Study on Influence of Tunnel Quality Defects on Lining Structure and its Reinforcement Design

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With the development of underground transportation, more and more tunnels have been constructed. As the main support structure of the tunnel, the lining is essential for the safe operation of the tunnel. However, typical tunnel quality defects such as voids and lining insufficient thickness can commonly occur, seriously threatening the durability and safety of lining structures. Unfortunately, with the long-term operation of the tunnel, the aging phenomenon of the lining is also inevitable. Consequently, it is crucial to clarify the influence of quality defects on the lining structure and identify effective reinforcement schemes. The main research contents of this thesis can be summarized as follows:

At first, the health inspection and formation cause for typical tunnel quality defects of void and lining insufficient thickness were systematically reviewed. The health inspection was summarized, including the inspection methods and defect distribution characteristics. The formation causes of void and insufficient thickness were discussed with the hierarchical structure model. In addition, the avoidable formation causes were marked, which can be applied as the main guidance for defect prevention.

Secondly, the fracture characteristics and cracking mechanism of the lining structure containing combined defects were explored with the finite element method (FEM)-cohesive zone model (CZM) method. Additionally, the cracking characteristics under the fiber-reinforced plastic (FRP)-polymer cement mortar (PCM) reinforcement method were evaluated. The main results indicated that the crack pattern and crack statistics are affected by the defect type and defect range. The cracking degree corresponding to the void zone is larger than that of the insufficient thickness zone. The cracking distribution of tensile ring cracks zone (TRCZ), shear ring cracks zone (SRCZ), shear longitudinal cracks zone (SLCZ), mixed-failure longitudinal cracks zone (MLCZ), and mixed-failure cross cracks zone (MCCZ) is determined. Furthermore, the FRP-PCM method presents a significant inhibition on the cracking of the lining inner surface.

Thirdly, the mechanical properties and failure mechanism of degraded linings with void quality defects that significantly affect the lining were investigated. The reinforcement effect of the FRP-PCM method on degraded linings with void quality defects was evaluated. The main results indicated that void layout and void distance significantly affect the mechanical properties. Especially, an obvious three-dimensional bending outwards phenomenon within the void-affected zone is observed. The lining deterioration degree and the void distribution exhibit an apparent influence on the failure characteristics. The FRP-PCM method can effectively reduce the plastic failure rate of the lining.

Then, the failure and time-dependent characteristics of linings with compound quality defect were investigated. Subsequently, the reinforcement effect under the FRP-PCM method was evaluated. Further, the impact of defect range and defect location on time-dependent characteristics of lining structures with compound defects were explored. The main results indicated that the failure and mechanical characteristics are significantly affected by defect location, defect range, lining degradation degree, and grade of the ground class. The FRP-PCM method can effectively improve the safety state and reduce the plastic rate of the lining, the reinforcement effect is closely related to the grade of FRP grids and lining deterioration degree. In addition, the mechanical properties, deformation, and failure rate of the lining structure exhibit a significant relation with time.

Further, the dynamic response of tunnel structures with void defects and lining defects was investigated. The effect of defect parameters on the distribution of mechanical and physical properties was investigated. Then, the effect of dynamic level, defect type, defect range, and reinforcement types on the variation of the acceleration and velocity dynamic response was analyzed by the standard spectral ratio (SSR). The main results indicated that the physical properties of peak acceleration and peak velocity are significantly affected by the defect type, defect range, and defect location. In addition, the distribution of acceleration SSR or velocity SSR is significantly influenced by the defect type, void range, and dynamic level. Moreover, the reinforcement type significantly affects the dynamic response of the lining structure.

Finally, the reinforcement design of the lining structure was discussed. As a prerequisite, an evaluation model of the influence degree of typical defects and disease on the health state of lining structures was constructed based on the fuzzy comprehensive evaluation (FCE) method. As an illustration, the application of the established FCE model was conducted. To conduct the reasonable reinforcement design, commonly applied reinforcement methods for defective lining structures were reviewed. Subsequently, the reinforcement design for the defective and diseased lining structure was suggested based on the FCE method. Further, the flowchart of reinforcement designs for lining structures was summarized.