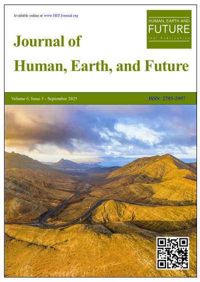
ISSN: 2785-2997

Available online at www.HEFJournal.org

Journal of
Human, Earth, and Future

Vol. 6, No. 3, September, 2025



Using Geoinformation Technologies for Evaluation and Resilience Forecast of Open Pit Walls

A. Ananin [1], Z. Tungushbayeva [1], G. Nurshaiykova [2*], A. Akylbaeva [2], A. Imashev [3], Sh. Zeitinova [3*], A. Gabitova [3]

[1] *"VNIItsvetmet", Affiliate of RSE "NC CPMRM RK", Ust-Kamenogorsk, 070004, Kazakhstan.*

[2] *D.Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, 070004, Kazakhstan*

[3] *Abylkas Saginov Karaganda Technical University, Karaganda, 100027, Kazakhstan.*

Received 05 March 2025; Revised 19 August 2025; Accepted 23 August 2025; Published 01 September 2025

Abstract

This study presents an analysis of open-pit bench stability based on laboratory strength testing of limestone and kinematic analysis of rock mass fracturing. The Hoek-Brown criterion was applied to determine the uniaxial compressive strength (UCS) of intact rock samples and the internal friction angle using RocData_v5. The UCS was measured at 82 MPa, with additional consideration given to the D factor, which accounts for blast-induced rock mass damage. Stability analysis was conducted using Dips and SWedge software, revealing that planar sliding and wedge failures dominate on the northeastern slope. The results indicate that 35% of fracture intersections fall within the critical wedge failure zone, and the actual bench stability is below the internationally accepted threshold (25–50%). To mitigate these risks, it is recommended to adjust the pit slope orientation to an azimuth of 325–310°, revise the Stage 2 pit design by reducing the bench angle to 60°, avoid bench strike directions between 330–360°, employ controlled blasting techniques, or increase berm width to 12 meters.

Keywords: Crack System; Open Pit Wall; Ledge; Stability Calculation; Kinematic Calculation; Geoinformation System.

1. Introduction

Slope stability is a critical concern in the safe and sustainable operation of open-pit mines. Geotechnical failures can result in operational delays, financial losses, and safety hazards. In recent years, the integration of Geographic Information Systems (GIS) with advanced geomechanical modeling tools has emerged as a powerful approach to assess and manage slope stability risks.

Numerous studies have demonstrated the effectiveness of numerical modeling using the Hoek–Brown failure criterion and other empirical or analytical methods in open-pit environments [1, 2]. Tools such as RocData, RS2, Dips, and SWedge are widely used to analyze both stress conditions and potential failure mechanisms in rock slopes. Moreover, the use of remote sensing data, UAV-based photogrammetry, LIDAR, and digital elevation models (DEMs) has significantly enhanced the accuracy of topographic and structural assessments [3, 4].

Despite these advances, many recent publications remain focused on large-scale mining operations. There is comparatively less attention paid to medium-sized limestone quarries where rock mass disturbance due to blasting and

* Corresponding author: gnurshaikova@edu.ektu.kz; zeitinova_rmpi@mail.ru

http://dx.doi.org/10.28991/HEF-2025-06-03-06

localized jointing patterns plays a critical role. In such contexts, the Disturbance Factor (D), as proposed by Hoek & Brown (2018), becomes particularly relevant for adjusting strength parameters during slope design [5-7].

This study presents a multi-method assessment of slope stability at the Sajayevka Quarry in East Kazakhstan. By integrating GIS, laboratory tests, joint network classification, and numerical modeling, the study addresses key aspects of slope reliability in disturbed limestone masses (see Figure 1). Recommendations are provided for bench geometry and design parameters suitable for similar geological contexts.

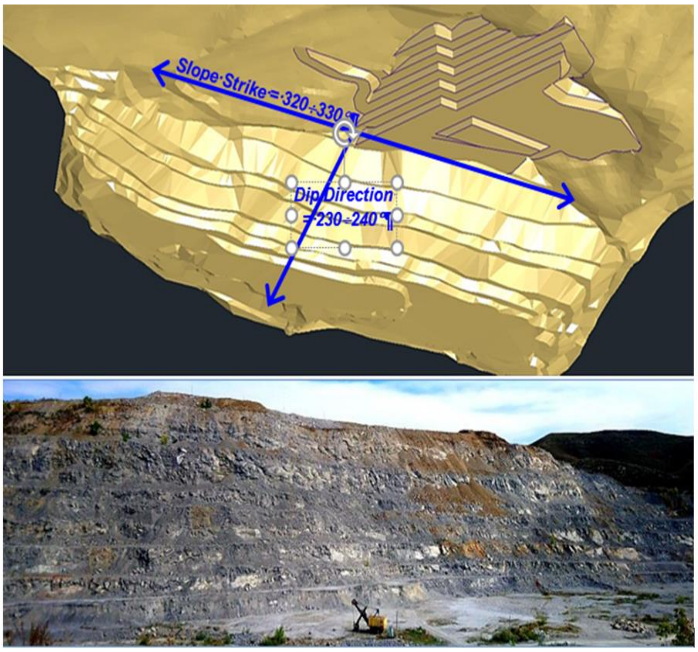


Figure 1. Actual state of the northeast wall

The Hoek-Brown criterion defines the ultimate values of the maximum principal stress σ_1 under confining pressure σ_3 (i.e., the strength of rock in a triaxial stress state) using a parabolic equation:

$$\sigma_1 = \sigma_3 + \sigma_0 \left(m_i \frac{\sigma_3}{\sigma_0} + s \right)^{0,5} \tag{1}$$

where; σ_0 is the uniaxial compressive strength (UCS or σ_{ci}) of intact rock, and mim_imi and sss are parameters dependent on the rock type. For intact rock samples, s=1.

The subscript *i* in *mi* indicates that it applies to an intact rock sample. Figure 2 presents the failure envelopes of the Hoek-Brown strength criterion for various values of the *mi* parameter. The shape of this diagram suggests that the *mi* parameter in the Hoek-Brown criterion is analogous to the internal friction angle in the Mohr-Coulomb criterion [2, 3], meaning that this parameter characterizes the increase in rock strength σ_1 with increasing confining pressure σ_3. The parameter *s* is analogous to the cohesion of rock in the Mohr-Coulomb criterion [7, 8].

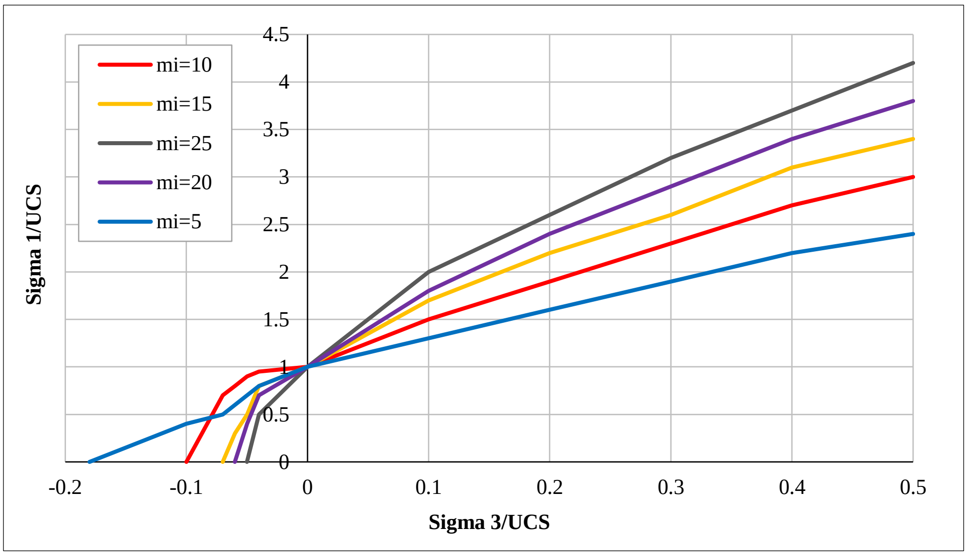


Figure 2. Hoek-Brown Strength Criteria for Different Values of Parameter mi

2. Research Methodology

The methodological framework of this study combines quantitative and graphical-analytical techniques for slope stability assessment, integrated with Geographic Information Systems (GIS) [9-12] for spatial analysis and visualization. The main stages of the methodology include:

Data collection:

- Geological and topographic information on the Sajayevka Quarry;
- Laboratory data on the strength characteristics of limestone (UCS, UTS, SCS);
- Field measurements of jointing, Rock Quality Designation (RQD), and survey data.

Determination of rock mass parameters:

- Calculation of the Geological Strength Index (GSI) based on RQD and joint condition parameters (Jr, Ja);
- Classification of the rock mass using the Hoek–Brown failure criterion, adjusted for disturbance (D factor).

Software applications:

- RocData – construction of strength envelopes and estimation of non-linear failure parameters;
- RS2 – numerical modeling of slope stability considering in-situ stress conditions;
- Dips and SWedge – kinematic analysis of slope stability based on joint orientation data.

Result interpretation and recommendations:

- Evaluation of safety factor (Factor of Safety, FoS);
- Determination of optimal slope angles and berm widths.

The following flowchart summarizes the research workflow (Figure 3).

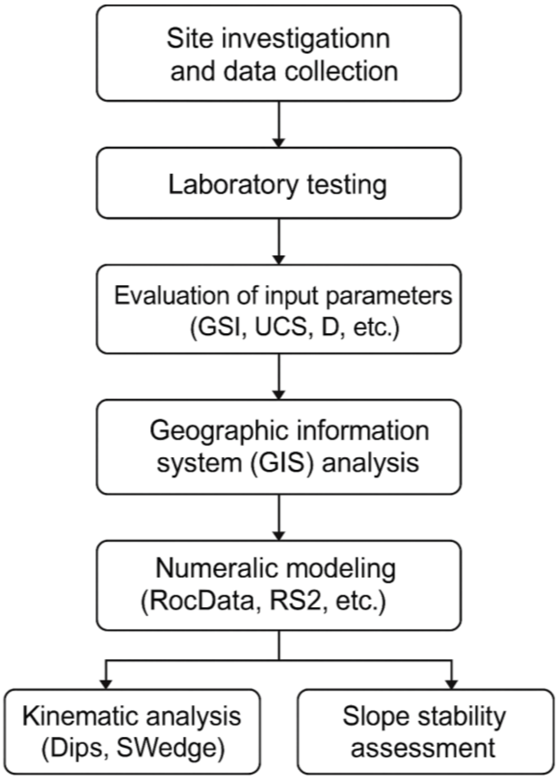


Figure 2. Flowchart of the methodological workflow

The Sazhaevskoye limestone deposit is located in the East Kazakhstan region and has been operated by the Ust-Kamenogorsk Cement Plant since 1964 (Figure 4). The reserves of the deposit within the "surface–horizon 505 m" level (with a bench height of 130 m) have been largely mined out by the first-stage open pit, which extends 1,050 m along the strike. The remaining reserves of categories B+C1 and C2 are located beneath a plagiogranite-porphyry dike, within the 500–450 m level, and are being extracted according to the second stage project.

Figure 3. Location of the Sajayevka Quarry in East Kazakhstan

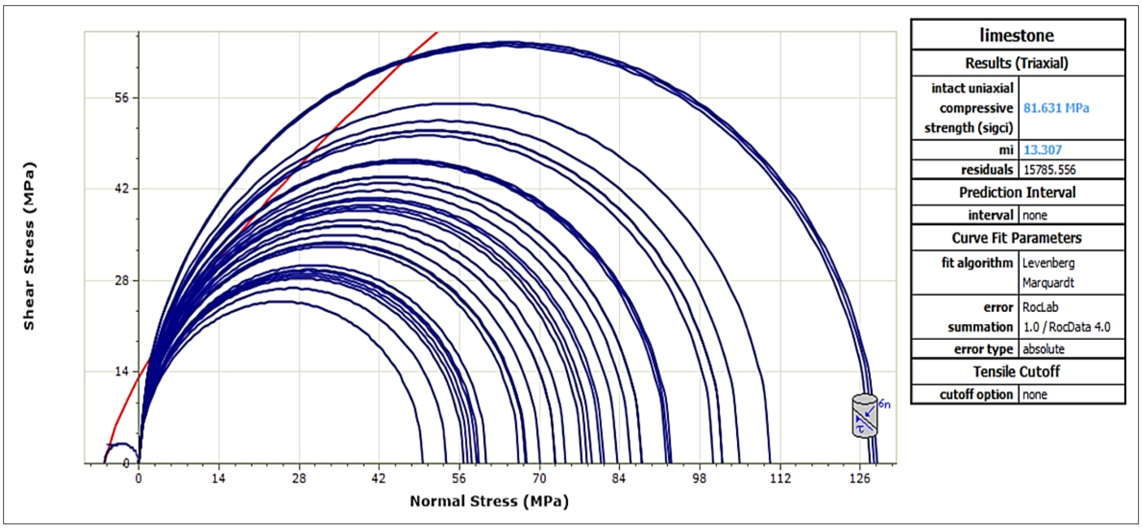
Special emphasis is placed on the Disturbance Factor (D), which characterizes the degree of rock mass damage resulting from blasting operations. Based on Rocscience recommendations and field data from the Sajayevka Quarry, a value of D = 1 was adopted, indicating a highly disturbed zone near the excavation face. This adjustment is justified by the observed reduction in cohesion and strength in field conditions compared to laboratory tests.

Additionally, geoinformation technologies were used for topographic analysis and slope visualization. Digital elevation models (DEMs) and the 2020 aerial photogrammetric map of the quarry were utilized to enhance slope geometry evaluation and identify potentially hazardous areas, which were then incorporated into Dips and RS2 modeling [13, 14].

For calculations and the construction of rock strength envelopes based on the Hoek-Brown criterion, RocData_v5 software (RocScience Inc.) was used. RocData includes a specialized module that processes laboratory test data for the studied rock type, including Uniaxial Compressive Strength (UCS), Uniaxial Tensile Strength (UTS or σ_t), Triaxial Compression Test results at different levels of confining pressure.

The strength envelope for limestones from the Sazhaevskoye open pit was built using individual UCS values and the average UTS value (Figure 5). The Hoek-Brown parameters σ_1 and m_i are determined from the best-fit envelope equation (shown in red) and have the following values:

- Uniaxial Compressive Strength σ_{ci} =82 MPa.
- Material Parameter m_i =13.



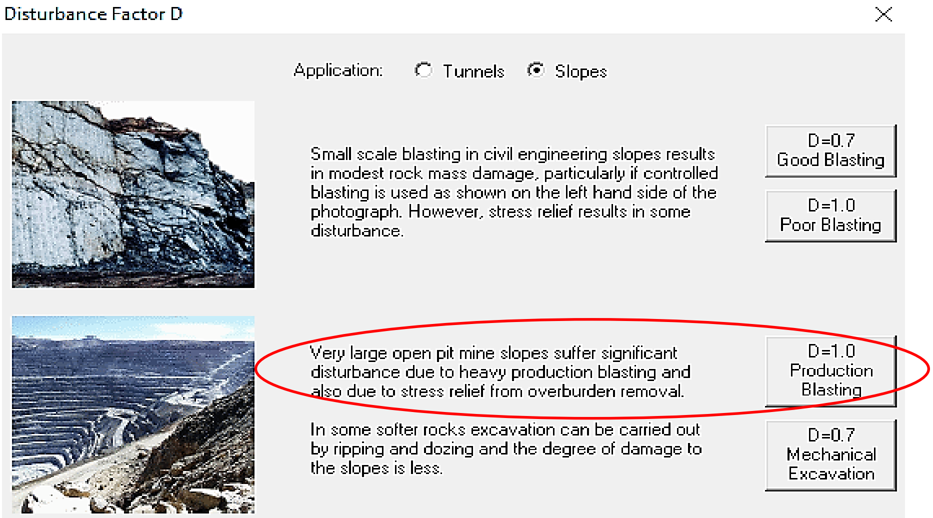


Figure 4. Recommendations for Determining the Disturbance Factor of the Rock Mass Due to Blasting Operations

It should be noted that the calculated σ_{ci} value corresponds to UCS. For over 20 years, E. Hoek and E.T. Brown have refined their failure criterion, introducing new parameters. Figure 4 illustrates the incorporation of the Disturbance Factor (D), which accounts for rock mass damage caused by blasting operations [1, 8].

For the Sazhaevskoye open pit, assumed value of D is 1. Using the RocData software, the strength and deformation properties of the homogeneous fractured rock mass of the Sazhaevskoye deposit were calculated (Figure 6). The blue curve represents the Hoek-Brown strength, considering both the fracture condition (GSI index) and the effect of blasting (Disturbance Factor, D) [15]. The red straight line corresponds to the Mohr-Coulomb strength criterion, determined for normal stress at the pit wall with a height H = 170 m. From this, the cohesion *Cm* and friction angle φ_m for the fractured rock mass were derived. The calculation results are presented in Table 1.

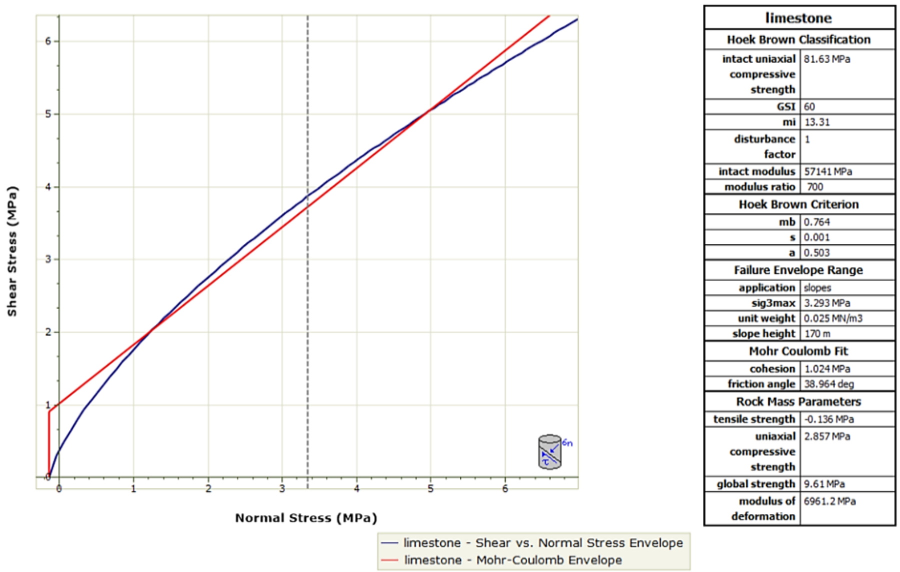


Figure 5. Strength Criteria of the Limestone Mass at the Pit Wall Scale

Table 1. Properties of the Fractured Limestone Mass

Properties of Limestone in Samples	
Uniaxial Compressive Strength (UCS), MPa	82
Parameter *mi*	13
Blast-Induced Rock Damage Factor, *D*	1
Modulus Ratio $MR = E_i/UCS$	700
Elastic Modulus E_i, GPa	57.1

Fracturing Characteristics	
Geological Strength Index *GSI*	60
Hoek-Brown Strength Criterion Parameters	
mb	0.764
S	0.001
a	0.503
Approximation Parameters for Mohr-Coulomb Strength Criterion	
Unit Weight of Rock, MN/m^3	0.025
Pit Wall Height, m	170
Horizontal Stresses, MPa	3.3
Mohr-Coulomb Strength Criterion Parameters in the Rock Mass	
Cohesion in Fractured Rock Mass, MPa	1.024
Internal Friction Angle, degrees	39
Properties of Fractured Rock Mass	
Tensile Strength of Rock Mass σ_t, MPa	-0.136
Compressive Strength of Rock Mass σ_{cm}, MPa	9.61
Deformation Modulus of Rock Mass *Erm*, MPa	7.0

The properties of the fractured limestone mass will be used in the numerical modeling of pit wall stability.

Kinematic analysis [1, 2] involves calculating the stability of rock blocks separated from the mass by fractures under the influence of self-weight. The forces that resist the displacement (sliding, toppling, or collapse) of detached rock blocks are friction and cohesion along fractures. These parameters are determined through direct shear tests on fractures (Direct Shear Test).

A preferable approach is to determine shear resistance parameters of fractures using back-analysis based on observed deformations [2, 3]. This method accounts for: scale effects, slope standing time, blasting impacts, atmospheric precipitation. As shown in studies [4, 16, 17], a reliable value for the friction angle along fractures can be obtained through laboratory shear tests, while cohesion values are more accurately determined via back-analysis. To achieve this, a database of deformation geometries is required. Often, this task is also solved using digital stereophotogrammetric slope surveying technology (Sirovision).

Visual observations indicate that the NE wall of the Sazhaevskoye open pit is characterized by widespread planar sliding along persistent fractures dipping into the pit, as well as wedge failures caused by intersecting discontinuities (Figure 7). The mathematical approach for analyzing these types of deformations differs [18-21].

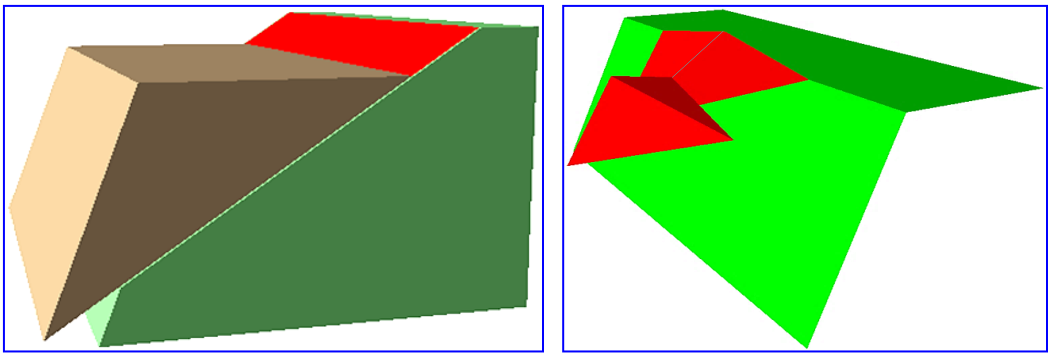


Figure 6. Bench deformation

The Dips software generates stereonet windows for fracture orientations, identifying zones where fractures may cause specific types of deformations. It also calculates the percentage of critically oriented fractures. In a preliminary approximation (a very rough estimate), this percentage can be considered as the probability of deformation occurrence for a given bench slope angle. For more accurate stochastic calculations (e.g., using the SBlock software), a much larger dataset on rock mass fracturing is required. In international practice [1, 7], the generally accepted deformation criterion is bench failure probability within 25–50%. This range depends on: wall type (working or ultimate pit wall), width of safety berms, Bench location relative to haul roads. Due to limited data on rock mass fracturing, the allowable probability of local bench instability for the Sazhaevskoye open pit is set at no more than 25% for further calculations.

Rock mass fracture data was used for kinematic analysis of bench stability at the northeastern (NE) wall using Dips 6 with the following input parameters:

- Bench strike: 320–330°
- Azimuth of bench dip direction: 230–240°
- Bench dip angle: 70°
- Friction angle along fractures (based on direct shear tests): φ' = 30°

The analysis of planar sliding deformations (Planar Sliding) in the NE wall benches is shown in Figure 8.

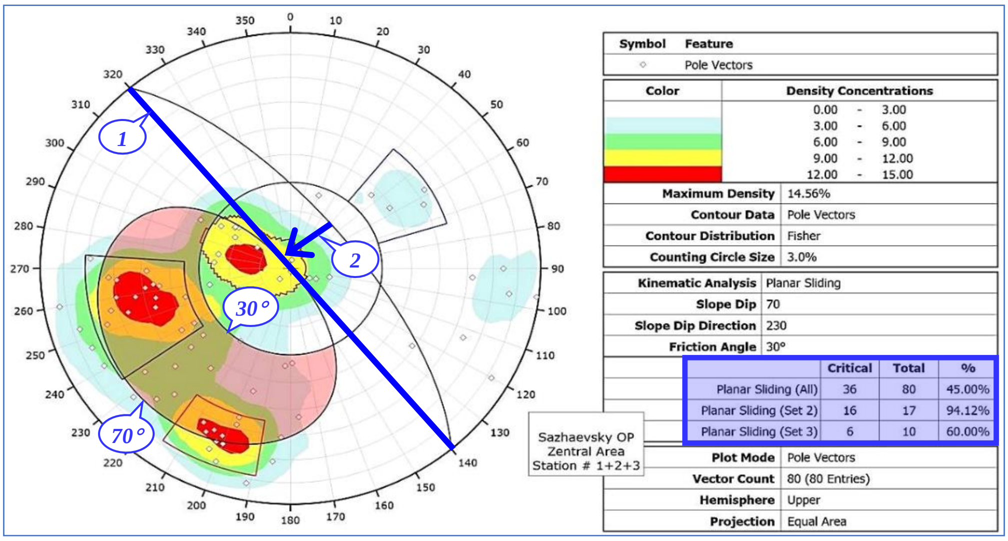
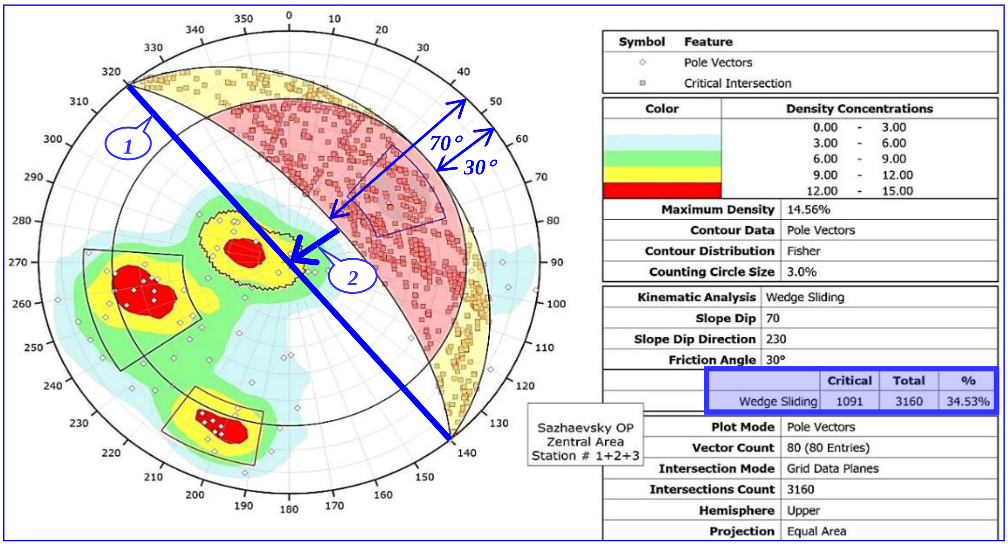


Figure 7. Kinematic Analysis of Planar Sliding Deformations in the NE Pit Wall

The window where planar sliding of blocks along fractures into the pit occurs is bounded on one side by the friction angle of the fractures (30°) and on the other by the bench inclination angle (70°), highlighted in color. Kinematic analysis indicates that almost all (94%) fractures of the second system, which dip into the pit, and 60% of fractures of the third system may lead to planar sliding deformations. The only exceptions are fractures with a dip angle less than the friction angle of 30°. Additionally, planar sliding is impossible if the dip angle of the fracture exceeds the bench inclination angle. Therefore, reducing the bench inclination angle decreases the likelihood of planar sliding along fractures dipping into the pit [22-27].

The analysis of potential wedge sliding deformations in the NE pit wall is shown in Figure 9. Wedge failures of rock blocks occur along intersecting fractures cutting through the slope when the intersection line (Intersection) is inclined into the pit at an angle greater than the friction angle of 30° but less than the slope inclination angle of 70°. In the NE pit wall, 80 recorded fractures used in the analysis form 3160 intersections. Of these, 1091 intersections fall into the critical wedge failure zone (highlighted in color in Figure 9), which accounts for 35% of all intersections.



Note: 1- Bench strike with an azimuth of 140 - 320°; 2- Bench inclination direction at an angle of 70° with an azimuth of 230°.

Figure 8. Kinematic Analysis Window for Wedge Failures in the Northern Pit Wall

The kinematic analysis of the stability of the benches in the NE pit wall of the Sazhaevsky quarry, designed according to the first-stage project, revealed relatively high probabilities of both planar sliding and wedge failures. These significantly exceed the acceptable deformation probabilities of 25–50% in global practice. This indicates that the actual condition of the NE pit wall, which does not meet industrial safety standards due to the loss of berm catchment capacity caused by collapses and debris accumulation, is a result of the kinematic instability of the benches [28-30].

A traditional method to improve bench stability is to reduce their inclination angles. The Dips program has been used to estimate, in a first approximation (very roughly), the probabilities of planar and wedge failures at different bench inclination angles (see Figure 10). Figure 11 shows the actual position of the northeastern slope in plan view, and Figure 12 shows it in sections III, V, and X.

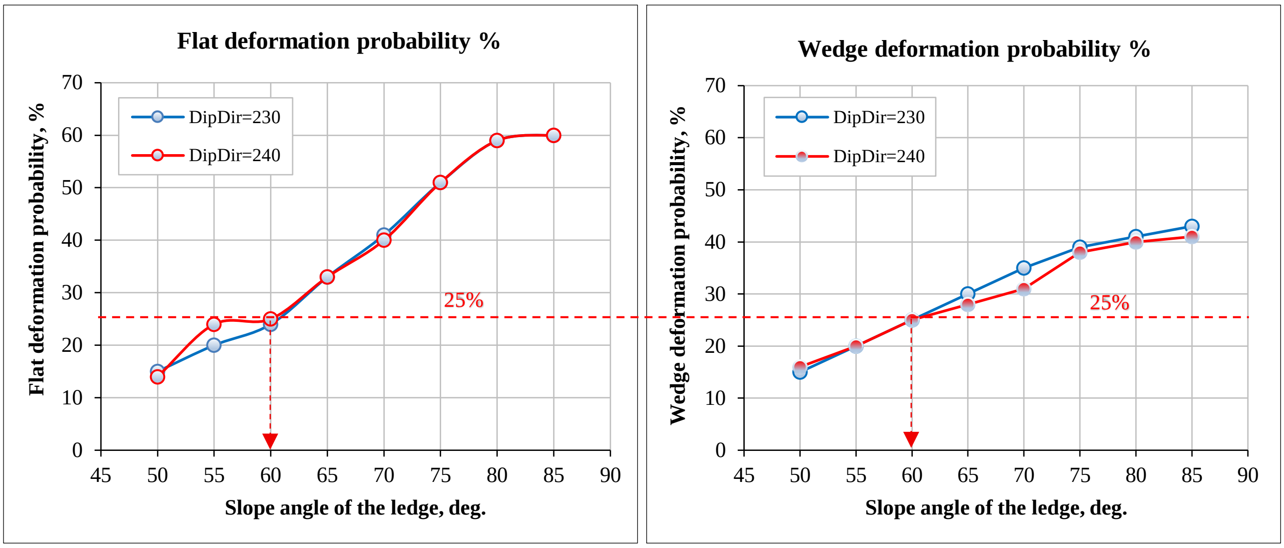


Figure 9. Probabilities of Planar and Wedge Failures of Benches in the Northeast Pit Wall

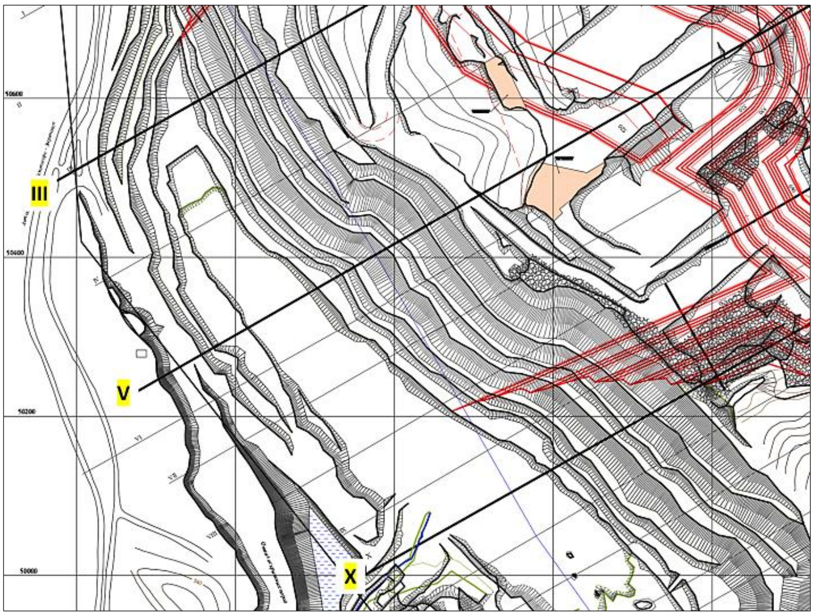


Figure 10. Actual Position of the Northeast Pit Wall along Sections III, IV, and X

The failure of benches and berms due to planar and wedge deformations allows for a back-calculation of shear resistance along fractures [9,16, 20]. The SWedge program (RocScience Inc.) was used for this purpose.

The following parameters were set in the program:

- Average orientation elements of two fractured systems, with an adjustment of the dip angle of the first system to the actual average slope angle of 42°.
- Bench configuration with a height of 10 m and an inclination angle of 70°.
- Friction angle along fractures φ' = 30°.

The back-calculation of cohesion C' along fractures consists of selecting a value at which the Safety Factor (SF) of a wedge block formed in the slope by fractures of the second and third systems equals 1.00. The results of the back-calculation [21, 22]. (Safety Factor = 1.003) are shown in Figure 13.

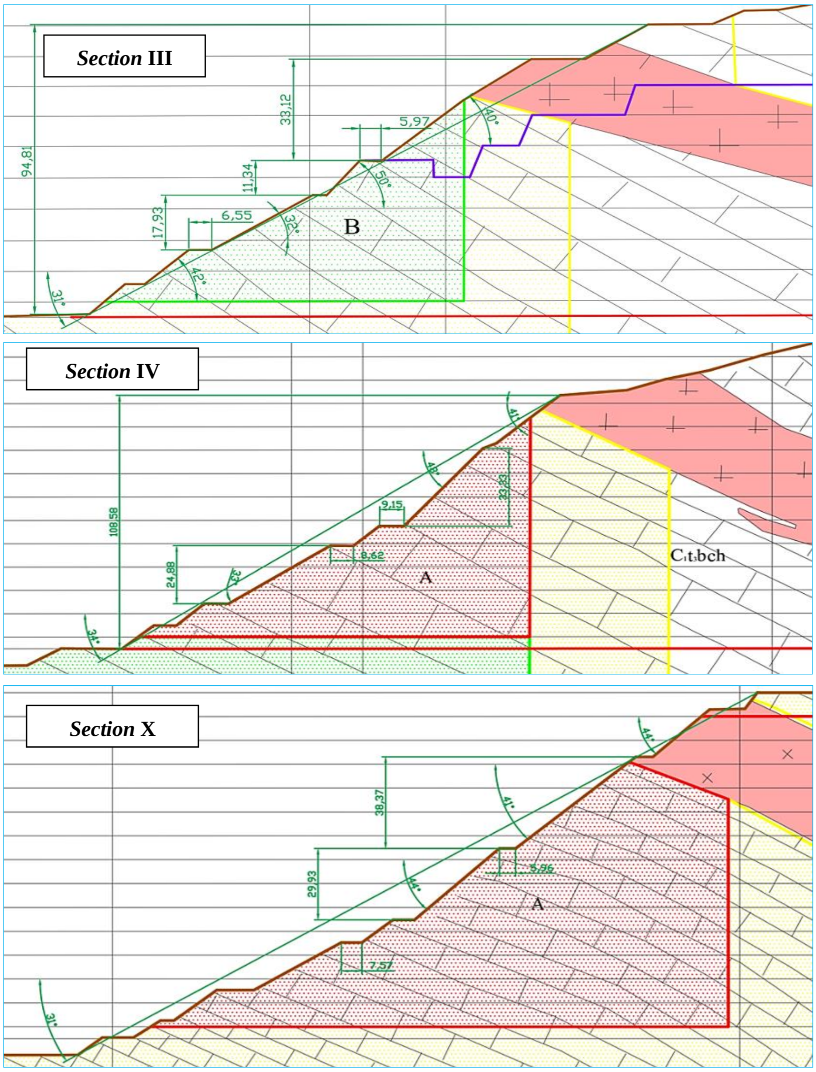


Figure 11. The design diagrams for the sections of the NE quarry slope

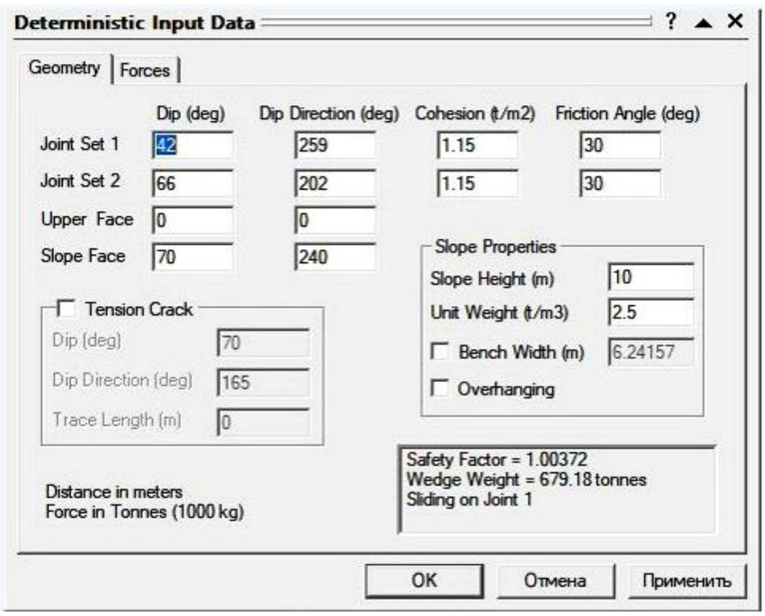


Figure 12. Back-Calculation of Cohesion along Fractures

3. Results and Discussion

The results of numerical and kinematic slope stability analyses at the Sajayevka Quarry confirm the critical importance of considering both the geomechanical properties of the rock mass and the characteristics of jointing during pit design. Simulations were conducted using models developed in ***RS2*** and ***SWedge***, with input parameters derived from laboratory testing and field observations.

The average ***uniaxial compressive strength (UCS)*** of limestone was measured at ***82 MPa***, with a standard deviation of ***21 MPa***, indicating moderate variability in the material (Coefficient of Variation = 26%). ***RQD values*** ranged from 57% to 89%, with a mean of **77%**, corresponding to competent and very competent rock masses.

Kinematic analysis revealed a high likelihood of ***planar and wedge failures*** in specific areas, particularly where slope angles exceeded 70°. Reducing the slope angle to ***60°*** decreased failure probability to an acceptable **25%**, in line with international engineering practice (as shown in DIPS analysis).

Application of the generalized ***Hoek–Brown failure criterion*** with parameters ***GSI = 60*** and ***D = 1*** enabled a more accurate assessment of strength degradation in the disturbed rock mass. The calculated equivalent strength parameters were: compressive strength of ***9.61 MPa***, cohesion of ***1.024 MPa***, and internal friction angle of ***39°***. These results underscore the necessity of incorporating the ***D-factor*** into stability assessments to reflect field conditions realistically.

An analysis of alternative ***berm widths*** indicated that a ***12-meter berm*** provides an adequate safety margin while minimizing loss of recoverable material. This width strikes an optimal balance between operational safety and productivity.

Topographic visualization and ***digital elevation models (DEMs)*** based on aerial photogrammetry further confirmed the presence of high-risk zones. As a result, local stabilization measures—such as slope angle correction and enhanced geotechnical monitoring—were recommended to mitigate potential failures.

The design boundary of the second phase of the quarry has a rather complex shape, with benches that change direction. Figure 14 shows the strike azimuths of the benches and their dip directions, which are necessary for calculating slope stability. It also indicates the section numbers for the slope stability calculations.

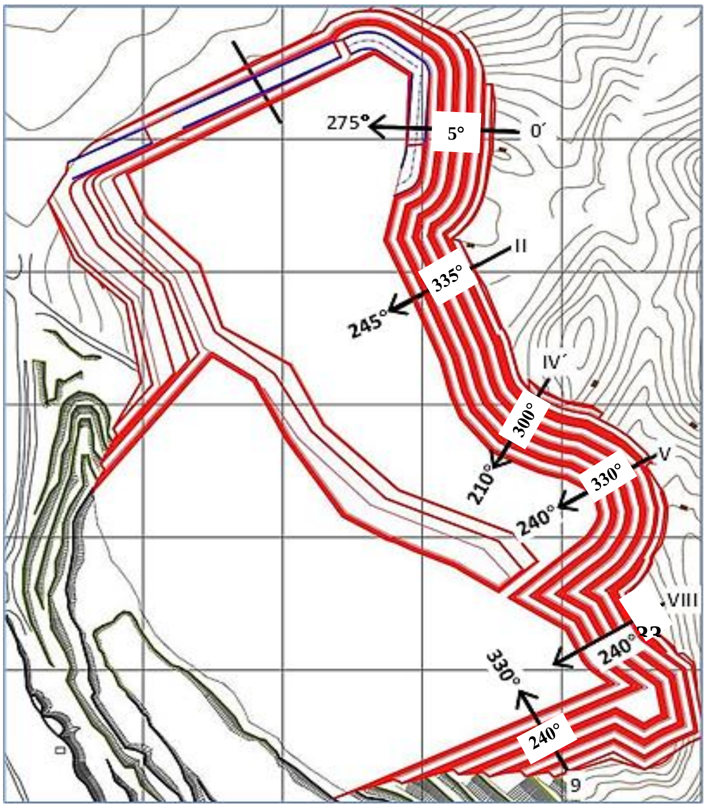


Figure 13. Design Contour of the Second-Stage Pit Expansion

The results obtained show that the designed sections of the northeastern quarry wall are oriented in unfavorable directions. Even with benches 30 meters high and a slope angle of 60°, they do not provide an adequate safety factor. To fundamentally improve the situation, it is necessary to orient the quarry wall or its sections with a strike azimuth of 325°–310°. These recommended directions are shown in blue lines in Figure 15.

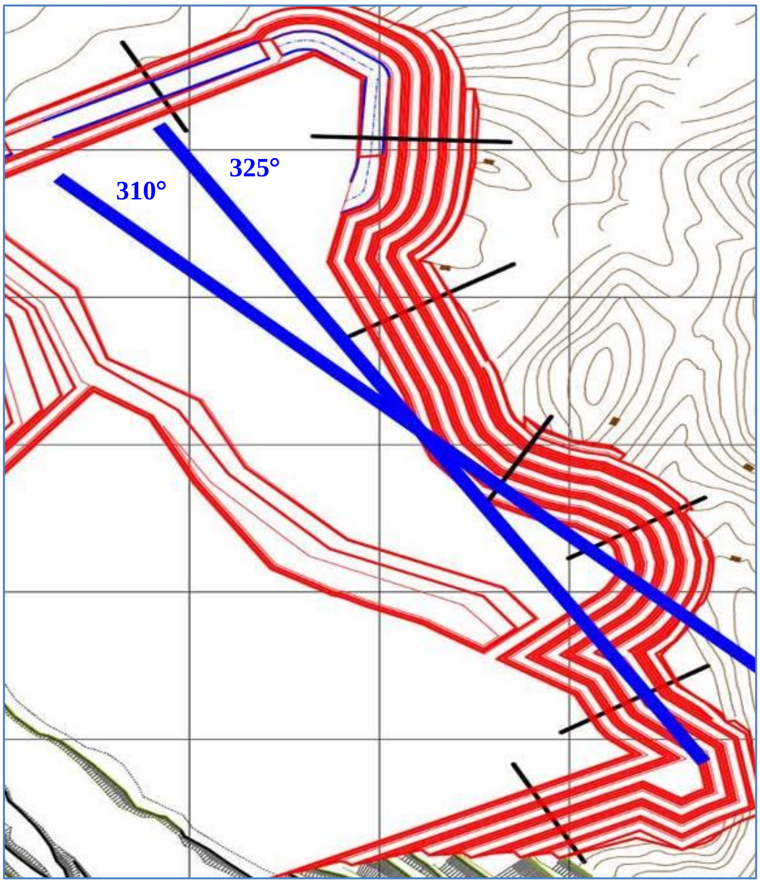


Figure 14. Recommended Pit Wall Orientations

The most unfavorable scenario was analyzed: the stability of triple-stacked benches with a total height of 30 m and an inclination angle of 60°, considering different pit wall orientations. The input data used for analysis included fracture sets (Joint Set 1, 2), fracture properties (Cohesion = C', Friction Angle = φ'), slope geometry (Slope Face). These parameters are illustrated in Figure 16, which also presents an example of a stability factor (Safety Factor) calculation for cross-section II. The bench inclination angle is 60° (Dip), with a dip direction of 245° (corresponding to a pit wall strike azimuth of 335°). The results of calculations are shown in the Figure 17.

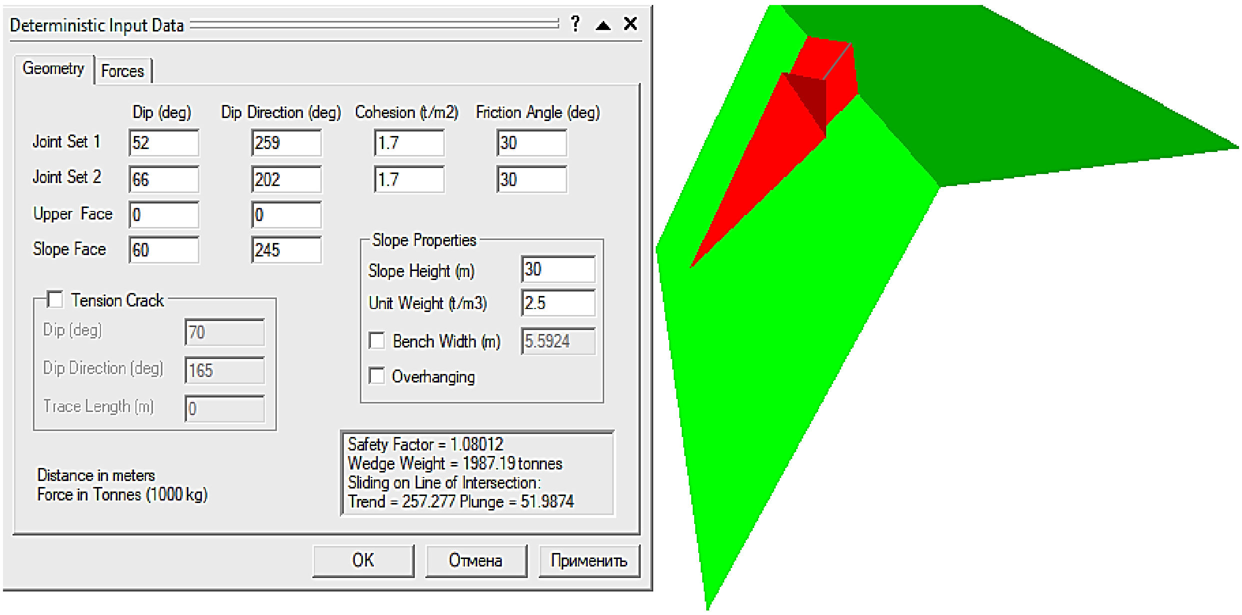


Figure 15. Input Data (Left) and Example of Bench Stability Factor Calculation

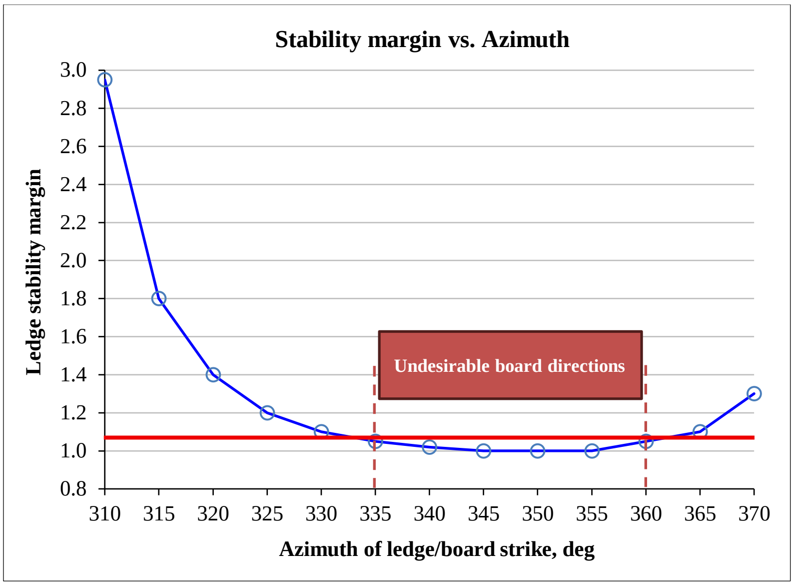


Figure 16. Dependence of Bench Stability on Orientation with undesirable Pit Wall orientations

4. Conclusion

The conducted study has clearly demonstrated the effectiveness of integrating geomechanical analysis with geoinformation technologies for assessing the stability of slopes at the Sajayevka Quarry. The results highlight the importance of a holistic approach that combines laboratory and field investigations, numerical modeling, and visualization based on digital elevation models (DEMs). The inclusion of key parameters—particularly the Disturbance Factor (D) and the Geological Strength Index (GSI)—allowed for a more accurate representation of in-situ conditions and supported the development of practical slope design recommendations.

The study proposed optimized design solutions for slope angles and berm widths that balance safety and operational efficiency. The application of RS2, SWedge, and Dips software facilitated the identification of potentially unstable areas and informed the implementation of stabilization measures. These findings provide valuable insights for similar geological settings in other regions. Future research should incorporate advanced remote monitoring technologies (e.g., UAVs, InSAR) to enable real-time slope stability assessments and enhance risk management.

Furthermore, it is crucial to integrate economic considerations with safety measures to achieve a sustainable balance between operational productivity and geotechnical risk mitigation. Adopting continuous monitoring systems can aid in detecting early signs of instability, allowing for timely intervention and reducing costly remediation efforts. The integration of real-time data from automated sensors, satellite observations, and UAV-based inspections will strengthen the responsiveness of mine management and ensure that operational decisions are informed by the latest field data. This proactive approach is vital for improving overall mine safety and supporting sustainable mining practices. Additionally, consideration of seasonal variations and climate change impacts on slope stability will become increasingly important, as extreme weather events may accelerate slope degradation and erosion processes. By accounting for these factors, mining operations can better manage risk, safeguard personnel, and protect the environment.

In summary, the study lays a strong foundation for modernizing slope stability management at the Sajayevka Quarry and similar sites. Implementing these recommendations can significantly enhance safety, reduce operational risks, and support the long-term sustainability of open-pit mining activities.

5. Declarations

5.1. Author Contributions

Conceptualization, Sh.Z. and G.N.; methodology, A.A.; software, A.A. and Z.T.; formal analysis, As.A. and A.G.; investigation, A.A. and Z.T.; resources, As.A. and A.I.; data curation, Z.T. and A.G.; writing—original draft preparation, G.N.; writing—review and editing, A.I. and Sh.Z.; visualization, Z.T.; supervision, G.N. and As.A.; project administration, A.A.; funding acquisition, G.N. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

This research was supported by project IRN BR24992854 “Development and implementation of competitive science-based technologies to ensure sustainable development of mining and metallurgy industry East Kazakhstan region”, funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

5.4. Institutional Review Board Statement

Not applicable.

5.5. Informed Consent Statement

Not applicable.

5.6. Declaration of Competing Interest

The authors declare that there are no conflicts of interest concerning the publication of this manuscript. Furthermore, all ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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