

Research on Uplift Mechanism of Shield Tunnel Based on Multi-factor Construction Conditions

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Abstract: In order to investigate the influence degree of each factor on tube sheet uplift and tube sheet uplift law of shield tunneling, this thesis takes the background of Zhengzhou Railway Transit Line 6 Phase I Project Weizhuang Station ~ Cargo Station Street Station Interval Project, and establishes ABAQUS finite element numerical model based on the influence factors such as shield thrust, slurry density, grouting pressure, etc., and analyzes the interaction relationship between the influence factors of tube sheet uplift caused by the shield tunneling construction period. The paper investigates the uplift law of tube sheet and the mechanism of influencing factors during the construction period of shield tunnel, and obtains the relationship between grouting pressure and tube sheet uplift, jack thrust and slurry density and tube sheet uplift under the influence of a single factor; the thesis also discovers the location of the maximum uplift and the basic law, as well as the basic range of the uplift and the reduction of the uplift value in the late stage through the comprehensive analysis and calculation of the uplift and the influencing factors under different working conditions. The paper also finds out the location and basic law of the maximum uplift of the tube sheet under different working conditions, and the basic range of the downsizing value of the uplift in the later stage.

Keywords: Shield tunnel; tube sheet uplift; grouting pressure; numerical simulation.

1. Introduction

The segment floating refers to the phenomenon of the segment floating upward for various reasons in the process of shield tunneling. In shield construction, the segment floating situation is not uncommon, which is affected by engineering geology and hydrogeological conditions, technical characteristics of shield tunneling, synchronous grouting technology, shield attitude control and other factors. The floating of the segment will produce shear stress on the end surface of the segment, causing the error, cracking, damage and water leakage of the segment, and reducing the compressive strength and impermeability of the segment structure.

In recent years, many scholars, relying on the specific engineering background, have used field test, numerical simulation and other methods to study the floating mechanism and force characteristics of the segments, and achieved a lot of research results.

Fu Helin et al[1]With the help of numerical analysis means, relying on the Hengyang second ring Road Hejiang set Xiangjiang tunnel project, the shield tunnel construction seepage field, ground stress field, mud and grouting pressure and other factors are analyzed, clear the influence of each factor on the tunnel construction. Wei Gang et al[2]The force model and calculation formula of the lining ring in the floating stage are proposed, and the internal force calculation of the lining ring is carried out by using the modified conventional lining design theory, so that the dynamic buoyancy has the greatest influence on the force of the segment. Xiao Ming Ming et al[3]The properties of formation material and grouting material are analyzed by finite element method, and the countermeasures and measures of controlling the tube floating are proposed. Ye Fei et al[4]Starting from the calculation of the minimum thickness of the shield tunnel, it is proposed that the dynamic buoyancy of the grouting

pressure is the main reason for the floating of the shield tunnel construction. Based on the analysis of the floating mechanism of the segment, some suggestions are put forward for the floating control of the segment.

2. Engineering Background

2.1. Engineering geology

The tunnel between Weizhuang Station and Freight Station of Zhengzhou Metro Line 6 is constructed by soil pressure balance shield method. The tunnel mainly passes through the silty clay layer and silty layer, which is plastic ~ hard plastic state, which belongs to medium compressive soil; the silt sand is medium dense ~ dense state, which belongs to low compressive soil.

2.2. Pipe ping

Pipe piece outer diameter 6.2m, inner diameter 5.5m, thickness 350mm, width 1.5m, using reinforced concrete structure lining ring. The segments are assembled by misjoints, that is, composed of 6 pieces of 1 top block K (21.5°), 2 adjacent blocks B 1-B 2 (single core angle 68°) and 3 standard blocks A 1-A 3 (single core angle 67.5°), with a ring width of 1.5m, concrete strength grade C 50 and anti-permeability grade P 12. The segments are connected with curved bolts: 12 M 30 bolts and 16 M 30 bolts. The segments are shown in Figure 1.

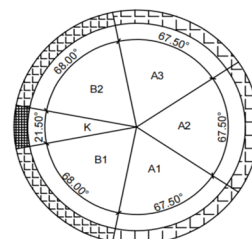


Figure 1. Piece block plot

3. Pipe Floating Influencing Factors Analysis and Working Condition Design

In order to clarify the influence of each factor on the floating of the segment, 10 sets of calculation conditions are

set. Among them, working condition 1 is considered as a control condition, and analyzed for each single factor, and the calculation condition is shown in Table 1.

In Table 1, working conditions 1-4 are slurry density; working conditions 5-7 are jack thrust; and working conditions 8~10 are grouting pressure

Table 1. Floating calculation condition table

Working condition number	Tunnel Diameter (m)	Lining Thickness (cm)	Concrete parameters	depth of burial (m)	Sout density (kg/m ³)	Chijacks thrust (Kn)	grouting pressure (Mpa)
1	6.2	35	C 50	20	1700	3000	0.2
2	6.2	35	C 50	20	1400	3000	0.2
3	6.2	35	C 50	20	2000	3000	0.2
4	6.2	35	C 50	20	2300	3000	0.2
5	6.2	35	C 50	20	1700	1000	0.2
6	6.2	35	C 50	20	1700	5000	0.2
7	6.2	35	C 50	20	1700	7000	0.2
8	6.2	35	C 50	20	1700	3000	0.1
9	6.2	35	C 50	20	1700	3000	0.3
10	6.2	35	C 50	20	1700	3000	0.4

4. Numerical Simulation of Tube Float Based on ABAQUS

To facilitate the calculation of finite element model and comparative analysis of different conditions, the following assumptions are made before numerical simulation:

4.1. Basic assumptions

Based on the soil pressure balance shield tunnel project between Weizhuang Station and Jiaozhan Street Station of Zhengzhou Metro Line 6, this paper adopts the numerical simulation method and establishes the numerical model of shield tunnel tunneling with Abaqus software.

(1) The thickness of the shield tunneling through the stratum and the surrounding soil is different, and there is no obvious regularity. In order to facilitate the modeling, the formation parameters are averaged within the depth range;

(2) The formation constitutive model adopts elastic and mole reservoir Lun plastic;

(3) Six rings of each ring are simplified into a whole, using a homogeneous circular ring model, set as isotropic;

(4) without considering the friction between the segments, the longitudinal and annular bolts;

(5) Suppose that the tunneling direction of the shield tunneling machine is the horizontal direction, and the change of slope and direction during the shield tunneling machine is not considered spend.

4.2. Model construction

(1) Model size

The segment model adopts thin-walled circular tubes with 25 rings, single ring length of 1.5m, total length of 37.5m, 6.2m, outer diameter of 5.5m, and segment wall thickness of 0.35m. The number is 1,2,..., 25 rings along the excavation direction. The average buried depth of tunnel axis is 20m, and the length of excavated soil unit is set to 1.5m; the formation model size is 50m×37.5m 40m (length, width and height); the shield machine adopts steel material, and the length of shield machine is 6m in the formation, the length of four ring segment; the grouting layer adopts thin-wall tube, the outer diameter is 6.6m, the inner diameter is 6.2m, and the thickness is 0.2m. The grouting layer, segment and stratum model all adopt 3D solid unit C 3D8R (eight-junction linear hexahedral unit), and the shield machine model adopts shell unit S 4R (thin shell with four-junction curved surface). The model has 45699 units and 51563 nodes.

(2) Coordinate system

In the modeling process, the X axis is set as the tunnel transverse, the Y axis is the tunnel longitudinal, and the Z axis is the vertical direction perpendicular to the axial direction of the tunnel.

(3) Material properties

In this model, there are four main materials: stratum, grouting layer, segment and shield machine. Among them, the parameters related to the stratum structure need to be obtained from the geological prospecting report of the construction site. The parameters of each stratum are shown in Table 2, and the parameters of the segment, grouting layer and shield machine are shown in Table 3.

Table 2. Table of related soil layer parameters

Formation type	modulus of elasticity / E (MPa)	severe / γ (kN · m ⁻³)	Poisson ratio μ	Cohesive force / C (kPa)	internal friction angle / ϕ (°)	osmotic coefficient / k(m/d)
silt	22	20	0.25	3	30	0.05
silty clay 10<	10.5	19.8	0.3	37.3	18.2	0.5
clayey silt	14.5	18.6	0.28	18.7	25	11

Table 3. Table of related material parameters

material	severe / $\gamma(\text{kN}\cdot\text{m}^{-3})$	modulus of elasticity / E (MPa)	Poisson ratio μ
duct piece	25	31050	0.2
Equal generation layer	20	20	0.32
shield tunneling machine	78.5	210000	0.3

(4) Finite element model construction

Based on the above selected parameters of each component and four types of units in the shield tunnel construction, the finite element model of the shield tunnel

construction is established. The grid diagram of stratum, segment, grouting layer and shield machine model are shown in Figure 5~8 respectively.

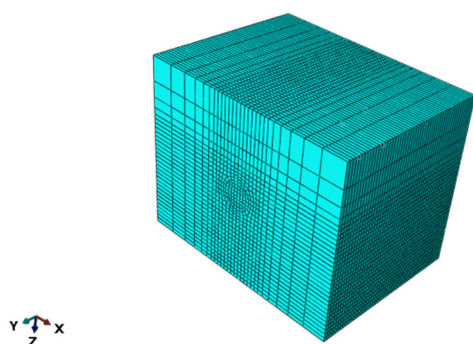


Figure 2. The Formation model

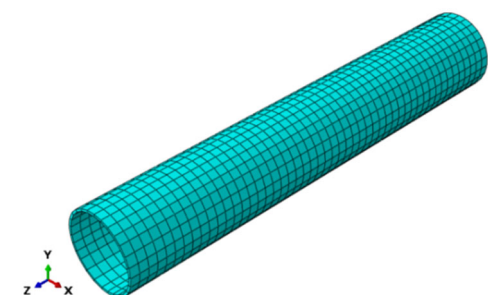


Figure 3. Injection grouting layer model

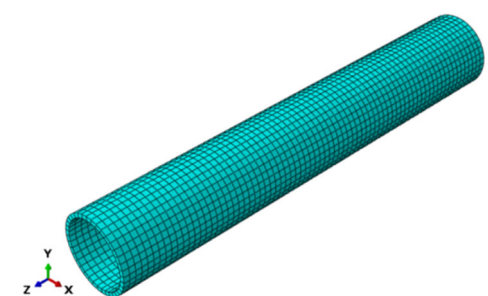


Figure 4. Pipe segment model

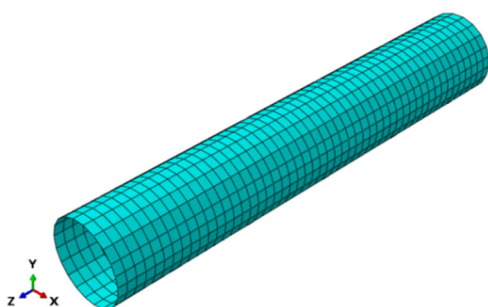


Figure 5. Shield tunneling machine model

4.3. Simulation process

Consider the influence of jack thrust and grouting pressure during shield tunneling. The grouting pressure is divided into the pressure of slurry to the surrounding soil layer and the pressure of slurry to the tube segment. The two kinds of grouting pressure are equal, which are respectively placed on the inner surface of the soil layer and the outer surface of the segment, that is, the grouting pressure on the upper and lower outer surface of the segment is equal, and there is no grouting pressure difference on the upper and lower outer surfaces. The jack thrust is uniformly applied on the torus of the segment. The jack thrust on the upper and lower outer surfaces of the segment is equal, and there is no reasoning difference on the upper and lower outer surfaces.

During the simulated excavation process, the "life and death" unit method is used to simulate the excavation. First, the removal command is used to delete the soil unit in front of the shield machine, and the soil unit is "killed". Then, the activation command is used to activate the shield machine unit in this position, that is, the position is replaced by the shield head ring. Subsequently, the removal command is used to delete the shield tail ring unit, that is, the shield tail ring is "killed", and the activation command is used to activate the segment unit and the shield tail ring unit, and apply the load and boundary conditions of the corresponding position. According to this method, the shield is calculated through the stratum, and finally the displacement and stress of soil layer and segments are obtained.

5. Analysis of the Numerical Simulation Results

The finite element model is adopted to analyze the floating situation of the segment under different working conditions, extract the floating amount and maximum floating amount of the segment, and then study the mechanism of slurry density, jack thrust and grouting pressure on the tube floating and the floating rule of the segment during the construction period.

5.1. Influence of slurry density on the floating of tube segment

In order to study the influence of slurry density on the floating of the segment, the slurry density is 1400 kg/m^3 , 1700 kg/m^3 , 2000 kg/m^3 and 2300 kg/m^3 respectively (corresponding to conditions 1 and 2~4 in Table 3), and the floating development curve of the segment is shown in Figure 6. As can be seen from the figure, under different slurry density, the development law of the tube float is the same, the maximum float occurs at 18 rings from the shield tail, and the maximum float is 16.44mm, 17.61mm, 19.12mm, 20.63mm. The main reason is that when the grouting pressure and the jack thrust are unchanged, the increase of the slurry density leads to the increase of the slurry buoyancy, so the floating amount of the segment increases.

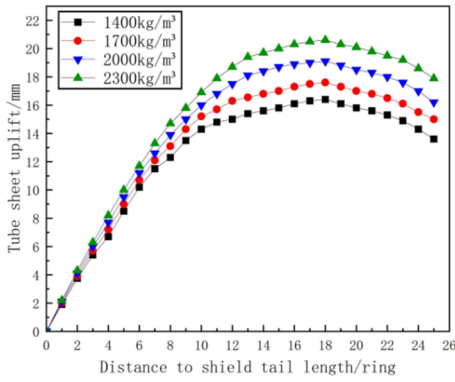


Figure 6. Development curve of tube segment float under different slurry densities

Further finishing, the relationship between the maximum floating amount of the segment and the slurry density was obtained, as shown in Figure 7. According to the data in the figure, every 100 kg/m³ increase in the mean slurry density increased by 0.47mm. It can be obtained that the serious density has little influence on the floating amount of the segment.

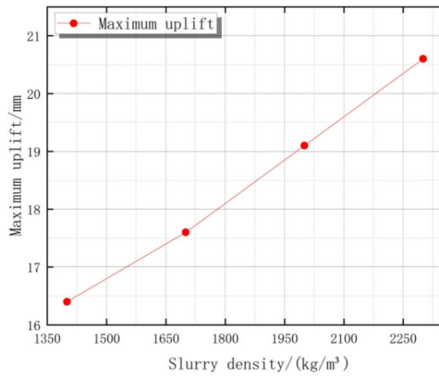


Figure 7. Maximum floating float and slurry density

5.2. Effect of jack thrust on tube floating

In this paper, the tunneling direction of the shield machine is horizontal, and there is no slope change in the tunneling process of the shield machine, and the jack thrust of the upper and lower sections of the segment is the same. The thrust of the jack is 1000、3000、5000 and 7000 kN respectively (corresponding to working condition 1 and 5~7 in Table 3). During the simulation, the jack thrust is equivalent to the uniform distribution load applied on the segment torus. After calculation, the thrust of the jack is 0.156Mpa, 0.467Mpa, 0.778Mpa and 1.090 Mpa, respectively. The calculated results are shown in Figure 8.

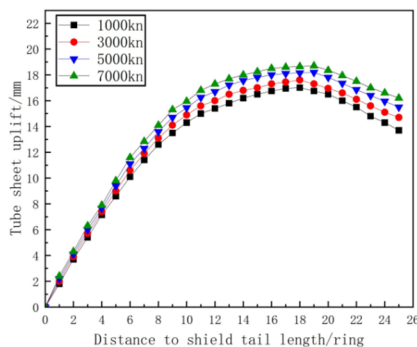


Figure 8. Development curve of lower segment float under different jack thrust

As can be seen from the figure, under the action of different jack thrust, the development trend of the segment floating amount is basically the same. With the increase of the jack thrust, the maximum floating amount of the segment is slightly backward. The maximum floating amount is 171mm, 17.61mm, 18.23mm, 18.75mm, respectively..0

Further arrange the maximum floating float and the jack thrust, as shown in Figure 9. According to the data in the figure, for every 1000 kn increase, the maximum float of the jack thrust increases by 0.28mm. It can be found that the influence of the jack thrust on the shield tunnel segment is not significant.

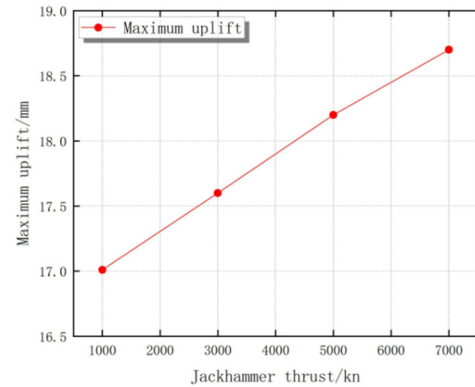


Figure 9. The relationship between the jack thrust and the floating amount of the tube piece

5.3. Influence of grouting pressure on tube floating

In the simulation process, the same application method is adopted as the jack thrust, that is, the average distribution load is used instead of the grouting pressure, and the solidified slurry is replaced by the equal replacement layer after the grouting pressure is removed. The grouting pressure is 0.1Mpa, 0.2Mpa, 0.3Mpa and 0.4 Mpa respectively (corresponding to working conditions 1 and 8 to 10 in Table 3), and the calculation results are shown in Figure 10.

From the figure, the tube float maximum 13.55mm, 17.61mm, 24.65mm, 29.33mm respectively, respectively in the shield tail ring 19,18,17,17 ring position, thus, the grouting pressure on the maximum float is significant, the tube grouting amount and grouting pressure, and with the increase of the value, the float peak will be closer to the shield tail.

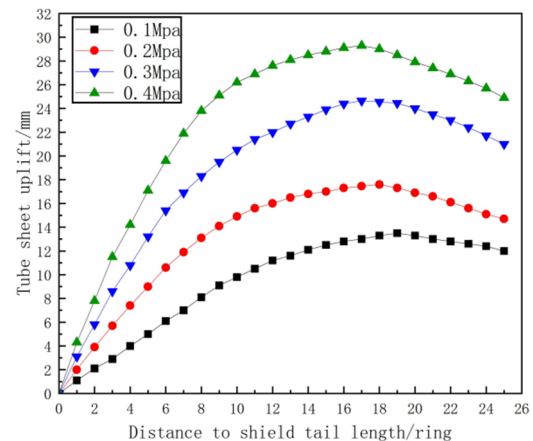


Figure 10. Development curve of tube segment float under different grouting pressures

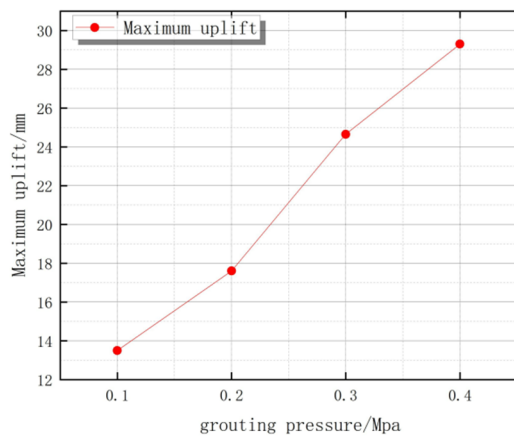


Figure 11. Relationship between grouting pressure and tube floating volume

Further finishing, the relationship diagram between the maximum floating amount of the segment and the grouting pressure is obtained, as shown in Figure 11. According to the data in the figure, the average grouting pressure increases by 0.1 Mpa by 5.3mm. The grouting pressure has a significant influence on the floating volume of the segment.

6. Summary

Through the finite element model, the mechanism of the slurry density and the jack thrust grouting pressure on the segment floating is analyzed, and the development law of the shield tunnel segment floating during the construction period and the mechanism of the influencing factors are proved. The main conclusions are as follows:

(1) Under the same geological conditions, the slurry density, the increased thrust and the grouting pressure, the jack increase, the jack thrust, the slurry density and the grouting pressure, the larger grouting pressure, the slurry density and the unchanged jack thrust will aggravate the floating of the segment during the shield tunnel construction period.

(2) Under different working conditions, the floating development trend of segments is basically the same. With the increase of the number of rings from the shield tail, the floating speed of segments changes from fast to slow, and the floating speed of segments gradually decreases after reaching the maximum value. The maximum floating amount of the segment is mainly located at the ring 17,18 and 19 from the shield tail.

(3) The greater the floating amount of the segment, the greater the extrusion degree of the oversoil, the greater the elastic deformation of the oversoil, the greater the rebound amount of the oversoil, and the greater the subsequent reduction value of the floating amount of the segment. Under each working condition, the maximum reduction value of the segment float is 4.4mm and the minimum is 1.1mm.

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