Frame structure analysis model for the effect of typical tunnel diseases on lining structure

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Abstract. The frame structure analysis method has been generally applied for the tunnel structure design, which was widely utilized due to its fast calculation speed and convenient modeling. In this paper, the frame analysis model was established to explore the effect of typical tunnel diseases of voids and lining insufficient thickness on the mechanical and deformation behavior of concrete linings. At first, the lining model with the diseases of void and lining insufficient thickness was established in the frame structure analysis platform. Subsequently, the lining inner force (taking the bending moment as an example) and the deformation behavior were explored. At final, the differences in the deformation behavior were investigated with different vertical loading conditions. The main results in this paper revealed that when the vertical loosening pressure can be transferred to the lining structure within the void zone, the maximum positive bending moment of the lining is located near the crown, while the maximum negative is at the shoulder, and the phenomenon of internal bending mainly occurs in the void area, and the phenomenon of external bending occurs at the shoulder. The lining has a significant downward displacement at the crown, while the deformation direction of the structure is outward at the shoulder. However, when the vertical loading cannot be transferred to the lining within the void zone, the obvious phenomenon of deformation outwards will occur within the void zone.

1. Introduction

During the operation of the tunnel structure, unsatisfactory diseases such as voids and insufficient lining thickness are common due to some adverse conditions [1-7]. The above diseases can be regarded as typical causes for many other defects [8]. Therefore, it is significant to make clear the influence of diseases such as voids and lining insufficient thickness on the tunnel structure.

Concerning the effect of voids behind the lining on the safety state of the tunnel structure, Zhang et al. [9] evaluated the effect of double voids behind the lining on the safety state of the tunnel structure. Meguid et al. [10] investigated the impact of voids on the circumferential stresses in the lining, the axial forces and bending moments were concentrated. Li et al. [11] carried out a two-dimensional finite element method
(FEM) to study the distribution of inner force with voids behind the lining, and the effect of void location, as well as the void size, were discussed. Zhang et al. [12] explored the effect of void size on the lining structure, and a three-dimensional model with a single void behind the lining was further established to make clear the effect of the longitudinal length of void on the tunnel structure. Jiang et al. [13] explored the void effect on the degraded lining structure based on the two-dimensional finite difference method (FDM). Furthermore, Zhang et al. [14] investigated the effect of voids behind the lining on the progressive failure of tunnel structure, and the inner force of the lining was also studied. On the other hand, regarding the effect of lining insufficient thickness on tunnel structure. Zhang et al. [15] studied the influence of insufficient lining thickness on tunnels, the distribution of inner force was investigated. Wang et al. [16] investigated the effect of multiply insufficient lining thickness on the safety state of tunnels, and the sensitivity for the location of insufficient thickness was further explored. Wang et al. [17] experimental studied the effect of insufficient lining thickness on the mechanical behavior of the tunnel.

In this paper, the effect of lining diseases on the mechanical and deformation behaviors was studied with the frame structure analysis model. At first, the model with typical tunnel diseases was established. Subsequently, the inner force was explored. Then, the deformation characteristics under different types of loosening pressure were investigated. Overall, this study is expected to improve the understanding of the effect of typical diseases on tunnel structure.

2. Model establishment

In this research, the assumed defected section of the tunnel lining structure can be presented in Fig.1a. As shown in Fig.1a, the thickness of the lining at the crown was significantly reduced, and avoid a range of 90° was assumed behind the lining. Since the disease is the superposition of insufficient lining thickness and void, this study is collectively referred to as a combined disease. In this paper, the upper-half lining structure was applied to establish the frame structure model. The calculation part of the model can be presented in Fig. 1b. Specifically, the cross-section of the analysis model was modeled with 33 nodes, and they covered the calculation part of the tunnel. Concerning the boundary conditions, the bottom of the model is a fixed hinge, and ground springs were arranged between the lining structure and the ground to simulate the action. Note that there is no spring action when there is no contact between the ground and the lining.
Figure 1. Model of tunnel lining: (a) lining section; (b) calculation part.

Regarding the loading condition, the vertical loading was applied to the top of the model. Kazue Nojo et al. [18] systematically divided the loosening load into two types, I: the case assuming that the relaxation load of colluvial soil acts on the back void part (vertical load A in Fig.2); II: the other case is the vertical load B in Fig.2. In this research, the loosening pressure was set as 69.96 kN/m², and the coefficient of rock resistance was set as 200,000 kN/m³. The selected load data has fully referred to the load requirements of the articles of Japan Road Association Based on tunnel maintenance management, which effectively reflects the appropriate stress characteristics of the tunnel [19].

Figure 2. Loading conditions: (a) vertical loading A [18]; (b) vertical loading B [18].

3. Numerical results

According to the frame structural analysis, the distribution of the lining inner force (taking the bending moment as the example) can be presented in Fig.3. It should be indicated that in this research when the value of the bending moment is positive, the lining structure bends inwards. Note that the maximum positive bending moment of the lining is located near the crown, while the maximum negative is at the shoulder, indicating that the phenomenon of bending inwards is mainly located at the void zone, while the phenomenon of bending outwards is at the shoulder. In addition, the lining would bend outwards at the void zone [9], while bends inwards in this research. The reason for this phenomenon is that the vertical loading condition in this paper is different from Zhang et al. [9]. Specifically, the loosening pressure can act on the lining at the void zone, while not for Zhang et al. [9]. In fact, the change of its research is supported by relevant theories for example Nie et al. [2].
The deformation characteristics after scaling up of the lining structure can be presented in Fig. 4. It is observed that the lining has a significant downward displacement at the crown, while the deformation direction of the structure is upward at the shoulder. In addition, according to the deformation behavior of the tunnel lining structure, the possible cracking zone can also be roughly judged. Specifically, at the position of the crown, the deformation characteristics of the lining tend to the inside, and the deflection is large, so it is easy to induce potential tensile cracks at this inner edge. Concerning the possible cracking behavior at the shoulder, the deformation characteristics of the lining tend to the outside, and the deflection is also large, so it is easy to induce possible tensile cracks at the outer edge of the shoulder. In addition, there may be a compressive fracture at the outside of the crown. Overall, cracks are more likely to appear in places with larger deflection of the lining.

![Figure 4. Deformation of tunnel lining structure under the loosening pressure. (Vertical loading A)](image)

The vertical load a is a given state, but there may be a vertical load B in the actual project [18]. Because there is a void behind the tunnel, the rock mass behind the void does not contact the tunnel lining. Therefore, the deformation results of the two load forms were compared as follows. It should be indicated that the loading condition here considers only the loosening pressure. In addition, concerning the lining section, assuming that the normal thickness was 0.45m, the thickness due to insufficient lining thickness was set to 0.3m. The void range at the crown was 2 times to range of lining insufficient thickness. The half tunnel lining thickness has relatively obvious mechanical characteristics under the same load, and it is more representative in practical engineering due to different surrounding rock and construction conditions. When there are combined diseases on the tunnel structure, the lining deformation characteristics after scaling up under the vertical loading A and B can be presented in Fig. 5. It is observed that the deformation characteristics are significantly affected by the type of vertical loosening pressure. Specifically, when the structure is subjected to the loosening pressure A, the lining moves down significantly at the void zone, while moves upwards obviously at the center of the void area for the loosening pressure B. In addition, concerning the distribution of possible cracking zone, tensile cracks are prone to occur at the outside of the void zone at the crown for the vertical loading B. Moreover, it can be noted that possible tensile cracks at the shoulder would gradually move closer to the support for the loosening pressure B.
4. Conclusions and Outlook

In this paper, the mechanical behavior and deformation characteristics of tunnel linings under the disease condition of insufficient lining thickness and void behind the lining were investigated with a frame structure analysis model, and then the possible cracking zone was also discussed. The main results in this research can be listed as follows:

(1) Regarding the distribution of inner force, when the vertical loosening pressure can be transferred to the lining structure in the void area, the maximum positive bending moment of the lining appears near the crown, the maximum negative bending moment appears at the shoulder, the phenomenon of internal bending mainly occurs in the void area, and the phenomenon of external bending occurs at the shoulder.

(2) Concerning the deformation characteristics of tunnel lining structure, the lining exhibits obvious downward deformation for loading condition A. When the vertical load cannot be transferred to the lining in the void area, there will be obvious upward deformation in the void area. The type of vertical loosening pressure has a significant effect on the deformation characteristics.

(3) In future work, it is necessary to carry out indoor tests, compare and optimize the calculation results of the frame structure model, and carry out the reinforcement design for the lining disease.
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