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Application of Laser Vision AI Monitoring Technology during Construction of Water Supply Tunnels Constructed by Combined Pipe Jacking and Shield Tunnelling Methods

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Abstract

Aiming at the technical limitations of conventional manual monitoring for composite pipe-jacking-shield water-supply tunnels under deep-buried,high-water-pressure and complex stratum conditions,including limited monitoring coverage,delayed data acquisition and insufficient capacity for pre-emptive risk early-warning,this paper proposes a dual-optical coaxial laser-video artificial intelligence(AI) monitoring technology.Using this system,we achieve millimetre-level deformation monitoring for vault settlement and cross-section convergence by synchronously acquiring three-dimensional coordinates of tunnels and apparent images of linings via laser ranging and visible-light imaging.Combined with deep-learning-based defect recognition techniques,this study constructs a multi-source heterogeneous monitoring system that considers both macroscopic structural deformation and microscopic lining damage.With a coupled model integrating numerical-quantitative identification and image-based qualitative verification,this study establishes a full-process intelligent early-warning and data-tracing mechanism that supports index comparison, heat-map-assisted verification and four-level risk-classification alert dispatching. A 58-day continuous field monitoring campaign was carried out on the composite pipe-jacking-shield tunnel beneath the Sunjiang Bridge of the Jinmen Water Supply Project.A total of 1377 valid datasets of vault settlement and 1019 datasets of haunch clearance convergence were collected.Monitoring results reveal that the cumulative vertical vault deformation of each tunnel cross-section ranges from -0.45 mm to 1.36 mm.The clearance-convergence deformation exhibits a three-stage evolutionary pattern: rapid development induced by excavation disturbance, decelerated growth due to stress redistribution,and stable creep of surrounding rock.The overall tunnel deformation remains controllable and the supporting system operates stably. The proposed monitoring system can accurately identify abnormal structural deformation and apparent lining defects of tunnels,deliver hierarchical, precise early-warnings as well as full-chain data traceability.It effectively improves dynamic construction-safety management capacity for complex hydraulic tunnels under high water pressure,is adaptable to construction conditions of composite pipe-jacking-shield tunnels, and shows promising prospects for engineering promotion and application.

Keywords

Pipe-jacking and Shield Composite Construction; Laser Vision; Artificial Intelligence; Real-time Monitoring; Deformation Characteristics; Hierarchical Early Warning.

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1. Introduction

Unprecedented large-scale construction of river-crossing water-supply tunnels has been undertaken globally in China,with ever-increasing burial depth and ambient water pressure.Complex geological and operational conditions,including karst strata,weathered and fractured rock masses,and tunnel intersections with water-sensitive urban structures,have become increasingly prevalent.Tunnel excavation and unloading frequently induce high risks of surrounding rock instability,water inrush,and mud burst.Statistical analysis of tunnel engineering accidents indicates that major structural hazards,such as lining cracking,local collapse,and pipe joint leakage,primarily stem from three key factors: inadequate support optimization at sections with abrupt changes in surrounding rock classes,misjudgment of structural deformation under high water pressure,and delayed monitoring and early-warning.

Conventional safety-monitoring systems for hydraulic tunnels predominantly rely on manual fixed-point sampling using total stations and convergence meters,as well as regular manual internal inspections.This monitoring mode exhibits inherent limitations.First,discrete measuring points and low sectional coverage fail to capture local concealed deformation of tunnel structures.Second,long manual data acquisition cycles lead to severe time lag,which only allows post-disaster retrospective analysis rather than proactive risk prevention and control.Third,such methods merely obtain numerical deformation data without intuitive evidence of lining-surface damage,including cracks,seepage,and spalling,leading to incomplete risk evaluation.

Three-dimensional (3D) laser scanning can acquire high-precision point cloud data of surrounding rocks and quantify structural deformation through section profile fitting.Nevertheless,independent laser scanning devices cannot capture in-situ visual images,making it impossible to distinguish structural deformation from lining surface defects.By contrast,binocular vision imaging enables automatic identification of lining cracks and seepage areas but lacks the capability for 3D displacement quantification,failing to meet the millimeter-level deformation control requirements for tunnel construction.

Numerous studies have advanced tunnel deformation monitoring and defect detection technologies.Wang et al.[1] extracted tunnel section profiles from point cloud data and conducted center-line analysis,effectively improving the accuracy and efficiency of tunnel deformation monitoring.Xiao et al.[2] integrated multiple monitoring techniques including 3D laser scanning,acoustic detection,and microseismic monitoring to investigate the time-dependent deformation of surrounding rocks in diversion tunnels.They proposed a collaborative analysis method for shallow damage and internal fracture evolution,revealing the temporal deformation and micro-fracture mechanisms of surrounding rocks and providing guidance for optimal support installation timing.Ma et al.[3] developed a 3D data acquisition method combining linear laser and binocular cameras,which achieves precise registration of laser contours and image pixels and significantly improves 3D reconstruction accuracy.Guo et al.[8] conducted research on multi-scale deformation monitoring using terrestrial 3D laser scanning, which fully validates the advantages of laser-based techniques for capturing deformations in underground engineering. Wang et al.[7] proposed a two-level information fusion perception strategy for tunnel environments, providing references for the fusion and processing of multi-source heterogeneous monitoring data.

To address the technical bottlenecks of single-sensor monitoring approaches and imperfect early-warning systems in existing tunnel safety monitoring,this study adopted a dual-optical coaxial laser-vision AI monitoring instrument.Combined with grayscale-image thermal quantification and deep-learning-based surface-defect recognition,we construct a multi-source-data-coupled hierarchical early-warning model.Field monitoring was implemented on the composite pipe-jacking-shield tunnel of the Jinmen Water Supply Project.This study systematically revealed the evolutionary characteristics of surrounding rock deformation in river-crossing hydraulic tunnels under high water pressure.This study provides a feasible technical reference for intelligent monitoring and dynamic safety management of similar underground hydraulic-engineering projects.

2. Laser-Vision AI Multi-source Fusion Monitoring Technology System

The integrated monitoring system is divided into three hierarchical modules,including the front-end hardware synchronous-acquisition layer,the cloud data matching and fusion layer,and the AI defect recognition and hierarchical early-warning layer.Its core technical workflow consists of two major stages: synchronous data acquisition and multi-source data coupling analysis.

2.1 Front-end Dual-optical Coaxial Synchronous Data Acquisition

The laser-vision AI monitoring instrument is equipped with a coaxial laser ranging module and a high-definition visible-light camera.Adopting a dual-optical-path synchronous acquisition architecture with consistent measuring points,the system realizes one-to-one correspondence between the three-dimensional (3D) coordinates of laser measurement points and image pixels,thereby eliminating temporal and spatial acquisition deviations.The monitoring device moves dynamically with the advancement of the composite pipe-jacking and shield tunneling machine,covering 2-3 monitoring sections in a single fixed deployment and continuously outputting two types of fundamental monitoring data:

(1) Laser 3D coordinate data.The system collects the X/Y/Z tri-axial coordinates of monitoring points arranged at the tunnel vault and haunch in real time.Vertical settlement and horizontal convergence displacement are calculated based on time-series coordinate differences,with a monitoring accuracy of ±0.5 mm.

(2) Visible-light image data.Complete on-site lining images of monitoring sections are synchronously captured,and original Red-Green-Blue (RGB) images are stored for subsequent surface defect recognition and grayscale feature quantification.

2.2 Multi-source Data Matching and Coupling Analysis Mechanism

This stage handles the processing and utilization of monitoring data and serves as the core link for monitoring and early-warning realization.The triaxial displacement of monitoring points is determined by calculating the coordinate differences of front-end-uploaded 3D data.The actual triaxial displacement values are compared with the threshold values preset on the cloud platform to trigger early-warnings once the monitoring data exceed the limits.

Image data serve as verification evidence for early-warning events.Image deformation is quantified by calculating grayscale differences between sequential images,and grayscale images are further converted into heat maps through color mapping transformation[4].When both triaxial displacement and image deformation exceed the threshold values simultaneously,the early-warning information is directly pushed to relevant management personnel.In cases where only a single indicator exceeds the limit,the alarm data are submitted to safety auditors for further verification and assessment.

3. Establishment of Excavation Instability Mechanism and Risk Indicator System for Water-Supply Tunnels

3.1 Classification of Excavation Instability Disasters for Water-Supply Tunnels

Water-supply tunnels are generally constructed through mountains,river valleys and complex stratified strata,presenting prominent engineering characteristics including large burial depth and span,complicated engineering geological conditions,variable surrounding rock stability during construction,and high seepage water pressure.Under coupled effects of complex geological and construction-related conditions,tunnel excavation operations are highly susceptible to inducing multiple types of instability disasters.Based on the on-site construction conditions and disaster evolution characteristics of water-supply tunnels,excavation-induced instability disasters in tunnel engineering are categorized into three types: shallow deformation disasters,local damage disasters, and overall instability disasters.

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Table 1. Classification of potential hazards in tunnel engineering

Disaster Category	Main Manifestations	Common Causes and Occurrence Conditions	Deformation and Evolution Characteristics
Shallow deformation	Vault settlement,horizontal displacement of side walls,and cross-section convergence deformation	Excavation unloading and time-dependent creep of surrounding rock masses	Low deformation rate with negligible hazard in the initial stage
Local damage	Initiation and propagation of inner lining cracks,surface rock spalling,local rock falling,and structural seepage	Broken surrounding rock and sections with developed joints and fissures	Intuitive external manifestation of continuous internal damage evolution in surrounding rock
Overall instability	Local collapse,working face instability,water and mud inrush,support structure failure,and ground surface subsidence	Coupled effects of surrounding rock structure and strength,regional in-situ stress,groundwater environment,and support quality conditions	Sudden occurrence and strong destructive power,posing severe threats to tunnel construction safety

3.2 Multi-source Risk Indicator Collection for Tunnels

Based on the classification and evolutionary mechanisms of instability disasters in water-supply tunnels and drawing on technical advantages of the laser-vision AI monitoring system,this study selects two core groups of risk indicators: quantitative structural-deformation indicators and apparent lining-defect indicators.A comprehensive surface risk monitoring system for tunnels is thereby established,realizing full-coverage monitoring ranging from macroscopic structural deformation to microscopic lining damage.

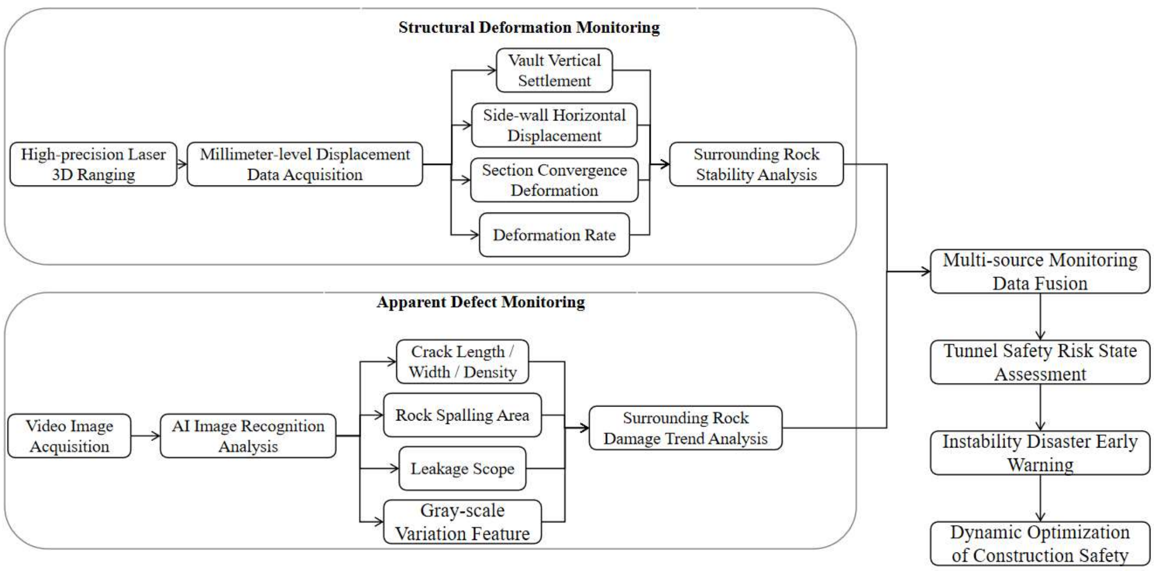

Figure 1. Acquisition route of tunnel risk monitoring indicators

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3.3 Classification Criteria for Tunnel Instability Risk

Referring to the Design Code for Hydraulic Tunnels (SL 279-2016),Technical Code for Construction Safety of Tunnel Engineering,as well as practical on-site experience,this study establishes a four-level risk-classification system for excavation-induced instability of water-supply tunnels according to indicator over-magnitude,deformation rate and defect-progression severity.The risk levels are defined as Level I (low risk,safely controllable),Level II (general risk,dynamic attention required),Level III (moderate risk,timely disposal required),and Level IV (major risk,emergency shutdown required), forming a standardized risk classification and evaluation system[5].

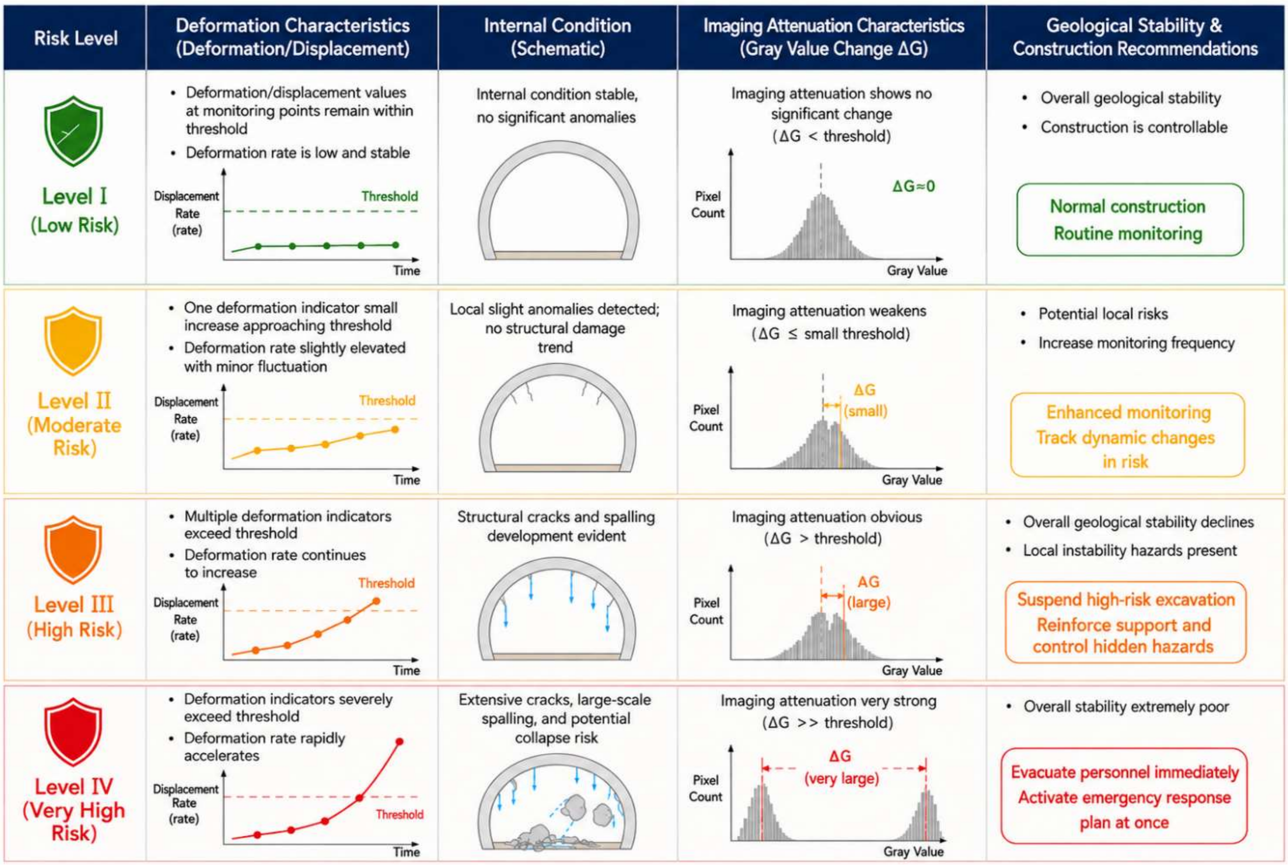

Figure 2. Risk assessment framework for tunnel construction

4. Engineering Application and Data Analysis

4.1 Project Overview

This work is based on a municipal water-supply guarantee project.The investigated tunnel section beneath a river-crossing bridge covers the pile number from S5+712.675 to S7+114.042,with a total length of approximately 1.40 km.A trenchless integrated pipe-jacking and shield construction method was adopted for tunnel excavation.For the pipe-jacking section,nominal diameter (DN) 3000 high-strength precast concrete drainage pipes were internally sleeved with DN2200 steel pipes,and the gaps between pipes were backfilled with C20 concrete.For the shield section,DN3000 precast C50 reinforced concrete shield segments with a thickness of 25 cm were adopted.Internal DN2200 steel pipes were installed,and C20 concrete was backfilled between adjacent segments.

One working shaft and one receiving shaft were arranged along the tunnel alignment.In the main river channel crossing section,the overburden depth above the pipe crown exceeds 6.0 m,and the elevation of the pipe centerline is -14.5 m.In the urban park crossing section,the overburden depth is greater than 18.5 m with an identical centerline elevation of -14.5 m.The main monitoring items include vault settlement,invert uplift,and clearance convergence.A total of 56 monitoring sections were arranged

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at an interval of 50 m,including 56 measuring points for vault settlement,56 measuring points for invert uplift,and 112 measuring points for clearance convergence.The cumulative deformation alarm threshold was set to 30 mm,and the daily deformation rate alarm threshold was 2 mm/d.

4.2 Data Acquisition and Sample Construction

According to the tunnel geological conditions and on-site construction layout,laser-vision AI monitoring instruments were deployed following the shield tunneling progress.The monitoring equipment was regularly moved forward with the advancement of the tunneling machine,stably covering 2－3 monitoring sections within the effective accuracy range for each fixed deployment.

The continuous field monitoring period lasted from April 2 to May 29,2026.Valid monitoring datasets were systematically screened and collected,including 13 vault settlement monitoring points with 1377 groups of effective settlement data,and 10 haunch convergence monitoring lines with 1019 groups of effective convergence data.A total of 3415 sets of in-situ laser spot positioning data were acquired throughout the monitoring campaign.

4.3 Data Analysis

4.3.1 Monitoring Curve and Characteristic Analysis

Data-fitting tools were used to generate time-varying curves for core monitoring indicators,including temporal evolution curves of tunnel vault settlement and cross-section convergence deformation.The sampling interval of all curves was consistent with the equipment acquisition frequency to ensure complete time-series continuity.The horizontal axis of the curves represents monitoring duration (d,days),and the vertical axis corresponds to deformation magnitude (mm).The full-cycle deformation evolution process of surrounding rock,including excavation disturbance,stress readjustment,and final stable equilibrium,was completely reproduced.

The cumulative deformation values of all vault monitoring points are mainly distributed in the range of -0.45-1.36 mm,indicating an overall low deformation amplitude without a sustained and rapid settlement growth trend.The deformation curves of each measuring point present minor fluctuations and phased adjustment characteristics throughout the monitoring period.The vertical displacement of the tunnel vault remains relatively stable on the whole during the entire construction monitoring stage.

The clearance-convergence monitoring curves reveal that the cumulative deformation at all monitoring points follows a typical three-stage evolutionary pattern over time,characterized by rapid initial growth,gradual deceleration in the middle stage,and eventual stabilization in the late construction stage.

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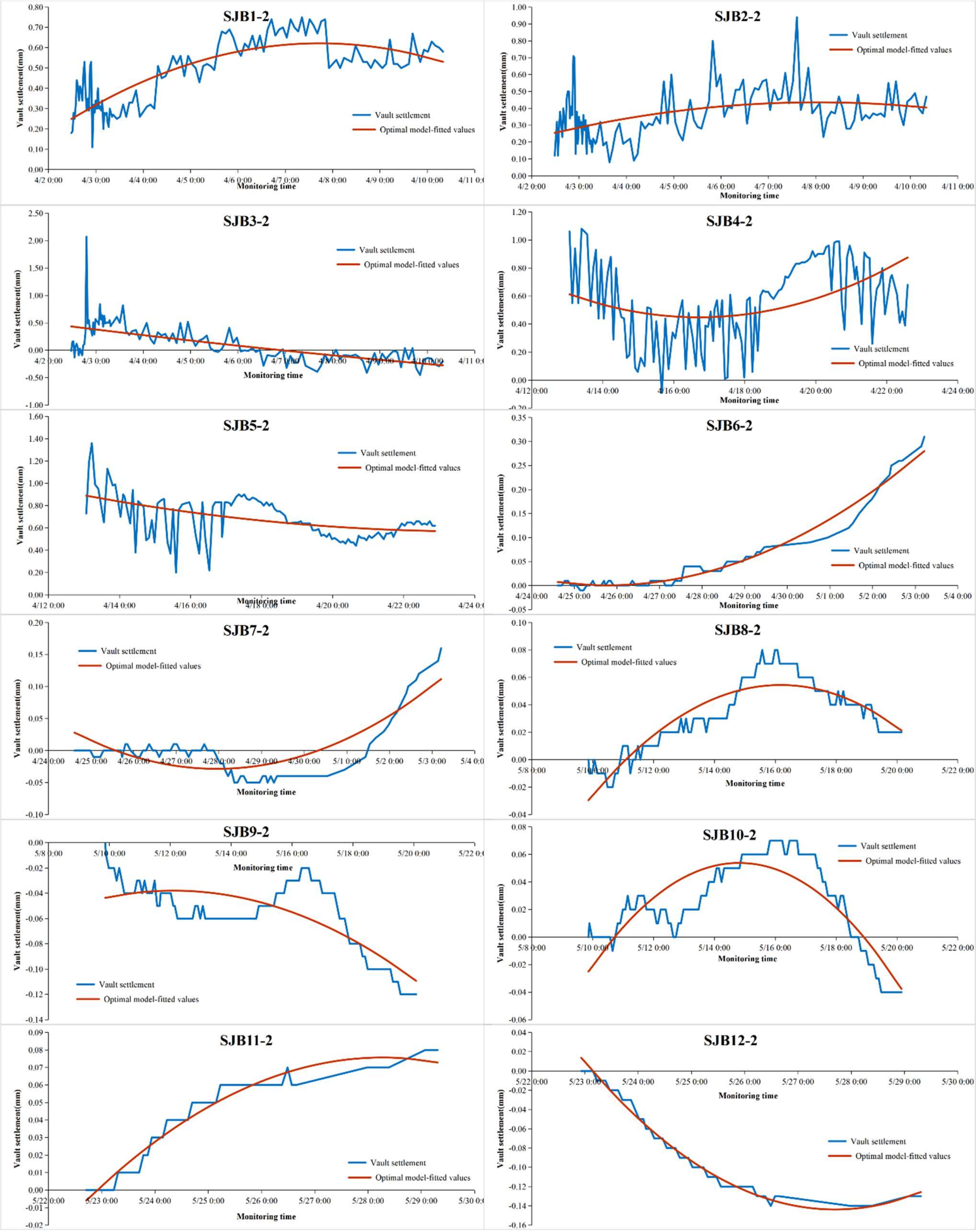

Figure 3. Cumulative displacement curves of tunnel vault settlement

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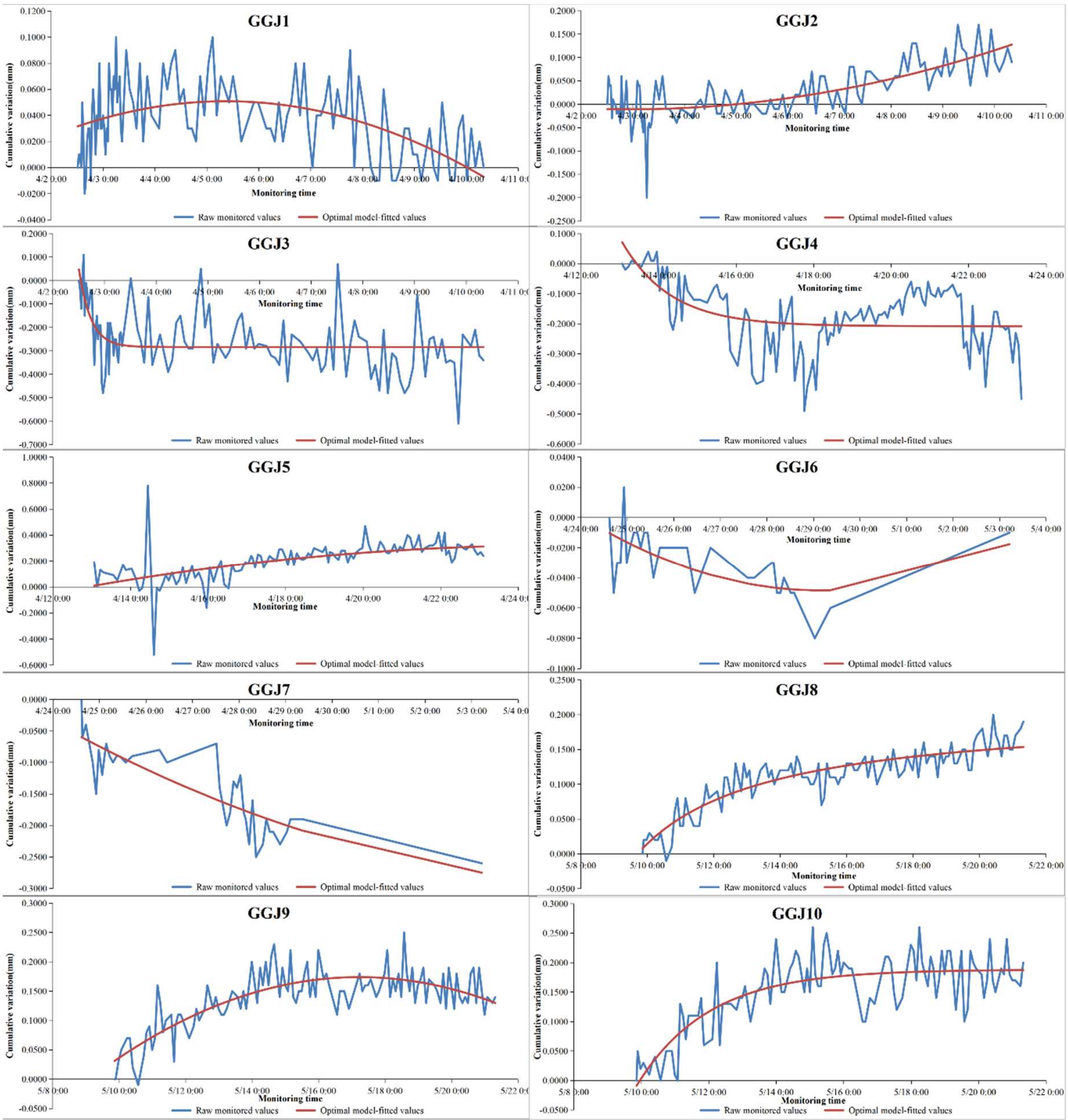

Figure 4. Cumulative displacement curves of tunnel clearance convergence

4.3.2 Coupling and Fusion Analysis Logic of Curves and Images

On-site scene picture

Original Monitoring Chart

Actual Monitoring Chart

Figure 5. On-site laser spot images

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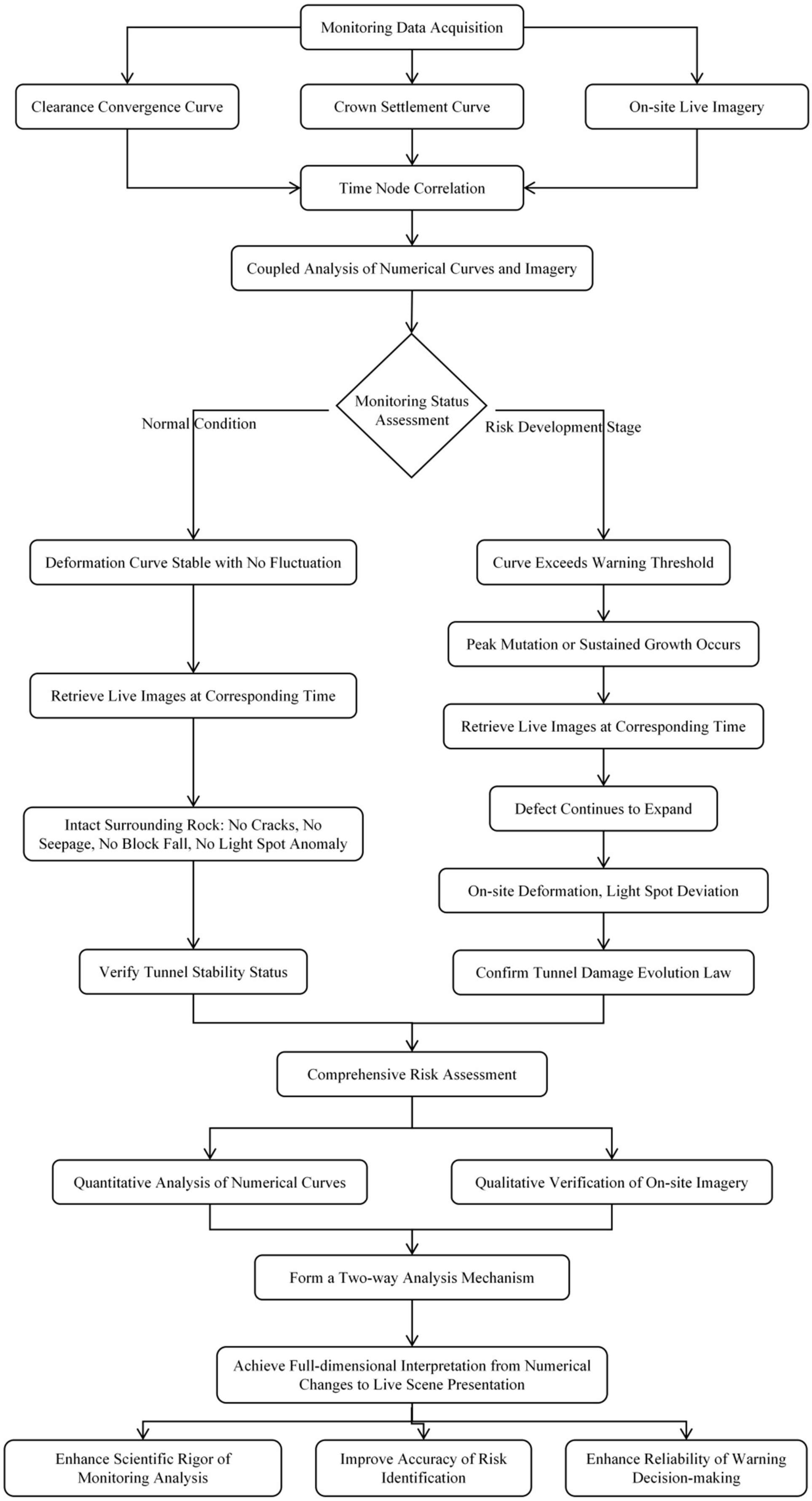

Figure 6. Logical flowchart of early-warning process

This study establishes a bidirectional analysis mechanism integrating quantitative judgment via numerical curves and qualitative verification via on-site images.This mechanism addresses the inherent defects of conventional single-data analysis: the lack of on-site visual support for pure numerical curves and the absence of quantitative basis for independent image identification.

Under normal working conditions,stable and fluctuation-free deformation curves correspond to intact surrounding rock without visible defects in on-site images and uniform color distribution in thermal maps.These evidences jointly verify the stable state of tunnel surrounding rock.During risk development stages,abrupt peak values and threshold exceedance in deformation curves can be mutually validated by the continuous propagation and expansion of lining defects in real-scene images,which accurately reflect the evolution law of tunnel structural damage.

The proposed coupling analysis model realizes full-dimensional interpretation of tunnel deformation risks from numerical variation to on-site visual manifestation,significantly improving the scientificity and accuracy of monitoring data analysis[6].The logical framework of the whole early-warning analysis process is demonstrated as follows.

4.4 Engineering Application Performance

The established multi-source-data-coupled early-warning model based on laser-vision monitoring technology was successfully applied to the water-supply tunnel project,yielding satisfactory practical performance in engineering application.

(1) The system realizes full-domain intelligent real-time monitoring during tunnel construction, effectively overcoming the inherent limitations of traditional monitoring methods,including single monitoring parameters and severe data time lag.

(2) A hierarchical early-warning and disposal mechanism is established to support graded risk control and targeted safety management.Low-risk conditions receive dynamic tracking; general-risk conditions trigger timely verification; major-risk conditions initiate emergency disposal.This workflow substantially improves the efficiency and refinement of construction safety management.

(3) Full-process traceability of monitoring data,on-site image records,and early-warning logs is achieved.This study provides a complete and reliable data foundation for engineering quality control, risk traceability analysis,and construction optimization of subsequent similar underground projects,demonstrating excellent practicability and broad prospects for engineering popularization and application.

5. Conclusion

(1) The proposed laser-vision AI monitoring technology adopts a dual-optical coaxial acquisition framework to synchronously obtain three-dimensional coordinates and on-site tunnel images.It realizes millimeter-scale quantitative monitoring of vault settlement and cross-section convergence, and achieves full-coverage perception of structural deformation and surface lining defects.This method effectively compensates for the deficiencies of traditional monitoring techniques,such as limited measuring points and delayed data acquisition.

(2) A bidirectional coupling analysis mechanism integrating numerical-quantitative evaluation and image-qualitative verification is established.Combined with the four-level risk-classification criterion,the system enables real-time identification of structural anomalies and hierarchical precise early-warnings.All monitoring data,image records and early-warning logs are fully traceable throughout the construction process,which greatly improves the refinement and efficiency of tunnel safety management and dynamic risk control.

(3) The developed monitoring system exhibits excellent engineering adaptability and popularization value.Targeting the characteristics of deep burial,high water pressure and complex geological conditions of water-supply tunnels,this technology is well adapted to composite pipe-jacking-shield construction conditions.It can accurately reveal the deformation evolution law of tunnel surrounding rocks,provide a reliable theoretical and technical basis for instability prevention and support

parameter optimization,and exhibit broad application prospects for similar hydraulic-tunnel engineering projects.

References

[1] Wang, H. J., & Xu, H. W. (2016). Application of tunnel section contour extraction from point clouds in tunnel monitoring. *Geospatial Information*, 14(3), 102-103, 106-109.

[2] Xiao, P. W., Yang, X. G., Qian, H. J., & et al. (2025). Optimal support time of hydraulic tunnels based on multi-source monitoring information. *Journal of Tunnel and Underground Engineering Disaster Prevention*, 7(1), 11-21.

[3] Ma, Q. L., Wang, X. H., Ma, L., & et al. (2025). Visual fusion perception method for driverless tunnels under uneven illumination. *Applied Optics*, 46(1), 89-101.

[4] Zhang, L. S., & Cheng, X. J. (2018). Tunnel deformation analysis method based on laser point cloud. *Chinese Journal of Lasers*, 45(4), 225-230.

[5] Zhang, J. K., Chen, C. Y., & Chen, H. (2016). Modeling the relationship between shield construction parameters and settlement deformation. *Science of Surveying and Mapping*, 41(8), 156-160.

[6] Zhang, K., Chen, D. F., Gao, M. X., & et al. (2021). Supervised learning-based edge recognition method for structural cracks of urban railway tunnels. *China Mechanical Engineering*, 32(4), 446-453.

[7] Wang, M. S., Bao, J. S., Xie, H. K., & et al. (2024). Two-level target-decision information fusion perception strategy for driverless vehicles in tunnel environments. *China Mechanical Engineering*, 35(3), 427-437.

[8] Guo, X. T., Yang, L. J., & Kang, Y. (2024). Multi-scale deformation monitoring based on terrestrial 3D laser scanning technology. *Laser & Optoelectronics Progress*, 61(8), 256-265.