Development and Implementation of Structural Safety and Typical Distress Long Term Monitoring Technology for Operating Tunnels

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Abstract. With rapid development of transport infrastructure in China, expressway tunnels had exceeded 17,000km by 2018. Tunnel projects are entering operation and maintenance periods. Tunnel operation and maintenance face serious distresses that compromise operation safety. It is urgent to develop long-term monitoring technology of tunnel structure safety and typical diseases, and develop relevant products to ensure the safety of tunnel operation. In this paper, a long-term monitoring system for operating tunnel structural safety and typical diseases is developed by analyzing the characteristics of tunnel diseases and studying the key technical problems of long-term online monitoring for structural safety. It has achieved good engineering application results, realized long-term online monitoring and early warning for operating tunnel structural safety and typical diseases, and ensured the safety of tunnel operation.

1. Introduction

With the rapid development of China's economy, tunnel construction has entered a period of rapid development. No matter in the construction stage or in the operation stage, most tunnels have different degrees of disease, and the maintenance is difficult. In the process of tunnel construction and operation, it is of practical engineering significance to monitor the safety of tunnel structure in real time. A tunnel monitoring system plays a role in preventing tunnel incidents since it can acquire in real time various information in the tunnel and display in real time traffic conditions in the tunnel [1-2].

Since 1950 China has invested considerable funds in National High-tech R&D Program (863 Program) and the National "Climbing" Program to support researches on automatic health diagnosis for large foundations and structures. These researches produced some results subsequently. Because the real-time monitoring system is expensive its use is currently limited to some key large-span bridge construction in China. For example, the structure monitoring system for Xupu Bridge in Shanghai consists of six monitoring subsystems: ambient temperature, bridge strain, deflection, girder vibration, stay cable vibration and vehicular load. The health monitoring system for Tsing Ma Bridge in Hong Kong employs nearly a thousand sensors to monitor bridge damage. As with Tsing Ma Bridge the Yangtze River Bridge in Jiangyin is also provided with a structure monitoring system. Zhao Xinyu, Shu...
Xuanwu et al. used structure warning system as a key subsystem of the real-time monitoring system and applied it to the large-span beam string structure of Guangzhou International Conference and Exhibition Center. Relatively speaking, the development of safety real-time monitoring technology for tunnel structure lags behind the same technology for bridge structure. This is because on one hand researchers and the public pay less attention to tunnel structure health monitoring and on the other hand tunnel structures are more complex and monitoring equipment is more difficult to install in a tunnel. With advances in monitoring technology, monitoring data processing and application is not only the most critical but also a sophisticated step in successful tunnel monitoring [3-4].

2. Status Quo of Safety and Distresses of Tunnel Structures in Service

Tunnel diseases seriously threaten the operation and safety of tunnels. Liu Ji, Shi Feng, Li Shiqiang, Wang Xingang et al. assessed tunnel distresses and studied their solutions. Main factors influencing tunnel health include water leakage, tunnel bottom distress, lining deterioration, cracks and other defects. They used comprehensive assessment methods and tunnel classification method to establish a health diagnosis system for Fangdoushan Tunnel [1-4]. Due to the influence of construction quality, hydrogeological conditions, environment and many other factors, there will be more or less diseases in the operation of highway tunnels, which will affect the operation safety. The most common diseases are cracks and water leakage [5].

2.1. Lining cracking damage.

Through field test, theoretical analysis and numerical calculation Cai Pengchao et al. conducted statistical analysis of lining quality defects, distribution of lining distresses and mechanism and on this basis performed in-depth research into lining structure safety classification [6]. Lining structure cracking damage: This damage is of the following types: 1) lining deformation -- transverse and longitudinal, the most common being transverse deformation of lining subjected to external forces; 2) lining movement -- transverse and longitudinal, part or all of the lining moving laterally, subsiding or rotating; 3) lining cracking. During railway operation stage, varying degrees of cracks appear on lining surfaces due to lining deformation, affecting the stability and reliability of the entire tunnel.

2.2. Water leakage.

Constructing a expressway tunnel would disrupt the equilibrium of the original groundwater system surrounding the tunnel. The groundwater would collect around the tunnel. If the aquifer is connected to surrounding ground and drainage facilities cannot adapt to this water system, expressway highway damages by water would result. According to relevant data, 3/4 of expressway tunnels that have been in use for more than eight years nationwide would experience distresses; nearly 90% of these suffer from water damage which comprises a major source of safety hazard for expressway tunnel operation. Tunnel damage by water will also have a serious impact on social development. Abrupt rise in humidity in a tunnel damaged by water results in short circuiting of cables in the tunnel, affects normal use of the tunnel, pose severe threats to travellers and cargo transport and indirectly cause other disasters. For example, water accumulation and seepage due to water damage initiates new cracks in the lining or widen existing cracks, leading to further deterioration in lining damage. In addition, due to its thermal expansion and contraction characteristics, water is also the main cause for lining cracking and swelling of surrounding ground.

3. Key Technical Issues and Countermeasures

3.1. Non-contact automatic monitoring of tunnel crown settlement.

1) Basic principle.

Based on the characteristics of tunnel settlement, we study and develop an automatic crown settlement monitoring device based on right triangle height measurement principle. This device measures in real time the distance from the target to reference plane with laser distance sensor and
uniaxial tilt angle sensor, calculates in real time the vertical distance from the target to reference plane using an equation and through monitoring of variations in vertical distance obtain the vertical movement distance and speed of the target to achieve automatic monitoring. Its principle is illustrated in Fig. 1.

Fig. 1 Basic principle

1) Implementation of automatic monitoring.

Settlement and displacement can be monitored automatically in practice by following the procedures below: ① Install a uniaxial tilt angle sensor inside a laser distance sensor to create an instrument that can measure distance and tilt angle simultaneously; ② Design a hangar to which the laser distance/angle sensor can be fixed and which allows free rotation of the sensor in horizontal and vertical planes (as shown in Fig. 2(a)), and mount the laser distance/angle sensor to a desired location at the tunnel crown; ③ Design a reference support with level bubble and leveling foot screw to mount and level the reference plane (see Fig. 2(b)), and install monitoring reference plane at a stable location behind the tunnel; ④ Adjust the laser direction and angle of the laser distance/angle sensor at the tunnel crown so that its laser reaches the monitoring reference plane; ⑤ Connect the laser distance/angle sensor to automatic acquisition instrument and set acquisition frequency to output in real time distance and tilt angle data. Using the algorithm based on right triangle height measurement principle obtain real-time elevation variation data to achieve automatic monitoring of tunnel settlement and deformation (see Fig. 2(c)).

(a) Laser device  (b) Reference plane  (c) Schematic layout of monitoring point and reference plane

Fig. 2 Composition and implementation of displacement monitoring system

3.2. Automatic real-time monitoring of apparent distresses in a tunnel.

1) Crack monitoring method based on video image processing technology.

Visually a crack in tunnel lining is in the form of concrete cracking for various reasons including direct external loads, secondary internal force in the structure and lining structure deformation such as thermal expansion. Once a tensile crack is created, there exists a gray level difference between sound concrete surface and the crack under unchanged light intensity. This development process is collected
by a camera. The gray level change allows the crack target to be identified and extracted using threshold, and then refined by computer. Because the image processed by computer is digital, the actual width of the crack (mm) is determined after pixel unit width is determined and evaluated as to if it is within allowable range. Meanwhile, record the data, mark crack location and establish time coordinate relation curves to predict and prepare for future trends.

2) Water leakage monitoring based on video image processing technology.

Due to water infiltration and absorption by concrete surface, there exists a distinct difference between dry and wet zones whether water leakage occurs at tunnel crown or sidewall or pavement. The camera mounted in the tunnel can monitor this development. This is based on the same principle and condition, i.e. changes in gray level. Segment water seepage zone through identification of water seepage image, establish time axis, determine the seriousness of water seepage according to the changes in seepage zone area with time and take appropriate precautions.

3) Spalling monitoring method based on video image processing technology.

Monitoring of spalling under the same light intensity can be implemented from two aspects: first, monitor the amount of spalling from crown in a tunnel cross section on the time axis using global compensation method and frame difference method to estimate risk level. This method has a drawback, i.e. the camera has a temporary blind field of view if the spalling speed is too high. This can be rectified by the second method. The final result of spalling is concrete block traces of varying sizes on the pavement or slight fracture signs on the pavement. This makes target segmentation possible through gray level differentiation. Similarly, establish area vs. time curves and assess spalling in conjunction with the first method.

4. Development and Application of Monitoring System

4.1. System architecture.

To address inadequate health monitoring during tunnel construction and operation and a lack of effective means to assess structural safety and make rehabilitation decisions, we create a monitoring system according to four levels of ”sensing, transmitting, knowing and application”. The system is composed mainly of front-end sensor in the tunnel for data acquisition and transmission, data transmission network and data remote transmission in the tunnel, monitoring data management software platform at main monitoring center and intelligent terminal for early warning. The system acquires data from monitoring instruments located at key positions of tunnel structure to fully reflect its damage and safety status and then transmits the data via ad hoc network in the tunnel to the field data transmission terminal equipment which sends the data remotely to the monitoring center server. The monitoring center server processes the monitoring information in real time, intelligently identifies structural defects, assesses structure safety status, makes single- or multi-indicator warnings and issues warning messages in real time to provide dynamic awareness of tunnel structure health status.
4.2. Function description.
According to the health monitoring requirements of tunnel structures, the system platform provides the following functions: ① Select typical cross sections with the most serious distresses and install surface strain gauges at the crown, left and right hances and sidewalls to monitor the state of stress. ② Install crack gauge in typical propagation-prone cracks selected according to periodic inspection, special test reports and field investigation to monitor the crack width in real time and distress development. ③ Install a HD camera in a typical water leakage section selected according to periodic tunnel inspection, special test reports and field investigation to acquire information on water leakage in real time; extract leakage area and water volume using image identification algorithms to observe the leakage status in real time. ④ Install a liquidometer at the weep-hole in a water rich section selected according to field investigation to monitor groundwater table in real time and observe dynamic movement of groundwater.

4.3. Software platform.
Fig. 4 displays the overall functional architecture of the software system. Considering the system work flow, the software system includes three levels: data interface, business logic and display & output.
To facilitate subsequent application in a wide area, the software is to employ an administrative division based management model for multiple projects that allows the same set of software to manage different monitoring projects in different areas simultaneously. The project management model is described below: there are several monitoring projects in an administrative division; each project includes several acquisition and transmission equipment items; each acquisition and transmission equipment item includes multiple channels; each channel corresponds to one sensor; each sensor is able to convert acquired value to physical value using an independent operational formula.

4.4. Application to actual project.
The developed system was applied and tested on a tunnel in service which experienced a lot of distresses including lining crack, water leakage, inflow and water pumping from pavement. Typical distresses at typical locations on the site were selected for long term monitoring for about 2 years. The monitoring effect was good and ensured the tunnel operation safety.

System integration  Front-end sensor

5. Conclusions
This paper has covered research on the safety of operating tunnel structures and development of appropriate system equipment which is effective in application.

1) We have developed a set of automatic monitoring equipment for settlement and displacement of tunnel support structure based on right triangle height measurement principle to achieve non-contact low-power automatic monitoring of settlement and displacement of an operating tunnel structure.

2) We proposed an automatic monitoring method for typical apparent distresses in tunnels based on image analysis principle to successfully realize online real-time multi-indicator monitoring of apparent distresses in the tunnel.

3) The application of the long term monitoring system for structural safety and typical distresses in an operating tunnel structure to actual project produced good results, demonstrating its stability and reliability. The proposed system is worth being applied in a wider area to safeguard tunnel operation.

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