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DESIGN AND IMPLEMENTATION OF A REMOTE HEALTH MONITORING SYSTEM OF ZOUMAGANG TUNNEL

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ABSTRACT

Zoumagang Tunnel in Dongguan city, Guangdong, China has been built for water supply for the residents. As two highway tunnels are under construction above Zoumagang Tunnel, long-term monitoring is required to study the health status of Zoumagang Tunnel during the construction and operation of two highway tunnels. Design and implementation of a remote health monitoring system are mainly presented and discussed in this paper. The remote health monitoring system consists of four subsystems: sensor data acquisition, sensor data transmission, monitoring data analysis and health status alert. In this paper, placement of over forty sensors in Zoumagang Tunnel and optical fiber based connection of sensor data loggers and in-situ computer are introduced. Then, the methods of real-time sampling and dynamic control for each sensor in the monitoring system are studied. For the health diagnosis of Zoumagang Tunnel, transmission method of sensor data from in-situ computers to remote server and the analysis method are implemented. Finally, a health status alert subsystem including sound, animation, email and SMS is designed for users. The remote health monitoring system, which has been successfully working over seven months until now, is proved to meet the requirements of health monitoring of Zoumagang Tunnel.

KEYWORDS

Tunnel health monitoring, remote data transmission, real-time sampling, health status alert.

INTRODUCTION

Dongjiang-Shenzhen Water Supply Project is a very important project which pumps water from Dongjiang River and supplies drinking and irrigation water for the Dongguan and Shenzhen residents. Zoumagang Tunnel (Bai 2001; Li *et al.* 2004), located in Dongguan, Guangdong, has been built as a part of Dongjiang-Shenzhen Water Supply Project to conduct water through Zoumagang Hill. Zoumagang Tunnel is the longest tunnel in the water supply project and has a length of over 3,000 meters, a width of 6.4 meters and a height of 7.2 meters. The surrounding rock of Zoumagang Tunnel mainly consists of migmatite and belongs to class Ⅱ rock. Secondary lining method is used in the surrounding rock of Zoumagang Tunnel and the lining thickness of tunnel arch, sidewall and floor is about 300mm. Most of the surrounding rock keeps in the stable condition.

Recently, a new highway project connecting Conghua and Dongguan, Cong-Guan Highway Project, is planned to build two highway tunnels through Zoumagang Hill. According to the project proposal, these two highway tunnels are planned to be built above Zoumagang Tunnel. The location of two highway tunnels and Zoumagang Tunnel in Zoumagang Hill is illustrated in Figure 1.

The method of drilling and blasting is used in the construction of these two highway tunnels, that will have a great influence on the safety of Zoumagang Tunnel. Therefore, during the construction and operation of two highway tunnels, long-term monitoring is required to study the health status of Zoumagang Tunnel and manage the construction progress of the highway tunnels.

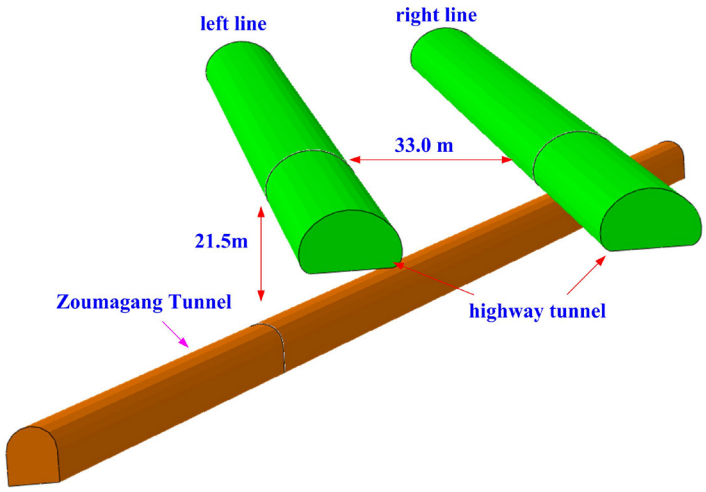

Figure 1. The location of two highway tunnels and Zoumagang Tunnel

As the depth of Zoumagang Tunnel is about 140 meters and the GRPS or 3G signals can't cover Zoumagang Tunnel, it's difficult to monitor the health status of Zoumagang Tunnel with the GRPS or 3G wireless sensors. In this study, we use the traditional sensors with wired connection and design and implement a remote real-time health monitoring system to solve the problems of long-term monitoring of Zoumagang Tunnel.

SENSORS PLACEMENT AND WIRED CONNECTION

To study the stability of Zoumagang Tunnel, the intersections of Zoumagang Tunnel and two highway tunnels are selected as the main monitoring area and equivalently divided into five monitoring sections. With the advice from the engineers of Cong-Guan Highway Project, two more monitoring sections extended about 40 meters from each intersection location are added to the monitoring area. Therefore, we mainly focus on the health status of these seven monitoring sections of Zoumagang Tunnel. The mileage numbers of these seven monitoring sections are Q2+077, Q2+117, Q2+142, Q2+167, Q2+192, Q2+217 and Q2+257, respectively. These monitoring sections are illustrated in the left part of Figure 2.

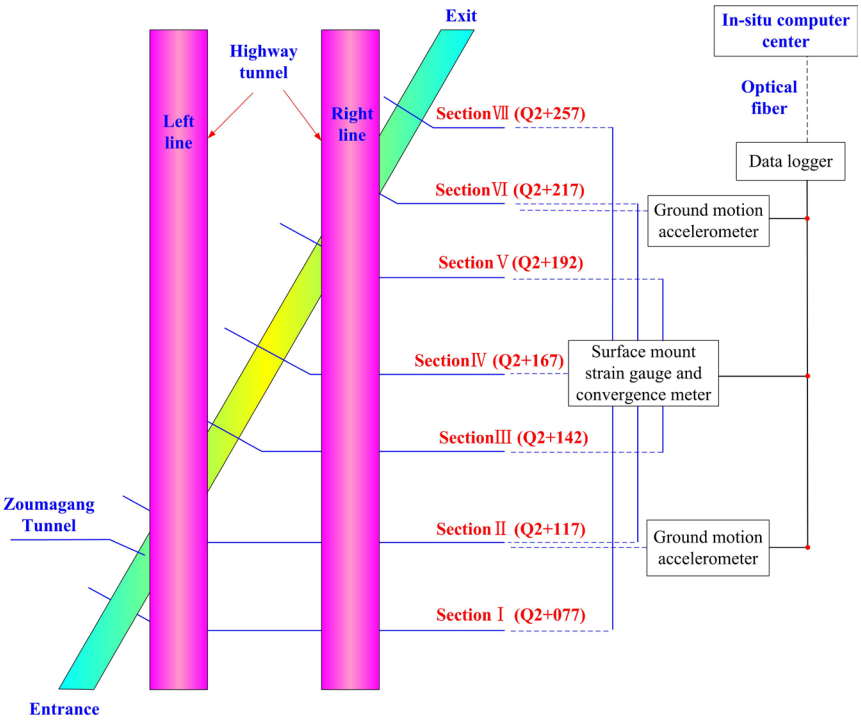

Figure 2. The schematic diagram of the monitoring system of Zoumagang Tunnel

Some sensors such as surface-mount strain gauges, convergence meters and ground motion accelerometers are placed in these seven monitoring sections. Surface-mount strain gauges and convergence meters are used to monitor the strain and deformation of Zoumagang Tunnel, while ground motion accelerometers are used to monitor the lining vibration of Zoumagang Tunnel during the drilling and blasting construction of the highway tunnels.

Each monitoring section composes of five monitoring points and the monitoring sensors are placed at these monitoring points. These monitoring points are located in the tunnel arch above the water surface. Thirty-five surface-mount strain gauges are placed at each monitoring point of each monitoring section and nine convergence meters are placed on the tunnel vault and at two monitoring points near the water surface in the sections of Q2+117, Q2+167 and Q2+217, while two ground motion accelerometers are placed on the tunnel vault in the sections of Q2+117 and Q2+217. The location of monitoring sensors in each section is illustrated in Figure 3 and the photo of monitoring sensors in section Q2+217 is shown in Figure 4. The type list of monitoring sensors is shown in the Table 1.

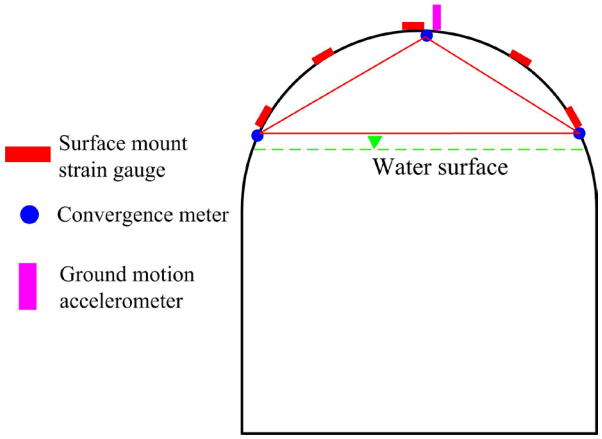

Figure 3. The location of monitoring sensors in each section

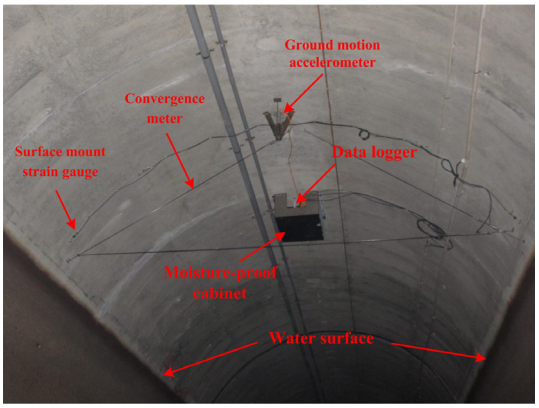

Figure 4. Monitoring sensors in section Q2+217

Table 1. The type list of monitoring sensors

Monitoring Sensor	Sensor Type	Number
Surface-mount strain gauge	Roctest SM-5A	35
Convergence meter	Gekon GK-4425	9
Ground motion accelerometer	Geosig AC-63	2

As monitoring data of all the monitoring sensors are collected by data logger, we need to connect the data logger to acquire the monitoring data. The in-situ computer center is about 4 kilometers far from the monitoring sections of Zoumagang Tunnel and monitoring data can't be transmitted so far by traditional data cables because of signal attenuation, so we use the optical fiber to transmit monitoring data and connect the data logger and the in-situ computer center. Photoelectric converters are also used on each end of the connection to convert electrical signals into optical signals or optical signals into electrical signals. The schematic diagram of the monitoring system including all the sensors and wired connection is illustrated in Figure 2.

SYSTEM DESIGN AND IMPLEMENT

In this study, the remote health monitoring system of Zoumagang Tunnel is developed in Visual C++ and runs on the platform of Microsoft Windows. The monitoring system is installed on the in-situ computer and remote server so that users working on the in-situ or in the remote office can observe the real-time monitoring data and check the health status. The remote health monitoring system adopts a new software UI style named Ribbon style, which is widely used in many latest software on Microsoft Windows, typically in Microsoft Office 2007 and 2010 versions. The screenshot of the monitoring system is illustrated in Figure 5.

The remote health monitoring system is an integrated system dealing with sensor data acquisition, transmission, storage and analysis. It consists of four subsystems: sensor data acquisition, sensor data transmission, monitoring data analysis and health status alert. These four subsystems and their research contents are shown in Figure 6 and described in the following sections.

Sensor Data Acquisition Subsystem

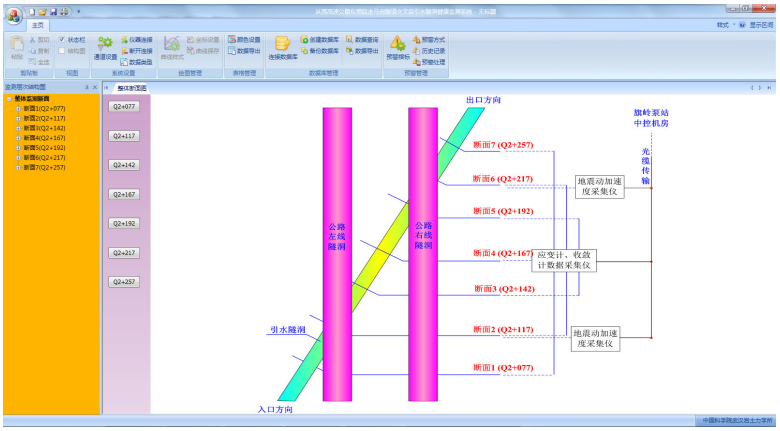

Figure 5 The screenshot of monitoring system

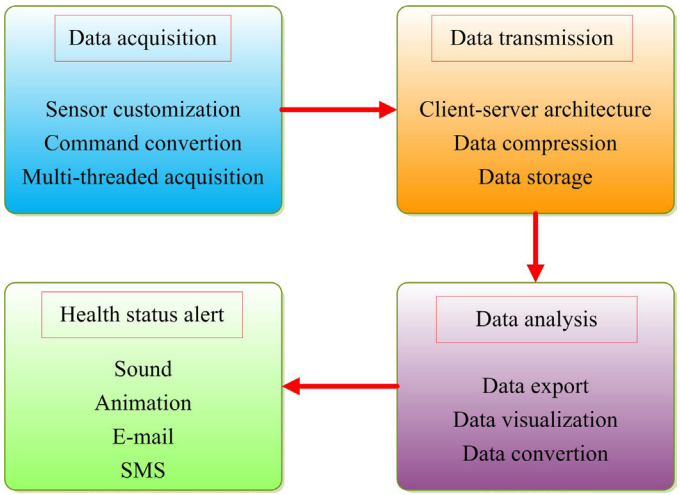

Figure 6. The four subsystems and their research contents

The sensor data acquisition subsystem is designed to acquire real-time monitoring data of all the monitoring sensors and control the communication of the in-situ computer and the data logger.

In the data acquisition subsystem, we provide a method for users to customize the monitoring parameters of sensors. For example, the blasting operation of the highway tunnels has a great influence on the safety of Zoumagang Tunnel so that the real-time sampling rates can be increased to get more sensor data and analyze the details when blasting operation happens. In addition, if a monitoring sensor doesn't work, users can remove it and add a new one at the same monitoring point. Meanwhile, the data acquisition subsystem needs to adapt to sensor change. The customization dialog box of monitoring sensors is shown in Figure 7.

Figure 7. The customization dialog box of monitoring sensors

A command convertion method is also provided in the data acquisition subsystem. The command convertion method is used to convert user commands to data logger commands and achieve sampling dynamic control for users. For example, if a user wants to stop the data logger sampling and then presses the stop button, the stop command defined by the data logger should be created in the subsystem before it is sent to the data logger. A C++ class is implemented to convert control commands such as starting sampling, stopping sampling and getting the status of a data logger. The more commands implemented in the subsystem, the more convenient for user to control the sensor sampling dynamically.

As over 40 sensors are deployed in the Zoumagang Tunnel and they are a little far away from the in-situ computer center, it will take at least several seconds for the data acquisition subsystem to collect all the sensor data. Multi-threaded design (Richter and Nasarre, 2011) is quite important to reduce the response time and increase the performance of the data acquisition subsystem. In this subsystem, a worker thread is created to communicate with the data logger. All the commands such as connecting the data logger and acquiring the monitoring data are transmitted via the worker thread. The feedback messages of the data logger such as sensor status and sensor data are also received via the worker thread. Moreover, the worker thread plays a key role in the real-time monitoring. For example, some useless feedback messages can be checked and ignored by the worker thread according to the message rules customized by users, which will efficiently reduce the times of data transfer and improve the real-time quality.

Sensor Data Transmission Subsystem

The sensor data transmission subsystem focuses on the research of data transmission including the relevant study such as transmission efficiency and data storage. Sensor data transmission is a very important part of the monitoring system, which is convenient for the users who work in the remote office to observe the real-time monitoring data, guide the progress of construction and make decisions with the experts.

As sampling rates of monitoring sensors can be changed by users when the monitoring system software is running, more sensor data may be collected than usual. This will increase the number of bytes transferred and reduce the transmission efficiency. The data compression method is applied in the data transmission subsystem to solve the problem. Zlib, a widely used data compression library and famous for its high compression ratio, free charge and portable across platforms, is used in the system. With the help of zlib library, sensor data can be compressed in the data stream and transmission time can be saved a lot.

In the sensor data transmission subsystem, the client-server architecture (Tanenbaum, 2002) is adopted to implement the remote transmission. The client-server architecture is a frequently used architecture that partitions tasks between the providers of a resource or service and the resource or service requesters. In this study, we partition the in-situ computer as a client and the remote server as a server, that is, the remote server will provide storage service for the in-situ computer to save monitoring data. The transmission mechanism is that the in-situ computer will send monitoring data to the remote server when receiving new monitoring data from the data logger. The remote communication between the in-situ computer and the remote server follows the TCP-IP protocols.

Data storage is also important for users to manage monitoring data in the data transmission subsystem. Data storage in the subsystem can be divided as two parts, data storage before transmission and data storage after transmission. Data storage before transmission is implemented in the in-situ computer to backup sensor data and retransmit lost sensor data during transmission. The implementation method is to save sensor data in Sqlite database, a famous open-source database system with its advantages of fast access speed, portable ability and open source. Data storage after transmission happens in the remote server when sensor data transmitted are received by the remote server. The solution of data storage after transmission is that sensor data are saved in Microsoft SQL Server database, a database system developed by Microsoft corporation with powerful database engine and complete function.

Monitoring Data Analysis Subsystem

The monitoring data analysis subsystem is designed to export, visualize and analyze the monitoring data stored in the database. Monitoring data can be read from the database and exported as a txt or Microsoft Excel file. Users can specify monitoring data of one or more monitoring sensors to export from the database. Also, monitoring data are visualized in the data analysis subsystem, such as being drawn as broken lines on the

figure and shown in the table. Users can review the broken lines or data table to find abnormal monitoring data.

Monitoring data need to be converted because the original values of monitoring sensor such as surface-mount strain gauges and convergence meters are collected as frequency values. Monitoring data of surface-mount strain gauges are converted without considering the effect of temperature as the temperature changes little in monitoring area of Zoumagang Tunnel. The convertion equation of surface-mount strain gauge can be expressed as

$$\varepsilon = G(f^2 - f_0^2) \tag{1}$$

where f is the measured frequency of monitoring sensor, f_0 is the initial frequency of monitoring sensor and G is the gauge factor. Monitoring data of convergence meters are also converted without considering the effect of temperature. The convertion equation of convergence meter can be express as

$$S = K(f^2 - f_0^2) \tag{2}$$

where f is the measured frequency of monitoring sensor, f_0 is the initial frequency of monitoring sensor and K is the gauge factor. In this study, we use the first measured frequency as the initial frequency f_0 and set G=4.0624*10^{-3}, K=3.0*10^{-5}.

Health Status Alert Subsystem

The health status alert subsystem is to remind users if something is in dangerous or emergent status. In the health status alert subsystem, the alert rules, especially the alert levels of measurements of monitoring sensors, are defined first by experts so that users can make clear the alert status of Zoumagang Tunnel.

An alert message generator of the subsystem is designed to describe the alert level, illustrate the details of monitoring sensors and give some advices for users when necessary. The alert message generator runs in the background and checks all the monitoring data according to the alert rules.

Many alert methods such as sound, animation, E-mail and SMS (Short Message Service) are implemented in the health status alert subsystem. The sound alert method is to make sounds which are specified by users or according to the default setting of the subsystem. Users can specify different sounds and define these sounds as different alert levels. The animation alert method is to use some flash buttons with different colors which also stand for different alert levels. These buttons begin to flash if the alerts of corresponding levels are triggered. The E-mail and SMS alert methods are to send E-mail and SMS to relevant users. The alert setting dialog box is shown in Figure 8.

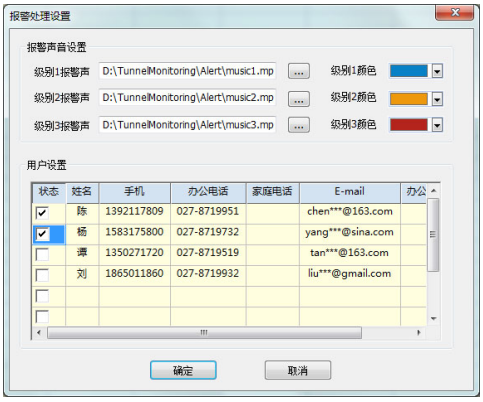

Figure 8. The alert setting dialog box

APPLICATION

The remote health monitoring system has been applied in Zoumagang Tunnel for over seven months. All the monitoring sensor data are collected at a frequency of once per hour and saved in the monitoring system. To simply the description of this section, we will take sensor data acquired from section Q2+117 during the latest seven months as an example. Figure 9 and Figure 10 show the broken line graphs of strain measurements and convergence measurements of section Q2+117. From the two figures, we can find that sensor data are continuously collected during the latest seven months, which is proved that the monitoring system is running

well. The broken lines between March 22 and April 8 look like straight lines because the power supply maintenance happened during this period, which led to stop collecting sensor data. Figure 11 shows the data table where more details of sensor data such as the exact sampling time and values are listed.

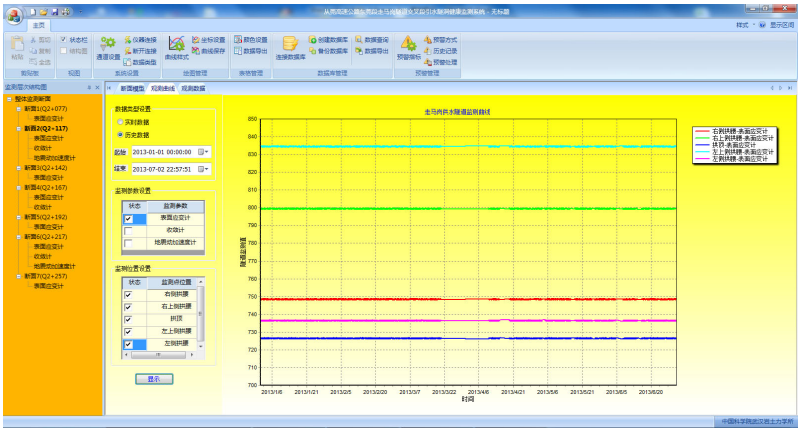

Figure 9. The broken lines graph of strain measurements

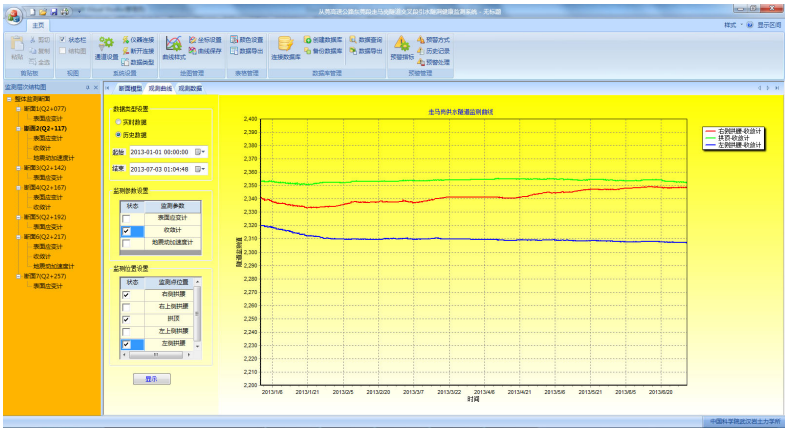

Figure 10. The broken lines graph of convergence measurements

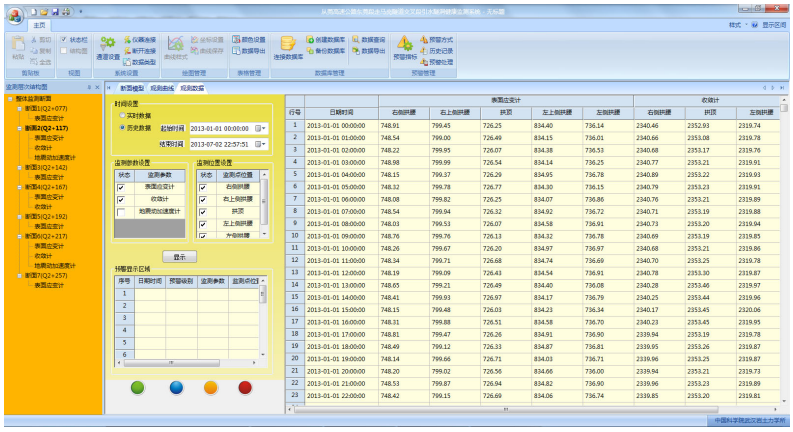

Figure 11. The data table of monitoring data

In this study, we mainly focus on the health status of Zoumagang Tunnel under the impact of highway construction, especially the impact of blasting operation. From Figure 9 and Figure 10, we can find that the strain measurements and the convergence measurements of section Q2+117 change very little, which shows that highway construction has little impact on Zoumagang Tunnel, that is, the health status of section Q2+117 is in safety. In order to further verify the conclusion, the minimum and maximum extremum of monitoring sensors listed in Table 2 are in the allowable range, which means that all the sensor data of section Q2+117 are acceptable and section Q2+117 is safe. Sensor data of other sections are checked by the same method. It's proved that most of sensor data are in the allowable range and Zoumagang Tunnel is safe.

CONCLUSION

The remote health monitoring system of Zoumagang Tunnel developed by authors has been working successfully for over seven months. All the sensor data can be continuously collected without any loss except

Table 2. The minimum and maximum extremum of monitoring sensors

Monitoring Sensor	Location	Minimum	Maximum	Reference
Surface-mount strain gauge(με)	Left	0	8	50
	Left-top	0	10	50
	Tunnel vault	0	11	50
	Right-top	0	12	50
	Right	0	9	50
Convergence meter(mm)	Left	-0.18	0.01	0.5
	Right	-0.12	0.09	0.5
	Horizon	-0.04	0.01	0.5
Ground motion accelerometer(g)	Tunnel vault	-0.01	0.02	0.05

during the period of power supply maintenance. It can be concluded that Zoumagang Tunnel is safe under the construction of two highway tunnels because most of sensor data collected over seven months are acceptable. The health monitoring system has the advantages of low costs, high automation and high efficiency and is convenient for users to monitoring health status and manage the monitoring sensors. The application shows the monitoring system can meet the requirements of health monitoring of Zoumagang Tunnel.

ACKNOWLEGEMENT

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