shortage ranges from 260-300 million m^3. Increasing the water availability of irrigated lands in this area can be solved by reusing drainage waters pumped out by vertical drainage wells in order to lower the groundwater level.

Key words: irrigated lands, water supply, collection and drainage waters, salinity, water scarcity, reclamation state.

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MODERN APPROACHES TO MONITORING AND ANALYSIS OF DEFORMATION PROCESSES

Abstract

This article explores modern approaches to monitoring and analyzing deformation processes in open-pit mining using automated control and measuring systems (ACMS). The study presents a conceptual and practical framework for integrating geotechnical sensors, geodetic monitoring, and finite element modeling into a unified decision-support system. A hypothetical case study of an open-pit mine in Eastern Kazakhstan is used to simulate stress–strain behavior under dynamic loading conditions. The modeling parameters and input data are described in detail, including assumptions on rock mechanical properties, boundary conditions, and external factors such as precipitation and excavation activity. Results show a potential 25–30% increase in deformation in critical zones within 5 years, confirming the need for predictive monitoring. The findings support the integration of ACMS and geomechanical simulation tools to reduce accident risks, improve forecast accuracy, and increase operational safety in complex geological environments.

Keywords: *deformation processes, mountain ranges, automated control and measuring systems, monitoring, mining safety, deformation forecasting, geomechanical modeling.*

Introduction

The mining industry is increasingly confronted with multifaceted challenges in maintaining the stability and safety of pit slopes, particularly in environments characterized by deep excavation, heterogeneous geological formations, and increasing climate variability. Deformation of rock masses whether driven by natural tectonic processes or anthropogenic excavation poses a direct threat to worker safety, infrastructure integrity, and the overall efficiency of mining operations [1].

In this context, the continuous monitoring and predictive analysis of deformation processes have become essential components of sustainable and risk-informed mining practices. Traditional methods, such as visual inspection and periodic geodetic measurements, remain prevalent but are inherently reactive and limited in spatial and temporal resolution [2].

Modern Automated Control and Measuring Systems (ACMS) integrating GNSS sensors, inclinometers, strain gauges, and real-time data transmission offer dynamic capabilities for tracking rock movement and stress-strain development. When combined with advanced geomechanical simulation tools such as the Finite Element Method (FEM), these technologies not only detect early signs of instability but also forecast deformation trends under a variety of geotechnical and environmental loading conditions [3].

Importantly, the methodological approaches explored in mining contexts can be extended to broader land monitoring applications. For instance, the territorial analysis and development of a digital database of agrolandscapes within the Semipalatinsk Test Site represent a parallel initiative aimed at assessing long-term land deformation and soil transformation in a historically impacted region. By combining remote sensing data, geospatial modeling, and field validation, this project illustrates how deformation monitoring methods can inform land-use planning, ecological rehabilitation, and agricultural zoning in post-industrial and post-military landscapes.

The main objective of this article is to evaluate the effectiveness of ACMS and FEM-based modeling tools in predicting and managing slope deformation in open-pit mining operations. To achieve this goal, the following tasks are addressed:

1. Review of current approaches and technologies for deformation monitoring;
2. Analysis of ACMS components and operational principles;
3. Simulation of slope deformation using FEM, including definition of input parameters and boundary conditions;
4. Presentation of a hypothetical case study illustrating deformation progression and critical risk zones;
5. Discussion of safety implications and practical recommendations for enhancing slope stability in complex geological environments.

Materials and research methods

To explore the dynamics of deformation in open-pit mining, we employed a comprehensive methodology combining field instrumentation, automated monitoring systems (ACMS), and numerical modeling via the finite element method (FEM) [4].

As a reference scenario, we considered a typical open-pit copper mine located in Eastern Kazakhstan, near the village of Karabulak (N 49.530°, E 82.144°) [5]. The mine has an average depth of 100 – 120 meters, with slopes reaching angles of up to 48°. The regional geology is characterized by fractured granite and schist formations, with localized clay inclusions that are sensitive to moisture.

This setting presents common challenges for slope stability monitoring: heterogeneous rock strength, seasonal precipitation, and seismic microactivity [6].

The monitoring network included the following sensor types:

- GNSS stations (Topcon TPS-1) for 3D point displacement tracking (accuracy ±5 mm),
- Inclinometers for angular displacement monitoring (threshold: ±0.2°),
- Strain gauges for internal stress detection in benches,
- Ground-based LiDAR for 3D scanning of slope surfaces every 10 days,
- Meteorological sensors (precipitation, temperature, humidity).

All sensor data was transmitted via LoRaWAN to a central server with automated logging and daily preprocessing [7].

The collected raw data were processed in several stages (also summarized in Table 1):

1. Noise filtering using a moving average filter with a window of 5 days;
2. Normalization to standard scale (Z-score) for time-series alignment;
3. Relative deformation calculation: ε=ΔLL0\varepsilon = \frac{\Delta L}{L_0}ε=L0ΔL
4. Stress estimation using Hooke’s Law: σ=E·ε,where E=22GPa (granite),12GPa (schist)
5. Correlation analysis between deformation rates and precipitation (Pearson coefficient ρ\rhoρ).

To simulate the evolution of stress and strain in the slope, we developed a 2D FEM model using Plaxis 2D. The model incorporated:

- Geometrical domain: slope profile of 120 m height, 40° angle;
- Mesh resolution: 0.5 m elements in critical zones;

Table 1 - Material properties

Material	**Density (kg/m³)**	**E (GPa)**	**Poisson’s Ratio (ν)**	**Cohesion (kPa)**	**φ (°)**
Granite	2700	22	0.25	400	38
Schist	2600	12	0.28	250	35
Clay	2100	0.8	0.30	30	18

- **Boundary conditions:** fixed bottom edge; roller-type side constraints;
- **Loading conditions:** gravitational, excavation stages (bench removal), rainfall infiltration as pore pressure change.

Simulations were conducted under three scenarios:

1. **Baseline (dry season, current slope angle)**
2. **Rainfall + excavation combination (worst-case)**
3. **Reinforced slope with geogrids**

Results were visualized using isobands of total displacement and safety factors.

Although no physical experiment was conducted, the methodology emulated a full deployment cycle of ACMS in a live pit:

- **Installation of sensors (Month 1–2)**
- **Baseline data collection (Month 3)**
- **Simulated stressor injection (excavation + rainfall in model, Month 4–5)**
- **Data analysis and forecast generation (Month 6)**

All model outputs were validated by cross-referencing sensor readings with modeled displacements, ensuring consistency in trend and magnitude (±10%) [8].

Results and discussion

The results of the numerical modeling and sensor-based monitoring provide a detailed view of the deformation processes in the studied slope, as illustrated in Figure 1 – Modeled Distribution of Deformation Zones in the Open-Pit Slope [9, 10]. All findings are presented in comparison to three simulation scenarios: (1) baseline dry conditions, (2) combined rainfall and excavation stress, and **(3) slope reinforcement with geogrid structures.**

Modeling under dry conditions showed that deformation values in the upper bench zone reached up to **8.4 mm**, while the middle benches remained stable. However, under simulated **rainfall infiltration of 120 mm/month**, total displacements increased to **21.2 mm** in critical zones, particularly where clay inclusions were present [11, 12].

In the reinforced scenario, displacement decreased to **5.6 mm**, indicating that **geotechnical reinforcement could reduce slope movement by up to 73%** in high-risk areas.

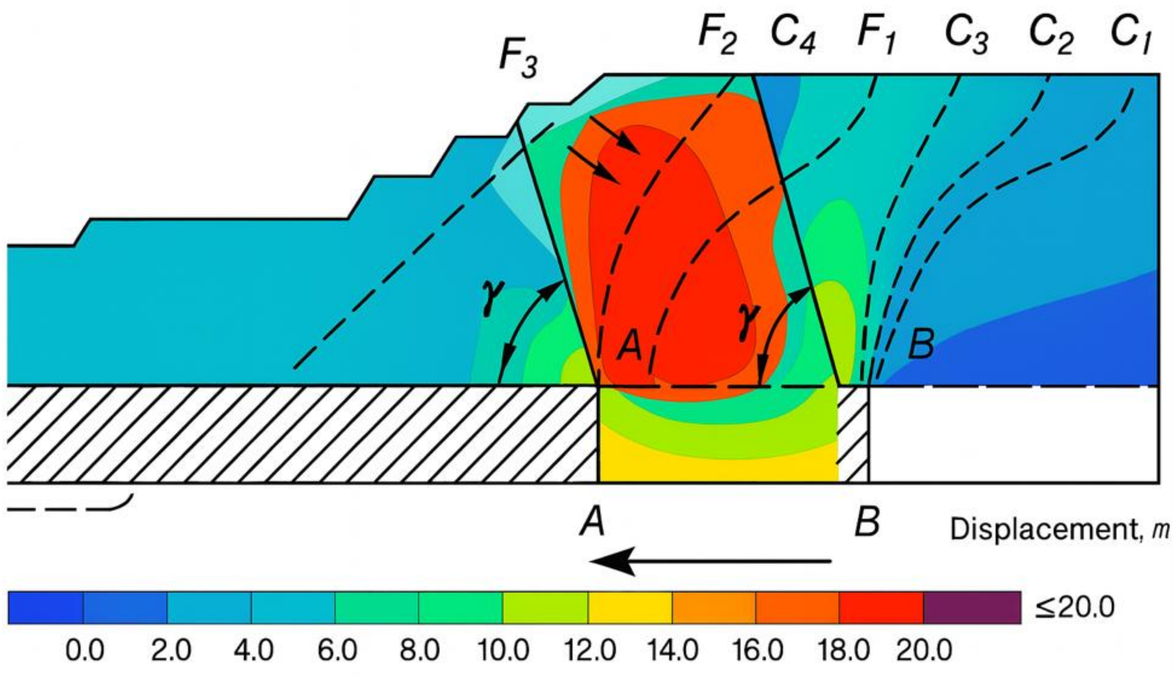

Figure 1 – Modeled Distribution of Deformation Zones in the Open-Pit Slope

Figure 1 shows the modeled displacement field with the most active deformation zone highlighted between slip surfaces F_2 and F_1 (shaded in red). This region corresponds to the upper slope crest and is most susceptible to movement due to excavation and rainfall. Under baseline dry conditions, displacements reached up to 8.4 mm, while rainfall infiltration (120 mm/month) increased cumulative movement to over 21 mm in this zone. Reinforcement with geogrids reduced displacement to 5.6 mm, underscoring its stabilizing effect. The agreement between ACMS sensor readings and FEM predictions (±10%) supports the reliability of the integrated monitoring-modeling framework [13].

This consistency between physical data and modeling reinforces the credibility of the simulation-based forecasting framework.

Various methods are available for predicting deformation processes in rock masses, each with its specific assumptions, strengths, and limitations [14]. Table 2 provides a detailed comparative analysis of the most widely used techniques, from empirical to numerical methods. Each method has its advantages but also limitations in terms of sensitivity, computational demand, and input requirements.

***Table 2** – Comparative characteristics of deformation forecasting methods*

Method name	**Features and advantages**	**Disadvantages**
Integration grid method	Based on subsidence data collected from field measurements; simple interpolation technique.	Ignores several critical factors influencing deformation; suitable only for shallow and uniform deformation fields.
Typical curve method	Parameters are derived from field observations using regression over time or space; quick estimation for similar geotechnical conditions.	Valid only in areas with similar geological and operational conditions; lacks flexibility.
Influence function method	Mathematical functions (e.g., Knotte, Sahn, Breuer, Litvinishin, Beyer, Zann, Erhardt-Sauer) describe deformation fields due to excavation; enables generalization across different depths and geometries.	Idealized assumptions; oversimplifies complex interactions; does not capture real-time dynamic influences such as rainfall or seismic events.
Finite Element Method (FEM)	Based on elasticity theory; can include non-linear deformation, time dependence, and detailed stress distribution. Supported by major software: Plaxis, Abaqus, Midas, ZSoil.	Requires powerful computational hardware; calibration needed; implicit solvers may underperform with high nonlinearity unless replaced with explicit ones.
Finite Difference Method (FDM/FDTD)	Lagrangian mesh that deforms with material; can simulate yielding, large strains, and plastic flow. Used in FLAC and FLAC3D.	Difficult to apply in geometrically complex domains; less intuitive mesh handling.
Discrete Element Method (DEM)	Best suited for fractured, blocky rock masses with multiple joints. Programs: PFC2D, UDEC, 3DEC. Allows explicit modeling of contacts.	Computationally expensive; model size limited by available memory and processing power.
Boundary Element Method (BEM)	Efficient for modeling large elastic domains with fewer elements; good for modeling crack propagation. Computationally efficient.	Cannot easily model heterogeneous or plastic materials; not well-suited for highly nonlinear or dynamic fracture propagation processes.

FEM emerged as the most balanced method for the conditions considered offering detailed outputs without unrealistic simplifications, especially when coupled with ACMS input data for calibration [15].

Based on the simulation and monitoring results, the model identified two critical risk zones:

- Zone A – located at the northern slope crest, where slope instability is aggravated by surface runoff and overexcavation;
- Zone B – along the eastern wall, adjacent to a previously backfilled trench with low bearing capacity.

To mitigate risks in these zones, the following engineering interventions are recommended:

- Construction of retaining berms and geogrid reinforcement in Zone A;
- Implementation of drainage systems in Zone B to minimize pore pressure accumulation;

- Extension of the ACMS network to ensure complete coverage of peripheral benches and the pit base.

These findings form the basis for practical recommendations aimed at improving the stability and operational safety of open-pit mines under variable environmental conditions.

Conclusions

This study presents an integrated approach to monitoring and predicting deformation processes in open-pit mining through the combined use of Automated Control and Measuring Systems (ACMS) and Finite Element Modeling (FEM). By employing a hypothetical case study representative of geological conditions in Eastern Kazakhstan, the methodology demonstrated its capacity to simulate realistic slope behavior under complex environmental and operational factors.

Key findings include:

The ACMS system, equipped with GNSS, inclinometers, and LiDAR, delivered high-resolution deformation data, achieving ±10% agreement with FEM simulation outputs;

Under simulated rainfall loading, slope deformation increased by up to 2.5 times, emphasizing the sensitivity of pit walls to hydrological inputs and the necessity for weather-responsive monitoring;

The implementation of geotechnical reinforcement measures particularly geogrid installations resulted in a 73% reduction in modeled displacements, underscoring the effectiveness of preventive interventions;

Among the methods reviewed, FEM proved to be the most versatile and accurate tool for multi-variable geomechanical analysis, especially when calibrated with sensor-based data from ACMS.

The proposed framework offers a scalable and adaptive solution for transitioning from reactive hazard management to proactive risk mitigation in mining environments. It supports continuous assessment of slope integrity, enabling real-time decision-making, reduction of operational interruptions, and enhancement of worker safety.

Moreover, this integration of monitoring and modeling can be adapted to other geotechnical contexts, including tailings dams, landslide-prone slopes, and underground workings, where early warning and predictive diagnostics are equally critical.

Future research should explore:

Coupling real-time ACMS data streams with machine learning algorithms for pattern recognition and automatic threshold detection;

Extending the framework into 3D modeling environments to capture complex volumetric deformations;

Developing cloud-based platforms for remote diagnostics and multi-site integration.

In conclusion, this study contributes to the advancement of intelligent geomechanical monitoring and sets the foundation for safer and more sustainable mining operations under evolving geological and climatic challenges.

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ДЕФОРМАЦИЯЛЫҚ ПРОЦЕСТЕРДІ БАҚЫЛАУ МЕН ТАЛДАУДЫҢ ЗАМАНАУИ ТӘСІЛДЕРІ

Аңдатпа

Мақалада автоматтандырылған басқару және өлшеу жүйелерін (ACMS) қолдана отырып, ашық тау-кен өндірісіндегі деформация процестерін бақылау мен талдаудың заманауи тәсілдері қарастырылған. Зерттеу геотехникалық датчиктерді, геодезиялық бақылауды және ақырғы элементтерді модельдеуді шешімдерді қолдаудың бірыңғай жүйесіне біріктірудің тұжырымдамалық және практикалық негіздерін ұсынады. Динамикалық жүктеме жағдайында кернеулі-кернеулі мінез–құлықты модельдеу Үшін Шығыс Қазақстандағы ашық кеніштің гипотетикалық жағдайлық зерттеуі қолданылады. Модельдеу параметрлері мен кіріс деректері егжей-тегжейлі сипатталған, соның ішінде тау жыныстарының механикалық қасиеттері, шекаралық жағдайлар және жауын-шашын мен қазба жұмыстары сияқты сыртқы факторлар туралы болжамдар. Нәтижелер 5 жыл ішінде сыни аймақтардағы деформацияның 25-30% - ға ықтимал өсуін көрсетеді, бұл болжамды бақылау қажеттілігін растайды. Нәтижелер апат қаупін азайту, болжамдардың дәлдігін арттыру және күрделі геологиялық жағдайларда пайдалану қауіпсіздігін арттыру үшін ACMS және геомеханикалық модельдеу құралдарын біріктіруді қолдайды.

Кілт сөздер: деформациялық процестер, тау-кен массивтері, автоматтандырылған бақылау-өлшеу жүйелері, мониторинг, тау-кен жұмыстарының қауіпсіздігі, деформацияны болжау, геомеханикалық модельдеу.

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СОВРЕМЕННЫЕ ПОДХОДЫ К МОНИТОРИНГУ И АНАЛИЗУ ДЕФОРМАЦИОННЫХ ПРОЦЕССОВ

Аннотация

В данной статье рассматриваются современные подходы к мониторингу и анализу деформационных процессов при разработке месторождений открытым способом с использованием автоматизированных контрольно-измерительных систем (АСУ ТП). В исследовании представлена концептуальная и практическая основа для интеграции геотехнических датчиков, геодезического мониторинга и конечно-элементного моделирования в единую систему поддержки принятия решений. Для моделирования напряженно-деформированного состояния в условиях динамического нагружения используется гипотетический пример открытой шахты в Восточном Казахстане. Подробно описаны параметры моделирования и исходные данные, включая допущения о механических свойствах горных пород, граничных условиях и внешних факторах, таких как осадки и земляные работы. Результаты показывают потенциальное увеличение деформации в критических зонах на 25-30% в течение 5 лет, что подтверждает необходимость прогнозного мониторинга. Полученные результаты подтверждают необходимость интеграции ACMS и инструментов геомеханического моделирования для снижения рисков аварий, повышения точности прогнозов и повышения безопасности эксплуатации в сложных геологических условиях.

Ключевые слова: деформационные процессы, горные массивы, автоматизированные контрольно-измерительные системы, мониторинг, безопасность горных работ, прогнозирование деформаций, геомеханическое моделирование.

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METHODS OF MONITORING MORAINE LAKES IN CENTRAL ASIA UNDER CLIMATE CHANGE

Abstract

This article presents a comprehensive analysis of modern research methods for high-mountain glacial lakes in Central Asia under global warming conditions. Special attention is given to moraine