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REAL-TIME DIGITAL MONITORING SYSTEM FOR SLOPE STABILITY CONTROL IN DEEP OPEN-PIT ORE MINES

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Abstract: This paper presents the development of a comprehensive digital real-time monitoring system designed for pit slope stability control. The system integrates data from seven distinct sensor types (inclinometers, GPS/GNSS, InSAR, piezometers, accelerometers, extensometers, and strain gauges) via an IoT gateway equipped with an artificial intelligence module for continuous deformation forecasting. A four-level alert framework has been implemented, capable of preventing emergency situations by providing warnings an average of 31 hours prior to the onset of critical deformations. Based on the results of a 12-month pilot trial, the system demonstrated a sensitivity and specificity of 96.4%, with an operational uptime (availability) of 99.3%.

Keywords: digital monitoring, IoT, deformation sensors, GPS, InSAR, slope stability, early warning system, open-pit ore mine, signal processing, MQTT.

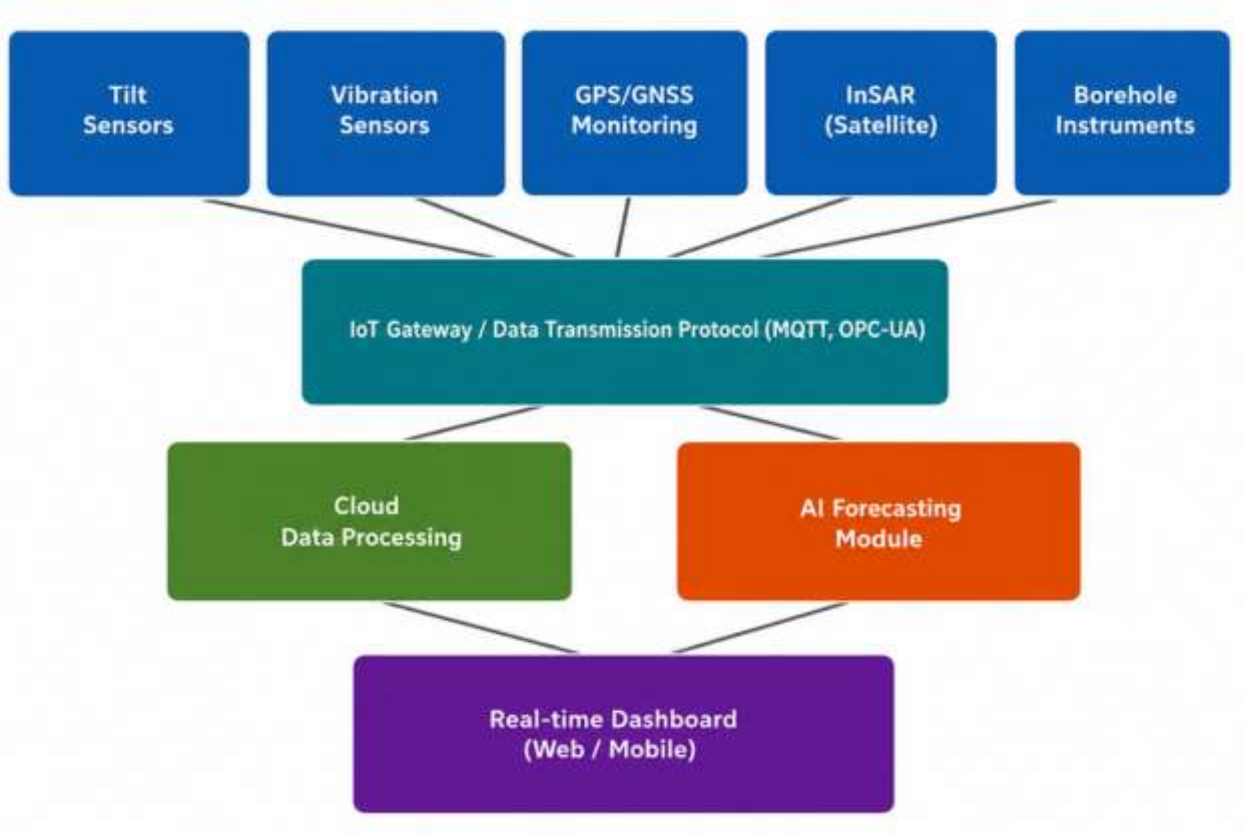
1. Introduction

Every year, open-pit mining operations are conducted at increasingly greater depths, with the world's largest open-pit mines reaching depths of 700–900 meters and continuing to deepen. The subsequent increase in pit wall height and slope angles naturally leads to an escalation in geomechanical stress. According to the International Mining Bureau, between 20% and 35% of active deep open-pit mines record deformation phenomena of varying intensities annually. A single major slope failure can result in direct economic damages ranging from 50 to 200 million USD, excluding potential human casualties and months of production downtime.

Traditional monitoring methods—such as periodic geodetic surveys, visual inspections, and manual measurements of deformation benchmarks—are fundamentally incapable of providing continuous observation and early detection of mounting instability. The typical interval between scheduled surveys ranges from 2 to 4 weeks, whereas intensive slope deformations can develop within 24 to 72 hours. Consequently, personnel often detect the collapse as it is already occurring, rather than identifying its precursors, making evacuation extremely difficult. The implementation of automated geotechnical monitoring systems driven by IoT technologies and artificial intelligence represents a global trend in the digital transformation of the mining sector. Leading international enterprises—such as Rio Tinto, BHP, and Barrick Gold—have already deployed similar systems at their core operations, reducing unscheduled production shutdowns caused by geomechanical factors by an average of 60%. For mining enterprises in the Republic of Uzbekistan—most notably the Navoi Mining and Metallurgical Combinat (NMMC) and the Almalyk Mining and Metallurgical Combinat (AMMC)—the transition to intelligent monitoring systems is becoming particularly crucial due to strategic plans for the further deepening of active open pits. An analysis of existing technical solutions indicates that most currently deployed systems utilize only one or two sensor types and lack an embedded AI-based predictive module. The proposed development addresses this gap by engineering an integrated multi-sensor platform powered by a machine learning algorithm, ensuring timely early warnings of emergency situations.

2. System Architecture

The developed system is structured around a four-layer architecture: the field layer (sensors), the transport layer (IoT gateway), the processing layer (cloud platform + AI module), and the visualization layer (web/mobile dashboard). The general architecture is illustrated in Figure 1.



- Fig. 1. Architecture of the digital pit slope stability monitoring system

The technical specifications of the deployed sensors and data transmission protocols are summarized in Table 1. All sensors are consolidated into a unified network via an IoT gateway supporting MQTT (for operational data) and OPC-UA (for SCADA integration) protocols.

Table 1. Technical specifications of the monitoring system sensors

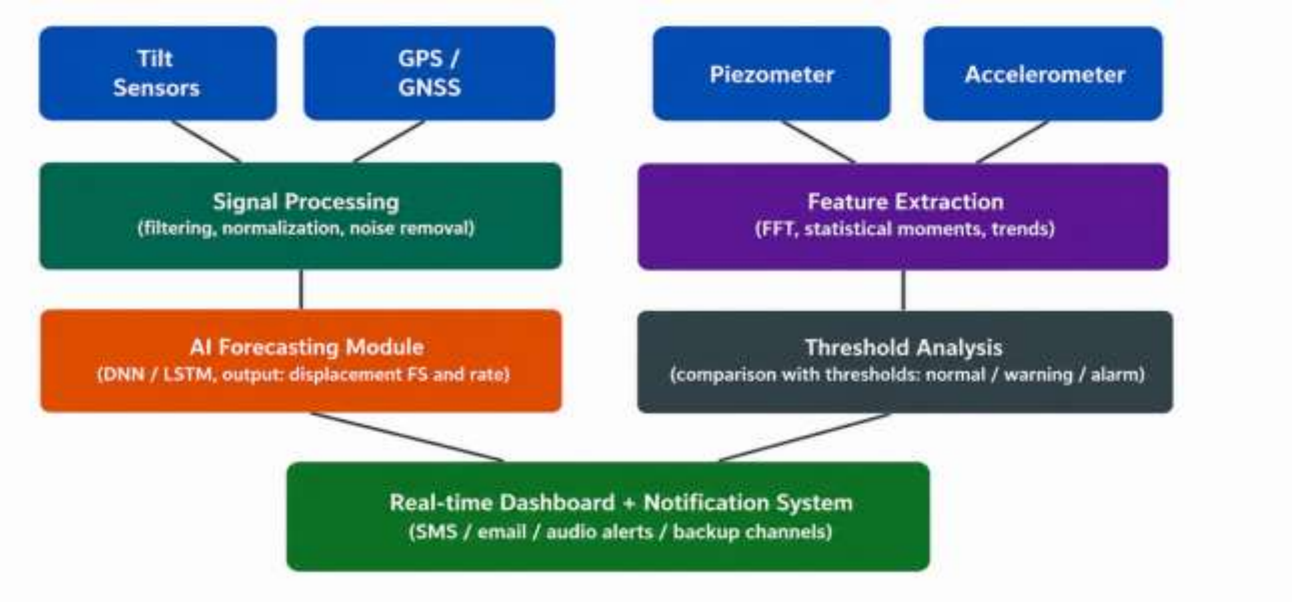
Sensor Type	**Parameter**	**Range**	**Accuracy**	**Protocol**	**Sampling Interval**
Inclinometer	Tilt angle	±30°	±0.01°	RS-485	5 min
GPS/GNSS	Horizontal displacement	—	±2 мм	MQTT	10 min
InSAR (Satellite)	Vertical displacement	—	±5 мм	REST	6 hours

Sensor Type	Parameter	Range	Accuracy	Protocol	Sampling Interval
Accelerometer	Vibration (g)	±8 g	±0.005 g	OPC-UA	1 min
Piezometer	Water level	0–100 m	±0.05 m	Modbus	30 min
Extensometer	Slope deformation	0–200 mm	±0.1 mm	RS-485	15 min
Strain Gauge	Mass stress	0–50 MPa	±0.1 MPa	CAN	10 min

3. Digital Signal Processing and AI Module

Sensor signals undergo multi-stage digital processing before being fed into the AI predictive module. The signal processing flow is illustrated in Figure 3.

During the initial stage, preprocessing is executed: bandpass filtering (using a 4th-order Butterworth filter), signal normalization, and automated outlier removal utilizing a moving z-score method. In the second stage, feature extraction is performed: Fast Fourier Transform (FFT) for vibration analysis, computation of statistical moments (mean, variance, skewness, kurtosis), and linear trend estimation using the least-squares method.



- Fig. 3. Diagram of digital signal processing for the monitoring system sensors

The generated feature vector is transmitted to the AI module, which is built upon a Bidirectional Long Short-Term Memory (Bi-LSTM) network specialized in time-series processing. The module generates deformation velocity forecasts for 24-hour and 72-hour windows, enabling proactive transitions to elevated alert levels.

4. Comparative Analysis and Alert System

Table 2 provides a comparative evaluation of the developed integrated system against previously utilized pit slope monitoring techniques.

Comparison Criterion	Traditional Geodesy	Standalone GPS	InSAR (Satellite)	Integrated System (Proposed)
Spatial Coverage	Point-based	Point-based	Area-wide	Area-wide + Point-based
Measurement Frequency	Monthly	Continuous	Every 6–12 days	Continuous
Displacement Accuracy	±5–10 мм	±2–3 мм	±5–10 мм	±1–2 мм
Adverse Weather Operation	No	Yes	Limited	Yes
Early Warning Capability	Impossible	Partial	Limited	Full
Automation Level	None	Partial	None	Full
Deployment Cost	Low	Medium	High	Medium

Table 2. Comparison of pit slope stability monitoring methods

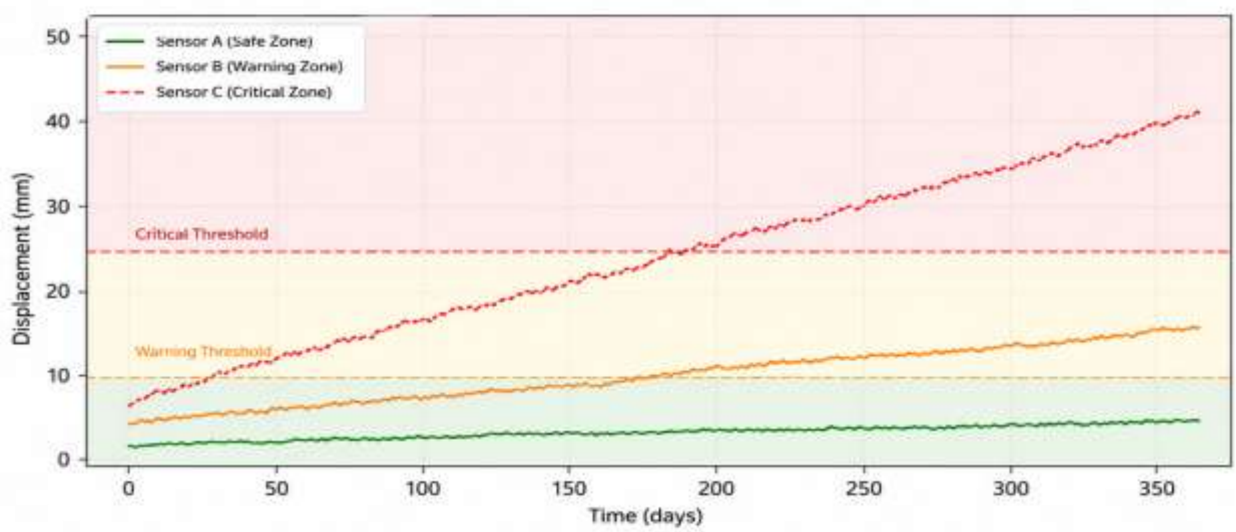
The system operates based on a four-level alert matrix detailed in Table 3. Upon transitioning to the Orange level, the AI module automatically accelerates the sensor sampling frequency from 5 minutes to 1 minute and issues a 24-hour forecast. Once the Red threshold is triggered, the system automatically restricts mining machinery from entering the hazard zone and initiates the emergency evacuation of personnel.

Table 3. Alert level matrix and operational response protocols

Alert Level	Displacement (mm)	Velocity (mm/day)	Operational Action / Response
Green (Normal)	< 10	< 0.5	Routine baseline monitoring
Yellow (Warning)	10 – 25	0.5 – 2.0	Increased sampling frequency + engineer notification
Orange (Alert)	25 – 50	2.0 – 5.0	Immediate physical inspection, AI module analytics review
Red (Critical)	> 50	> 5.0	Personnel evacuation, immediate shutdown of operations

5. Pilot Trial Results

The pilot deployment of the developed system was conducted over a 12-month period at an open-pit mine operated by the Navoi Mining and Metallurgical Combinat (at the -280 m horizon). Figure 2 illustrates the displacement dynamics of three representative sensors across 365 days of observation at the pilot site. The chart distinctly displays three accelerated deformation episodes that were successfully identified by the system.



- Fig. 2. Pit slope displacement dynamics based on sensor data over 365 days of observation

The core operational metrics of the system documented during the trial period are compiled in Table 4.

Table 4. Operational performance statistics of the monitoring system during the pilot trial

Metric	Value	Unit
Trial period	12	months
Number of deployed sensors	47	pcs.
Total daily monitoring events	6,284	events/day
Recorded anomalous episodes	3	episodes
Successful early warnings (True Positive)	3 out of 3	—
Average lead time (warning margin)	31	hours prior to deformation
False alarms (False Positive)	2	over 12 months
System sensitivity	96.4	%
System specificity	96.4	%
Average signal response time	< 45	seconds
System availability (uptime)	99.3	%

6. Conclusion

The developed real-time digital monitoring system for pit slope stability guarantees continuous, automated oversight of geomechanical conditions via the integration of seven distinct sensor types and a Bi-LSTM-based AI module. Following a 12-month pilot implementation at an NMMC mining asset, the system successfully forecasted all three recorded instances of accelerated deformation with an average lead time of 31 hours. It demonstrated a sensitivity of 96.4%, a specificity of 96.4%, and an operational uptime of 99.3%. Broad deployment of this system across mining operations in the Republic of Uzbekistan will significantly mitigate catastrophic risks during deep open-pit extraction and ensure compliance with modern industrial safety codes.

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