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Study on effect of segments erection tolerance and wedge-shaped segment on segment ring in shield tunnel

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Abstract: Deformation and dislocations of segments of shield tunnel in construction stage have apparent effect on tunnel structure stress and even cause local cracks and breakage in tunnel. 3D finite element method was used to analyze two segment ring models under uniform injected pressure: (1) segment ring without wedge-shaped segment, which has 16 types of preinstall erection tolerance; (2) segment ring with wedge-shaped segment, which has no preinstall erection tolerance. The analysis results indicate that different erection tolerances can cause irregular deformation in segment ring under uniform injected pressure, and that the tolerance values are enlarged further. Wedge-shaped segment apparently affects the overall deformation of segment ring without erection tolerances. The uniform injected pressure can cause deformation of ring with wedge-shaped segment irregular, and dislocations also appear in this situation. The stress of segment with erection tolerances is much larger than that of segment without erection tolerances. Enlarging the central angle of wedge-shaped segment can make the irregular deformation and dislocations of segments smaller. The analysis results also provide basis for erection tolerance control and improvement of segment constitution.

Key words: Shield tunnel, Segment, Erection tolerance, 3D finite element analysis
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INTRODUCTION

Shield tunnel method has become the most preferred method in city tunnel construction because of its excellent attributes: little effect on surrounding environment, fast and safe construction, outstanding performance in earthquake resistance, etc. (Zhang *et al*., 2004). In different shield tunnels, the arrangement and number of segments are different, but the whole assembling process is generally the same. The assembling process begins with A2P, then A1P, A3P, BP, CP, and finally KP (Fig.1). The weightlifting carries every segment to the preset position. Under the premise of no impact with other segments, the lifting jack of weightlifting moves slightly, and the workers tighten the bolts. The sequence of tightening bolts is bolts between the segments in one ring and then the bolts between rings. After finishing the process mentioned above, the shield machine drives forward. Simultaneously, some special liquid is injected through injected holes on segments in order to fill in the gap between exterior soil layer and segments.

In the construction process mentioned above, dislocations often happen between segment rings and segments in one ring (Fig.2).

Many factors result in dislocation, including manufacturing dimension tolerance, improper erection, non-uniform injected pressure, shield machine altitude control (Blom *et al*., 1999; Qin *et al*., 2004), shield machine extrusion pressure on segment rings caused by inconsistent axis between segment rings and shield machine when shield machine drives forward, etc. (Kasper and Meschke, 2004; Tajima *et al*., 2006; Kiriyama *et al*., 2005). Former researches neglected the effect of segments erection tolerance and segment constitution on the overall structure. Actually, erection tolerances of segment and wedge-shaped segment have obvious effect on the overall

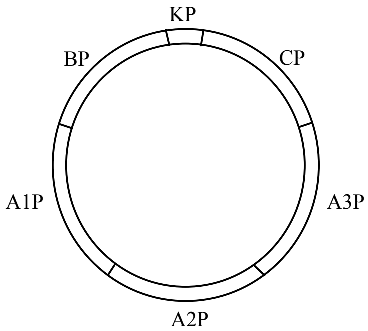


Fig.1 Segment arrangement and relative numbering

Fig.2 Dislocation between segments

deformation of rings at construction stage and also cause non-uniform stress distribution and irregular dislocation.

In the present paper, 3D finite element method was used to analyze the segment ring with preinstall erection tolerance without wedge-shaped segment and segment ring without preinstall erection tolerance with wedge-shaped segment. The results provide basis for erection tolerance control and improvement of segment constitution.

FINITE ELEMENT MODEL

Segment dimension (DIGMC, 2002)

(1) Segment ring without wedge-shaped segment, which has 16 types of preinstall erection tolerance: external diameter is 6 m; internal diameter is 5.4 m; width is 1.5 m, thickness is 0.3 m. The segment ring consists of 1 wedge-shaped segment (KP), 2 adjacent segments (BP and CP) and 3 standard segments (A1P~A3P). Central angles of plugged segment, adjacent segments, and standard segment are 15.4°, 64.3°, and 72°, respectively.

(2) Segment ring with wedge-shaped segment, which has no preinstall erection tolerance: the dimension and the segment ring composition are the same as those in Case (1). Central angles of the front part of wedge-shaped segment, the rear part of wedge-shaped segment, the front part of adjacent segment, the rear part of adjacent segment and the standard segment are 20.4408°, 10.3524°, 61.7796°, 66.8238° and 72°, respectively.

Fig.1 shows the arrangement and number of segments.

Material parameters

(1) Segment concrete: Poisson ratio is 0.2; Young's modulus is 3.45×10^7 kPa.

(2) Rubber sealing rod: Poisson ratio is 0.4; Young's modulus is 7.8×10^3 kPa.

(3) Joint bolt: Poisson ratio is 0.25; Young's modulus is 2.0×10^8 kPa.

Adoptive element and considered factors

Two types of computational model were used in this paper (Fig.3). One was ring with preinstall erection tolerance without wedge-shaped segment. Another was ring without preinstall erection tolerance with wedge-shaped segment. The effect of erection tolerance and wedge-shaped segment on the whole ring was respectively analyzed in the two models. Two hundred and fifty kN/m^2 radial uniform pressure acted on all models in order to eliminate the effect of non-uniform loads. According to (DIGMC, 2002) and considering the different boundary conditions, erection tolerances were introduced to segments KP, BP, A1P and A2P in models with preinstall erection tolerance. The tolerance included 1 or 2 mm in direction of inside and outside tunnel. In models without preinstall erection tolerance with wedge-shaped segment, ideal constraint was applied to the front of and behind the models (Fig.4). 3D solid element simulated the segment and rubber sealing rod. 3D truss element simulated the joint bolts. The initial strain was applied to truss element to simulate the pre-tightening twist moment 300 kN·m in construction stage. In the two types of models, the sealing rods were simplified (Fig.5). There are contact surfaces between the sealing rods, and the friction factor was 0.3. The contact surfaces could simulate the process of extrusion, separation and relative shift.

Mesh generation of two types of model are shown in Figs.3~5. The models were totally 26004 elements and 33366 nodes.

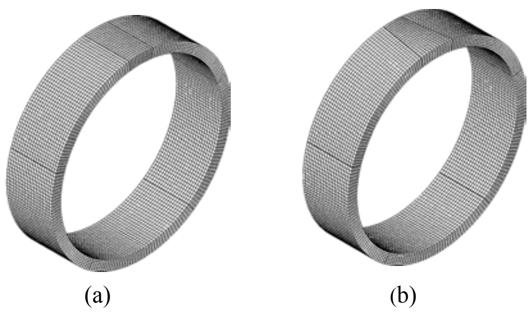


Fig.3 Mesh of the whole ring. (a) Model without wedge-shaped segment; (b) Model with wedge-shaped segment

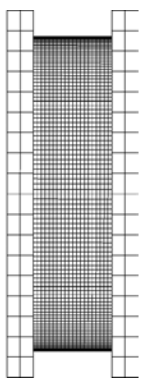


Fig.4 Model with rear and front restraints

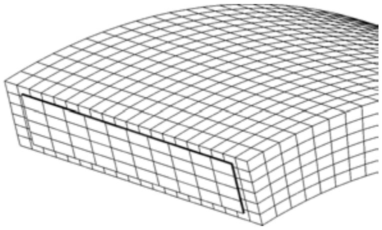


Fig.5 Mesh of joint

RESULTS AND ANALYSIS

The main purpose in the present work was to analyze the effect of different erection tolerances and wedge-shaped segments on the whole ring. So the results and analysis focused on ring deformation and relative displacement of segment end surface. The results of segment stress and strain are not shown in the following part.

Results of model without wedge-shaped segment

Table 1 and Fig.6 show the results of model without wedge-shaped segment. For the same segment with tolerance, different tolerances just caused different relative displacement values, hence Fig.6 just demonstrates 8 displacement graphs of them.

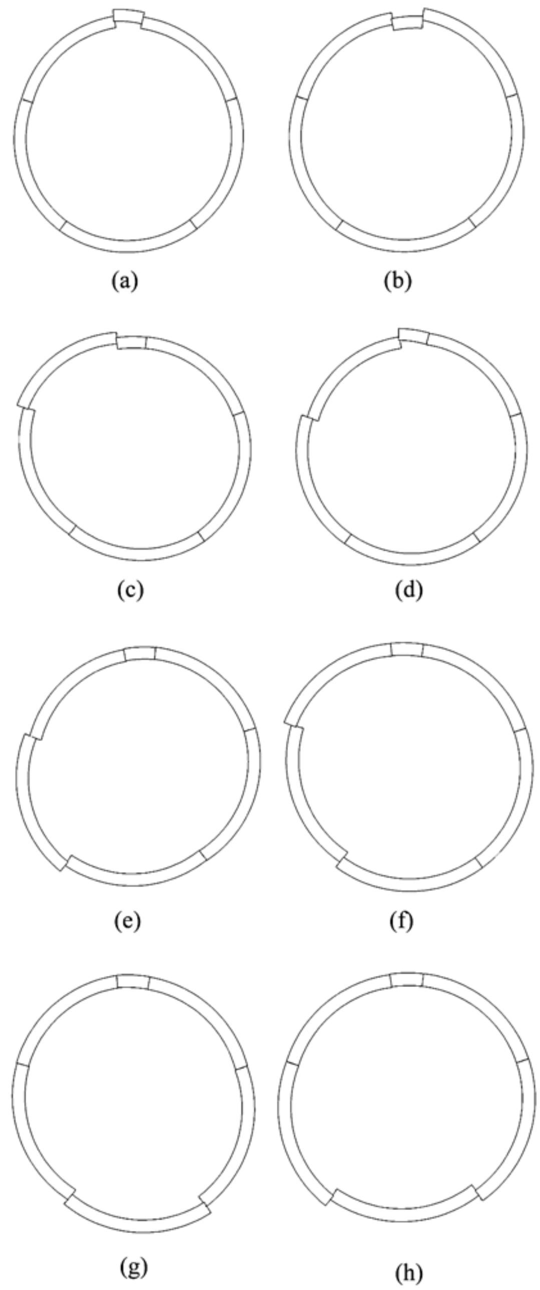


Fig.6 Displacement of rings without wedge-shaped segment (enlarged 20 times). (a) Tolerance 1; (b) Tolerance 3; (c) Tolerance 5; (d) Tolerance 7; (e) Tolerance 9; (f) Tolerance 11; (g) Tolerance 13; (h) Tolerance 15

Table 1 Results of model without wedge-shaped segment

Tolerance number	Segment	Tolerance direction (outside or inside tunnel)	Tolerance dimension (mm)	Maximum value of relative displacement (mm)	Worst effect on the whole ring
1	KP	Outside	1	10.5	KP was extruded out by BP and CP
2	KP	Outside	2	8.9	KP was extruded out by BP and CP
3	KP	Inside	1	9.4	BP and CP were extruded out by KP
4	KP	Inside	2	8.6	BP and CP were extruded out by KP
5	BP	Outside	1	8.5	BP was extruded out by KP and A1P
6	BP	Outside	2	7.7	BP was extruded out by KP and A1P
7	BP	Inside	1	10.5	KP was extruded out by BP
8	BP	Inside	2	9.0	KP was extruded out by BP
9	A1P	Outside	1	8.6	A1P was extruded out by BP and A2P; KP moved towards outside tunnel
10	A1P	Outside	2	7.7	A1P was extruded out by BP and A2P; KP moved towards outside tunnel
11	A1P	Inside	1	8.5	BP was extruded out by A1P
12	A1P	Inside	2	7.3	BP was extruded out by A1P; the joint of A3P moved towards outside tunnel
13	A2P	Outside	1	8.6	A2P was extruded out by A1P and A3P; KP, BP and the joint of CP moved towards outside tunnel
14	A2P	Outside	2	7.7	A2P was extruded out by A1P and A3P; KP, BP and the joint of CP moved towards outside tunnel
15	A2P	Inside	1	8.1	A2P was extruded out by A1P and A3P; KP moved towards outside tunnel
16	A2P	Inside	2	7.2	A2P was extruded out by A1P and A3P; KP moved towards outside tunnel

Results of model with wedge-shaped segments

Maximum value of the relative displacement is 3.0 mm. Fig.7 shows the displacement graph.

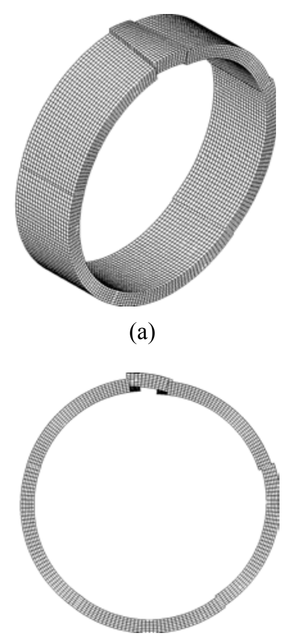

(a)
(b)

Fig.7 Displacement of rings with wedge-shaped segments (enlarged 70 times). (a) Perspective view; (b) *xy* view

Analysis

1. Erection tolerance analysis

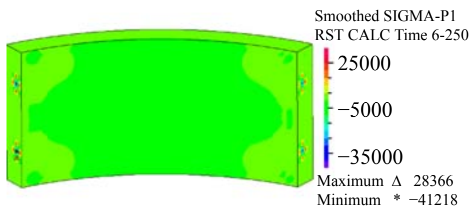
Table 1 and Fig.6 indicate such circular structure composed of segments is considerably sensitive to erection tolerance. Under radial uniform pressure and 1 or 2 mm erection tolerance, maximum dislocation value may reach 10 times initial erection tolerance. At the same time, other segments without tolerance are affected to a certain extent. From BP of model Tolerance 1, Fig.8 indicates that non-uniform compression caused by dislocation makes the segment stress much greater than that of model without erection tolerance. Actually, tolerances distribute randomly and are not limited to some segment. So, under the loads, irregular dislocations happen. In actual case, loads are not always uniform. If peak value of non-uniform loads acts on segment with erection tolerance, dislocation value would be ultimately enlarged.

Longitudinal and circumferential bolts restrain the dislocation, and the dislocation values do not always reach the value shown in Table 1. The restraints from bolts cause squeeze between bolts and segment bolt holes. This can make the segment bolt holes crack and cause segment local breakage.

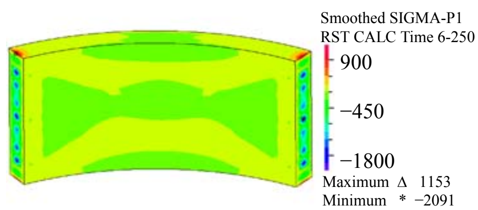
2. Effect of wedge-shaped segment

The relative displacement value and results shown in Fig.7 indicate the wedge-shaped segment obviously affects the whole ring. Under radial uniform pressure, KP has anteverted trend making relative displacement between KP and BP, CP (Fig.7). Joint between wedge-shaped segment and adjacent segment is skew surface. This makes the anteverted trend turn to torsion and causes other segment displacement from inside or outside plane displacement to space irregular displacement. Under the restraint of front and rear rings, the torsion of wedge-shaped segment is limited and squeezed out by BP and CP (Fig.7). Dislocations happen without erection tolerance. The whole ring applies 2280 kN extrusion force to front and rear segment rings. When the dislocations reach some value and other unpredictable loads such as non-uniform pressure from tail of shield machine act on the ring, stress concentration happens (Fig.9a) and breakage near bolt hole appears (Fig.9b).

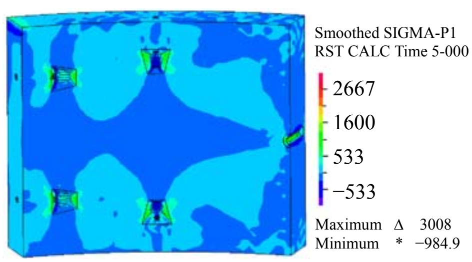
When the central angle of wedge-shaped segment is less, the wedge-shaped segment is easily affected by other segments. In order to analyze the effect of central angle of wedge-shaped segment, the model shown in Fig.3b was used again under the same loads, with the same wedge-shaped value and different central angle. The results are: (1) Central angles of the front part and the rear part are 36° and 25.9116°, respectively; and the maximum value of relative displacement is 2.0 mm; (2) Central angles of the front part and the rear part are 48° and 37.9116°, respectively, and the maximum value of the relative displacement is 1.7 mm. The alterative amplitude of the relative displacement is not great, but its significance is obvious. In (DIGMC, 2002), distances between bolts and bolt holes are 3 mm. Increasing the central angle of wedge-shaped segment decreases the irregular displacement of ring. And this can provide more space for bolts and bolt holes, and reduce their



(a)

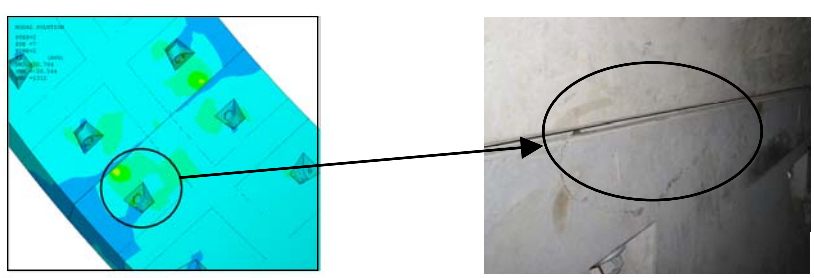


(b)



(c)

Fig.8 σ_1 contour of BP. (a) In model Tolerance 1; (b) In model without erection tolerance; (c) In elaborate half model without erection tolerance. Unit: kN/m^2



(a) (b)

Fig.9 (a) σ_1 contour of relative torsion between two segments (MPa); (b) Cracking on segments in shield tunnel during construction

possibility of mutual squeezing under uncertain condition in construction and regular service. It is significant for reducing the case of cracking near bolt holes and improves the waterproof performance and durability.

CONCLUSION

Analysis of the segment ring with preinstall erection tolerance without wedge-shaped segment and segment ring with wedge-shaped segment without preinstall erection tolerance yields the following conclusions:

(1) Erection tolerance can cause irregular deformation under uniform injected pressure. It can also cause irregular dislocation, and weaken the waterproof performance and durability. Erection accuracy must be increased as much as possible, especially BP, CP and KP.

(2) In the process of segment manufacture, 11 tolerances (DIGMC, 2002) control the accuracy including longitudinal seam taper, longitudinal joint deflection angle, segment width, segment thickness, arc length, inside radius, center radius of seal groove, groove dimension, smoothness of circular seam, smoothness of longitudinal seam and bolt position. Every item has plus-minus control tolerance. Because the circular structure has considerable sensitivity to loads, if the segments are marked with plus or minus margin of tolerance before leaving the factory, proper segments can be selected in erection. And this can improve the erection accuracy of segment rings.

(3) Wedge-shaped segments obviously affect the deformation of segment ring. Due to non-uniform loads in the longitudinal direction, even considering the longitudinal integral effect, the deformation still has significant effect on shield tunnel. So wedge-shaped value should be decreased and central angle of it should be enlarged, which can resist the possible erection tolerance of the adjacent segments and dislocations caused by non-uniform loads.

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