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# A Study on the Monitoring Technology for the Second Jiaozhou Bay Subsea Tunnel Project

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ABSTRACT: The Second Jiaozhou Bay Subsea Tunnel (hereinafter referred to as "JBSST") in Qingdao is currently the largest-scale and longest subsea road tunnel in Asia. The tunnel was constructed using a combination of drill-and-blast (D&B) and tunnel boring machine (TBM) methods. Due to numerous hazards such as subsea fault zones, deep weathering troughs, and weak fractured zones, the project faces extremely high risks and challenges. This paper systematically investigates the overall tunnel monitoring implementation scheme including the scope of instrumentation and measurement, intelligent blast vibration monitoring, the integration of construction-phase and operation-phase monitoring, and the development of a digital monitoring platform, by taking into account the risks and challenges faced in the tunnel. The results from the project implementation validate the effectiveness and applicability of the proposed scheme.

## 1 INSTRUCTION

The JBSST is Asia's longest subsea road tunnel project. It employs a construction method that combines D&B and TBM. The tunnel is 17.5 km long, with the maximum overburden of approximately 115 m below sea level as shown in Figure 1 (Xiao et al. 2023, Qu et al. 2024). The JBSST passes through various geological units and will inevitably encounter adverse geological bodies such as subsea fracture zones, faults, weathered deep troughs, and weak fractured zones, giving rise to a multitude of significant geohazard risks (Qu et al. 2024, Li et al. 2024). Twenty-two structural zones have been identified in which the rock mass is fractured, making it highly susceptible to tunnel lining dislocation, structural fractures, and potential collapses, as well as water and mud inrush disasters (Wu et al. 2023). The geological longitudinal profile of the JBSST is shown in Figure 2. The D&B sections of the tunnel are situated near densely populated residential areas within the urban built-up zone. The offshore section constructed using the D&B method on the Huangdao side underpasses a "100,000-ton" crude oil transfer terminal, which is highly sensitive to potential ground vibrations and noise from construction activities (Chen et al. 2024). The complex geological conditions and sensitive surrounding environment present world-class challenges for the monitoring tasks.To address these risks and challenges, a monitoring scheme during the tunnelling and operation is developed. This paper investigates major technologies employed in the scheme.

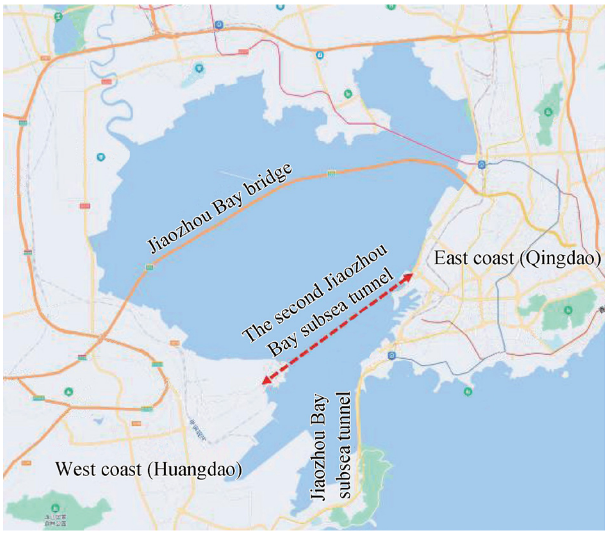


Figure 1. Location map of the JBSST

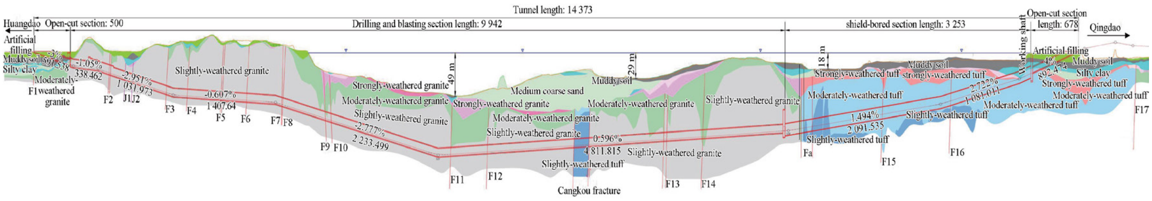


Figure 2. Longitudinal geological profile showing the major fault zones traversed by the JBSST

## 2 MONITORING TECHNOLOGY

### 2.1 Overall Monitoring Scheme

The monitoring scheme for the JBSST has been designed with the principles of "precision, comprehensiveness, reliability, and cost-effectiveness" in mind. In conjunction with the construction methods and geological risks, a specified monitoring system has been established. For the D&B sections, crown settlement, clearance convergence, and peak particle velocity (PPV, the maximum value in three orthogonal directions) are the core indicators. These are supplemented by monitoring items such as internal displacement of the surrounding rock, surrounding rock pressure, support structure stress, and water pressure, focusing on the assessment of surrounding rock stability and blast impact. For the TBM sections, segment displacement (vertical displacement, horizontal convergence) is the core indicator, supplemented by segment stress, bolt stress, surrounding rock pressure, and water pressure, focusing on the synergistic monitoring of structural forces and ground deformation. Guided by the principle of "highlighting key points while ensuring comprehensive coverage", the entire monitoring system targets critical risks such as surrounding rock stability and blast impact in the D&B sections, and segment structural forces in TBM sections. Monitoring points are densified at critical locations like subsea fault zones, covering the entire cycle from construction to operation. Millimetre-level precision control is achieved through automated monitoring. The arrangement of monitoring sections in the D&B tunnel is shown in Figure 3, and the layout of displacement monitoring points in the TBM sections is shown in Figure 4.

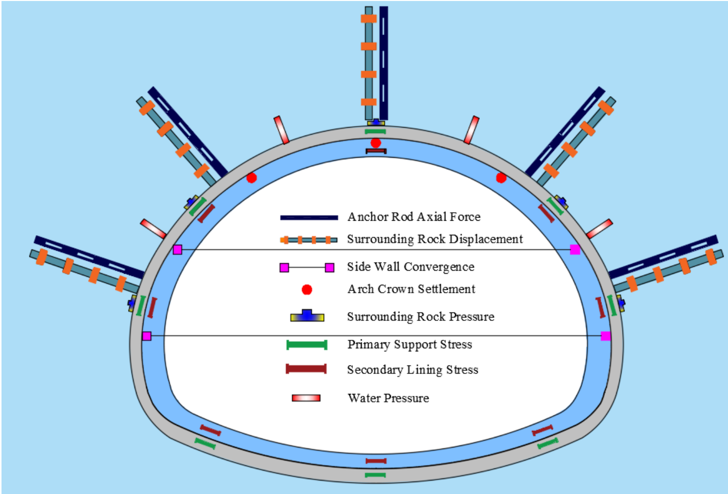

Figure 3. Setup of Monitoring Items for D&B Tunnels

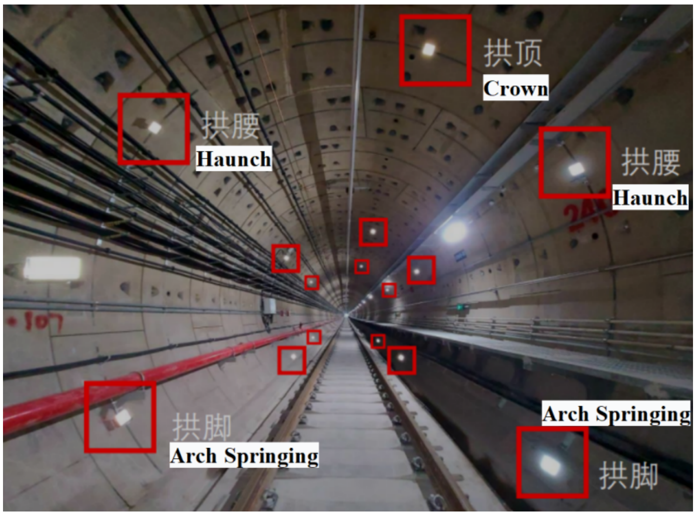

Figure 4. Layout of Displacement Monitoring Points for TBM Tunnels

## 2.2 Intelligent PPV Monitoring

To address the challenge of vibration control for blasting construction near sensitive environments, an automated monitoring system based on the Internet of Things (IoT) was developed, forming an integrated "perception-transmission-analysis-decision" solution as shown in Figure 5. In terms of hardware architecture, high-precision vibrating wire triaxial sensor arrays are employed to achieve precise acquisition of PPV vector data. A hybrid communication network solves the data transmission challenges in complex environments. At the software level, a BIM visualization module and an intelligent analysis platform were developed and integrated. This constructs a multi-source dataset incorporating blasting parameters, geological characteristics, and vibration responses, establishing a vibration velocity prediction model. This enables early warning of PPV and back-analysis for optimizing construction parameters, enhancing the timeliness and decision-support value of monitoring results. Comparison with traditional technology is shown in Table 1. The innovations of this monitoring scheme are:

– Achieving "real-time spatial distribution reconstruction - time-series trend prediction - dynamic risk level assessment" of PPV effects through automated data acquisition, intelligent noise filtering algorithms, and a 3D visualization analysis platform.

- The intelligent early warning model, incorporating engineering geological features and blasting techniques, improves warning accuracy by 30% compared to traditional single-threshold methods.
- Lightweight sensor integration technology enables the rapid deployment of miniaturized equipment in complex tunnel environments, increasing installation efficiency by 50%.

Table 1. Performance Comparison of Intelligent PPV Monitoring

| Comparison Content | Traditional PPV Monitoring | Intelligent PPV Monitoring |
|---|---|---|
| Overlimit Times / Monitoring Times | 33/275 | 3/202 |
| Data Calculation and Analysis Time (s) | 220 | 120 |
| Sensor Installation and Layout Time (min) | 20 | 10 |
| Data Source. | The Inclined Shaft of the JBSST (Jul-Oct 2021). | The North Line Tunnel of the JBSST(Jun-Aug 2023) |

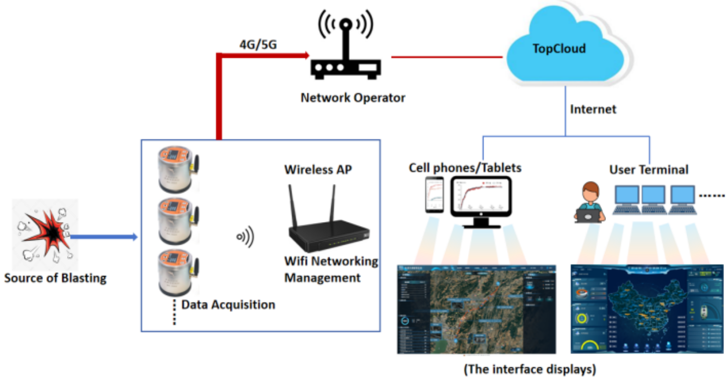


Figure 5. Intelligent Monitoring of PPV

## 2.3 Integrated Construction-Operation Phase Monitoring

Given the technical limitations of traditional monitoring, which is often characterized by phased implementation and data discontinuity, the concept of tunnel monitoring is elevated from ensuring construction-phase safety to guarantee the entire lifecycle (hereinafter referred to as "EL") safety and an Integrated Construction-Operation Phase Health Monitoring System is established. By pre-embedding lifecycle sensors and integrating intelligent monitoring technologies, the continuity and traceability of monitoring data at key risk locations is ensured, to solve the traditional issue of the "separation between construction and operation phases. The sensor design adopts an integrated approach such that operation-phase monitoring elements are pre-embedded during the construction phase. This approach prevents secondary damage to the structure from retrofitting sensors later and reduces the EL monitoring cost by over 30%, the comparison of monitoring costs is shown in Table 2. The monitoring section for the EL is shown in Figure 6. In the D&B tunnels, vibrating wire pressure cells and fiber Bragg grating (FBG) strain gauges are pre-embedded between the primary support and secondary lining in fault fracture zones and weak surrounding rock sections to monitor changes in surrounding rock pressure and lining stress. FBG displacement meters and bolt stress gauges are pre-embedded at segment joints and sections traversing fracture zones, with bolt stress gauges embedded within segment connecting bolts. During construction, segment convergence and bolt forces are monitored. During operation in the D&B tunnels, structural deformation is scanned in real-time via a distributed optical fiber network. A "segment-surrounding rock synergistic monitoring" mode is adopted. Earth pressure cells and pore water pressure gauges are simultaneously installed behind the TBM cutterhead. During construction, this setup assesses the disturbance of surrounding soil caused by TBM advancement. During operation, it monitors the impact of long-term ground creep on the structure.The layout of TBM tunnel monitoring sensors is shown in Figure 7.

Table 2. Comparison of Monitoring Costs

| Comparison Content | Traditional Monitoring | Integrated Construction-Operation Phase Monitoring |
| --- | --- | --- |
| Construction Monitoring Cost | CNY 2.0 M | CNY 6.0 M |
| Operational Monitoring Cost | CNY 6.8 M | |
| Data Source | Costs for 12 monitoring sections of a tunnel in Southern China. | Costs for 12 monitoring sections of the JBSST. |

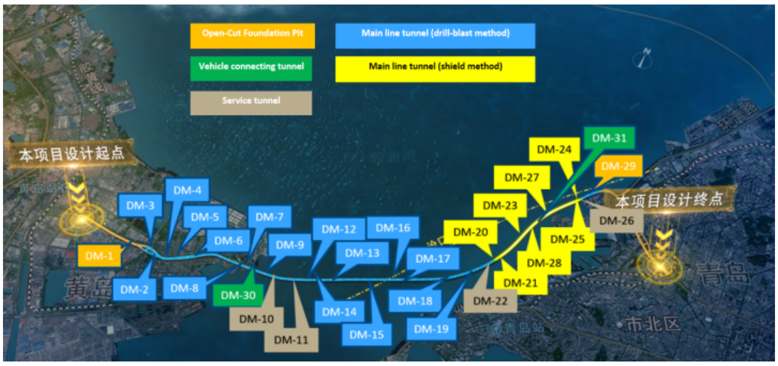

Figure 6. Integrated Monitoring Sections for Construction and Operation Phases

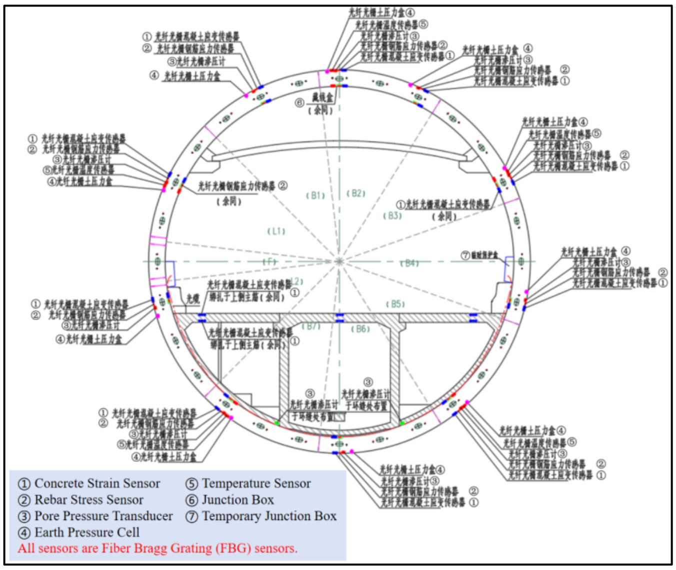

Figure 7. Sensor Layout for Health Monitoring of the TBM Sections

## 2.4 Construction of the Digital Monitoring Platform

For the JBSST project, a dedicated digital monitoring platform is constructed to meet the project's complex monitoring demands, as shown in Figure 8. The platform utilizes BIM+GIS technology as its core framework and integrates key information such as structural segments, fault zones, and on-site monitoring point positions. The platform then integrates IoT devices, big data modules for processing real-time monitoring data, and intelligent algorithms to establish a monitoring system characterized by "the digitalization of the entire process and EL integration". The schematic of the early warning display interface is shown in Figure 9. Here, "full-process digitalization" covers the whole workflow from on-site data collection to automated calculation and online report output, while "EL integration" links construction-phase monitoring with operation-phase health tracking. Its technical features and innovations are reflected in:

- Automated Multi-source Data Acquisition and Fusion. Employing a "24-hour automated acquisition as primary + human-machine collaboration as auxiliary" model, it integrates diverse devices such as vibrating wire sensors, FBG sensors, and LiDAR.
- Intelligent and Visualized Risk Prevention and Control. Establishing an "intelligent early warning - dynamic back-analysis - closed-loop management" system. Based on a BP(Back Propagation) neural network model, it predicts trends in monitoring data, improving warning accuracy by 40% compared to traditional threshold methods. For instance, when monitoring data exceeds limits, the system automatically triggers an alarm, synchronously pushes information to all stakeholders, and highlights the risk area in the linked BIM model, achieving a "monitoring-analysis-handling" response within 10 minutes (down from 90 minutes).
- Full Coverage of Construction Methods and System Synergy. Developing dedicated subsystems for different construction methods like D&B and TBM. These subsystems communicate with the platform through standardized data interfaces, solving the "data silo" problem inherent in traditional isolated multi-system operations.
- Digital Reconstruction of Management Processes. Implementing the entire process of monitoring data acquisition, calculation, and warning online.

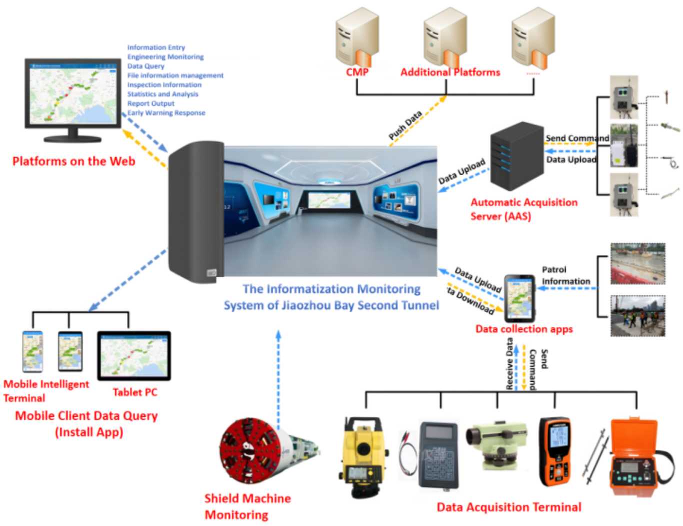

Figure 8. Information-based Monitoring Platform

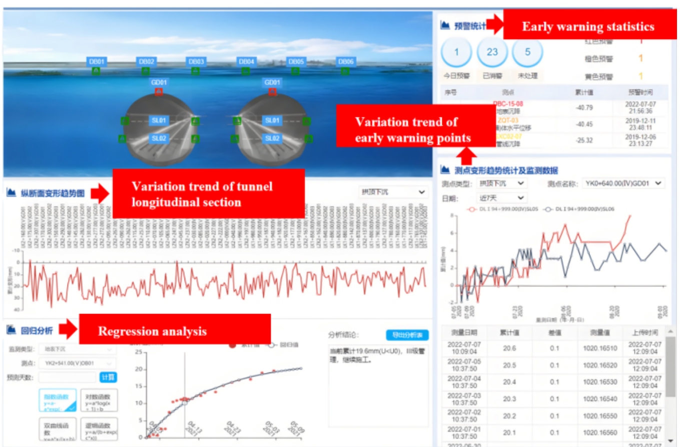

Figure 9. Structural Deformation Early Warning on the Display Interface

## 3 CONCLUSIONS

From this study, the conclusions can be drawn as follows:

(1) Effectiveness of the Monitoring Technology System. The information-based and automated integrated instrumentation and measurement technology system established has effectively controlled safety risks during the construction phase of the subsea tunnel, the warning response efficiency is nine times as high as that of traditional systems. Particularly under complex conditions such as traversing 22 structural zones and high-water-pressure and water-rich strata, it has achieved 234 early warnings, innovations in EL Monitoring, and dynamic control of disasters like structural deformation.

(2) Pioneering the "Integrated Construction-Operation Phase Monitoring System," continuous EL data acquisition is achieved through sensor pre-embedding technology. This overcomes the technical bottleneck of traditional monitoring, characterized by "phased implementation and data discontinuity," reduces EL monitoring costs by over 30%, offers foundational data support for the long-term health assessment of the tunnel, and ensures seamless integration of the "construction-operation" monitoring system for the subsea tunnel.

(3) Effectiveness of Intelligent PPV Monitoring. This solution has reduced the rate of PPV velocity exceeding limits from 12% to 1.5%, and improved monitoring data processing efficiency by 80%. It offers comprehensive technical support for tunnel blasting construction near sensitive targets, encompassing "real-time monitoring - intelligent analysis - active control," thereby promoting the shift from empirical to digital and intelligent PPV control.

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