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Safety Monitoring Technologies for the Water Resources Allocation Project in the Pearl River Delta: Challenges and Innovations

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Abstract: The Pearl River Delta Water Resources Allocation Project is characterized by an extensive distribution of buildings along a lengthy alignment and the application of diverse construction methodologies. Given these complexities, comprehensive safety monitoring measures are essential during both the temporary construction and operational phases to ensure the structural integrity and safety of the project. This study examines the critical aspects of safety monitoring, tailored to the unique characteristics and demands of the project, by focusing on the monitoring objectives, specific monitoring tasks, and the inherent challenges posed by the project's scope and variety. Emphasis is placed on identifying key safety monitoring difficulties, such as maintaining accuracy across varying construction methods and terrain conditions, and ensuring compliance with evolving regulatory standards. Additionally, innovative solutions and advanced monitoring techniques that address these challenges are explored, highlighting the integration of novel technologies and approaches that enhance monitoring effectiveness. The discussion is framed within the context of existing engineering requirements and regulatory frameworks, providing insights into the strategic implementation of safety monitoring protocols that are both adaptable and robust. This paper contributes to the ongoing discourse on the safety management of large-scale water resource projects by presenting a detailed analysis of the challenges encountered and the innovations employed to mitigate risks, thus supporting sustainable and safe development in complex engineering environments.

Keywords: Pearl River Delta Water Resources Allocation Project; Safety monitoring challenges; Monitoring innovations; Construction safety; Engineering compliance

1 Introduction

The Pearl River Delta region plays a significant role in the overall economic and social development and the broader context of reform and opening up in China. However, there exists an imbalance between economic development and water resource allocation in this region. The economic and population centers are concentrated in the eastern part, while water resources are abundant in the western part [1, 2]. The Dongjiang River Basin, for instance, has an average annual runoff of 25.7 billion cubic meters, with the utilization rate of water resources approaching the warning line of 40%. Meanwhile, the Xijiang River Basin has an average annual runoff of 230.2 billion cubic meters, with a low utilization rate of only 1.3%. To coordinate the development and utilization of water resources between the eastern and western parts of Guangdong Province, it is necessary to transfer the abundant water resources with low utilization rates from the Xijiang River Basin to the water-scarce Dongjiang River Basin, thereby optimizing water resource allocation between the eastern and western regions of the Pearl River Delta [3, 4].

The Pearl River Delta Water Resources Allocation Project is characterized by its large scale and high implementation difficulty. It is the longest water transfer tunnel in China constructed using the shield tunneling method and incorporates the most advanced monitoring technologies and instruments in the country [5]. Therefore, more targeted, scientific, and efficient monitoring work is required. This imposes new demands and standards on the performance of monitoring instruments, the embedding and installation process, the protective measures for the instruments, and the network communication methods. Moreover, the feasibility and convenience of on-site implementation must be fully considered to facilitate the timely conduct of monitoring work [6].

2 Project Overview

The Pearl River Delta Water Resources Allocation Project is an important water resource allocation project proposed in the *Comprehensive Plan of the Pearl River Basin (2012-2030)*, approved by the State Council, and is one of the 172 major water-saving and water supply projects that the State Council has mandated to accelerate construction. The project's goal is to create a modern ecological and intelligent water conservancy project [4]. The project involves diverting water from the Xijiang River system in the western Pearl River Delta network area to the eastern Pearl River Delta. The primary water supply targets are the water-scarce areas of Nansha District of Guangzhou, Shenzhen, and Dongguan. Implementing this project will effectively address the water shortage issues faced by these cities in their economic development, change the single water supply pattern of Nansha District of Guangzhou from the downstream Sand Bay waterway of the Beijiang River and the water supply pattern of Shenzhen and Dongguan from the Dongjiang River, and improve water supply security and emergency backup capacity. It will also appropriately improve the ecological environmental flow of the downstream Dongjiang River during the dry season, which is of great significance for maintaining the water supply security and sustainable economic and social development of Nansha District, Shenzhen, and Dongguan. The overall layout of the Pearl River Delta Water Resources Allocation Project is shown in Figure 1. The project is classified as Grade I. The designed flow rate is 80 m^3/s, the designed scale is 1.787 billion m^3/s, with a design flood standard of a 100-year return period and a check flood standard of a 300-year return period. The total length of the water transfer line is 113.2 km, and the water transfer tunnel is constructed underground at an average depth of 40–60 m using a deep-buried tunnel approach [2, 3], mainly employing the shield tunneling method. The working shafts have deep foundation pits, and the water transfer tunnels are long, distributed in densely populated large cities. Should any safety incident occur, the consequences would be severe. To ensure the safe and stable operation during the construction and operation periods, advanced safety monitoring technologies have been adopted for the project [7].

Figure 1. Schematic diagram of the overall layout of the Pearl River Delta Water Resources Allocation Project

3 Monitoring Objectives

The objective of safety monitoring for the project is to select monitoring items reasonably based on the type and level of the structures and to arrange the monitoring layout appropriately according to geological conditions and structural characteristics. This aims to obtain information about the safety and operational status of the structures during both the construction and operation periods, thus providing a basis for guiding construction, feedback, optimizing design, and ensuring safety during the operational phase [8].

As an essential component of the modern concept of information-based construction, safety monitoring during the construction period enables early identification and judgment of potential major quality and safety issues that may arise during construction. This provides a foundation for the project to take preventive and remedial measures in advance, thereby ensuring construction progress and safety. Meanwhile, safety monitoring results and information can also provide feedback to the design, enriching design parameters and foundational data, which has important guiding significance for improving construction processes and enhancing design quality. By analyzing and organizing various monitoring results, it is possible to summarize project experience and change patterns while also considering the needs of engineering research [8, 9].

4 Classification of Monitoring Items

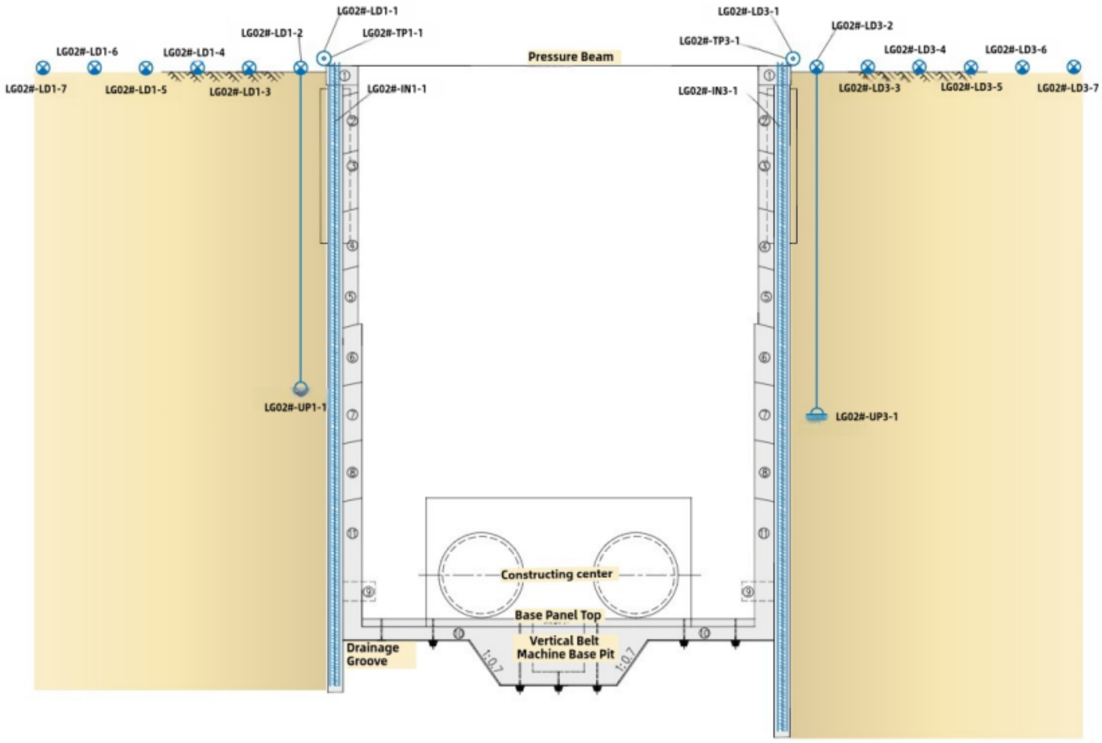

Figure 2. Layout of monitoring instruments for foundation pits of working shafts

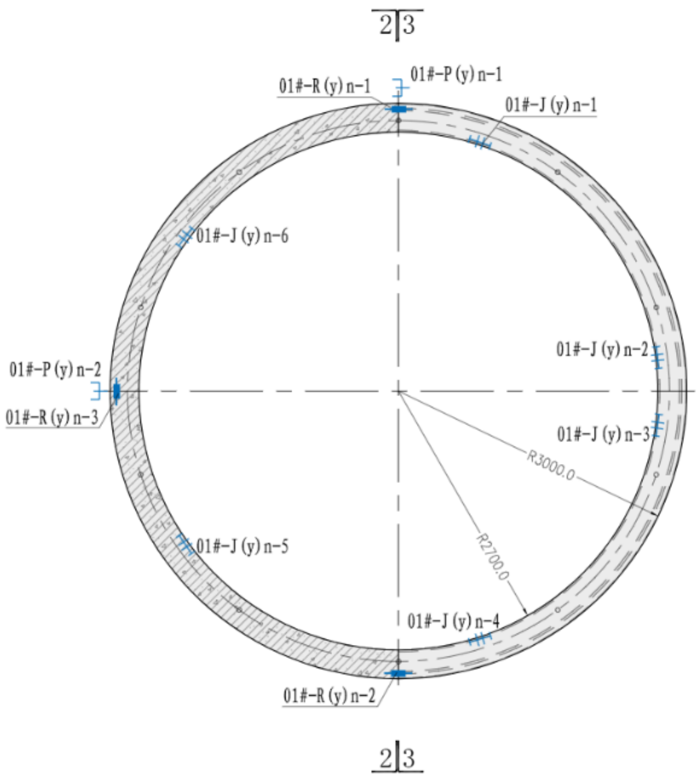

Figure 3. Layout of monitoring instruments for tunnel monitoring cross-sections

The scope of safety monitoring for the Pearl River Delta Water Resources Allocation Project includes: the double-line shield tunnel from Liyuzhou to Gaoxinsha Reservoir, the single-line shield tunnel for the main water transfer line, the single-line shield tunnel for the Nansha branch, working shafts, maintenance or seepage drainage shafts, pumping stations, reservoirs, intake gates, water diversion points, and others [10, 11]. The main monitoring items are as follows:

(1) Temporary Monitoring of Working Shafts and Pump Station Foundation Pits: Surface deformation monitoring, deep horizontal displacement monitoring, groundwater level monitoring, internal force monitoring of retaining walls, internal force monitoring of supports, soil pressure monitoring, etc. The layout of monitoring instruments for the foundation pits of working shafts is shown in Figure 2.

(2) Shield Tunnel Monitoring: Monitoring of tunnel convergence deformation, tunnel settlement deformation, lining segment joint deformation, lining segment longitudinal deformation; external water pressure, seepage pressure; soil pressure, lining segment stress and strain, bolt stress, inner lining steel pipe stress and strain, anchor cable stress, etc. The layout of monitoring instruments for tunnel monitoring cross-sections is shown in Figure 3.

(3) Pump Station Monitoring: Surface deformation monitoring, foundation settlement monitoring, joint deformation monitoring, uplift pressure monitoring, groundwater level monitoring, soil pressure monitoring, steel pipe stress monitoring, water level monitoring in front of intake gates, etc.

(4) Reservoir Monitoring: Surface deformation monitoring, internal deformation monitoring, phreatic line and groundwater level monitoring, seepage pressure monitoring at the reservoir bottom, seepage flow monitoring, etc.

(5) Gate Monitoring: Surface deformation monitoring, uplift pressure monitoring, water level monitoring.

(6) Special Monitoring Along Water Transfer Line: Internal water pressure monitoring, sediment content monitoring, siltation monitoring, etc.

(7) Environmental Monitoring: Atmospheric temperature and humidity, rainfall, atmospheric pressure, evaporation, wind direction and speed, etc.

(8) Surrounding Environment Monitoring: Monitoring of deformation of existing buildings, structures, facilities, pipelines, and roads that may be affected by the construction of working shafts, pump station foundation pits, and tunnels.

The main monitoring instruments used in the project include rebar gauges, steel plate gauges, soil pressure gauges, piezometers, strain gauges, multipoint displacement meters, joint meters, flow meters, thermometers, inclinometers, bolt stress gauges, and others. Automated safety monitoring data acquisition devices are installed simultaneously with monitoring instruments. The information management system for safety monitoring was completed and deployed for application at the beginning of the project, achieving comprehensive automated safety monitoring during the construction period by combining wireless transmission technology.

5 Challenges in Project Monitoring

5.1 Long Water Transfer Line and Diverse Monitoring Items

The entire line includes 37 foundation pits for working shafts, with depths ranging from 14.5 to 74.0 meters, of which 22 have depths exceeding 50.0 meters. The total length of the water diversion tunnel is 154 km, primarily constructed using the shield tunneling method, and it employs pre-embedded monitoring instrument technology in the segments. The safety monitoring involves four major categories: environmental monitoring, surface (internal) deformation monitoring, seepage monitoring, and stress-strain monitoring, encompassing nearly 30 subcategories of monitoring items. There are 5,131 monitoring instruments (points) installed within the working shafts (foundation pits) and tunnels, with two full-length sensing optical cables deployed at the top and waist of each tunnel. The installation and observation workload for settlement points of surface buildings affected by tunnel construction is substantial. The surface building monitoring points include 21,647 points across the Guangzhu West Expressway, Dongxin Expressway, Nansha Port Expressway, Jingzhu Expressway, Yuhuang Branch Line, levees, high-voltage towers, residential houses along the route, and the ground surface along the route. The extensive distribution of project buildings, along with the variety of building types and simultaneous construction across multiple lines, points, and working faces, necessitates a meticulous construction organization plan, significant human and equipment resource investment, and high organizational, coordination, and management capabilities.

5.2 Complex Installation Procedures for Monitoring Instruments

Monitoring instruments and cables installed within shield tunnel segments require reserved installation slots (holes) during segment prefabrication, which necessitates close cooperation between the design team and segment prefabrication production units. The installation of monitoring instruments between the segments and steel linings presents a small working area, limited time, and difficulties in protecting the installed instruments and cables. The installation process for fixed-point strain-sensing optical cables involves multiple procedures and high standards. The installation process requires horizontal pre-stretching of the fixed-point optical cables, manually controlled to maintain the stretch without movement, followed by the rapid installation of fixtures, which demands high technical skills from the installation personnel. Fixed-point strain-sensing optical cables are a type of distributed fiber optic sensor; damage to any point can cause the entire sensor line to fail to read data. Since they are installed between the segments and linings, the working area is narrow, the construction period is tight, and the installation is challenging, requiring high technical proficiency.

5.3 High Requirements for the Development and Integration of the Safety Monitoring Information Management System

The Pearl River Delta Water Resources Allocation Project features a long route and diverse types of hydraulic structures, including water transfer tunnels, reservoirs, gates, and pumping stations. The variety and large number of monitoring instruments and data collection devices, combined with both manual observation and automated collection modes, create a complex business process that imposes high demands on the functionality of the safety monitoring information management system. The system covers information collection, management, collation, analysis, monitoring, alarm, and visualization display modules, and it is open for use by safety monitoring contractors from other sections. Therefore, the system's professionalism, practicality, and advancement are of high importance, and the workload for system operation and maintenance is substantial.

The automated equipment uses various communication interfaces, including Ethernet, NB-IOT wireless methods, and 4G mobile communication, with different communication protocols, most of which are proprietary protocols from different manufacturers. The standard interface conversion for various types of equipment communication protocols, along with the custom development of corresponding interface communication and collection programs, requires a high level of software and hardware development capabilities from the project team, resulting in significant integration difficulties. The system must be integrated with various business systems of the Pearl River Delta Water Resources Allocation Project, such as the digital portal, mobile portal, smart construction site management information platform, archive management system, and BIM+GIS platform, to meet the requirements for intelligent engineering connectivity and unified supervision, presenting considerable challenges in system integration [12].

6 Innovations in Monitoring

6.1 Establishment of an Expert Leadership Team

Each safety monitoring participant unit is required by contract to set up an expert leadership team, enhancing the supervision of on-site project implementation and providing technical guidance and consultation. This ensures the investment of technical resources by all safety monitoring participants. Furthermore, the project expert team is required to participate in the entire process of project blueprint review, safety monitoring technical disclosure, and the review of safety monitoring implementation plans. The team has also frequently participated in meetings for analyzing abnormal data and handling early warnings during project implementation.

6.2 Designation of a Leading Unit for Safety Monitoring

The leading unit for safety monitoring assumes some of the responsibilities and functions of the owner's supervision. This includes establishing a standardized format and procedures for archiving safety monitoring data for the Pearl River Delta Water Resources Allocation Project, organizing safety monitoring work meetings, summarizing and analyzing safety monitoring data, building and maintaining the safety monitoring information management system, conducting re-surveys of the construction control network at the interfaces of the four safety monitoring sections, and providing safety monitoring services during the first year after acceptance. After the project's commencement, the leading unit for safety monitoring swiftly carried out work deployments, immediately involving high-quality, experienced management personnel with strong coordination skills, along with professional technical teams. They established safety monitoring work systems, processes, standards, and formats for each section of the Pearl River Delta Water Resources Allocation Project, and developed and deployed the safety monitoring information management system. The unit also assisted the owner in the overall planning of the safety monitoring work across the line, organized monthly safety monitoring meetings and other specialized meetings, consolidated and drafted the monthly safety monitoring data analysis reports and bulletins for the Pearl River Delta Project, and organized the preparation of the annual safety monitoring report for the entire line [13].

6.3 Deployment of the Safety Monitoring Information Management System

The interface of the safety monitoring system deployed for the Pearl River Delta Water Resources Allocation Project is shown in Figure 4. The safety monitoring information management system for the Pearl River Delta Project completed the development of 14 basic functional modules during the construction period, reviewed and approved 21 safety monitoring BIM models, and completed system penetration testing [14]. The safety monitoring information management system is open for use by six supervision sections, four safety monitoring sections, and 14 civil construction sections across the entire line. The system is utilized for reporting, comparative analysis, and abnormal statistics of monitoring data, thereby improving the efficiency of safety monitoring work. Zheng et al. [15] introduced the Cuckoo Search algorithm to obtain the optimal process line for identifying outliers. Based on this, an optimized gross error identification model was proposed and integrated into the safety monitoring information management system. The interface for gross error identification within the system is shown in Figure 5. The use of dedicated analysis and calculation modules enables correlation analysis of monitoring data, phreatic line analysis, convergence deformation analysis, statistical deformation analysis, and safety analysis and evaluation, thereby enhancing the depth and timeliness of monitoring data analysis within the system. The interface for the dedicated analysis and calculation modules is shown in Figure 6. By using the safety monitoring information management system to statistically track the frequency of data uploads for each safety monitoring section, the system strengthens the supervision and assessment of the timeliness of safety monitoring data reporting. Since the commencement of the Pearl River Delta Project, the system has been operating stably for four years. Currently, the system has over 600 users, with more than 200 users proficient in long-term use of the monitoring system. A total of 4.7 million monitoring data points and 20,641 inspection records have been entered into the system, fully utilizing the safety monitoring role of each participating unit in the project's implementation process [3].

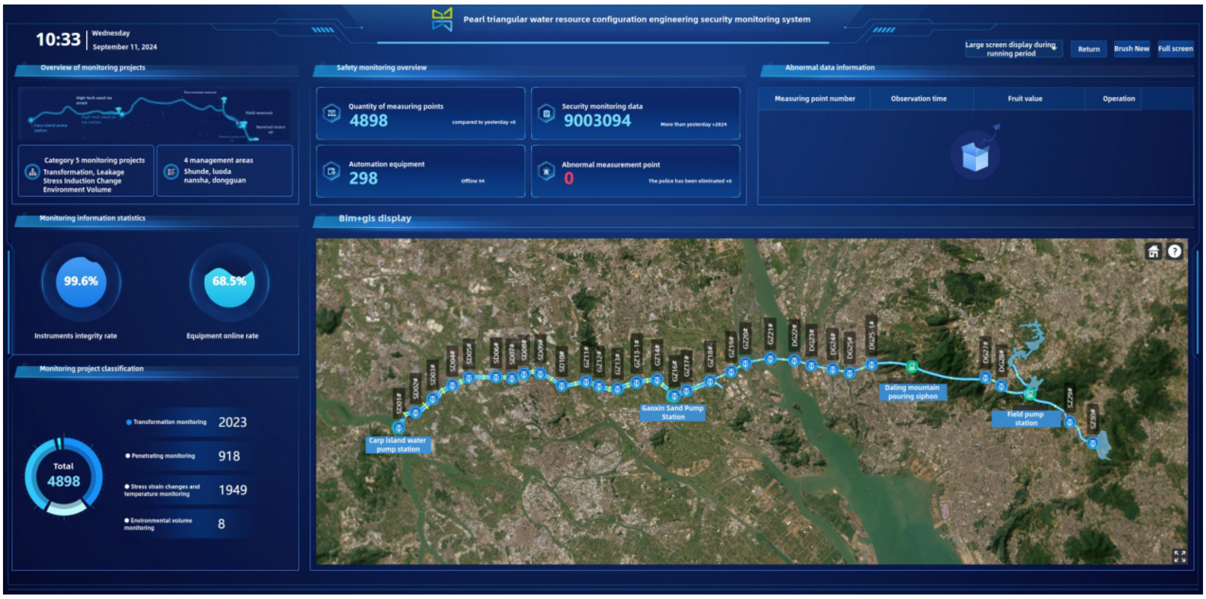

Figure 4. Interface of the safety monitoring system for the Pearl River Delta Water Resources Allocation Project

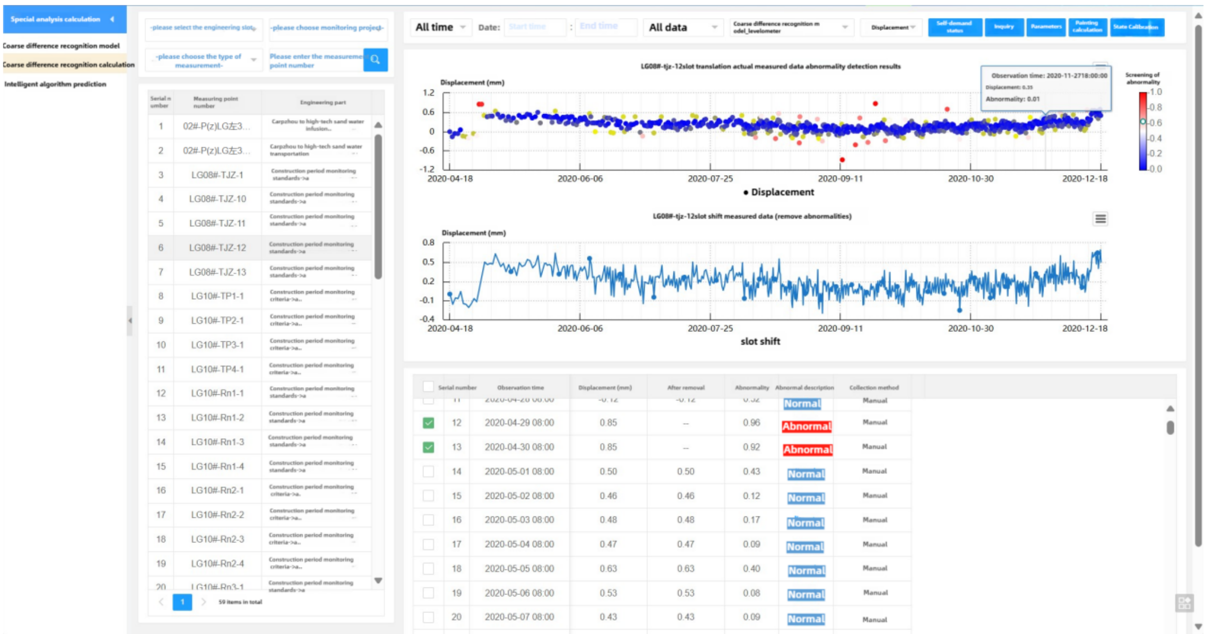

Figure 5. Interface of the gross error identification model in the safety monitoring system

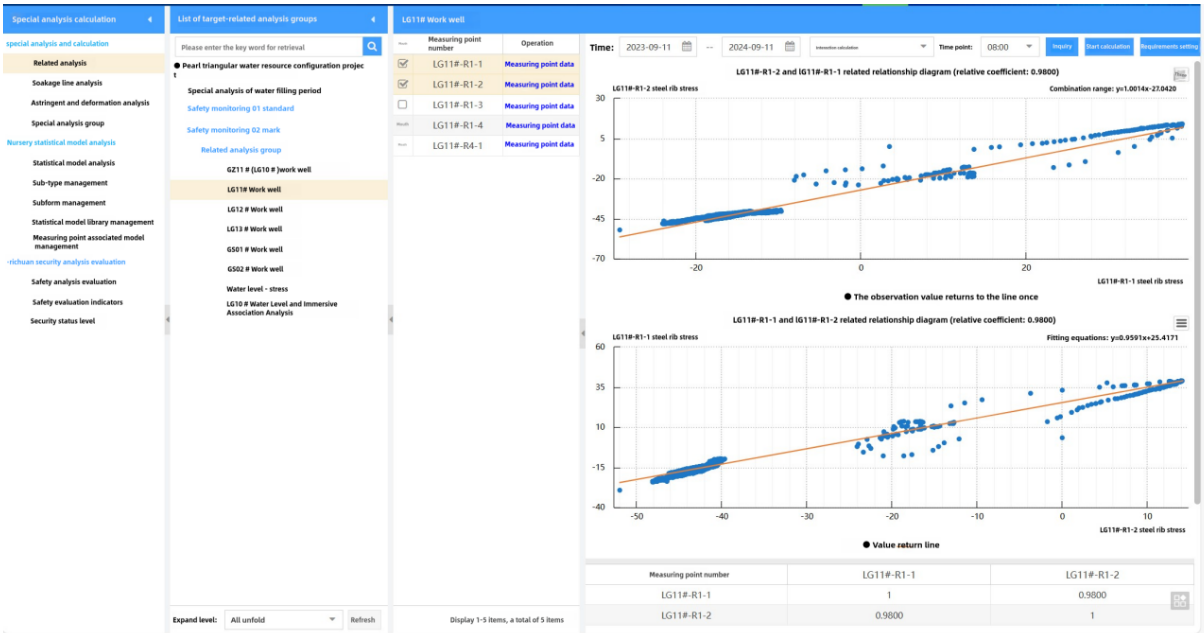

Figure 6. Interface of the specialized analysis calculation module in the safety monitoring system

6.4 Automation of Safety Monitoring During the Construction Period

Figure 7. Installation of automated monitoring equipment during the construction period

The development of automated dam safety monitoring equipment began abroad in the late 1980s. The U.S. Bureau of Reclamation installed a centralized data acquisition system on the Monticello Arch Dam in 1981. Since 1982, distributed data acquisition systems have been installed on four arch dams, including Flaming Gorge [16]. Although the automation of dam safety monitoring in China started relatively late, the country has successfully developed and widely implemented distributed data acquisition units, intelligent data acquisition modules, wireless communication modules, lightning protection modules, and intelligent distributed safety monitoring data acquisition systems, as well as dam safety information management network software. These systems are compatible with various sensors and measurement methods. It is rare, both domestically and internationally, to achieve automated monitoring during the construction period. This project has adopted a hybrid data acquisition system to automate safety monitoring during the construction phase. Automated safety monitoring data collection devices are installed simultaneously with the monitoring instruments, ensuring the timeliness of monitoring data during construction [17]. The construction unit evaluates the implementation of automated safety monitoring through an assessment system, with a cumulative total of 7.65 million pieces of monitoring data collected. The installation of automated monitoring equipment during the construction period is shown in Figure 7.

6.5 Application of Distributed Fiber Optic Sensing Technology

Distributed fiber optic sensing technology is based on Raman scattering and Brillouin scattering effects. It uses optical fibers as both sensitive sensing elements and signal transmission media. Through advanced Optical Time-Domain Reflectometry (OTDR) and Optical Frequency-Domain Reflectometry (OFDR) technologies, it detects temperature and strain variations at different positions along the fiber. This technology is characterized by its resistance to electromagnetic interference, corrosion resistance, long-distance monitoring capability, high sensitivity, and high accuracy. The Pearl River Delta Water Resources Allocation Project innovatively adopts distributed fiber optic sensing technology to achieve precise location detection, fine sensing, and comprehensive perception of abnormal conditions in long-distance water transfer tunnel structures [18, 19]. It is the first project in the domestic water conservancy industry to achieve full-line fixed-point monitoring and currently the longest distributed fiber optic monitoring scheme [18, 20]. The project utilizes the highest quantity of distributed strain-sensing fibers in China, with a total length of 98,284 meters and approximately 65,000 sensing points, each with a fixed-point strain sensor every 1.5 meters. The data collected by the distributed fiber optic system is visualized as a cloud map, as shown in Figure 8. Additionally, the project integrates various Internet of Things (IoT) technologies [21, 22] and Beidou technology to achieve automatic monitoring of the long-distance water transfer tunnel structures and their impact on surrounding buildings for the first time. A safety monitoring management platform has been established, and an intelligent gross error identification system has been developed to realize intelligent identification of massive abnormal monitoring data, automatic data collation, and automatic early warning across the entire line, significantly enhancing the timeliness and scientific accuracy of safety monitoring as the project's eyes and ears.

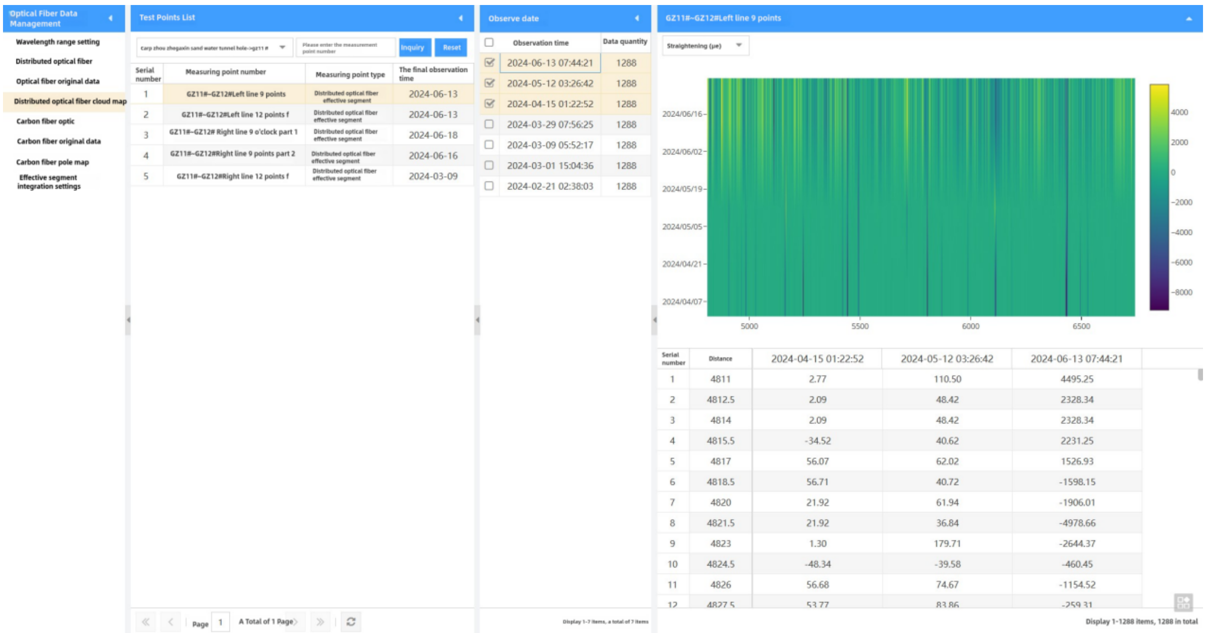

Figure 8. Cloud map display of data collected by the distributed fiber optic system

6.6 Implementation of 3D Laser Scanning for Formed Tunnels

Three-dimensional laser scanning technology utilizes the principle of laser ranging to rapidly measure and record the 3D coordinates, reflectivity, and texture information of a large number of dense points on the surface of the measured object. This technology enables the quick reconstruction of a three-dimensional model of the target, providing line, surface, and volume data. In this project, 3D laser scanning technology and a large-scale 3D laser point cloud block-by-block classification algorithm were applied to the initial 3D laser scanning of surface buildings and tunnels along the construction line. The use of 3D laser scanning technology and point cloud classification algorithms has improved the efficiency of building safety monitoring, solved the problem of monitoring deformation of large-area buildings along the route, and facilitated the evaluation of the quality grade of formed tunnel structures. It also provides reliable three-dimensional archival data for the construction process. The point cloud of the tunnel scanned using 3D laser scanning is shown in Figure 9, and the 3D laser scan point cloud of the fork pipe section of the pump station pressure water tank is shown in Figure 10.

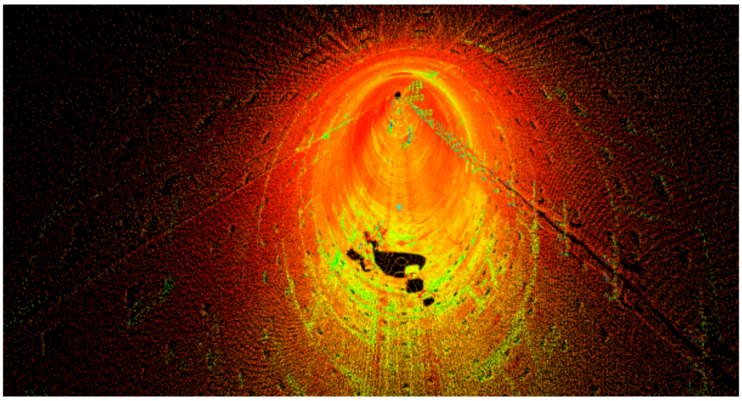

Figure 9. 3D laser scan point cloud inside the tunnel

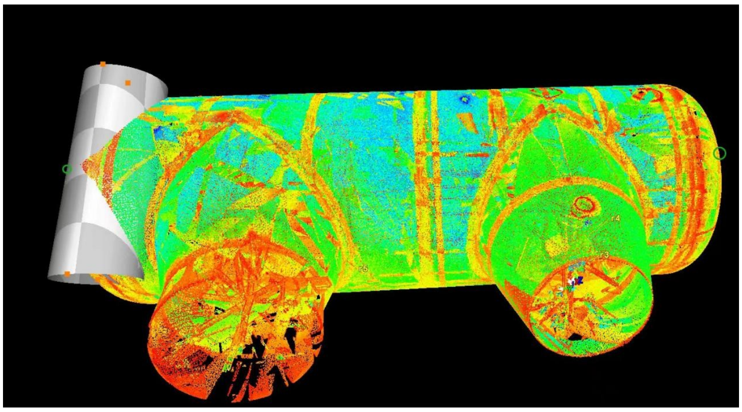

Figure 10. 3D laser scan point cloud of the fork pipe section of the pump station pressure water tank

6.7 Optimization of Monitoring Sensor Installation

During the implementation of safety monitoring in the Pearl River Delta, participating safety monitoring units have developed and optimized various types of underground engineering monitoring sensor installation devices and application methods. This has enabled the timely capture and monitoring of external water pressure data at multiple measurement points. The widespread application of this technology has significantly optimized the process of installing monitoring sensors in underground chambers of long-distance water diversion projects, reduced project costs, improved the timeliness of monitoring data, and ensured data accuracy. This advancement has enhanced the emergency response and decision-making capabilities of smart engineering during the construction period in the Pearl River Delta, providing crucial technical support to ensure the safety of people's lives and property, resulting in significant economic and social benefits.

6.8 Establishment of a Comprehensive Early Warning Management System

To clarify the responsibilities of all parties involved in the early warning, response, and cancellation stages of the monitoring and early warning management process for the Pearl River Delta Water Resources Allocation Project, and to standardize the conditions and workflows for early warning and cancellation, a *Safety Early Warning and Cancellation Management Guide for the Pearl River Delta Water Resources Allocation Project* was specially formulated. This guide aims to ensure project safety, protect the surrounding environment, and maintain timely, orderly, and efficient safety monitoring and early warning work, thereby providing a reliable basis for optimized design and construction guidance. The early warning response process is shown in Figure 11. A comprehensive early warning management system was established for different structures and construction processes. Each participating unit has an engineering safety monitoring institution and has appointed a leadership member responsible for engineering safety early warnings. The standardized management content and professional management personnel ensure the effective application of the safety early warning management system in this project. In conjunction with the safety monitoring information management system, a total of 26 early warnings have been issued to date, mainly focusing on groundwater level drops beyond the limit during foundation pit excavation of working shafts and surface settlement beyond the limit during shield tunneling. In response to these early warnings, experts are promptly organized to analyze the situations, and relevant measures are implemented following the early warning and cancellation work guidelines to ensure project safety. The statistics of early warning situations in the safety monitoring system's early warning event management module are shown in Figure 12.

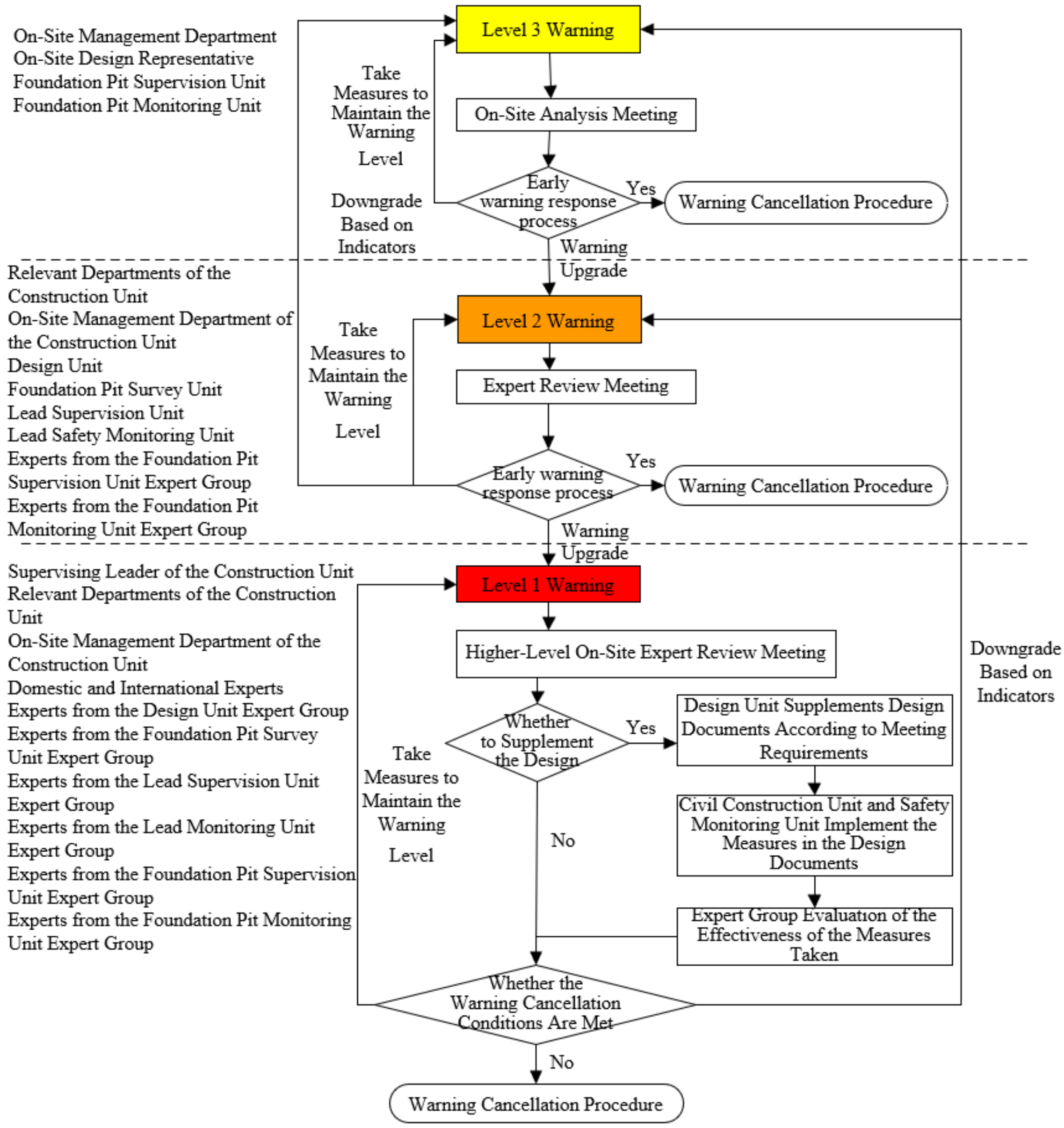

Figure 11. Early warning response process

7 Conclusion and Future Prospects

Long-distance, deep-buried water transfer tunnels constructed using multiple methods are relatively rare in China. Reasonable safety monitoring has provided strong assurance for the safety and reliability of such projects during the construction period. It not only verifies the design but also, when combined with dynamic design, can effectively reduce project investment or eliminate safety hazards. Additionally, it provides a reliable basis for management units to analyze and evaluate project safety and make operational management decisions. The data collected subsequently offers effective support for future scientific research and provides valuable experience for similar projects. The future development trends in safety monitoring can be summarized as follows:

(1) On the basis of the safety monitoring information management system, a comprehensive information management system should be formed by integrating systems such as hydrological monitoring, gate control, and video surveillance to achieve comprehensive monitoring and control.

(2) Centered on the river basin, the integration of monitoring information systems for various water conservancy projects should be carried out to achieve unified management, remote control, monitoring data collection, analysis, evaluation, and network reporting in an integrated manner.

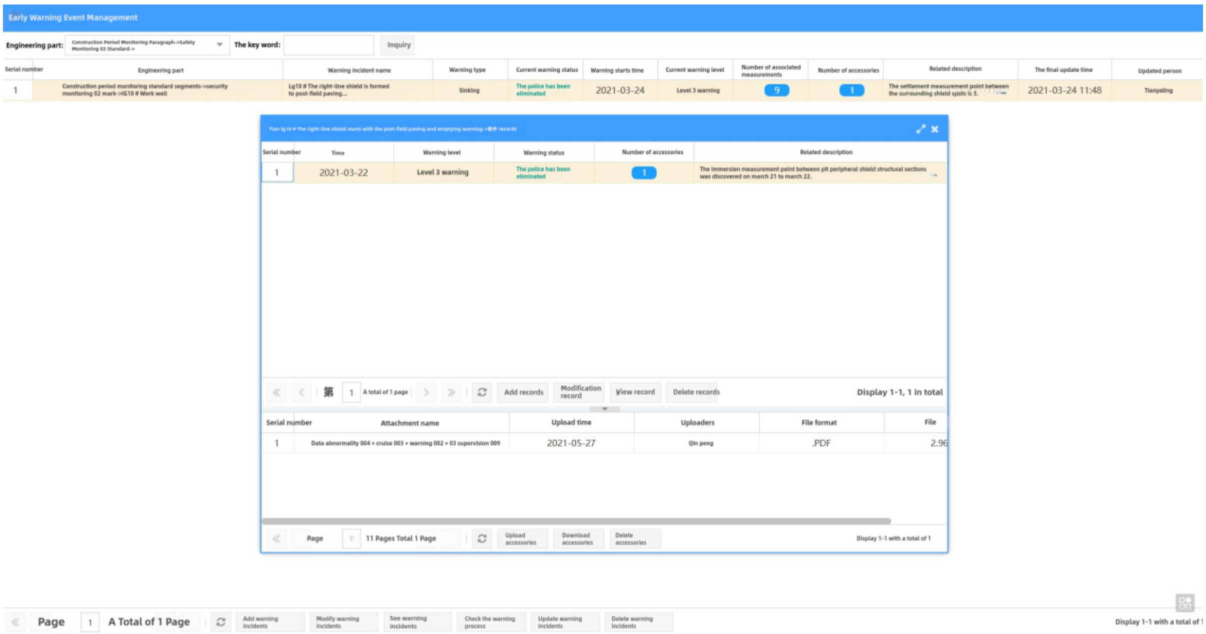

Figure 12. Statistics of early warning situations in the early warning event management module of the safety monitoring system

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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 they have no conflicts of interest.

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