Research Article

Development and Application of an Integrated Monitoring and Early Warning Platform for Land Transportation Infrastructure under Special Engineering Conditions

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To ensure the safety service performance of land transportation infrastructure under special engineering conditions, centering on the characteristics of structures such as the road high-steep slope, high embankment, special subgrade, railway track, and airport pavement, an integrated monitoring and early warning platform based on health monitoring and safety evaluation was built through the combined design of the safety indicator module, monitoring data module, information processing module, numerical simulation module, inversion prediction analysis module, and safety early warning module. The data interaction between the integrated platform and five monitoring subplatforms was realized by the B/S mode, and the related function interfaces were established. The research results show that as the monitoring data storage analysis and early warning carrier, the integrated monitoring and early warning platform not only presents key data such as comprehensive early warning information, evaluation indicators, and monitoring elements but also realizes the intelligent, automatic, and visual presentation of monitoring data. In addition, relying on the high-steep slope of the Hohhot-Bikeqi Highway (section: K528+215~K528+525), through the application of the high-steep slope monitoring and early warning subplatform system in the practical project, it is verified that the platform has a good monitoring and early warning effect, which provides a reliable platform guarantee for the health monitoring and safety operation of the project.

1. Introduction

With the rapid development of China’s economy, the construction of land transportation infrastructure is constantly strengthened and improved; in the process of engineering construction, a large number of road high-steep slopes [1, 2], high embankment [3], special subgrade [4–6], railway track [7, 8], airport pavement [9], and other special conditions of engineering structures [10–13] are inevitable. Under the long-term influence of various natural and engineering factors, especially in recent years, the global extreme climate conditions occur frequently; the above engineering structure section has become an important disaster risk area in land transportation infrastructure, greatly increasing the land transportation infrastructure maintenance costs, significantly reducing the land transportation infrastructure service capacity, causing huge losses to national economic construction, and producing bad social impact. Therefore, the stability and health security problems of the high-steep slope, high embankment, special subgrade, and other engineering structures in land transportation infrastructure under special conditions need to be solved.

In fact, the stability and health security of engineering structures largely depend on monitoring and comprehensive evaluation. In the previous land transportation infrastructure engineering, in order to monitor the unstable area of projects, some manual monitoring methods are commonly used. But the traditional monitoring and health evaluation methods have high human cost, subjectivity, uncertainty, and poor effectiveness [14–17], which makes the timeliness...
and scientificalness of engineering health monitoring and evaluation urgent. With the development of information technologies such as the Internet, the Internet of Things, big data, and artificial intelligence, intelligent monitoring equipment represented by wireless sensors, fiber optic sensors, and radar is gradually replacing manual monitoring equipment, realizing deep integration with the transportation industry, and being applied in engineering health monitoring and evaluation [18–28]. Yan et al. [29] combined with the structural characteristics and operation and maintenance needs of the Hutong Changjiang River Bridge independently designed an integrated health monitoring system of “vehicle-line-bridge-ambience”; the system can all-sidedly reflect the structural conditions and vehicle travelling conditions of the bridge. Hong-Nan et al. [30] developed a structured health monitoring system according to the structural characteristics and safety construction requirements of Dalian Stadium; with the help of the monitoring system, it can obtain a large number of data about the structural state of the stadium and realize the continuous synchronous collection of multiple physical quantities, automatic data storage, automatic generation of reports, automatic alarm and multimode display, and other functions. Xu et al. [31] took the concrete temperature and seepage of Jinghong Hydropower Station dam as the monitoring object and proposed a distributed optical fiber temperature measuring system and temperature inspection method, which can quickly and accurately monitor the changes in the temperature field inside the dam concrete structure.

At present, the health monitoring system for engineering structures has many applications at home and abroad but is mainly used for large bridges [18, 24, 25, 29, 32, 33], tall buildings [26, 30, 34, 35], water conservancy projects [27, 31], and other engineering fields, and its application in major structures such as high-steep slope, high embankment, and special subgrade is generally less, especially that the health monitoring and safety evaluation system for the whole life cycle has not been established, which is an urgent need to be studied. Therefore, according to the operation security technical problems of road high-steep slope, high embankment, special subgrade, railway track, and airport pavement, it has a very urgent demand to study the technology of real-time health monitoring and lifecycle safety evaluation under the normal service conditions and build the safety evaluation and comprehensive monitoring and early warning platform characterized by visualization, information, and intelligence.

For that reason, around the establishment of the lifecycle health indicators and safety evaluation system of road high-steep slope, high embankment, special subgrade, and other engineering structures and through the combined design of safety indicator module, monitoring data module, information processing module, numerical simulation module, inversion prediction and analysis module, and safety early warning module, the integrated platform for health monitoring, safety evaluation, and early warning characterized by visualization, information, and intelligence was developed, in which the B/S (browser/server) mode is adopted to realize the data interaction and related function interface generation with various monitoring subplatforms such as high-steep slope, high embankment, special subgrade, railway track, and airport pavement. In addition, the high-steep slope of the Hohhot-Bikeqi Highway (section: K528+215~K528+525) is used as the demonstration application project, through which the monitoring and early warning effect of the platform is verified.

2. Design Scheme of the Integrated Monitoring and Early Warning Platform

2.1. Overall Plan. The integrated monitoring and early warning platform developed in this paper is constructed with the idea of highlighting primary-secondary relationships and hierarchical presentation, which consists of one comprehensive platform system and five classes of subplatform systems including the road high-steep slope, high embankment, special subgrade, railway track, and airport pavement. Subplatforms analyze their functional modules according to their respective technical indicators and develop the hardware and software to implement the functional modules. Based on the functional modules, a series of other functions such as electronic map, monitoring project overview, health characterization indicators and safety evaluation indicators, real-time and historical monitoring data, disaster warning information, and video surveillance are uniformly integrated on the comprehensive platform, which can exchange data with subplatforms in the B/S (browser/server) mode.

In addition, in order to facilitate responsible departments and technicians to use the platforms to carry out health monitoring and safety operation management of the above engineering structures, the comprehensive platform is defined as the primary monitoring and early warning platform, mainly presenting the key indicators, evaluation conclusions and early warning information of related projects, and the other 5 subplatforms defined as the secondary platform, mainly presenting all monitoring elements, evaluation indicators, and video surveillance images. The overall framework of the integrated platform system developed in this paper is shown in Figure 1, and the connection mode is shown in Figure 2.

2.2. Structural Design. The structural design of the integrated platform system as described above includes 6 parts: data layer, support layer, application layer, performance layer, access layer, and external public interface. Their respective technical functions are as follows.

2.2.1. Data Layer. The data layer can manage and store both structured and unstructured data, and structured data includes XML and DBMS; unstructured data includes TXT, HTML and other text files, MP3, AVI, RM, WMV, MPG and other audio and video files, DOC, PPT, XLS and other Office series files, JPG, GIF, BMP, PNG, PSD and other graphics and image files, ZIP, PDF, SWF, and other format files. The data layer supports the Web Service modular components on the data interface, at the same time, and shall
provide the application programming interface API for various data operations.

2.2.2. Support Layer. Through the application server, the support layer provides support for the application layer, including information collection, data conversion, retrieval engine, unified user, access statistics, process definition, data delivery, and sharing. And through API, PORTLET, Web Service, JMS, MQ, DI, URL, DBMS, and other interface services, support of the external resource integrates the base data of content management, and the content management integrates the application data of external data resource.

2.2.3. Application Layer. The application layer can realize information release management, website group management, system management, plug-in component management (all nonwebsite applications are managed uniformly here in the way of components to ensure unified management for all users), single point login SSO (SingleSignOn), personalized customization, RSS (Really Simple Syndication), etc.
2.2.4. Performance Layer. The final performance of the website is a group of website systems with the same standard and the same specification, which includes the settlement center portal and the enterprise subwebsites. At the same time, the system provides different forms of information resources for different applications of the application layer, including Web, WAP, Portlet, RSS, E-mail, and SMS.

2.2.5. Access Layer. The access layer enables the user to access the performance layer through various terminal devices to obtain information resources.

2.2.6. External Public Interface. The external public interface provides a large number of application interfaces for the management layer, application layer, and performance layer of information resources, including API, Portlet, Web Service, JMS, MQ, DBMS, and URL.

2.3. Technical Requirements

2.3.1. Precision Requirements

(1) Data Acquisition Accuracy. It can meet the needs of establishing security thresholds and early warning mathematical models of different early warning indicators and building a comprehensive monitoring and early warning platform system based on cloud architecture.

(2) Data Processing and Calculation Accuracy. The cumulative error brought by data processing and calculation is not greater than the maximum benchmark accuracy of all data sources.

(3) Display Accuracy. (a) Angle display is accurate to 0.01 degrees; (b) position is accurate to 0.01 points when displaying latitude and longitude information; (c) distance/displacement display is accurate to 1.0 m.

2.3.2. Time Characteristic Requirements. (1) Information sending/receiving display time delay is not more than 1 s; (2) man-machine command/instruction response time delay is not more than 50 ms; (3) model calculation period is not more than 1 s; (4) display screen refresh rate is not less than 20 times/s.

2.3.3. Requirements for Flexibility. (1) Each functional module is independent of each other to improve software portability; (2) the software system can be installed and run under Windows XP or Windows 7 operating system; (3) modular design is adopted to improve model software augmentability and support software function expansion; (4) software is encapsulated into C function or callable C library and can run the software away from the development and compilation environment.

2.3.4. Interface Requirements. (1) A functional module can be called by the function of other functional modules; (2) a functional module can also call the function of other functional modules; (3) when a functional module can be called by the function of other functional modules, all parameters are passed in the form of actual parameters without global variables as far as possible; (4) during functional module calling, ensure that the types of actual and formal parameters are consistent; (5) when functional modules pass the data in the form of function parameters, use formal parameters to
2.3.5. Interface Requirements. (1) It has the correct way to select buttons and menus; (2) it has the input dialog interface of initial parameters; (3) the user interface meets the man-machine efficacy principle and is friendly and simple; (4) the interface vividly shows the health monitoring and safety evaluation state; (5) the software interface can generate distinct warning information items.

2.3.6. System Hardware Requirements. (1) The master CPU core number is not less than 4 cores, and the main frequency is not less than 2.3 GHz; (2) memory is not less than 4 GB DDR3 SDRAM; (3) hard disk is not less than 500 GB; (4) computer hardware working temperature is 0°C to 40°C, and relative humidity is <95%; (5) data acquisition system working temperature is -40°C to 60°C, and relative humidity is <95%.

3. Interface Function of the Integrated Monitoring and Early Warning Platform

The interface of the integrated monitoring and early warning platform includes two parts: the primary interface and the secondary interface. The former can call the latter and present the key indicators, evaluation conclusions, and early warning information, while the latter can realize the embodiment of the former and present all monitoring elements, evaluation indicators, and video surveillance images of the project.

3.1. Primary Interface. Define the comprehensive monitoring and early warning platform as the primary interface, as shown in Figure 3. On the left side, the primary interface shows the number of the projects being monitored and related monitoring indicators, which include the road high-steep slope, high embankment, special subgrade, railway track, and airport pavement. In the upper part of the middle, the primary interface shows button links; click to enter the related secondary interface to display the specific monitoring information. The central location of the primary interface shows the actual geographical location of the projects being monitored. The right side of the primary interface shows the warning information of the project of the certain early warning indicator reaching the safety threshold.

3.2. Secondary Interface. Each monitoring and early warning subplatform is defined as the secondary interface, including the 5 subplatforms of road high-steep slope, high embankment, special subgrade, railway track, and airport pavement. Take the monitoring and early warning subplatform of high-
Table 1: The monitoring scheme of high-steep slope.

| Number | Monitoring | Monitoring equipment                              | Monitoring purpose                                                                 |
|--------|------------|--------------------------------------------------|------------------------------------------------------------------------------------|
| 1      | Anchor cable stress | Anchor cable load cell | Determine whether the tension of anchor cable meets the design requirements and intuitively reflect the support effect of anchor cable. |
| 2      | Slope surface displacement | Guyed displacement meter | Monitor the slope surface displacement and analyze the slope stability.             |
| 3      | Structure tilt | Inclination sensor | Reflect on the deformation of the slope support structure and judge the support effect. |
| 4      | Rainfall | Rain gauge | Analyze the influence of rainfall on slope stability.                                |
| 5      | HD image | Video monitor with 4G spherical video camera | Observe the project site situation.                                                 |

Deep slope as an example to illustrate the secondary interface function. As shown in Figure 4, click the “Data cycle” button in the upper right corner of the secondary interface to realize the data viewing at different times, and click the “Video surveillance” button to realize viewing the real-time monitoring images. Click the “Return” button in the upper left corner of the secondary interface to return to the primary interface.

According to the structural characteristics of road high-steep slope, high embankment, special road subgrade, railway track, and airport pavement, the corresponding content of monitoring and early warning is as follows: (1) road high-steep slope mainly includes slope surface displacement, anchor cable/bolt stress, top displacement, and tilt of support structure; (2) high embankment mainly includes settlement, deep horizontal displacement, and slope displacement; (3) special subgrade mainly includes pore water pressure, total settlement, layered settlement, surface horizontal displacement, and deep horizontal displacement; (4) railway track mainly includes creeping displacement of switch rail, rail temperature, rail damage (crack and broken rail), and vibration; (5) airport pavement mainly includes PCI (Pavement Condition Index), IRI (International Roughness Index), PCN (Pavement Classification Number), and friction coefficient. The above monitoring data and change trends will be displayed in the secondary interface in real time through each subplatform.

4. Demonstration and Application of the Integrated Monitoring and Early Warning Platform

4.1. Project Overview. The right slope of the Hohhot-Bikeqi Highway (section K528+215~K528+525) passes through the Daqingshan state reserve, where steep slope cutting is adopted in order to reduce the environmental damage caused by slope excavation. However, due to fracture development and fragmentation of the slope rock, it is difficult to stabilize the steep slope, so it is necessary to support the excavated slope. There are four specific support schemes: pile-sheet retaining+anchor cable frame+bolt frame, pile-sheet retaining+anchor cable frame, retaining wall+anchor cable frame, and retaining wall. The right slope of section K528+308~K528+398 is about 30 m high, where the support scheme is the following: the first slope by pile-sheet retaining, the second slope by anchor cable frame, and the third slope by bolt frame. The right slope of section K528+230~K528+266 adopts the support scheme: the first slope by retaining wall and the second slope by anchor cable frame.

Based on the above monitoring and early warning sub-platform of the high-steep slope, the right slope of section K528+215~K528+525 is selected for health monitoring and safety evaluation (see Figure 5) to determine the stability and safety state and verify the monitoring and early warning effect of the platform in combination with the actual operation situation of the highway.

4.2. Monitoring Scheme Design. According to the above support scheme, the monitoring equipment such as anchor cable load cell, guyed displacement meter, inclination sensor, rainfall gauge, and video monitor is arranged in the demonstration section to realize the intelligent, automatic, and visual monitoring of the site situation. The specific monitoring scheme is shown in Table 1.

4.3. Construction of the Monitoring and Early Warning Platform

4.3.1. Data Acquisition and Transmission. The on-site monitoring data acquisition equipment adopted in the demonstration project includes a 16-channel wireless data acquisition instrument and an 8-channel string acquisition instrument, which has the characteristics of good stability and simple operation and can meet the application needs to the greatest extent. In addition, considering that the centralized collection system and wired transmission mode are more inconvenient for the structural construction of the demonstration project, the demonstration project monitoring system adopts distributed measurement system and wireless transmission.

The wireless transmission mode realizes data transmission with the help of a GPRS network, as long as the mobile phone signal can be reached, which has a wide transmission range and transmits the data to the server, in order to realize the data query and retrieval of any computer. The wireless GPRS data transmission server system is shown in Figure 6.

4.3.2. Monitoring and Early Warning Subplatform. The design principle and interface function of the monitoring...
and early warning platform adopted in the demonstration project are the same as the monitoring and early warning subplatform of the high-steep slope described above, which will not be repeated here.

4.4. Analysis of Monitoring Data Results. Up to now, the monitoring and early warning platform continues to operate normally, and the health condition of the demonstration project is good. Due to the limited length of the paper, only the monitoring data of some periods is selected here for analysis and explanation, and the change trend of monitoring indicators in other periods is basically consistent with this. Because the demonstration project is located in the Daqingshan state reserve where the annual rainfall is very small, the rainfall monitoring data is almost 0, and it is not analyzed. The following monitoring data is obtained by clicking the “Data cycle” button in the platform interface.

4.4.1. Analysis of Anchor Cable Stress Monitoring Data. Two sets of anchor cable stress monitoring equipment are arranged on the high slope of the demonstration project, and the anchor cable load cell is used to monitor the stress of the anchor cable. The representative monitoring data are shown in Figure 7.

As can be seen from Figure 7, the stress variation of the anchor cable is within -1.50~1.50 MPa, and the tension...
the anchor cable meets the design requirements. In general, the change trend of the anchor cable stress is stable, showing a short-term vertical shock with 0 MPa as the axis, indicating that the anchor cable support effect is good.

4.4.2. Analysis of Slope Surface Displacement Monitoring Data. Three sets of slope surface displacement monitoring equipment are set up on the high slope of the demonstration project. The guyed displacement meter is used to monitor the slope surface displacement. The representative monitoring data are shown in Figure 8.

As can be seen from Figure 8, the monitoring data of the guyed displacement meter is within -0.45~0.35 mm, the change range is small, and the general trend is vertical shock, which indicates that the slope is stable and no surface cracking.

4.4.3. Analysis of Structure Tilt Monitoring Data. Two sets of structural tilt monitoring equipment are arranged on the...
high slope of the demonstration project. The inclination sensor is used to monitor the structure tilt. The representative monitoring data are shown in Figure 9.

As can be seen from Figure 9, the monitoring data of the inclination sensor changes within -0.6°~1.2°, indicating that the retaining wall structure is stable and the support effect is good.

4.5. Application Effect Evaluation. According to the above monitoring data analysis, the monitoring data of the monitoring indicators such as anchor cable stress, slope surface displacement, and structural tilt of the demonstration project are stable, and all show a small vertical shock change. In addition, by checking the warning information displayed on the right side of the primary interface, it can be seen that all the monitoring indicators do not reach the alarm limit, and no alarm information appears in the monitoring background, indicating that the slope is in a stable and safe state, which is consistent with the actual operation of the highway.

5. Conclusion

(i) Through the combined design of the safety indicator module, monitoring data module, information processing module, numerical simulation module, inversion prediction and analysis module, and safety warning module, the integrated monitoring and early warning platform was developed, in which the B/S (browser/server) mode is adopted to realize the data interaction with other monitoring and early warning subplatforms such as road high-steep slope, high embankment, special subgrade, railway track, and airport pavement

(ii) The integrated monitoring and early warning platform not only presents the comprehensive early warning information, evaluation indicators, monitoring elements, and other key data but also realizes the intelligent, automatic, and visual monitoring of road high-steep slope, high embankment, special subgrade, railway track, and airport pavement, thus providing an important health monitoring and early warning platform for land transportation infrastructure under special engineering conditions

(iii) Through the demonstration application of the high-steep slope monitoring and early warning platform, the platform effect has proved good, which can provide real-time health monitoring and safety evaluation technical service for the project and ensure the healthy operation of the project

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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