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Rolling-induced inner force in lining of DOT shield tunnel

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ABSTRACT: Double-O-Tube (DOT) shield machine is more likely to roll during DOT tunnel construction and rolling correction operation is always conducted during construction. The inner force in lining will be changed during the process of rolling correction. In this paper, finite element method is adopted to analyze the inner force in lining caused by rolling correction during construction. The results indicated that it is much different between the inner forces in lining by considering rolling correction operation or not. With the rolling angle increasing, the inner force in some point increases and in some other points decrease. Therefore, the reasonable design is that the redistribution of inner force in lining during construction should be considered.

1 INTRODUCTION

There are a lot of disadvantages for the single circular shield tunnel (SCST) method, such as: *i*) occupying much underground space, *ii*) requiring high construction cost, and *iii*) needing long construction period, etc. For this reason, an idea to construct two tunnels using one shield machine simultaneously was proposed in Japan in the early 1980s, which is called Double-O-Tube (DOT) shield tunneling method. In 1989, DOT technology was firstly applied in a practical tunnel project in Hiroshima (RANSTT, 1998). The design method for the lining of DOT tunnel follows that for the SCST, in which the load on the lining is considered symmetrically distributed at the both sides of tunnel central line and the inner forces on the lining of both sides is considered to be the same. However, during shield excavation, the shield machine will move in yawing, pitching, and rolling actions and direction correction operation is always performed. Rolling will change the symmetric condition of the cross section of DOT tunnel. Therefore, rolling correction should be conducted from time to time in construction. The rolling correction operation is to make the shield and/or tunnel to roll inversely by applying a correcting moment through grouting or something else. Thus, additional loading will act on the lining of DOT tunnel. In the conventional design method of the DOT tunnel, the rolling correction induced-load on the lining is not considered (RANSTT, 1998; Yuan et al, 2005). Hence, the design may be not safe. In this paper the inner force in lining caused by rolling correction operation is investigated using finite element method (FEM).

2 MECHANISMS OF ROLLING

The rolling in DOT shield construction are unavoidable because: *i*) Asymmetry of the cross section of DOT shield machine caused by manufacturing error; *ii*) non-balanced weight at the both sides of the DOT shield machine; *iii*) difference of the traction force of the trolley at the both sides; *iv*) difference of torques of the both cutter-disks due to the different soil properties at the two sides and the different pressure in the chamber at both sides; *v*) different earth loads due to the different hypsography such as cliff or aslant at the two sides; *vi*) lose of the real-time grouted slurry at the tail. In addition, the different supporting position of belt conveyor may also cause rolling. During DOT tunnel construction, the rolling is needed due to one or the combination of several of the aforementioned reasons.

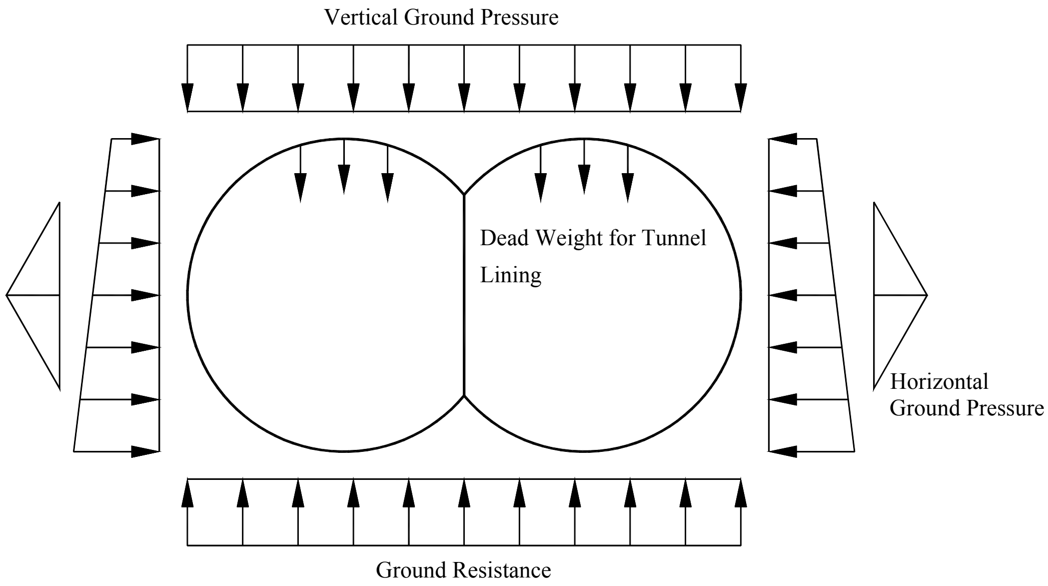


Fig.1 Design model for tunnel lining

3 DESIGN MODEL FOR TUNNEL LINING

After the design model for the lining of circular shield tunnel lining was proposed by Hewett and Johason (1922), in which elastic reaction was initially considered, many new design methods have been proposed, including link-rod model (Guan, 1993), modified routine method, and beam-spring model (Kubo, 1968) etc. All of the aforementioned models can be also applied in the DOT tunnel design. The modified routine method is generally employed in many countries. The modified routine method (MRM) is derived from routine method and its basic assumption is that the lining is a ring whose bending stiffness is uniform. In MRM, the decrease of the bending stiffness at the joint is considered as the decrease of the ring, that is to say, the equivalent stiffness is ηEI (η is equivalent stiffness factor and $\eta \leq 1$). In addition, factor ζ (rate of bending moment increase) is adopted in calculating bending moment at the joint. $(1+\zeta)M_0$ is adopted as the main moment for segment and $(1-\zeta)M_0$ is taken as the design moment of the joint. The key of MRM is how to determine two factors η and ζ. In the present design approach of DOT tunnel as shown in Figure 1, external forces are vertical and horizontal earth pressure, gravity of tunnel lining, vertical and horizontal reaction force (RANSTT, 1998; Yuan et al, 2005). However, rolling-correction-induced load (RCIL) is not taken into consideration in the present design approach. The effect of RCIL on the behavior of DOT tunnel lining is discussed in the following sections.

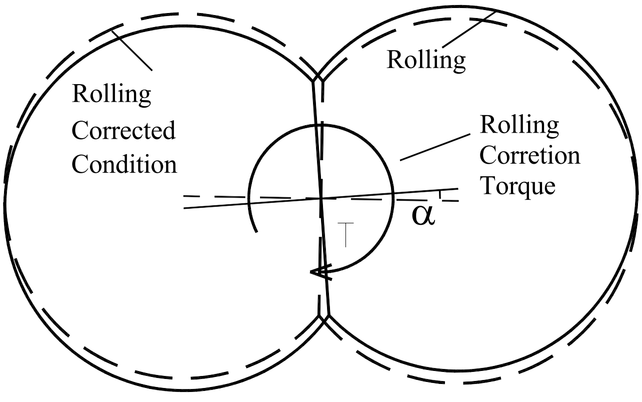


Fig.2 Rolling correcting torque on tunnel lining

4 MODELING APPROACHES

The rolling correction operations such as single side loading, secondly grouting, opposite rotating of cutter disks will induce a torque to tunnel lining and/or shield machine, as shown in Figure 2, resulting in additional inner forces in the tunnel lining. The inner forces are calculated using FEM analysis. An initial rolling angle ranging from 0° to 3.2° is assumed to set the rolled mode of the DOT tunnel. Then, the inner forces are calculated via applying an inverse torque on the lining with the opposite direction of rolling.

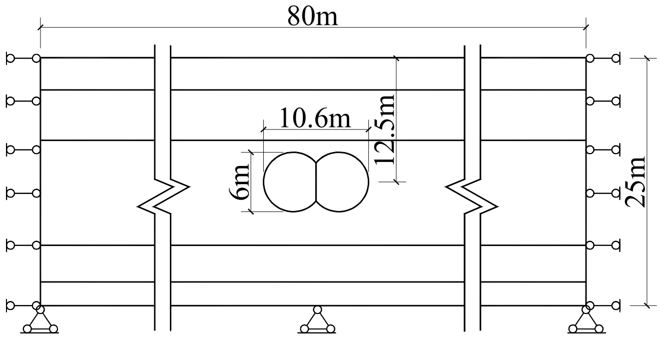


Fig.3 Calculation model for rolling correction of DOT tunnel

4.1 Range of Calculation

To simplify the calculation, plain-strain condition is adopted to calculate the inner force change in the lining due to rolling correction. Figure 3 depicts the calculation model. The calculation range was set up as follows: the diameter of the DOT shield is 6 m; the centre-to-centre distance between the two tunnels is 4.6 m; the depth of the centreline of the rings is 12.5 m; the bottom boundary is 12.5 m under the centreline (see Figure 3). The side boundaries are 40 m far away from the centre of the tunnel.

4.2 Initial and Boundary Conditions

The initial conditions include the initial pore water pressure and the initial earth pressure. Groundwater located at 1.5 m below the ground surface, which is used to calculate magnitude of the pore water pressure. Vertical effective stress is determined from the gravity and pore pressure. Lateral effective earth pressure is determined as vertical effective stress multiplying the coefficient of lateral earth pressure K_0.

The boundary conditions are set of as: inside the lining, it is a free boundary; at two-side boundaries, the horizontal displacements are constrained; and at the bottom, both horizontal and vertical displacements are constrained.

Table 1 Parameters of each soil layer

Earth Layer	Thickness (m)	Water Content. (%)	γt (kN/m^3)	K_0	Γ	λ	κ	M
Filling	3.2	11.1	20	0.55	2.34	0.12	0.024	0.8
Silt	5.1	43.7	17.6	0.5	3.29	0.20	0.044	1
Soft Clay	10.6	49.1	17.0	0.5	3.84	0.28	0.056	0.8
Clay	3.7	36.1	18.1	0.5	3.08	0.20	0.040	1
Silty Clay	2.4	33.6	18.3	0.5	3.02	0.20	0.040	1

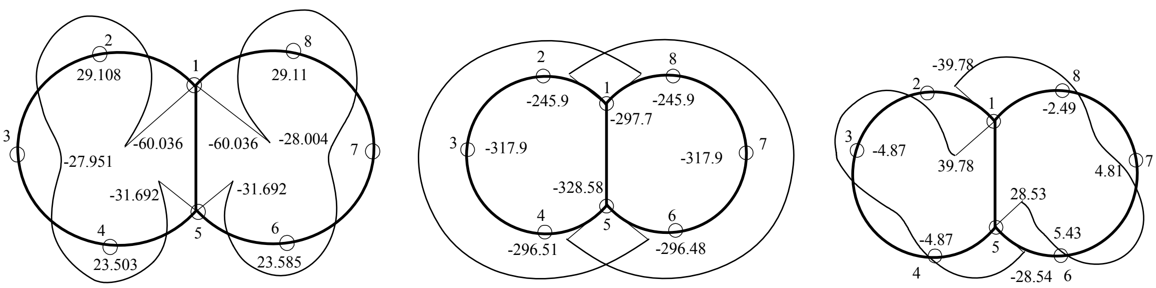
4.3 Parameters

In the calculation, the soft subsoils are divided into 5 layers, as tabulated in Table 1. Modified Cam-Clay model is used to simulate the stress-strain relation of the soft soils. The parameters of each layer are shown in Table 1. λ, κ, K_0 were obtained from consolidation test (Please mention how to determine K_0 from odeometer test) and M was obtained from triaxial test; and Poisson's ratio was determined based on the experience. The lining is assumed as the elastic material: its stiffness EI=1.23×10^5 kN/m; EA=1.21×10^7 kN-m^2/m; equivalent thickness is 0.35 m; gravitation load strength of tunnel lining is 8.4 kN/m; Poisson's ratio ν= 0.15.

5 RESULTS AND DISCUSSIONS

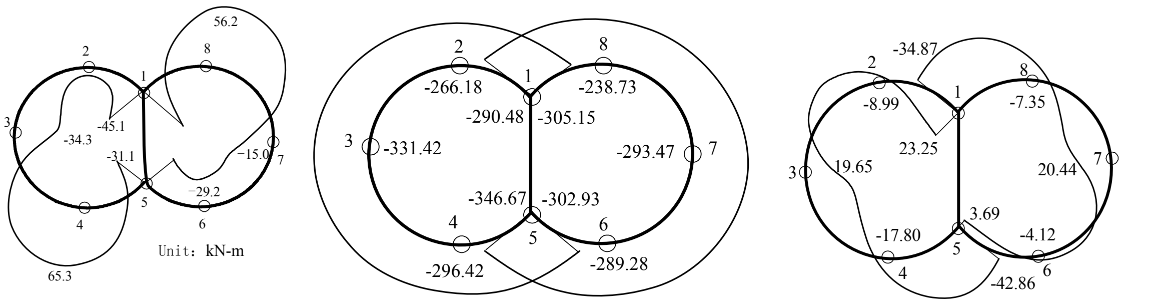
5.1 Inner Forces Caused by Rolling-Correction Load

Figure 4 illustrates the moment, the axial force, and the shear force in DOT tunnel lining without rolling-correction load. As shown in the figure, the maximum controlling inner forces in the lining are: moments M_{max}=-62.2 kN-m, axial force N_{max}=-327.73 kN, and shear force Q_{max}=-40.67 kN. The circlets marked on the lining are the controllable nodes. Figure 5 shows the inner forces when the rolling-correction angle is 0.6°, which is the allowable rolling angle of Shanghai Metro construction. Comparing Figure 4a with Figure 5a, it can be found that there is a big change of the shape of moment; the moments at Node 2 and Node 6 changed their signs (direction) and although the sign of moments at the other Nodes does not change, the magnitudes increase noticeably. Although the shape of axial force and shear force in Figure 5b and Figure 5c keeps the similar to that in Figure 4b and Figure 4c, their magnitude increases significantly. In the following section, the variation of inner forces at eight controlling Nodes with rolling correction angle will be discussed in details.



(a) Moment (kNm) (b) Axial Force (kN) (c) Shear Force (kN)

Fig.4 Distribution of moment, axial force, and shear force in tunnel lining without rolling



(a) Moment (kNm) (b) Axial Force (kN) (c) Shear Force (kN)

Fig.5 Moment, axial force, and shear force in tunnel lining under rolling correcting angle of 0.6°

5.2 Moment Change with the Rolling-Correction Angle

Figure 6 shows the changes of the bending moments at the eight nodes with variation of the rolling-correction angles. The intersect points to vertical direction are the case without rolling-correction load. As shown in the figure, the changes of the moments at each node are not the same. According to Shanghai metro construction codes, the largest changes of the moments are at Node 4, Node 6, and Node 8. Comparing to the without rolling-correction case, the moment increases 31.5 kN-m for Node 4, 72.8 kN-m for Node 6, and 26.9 kN-m for Node 8 with an increase rate of 134%, 310%, and 92.4%, respectively. Thus, the rolling-correction induced significantly inner force in lining is very large.

Moreover, after the rolling correction, the positions of control nodes have changed; some of them even changed their sign. If the rolling-correction angle reached 3.0°, at some nodes, the moment increases 5 to 6 times. This phenomenon is very dangerous to tunnel structure.

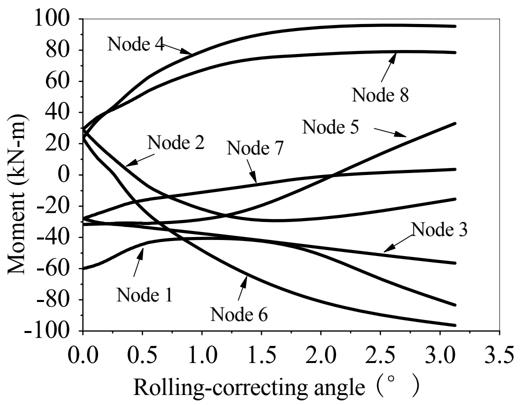


Fig.6 Variation of the moment with rolling correcting angle

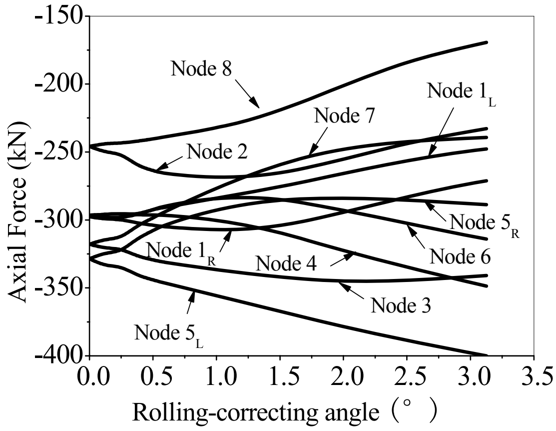


Fig.7 Variation of the axial force with rolling correcting angle

5.3 Changes of Axial Force with the Rolling-Correction Angle

Figure 7 illustrates the variation of axial forces at the eight controlling nodes. Changes of axial forces with the rolling-correction angle at each node are quite different. When the rolling-correction angle is less than 0.6°, the changes of the axial force at each node are less than 10%. Even though the rolling-correction angle reaches 3.0°, the maximum axial force only increases about 30%. If the rolling-correction angle increases, axial forces in the lining increase continually and always compression.

5.4 Changes of Shear Force with the Rolling-Correction Angle

Figure 8 depicts the variation of shear forces at the eight controlling nodes with rolling-correction angle. Changes of shear forces with the rolling-correction angle are similar to those of moment as shown in Figure 6. When the rolling-correction angle is less than 0.6° (the allowable value of Shanghai Metro), the changes of shear forces at Node 1, Node 3, and Node 5 are very large. At Node 1, the shear force decreases 19.5 kN with the decrease rate of 50%; at Node 3, the shear force increases 20 kN with the increase rate of 400%; and at Node 5, the shear force increases 16.5 kN with the increase rate of 55%, respectively. Even though the rolling-correction angle reaches 3.0°, the maximum axial force only increases about 30%. The sign of shear force at Node 3 changed. With the increase of rolling-correction angle, the shear forces increase continuously and the maximum is about 6 times the original value. According to the aforementioned results, for the DOT tunnel, rolling-correction has a very significant influence on the inner forces of the lining. The rolling-correction forces should be taken into consideration in tunnel structure design.

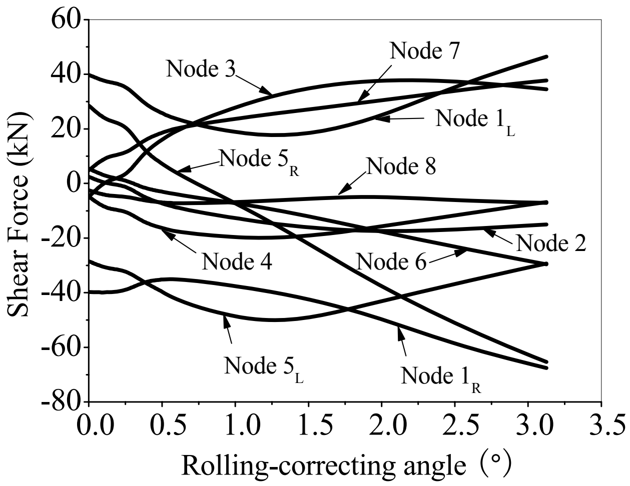


Fig.8 Variation of the shear force with rolling correcting angle

6 CONCLUSIONS

Based on the calculation results of FEM analysis, the following conclusions can be drawn:

-The inner forces alter significantly due to the rolling-correction operation during DOT tunnel construction. With the increase of the rolling-correction angle, the magnitude of inner forces decreases remarkably and even at some nodes in the lining, the sign of inner forces changes. Moreover, a reasonable design of DOT tunnel lining should consider this type of inner force redistribution induced by rolling-correction operation.

-Within the allowable rolling angle of Shanghai metro (0.6°), the change of the axial forces is less than 10% whereas the change of moment and shear force are very large. The maximum change of moment is from +20 kN-m to -30 kN-m. The shear force also changes its sign and its magnitude changes from -5 kN to +20 kN.

-If the rolling-correction angle increases, the axial force increases but keeps in compression range. If the rolling-correction angle increases from 0.6° to 3.0°, the moment increases 5 times the value without rolling-correction operation and the shear force is about 6 times the value without rolling-correction operation. Thus, the rolling angle should be controlled as small as possible.

-In the design of DOT shield tunnel structure, the inner forces caused by the rolling-correction operation shall not be ignorant. During construction, the rolling angle should be strictly controlled within a small range, i.e. 0.6 degrees and the rolling correction-operation should be carefully conducted.

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