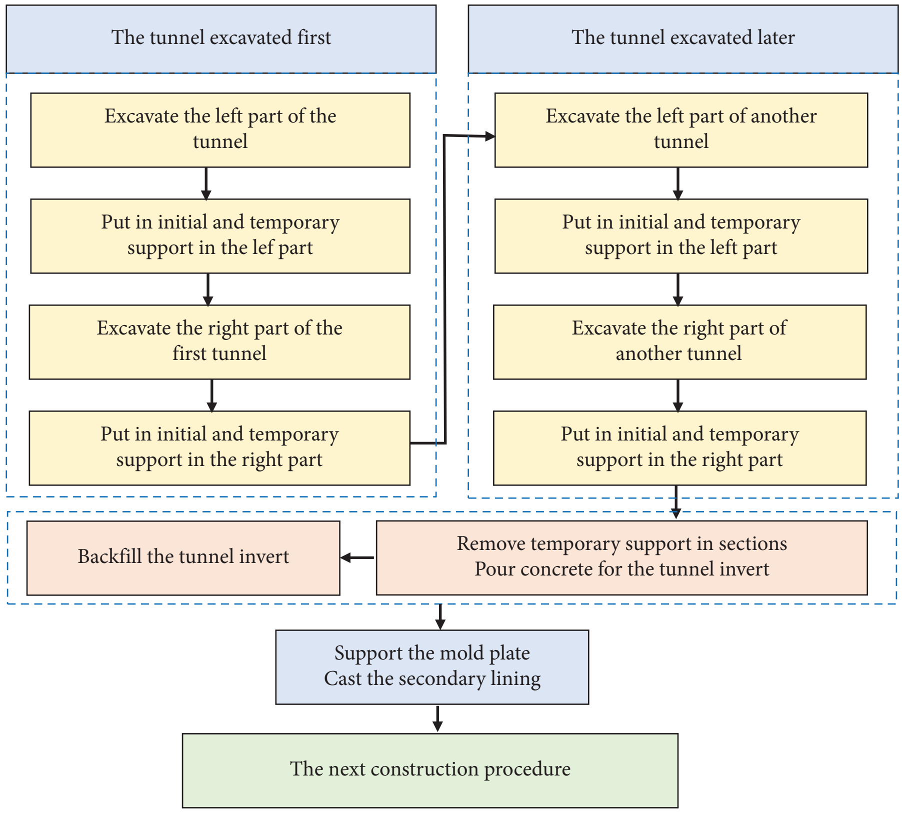


FIGURE 3: The construction process flow chart of CD method.

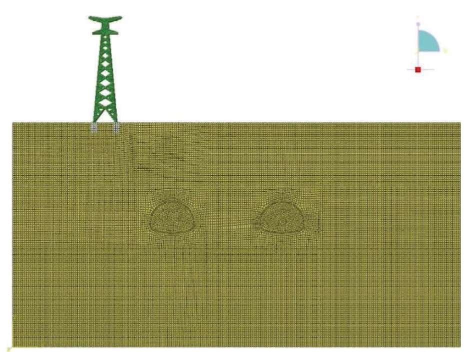


FIGURE 4: Schematic diagram of numerical model.

also shows the relevant geometric parameters of the tunnel and tower location.

In order to deeply study the influence of the excavation sequence of the left and right lines of the new small clear distance tunnel on the safety of the existing high voltage transmission tower foundation, various construction schemes were simulated, including simultaneous excavation of the left and right lines, excavation of the left line first, and excavation of the right line first.

4. Verification of Numerical Methods

The ABQUAS numerical simulation method has the advantages of convenient modeling and accurate calculation when simulating tunnel excavation and other working conditions, but whether it can accurately calculate the settlement and stability of adjacent transmission tower foundation caused by tunnel excavation needs further verification. In order to verify the accuracy of the numerical method, the tunnel is simplified as a circular cavern, and the stratum is simplified as an elastic homogeneous soil layer. The theoretical method is used to derive and calculate the induced stress of the tower foundation caused by the cavern excavation, and the numerical simulation results under the same working conditions are used for comparison.

4.1. Theoretical Solution of Induced Stress Caused by Cavern Excavation. It can be seen from elasticity [26] that the stress distribution of surrounding rock of circular cavern under elastic state is

Table 1: Material parameters of soil and lining structure.

The soil or structure	Density (kg/m^3)	Elasticity modulus (MPa)	Poisson's ratio	Frictional angle (°)	Cohesion (kPa)
Miscellaneous fill	1600	7	0.35	19	22
Loess soil	1680	8	0.32	21	23
Silt	1730	10.6	0.31	22	26
Silty clay	1780	12.5	0.29	21	27
Primary lining	2500	32000	0.15	—	—
Secondary lining	2500	36000	0.15	—	—
Concrete	2500	30000	0.20	—	—

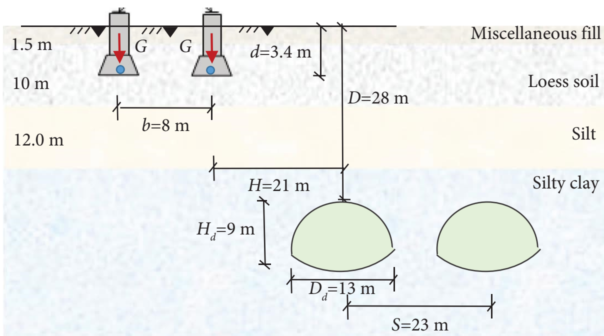


Figure 5: Schematic diagram of stratum distribution and location relationship between new tunnel and tower foundation.

$$\sigma_r = -\frac{r^2}{l^2}q_a - \left(1 - \frac{r^2}{l^2}\right)q_b,$$
$$\sigma_\theta = \frac{r^2}{l^2}q_a - \left(1 + \frac{r^2}{l^2}\right)q_b, \tag{1}$$

where σ_r and σ_θ are radial and circumferential normal stress, respectively. r is the cavern radius. l is the distance between the measuring point in surrounding rock and the tunnel center. q_a is the wall pressure stress in the cavern. q_b is the uniform geo-stress.

When the tunnel is excavated or expanded, the induced stress caused by the unloading of the tunnel shall be considered. For the problem of induced stress in circular tunnels, some researchers [27] have deduced the circumferential induced stress value $\sigma_{\theta\theta}$, radial induced stress values σ_{rr} and shear stress $\sigma_{\theta r}$ of circular section cavern elastic zone with radius r at different distances and angles from the center through elastic theory. In combination with the relevant dimensions shown in Figure 6, the stress components at point M are, respectively, expressed as

$$\sigma_{rr} = \frac{\sigma_V}{2}\left[(1 + K_0)\left(1 - \frac{r^2}{l^2}\right) - (1 - K_0)\left(1 - 4\frac{r^2}{l^2} + 3\frac{r^4}{l^4}\right)\cos 2\theta\right], \tag{2}$$

$$\sigma_{\theta\theta} = \frac{\sigma_V}{2}\left[(1 + K_0)\left(1 + \frac{r^2}{l^2}\right) + (1 - K_0)\left(1 + 3\frac{r^4}{l^4}\right)\cos 2\theta\right], \tag{3}$$

$$\sigma_{\theta r} = \frac{\sigma_V}{2}\left[(1 - K_0)\left(1 + 2\frac{r^2}{l^2} - 3\frac{r^4}{l^4}\right)\sin 2\theta\right], \tag{4}$$

where K_0 is the coefficient of static earth pressure. θ is the location angle of the induced point M, as shown in Figure 6. σ_V is the vertical geo-stress at the tunnel location. If the tectonic stress of surrounding rock is not considered, σ_V is the product of soil weight γ and the buried depth of the tunnel center Z, namely,

$$\sigma_V = \gamma \cdot Z. \tag{5}$$

Therefore, the radial and circumferential-induced stress of each base of tower caused by tunnel excavation as shown in Figure 5 can be obtained by equations (2)–(4). If the tunnel section is simplified as a standard circle, its diameter is taken as the maximum excavation width D_d. According to the location relationship between the tunnel and the tower foundation as shown in Figure 5, a calculation model for induced stress at the tower foundation caused by tunnel excavation as shown in Figure 7 can be established in the x-O-z plane.

As shown in Figure 7, if the influence of the tower foundation width is not considered, the tiny elements can be established from the radial and circumferential induced stresses at the center points A and B of the foundation basement. Accordingly, the average induced stresses in the

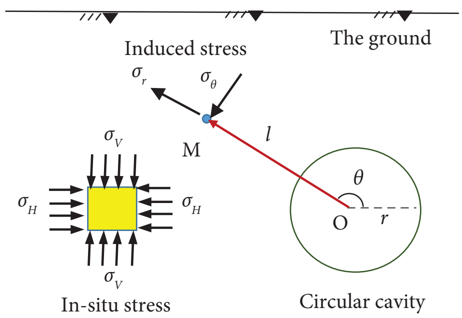


Figure 6: Schematic diagram of induced stress caused by excavation of circular cavity.

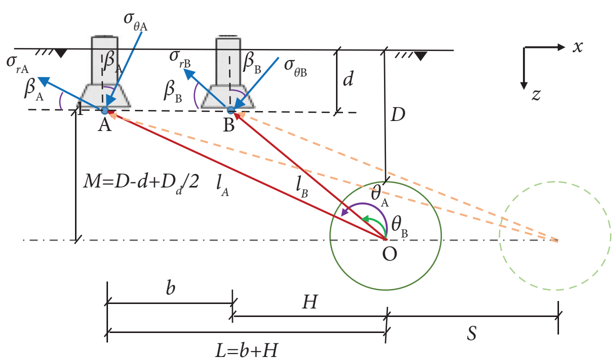


Figure 7: Schematic view of the tangential and radial induced stresses applied to the bottom of tower foundation.

vertical direction of the tower base σ_{zA}' and σ_{zB}' can be calculated according to the balance relationship of the forces at the tiny elements and the geometric relationship, expressed as

$$\sigma_{zA}' = \left(\frac{\sigma_{rrA} + \sigma_{\theta\theta A}}{2}\right) + \left(\frac{\sigma_{\theta\theta A} - \sigma_{rrA}}{2}\right)\cos 2\beta_A + \sigma_{\theta rA}\sin 2\beta_A, \tag{6}$$

$$\sigma_{zB}' = \left(\frac{\sigma_{rrB} + \sigma_{\theta\theta B}}{2}\right) + \left(\frac{\sigma_{\theta\theta B} - \sigma_{rrB}}{2}\right)\cos 2\beta_A + \sigma_{\theta rB}\sin 2\beta_B, \tag{7}$$

where

$$\beta_A = \arctan\left(\frac{D - d + D_d/2}{b + H}\right), \quad \beta_B = \arctan\left(\frac{D - d + D_d/2}{H}\right). \tag{8}$$

When equations (2) to (5) are substituted into equations (6) and (7), the average induced stresses in the vertical direction σ_{zA}' and σ_{zB}' can be rewritten as

$$\sigma_{zA}' = \frac{\gamma H}{2}\left\{\begin{array}{l}\left[(1+K_0) + 2(1-K_0)\left(\frac{r^2}{l_A^2}\right)\cos 2\theta_A\right] + \\ \left[\begin{array}{l}(1+K_0)\left(\frac{r^2}{l_A^2}\right) + (1-K_0) \\ \left(1 - 2\frac{r^2}{l_A^2} + 3\frac{r^4}{l_A^4}\right)\cos 2\theta_A\end{array}\right]\cos 2\beta_A - \\ \left[(1-K_0)\left(1 + 2\frac{r^2}{l_A^2} + 3\frac{r^4}{l_A^4}\right)\sin 2\theta_A\right]\sin 2\beta_A\end{array}\right\}, \tag{9}$$

$$\sigma_{zB}' = \frac{\gamma H}{2}\left\{\begin{array}{l}\left[(1+K_0) + 2(1-K_0)\left(\frac{r^2}{l_B^2}\right)\cos 2\theta_B\right] + \\ \left[\begin{array}{l}(1+K_0)\left(\frac{r^2}{l_B^2}\right) + (1-K_0) \\ \left(1 - 2\frac{r^2}{l_B^2} + 3\frac{r^4}{l_B^4}\right)\cos 2\theta_B\end{array}\right]\cos 2\beta_B - \\ \left[(1-K_0)\left(1 + 2\frac{r^2}{l_B^2} + 3\frac{r^4}{l_B^4}\right)\sin 2\theta_B\right]\sin 2\beta_B\end{array}\right\}. \tag{10}$$

In addition, from the geometric relationship shown in Figure 7, there are

$$\theta_A = \pi - \beta_A, \quad \theta_B = \pi - \beta_B, \tag{11}$$

$$r = \frac{D_d}{2}, \tag{12}$$

$$\left\{\begin{array}{l} l_A = \sqrt{(b+H)^2 + \left(D - d + \frac{D_d}{2}\right)^2}, \\ l_b = \sqrt{H^2 + \left(D - d + \frac{D_d}{2}\right)^2}. \end{array}\right. \tag{13}$$

When equations (11) to (13) are put into equations (9) and (10), the vertical induced stress at points A and B can be simplified as

$$\sigma_{zA}^{'}=\frac{\gamma H}{2}\left[\begin{array}{c}(1+K_0)-(1-K_0)\left(2\frac{(D_d/2)^2}{(b+H)^2+(D-d+D_d/2)^2}-3\frac{(D_d/2)^4}{\left[(b+H)^2+(D-d+D_d/2)^2\right]^2}\right)\\+(3-K_0)\left(\frac{(D_d/2)^2}{(b+H)^2+(D-\ d+D_d/2)^2}\right)\cos 2\beta_A+(1-k_0)\cos 4\beta_A\end{array}\right], \tag{14}$$

$$\sigma_{zB}^{'}=\frac{\gamma H}{2}\left[\begin{array}{c}(1+K_0)-(1-K_0)\left(2\frac{(D_d/2)^2}{(H)^2+(D-d+D_d/2)^2}-3\frac{(D_d/2)^4}{\left[(H)^2+(D-d+D_d/2)^2\right]^2}\right)\\+(3-K_0)\left(\frac{(D_d/2)^2}{(H)^2+(D-\ d+D_d/2)^2}\right)\cos 2\beta_B+(1-k_0)\cos 4\beta_B\end{array}\right]. \tag{15}$$

Therefore, as shown in Figure 7, when the left tunnel is excavated, the vertical induced stress at points A and B at the center of the high-voltage tower base can be calculated according to equations (14) and (15). However, it should be noted that the previous derivation is the theoretical result under the assumption that the foundation soil is in an elastic state and the tunnel is unloaded once as an ideal circle, which does not represent the actual value. The theoretical solution is only used as a reference to verify the numerical simulation results under the same working conditions.

As shown in Figure 2, the bottom area of the tower leg foundation is A_s, the vertical force on the compression side of the tower leg is N, the vertical force on the tension side is T, and the dead weight of the tower foundation is G. If the foundation is assumed to be homogeneous soil, its gravity is γ. Then, when the tunnel is not excavated, the additional stress of the base at A and B at the bottom center of the tower foundation can be expressed as

$$\begin{cases}\sigma_{0A}=\dfrac{\gamma_G A_s d+T}{A_s}-\gamma d,\\[2ex]\sigma_{0B}=\dfrac{\gamma_G A_s d+N}{A_s}-\gamma d,\end{cases} \tag{16}$$

where γ_G is the weighted average unit weight of foundation and upper soil, generally taken as 20 kN/m^3. Therefore, when the left tunnel is excavated as shown in Figure 7, the additional stress of points A and B at the center of the tower base bottom can be obtained by superposition of formulas (14)–(16), which is expressed as

$$\begin{cases}\sigma_A=\sigma_{0A}+\sigma_{zA}^{'},\\\sigma_B=\sigma_{0B}+\sigma_{zB}^{'}.\end{cases} \tag{17}$$

Similarly, when the right tunnel is excavated, the additional stress at the tower base can also be calculated according to equation (17). It should be noted that when calculating the induced stress caused by the excavation of the right tunnel, it is necessary to accurately calculate the l_A and l_B values according to the geometric relationship shown in Figure 7. The induced stress generated by simultaneous excavation of two tunnels can be calculated by adding the calculated result of the left single tunnel and the induced stress calculated by the right tunnel according to the superposition principle.

4.2. Comparative Verification. In this section, the simplified theoretical method in Section 4.1 will be adopted to calculate the additional stress at the bottom of the tower foundation caused by the excavation of the left tunnel. In calculation, the tower foundation forces are set as $N=960$ kN, $T=370$ kN. The area of foundation is $As=2.2\times 2.2$ m^2. The weight of homogeneous soil layer is $\gamma=18$ kN/m^3, and the earth pressure coefficient is taken as $K_0=0.56$. Values of the geometric parameters related to tower and tunnel shall be taken according to Figure 5, i.e., $D=28$ m, $H_d=9$ m, $H=21$ m, $b=8$ m, $d=3.4$ m. Since the tunnel section is not formed by one excavation, the tunnel radius can be taken as 1, 3, 5, and 7 m, respectively, to simulate the calculation results of different excavation progress.

The modeling shall be carried out according to the method described in Section 2. The numerical simulation results shall be compared with the theoretical calculation results under the same working conditions to achieve mutual verification. Only the plane model is used during the numerical modeling, and the soil layer is homogeneous. The tunnel is set as a circle with alterable radii. However, the existing holes cannot be set in the initial modeling process. Instead, the tunnel is formed by the way of excavation after modeling, that is, the corresponding unloading force is applied to the model. The effect of this method can correspond to the theoretical assumptions in the paper. Other parameters are consistent with those adopted in theoretical calculation. The calculation results are shown in Table 2.

It is obvious from Table 2 that the theoretical and numerical simulation calculation results under the same working conditions are relatively close, especially when the tunnel excavation radius is small. Thus, the accuracy of the theory and numerical methods in this paper is mutually verified. However, from the calculation results, there is little difference between the numerical results and the theoretical

Table 2: Comparison between theoretical and numerical simulation results.

Tunnel radius r (m)	σ_A (kPa)		σ_B (kPa)	
	Theoretical results	Numerical results	Theoretical results	Numerical results
1	91.2	89.7	221.65	219.3
3	100.76	98.9	226.06	234.6
5	109.91	110.3	231.95	240.1
7	116.44	121.5	235.93	255.6

results of the additional stress at the bottom of the column far away from the tunnel (σ_A), while the theoretical results of the additional stress at the bottom of the column near the tunnel σ_B are generally larger than the numerical results. The main reason is that the theoretical calculation assumes that the soil is completely elastic, while the elastoplasticity of the soil may have some influence on the results in the simulation calculation, and the soil at the bottom of the tower near the tunnel is more likely to enter the elasto-plastic stage.

4.3. Parametric Analysis. As shown in Figure 1, the horizontal distances between the tunnel line and the ground surface of 74 #–77 # towers are 21–38 meters, and the tunnel construction process will inevitably have a certain impact on each tower. Therefore, in this section, the assumed model in Section 4.1 is used to theoretically calculate the induced stress values of the tower foundation with different horizontal distance distribution $H = 21$ to 38 m caused by tunnel excavation in the x-O-z plane. In calculation, the tunnel diameter is set as the actual maximum excavation width of 13 m. Other parameters are consistent with Section 4.2. In order to analyze the impact of construction sequence, in addition to the calculation of single tunnel excavation on the left side, the excavation of single tunnel on the right side and the simultaneous excavation of two caverns are calculated separately. The calculation results are shown in Figure 8.

It can be seen from Figure 8 that the induced stress value at the base point of the tower foundation adjacent to the excavated tunnel decreases significantly with the increase of the distance between the tower and the tunnel, indicating that the farther the tunnel is from the tower foundation, the smaller the impact on the tower foundation. The induced stress of double tunnel excavation is much higher than that of single tunnel excavation. Therefore, to reduce tunnel excavation, it is recommended to excavate the left and right tunnels step by step.

5. Numerical Simulation Results

5.1. Comparison of Construction Schemes. It can be seen from Section 4.3 that the additional stress on the tower base caused by the excavation of the left and right tunnels is different. While the settlement of the tower foundation during the excavation of the tunnel is related to the additional stress increment. Therefore, theoretically, there will be a slight difference between the first excavation of the left tunnel (close to the tower) and the first excavation of the right tunnel (far from the tower) on the settlement of the tower foundation. In order to compare the three construction schemes described in Section 2, numerical simulation is used to calculate the displacement of tower foundation under the three construction schemes, and judgment is made according to the allowable value of displacement. According to Article 7.1.8 of *Code for Construction and Acceptance of 110 kV~750 kV Overhead Transmission Line* (GB50233-2014), Article 5.3.1 of *Technical Code for Design of Overhead Transmission Line Foundation* (DL/T5219-2014), Article 7.2.5 of *Code for Design of High-Rising Structures* (GB50135-2019), and relevant requirements of the power department [28–30], the deformation control standards for the foundation of tangent pole and tower in this project are formulated as follows: (1) the maximum allowable settlement is 40 mm; (2) horizontal line displacement between tower foundation center and central pile ≤30 mm; (3) the allowable value of foundation inclination degree is 6‰.

Figure 9 shows the vertical displacement cloud pictures under three construction schemes (Scheme 1: excavation of the left tunnel followed by the right tunnel, Scheme 2: excavation of the right tunnel followed by the left tunnel, and Scheme 3: excavation of the two tunnels at the same time). It can be seen from the calculation results that the vertical settlement difference of the foundation under Scheme 1 is 7.2 mm, and the maximum vertical settlement of the foundation is 29.92 mm. Under Scheme 2, the vertical settlement difference of the foundation is 5.9 mm, and the maximum vertical settlement of the foundation is 23.56 mm. Under Scheme 3, the vertical settlement difference of the foundation is 12.4 mm, and the maximum vertical settlement of the foundation is 37.27 mm.

In Scheme 1, the maximum inclination of the tower is 0.9‰, in Scheme 2, it is 0.74‰, and in Scheme 3, it is 1.55‰. Therefore, considering the inclination of the tower foundation alone, the tower is safe during the tunnel excavation of any scheme. The displacement values under these three schemes are also less than the allowable values, and only when two tunnels are excavated at the same time, the displacement value is close to the maximum allowable displacement value. According to the previous maximum displacement value and the sensitivity of the tower to inclination, in order to ensure that there is no accident in the operation of the tower, Scheme 2 should be selected to excavate the tunnel. That is, the left tunnel shall be excavated after the construction of the right tunnel is completed.

5.2. Displacement Field of Tower Foundation Caused by CD Method Construction. Based on the results in Section 4.1, it is determined to excavate the right tunnel with a slightly greater distance from the tower base and then carry out the

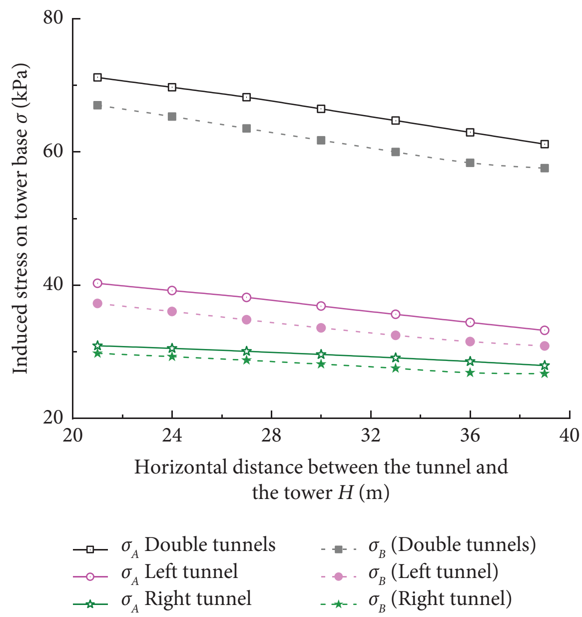
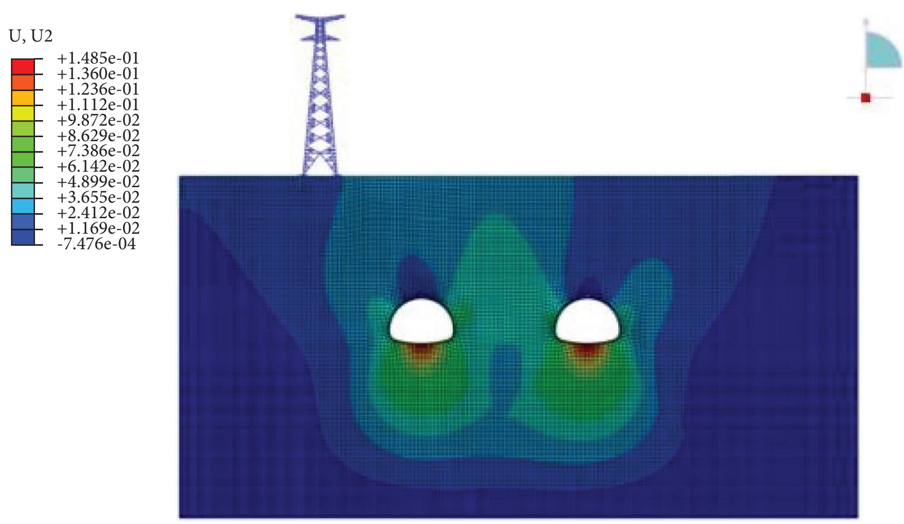
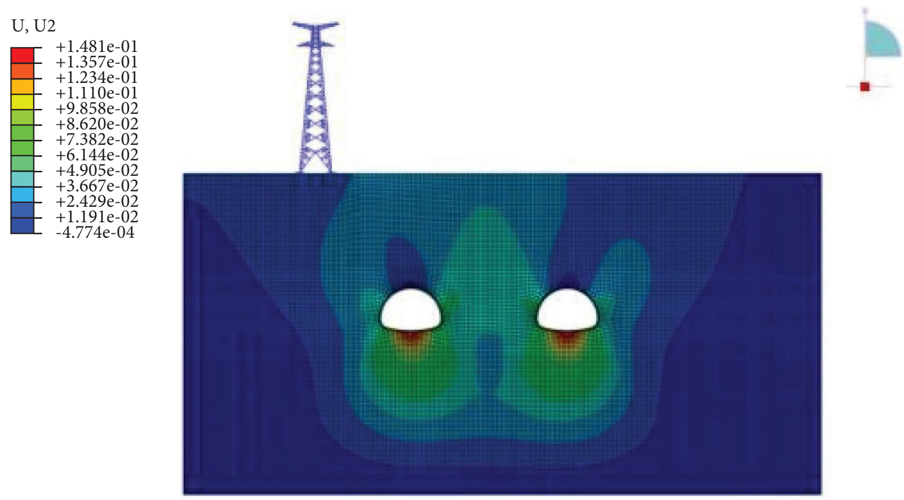


Figure 8: The induced stress under different horizontal between the tunnel and tower.

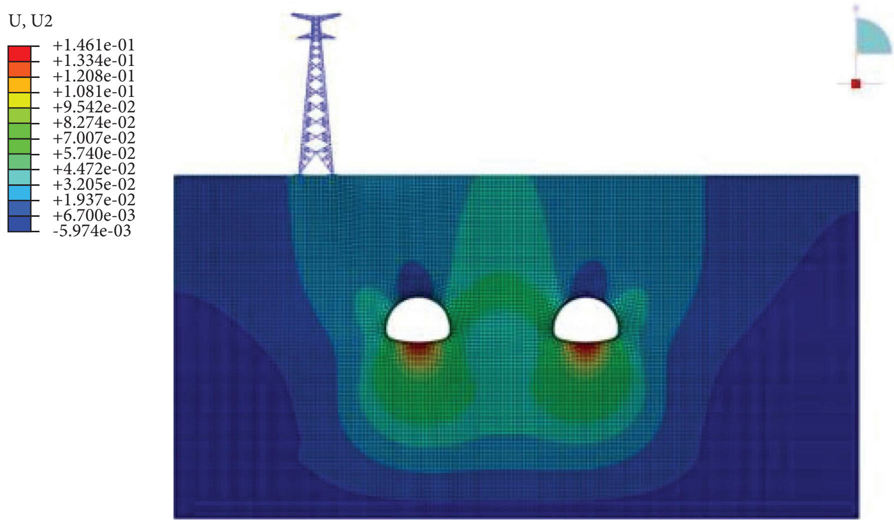


(a)



(b)

Figure 9: Continued.



(c)

Figure 9: Vertical displacement cloud pictures under different construction sequence. (a) Scheme 1: excavation of the left tunnel followed by the right tunnel. (b) Scheme 2: excavation of the right tunnel followed by the left tunnel. (c) Scheme 3: excavation of the two tunnels at the same time.

construction of the left tunnel after the completion of the right tunnel, while the CD method is used for single hole construction. The impact of the CD method construction process on the tower foundation displacement will analyze in detail in this section. Considering that too much mesh division of the 3D model when simulate the construction schedule will lead to lengthy calculation time, each excavation step is simulated once along the strike axis of the tunnel in the process of numerical simulation, that is, each excavation length of the upper and lower steps is 8 m. The upper and lower steps each account for half of the net height of the tunnel. The specific construction steps of the CD method are described in Figure 3.

The displacement in the vertical direction of point A at the bottom of the left tower leg and point B at the bottom of the right tower leg of the tower foundation is monitored during the simulation. The newly added vertical displacement at points A and B after each construction step is recorded as ΔS_A and ΔS_B, and the cumulative displacement is S_A and S_B. The change rule of displacement with construction steps is shown in Figure 10. In Figure 10, "Ex-Left-R" is short for "Excavate the left part of the right tunnel," represents the first construction step of the CD method in Figure 3. "Su-Left-L" means "Support left part of the left tunnel." "*L*" and "*R*" are short for "left" and "right," represent the left tunnel and the right tunnel, respectively.

It can be seen from Figure 11 that during the first step of construction (i.e., the left half of the right tunnel), both tower legs have a certain settlement, indicating that once the tunnel is excavated, the induced stress on the adjacent foundation will cause settlement. Then, before the excavation of the left tunnel, the corresponding settlement of each construction step has a slow growth, and the increment is far less than the settlement of the first construction step. When the cavern close to the tower (i.e., the left tunnel) is excavated, the settlement of the right tower leg increases greatly, reflecting that the closer the cavern is excavated, the more obvious the influence is. The growth of the displacement of left tower leg is slightly delayed compared with that of the right tower leg, mainly because the stress transmission caused by the deformation of the surrounding soil mass is not formed at once after the excavation of the tunnel. It can also be seen from the figure that although there is no excavation of the soil mass in the support section, the settlement is also gradually increasing, mainly because the foundation settlement caused by the additional stress generated by the excavation of the foundation settlement tunnel is slowly increasing over time, which is related to the consolidation parameters of the foundation soil. When the two tunnels are excavated, the settlement increment of the two tower leg foundations is very small in the subsequent construction steps, and the total settlement on both sides tends to be stable gradually. According to the calculation results in Figure 11, the maximum cumulative settlement of two tower legs shall not exceed 30 mm, meeting the specification requirements.

In addition, Figure 11 shows the change rule of the inclination of the tower foundation with the construction steps. It can be seen from the figure that the inclination of tower foundation increases slowly, then increases rapidly, and finally decreases gradually with the construction. The curve reflects the law of inequality and asynchronous changes of the two tower leg foundations settlements during the construction of the tunnel adjacent to the tower. The closer the tower foundation is to the tunnel, the faster its settlement occurs and the greater its settlement, and vice versa. When the tunnel is far away from the tower (the right tunnel), the settlement of both tower legs is small and the inclination of the foundation is small. When the left tunnel is excavated, the right tower leg quickly shows obvious settlement due to its closest distance, while the time for the left

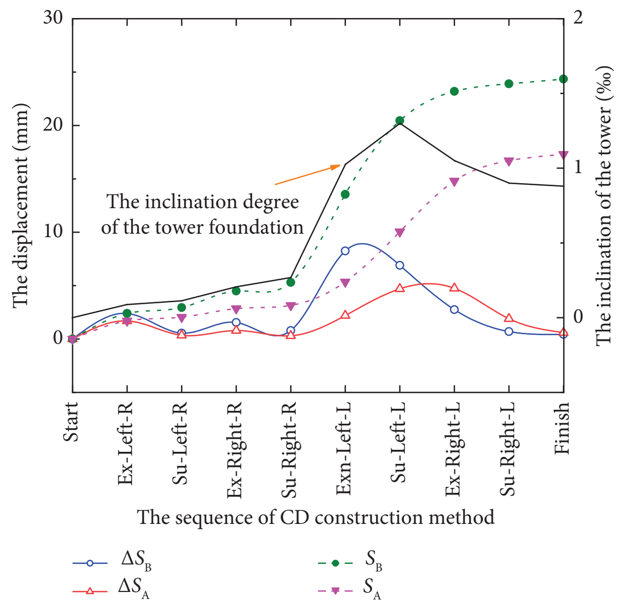


FIGURE 10: The settlement and inclination law of tower foundation corresponding to different construction progress.

tower leg to reach the maximum settlement is delayed. Therefore, the maximum inclination of tower foundation occurs when the left tunnel is excavated. The final inclination is about 1‰, so it can be judged that the impact of this excavation on the tower is safe and controllable.

5.3. Analysis of the Influence of the Distance between Tunnels and Tower on Tower Stability. It can be seen from Section 4.3 that the distance between the tunnel and the tower will have a significant impact on the foundation stress of the tower and, therefore, on its stability. In order to provide reference and suggestions for similar projects, the influence of the horizontal distance between the tunnel and the tower on the stability of the tower foundation will be analyzed in this section. During calculation, the horizontal distance between the tower foundation and the tunnel H is adopted 21 to 0 m.

Figure 11 shows the corresponding cloud pictures of tower foundation displacement considering the CD method construction when $H = 21$ m, 10.5 m and $H = 0$ m, respectively. Wherein, $H = 0$ m is the working condition where the tower is located directly above the left tunnel, which is the most unfavorable condition when the tower is close to the tunnel. Compared with Figures 9(b) and 11(a), the support wall in the middle of each tunnel will have a certain impact on the results during the CD method construction, but the impact is small. The maximum vertical displacement of the foundation calculated in Figure 11(a) is 26.23 mm, and the settlement difference is 7.12 mm. When H decreases (Figures 11(b) and 11(c)), the change of displacement cloud picture is small and the displacement distribution is similar. The maximum vertical settlements of the foundation in Figures 11(b) and 11(c) are 44.93 mm and 96.24 mm, respectively. The settlement differences are 13.08 and 3.72. The settlement has increased significantly.

Figure 12 shows the change curve of the maximum vertical displacement value of the foundation and the tower foundation inclination under different H conditions. Obviously, the closer the distance is, the greater the total settlement of tower foundation. Under the engineering conditions in this paper, when H is less than 16 m, the total settlement is more than 40 mm, exceeding the allowable value, which will have a great threat on normal operation. However, the tower foundation inclination first increases and then decreases with the increase of H, but the maximum inclination is about 2‰. The main reason for the decrease of the inclination at close distance is that the induced stress of the two tower legs foundations at a small distance will increase, and the difference between stress values will gradually decrease, thus the corresponding settlement difference of tower foundations will also decrease.

Figure 13 shows the change curve of soil stress in the base with the excavation steps at different positions of the tower. In the curve, the horizontal coordinate 1-2 refers to the excavation of the left half of the right tunnel, 2-3 refers to the excavation of the right half of the right tunnel, 3-4 refers to the excavation of the left half of the left tunnel, and 4-5 refers to the excavation of the right half of the right tunnel. In the process of 1–3, Mises stress value slightly increases under $H = 10.5$ m and 21 m working conditions, mainly due to the induced stress. However, the stress of $H = 0$ m decreases to a certain extent, mainly because the tower is located directly above the tunnel, and the settlement occurs quickly after excavation, and the stress release is fast. However, in the 3–5 process, redistribution and stress reduction occur only under $H = 10.5$ m and 21 m working conditions, but the induced stress is very large under $H = 0$ m working conditions. Therefore, the excavation of the tunnel close to the tower will have a great impact on the tower foundation. In addition to the risk of inclination, the tower will also have a large foundation settlement or local

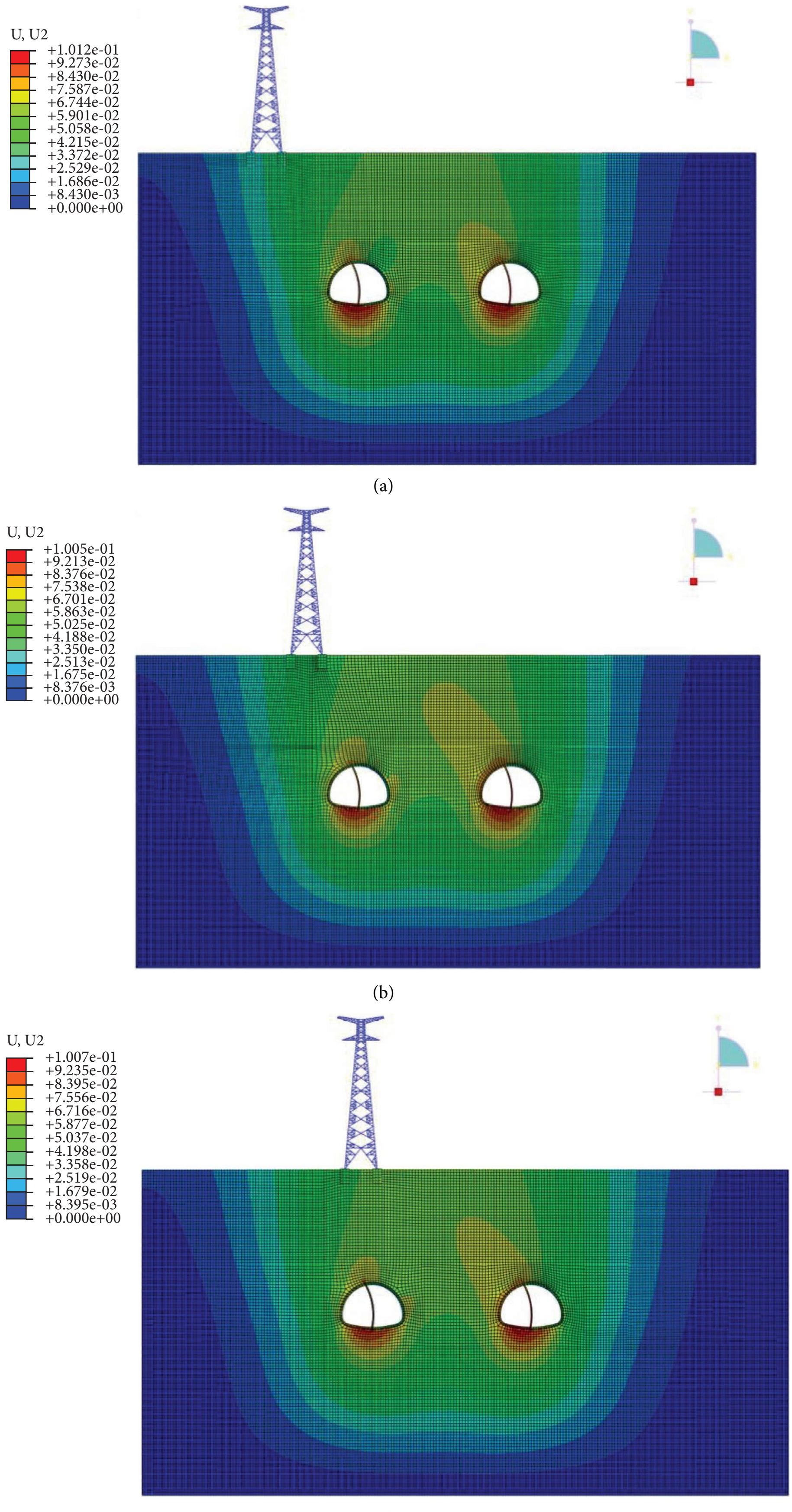


Figure 11: Vertical displacement cloud pictures under three cases with different horizontal distance between tunnel and tower. (a) $H = 21$ m. (b) $H = 10.5$ m. (c) $H = 0$ m.

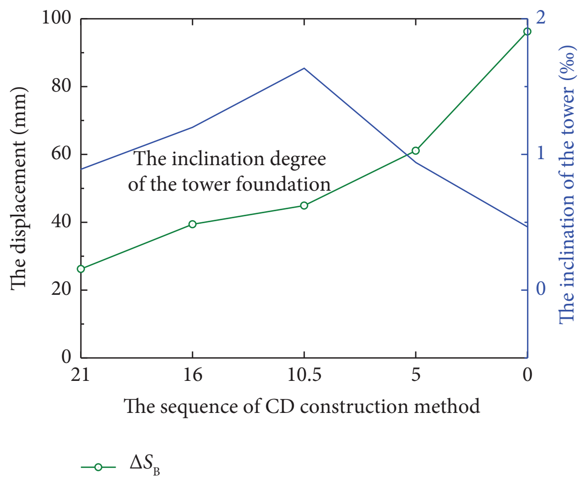


FIGURE 12: The max vertical displacement and the inclination of tower under the sequence of CD construction method.

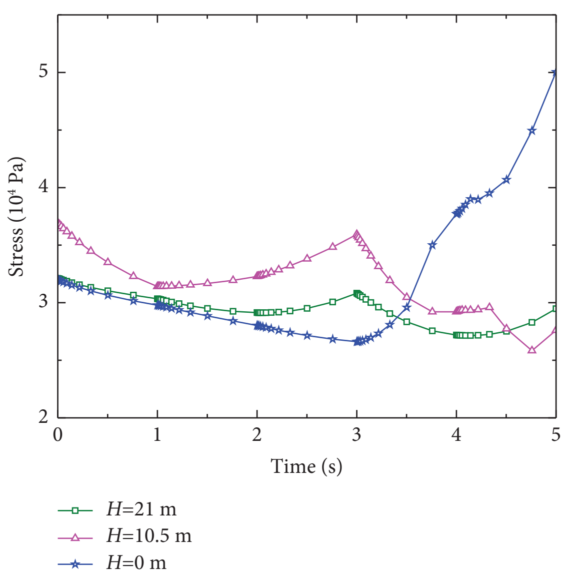


FIGURE 13: Change curve of soil stress with time at different positions of the tower.

damage of the foundation soil. Therefore, it must be reinforced during construction.

6. Conclusions

Through numerical simulation, the influence of small clear distance loess tunnel excavation on the stress and deformation of adjacent high-voltage tower foundation is analyzed, and the calculated results of induced stress of foundation are compared with theoretical analysis, and conclusions are as follows:

(1) The synchronous excavation construction scheme for the left and right lines of the new tunnel has the greatest impact on the adjacent tower foundation. Through comparison, it is found that the construction of the right tunnel followed by the construction of the left tunnel is the best, and the total settlement and inclination of the corresponding tower foundation are the minimum.

(2) Once the tunnel is excavated, the induced stress will be generated on the adjacent tower foundation, which will cause settlement. The closer the tunnel is, the greater the induced stress is.

(3) With the decrease of the distance between the tower and the tunnel, the maximum settlement of the tower foundation caused by tunnel excavation gradually increases, and the growth rate also gradually increases. However, the inclination of tower foundation increases first and then decreases. When the tower is directly above the tunnel, the settlement is maximum but the inclination is small. Therefore, it is not comprehensive to simply use the inclination to measure the stability of the tower foundation under the engineering disturbance such as tunnel excavation. It should also be combined with the settlement to make a comprehensive judgment.

Data Availability

No data were used to support the findings of this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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