Damage Detection of Shield Tunnel Segment Joints Based On Changes in the Rotations of Joints

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Abstract. The relationship between the damage of the segment joint and the change in the rotation of the joint was studied. First, the finite element model of the tunnel was established to analyze the displacement changes before and after the structural damage. Then, according to the relationship between the displacement and the rotational angle, the changes in rotation of the joints before and after the damage were calculated. Finally, the relationship between the changes in the rotations of the joints and damages of the joints was analyzed. The results show that the change in the rotation of joint is a good indicator for identifying joint damage.

1. Introduction

The construction of tunnel engineering not only brings convenience to transportation, but also greatly promotes economic development. However, due to the influence of some unfavorable factors, the tunnel structures have appeared many diseases. Several common diseases include segmental cracking, tunnel deformation and leakage of segment joints [1]. These diseases not only shorten the service life of the tunnel, but also increase the cost of tunnel maintenance and even pose a serious threat to the safety of pedestrians and vehicles in tunnels. Therefore, structural health monitoring has become a research focus in recent years [2]. The segment joints are the weak links of shield tunnels. It is important to study the influence of joint damage on the performance of the tunnels.

2. Damage detection of shield tunnel segment joints

2.1. Configuration of a shield tunnel

This study was based on the project of Shanghai Metro Line 2. The shield tunnel of Shanghai Metro Line 2 is 8-15m in buried depth. Each ring of the tunnel is made up of 6 segments, and the central angles of each segment are 16°, 4×65° and 84°, respectively. The thickness of the segment is 0.35 m, the width is 1 m, the outer diameter is 6.2 m, and the inner diameter is 5.85 m. The 6 segments are tightly connected by two M30 bolts, and the longitudinal rings are connected by 17 longitudinal bolts. The diagram of the tunnel is shown in Fig. 1. The tunnel is subjected to water pressure and earth pressure. The sum of the top water pressure and the earth pressure is 90 kN/m², and the sum of the lateral water pressure and the earth pressure is 40 kN/m².
2.2. Basic assumption

Compared with the size of the tunnel segment, the displacements and rotation angles at the segment joints of the tunnel are small under load. Regardless of the difference in segment material, it is assumed that the segment material is an isotropic homogeneous material.

Since the sizes of the gaskets between the segments are very small relative to the sizes of the segments, their effects are ignored in the finite element model.

2.3. Finite element model

The Shanghai Metro Line 2 tunnel is formed by aligning the longitudinal joints. Each ring has similar mechanical characteristics, therefore, a ring is taken as analysis object. The finite element model of tunnel was created using ANSYS software. The friction and extrusion at the tunnel segment joints were simulated using the face-to-face contact elements Contact174 and Target170. The bolts connecting the segments are simulated by the element Link10. The elastic modulus of the bolts is 200GPa, the density is 7800 kg/m$^3$, the Poisson's ratio is 0.3, and the initial preload of the bolt is simulated by the initial strain of the bolt. The reinforced concrete segment is simulated by the element Solid65, which has a modulus of elasticity of 35GPa and a density of 2500 kg/m$^3$. The spring element Combin14 is used to simulate the effect of the soil and segments of other rings. In addition, the element Surf154 is used to control the loading direction of the soil load. In the mesh generation, the segment is divided into 72 equal parts along the ring direction, divided into 5 equal parts along the thickness of the tunnel, and divided into 8 equal parts along the width of the tunnel. Each bolt is modelled using an element. There are a total of 7703 elements after meshing. The finite element model of the tunnel is shown Fig. 2.
2.4. Damage simulation method
The damage is simulated by the reduction of the elastic modulus, that is, the elastic modulus is reduced at the joint of the segment, and the influence depth is equal to the thickness of the segment. The extent of damage is defined as

\[ D(t) = 1 - \frac{E(t)}{E} \]  

Where \( E \) and \( E(t) \) are the elastic modulus of undamaged and damaged joints, respectively.

2.5. The changes in the rotations of joints
Through finite element analysis, the displacement of each node before and after the damage can be obtained. The opening amount at the segment joint can be obtained by the displacement of the nodes 1 and 2 at the inner and outer edges of the segment, as shown in Fig. 3.

According to the hypothesis, the rotation of joint meets the following relationship:

\[ \theta = 2 \left[ \frac{S_1 + S_2}{h} \right] = \frac{2(\sqrt{\Delta x_1^2 + \Delta y_1^2} + \sqrt{\Delta x_2^2 + \Delta y_2^2})}{h} \]  

Where \( \Delta x_1 \) and \( \Delta y_1 \) are the change in the horizontal and vertical coordinates of the inner point of the segment, respectively. \( \Delta x_2 \) and \( \Delta y_2 \) are the change in the horizontal and vertical coordinates of the outer point of the segment, respectively. \( S_1 \) and \( S_2 \) are the displacements of the inner and outer points of the segment, respectively. \( h \) is the thickness of the segment.

2.6. Damage cases and analysis results
Because the tunnel segment joints are symmetrical, take three joints, \( P_0 \), \( P_1 \) and \( P_2 \), to study the effects of joint damage. Assume that the joints, \( P_0 \), \( P_1 \) and \( P_2 \) are damaged by 10%, 20%, 30% and
40\%, respectively, and then calculate the changes in the rotation of the joints under various damage cases. The results are shown in Figs. 4, 5 and 6.

It can be seen from the figures that the changes in the rotational angles at the joints without damage are quite small, and the change in the rotational angle where the damage occurs is significant. Therefore, the change in the rotation of the tunnel segment joint is a good indicator for the location of the joint damage. In addition, the change in the rotation of the joint is proportional to the extent of damage. The greater the damage to the joint, the greater the change in the rotation of the joint. Therefore, the change in the rotation of the joint can also be used to identify damage extent.

![Fig. 4 Changes in rotational angles with $P_0$ damaged](image1)

![Fig. 5 Changes in rotational angles with $P_1$ damaged](image2)
3. Conclusion
The change in the rotation of the segment joint is a good indicator for identifying damage of the joint. Not only the location of damage but also the extent of the damage can be identified by changes in the rotation of the joint. In order to identify the specific extent of damage, the quantitative relationship between the change in the rotation of the joint and the extent of damage needs further study.

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