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Analysis of Effect of Under-cross Slurry Shield Tunneling on Embankment of the Yangtze River

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Abstract: To build cross-river tunnel in the lower reaches of the Yangtze River, it is inevitable to under-pass the embankment and the unevenly distributed soft soil layer, which greatly increases the risk of construction. Based on the background of diversion tunnel project of ultra-supercritical generating units for an electric plant in the south of Jiangsu province, a three-dimensional FEM study is carried out to simulate the slurry tunneling across the embankment of the Yangtze River and the unevenly distributed soft soil. The result of simulation shows that the setting rate surged when the slurry shield drove to the soft soil layer under the embankment. To solve the settlement problem in the process of slurry shield passing through the embankment, measures for controlling the slurry driving parameters, such as slurry pressure and grouting pressure, are proposed so as to reduce the risks and insure safety of the embankment.

Keywords: *slurry shield; embankment; soft soil; construction control*

1. Introduction

With the increasing use of ultra- supercritical units in the downstream of Yangtze River, slurry shield has been more and more used in diversion tunnel construction projects. To build cross-river tunnel in the lower reaches of the Yangtze River, it is inevitable to under-pass the embankment and the unevenly distributed soft soil layer. Because soft soil is sensitive to deformation and possess low shear strength, their use may lead to structural damage during construction and throughout the life of a project [1]. So, one issue of great concern is how to protect the embankments against severe damage from shield tunneling [2].

The mechanism of ground settlement during shield tunneling is extensively studied in the field of engineering. In 1969, Peck proposed the concept of stratum loss on the basis of a large amount of measured data of ground settlement caused by engineering construction [3]. Stratum loss describes a situation equivalent to the removal of soil mass due to shield tunneling. Many scholars tend to believe that ground settlement during shield tunneling is the result of combined factors.

In tunnel construction, excavation unloading results in disruption of original stress balance, which further leads to the generation of excess hydrostatic pressure in the soil mass surrounding the tunnel. As this pressure is dissipated, the stratum will undergo drainage consolidation and deformation and hence settlement. Since the soil mass is disturbed, the soil skeleton experiences persistent compressive deformation, which is known as soil creepage. The reconsolidation and creepage of remodeled soil subjected to disturbance or shear failure are also part of the stratum loss. That is, stratum loss consists of two parts. One is stratum loss without drainage, which is related to the process immediately after shield tunneling or tunnel excavation; the other is the stratum loss caused by soil consolidation and creepage.

The major factors of ground settlement include shield type, shield tunneling parameters (tunneling force and speed, rotation speed of cutter head and screw conveyor, slurry pressure); soil properties and groundwater table distribution; burial depth of tunnel and underlying load; geometric size of tunnel and lining size. Among them, soil properties and groundwater table distribution are important factors and constant after site selection. However, tunneling parameters can be changed depending on the circumstances. As the shield crosses the embankment, the water and soil pressure at the excavation face will change dynamically due to overloading from the embankment.

As the cutting ring of the shield approaches the embankment, the slurry pressure reaches the maximum. If this pressure cannot be adjusted timely with the water and soil pressure, soil mass failure will take place, leading to substantial ground settlement. If the shield passes through the soil layer with non-uniform hardness, the tunneling force and torsional moment will change dramatically. The shield machine will deviate towards the softer side of the soil layer, leading to a change of tunneling direction.

For different soil properties, construction conditions and demands, shield tunneling parameters should be changed and optimized so as to ensure the stability of the excavation face and reduce disturbance to the soil mass. Controlling settlement and ensuring safety of the embankment are the priorities in the tunneling project.

2. Project overview and geological conditions:

2.1. Engineering background:

The tunnels were designed as double horizontally parallel lines (tunnel of the west line and tunnel of the east line). The distance between two axial lines of the two tunnels is 21.6 m. The total length of both tunnels is approximately 945 m. The length of the section under the land is 75 m, and the length of the rest of the section under the Yangtze River is 870 m. Shield-driven tunneling method was adopted for construction. The introduction shaft of the shield tunnel is 25 m away from the Yangtze River embankment. The inside and outside diameters of tunnels are 4.2m and 4.8m respectively, the thickness of segment is 0.3m.

2.2. Geological conditions:

According to the geotechnical investigation reports, the strata in the study site are all Quaternary sediments. The foundation mainly consists of silty clay and sandy layers which divided into several sub-layers. The diversion tunnel is located in the river bed where soft clay, silt, silty sand and fine sand are interbedded. The strata are softer in the upper part and harder in the lower part, with obvious non-uniformity of stratum thickness. The strata distribution is as follows: (1) silty sand interbedded with silt, in gray to steel gray, with high saturation and mild compactness; (2) muddy silty clay, in gray color, soft plastic, with non-uniform soil properties; (3) silty clay interbedded with silty sand: in gray color, very moist, soft plastic to moldable, with non-uniform soil properties and containing humus, argillaceous nuclei and air holes, local shallow gas pool (biogas); (4) silt: in gray color, with non-uniform soil properties, moderate compactness, very moist, containing mica, interbedded with silty sand and thin-layer silty clay; (5) silty clay: in gray color, non-uniform, moderate to high compactness, containing moderately coarse sand locally. At the initial stage of shield tunneling (across the embankment), the shield first passes through (1) silt sand interbedded with silt, then through (2) muddy silty clay: The cross-sectional view of strata crossed by shield tunneling in shown in Fig. 1.

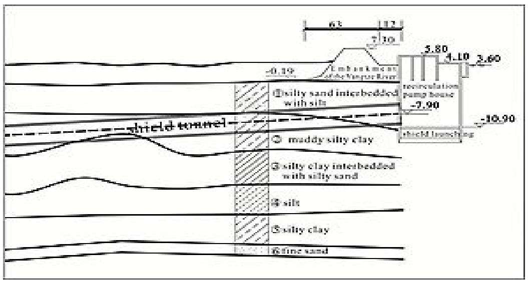

***Figure 1**. Sectional view of strata crossed by shield tunneling*

3. Building of 3D FE model:

Plaxis3D software is used for the 3D finite element analysis (FEA) of deformation of non-uniform hardness soil below the embankment under shield tunneling. Development in Holland, Plaxis3D is specialized for 3D FEA of deformation and stability problems in geotechnical engineering. It can be applied to the projects of foundation excavation and tunnel excavation, especially in soft soils.

3.1. Computational model:

Due to symmetry, only one half of the structure is modeled. To eliminate the boundary effect in model calculation, the computation domain dimension X×Y×Z is 40m×144.5m×47.9m, where Y is the tunneling direction; X is the direction perpendicular to Y within the plane; Z is the direction of soil thickness. The embankment is constructed with plain fill, with height of 7.2m; the width of the upper and lower embankment is 30m and 75m, respectively, and the soil thickness is 40m. The center of the tunnel is located at -7.9m; the outer diameter of the tunnel is 4.8m, and the inner diameter 4.2m. The length of the shield machine is 5.4m. The total tunneling distance is 77.4m, with one excavation face at every 0.9m. Thus there are a total of 86 excavation faces, as shown in Fig. 2.

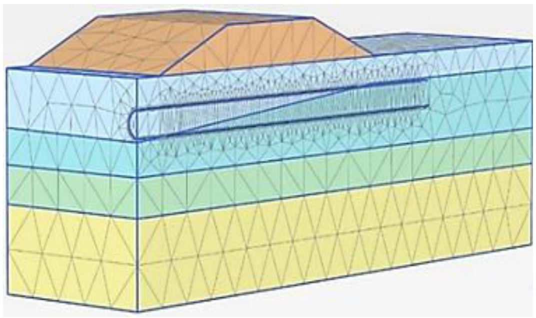

***Figure 2**. 3-D FE model*

3.2. Material model:

The model consists of five layers of soil, and the embankment is constructed with plain fill. Below the embankment, the soil layer in the computational domain is simplified into four layers of soil: silty sand interbedded with silt, muddy silty clay, silty clay interbedded with silty sand, and silt. The plasticity of soil mass is described by the Mohr-Coulomb law. The lining is made of reinforced concrete, which is linear plastic material. The shield machine is treated as plate element, with linearity and isotropicity. The shield has a micro-cone structure and the section shrinkage is set as 0.5%. The material parameters of the model are shown in Table 1.

***Table 1.** Parameters of model*

Material		Thickness (m)	Gravity density (kN/m3)	Young's modulus (kN/m2)	Poisson's ratio	Cohesion (kPa)	Angle of friction ()
Soil	Plain fill	7.2	18.3	12E03	0.4	9.5	24.4

layer	Silty sand interbedded with silt	7.9-12.7	19.1	35E03	0.25	6	30
	muddy Silty clay	6.5-11.3	18.2	15E03	0.45	9.8	19.9
	Silty clay interbedded with silty sand	6.5	18.3	16.4E03	0.35	9.5	24.4
	Silt	16	18.7	31.74E03	0.35	5.4	29.8
Lining	concrete	0.3	120	3.1 E07	0.18		

3.3. Simulation based on FE model:

After mesh generation, the initial crustal stress balance is imposed. For every tunneling by one step, a distance of 0.9m is excavated. The construction process is simulated as follows: freeze the soil mass under excavation and apply stress to tunnel face → activate the lining and apply force provided by the hoisting jack → activate the grouting pressure → repeat the above steps until the excavation is over. The vertical displacement nephogram below the embankment crossed by shield tunneling is shown in Fig. 3.

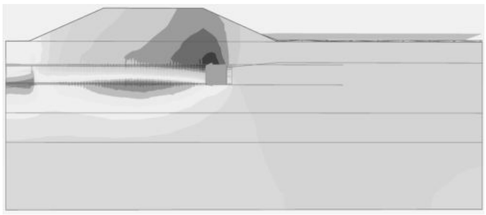

Figure 3. *Vertical displacement nephogram*

4. Simulation result analysis:

4.1. Analysis of ground settlement of the embankment:

Three representative positions, A, B and C, are selected at the top of embankment. A and C are located at embankment shoulder and B at the central axis of the embankment. Fig. 4 is the sectional view of the model.

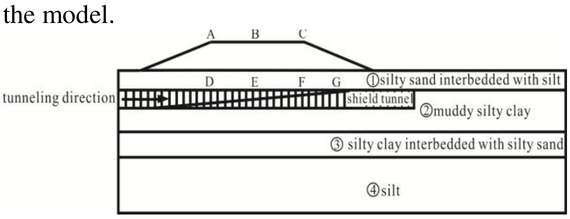

Figure 4. *Sectional view of model*

Fig. 5 shows the variation of settlement at three positions with excavation. All three curves are asymmetric parabolas. Along with shield tunneling, the settlement at the top of the embankment increases. When the shield tail passes through the cross section, the settlement at the three positions reaches the maximum. As the shield tail leaves, the settlement gradually decreases.

As shown in Fig. 5, the settlement of position B is larger than that of position A, and the settlement of position C is slightly larger than that of position B. According to the distribution pattern of superimposed stress under embankment loading, the superimposed stress acting on the soil mass below B is the largest, leading to greater settlement of B than A.

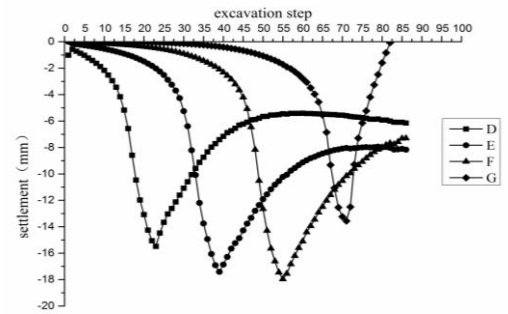

Figure 5. *Ground settlement of embankment*

As the shield moves from the position below B to below C, the lithology changes from silty sand interbedded with silt to muddy silty clay. Below C, shield machine is largely surrounded by silty clay, which is soft and has low strength, high compressibility and poor engineering properties. Thus the soil undergoes substantial deformation due to excavation unloading. That is why the settlement of C is larger than that of B. Moreover, as seen from curve C, the settlement increases abruptly when the shield advances to the position below C (56 steps of excavation). Due to combined action of stratum loss and soft soil layer, the abrupt settlement changes at C can lead to cracking of the embankment, threatening the stability. Therefore, the section from B to C is the major region of adjustment of slurry shield tunneling parameters for reducing non-uniform settlement.

4.2. Analysis of tunnel settlement:

To analyze the deformation of tunnel during shield tunneling, 4 representative positions (D, E, F and G) are selected in the soil mass above the tunnel. D and F are located below embankment shoulders on the two sides; E is located at the central axis of the top of the embankment; G is located below the mid-point of the slope. Fig. 6 shows the settlement variation of the 4 positions in soil mass above the tunnel due to excavation. Along with shield tunneling, the settlement of the soil mass around the tunnel increases. As the shield tail leaves the cross section, the tunnel settlement decreases gradually. Due to combined effect of embankment overloading and soft soil layer, the settlement rates at the four positions obviously increase with tunneling. Similar to the settlement variation of the top of embankment, the settlement of position E is greater than that of position D, while the settlement of F is slightly higher than that of E. Overloading at G is smaller than that at D, E and F, resulting in smaller settlement. Under the action of grouting pressure, the soil mass bulges out. Therefore, embankment overloading has a non-negligible impact on the tunnel. Tunneling parameters should be adjusted timely according to the amount of overloading and properties of the soil layer, so as to prevent dislocation of tunnel segment due to excess tunnel settlement.

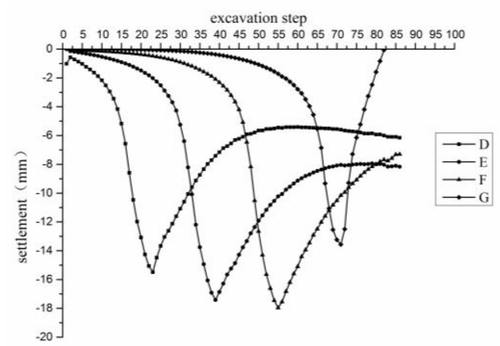

***Figure 6**. Settlement of tunnel*

5. Control of shield tunneling parameters:

Numerical simulation shows that when the shield passes under the embankment, non-uniform settlement takes place in the surrounding strata and the embankment due to embankment overloading and the non-uniform soil layers under the embankment. Adjustment of tunneling parameters and other measures in real-time is necessary to ensure safety and stability and to reduce non-uniform settlement of strata and embankment [4].

5.1. Slurry pressure:

Slurry pressure is an important tunneling parameter. Slurry pressure at the cutting ring of the shield directly determines the stability of the excavation face. If the slurry pressure is too small, the instability of the excavation face will occur, leading to large strata displacement; if the slurry pressure is too large, the strata will split, leading to collapse and reflux of river water [5].

When the shield passes across the embankment, the slurry pressure should be determined with consideration of embankment overloading. Using the formula for calculating the upper and lower limit of slurry pressure, the lower limit of slurry pressure is obtained [6]:

$$P_{fl} = P_1 + P_2 + P_3 + P_4 = \gamma_w h + K_a\left[(\gamma - \gamma_w)h + \gamma(H-h)\right] - 2c\sqrt{K_a} + 20 + K_a\sigma_{az|z=7.9} \quad (1)$$

Where, P_{fu} is the lower limit of slurry pressure at the cutting ring of shield (kPa); P_1, P_2, P_3, P_4 are pore water stress in the strata of the excavation face, earth pressure acting horizontally on the excavation face, preload (20-30 kN/m^3) based on consideration of error and fluctuation of slurry pressure, and the sum of horizontal superimposed stress acting on the four positions due to embankment overloading, respectively. K_a is coefficient of active earth pressure; γ and γ_w are gravity densities (kN/m^3) of earth and water, respectively;   is cohesion; $\sigma_{az|z=7.9}$ is vertical superimposed stress (kPa) due to embankment loading at

Upper limit of slurry pressure is given by,

$$P_{fu} = P_1 + P_2 + P_3 + P_4 = \gamma_w h + K_0\left[(\gamma - \gamma_w)h + \gamma(H-h)\right] + 20 + K_0\sigma_{az|z=7.9} \quad (2)$$

Where, Pfu is the upper limit of slurry pressure at the cutting ring of shield (kPa); K_0 is coefficient of earth pressure at rest.

Using formula (1) and (2), the upper and lower limits of slurry pressure in silty sand interbedded with silt and in muddy silty clay are calculated, respectively, as shown in Fig. 7 (the origin of x axis corresponds to the central axis of embankment bottom).

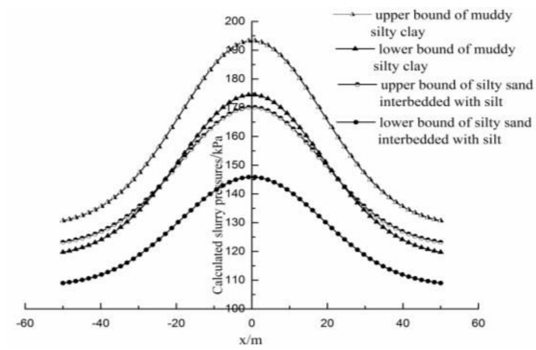

***Figure 7.** Calculated slurry pressures*

According to Fig. 7, slurry pressure shows a parabolic distribution, taking the central axis of embankment as the axis of symmetry. The upper and lower limits of slurry pressure in the muddy silty clay are higher than those of shield in the silty sand interbedded with silt. As the cutting ring of the sheath passes from foot to top of the embankment, the calculated slurry pressure increases gradually until reaching the maximum at the central axis of embankment. When the cutting ring of the shield passes through the section below the top of the embankment, the cutting ring leaves the layer of silty sand interbedded with silt and enters the layer of muddy silty clay, leading to a gradual increase of slurry pressure. As the cutting ring of the shield passes from top to foot of the embankment, the slurry pressure decreases mildly. After entering the layer of silty sand interbedded with silt, the clay, slurry and groundwater are easy to agglomerate and stick to the cutter head. This may cause blockage of slurry warehouse and slurry pump. Increasing the slurry pressure can improve the ability of slurry in carrying away the clods.

5.2. Grouting pressure:

Synchronized grouting should be performed immediately after the lining is assembled, so as to fill up the spaces of the structure [7]. After the shield passes, secondary grouting is performed for the soil mass around the lining to consolidate the soil mass. If the grouting pressure is too small, the soil mass will settle considerably; if it is too large, the soil mass may be destroyed, causing the strata to bulge out, which is detrimental to embankment stability. FE simulation indicates that when the shield passes below the embankment and the lithology transition area, the grouting pressure and grouting amount should be increased to reduce strata deformation. The grouting parameters should be adjusted constantly to ensure proper grouting.

5.3. Tunneling speed:

While ensuring the stability of the excavation face, properly increasing the tunneling speed can reduce the time of shield staying below the embankment and thus the embankment settlement caused by the weight of shield [8]. As the shield passes through the region of non-uniform thickness of overlying soil and the region transiting from lithology of silty sand interbedded with silt to muddy silty clay, the shield should be kept in dynamic equilibrium. The excavation movement of the shield must be gentle in deformation-sensitive regions. Real-time monitoring is necessary to avoid intense disturbance to the strata caused by the fluctuating tunneling speed.

6. Conclusion:

Diversion tunnel of ultra-supercritical generating units for an electric plant in the south of Jiangsu province is studied by numerical simulation using Plaxis3D. As the shield passes through the non-uniform soft soil layers, the effect of tunneling parameters on embankment settlement is discussed. The following conclusions are obtained:

(1) Representative positions are selected on the tunnel and the embankment. As the shield advances, the settlement of soil mass around the tunnel and the settlement of the top of the embankment increase gradually. The settlement decreases as the shield leaves. The settlement at the central axis of the embankment is larger than the settlement at the embankment shoulder. When the shield passes through the lithology transition region, the soil mass around the tunnel shows an increasing settlement and the settlement of the embankment top changes abruptly.

(2) The upper and lower limits of slurry pressure in muddy silty clay and silty sand interbedded with silt are calculated. The slurry pressure shows a parabolic distribution pattern with the central axis of embankment as the symmetry axis. The maximum pressure occurs near the central axis of embankment. The upper and lower limits of slurry pressure in the muddy silty clay are both higher than the pressure in silty sand interbedded with silt.

(3) When the shield passes through the region of non-uniform thickness of overlying soil and the region of lithology transition, the tunneling parameters (slurry pressure, grouting pressure and tunneling speed) should be adapted to reduce disturbance to the embankment. As the cutting ring of shield passes from foot to top of the embankment and through the region of lithology transition below the top of the embankment, the slurry pressure should be increased to ensure stability of the excavation face. In the meantime, synchronized grouting should be performed during tunneling at proper pressure and amount. While ensuring the stability of the excavation face, the tunneling speed should be decreased to reduce the time of shield staying below the embankment. The shield should be kept in dynamic equilibrium during tunneling.

7. Acknowledgements:

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References:

[1] Kempfert H, Gebreselassie B (2006) Excavations and Foundations in SoftSoils. Springer-Verlag, Berlin, Heidelberg, Germany.

[2] Lin CG, Wu SM, Xia TD. (2015) Design of shield tunnel lining taking fluctuations of river stage into account. Tunneling and Underground Space Technology 45:107–127.

[3] PECK R B. Deep excavations and tunneling in soft ground[C]// State of the art report. Proceedings of 7th International Conference on Soil Mechanics and Foundation Engineering. Mexico City: 1969: 225–290.

[4] Ding LY, Zhang LM, Wu XG et al .2014. Safety management in tunnel construction: Case study of Wuhan metro construction in China. Safety Science, 62, 8-15.

[5] Hu XD, Guo W, Zhang LY et al.2014.Application of liquid nitrogen freezing to recovery of a collapsed shield tunnel. Journal of Performance of Constructed Facilities, 28, 1-14.

[6] Wu SM, Lin CG, Zhang ZM et al.2011. Risk analysis and control for slurry shield under-passing embankment. Chinese Journal of Rock Mechanics and Engineering, 30(5): 1034-1042.

[7] Li XG; Chen XS .2012. Using grouting of shield tunneling to reduce settlements of overlying tunnels case study in Shenzhen metro construction. Journal of Construction Engineering and Management, 138, 574-584.

[8] Min FL, Zhu W, Lin C.2015.Opening the excavation chamber of the large-diameter size slurry shield: A case study in Nanjing Yangtze River Tunnel in China. Tunneling and Underground Space Technology, 46, 18-27.