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Discussion on Structural Health Monitoring of Urban Underground Road Tunnel

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Abstract: The number of urban underground road tunnels in China is increasing year by year, and health monitoring of tunnels is an effective management method to ensure their structural integrity. However, for shorter underground road tunnel projects, insufficient investment often leads to less frequent application of health monitoring systems. The application of intelligent structural health monitoring means can not only reduce the project cost but also help workers fully understand the actual situation of the tunnel structure. Therefore, this paper analyzes the characteristics, problems, and design of the urban underground road tunnel structural health monitoring system, and discusses the implementation of the urban underground road tunnel structural health monitoring system.

Keywords: Urban underground road; Tunnel structure; Health monitoring

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1. Introduction

With China's accelerated urbanization process, there is a significant increase in population and motor vehicles, bringing greater pressure on urban road transport. Among them, the more common problems include environmental pollution, traffic jams, etc., especially in the core urban areas. In order to effectively solve these problems, it is necessary to continuously strengthen the development of underground space and increase underground roads and underground buildings, so as to alleviate urban traffic congestion. The ages of various types of tunnels vary, and in the process of long-term underground operation, problems such as insufficient maintenance and construction defects have gradually become prominent. These problems can lead to structural deformation of underground road tunnels under the combined effect of external factors, which brings potential safety risks and seriously hampers the normal operation of the tunnels. For this reason, it is necessary to strengthen the safety monitoring of tunnels during construction and operation, and constantly pay attention to their operating status.

2. Technical characteristics of structural health monitoring of urban underground road tunnels

2.1. Continuity of monitoring process

Operation and construction are two important phases in the structural health monitoring of urban underground road tunnels, and the monitoring of the construction phase can ensure the safety of engineering construction and provide feedback on the construction situation. The health monitoring of the operation phase can effectively ensure that the tunnel can safely carry out the relevant operation work. The construction of underground road tunnels destroys the equilibrium of the original stratum, and a new equilibrium can be formed through the operation phase, with a certain continuity between these two phases in the actual application process. Therefore, only by strengthening the understanding of the construction and operation phases of the tunnel structure, can the health monitoring system be continuously optimized and improved [1].

2.2. Complexity of tunnel structure

Segment structure is the main force in tunnels. The mechanical response of tunnel structure can be produced by the joint action of stratum structure and segment structure. There are many external factors of force, and the effect and influence of each factor differ. Compared with structures with strong loading capacity such as ground bridges and other large buildings, tunnel structures need to pass through the ground to map the external loads to the tube sheet structure. Therefore, the influence of external loads on tunnel structures is relatively small, and the specific degree of influence and influencing factors need to be studied and explored in depth.

2.3. Durability of monitoring elements

As the outer side of the tunnel structure is a stratum, most of the monitoring elements need to be pre-buried, which requires continuous strengthening of the quality and durability of the monitoring elements. Due to the special environment of tunnel construction, it is necessary to fully consider its durability in wet environments while meeting the basic principles. Therefore, fiber grating sensors can be used to obtain relevant information; this sensor has strong corrosion resistance, small signal attenuation, and strong anti-electromagnetic interference performance, so it is widely used in tunnel monitoring systems [2].

3. Issues in the structural health monitoring system of urban underground road tunnels

3.1. Selection of sensor

In the underground road tunnel structure, multiple sensors will be buried in each section; when selecting the sensors, the sensors with automatic identification numbers should be used to improve the safety and reliability of the wiring work. For example, MEMS sensor has the advantages of low power consumption, small size, convenient deployment, etc., and has been rapidly developed through comparisons and tests before application. In addition, it is necessary to understand the specific conditions and factors in the construction process, so as to clarify the range of the sensor. For instance, the grouting link in the construction process will have an impact on the stress of the segment reinforcement, and the influence of different positions is also different, thus is affected by factors such as assembly stress and jacking force. Some underground road tunnels with large internal diameters should be strengthened in the actual construction and application process to pay more attention to their internal structure, so as to minimize the impact on tunnel safety and quality.

3.2. Selection of monitoring location and content

When choosing the monitoring content, the external water and land pressure can directly affect the deformation and force situation of the building. Settlement data and structural deformation are important factors in determining the safety and practicality of the structure, while the grouting pressure and assembling stress during the construction process will have a direct impact on the structural internal force of the tunnel, thus it is necessary to monitor the structural deformation, structural internal force, etc., as the main monitoring content [3].

When choosing the monitoring location, it is necessary to take into account the surrounding situation and actual conditions of the tunnel, and further screen the deepest and shallowest part of the tunnel, the place where the quality of construction is insufficient, and the place where the condition of the stratum has changed. Since quality problems occurring in tunnel construction are unavoidable and unpredictable, it is necessary to pay sufficient attention and concern to them. In addition, in order to facilitate the analysis and verification of monitoring data, the monitoring objects should be placed in the same or similar sections as far as possible.

3.3. Data synthesis and integration

A large amount of monitoring data is obtained through manual monitoring, automatic monitoring, and geological monitoring of the tunnel structure, which is used to determine the actual health status of the tunnel structure. For example, during the construction of underground road tunnels, quality issues or leakage of tube sheets are highly likely to occur during construction. Therefore, the tunnel structural health monitoring system is not a stand-alone system, but rather, information and data should be accumulated at the beginning of the construction work. In the construction of a tunnel project, data such as construction monitoring and quality are uniformly managed through digital technology, and data such as design and construction are effectively integrated, so as to provide a good platform for data integration of the health monitoring system [4].

3.4. Visualization of health monitoring

Typically, operation managers carry out management after the completion of the tunnel, but due to a lack of strong professional skills, they are not familiar with and do not fully understand the design and construction of the project. Therefore, the application of the health monitoring visualization platform needs to be as intuitive as possible in the management process, simple in presenting the required content, and monitor the data through the three-dimensional view and two-dimensional plan, etc., for better observation and analysis.

3.5. Structural health assessment

Health assessment of the tunnel structure can provide an important reference for maintenance work and programs. In the comprehensive evaluation of a particular structure, applying clearer mechanical concepts enhances the precision of the assessment. The results are highly targeted, fully reflecting issues such as water leakage and structural deformation. Through the comprehensive analysis and evaluation of the geological conditions of the tunnel, the overall state of the entire structure can be derived, and according to the specific conditions of underground tunnels, the pre-buried depth is divided and evaluated to better carry out maintenance and repair work [5].

4. Design of urban underground road tunnel structural health monitoring system

4.1. Architecture of the system

The data layer, interface layer, business layer, and presentation layer together constitute the system design architecture. Among them, the main function and role of the presentation layer is to strengthen the interaction between users and the system through the visualization pane, which can also improve the system's risk resistance and reduce communication costs [6]. While there are more functional services in the business layer, its most critical role is to communicate and connect instructions. The interface layer provides effective access to the relevant data in the read/write persistence container in order to achieve the separation of method and business. The data layer is mainly used to store computer-aided design drawings, data files, etc., so as to achieve the separation of program and data [7].

4.2. General framework of the system

The system mainly consists of several modules: the first module is collecting data. After the typical monitoring items and locations are clarified, the dynamic response of the tunnel structure is tested and collected by sensing devices. The second module is remote monitoring. The information monitored by the sensors on each section is transmitted to the remote monitoring unit through the content, and the data are organized and transmitted [8]. The third module is data transmission. Due to the complex environment of underground road tunnels, a wired connection is the main contact between various devices during the construction process. As the communication distance between the sensor network and the remote monitoring unit is close, and the external interference is small, it can be directly connected through the cable. Since the central control room and remote monitoring unit are mainly connected through the alignment channel, which often contains high-voltage lines, fiber optic transmission can be applied to minimize signal interference effectively [9].

5. Implementation of structural health monitoring system for urban underground road tunnels

5.1. Monitoring section

Based on the actual design and survey data of the line, the left and right sections traverse a deep ravine approximately 60 meters in depth and 300 meters in width. The surrounding rock mainly consists of siltstone and heavily weathered sandstone, with the section located at the boundary between these two materials, classified as Class V surrounding rock. Given the high degree of fracturing in the rock mass, an overrun small conduit support system has been applied, which is suitable for such conditions. Considering the tunnel's geomorphology, geology, and support method, the section with the poorest overall condition on both the left and right lines of Chang'an has been identified as particularly prone to safety risks. To address this, it is crucial to establish a structural health monitoring system in this section to ensure effective monitoring and safety management.

Therefore, this paper focuses on a tunnel structure as the main research object, with particular emphasis on the stress state and deformation level, which are key factors in tunnel deformation and collapse. To address these issues, structural health monitoring is applied during the tunnel's operational phase, with special attention given to deformation values and concrete strain measurements. Critical monitoring parameters include the stress of the second-lining concrete and the stress of the second-lining reinforcement. In the monitoring process, 10 concrete strain gauges and 10 rebar stress gauges are installed in the designated monitoring section, while a convergence monitor is placed on the surface of the lining structure to ensure comprehensive structural monitoring. Vibrating wire strain sensors are selected based on monitoring requirements and actual working conditions, and welded to the specified points. Additionally, laser sensors are organized into a network.

Remote monitoring equipment is deployed at each observation point to collect and manage data, ensuring both authenticity and reliability [10].

5.2. Health status evaluation

The health status evaluation system for urban underground road tunnel structures is complex, primarily utilizing fuzzy theory and hierarchical analysis. This approach allows the evaluation system to effectively combine both manual and automatic monitoring methods. By doing so, the system facilitates a detailed analysis of the tunnel structure's health while enabling the transmission of relevant data and reports for continuous monitoring and assessment.

Currently, certain underground road tunnel structures have gradually unified structural thresholds and monitoring indicators. For example, the monitoring and warning indicator system used in the "yellow tunnel" can be effectively applied [11]. Additionally, health diagnostic index systems for some underground road tunnel structures have been established, allowing for the quantification of health status diagnostic indicators. This process helps clarify relevant diagnostic indicators and characteristics, while also improving the overall evaluation standards for tunnel health monitoring.

According to the five-level classification method, tunnel structures are categorized into five grades: A, B, C, D, and E. Level A indicates an "intact" structure, Level B signifies "slight" damage, Level C represents "more serious" damage, Level D denotes "serious" damage, and Level E reflects "extremely serious" conditions. The health condition and classification of the tunnel structure are determined based on load capacity, allowable deformation range, and artificial monitoring indicators such as engineering reinforcement stress and lining deformation. Additionally, the strain safety level is classified based on the strength of the second lining concrete and reinforcement stress, which is also divided into five levels. The strength of Level A is lower than 70%, the strength of Level B is between 70% and 80%, the strength of Level C is between 80% and 90%, the strength of Level D is between 90% and 100%, and the strength of Level E is more than 100%. Based on relevant standards and regulations, the deformation health level of the tunnel structure section can be determined. The system provides real-time warnings and monitoring for all structural elements, with warnings initiated from Level C. These include both auditory and visual (color) warnings, particularly for critical tunnel structures. This process ensures a comprehensive evaluation of the tunnel's health and generates corresponding health evaluation reports.

6. Conclusion

In summary, when analyzing and discussing the structural health monitoring of urban underground road tunnels, it is essential to establish health evaluation standards that align with the actual load-bearing conditions of the tunnel structure. This paper provided a detailed analysis of key elements within the structural health monitoring system, including the selection of sensors, monitoring positions, and content, as well as the comprehensive integration and visualization of data for health detection and structural evaluation. Additionally, the paper designed the structural health monitoring system's architecture and general framework, focusing on the application of the system in monitoring sections and evaluating the structural health of urban underground road tunnels. This approach ensures that the safety of the tunnel structure is maintained, and effective health monitoring can be conducted to prevent structural failures and ensure operational security.

Disclosure statement

The author declares no conflict of interest.

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