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Long-Term Safety Monitoring System Design and Risk Control for Submarine Tunnel

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Abstract: The research on the long-term safety monitoring system of major projects has increasingly drawn the attention of project researchers and scientific researchers. It is of great significance to the research on long-term stress condition of project structure, disaster prewarning and preventing, and disaster risk management. Xiang'an Submarine Tunnel in Xiamen, the first submarine tunnel in China, tunnels through complex stratum conditions. Landslide, water inrush, mud burst and other geologic hazards can easily occur during the period of tunnel construction and operation. Long-time safety monitoring of the tunnel structure must be done in order to get the mechanical property and deformation characteristics of the tunnel structure in the operation period in real time, to make instant and accurate evaluation of the structure safety and to avoid the happening of geologic hazards. Based on the long-term monitoring research on submarine tunnel with Xiang'an Submarine Tunnel being the subject, this dissertation establishes a long-term monitoring system of submarine tunnel, and insists that long-term monitoring system comprises monitoring project setup, measuring points placement, sensor system constituents and type selection, data acquiring device selection and automation monitoring system networking. The establishment of long-term monitoring safety management standards of submarine tunnel includes the secondary-lining displacement management standard for submarine tunnel, the stress management standard for the secondary lining, hydraulic pressure management standard, reinforced steel corrosion monitoring management standard, and earthquake acceleration management standard. This reserach also tries to develop the long-term monitoring system software for submarine tunnel, implement the long-term monitoring data acquisition in real time, data analysis, structure safety decision and prewarning for submarine tunnel. It is expected that the research findings in this study can provide reference for the long-term monitoring, disaster prewarning and risk management of submarine tunnel which is under construction or to be constructed home and abroad.

Keywords: Submarine tunnel; Long-term monitoring; Disaster warning; Risk control

1 Introduction

Long-term structural safety monitoring is a relevant tool to obtain useful information aimed at the safety and maintenance of infrastructures. It is an information source of utmost importance concerning the structural performance. Long-term structural safety monitoring has evolved to become economically advantageous contributing to a more efficient exploitation of the infrastructures [1-3].

In recent years, the long-term structural safety monitoring project research on key projects has been increasingly attached to importance in the project world, because this type of research has great significance for the research on long-term stress condition of project structure, disaster warning and preventing, and disaster risk management. There are long-term structural safety monitoring researches on large-scaled bridge, concrete pavement, reservoir dam and large-scaled slope both home and abroad, and these researches have made makeable social and economic benefits. Long-term monitoring systems have been implemented on bridges in Europe [4, 5], the United States [6, 7], Canada [8, 9], Japan [10, 11], Korea [12, 13], and other countries. Typical examples are the Confederation Bridge in Canada [14], the Commodore Barry Bridge in United States [15], the Akashi Kaikyo Bridge in Japan [16], and the Seohae Bridge in Korea [17]. In China, typical examples are the Tsing Ma Bridge in Hong Kong [18], the Nanjing Yangtse River Bride [19], Wuhu Yangtze River Bridge [20], and so on, the objectives are to establish the structural safety monitoring and state assessment system to monitor the structural responses and working conditions in real time and to analyse the structural working state using information obtained from the measured data and assess the reliability and it will be also provided the scientific decision making bases for the bridge management and maintenance. However, for underground structures, the application of monitoring systems during construction and operation is scarcely put into practice [21, 22].

The complex geologic condition bored through by submarine tunnel, the large hydraulic pressure, the material property degeneration and earthquake caused by sea water corrosion and other factors seriously threat the safety of submarine tunnel. If the structure of the tunnel is destroyed in the operation period, geologic hazards such as landslide, water inrush, mud burst, etc easily occur, and such hazards can result in catastrophic consequences to the safety of the lives and property of human beings. Therefore, developing safe and long-term monitoring and risk management research in the period of submarine tunnel operation, making real-time monitoring for the mechanical state and deformation state for the tunnel structure, making safety evaluation and disaster risk evaluation instantly and accurately, and avoiding geological hazards happening can have great theoretical value and practical meaning.[23]

Xiang'an Submarine Tunnel in Xiamen, which is the first submarine tunnel in China, tunnels through different positions, tunnels through partially and down tunnels through multiple fault zones; the fault zones are completely-weathered granites which are very thick and form weathered ditches; the fault zone is low in rock strength, weak in self-stabilizing property and is subject to permeable disastrous geological disasters. Therefore, with Xiang'an Submarine Tunnel in Xiamen as the research subject, this dissertation tries to develop the research on long-term safety monitoring system design and risk management for submarine tunnel, and it is hopes the research findings generate precious reference value for similar projects both home and abroad.

2 Structure of WDM Network

2.1. Monitoring project and cross-section arrangement

The cross-section arrangement monitoring of the long-term safety monitoring system is based on the principle of the engineering geology and hydrologic geology places where geological disasters easily happen, such as the weathered ditch zone (F1, F2, F3, F4) crossed by a tunnel, the shallow barrel burial zone, the fault zone belt, the shaft and other supporting structures in unstable engineering geological condition and the tunnel barrel deforming easily. Therefore, the arrangement for the monitored cross-section of Xiang'an Submarine Tunnel is like this: twelve cross-sections on the left line tunnel, eight cross-sections on the right line tunnel, one cross-section on the service tunnel, and in total, there are twenty-one cross-sections.

The range of the long-term monitoring for Xiang'an Submarine Tunnel includes: (A) the support hydraulic pressure monitoring at the initial state; (B) the contact pressure monitoring between the surrounding rocks and the initial supports; (C) the stress monitoring of section steel in the primary support; (D) hydraulic pressure monitoring in the secondary lining; (E) the contact pressure monitoring between the initial stage supports and the secondary lining; (F) the stress monitoring in the secondary lining; (G) the surface strain monitoring in the secondary lining; (H) earthquake monitoring; (I) the displacement monitoring in the secondary lining; (J) the reinforced steel corrosion monitoring. The monitoring cross-sections and the monitoring projects are listed in table 1.

2.2. Sensor system

The sensor system mainly comprises a deformation monitoring sub-system, a fiber grating sensor sub-system, a vibrating wire sensor sub-system, a corrosion sensor system and an earthquake acceleration sensor sub-system. The composition of the sensor system is shown in figure 1.

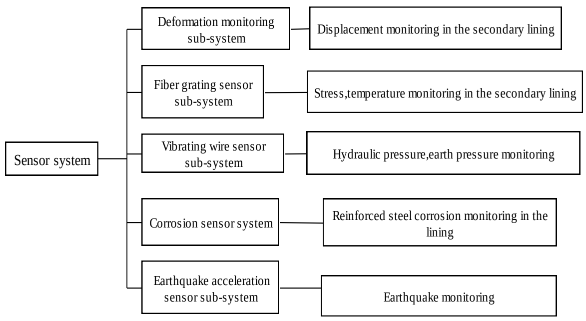

Figure 1 Sensor system composition

Due to the importance of long-term safety monitoring for submarine tunnel and the working environment where the sensor is corroded by sea water, this research launched a wide range of investigations into the rock soil sensor property both home and abroad, and eventually determines the types of the sensor, which is shown in Table 2.

Table 1 Cross-sections and monitoring projects of long-term safety monitoring for Xiang'an Submarine Tunnel

Tunnel name	Section Numbering	Section mileage	Geological conditions	Monitoring projects A	B	C	D	E	F	G	H	I	J
Passenger tunnel (Left line)	1	ZK7+050	Soft rock, shallow						√				
	2	ZK7+150	Soft rock, shallow						√				
	3	ZK8+283	F1						√				√
	4	ZK8+893	F1				√	√					
	5	ZK8+905	F4					√	√				
	6	ZK8+912	F4	√	√	√	√	√	√	√		√	√
	7	ZK8+918	F4					√	√				√
	8	ZK8+967	Soft rock					√	√				√
	9	ZK10+168	F2						√				
	10	ZK10+178	F2						√				√
	11	ZK10+188	F2						√				
	12	ZK10+198	F2						√				√
Service tunnel	13	NK8+950	Soft rock				√	√	√				√
Passenger tunnel (Right line)	14	YK8+414	F4						√				
	15	YK8+424	F4	√	√	√	√	√	√	√	√	√	
	16	YK8+434	F4					√	√				√
	17	YK10+680	F2						√				√
	18	YK11+050	Soft rock						√				
	19	YK11+290	Soft rock					√	√				
	20	YK11+310	Soft rock					√	√				
	21	YK11+315	Soft rock					√	√				

Table 2 Monitoring projects and sensor of long-term safety monitoring for Submarine Tunnel

Monitoring projects	Sensor	Measurement range	Precision
Contact pressure	TPC Type vibrating wire soil pressure gauge	0~2MPa	± 0.1%F.S.
hydraulic pressure	PWS Type vibrating wire osmometer	0~1MPa	± 0.1%F.S.
Displacement of secondary lining	vibrating wire displacement sensor	25mm	± 0.1%F.S.
	Electrolyte type angular displacement sensor	±50 °	0.01Radian
Stress of secondary lining	Embedding Fiber Bragg Grating strain sensor	±1500$\mu\varepsilon$	± 0.2%F.S.
surface strain of secondary lining	Surface Fiber Bragg Grating strain sensor	±1000$\mu\varepsilon$	± 0.2%F.S.
Stress of section steel in the primary support	Bonded Fiber Bragg Grating Strain Sensor	±1500$\mu\varepsilon$	± 0.2%F.S.
Concrete temperature	Fiber Bragg Grating Temperature Sensor	-50℃ ~ +150℃	± 0.2%F.S.
Earthquake acceleration	AC-63 three-direction acceleration sensor	±0.5g	<0.2%

2.3 Data acquiring system

1. Data acquiring device

Data acquisition mainly comprises structure deformation data acquisition, fiber grating strain data acquisition, vibrating wire stress, strain, soil pressure and hydraulic pressure data acquisition, earthquake acceleration data acquisition and reinforced steel corrosion data acquisition. These data acquisitions are shown in figure 2.

2. Automation monitoring system networking

(1) Vibrating wire type and electrolyte type sensors networking scheme

The simulated signal sensors of cross-section positions installed by vibrating wire type and electrolyte balanced type are relatively concentrated. The number of the data acquisition channels (including the reading of the sensors' temperature) needed by the simulated signal type sensors, the sensor signal transmission distance, the data remote transmission and other factors are taken into integrative consideration; the automation data acquisition system of the simulated signal type sensor is optimally combined into three sets of Microprogrammed Control Units (MCU). The MCU comprises a DT515 data acquisition instrument, an electric power system, a surge release module and a waterproof chassis, and these components are respectively installed in YK8+428, ZK8+910 and YK11+310 these three mileages which are respectively called MCU-1, MCU-2 and MCU-3. The networking of the vibrating wire type sensor and the electrolyte type sensor are shown in figure 3.

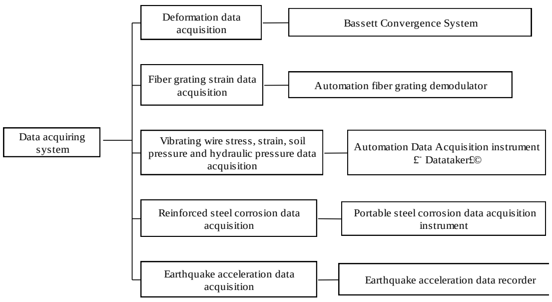

Figure 2 Data acquiring system composition

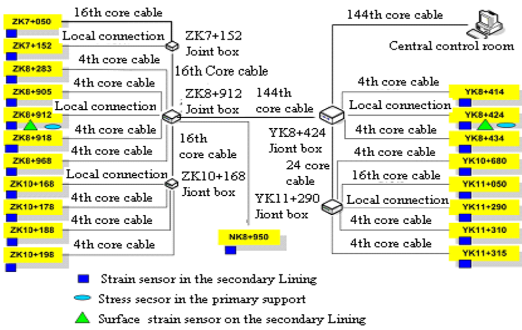

Figure 4 Graph of fiber grating sensor networking

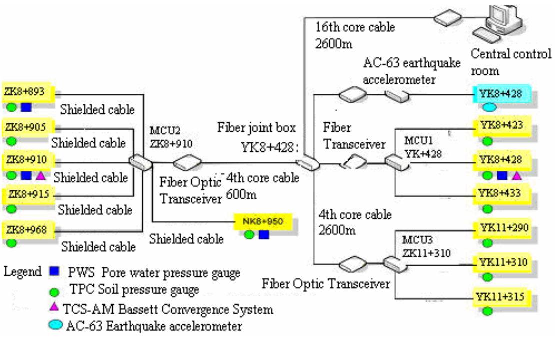

Figure 3 Schematic diagram of networking of the vibrating wire type sensor and the electrolyte type sensor

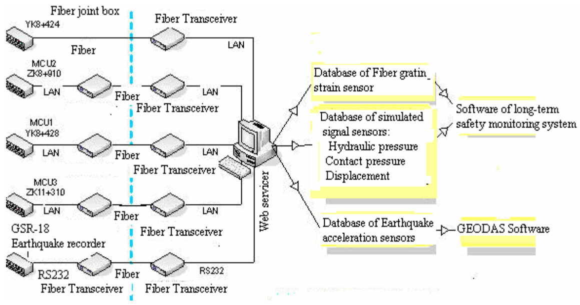

Figure 5 Data flow in the master control chamber

(2) Fiber grating sensor networking

After the fiber sensor is installed, the signal fiber networking reserved in the pre-buried electric cable is switched in the signal junction box in corresponding position and later is switched in the bus junction box. Finally, the signal fiber networking is switched in the monitoring center through the master communication optic-cables. The fiber grating sensor networking graph is shown in figure 4.

2.4 Data management system

As shown in the long-term safety monitoring data type, the long-term safety monitoring data features in large quantity and multiple types of data. To store the data effectively, all the data gained from the data acquisition instrument can be read into a database. The data flow in the master control chamber can be seen in figure 5.

3. Risk control in long-Tterm safety monitoring

Through theory analysis, model test, numerical simulation and other means, the structure deformation management standard, the stress management standard, the hydraulic pressure management standard, the earthquake acceleration management standard and the reinforced steel corrosion management standard are established for Xiang'an Submarine Tunnel. The tunnel structure safety in the operation period is judged according to the monitoring result, which can prewarn and prevent geological disasters.

3.1. Secondary lining displacement management standard

The secondary lining displacement management standard for Xiang'an Submarine Tunnel is shown in table 3.

3.2. The stress management standard for secondary lining structure

The concrete strength level of the Xiang'an Submarine Tunnel is C50, and the ultimate compressive strength and the ultimate tensile strength are respectively 36.5 MPa and 3.1MPa. Based on said standards, the stress management standard is established, which is shown in table 4.

3.3. The determination of the stress management standard (MPa) for secondary lining structure of Xiang'an Submarine Tunnel

The hydraulic pressure control standards under the condition of different surrounding rock types and supporting types in Xiang'an Submarine Tunnel are shown in table 5 and table 6.

Table 3 The secondary lining displacement management standard for Xiang'an Submarine Tunnel

Surrounding rock classification	Burial depth type	Type of supporting structure	Limit displacement (mm)	
			Vault	Side wall
Ⅴ	deep burial	S5d	5~10.8	6~7.4
	shallow burial	S5c	4.0~8.6	5~6.5
Ⅳ	deep burial	S4b	3.1~7.2	3~5.7
Ⅲ	deep burial	S3b	5.2~8.9	4~5.3

Table 4 The stress management standard (MPa) for secondary lining structure of Xiang'an Submarine Tunnel

Concrete grade	Management stress	Degrees of hazard	Managerial class	Repair and maintenance measures
Concrete grade C50	$\sigma_- < -36.5$	Destructive	I	Special examination
	$-36.5 < \sigma_- \leqslant -24.3$	Dangerous		
	$-24.3 < \sigma_- \leqslant -12.2$	Abnormal	II	Contingent examination
	$\sigma_- \geqslant -12.2$	Normal	III	Regular examination
	Management stress	Degrees of hazard	Managerial class	Repair and maintenance measures
	$\sigma_+ > 3.1$	Destructive	I	Special examination
	$2.1 < \sigma_+ \leqslant 3.1$	Dangerous		
	$1 < \sigma_+ \leqslant 2.1$	Abnormal	II	Contingent examination
	$\sigma_+ \leqslant 1$	Normal	III	Regular examination

Notes: σ_- refers to press stress; σ_+ refers to tension stress

Table 5 The hydraulic pressure P_n control standard of Xiang'an Submarine Tunnel

Surrounding rock classification	Burial depth type	Underground water types	Type of supporting structure	Critical hydraulic pressure (kPa)	Reduced water head (m)
Ⅴ	Deep burial	marine zone	S5d	575	57.5
	Shallow burial	marine zone	S5d	363	36.3
	Deep burial	Intertidal zone	S5c	237	23.7
Ⅳ	Deep burial	Marine zone	S4b	542	54.2
Ⅲ	Deep burial	marine zone	S3b	463	46.3

Table 6 Hydraulic pressure management standard for Xiang'an Submarine Tunnel

Managerial hydraulic pressure	Degrees of hazard	Managerial class	Repair and maintenance measures
$P > P_n$	Unsafe	I	Special examination
$2/3P_n < P \leq 2/3P_n$	Dangerous		
$1/3P_n \leq P \leq 2/3P_n$	Comparatively Safe	II	Contingent examination
$P < 1/3P_n$	Safe	III	Regular examination

Notes: P is the actual measured hydraulic pressure; P_n is corresponding critical hydraulic pressure

3.4. Corrosion monitoring management standard

Aiming at the fiber grating physical sensor, the reserved sensor joint is connected into the acquiring instrument to read the grating center wavelength. The variable quantity of the center wavelength of each sensor is reduced to the volumetric change of reinforced steel. The reduced volumetric change of the reinforced steel is compared with the original volume of the reinforced steel, and then the corrosion degree of the reinforced steel is evaluated. For the reinforced steel used in the secondary lining of Xiang'an Submarine Tunnel, its diameter is 25mm. The corrosion evaluation standard is listed as follows:

When $\Delta\lambda_b$ ranges from 0-3nm, the corrosion rate is 0-0.5%, and the corrosion degree is slight; when $\Delta\lambda_b$ ranges from 4-6nm, the corrosion rate is 0.5%-1%, and the corrosion degree is medium; when $\Delta\lambda_b$ ranges from 7-9nm, the corrosion rate is 1%-1.5%, and the corrosion degree is serious. $\Delta\lambda_b$ is the center wavelength variable-quantity of the fiber grating corrosion sensor.

3.5. Earthquake acceleration management standard

The designed earthquake peak acceleration of Xiang'an Submarine Tunnel is 0.15g. Therefore, in the long-term monitoring, when the earthquake peak acceleration is more than 0.15g, a structure damage inspection should be done instantly.

4 Long-term monitoring system software development

To meet the need of long-term real-time monitoring and safety evaluation for the submarine tunnel in the operation period, this research develops an automation management system integrating data acquisition, data analysis, structure safety decision and warning.

The software system comprises the server terminal and the client terminal PC subsystems. The server terminal PC subsystem is responsible for inputting initial data and makes operations such as calculation, statistics, analysis, process, etc to the input data, forms final measuring data (the engineering quantity) and stores the data in a database according to certain rules. Further, the server terminal PC subsystem displays the data in real time, makes alarm indications, queries and derives relevant data. The client terminal PC subsystem only receives the synchronous data from the server terminal PC subsystem, and displays the synchronous data in real time, makes alarm indications, queries and derives relevant data, etc. The long-term monitoring system frame of the Xiang'an Submarine Tunnel is shown in figure 6. The functional module setup in the software is shown in figure 7.

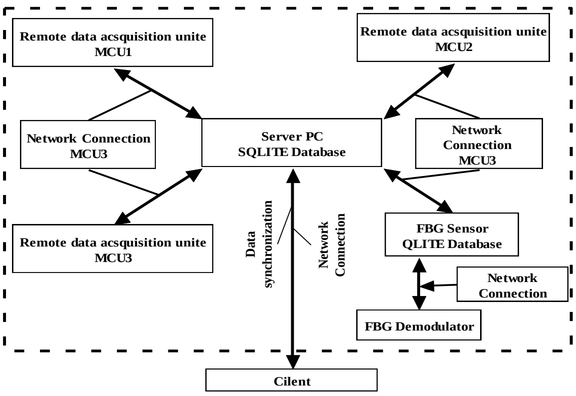

Figure 6 Frame diagram of Long-term safety monitoring system for Xiang'an Submarine Tunnel

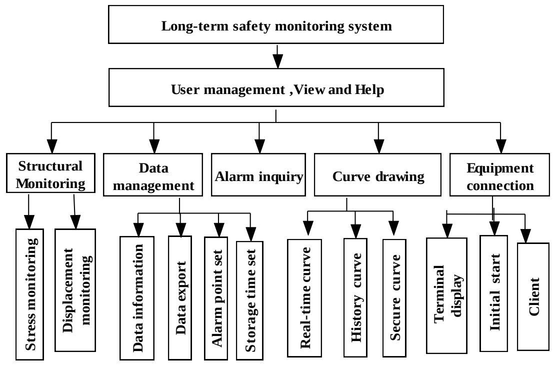

Figure 7 Function module of Long-term safety monitoring system for Xiang'an Submarine Tunnel

5 Conclusions

With Xiang'an Submarine Tunnel in Xiamen being the subject, this dissertation develops the long-term safety monitoring system design and risk management for submarine tunnel and mainly gets following findings:

(1) The establishment of a long-term monitoring system of submarine tunnel which comprises monitoring project setup, measuring points placement, sensor system constituents and type selection, data acquiring device selection and automation monitoring system networking.

(2) The establishment of long-term monitoring standards of submarine tunnel for safety analysis management which includes the secondary-lining displacement management standard for submarine tunnel, the stress management standard for the secondary lining, hydraulic pressure management standard, reinforced steel corrosion monitoring management stand, and earthquake acceleration management standard.

(3) This research develops a long-term monitoring system software of submarine tunnel and implements long-term monitoring data acquisition in real time, data analysis, structure safety decision and prewarning for submarine tunnel.

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