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Establishment of Nanchang Honggu Tunnel health monitoring and assessment system

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Abstract: Based on the background of the Nanchang Honggu Tunnel, which is the largest inland river immersed tunnel to date in China, some research work on the construction of the Nanchang Honggu Tunnel health monitoring and assessment system is introduced. The platform of the health monitoring and assessment system is established with a relatively mature structure, including the sensor subsystem, data acquisition subsystem, data transmission subsystem, database subsystem, data processing and control subsystem, and health assessment and pre-warning subsystem. Monitoring index selection, sensor selection and sensor layout are fully considered in the health monitoring design and technology scheme. The fuzzy-AHP (analytic hierarchy process) evaluation method is employed to establish the Honggu Tunnel health assessment model, and the index weight determination method and grading control criterion are investigated and given. Then, the functions of the software system are achieved with advanced cloud platform technology, and the running costs of the system is reduced greatly. In summary, the establishment of the Nanchang Honggu Tunnel health monitoring and assessment system is described and such a system can realize real-time monitoring of the Honggu Tunnel and make it more convenient for implementing health assessment, pre-warning, and some other functions. Managers can operate the system using PCs and cell phones. At the same time, the relevant work on this system can provide a good reference for other immersed tunnels.

Key words: immersed tunnel; health monitoring; system platform; analytic hierarchy process (AHP) model

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In the dual role of long-term natural environment and operation environment, leakage, unhomogeneous deformation, cracks and other structural disease will threaten the operation safety performance and service performance of the immersed tunnel. Furthermore, maintenance difficulty and financial costs increase dramatically with the increase in disease degree. Therefore, it is important to understand the development of tunnel disease and analyze the health status of the structure in real-time, so as to make timely maintenance strategies.

Since the 1990s, health monitoring systems have attracted the attention of academia and the engineering community. In civil engineering, the health monitoring system was applied to bridges, such as Shanghai Xupu Bridge[1], Flintshire Bridge[2], Akashi Kaikyo Bridge[3], and Great Belt East Bridge[4]. Subsequently, it was applied to buildings and shield tunnels, such as the building in Japan[5], the LBPSB building in California[6], Stafford Medical Building in Vermont University[7], the high-speed rail tunnel in Korea[8], and the bored tunnel in Singapore[9]. Immersed tunnels have also been built with health monitoring systems recently, such as the Yongjiang immersed tunnel[10] and Zhoutouzui immersed tunnel[11] in China.

The Nanchang Honggu Tunnel is the largest inland river immersed tunnel in China with complex geological and fracture conditions. The construction of the health monitoring and assessment system will provide strong support for its safe and economic operation and maintenance. Structure health monitoring and assessment cases of large immersed tunnels are rarely seen in the literature to date. There is no monitoring and structural health assessment criteria for immersed tunnels in China. The structural health monitoring and assessment system of this project has to be designed according to the hydrological, geological, structural characteristics and technical requirements of the operation, maintenance, monitoring and health assessment of the tunnel.

Based on the construction practice of the Nanchang Honggu Tunnel health monitoring and assessment system, this paper describes important contents of the health monitoring scheme, sensors layout, health assessment model and software functions.

1 Engineering Background

The total length of Nanchang Honggu Tunnel is about 2 650 m, including 1 305 m immersed tube section. Among 12 immersed tube segments, nine separate segments make up a total of 115 m in length, and the other three are 90 m. Construction clearance is 11.5 m × 4.5 m, and the cross section size is 30 m × 8.3 m. The runoff of the Ganjiang river is concentrated in April to June,

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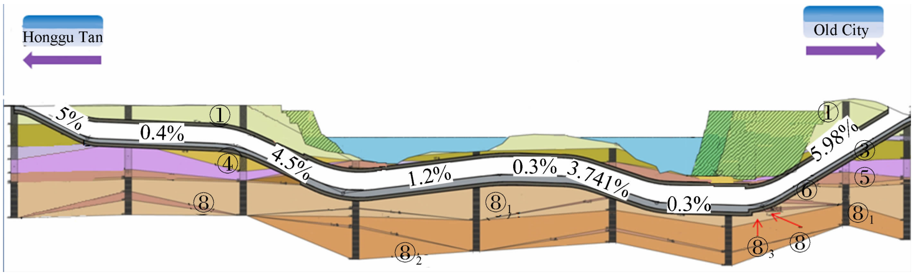
accounting for 49.6% of the year, which causes a highly fluctuating water level from the rainy season to dry season. Fig. 1 shows the tunnel crossing file and stratigraphic distribution, and Fig. 2 shows the tunnel cross section.



①— Backfill; ③— Fine sand; ④— Medium sand; ⑤ —Coarse sand; ⑥ —Gravel sand
⑧—Strongly weathering powder sandstone; $⑧_1$—Medium weathering powder sandstone
$⑧_2$—Slightly weathering powder sandstone; $⑧_3$—Calcareous mudstone

Fig. 1 Tunnel crossing profile and stratigraphic distribution

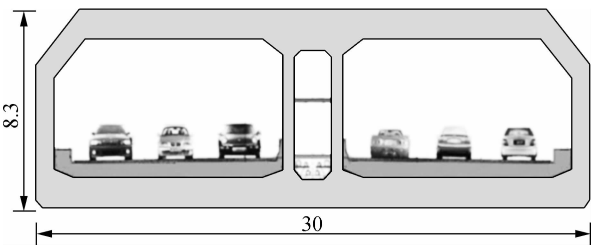


Fig. 2 Tunnel cross section (unit: m)

2 Honggu Tunnel Health Monitoring and Assessment System Platform

The Honggu Tunnel health monitoring and assessment system consists of the hardware system and software system. The hardware system includes the sensor subsystem, data acquisition subsystem and data transmission subsystem. The software system includes the database subsystem, data processing and control subsystem, and the health assessment and pre-warning subsystem. The functions of the whole system are realized by the coordination of each subsystem. Fig. 3 shows the platform architecture of the Honggu Tunnel health monitoring and assessment system.

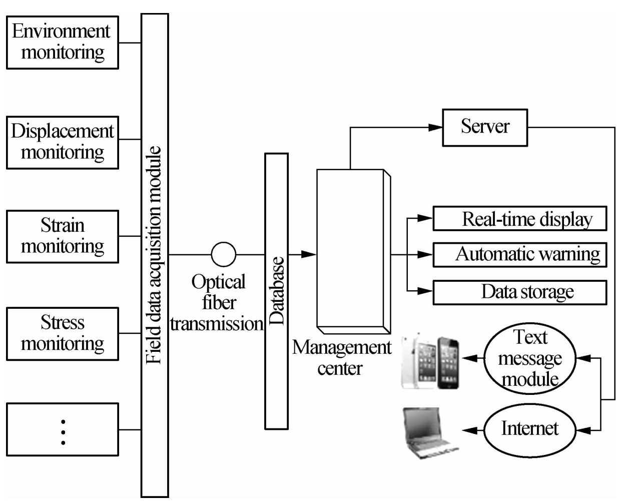


Fig. 3 Platform architecture of the health monitoring and assessment system

- Sensor subsystem As a basic part of the whole monitoring system, the automatic monitoring sensor subsystem is the sensing layer, which can provide authentic, real-time and reliable monitoring data for all monitoring items. It includes the pre-buried magnetic flux sensor, pressure box, crack gauge, buried strain gauge and steel bar meter, etc.
- Data acquisition subsystem The data acquisition subsystem's role is to collect signals such as sound, light, electricity and magnetism, which are measured by the sensor subsystem, and process them into digital signals. Various acquisition equipment is used according to various output signals in this project. The magnetic flux collection instrument V1.0 corresponds to the magnetic flux sensors, the multi-channel vibration acquisition instrument corresponds to the pressure box, buried strain gauge and steel bar meter, and the signal data acquisition system V1.0 corresponds to the crack meter.
- Data transmission subsystem The digital signals processed by the data acquisition subsystem are required for sending to the database center for analysis and processing through the data transmission subsystem. In view of the fact that the wireless signal is weak in the Honggu Tunnel, the sensors are integrated through the wired mode, and then, data is transmitted to the monitoring center through the optical fibers, and then to the cloud base via the network. Data access is performed on computers of the mobile terminals.
- Database subsystem The database subsystem is a data processing system. In this project, the tunnel manager is administrated to share the database with the software system maintenance company which is the database operator.
- Data processing and control subsystem Data transmitted from the data transmission subsystem requires further processing and analysis through data processing and the control subsystem. This subsystem implemented the

data query, storage, extraction, processing and visualization, etc., and controlled data acquisition equipment installed in the tunnel.

- Health assessment and pre-warning subsystem The main function of the health assessment and pre-warning subsystem is to evaluate and analyze the health status of each monitoring section and the whole structure based on the established Honggu Tunnel health assessment model and sent out real-time warnings of the corresponding health status.

3 Health Monitoring and Assessment System

3.1 Honggu Tunnel health monitoring technical scheme

Monitoring indices are selected by considering the tunnel design scheme[12-14] and geological condition. Fig. 4 shows the details of the monitoring sensors' placement.

The implementation of monitoring contents is based on the combination of real-time monitoring and artificial regular monitoring. Monitoring content and corresponding sensors are listed in Tab. 1.

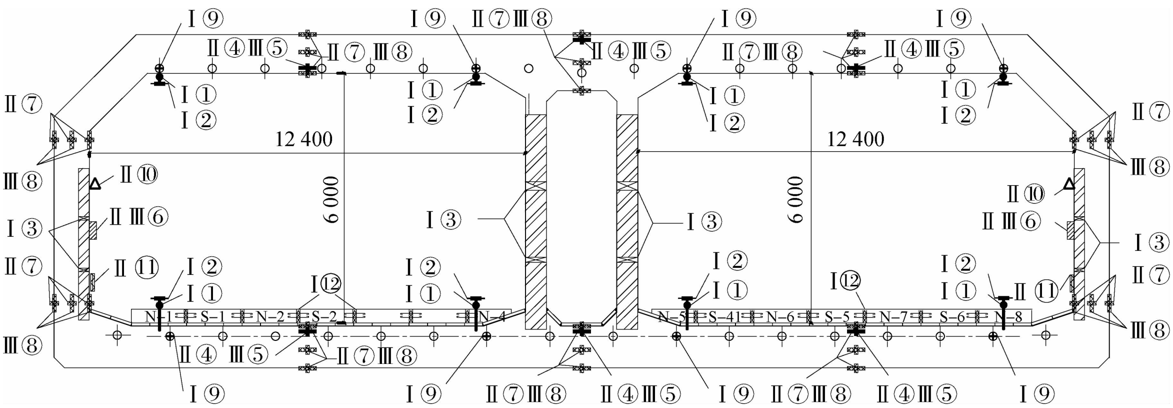
The pipe joint section is very vulnerable. Once uneven settlement or tensile displacement between adjacent pipes exceeds the shear key or rubber gaskets' capacity, shear key or rubber gaskets will fail, which can cause the tunnel to be out of operation. Therefore, in this project, sensors are mainly placed in the pipe joint section, the maximum height of water level section, the middle of the tunnel segment section and where the longitudinal gradient changes.

3.2 Honggu Tunnel health assessment model

3.2.1 Establishment of hierarchical assessment model

Comprehensive assessment of the immersed tunnel transforms the tunnel structure into a number of key indicators, and then the evaluation criteria of the indicators is established by theoretical research, engineering experience and existing specification. The mathematical model of comprehensive assessment methods is introduced to calculate the reference value F, which reflects tunnel health status[15-18].

The analytic hierarchy process (AHP) method[19] is adopted to establish the Honggu Tunnel health assessment model. Fig. 5 shows the details of the model.



①—Joint displacement (longitudinal); ②—Joint displacement (transverse); ③—Shear key stress(vertical);
④—Rebar stress (transverse); ⑤—Rebar stress (longitudinal); ⑥—Tunnel settlement;
⑦—Concrete stress (transverse); ⑧—Concrete stress (longitudinal); ⑨—PC cable tensile force;
⑩—Tunnel tube inclination; ⑪—Tunnel structure crack; ⑫—Shear key stress(horizontal)

Fig. 4 Sensors placement

Tab. 1 Health monitoring scheme

Method	Monitoring index	Sensor
Real-time monitoring	Uneven settlement	Differential pressure gauge
	Joint opening and displacement	Crack meter
	Rebar stress	Vibrating string steelbar meter
	Concrete stress and temperature	Concrete stress and thermo meter
	Shear key stress	Pressure box
	Anchor cable tensile force	Magnetic flux anchor cable stress meter
	Tube inclination	Tiltmeter
Regular monitoring	Local settlement	Leveling
	Cracks	Crack meter + Artificial survey
	Leakage	Artificial survey
	Water level	Water level meter
	Thickness of cover layer	Sound locater

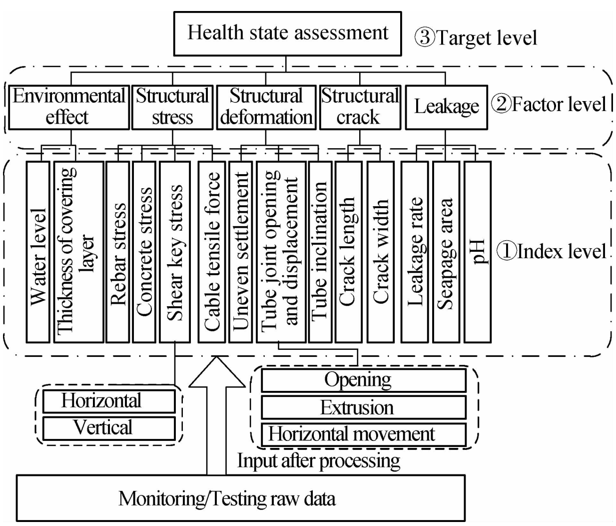


Fig. 5 Honggu Tunnel health assessment system hierarchical model

3.2.2 Determination of subjective weight of health assessment index

In comprehensive evaluating programs, the traditional AHP method uses 1-9 scale methods to construct the judgment matrix. When the order of the judgment matrix is large, it is difficult to satisfy the consistency requirements of the judgment matrix. The multiplication scale method[20] is an improved AHP method, 1-9 scales in the AHP method is replaced by 1-2 scales, by means of the same and slightly larger. When the importance of index A is the same as that of index B, the judgment scale is 1, and the weights of index A and index B are 0.5 and 0.5, respectively. Similarly, index A is slightly larger than index B; the judgment scale is 2; and the weights of index A and index B are 0.575 and 0.425, respectively. This method has better judgment transitivity and rational scale value compared with the traditional AHP method. In this project, the multiplication scale method was introduced to determine the subjective weight.

3.2.3 Establishment of index assessment criteria

The health assessment of the whole structure was based on the assessment of indices in the index layer. Based on the design data, relevant specifications and published literature, index assessment criteria were specified. Health status is divided into four grades, both in the index assessment and whole structure assessment. Index assessment criteria is shown in Tab. 2.

The overall criteria of the tunnel health assessment and coping principle is described in Tab. 3, and the procedure to determine the comprehensive assessment value F is interpreted in the following part.

3.2.4 Determination of objective weight of health assessment index

The entropy weight method is widely used in objective weight determination[21-23]. It is supposed that the index weight is determined according to the amount of information contained in each index. In this project, the entropy weight method is introduced to determine the objective weight. Specific steps are as follows:

1) Establish the judgment matrix of tunnel health state,

$$\boldsymbol{R} = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & & \vdots \\ x_{n1} & \cdots & x_{nn} \end{bmatrix} \tag{1}$$

2) Normalize the judgment matrix,

$$\boldsymbol{b}_{ij} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} \tag{2}$$

where $x_{\max}$, $x_{\min}$ are the most satisfied and least satisfied indices of each health level, respectively.

3) Determine the entropy of assessment index,

Tab. 2 Index assessment criteria

Index	*A*	*B*	*C*	*D*
Rebar stress/MPa	≤270	270 to 306	306 to 360	≥360
Concrete stress/MPa	≤14.33	14.33 to 16.24	16.24 to 19.1	≥19.1
Horizontal shear key stress/MPa	≤0.62	0.62 to 0.7	0.7 to 0.82	≥0.82
Vertical shear key stress/MPa	≤1.5	1.5 to 1.7	1.7 to 2	≥2
Anchor cable tensile force/kN	≤1 334	1 334 to 1 570	1 570 to 1 847	≥1 847
Joint opening/mm	≤21.6	21.6 to 25	25 to 28.3	≥28.3
Joint extrusion/mm	≤20.5	20.5 to 23.3	23.3 to 33.3	≥33.3
Joint horizontal displacement/mm	≤20	20 to 25	25 to 30	≥30
Tube inclination/($10^{-4}\pi$ · rad)	≤0.955	0.955 to 1.273	1.273 to 1.592	≥1.592
Uneven settlement/mm	≤30	30 to 40	40 to 50	≥50
Water level/m	≤18	18 to 21	21 to 24	>24
Thickness of cover layer/m	≤H+2	H+2 to H+3	H+3 to H+4	>H+4
Crack length/m	≤2	2 to 5	5 to 10	>10
Crack width/mm	≤0.2	0.2 to 0.3	0.3 to 0.4	>0.4
Seepage area/(seepage area · waterproofing · area^{-1})	<0.01/1 000	0.01/1 000 to 0.1/1 000	0.1/1 000 to 1/1 000	>1/1 000
Leakage rate/(drop · min^{-1})	<5	5 to 60	60 to 300	>300
Leakage pH	6.5 to 7	6 to 6.5	5.5 to 6	<5.5

Note: H is the design thickness of the backfill layer.

Tab. 3 Quantitative grade classification of tunnel disease

Grade	Health status	Comprehensive assessment value F	Countermeasure
A	Not damaged or slightly damaged	$3.5 < F \leqslant 4.0$	Monitoring
B	Damaged	$2.5 < F \leqslant 3.5$	Ready to take countermeasure
C	Relatively serious damage	$1.5 < F \leqslant 2.5$	Take countermeasure as soon as possible
D	Seriously damaged	$1.0 < F \leqslant 1.5$	Take countermeasure instantly

$$H_i = -\frac{1}{\ln m}\sum_{j=1}^{m} f_{ij}\ln f_{ij} \qquad (3)$$

$$f_{ij} = \frac{1+\boldsymbol{b}_{ij}}{\sum_{j=1}^{m}(1+\boldsymbol{b}_{ij})} \qquad (4)$$

where f_{ij} is the specific weight of the i-th assessment object.

4) Calculate the entropy weight,

$$\omega_i = \frac{1-H_i}{n-\sum_{i=1}^{n} H_i} \qquad (5)$$

3.2.5 Fusion weight

The commonly used methods of fusion weight calculation are the weighted arithmetic mean, weighted square root and weighted square sum, etc. In this paper, the weighted arithmetic mean[20] method is used, and the subjective weight is regarded as a little more important than the objective weight. The fusion weight calculation formula is

$$\omega_i = 0.575\omega_{1i} + 0.425\omega_{2i} \qquad (6)$$

where ω_{1i} is the subjective weight and ω_{2i} is the objective weight.

3.2.6 Flowchart of the evaluation procedure

With the aforementioned work, the fuzzy-AHP evaluation method can be carried out through the following flowchart (see Fig. 6). Membership grade vector $\boldsymbol{R}_1$ is the evaluation vector of the index level; $\boldsymbol{R}_2$ is the evaluation vector of the factor level; and $\boldsymbol{R}_3$ is the evaluation vector of the target level; Grade vector $\boldsymbol{G} = \{3.75, 3, 2, 1.25\}$ according to Tab. 3.

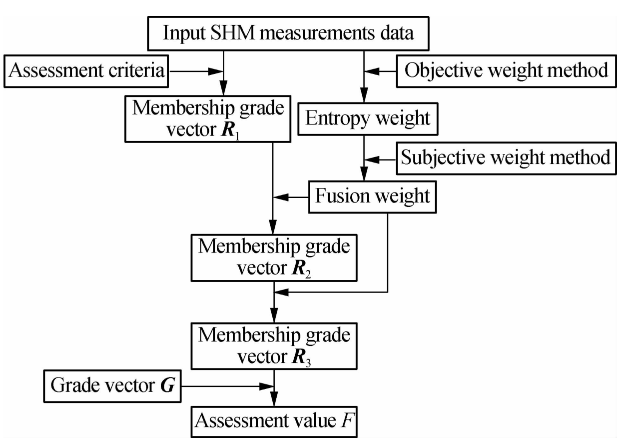


Fig. 6 Flowchart of the fuzzy-AHP evaluation procedure

3.3 Honggu Tunnel health monitoring and assessment software system

The software system of this project adopted the hierarchical B/S structure, .NET development platform, and ASP.NET as well as ADO.NET as the core technology. Fig. 7 shows a diagram of the system network topology. Fig. 8 shows a diagram of the system software structure. Fig. 9 shows the software interface in PCs. The platform function is described in Tab. 4.

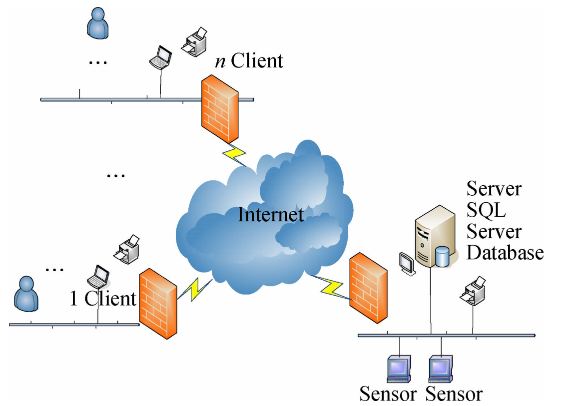


Fig. 7 Network topology diagram

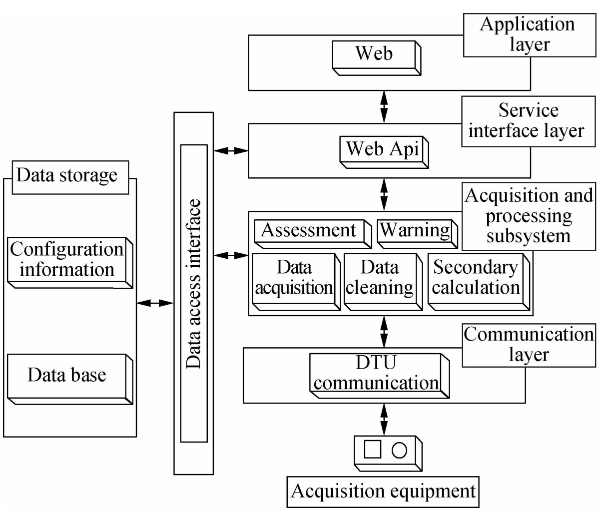


Fig. 8 Software structure diagram

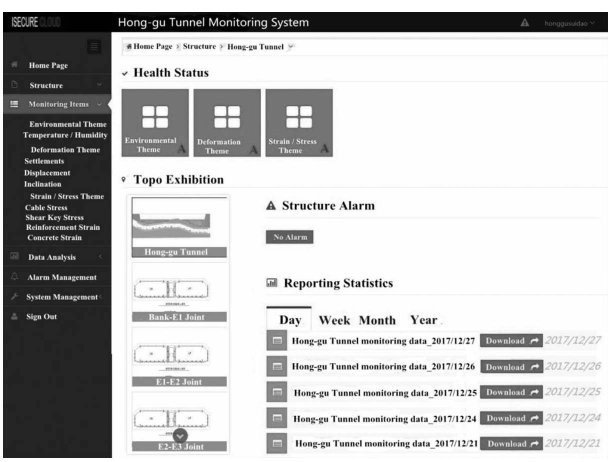


Fig. 9 Software interface in PCs

Tab. 4 Platform function description

Name	Functional specification
Homepage	GIS topology, health status of structures, warning of structures, work reports
Structure	Health status of structure selected, Topo exhibition, warning of structure selected, work report of structure selected, monitoring index chart
Monitoring program	Deformation theme, strain/stress theme, force theme
Data analysis	Data comparison, data association, report management
Warning management	Warning information, processed warning information, unprocessed warning information, batch processing of warning information
System configuration	User log, text message push management

4 Conclusions

1) The subsystems of the health monitoring and assessment system of the Nanchang Honggu Tunnel are elaborated from two aspects, i. e., the hardware system and the software system. The whole system includes the sensor subsystem, data acquisition subsystem, data transmission subsystem, database subsystem, data processing and control subsystem, and health assessment and pre-warning subsystem.

2) The health monitoring scheme is designed for the Nanchang Honggu Tunnel, including monitoring indices, monitoring methods, sensor selection, sensor layout and so on.

3) The AHP model for the structural health assessment of the Nanchang Honggu Tunnel is established. The structural health assessment is evaluated hierarchically from three levels: index level, factor level and target level.

4) The entropy weight method and multiplication scale method are employed to determine the objective weight and subjective weight separately. Then, they are integrated into a fusion weight by the weighted arithmetic mean method. This method improves the inadequacy of the conventional subjective weight method, which cannot consider the field measured data information.

5) The flowchart of the Nanchang Honggu Tunnel health monitoring and assessment system is given, and the structure and compiling technology of the software system are described in detail. The established health monitoring and assessment system provides efficient technical support for the Honggu tunnel management and maintenance and it also provides a good reference for other immersed tunnels.

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南昌红谷隧道健康监测与评价系统构建

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摘要：以目前中国最大的内河沉管隧道−南昌红谷隧道为背景，介绍了南昌红谷隧道健康监测与评价系统建设中的研究工作. 采用目前较为成熟的模式构建了监测评价系统平台，该系统平台包括传感器子系统、数据采集子系统、数据传输子系统、数据库子系统、数据处理与控制子系统、健康评价与预警子系统. 健康监测内容与监测方案设计中充分考虑了监测指标、监测传感器的选取及传感器布设等关键内容. 采用模糊−层次综合分析方法建立了南昌红谷隧道健康评价模型，研究并给出了评价指标权重的确定方法和分级控制标准. 采用先进的云平台技术实现了监测与评价系统软件功能，降低了管理单位的运营成本. 介绍了基于南昌红谷隧道健康监测与评价系统的相关研究，该系统实现了对红谷隧道的实时监控，并使健康评价、预警等功能更加便捷，管理人员在电脑和手机端都可以实现系统的远程操作. 相关研究工作也可为其他沉管隧道健康监测、评价系统的构建提供参考.

关键词：沉管隧道；健康监测；系统平台；AHP 模型

中图分类号：U457