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A Review on Smart Early-Warning Using 3D Point Clouds for Slope Monitoring in Mining Areas of Northwest China

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ABSTRACT

Located in a typical windy and arid mining region of Northwest China, the study area is characterized by widespread high-steep slope structures in its open-pit mines, exemplified by slopes with vertical relief exceeding 280 meters. Affected by prominent regional faulting, over 35% of the rock mass contains densely distributed joint sets, significantly weakening the shear strength of structural planes. This region faces multiple environmental stressors: annual sand-dust events exceeding 210 days, triggering particle migration on slope surfaces and erosion/damage to monitoring equipment; seasonal infiltration of high-altitude snowmelt water into fracture networks, causing dynamic fluctuations in hydrostatic pressure; and frequent blasting operations generating peak particle velocities (PPV) ⩾ 5 cm/s, exacerbating rock mass fatigue damage. Over the past decade, the area has recorded numerous incidents of open-pit slope failure, resulting in significant economic losses and casualties. These events highlight the limitations of conventional monitoring methods (e. g., manual inspection, sensor networks) in the coupled challenging environment of intense wind-blown sand disturbance and blasting vibrations, including monitoring blind spots, limited precision, and risks of data interruption. Three-dimensional (3D) point cloud technology (LiDAR / Oblique Photogrammetry) has emerged as a core technology to overcome these traditional bottlenecks, leveraging its capability for sub-centimeter spatial continuity perception and time-series deformation field reconstruction. This enables millimeter-scale deformation field resolution and quantitative characterization of rock mass structural parameters, driving a paradigm shift in mine safety monitoring from discrete point analysis towards smart early-warning based on comprehensive 3D field data. This paper systematically reviews research progress on the 3D point cloud smart early-warning technology chain tailored for the unique operational conditions in mining areas of Northwest China , analyzes technical bottlenecks, and outlines adaptive development paths.

KEYWORDS

3D Point clouds; Slope monitoring; Smart early-warning; Mine safety; Deep learning

1 Introduction

1.1 Unique safety challenges of slopes in mining areas of northwest China

Open-pit mines in the studied mining areas of Northwest China are predominantly characterized by high-steep slopes. An exemplar slope in this region reaches a maximum height of 284 meters. The rock mass, dissected by prominent regional faulting , contains densely distributed joint sets exceeding 35% of the total volume, significantly compromising the shear strength of structural planes. This region is subjected to multiple environmental stressors: annual sand-dust events surpassing 210 days, inducing particle migration on slope surfaces and accelerated wear of monitoring equipment; seasonal infiltration of high-altitude snowmelt water into fracture networks, causing abrupt fluctuations in hydrostatic pressure; and frequent blasting operations (with peak particle velocity ⩾ 5 cm/s) that exacerbate rock mass fatigue damage. Over the past decade, these areas have documented multiple slope failure incidents in their open-pit mines. A representative case involved a major landslide at an open-pit iron mine, resulting in direct economic losses of 20 million yuan and casualties (National Mine Safety Administration report). These incidents underscore the inherent failure risks of conventional monitoring systems under such extreme operational conditions.

1.2 Limitations of existing methods and advantages of point cloud technology

Existing monitoring approaches exhibit systematic limitations in such challenging mining environments in Northwest China, particularly in capturing localized deformations and latent cracks [1]. Manual inspections are constrained by steep terrain and blast exclusion zones, resulting in observational blind spots and inefficiency [2]. Sensor networks are prone to data interruption due to windblown sand erosion [3]. Conversely, 3D point cloud technology demonstrates unparalleled advantages through its spatial continuous sampling capability at millimeter-level precision: (i) Quantifying 3D displacement vectors of rock mass structural planes via multi-temporal point cloud differencing enables early warning of potential wedge failures; (ii) Reconstructing time-series aeolian erosion thickness models from sequential point clouds; and (iii) Facilitating semi-automatic crack identification in hazardous zones through unmanned aerial vehicle (UAV) platforms [4-10].

Point cloud technology is catalyzing a paradigm shift in mine safety monitoring—evolving from traditional "discrete point analysis" towards comprehensive "3D field-based early warning." Focusing on the representative windy-arid mining environment of Northwest China, this paper systematically reviews the technology chain for point cloud-driven smart early warning. It analyzes innovations across the entire workflow, from adaptive data acquisition and intelligent information extraction to warning model construction, thereby establishing a theoretical cornerstone and technical anchor for disaster prevention in high-risk mining regions.

2 Point cloud data acquisition and challenges for mining areas of northwest China

2.1 Adaptive acquisition technologies and case studies

For monitoring high-steep rock slopes in the studied mining areas , Terrestrial Laser Scanning (TLS) technology enables efficient extraction of structural plane parameters through point cloud clustering algorithms. As demonstrated in a representative coal mine application [11], strategically deploying scanners on stable sandstone pedestals and implementing redundant multi-station scanning effectively mitigated wind-blown sand interference. This approach automatically identified 157 sets of controlling structural plane data. The analysis revealed that forward-inclined bedding planes (dip angle 52°±8°) are predominantly susceptible to planar sliding, whereas counter-inclined zones (dip angle -35° ±12°) exhibit a higher risk of toppling failure. To analyze the toppling mechanism, a three-dimensional Distinct Block Modeling (3D DBM) approach was employed to construct the slope's geometric network. Technical validation at a copper mine site confirmed [12]: when the rock mass friction angle falls below 32° and joint spacing exceeds 2.3 meters, the steep slope shoulder areas (gradient >65°) experience significantly elevated instability risks. This technique successfully reconstructed the progressive failure trajectory of a 35-cubic-meter toppling block at the crest in 2022. Achieving centimeter-level displacement monitoring accuracy, the 3D DBM provided a more accurate depiction of the complex failure mechanism induced by mining disturbances compared to traditional 2D Limit Equilibrium Methods (LEM). The implementation of this method furnished quantitative guidelines for cable bolt reinforcement design in steep slopes, resulting in a 37.5% reduction in support costs and providing 14-day advance warnings for impending slope shoulder failure.

2.2 Data quality control under harsh environmental conditions

Addressing challenges like intense wind-blown sand and data gaps during freeze-thaw periods in Northwest China mining areas requires combining precision control for discontinuity extraction with multi-source compensation strategies to optimize data quality. Research confirms that discrepancies in discontinuity extraction methodologies significantly impact slope stability assessment outcomes (validated by the Špičunak case study) [13]. Adaptive radius filtering (dynamically adjusted between 0.2 – 0.3m) effectively isolates wind-blown sand noise based on lithological reflection characteristics (sandstone >40%), thereby enhancing the point cloud signal-to-noise ratio by a factor of 3.2. During freeze-thaw cycles, integration with Sentinel-1 InSAR phase unwrapping data (±0.33mm precision) compensates for data completeness, increasing it from 58% to 94%. In the discontinuity extraction phase, a semi-automated approach fused with manual mapping (employing the Discontinuity Set Extractor for initial screening and CloudCompare for manual orientation verification) ensures key metric errors—such as the weighted density error of discontinuity orientations—remain below 5°. Field validation achieved a fracture recognition accuracy of 89.7% [11], confirming that controlling directional accuracy is more critical than merely increasing data volume (consistent with core international research findings), substantially reducing the risk of misinterpretation in subsequent rockfall susceptibility assessments.

3 Intelligent perception of slope state driven by point clouds

3.1 State-of-the-art feature extraction techniques in windy-sandy regions

Extracting meaningful features from point clouds in mining areas of Northwest China faces significant challenges due to intense windblown sand and seasonal climatic variations, compounded by multi-source noise interference from vegetation cover, rock debris accumulation, and snow cover. Traditional geometric thresholding methods (e. g., the CANUPO tool) demonstrate limited adaptability to seasonal vegetation phenology (growth/dormancy cycles) and snow cover changes in such complex environments, often yielding classification accuracies below 75%. In contrast, the Random Forest (RF) machine learning algorithm achieves precise classification of four target classes (vegetation, rock debris, snow, and bedrock) by integrating multi-scale geometric neighborhood features (e. g., curvature, normal vector angles), temporal variation features, and reflection intensity characteristics. Evaluated on summer and winter point cloud datasets from a representative coal mine, this technique achieved an F-score exceeding 0.9 and bedrock recognition accuracy > 95%. Its core advantage lies in the model trained on a limited dataset (samples from two seasons), exhibiting generalizability to new, unseen scanning periods. This effectively handles the complex interplay of alternating sand and snow conditions, as evidenced in an iron ore mine application, where the misclassification rate of rock debris during snow cover periods was reduced by 63% compared to conventional methods. For structural plane identification in rock masses, a multi-resolution feature fusion algorithm incorporates an anti-interference mechanism during point cloud segmentation. It employs multiscale neighborhood normal vector clustering to detect regions with consistent orientation and integrates time-series displacement anomaly analysis (excluding wind-eroded debris disturbances), stabilizing joint plane orientation measurement errors within ±0.02° (validated in a gold mine case study). Despite these advances, notable limitations persist: the RF algorithm entails approximately 40% higher computational overhead than geometric thresholding methods, increasing single-scan data processing time to 3.2 hours in the studied mines; concurrently, severely dense sandstorms (visibility <50m) degrade point cloud penetration, causing up to 26% loss in bedrock surface feature extraction completeness (based on 2022 winter field data). Future research necessitates developing lightweight classification models and exploring millimeter-wave radar-assisted penetration schemes to meet the timeliness demands of high-frequency monitoring in mining areas [14].

3.2 Catastrophe mechanism correlation analysis for northwest mining areas

The optimization of the slope angle in Section 3 of a deep coal mine exemplifies how catastrophe prevention relies on systematic collaboration between geological investigation and engineering design. The research team precisely determined geotechnical physical-mechanical parameters through engineering geological surveys. Finite Difference Method (FDM) numerical simulations revealed that planar sliding within forward-inclined bedded rock masses dominated the slope failure mode. Subsequently, Limit Equilibrium Methods (LEM) were employed to calculate the stability coefficients for the non-working and end walls. Based on synergistic analysis of the failure mechanism and the mining plan, the slope angle was optimized within the safety threshold range. Post-construction deformation monitoring data confirmed that slope displacement consistently stabilized within the millimeter range, exhibiting no significant abnormal deformation, thereby validating the effectiveness of the optimization scheme for long-term stability control. This case study elucidates the core logic of catastrophe prevention: a closed-loop framework integrating accurate geological condition interpretation and dynamic adaptation of engineering parameters. Geological surveys provide intrinsic rock mass properties; numerical simulations uncover instability mechanisms; limit equilibrium quantifies safety thresholds; slope optimization achieves structural reinforcement; and finally, monitoring data confirms prevention efficacy. Moving forward, integrating such empirical engineering knowledge as priori constraints into intelligent early-warning models is crucial. By dynamically calibrating rock mass constitutive parameters using real-time point cloud displacement data, a more resilient disaster prevention and control system can be developed, better suited to the complex environmental challenges of mining areas in Northwest China.

4 Technical synergy and standardization in mining area scenarios

The point cloud monitoring technology in Northwest China mining areas faces triple challenges: hardware performance bottlenecks, insufficient environmental adaptability, and system integration obstacles. At the hardware level, sensor thermal drift errors in extreme temperature differential environments can reach 3.8 mm (field data from a representative coal mine in winter), necessitating active temperature control systems and sand-proof radome designs with >95% dust filtration efficiency. Strong wind conditions require drone platforms to withstand gusts exceeding 10 m/s, reducing crash risks through center-of-gravity balancing and redundant rotor design. The core algorithmic challenge lies in aeolian noise masking micro-deformation signals: in a monitored west slope area, valid point cloud data dropped to 52% during sandstorms. A multi-scale feature separation model combining wavelet packet denoising with 3D convolutional neural networks improved valid signal recognition to 85%, but increased single-process duration to 4.2 hours. System integration is constrained by high edge computing node costs (>¥120,000 per node) and insufficient 5G bandwidth (<60Mbps peak transmission rate), resulting in >3-minute warning delays.

To address these challenges, a tripartite synergy approach integrating technology adaptation, management mechanisms, and regional standards is required: Technologically, ground-based synthetic aperture radar (GB-SAR) compensates for point cloud data gaps, achieving ±1.3mm deformation field reconstruction accuracy after Kalman filtering fusion (validated at a regional copper mine). Managerially, mine operators and research institutions co-develop shared databases (27 slope cases integrated), with equipment calibration protocols and extreme-weather scanning contingency plans. Standardization-wise, provincial geological authorities lead formulation of the "Open-Pit Mine Point Cloud Monitoring Technical Specification for Arid Regions", mandating rigid metrics including ⩽300m sensor spacing, ⩾ 500 points/m^2 cloud density, and ⩾1 effective daily scan. Implementation at monitored sites yielded significant results: 2023 windy season valid data acquisition reached 73% (vs. 42% in 2022), false alarm rate dropped to 9.2%, and shared edge nodes reduced unit costs by 58%.

This synergy model demonstrates three breakthroughs: First, quantitative thresholds for scanning frequency and point density (e.g., 300m spacing, 500 points/m²) provide clear equipment selection criteria. Second, management protocols enable intelligent coordination between scanning operations and weather alerts (drone missions auto-pause at wind speeds >Level 8). Third, GB-SAR and point cloud technologies form spatiotemporal complements, enhancing monitoring continuity. Current limitations in data transmission rates and lightweight models require advancing satellite-edge computing deployment and federated learning R&D to ultimately establish an integrated "air-space-ground" intelligent prevention system.

5 Technological evolution pathways for western mining regions

Future research should focus on three key directions: multimodal data fusion, cross-scale risk prediction, and localization of standards [15-19]. In intelligent rock mass structure identification, Lato et al.' s automated 3D structural mapping technology (International Journal of Rock Mechanics 2012) offers a new paradigm for open-pit mine slope joint network analysis. By employing normal vector clustering and region-growing algorithms, this method achieves automated extraction of joint orientation and trace length with 91% accuracy. Its application in steep-slope coal mining areas of Northwest China requires enhanced robustness against aeolian noise—such as incorporating infrared point clouds for auxiliary feature matching (responding to thermal differentials) and embedding manual verification in post-processing to address missegmentation caused by rock debris occlusion. Disaster prediction models must deeply integrate mechanistic and data-driven approaches: Dunham's Rockfall Activity Index (RAI) morphological risk assessment system based on laser scanning point clouds (Engineering Geology 2017) should be further coupled with multi-physics seepage-vibration fields, for instance, using point cloud displacement gradients to quantify blast disturbance coefficient $\beta\left(\beta = \nabla D / \nabla D_0\right)$, thereby establishing a composite risk evaluation model better adapted to dynamic mining environments.

Geotechnical stability assessment technology must evolve toward 3D dynamic diagnostics. Ferrero's multilevel rock mass risk framework (Landslides 2011) demonstrates that spatial topological relationships of structural planes determine rock block stability classification, while Li et al.' s post-earthquake slope monitoring technique (Rock Mechanics 2020) verifies the effectiveness of temporal point clouds in tracking block creep trajectories (±1.4mm accuracy). For mining area applications in the region, integrating these technologies is critical: combining automated structural plane orientation extraction from point clouds (Idrees' cavern stability assessment method, Journal of RMGE 2018) with slope micro-deformation monitoring to establish a dual-parameter early-warning criterion encompassing structural plane degradation and displacement acceleration. This will support formulating the "Northwest Mining Region Jointed Rock Mass Time-Dependent Instability Evaluation Standard." Ultimately, a technology-standard-system will be achieved: automated identification reduces costs and enhances efficiency (lowering manual surveying intensity by 68%), multi-field fusion models improve warning accuracy (AUC⩾0.95 with optimized RAI), and dynamic monitoring ensures standard applicability (differential adaptation across varied geological belts).

6 Conclusion

The implementation of intelligent point cloud early-warning technology in mining areas of Northwest China has validated its high-precision 3D monitoring capabilities, demonstrating significant advantages in quantitative rock mass characterization and deformation field reconstruction. Current techniques partially overcome aeolian noise, blasting vibrations, and freeze-thaw disturbances through adaptive filtering and multi-source data fusion, achieving millimeter-level displacement detection (±1.2 mm accuracy) and 93% fracture recognition rates, thereby providing a reliable data foundation for slope risk prevention. However, coupled effects in complex environments remain the core bottleneck, necessitating breakthroughs in sensor environmental adaptability and multi-physics-coupled early-warning models. Future development should prioritize multimodal federated learning frameworks to enhance model generalization via cross-mining-region knowledge transfer. Concurrently, lightweight edge computing hardware deployment and regional technical standards (e.g., the Arid-region Mining Point Cloud Monitoring Technical Specification) must be advanced to establish an air-space-ground integrated intelligent monitoring system, supporting the safe and efficient development of mining resources in the region.

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