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Numerical Modelling of Slope Stability for a Placer Deposit: Case Study of the Motronivskyi Open-Pit Mine, Ukraine

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Abstract

Open-pit development of placer deposits in moisture-sensitive, layered sediments requires slope designs that explicitly account for transient hydrology. This study assesses the stability of the eastern non-working wall at the Motronivskyi open-pit mine at Malyshevske zircon-rutile-ilmenite placer deposit (Vilnohirsk, Ukraine) composed of loams, clays, and Sarmatian sands. The research integrated engineering-geological survey data with stratigraphy and laboratory-measured strength parameters for "Northern", "Central", and "Southern" pit-wall profiles considering their geometry and hydrogeologic conditions. Numerical analyses used the Phase2 (Rocscience Inc.) finite-element method with a Mohr-Coulomb model and shear-strength reduction to obtain safety factors supported by a classification of landslide hazard levels. Under natural moisture, the safety factor values indicate generally stable conditions: "Northern" – 1.65, "Central" – 1.52, and "Southern" – 1.62. When water-saturated rock massif due to rainfall impact or groundwater rise, the safety factors drop to 1.20, 1.05, and 1.18, respectively. The analysis of shear strains and total displacements in the rock mass represents how wetting sharply lowers effective strength and shifts failure modes from shallow sloughing to coherent bench-scale slides, which can guide operational slope design and water-management strategies in similar placer-deposit settings.

Keywords:
open-pit mine; placer deposit; slope stability; numerical analyses; safety factor

1. Introduction

Optimizing parameters of quarry slopes and sides is an important technological task in the surface mining of mineral deposits (**Sobko et al., 2022; Anisimov, 2015**). As the steepness of the slope increases, the tangential (shear) stresses increase as well, and when they reach values that exceed the limit of the rock shear resistance, slope failure occurs with a certain displacement of the rock mass along the failure surface (**Cherep, 2024, Moldabayev et al., 2021; Rakishev et al., 2014;**). In addition to geometric parameters, rock properties, groundwater flow, hydrogeological characteristics of the deposit, and technological factors significantly affect the slope stability (**Kovrov et al., 2016; Sdvizhkova et al., 2014**). The continuous geotechnical monitoring consists of a set of measures to maintain slopes, pit sides, and overburden dumps in a stable state by changing their geometry and considering structural features of the rock massif and its variable physical and mechanical properties, hydrogeological and technogenic factors, etc. (**Adamchuk et al., 2023; Anisimova et al., 2022; Babii et al., 2019; Chetverik et al., 2013; Chetveryk et al., 2017; Shashenko et al., 2019**).

Open-pit mining of placer deposits commonly involves excavation through weakly consolidated, often stratified sediments (sand, gravel, silt, loam, and clay lenses). These deposits are highly sensitive to changes in moisture: infiltration from precipitation and changes to local hydrology substantially affect matric suction and pore-water pressure, which in turn control effective stress and shear strength of slope materials (**Li et al., 2024; Yang et al., 2023**). Recent studies emphasize the dominant role of transient hydrology in triggering slope failures in soft sediments and in open-pit settings (**Babets et al., 2023; Shapoval et al., 2020**). Placer deposits typically present strong stratigraphic contrasts including permeable sands and overlying less permeable silts or clays that create water tables, lateral seepage, and concentrated pore-pressure zones that commonly act as slip surfaces or trigger zones for slopes failures (**Belay et al., 2025; Fredlund & Rahardjo, 1993**).

Excavation changes hydraulic boundaries and may create perched water or concentrate lateral seepage at low-permeability interfaces, promoting deep or planar

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sliding. Field and numerical case studies for open pits show that mining-rainfall coupling can nonlinearly amplify deformation and accelerate slope failure (**Rezaei et al., 2024; Li et al., 2024**). These case studies of placer and other soft-rock open pits underline the importance of layered geometry and transient pore-pressure accumulation in determining failure type and timing.

Slope stability issues gain more importance at quarries with worked-out soft overburdened rocks. Thus, the development of placer deposits of titanium-zirconium ores, which are a valuable strategic raw material in Ukraine, is complicated by a complex of geological, hydrogeological, and man-made factors that affect mining technology (**Lozhnikov et al., 2024**). The substantiation of reducing the safety factor of the open pit side by only 5% allows to reduce the volume of overburden rocks and the area of the pit from 1.5 to 20%, depending on the mining and geological conditions of the mineral deposit. It is also known that in quarries with a depth of up to 300 m, an increase in the resulting angle of inclination of the side by 3-4° allows to reduce the volume of overburden to 10-11 million m^3 per 1 km of the working front, which increases the overall efficiency of surface mining operations (**Kovrov et al., 2020**).

Therefore, ensuring the stability of slopes and sides of pits during the development of mineral deposits is an element of technological and environmental safety in the context of the national strategies for sustainable development (**Pivnyak et al., 2013; Saik et al., 2023; Cherep, 2024; Prokopenko et al., 2021**).

Malyshevske deposit of zircon-rutile-ilmenite placer ore is located northeast of the city of Vilnohirsk (Central Ukraine) and developed via surface mining. The technological feature of this deposit is characterized by complicated and variable mining and geological conditions of development. Considering the hydrogeological conditions and water-saturated rock massif, there is a danger of landslides on the pit slopes and in the vicinity of overburden heaps. A comprehensive geomechanical assessment of the slope stability and prognosis of landslide potential risks serve as a basis for safe and effective open pit mining technology (**Sobko, 2008**).

Despite numerous publications devoted to open-pit mining at the Malyshevske placer deposit, the integrated consideration of hydrogeological conditions and transient changes in the moisture state of layered soft rocks (loams, clays, and sands) and their coupled influence on pit-slope stability remains insufficiently investigated. This study addresses this gap by combining site-specific stratigraphy and laboratory-derived "strength-deformation" parameters with FEM-based shear-strength reduction analyses for three representative profiles of the eastern non-working wall at the Motronivskyi open-pit mine under natural-moisture and water-saturated conditions.

The purpose of the study is to determine the stability parameters of the slopes of the eastern non-working wall of the Motronivskyi open-pit mine by analyzing its three representative slope profiles ("Northern", "Central", and "Southern") considering the geometry of slopes, physical and mechanical properties of soft sedimentary rocks, hydrogeological characteristics under natural-moisture and water-saturated conditions.

2. Methods

To evaluate the geomechanical stability of slopes at the open pit while developing the ore deposit, the data of engineering and geological surveys, technological schemes of surface mining operations, and physical-mechanical properties of sedimentary rocks were used. The finite element analysis module of the Phase2 software by Rocscience Inc. was applied for numerical simulation of slope stability. The maximum shear strains in the slopes are calculated according to the following expression:

$$\varepsilon_{\max} = \frac{\varepsilon_1 - \varepsilon_3}{2}, \quad (1)$$

Where:

ε_1 – maximum and minimum main deformations (dimensionless),

ε_3 – maximum and minimum main deformations (dimensionless).

The ε_1 and ε_3 correspond to the values of the maximum and minimum stresses σ_1 and σ_3 (**RS2 Tutorials, 2021**).

The empirical classification of maximum shear strain values which occur in slopes, quarry sides, and overburden dumps (see **Table 1**) gives a range of landslide hazard effects due to the influence of natural or man-made instability factors (**Kovrov et al., 2020**).

This research considers a scenario of water saturation of the rock massif due to rainfall infiltration or groundwater table rise. In particular, the increase of water saturation in the massif of soft sedimentary rocks can lead to a decrease in the physical and mechanical properties of loams and clays, and the creation of unfavourable conditions for development of slip surface and landslide processes. The Mohr-Coulomb failure criterion was selected for evaluation of plastic deformations and shear strains in the rock massif.

In analytical studies of the parameters of the elastic-plastic state, Mohr's strength criterion with a linear envelope of the principal stresses circles is most often used. The physical and mechanical characteristics included in the condition of strength are the angle of internal friction ρ and cohesion C, or uniaxial compressive strength R_c and uniaxial tensile strength R_p.

When estimating the limit state, the Mohr-Coulomb linear relation is expressed as:

$$\tau = C + \sigma_n \mathrm{tg}\varphi, \quad (2)$$

Where:

τ – shear stress (kPa),

σ_n – normal stress (kPa),

C – cohesion (kPa),

φ – angle of internal friction (degree).

Table 1: Classification of maximum shear strains in the slopes and sides of quarries

Maximum shear strains	Values, dimensionless	Landslide hazard effects
Low	$\varepsilon_{max} \leq 0.05$	Slight shifts or subsidence in the massif, local surface sliding processes on slopes
Moderate	$0.05 < \varepsilon_{max} \leq 0.1$	Horizontal displacements dominate over vertical ones, zonal sliding processes and visible cracks in slopes
Average	$0.1 < \varepsilon_{max} \leq 0.5$	Formation of landslide areas with local sliding surfaces, slope failure, rockfalls (rockflows) and landslides on slip surface
Critical	$0.5 < \varepsilon_{max} \leq 1.0$	The formation of areas with continuous sliding surfaces and rock failure phenomena with landslides
Catastrophic	$\varepsilon_{max} \geq 1.0$	Large-scale landslides in one or more slopes (sides) of an open pit

Table 2: Classification of landslide hazard of slopes and sides of quarries by SRF value

Levels of landslide hazard in slopes	SRF range	Classification of landslide hazard
Low	SRF ≥ 1.5	I
Moderate	1.2 < SRF ≤ 1.5	II
Average	1.1 < SRF ≤ 1.2	III
Increased	1.0 < SRF ≤ 1.1	IV
Critical	SRF = 1.0	V

The Shear Strength Reduction (SSR) function in Phase2 allows for the automatic performance of a finite-element analysis and the calculation of the critical Strength Reduction Factor (SRF) for the selected model, which is equivalent to the slope safety factor (SF). The algorithm for calculating the SRF values includes an iterative calculation of the strength in all elements within the slope model with the help of stepwise loading. It involves iteratively reducing the shear strength parameters (C and φ) of all materials until numerical non-convergence occurs, indicating slope failure. The factor by which strength is reduced at failure is the SRF. As a result, the stresses on the slope reach the shear strength limit and the rock mass displacement occurs. The process of SRF calculations is repeated until the moment of loss of the stable state by the slope that is graphically expressed in the form of the sliding surface in the rock massif (**RS2 Tutorials, 2021**).

The geomechanical criterion for assessing the state of natural slopes and man-made slopes is the SF or its equivalent represented as Strength Reduction Factor (SRF), which represents the ratio of the retaining F_{ret} and shearing F_{shear} forces in the slope area along the potential sliding surface, i.e. SRF = F_{ret} / F_{shear}. There are three possible states of slope stability, namely: if SRF > 1.0, the slope is stable; SRF = 1.0 corresponds to the limit state and initiation of a slope deformation, and SRF < 1.0 indicates the full failure with a landslide phenomenon.

The level of landslide hazard on the selected profiles of the eastern non-working edge of the quarry is determined by the results of calculating the SRF and comparing it with the landslide hazard scale (see **Table 2**).

The proposed classification makes it possible to determine the level of landslide hazard for natural and technogenic slopes and predict possible shear strains and displacements in the rock massif for further development of effective anti-landslides engineering protective measures.

Laboratory testing was performed on representative samples of loams, clays, and sand collected from the stratigraphic layers of sedimentary rocks. Bulk density and natural moisture content were determined by gravimetric methods, while shear strength parameters (C and φ) were obtained from standard shear tests. Deformation modulus E and Poisson's ratio ν were derived from "stress–strain" curves during standard compression tests. The resulting parameters were used as Mohr–Coulomb inputs for the numerical models.

3. Results

3.1. General geological data and physical properties of sedimentary rocks

The Malyshevske deposit of zircon-rutile-ilmenite placer ore is located northeast of the city of Vilnohirsk (Verknyodniprovskyi District, Dnipropetrovsk oblast, Ukraine) and developed via surface mining (see **Figure 1**). The geographical coordinates of the investigated site are 48.5707° north latitude and 33.9864° east longitude. The technological feature of this deposit is characterized by variable mining and geological conditions. Quaternary and Neogene rocks are involved in the geological structure of this territory. Soils of eolian-deluvial origin are presented by tough-plastic and soft-plastic loams. Hard, macroporous, brownish-yellow, pale-yellow loams are widely distributed, and they lie under the soil-vegetation layer. The thickness of loams of a solid consistency varies from 8-9 m. Plastic brownish-yellow loams lie under hard loams at a depth of 9-10 m. Deluvial soils are represented by red-brown clays that lie below the layer of eolian-deluvial soils. The thickness of clay layers achieves at least 10 m (**Sobko, 2008**).

The physical and mechanical properties of soils and soft sedimentary rocks (see **Table 3**) presented in the geological structure of the placer ore deposit as separate



Figure 1: Site location: a. Map of Ukraine (Retrieved from: https://www.mappr.co/location/ukraine/).
b. Vilnohirsk City area (Retrieved from: https://www.mapquest.com/ua/dnipropetrovska-oblast/vilnohirsk-364473355).
c. Motronivskyi open-pit mine location, Ukraine (48.5707° N and 33.9864° E), retrieved from Google maps.

engineering and geological elements (EGE) are obtained by standard geomechanical test techniques.

The results of studies of the physical and mechanical properties of the sands of the Sarmatian layer lying at the elevation points +110.0 m, +105.0 m, and +100.0 m are presented in **Table 4**.

According to the results of engineering and geological measurements, it was determined that Sarmatian sands have variable values of the angle of internal friction and specific cohesion, which depends on the water saturation of geological layers due to the rise of groundwater level.

The slope stability calculations were carried out for 3 profiles of the eastern non-working side of the Motronivskyi open pit mine of the Malyshevske placer deposit, which are named as "Northern", "Central" and "Southern" (see **Figure 2**).

Boundary conditions for the geometry of the selected profiles of the open pit are as follows:

"Northern" – 121 m from the upper crest of the first bench to the toe (elevation +105 m), and the distance of 133 m to the protective bench. The resulting angle is 16° (to the protective bench) and 18° (to the toe).

"Central" – 127 m from the upper crest of the first bench to the toe (elevation +105 m), and the distance of 138 m to the protective bench. The resulting angle is between 18° (to the protective bench) and 20° (to the toe).

"Southern" – 143 m from the upper crest of the first bench to the toe (elevation +105 m), and the distance of 167 m to the protective bench. The resulting angle is 16° (to the protective bench) and 19° (to the toe).

Slope stability assessment for the eastern non-working side of the Motronivskyi open pit is carried out with

Table 3: Physical and mechanical properties of soils and soft sedimentary rocks

Engineering and geological elements (EGE)	Soil specific gravity γ, kN/m^3*	Specific cohesion C, kPa*	Angle of internal friction, φ, degree*	Deformation modulus E, kPa*	Poisson's ratio μ, dimensionless
EGE-1 – Soil-vegetation layer	15.5/14.0	-	-	2800 1200	0.35
EGE-2 – Hard, macroporous, brownish-yellow loams	16.0/15.8	16/7	16/14	6800 4200	0.35
EGE-3 – Rigid loams	19.7/19.5	27/14	22/18	25000 18000	0.35
EGE-4 – Soft plastic loams	19.6/19.5	22/16	18/15	20000 13000	0.35
EGE-5 – Red-brown clays	19.5/19.2	51/22	20/16	35000 20000	0.42
EGE-6 – Sands	19.8/19.0	2/0	31/12	40000 25000	0.30

* Indicators of sedimentary rock properties in natural (numerator) and water-saturated state (denominator)

Table 4: Physical and mechanical properties of Sarmatian sands

Engineering and geological elements (EGE)	Soil specific gravity γ, kN/m^3*	Specific cohesion C, kPa*	Angle of internal friction, φ, degree*	Deformation modulus E, kPa*	Poisson's ratio μ, dimensionless
Fine sand	Elevation mark +110 m				
	16.7/16.7	39/18	30/25	25000 18000	0.3
	Elevation mark +105 m				
	17.1/17.1	35/17	31/28	25000 18000	0.3
	Elevation mark +100 m				
	19.7/19.7	39/32	25/23	25000 18000	0.3

* Indicators of sedimentary rock properties in natural (numerator) and water-saturated state (denominator)

consideration of geometric parameters, physical and mechanical properties of soft sedimentary rocks.

3.2. *Slope stability assessment for selected quarry profiles*

3.2.1. "Northern" profile

The "Northern" profile of the eastern non-working side of the pit side consists of 5 benches with Quaternary deposits like loams and clays, and Sarmatian sands (see **Figure 3**). The geological layers have a slight inclination in the direction of the quarry working area. The absolute elevation mark of the day surface is +146 m, the level of the lower bench toe is +105 m. The width of the benches varies in the range of 10-28 m. The angle of inclination of the bench slopes is up to 56°.

The "Northern" profile has SRF = 1.65 under natural moisture conditions. The level of landslide hazard is low. Shear strains in the slope rock massif are insignificant: ε_{max} = 0.05-0.07 (see **Figure 4**). The layers of loam on the 2nd and 3rd benches are subjected to the greatest

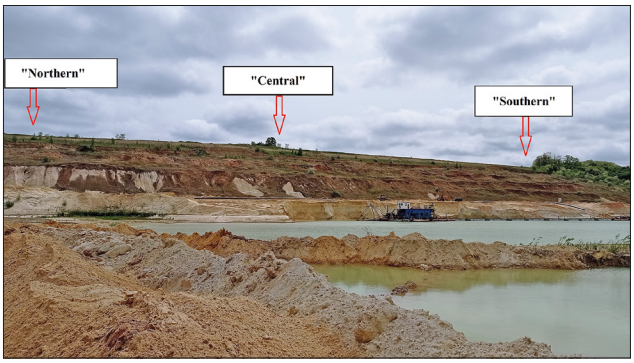


Figure 2: General view of the Eastern non-working side of the open pit with selected profiles: "Northern", "Central", "Southern"

deformations in the form of rockslide without the formation of a continuous sliding surface. Total displacements in the massif of rocks are also insignificant $U_{x\text{-}y}$ = 0.2-0.3 m, which do not pose a threat of rock displacement.

Under conditions of the slope water saturation due to atmospheric precipitation or hydrogeological factors,

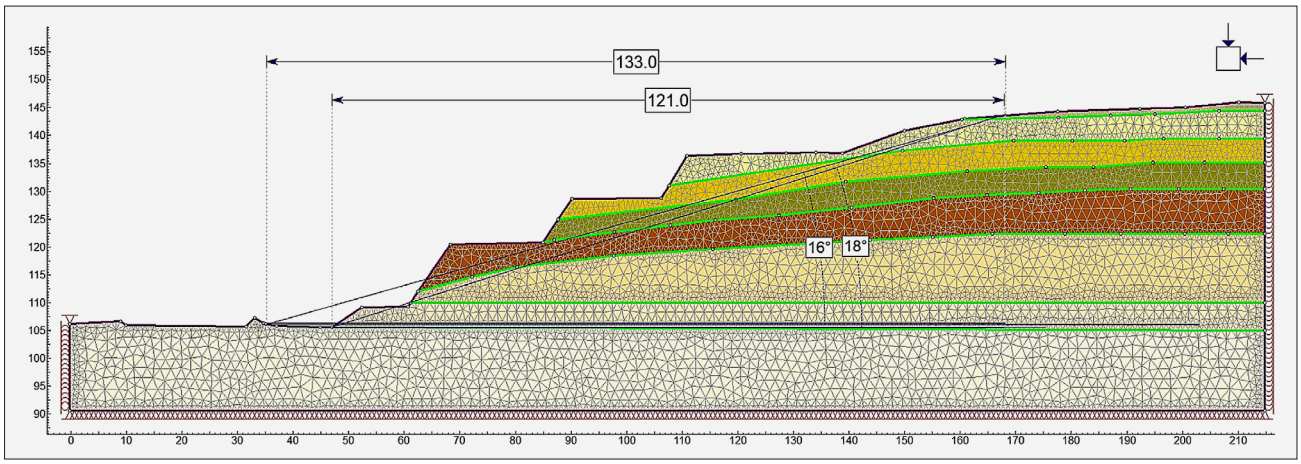


Figure 3: "Northern" profile of the eastern non-working side of the quarry

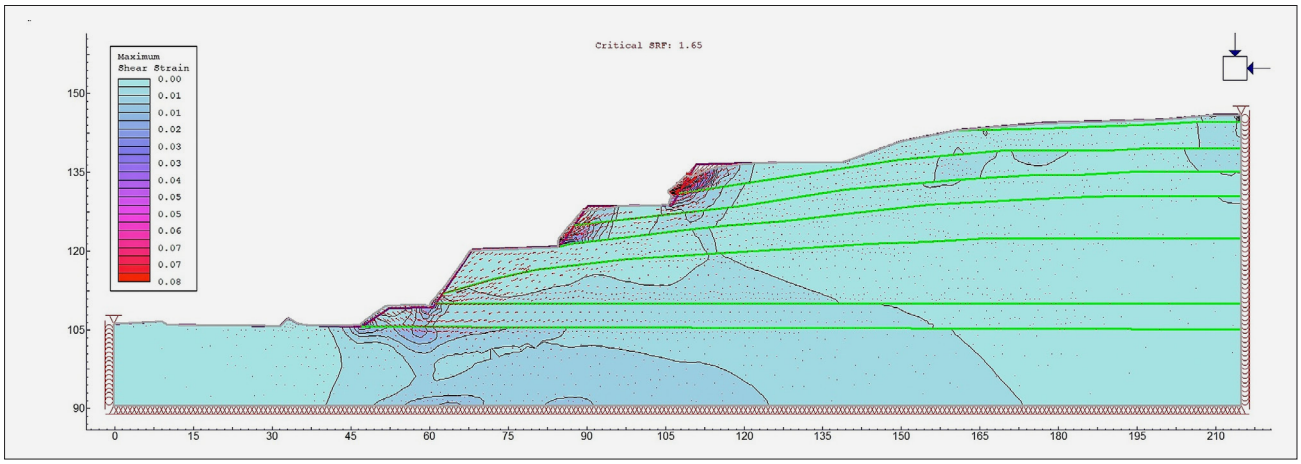


Figure 4: General shear deformations along the "Northern" profile

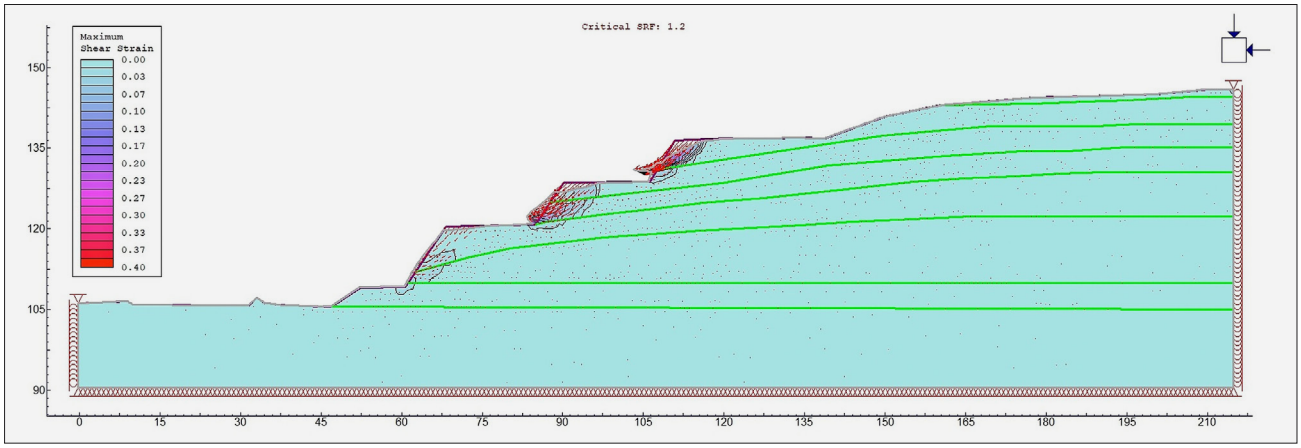


Figure 5: Shear strains in the water-saturated slope along the "Northern" profile

the strength properties of the rock massif and the stability of the pit side decrease. In the water-saturated massif SRF = 1.20. The level of landslide hazard is average.

Shear deformations in the slope massif of rocks increase and become moderate: ε_{max} = 0.23-0.37 (see **Figure 5**). The loam layers on the 2nd and 3rd benches undergo the greatest deformations in the form of landslides with the formation of local sliding surfaces. However, the landslide masses are maximally displaced by 3-6 m on the lower benches. A continuous sliding surface is not formed and the side of the quarry remains in a stable state.

Total displacements in the massif of rocks in the water-saturated massif increase to $U_{x\text{-}y}$ = 0.6-0.9 м in the form of local rockslides in 2nd and 3rd slopes. On the 4th bench, at the contact of layers of red-brown clays and

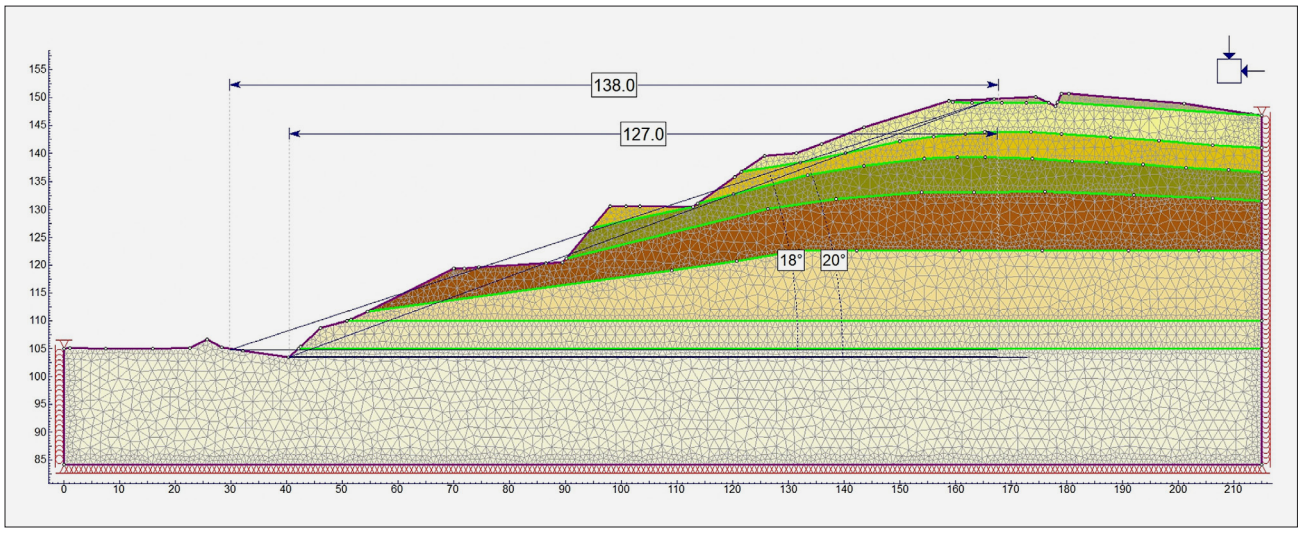


Figure 6: "Central" profile of the eastern non-working side of the quarry

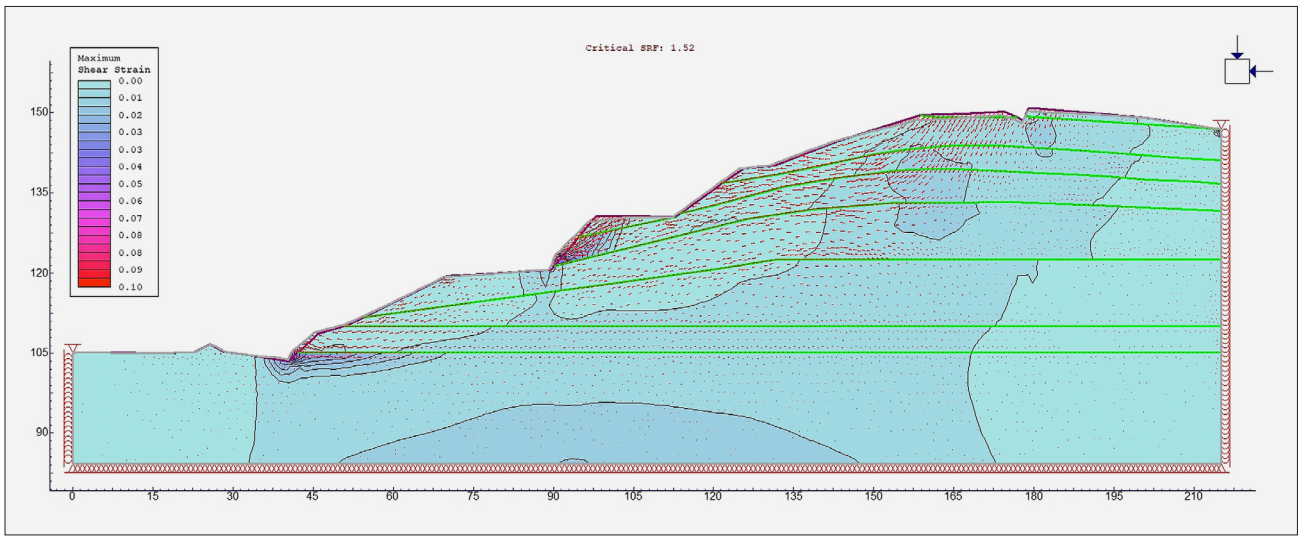


Figure 7: General shear deformations along the "Central" profile

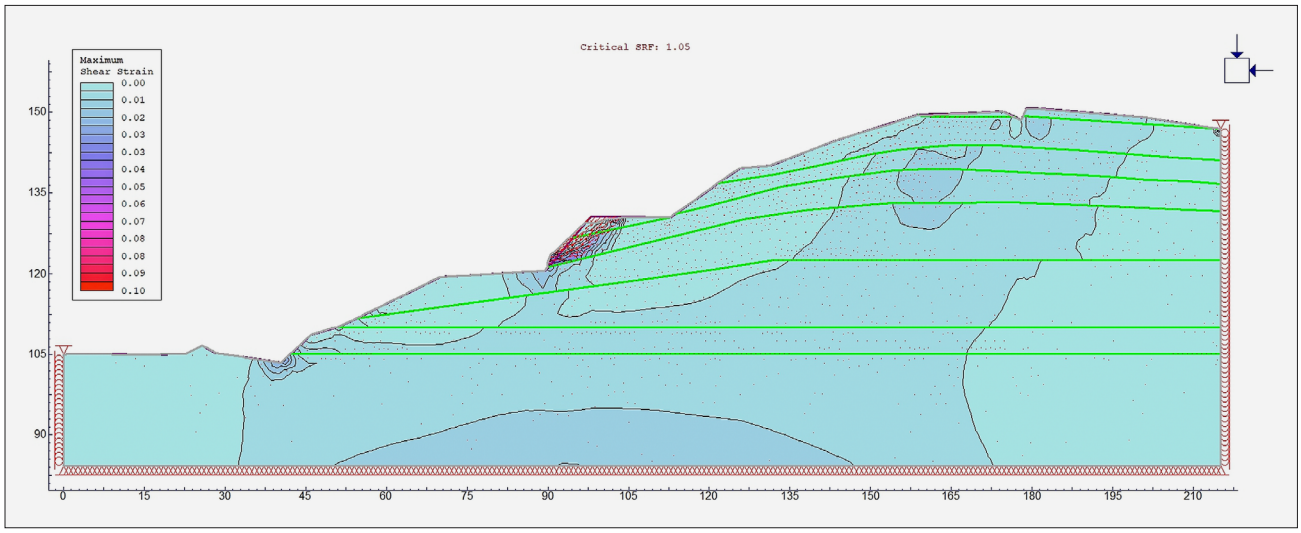


Figure 8: Shear deformations in the water-saturated massif along the "Central" profile

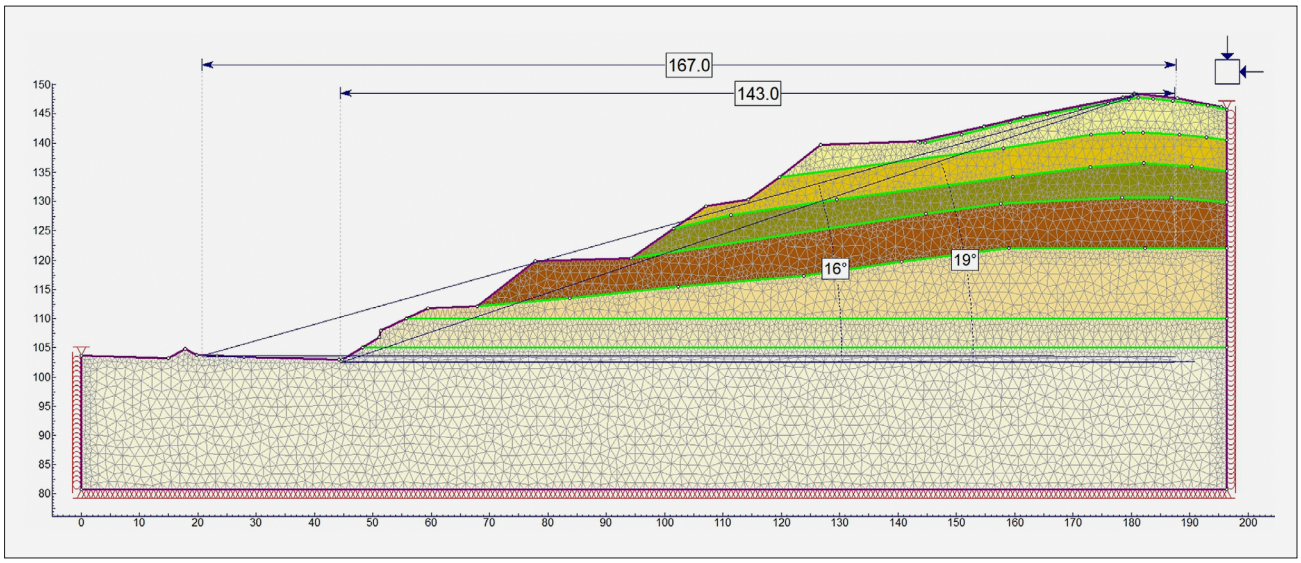


Figure 9: "Southern" profile of the eastern non-working side of the quarry

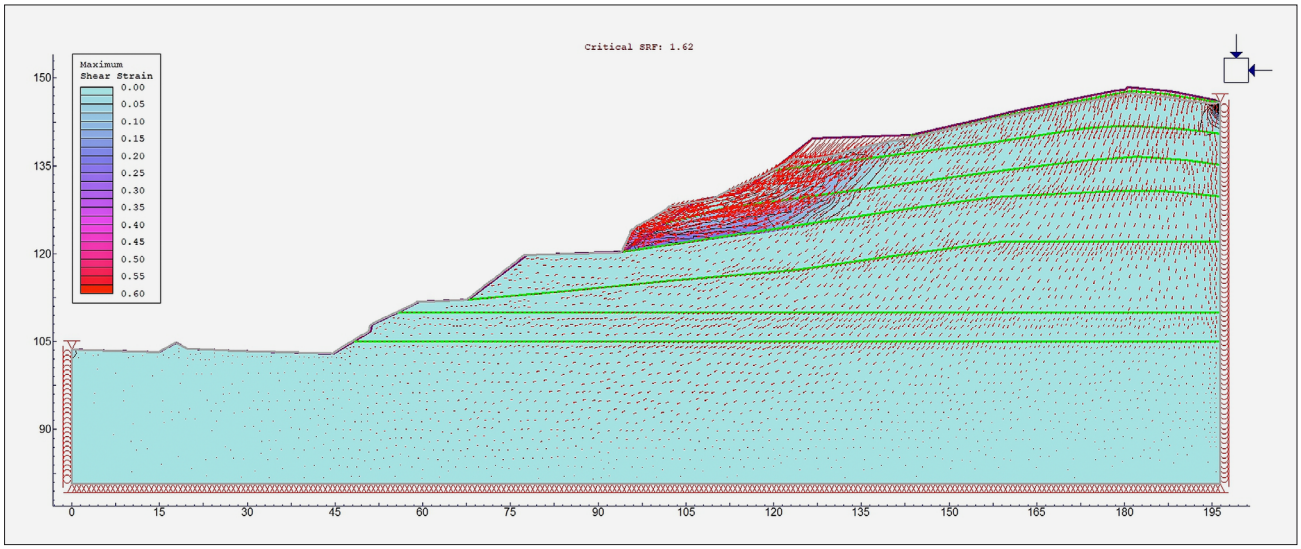


Figure 10: General shear deformations along the "Southern" profile

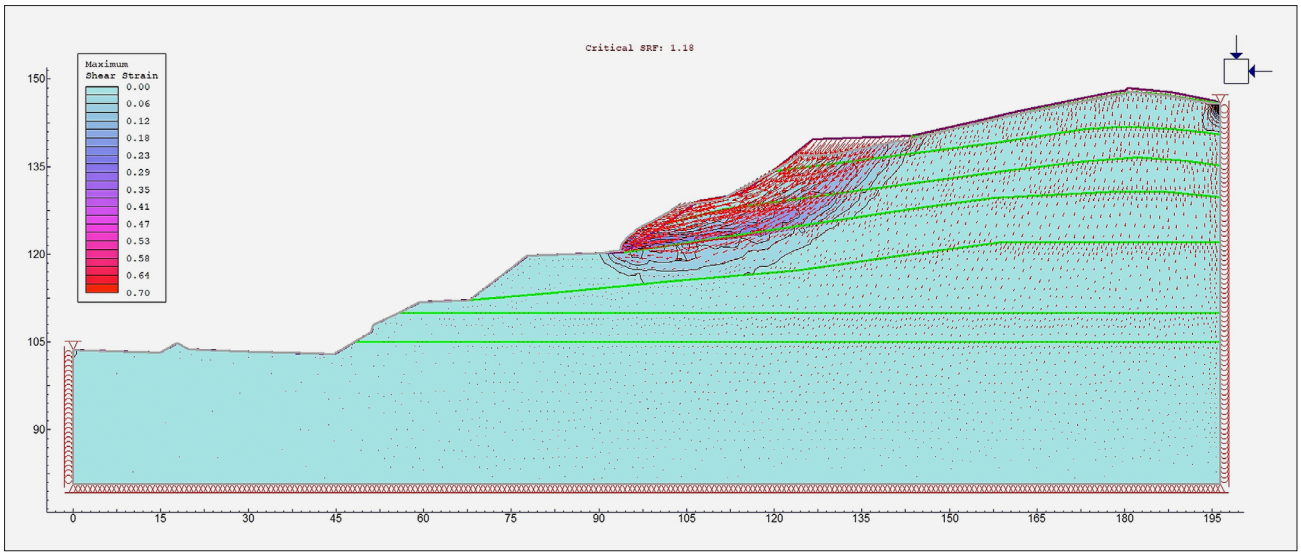


Figure 11: Shear deformations in the water-saturated slope massif along the "Southern" profile

Sarmatian sands, minor screes may occur, which do not pose a threat of landslide in the direction of the protective bench.

3.2.2. "Central" profile

The "Central" profile of the eastern non-working side of the quarry consists of 5 benches and includes Quaternary deposits of loams, clays and Sarmatian sands, the layers of which have an inclination in the direction of the mine working (see **Figure 6**).

The absolute elevation mark is +150 m, the level of the lower bench toe is +105 m. The width of the benches varies in the range of 10-28 m. The angle of inclination of the bench slopes is up to 56°.

The "Central" profile has SRF = 1.52 under conditions of natural rock mass moisture. The level of landslide hazard is low. Shear deformations in the adjacent massif of rocks are insignificant and ε_{max} = 0.07-0.10 (see **Figure 7**). The third bench undergoes landslide deformations at the contact of loams and red-brown clays without the formation of a continuous sliding surface.

The general displacements in the massif of rocks extend for the entire open pit side, but their values are insignificant and $U_{x\text{-}y}$ = 0.10-0.16 m, which does not pose a threat of a landslide.

Under conditions of water-saturated slope massif due to atmospheric precipitation or hydrogeological factors, the profile "Central" has SRF = 1.05. The level of landslide hazard is high. Shear deformations in the slope increase and become moderate: ε_{max} = 0.08-0.10 (see **Figure 8**). The 3rd bench undergoes the largest deformations in the form of landslides with the formation of a local sliding surface. However, the sliding masses can move on the lower bench 3-4 m. A solid sliding surface is not formed, and the side of the quarry remains in a stable state.

The total displacements in the massif of rocks in the water-saturated massif increase to $U_{x\text{-}y}$ = 0.08…0.13 m, however, a slight local shift in the form of a rockslide is possible only in the 3rd slope. The rest of the benches are in extremely stable condition, even under the conditions of an overmoistened massif.

3.2.3. "Southern" profile

The "Southern" profile of the eastern non-working side of the quarry side consists of 5 benches and includes layers of loams, clays and Sarmatian sands, the layers of which have a slight inclination in the direction of the mine working (see **Figure 9**). The absolute elevation mark of the day surface is +149 m, the point of the lower bench toe is +105 m. The width of benches varies in the range of 8-15 m. The angle of slopes inclination of benches is up to 45°.

The "Southern" profile has SRF = 1.62 under conditions of natural rock-mass moisture, corresponding to a low hazard level (see **Table 2**). Although localised maximum shear strains reach average-to-critical values (ε_{max} = 0.40–0.60; **Table 1**) and delineate a potential continuous sliding surface of total length 35–40 m within the loam layers, the global SRF indicates that the modelled slope remains in overall equilibrium under these boundary conditions. It means that high local strains can coexist with a globally stable SRF due to localized plasticity of soft sedimentary rocks.

Table 5: Results of the slope stability simulation of the pit side according to selected profiles

Profiles of the quarry side	Shear reduction factor of the quarry side	
	with a natural moisture	in a water-saturated rock massif
"Northern"	1.65	1.20
"Central"	1.52	1.05
"Southern"	1.62	1.18

The level of landslide hazard for the "Southern" profile is low. Shear deformations in the adjacent massif of rocks are average: ε_{max} = 0.40-0.60 (see **Figure 10**). The 2nd and 3rd benches undergo deformations, in which a continuous sliding surface can be formed as a solid surface with a total length of 35-40 m in the loam layers.

Total displacements in the slope massif along the "Southern" profile propagate almost on the entire open pit side but 2nd and 3rd benches deserve special attention, in which there is a high probability of a solid landslide body formation with significant displacements $U_{x\text{-}y}$ = 1.28-1.70 m. The lower benches remain in a relatively stable state.

Under conditions of the slope massif water saturation due to atmospheric precipitation or hydrogeological factors along the "Southern" profile, the SRF = 1.18. The level of landslide hazard is average. Shear deformations in the slope increase from medium to significant: ε_{max} = 0.47-0.70 (see **Figure 11**). The largest deformations remain in the 2nd and 3rd benches in the loam layers in the form of landslides with the formation of a continuous sliding surface. The rest of the benches remain in a relatively stable state.

Total displacements in the water-saturated slope massif increase to the values of $U_{x\text{-}y}$ = 1.5-3.0 m, which corresponds to the stage of a large-scale landslide up to 40 m along the quarry side. The rest of the benches are in boundary stable condition.

The results of numerical simulation of the open-pit stability are summarized in **Table 5**. Thus, the "Central" profile is the most prone to landslides, in which there is a threat of a large-scale landslide that can capture the 2nd and 3rd benches of the pit side. In general, the eastern non-working side of the Motronivskyi quarry is in a stable state, which depends mainly on the slope geometry and the rock water saturation effects.

A protective bench with a height of 2 m along the whole pit side was filled up as an anti-landslide measure, to prevent the mining area from sliding rock mass under

conditions of water saturation soft sedimentary rocks. The implementation of additional anti-landslide measures on the studied site of the eastern non-working side of the Motronivskyi quarry is not required, except for constant hydrogeological monitoring.

4. Discussion

The reduction in SRF after "water saturation" in all investigated slopes is consistent with classical laws of soil mechanics. Rainfall infiltration and groundwater rise reduce matric suction, increase pore-water pressure, and reduce apparent cohesion and frictional resistance of fine and mixed sediments. This behaviour is reported in many experimental and numerical studies and is frequently the dominant mechanism for rainfall-triggered instability in open-pit and natural slopes (**Fredlund & Rahardjo, 1993; Li et al., 2024**).

The drop from 1.65 to 1.20 in the slope of "Northern" profile is substantial: it represents the decrease from a low to average level of landslide hazard in the slope when additional destabilising effects of further water saturation could provoke larger failures. Strains ε_{max} rising from ~ 0.05-0.07 to ~ 0.23-0.37 (a ~4-6× increase) indicates a transition from mostly elastic with small-strain response toward significant inelastic deformation and localized yielding in the loam and clay layers of benches 2-3. In many numerical and field studies, small strains (order 10^{-3}-10^{-2}) correspond to elastic behaviour with negligible permanent displacement; larger shear strains (order 10^{-2}-10^{-1} and above) mark plastic yielding, strain-softening or development of local failure zones (**Coetsee et al. 2020**).

Thus observed strain growth is a clear numerical signature of incipient local failure concentrated on weaker benches (2 and 3). Displacements *U* growing from 0.2-0.3 m to 0.6-0.9 m is consistent with field observations and numerical simulations of rainfall-induced shallow slides and bench-scale sloughing in open pits. Many case studies show that rainfall or pore-pressure increase leads to local displacements on the order of decimetres to metres depending on the geometry and material (**Tang et al., 2024; Zhang et al., 2024**). The magnitude fits the class of local bench failures rather than full-height slope collapses which are typically associated with through-going slip surfaces in much larger volumes.

The modelling shows the formation of local sliding surfaces in loam layers of 2nd and 3rd benches but not a continuous basal slip. The weaker loam layers are discontinuous or thin and occur at bench levels where localized saturation and loss of suction produce weak, shallow slip planes (typical in layered placer or colluvial deposits. The clay or low-permeability interbeds may impede full-depth saturation of the entire slope, producing perched zones that drive bench-scale failures rather than deep basal slides. Bench geometry (bench widths 10-28 m, steep bench face angles up to 56°) promotes shallow sloughing at the face while the overall mass remains intact until a continuous slip plane forms. Similar patterns of shallow bench sloughing and local translational slides under wetting are well documented in open-pit and quarry case studies (**Tang et al., 2024; Chen et al., 2023**).

The "Central" profile with SRF = 1.52 under natural moisture indicates a low level of landslide hazard in the slope with small shear strains and deformations. Under the water-saturated condition SRF falls to 1.05, i.e. almost to the failure threshold (SRF ≈ 1.0). This large reduction with ≈ 30% of relative drop is typical of variably saturated slopes where water saturation diminishes matric suction and raises pore pressures, thereby reducing apparent cohesion and effective stress (**Fredlund & Rahardjo, 1993**).

Shear strains values ε_{max} (0.07-0.10) localised at bench 3 imply small-to-moderate plastic strains concentrated at contacts between loams and clays on bench 3. Numerically, such strains indicate incipient to developing local yielding rather than wholesale deep-seated failure. This matches many open-pit case studies where weak interbeds or discontinuous loam layers produce local translational or bench-scale slides before the formation of a continuous basal slip surface (**Moradi et al., 2024; Chen et al., 2023**). Displacement magnitudes remain modest (0.08-0.16 m) that are consistent with local sloughing, bench-scale movement or limited rockslide blocks, not with full-height slope collapse. Such decimetre-scale movements under wetting are typical for layered, weakly consolidated quarry faces (**Tang et al., 2024; Li et al., 2024**).

The observed behaviour is due to the loss of matric suction with increasing pore pressure. Rainfall or hydraulic recharge reduces suction in the loam and sand units and raises pore pressures near the loam-clay contact; effective stress reduces and shear strength drops (**Yeh et al., 2021**). This single mechanism explains the SRF fall in the water-saturated scenario. The "Central" profile contains loams and red-brown clays, so perched water above clay lenses produces lateral seepage and concentration of pore pressure at the bench contacts (a common cause of localized planar slides in open pits). Bench 3 is the most affected because geometry and stratigraphy favour perched accumulation there. This mechanism is discussed in many slope case studies and numerical analyses. Since the result shows localised sliding rather than through-going basal failure, the clay layer(s) and stratigraphic arrangement likely prevented complete saturation of the deeper base of the slope, hence failure remains local. Similar behaviour is reported when permeability contrasts impede downward percolation and instead produce bench-scale instability (**Yeh et al., 2021; Huang et al., 2025**).

For the "Southern" profile the SRF = 1.62 indicates a low level of landslide hazard but vulnerable to changes because the slope already shows substantial shear defor-

mation indices (ε_{max} up to 0.60). The drop to SRF = 1.18 under increased saturation shows that the slope is hydrologically sensitive: moderate additional pore pressure increase or further weakening would approach failure (SRF ≈ 1). This pattern presents a slope with a margin under dry conditions that is substantially reduced by wetting in variably saturated, layered sediments (**Fredlund & Rahardjo, 1993; Li et al., 2024**).

High shear deformation (ε_{max} ≈ 0.40-0.70) magnitudes are substantial and indicate the development of broad plastic zones and strain localization. In practical terms, ε_{max} = 0.4-0.7 and correspond to major inelastic deformation and the formation of a coherent sliding mass in the loam layers of benches 2-3. Such behaviour predicts an already developing and potentially mobile slide mass. Similar strain indicators precede large bench slides in documented mine case histories (**Tang et al., 2024; Chen et al., 2023**). Displacements of U_{x-y} ≈ 1.28-3.0 m indicate large shallow and bench-scale landsliding. In an open-pit setting such movement typically results in bench collapse, loss of integrity, infrastructure damage at the toe, and serious safety risks. Many HM studies and field cases report similar metre-scale displacements where perched saturation and lateral seepage produce planar slides along weak interbeds (**Li et al., 2024**). The formation of a continuous sliding surface of 35-40 m length across benches 2-3 represents a coherent sliding body, not merely shallow sloughing. That the model predicts this under both natural and water-saturated states implies the geometry and stratigraphy are predisposed to translational sliding: thin, laterally continuous loam layers with low strength that dip unfavorably and receive concentrated infiltration or perched flow. Even though SRF under "natural" conditions exceeds 1.5, the combination of already large shear strains and the existence of a continuous weak layer make the "Southern" profile intrinsically vulnerable; additional wetting pushes it toward a large-scale bench slide.

Thus, the "Central" profile is most critical (SRF=1.05 when saturated), requiring the most vigilant water management and monitoring.

5. Conclusions

Slope stability in open-pit placer deposits composed of soft, moisture-sensitive sedimentary rocks is primarily a hydrology-controlled problem interconnected with rainfall infiltration, perched groundwater, and increases in pore-water pressure that causes instability phenomena. The results of slope stability assessment for the eastern non-working side of the Motronivskyi open pit of Malyshevske placer deposit allowed us to make the following suggestions.

1. The main factors of stability and sliding risk of benches and sides of the quarry are the geometry of slopes and benches, physical and mechanical properties of soft sedimentary rocks in natural conditions and the water-saturated massif. The slope stability and landslide hazard assessment for the quarry sides was carried out based on the SRF calculated values and proposed landslide hazard scale.

2. For the "Northern" profile under the conditions of natural soil moisture SRF = 1.65. The level of landslide hazard is low. The total displacements in the massif of rocks are also insignificant U_{x-y} = 0.2-0.3 m, which do not pose a rockslide threat. In the water-saturated massif the SRF = 1.20. The level of landslide hazard is average. General displacements in the rock massif in the water-saturated condition increase to the values of U_{x-y} = 0.6-0.9 m in the form of overflows and landslides in slopes of 2nd and 3rd benches but do not pose a landslide threat in the direction of the protective bench.

3. For the "Central" profile under the conditions of natural soil moisture SRF = 1.52. The level of landslide hazard is low. The 3rd bench undergoes deformations in the form of overflows at the contact of loams and red-brown clays without the formation of a continuous sliding surface in the bench. The total displacements in the massif of rocks cover almost the entire massif, but their values are small U_{x-y} = 0.10-0.16 m. Under water saturation conditions along the "Central" profile, the SRF = 1.05. The level of landslide hazard is high. Total displacements in in the water-saturated massif are U_{x-y} = 0.08-0.13 m, however, a continuous sliding surface is not formed, and the quarry side remains in a stable state.

4. For the "Southern" profile under the conditions of natural soil moisture SRF = 1.62. The level of landslide hazard is low. The 2nd and 3rd benches undergo deformations, in which a continuous sliding surface can be formed with a total length of the sliding body up to 35-40 m in the loam layers. Total displacements in the massif are U_{x-y} = 1.28-1.70 m. In the water-saturated massif along the "Southern" profile the SRF = 1.18. The level of landslide hazard is average. The total displacements in the rock massif in the water-saturated massif increase to the values of U_{x-y} = 1.5-3.0 m which corresponds to the stage of a large-scale displacement up to 40 m across the quarry side. The rest of the benches are in extremely stable condition.

5. Thus, the eastern non-working side of the Motronivskyi quarry is in a stable state, which depends mainly on the geometry parameters of the benches and the water saturation of the rock massif. The most landslide-prone is the "Central" profile which has a threat of a large-scale landslide on the 2nd and 3rd benches of the pit wall.

A protective bench with a height of 2 m along the whole pit side was filled up as an anti-landslide measure, to prevent the mining area from sliding rock mass under conditions of water saturation soft sedimentary rocks.

Therefore, the study demonstrates that transient saturation is the primary factor reducing the factor of safety from stable (1.52-1.65) to critical (1.05-1.20) levels in this placer deposit setting.

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SAŽETAK

Numeričko modeliranje stabilnosti kosina u nanosnome ležištu: studija slučaja površinskoga kopa Motronivsk, Ukrajina

Površinska eksploatacija nanosnih ležišta u slojevitim sedimentima osjetljivima na saturaciju vodom zahtijeva projektiranje kosina koje izričito uzima u obzir prolazne hidrološke uvjete. U radu se procjenjuje stabilnost neaktivnoga istočnog boka površinskoga kopa Motronivsk, koji se nalazi u ležištu cirkon-rutil-ilmenitnoga nanosnog tipa Mališevske (Vilnohirsk, Ukrajina), u kojemu prevladavaju ilovače, gline i sarmatski pijesci. Istraživanje objedinjuje podatke inženjerskogeoloških istraživanja sa stratigrafskim odnosima i laboratorijski određenim parametrima čvrstoće za profile „Sjeverni", „Središnji" i „Južni" bok kopa, uzimajući u obzir njihovu geometriju i hidrogeološke uvjete. Numeričke analize provedene su metodom konačnih elemenata u programu Phase2 (Rocscience Inc.), primjenom Mohr-Coulombova modela te metode redukcije posmične čvrstoće za određivanje koeficijenta sigurnosti, uz pripadajuću klasifikaciju razina opasnosti od klizišta. U uvjetima prirodne vlažnosti dobivene vrijednosti koeficijenta sigurnosti upućuju na općenito stabilno stanje kosina: „Sjeverni" – 1,65, „Središnji" – 1,52 i „Južni" – 1,62. U slučaju zasićenja stijenske mase vodom uslijed oborina ili porasta razine podzemne vode koeficijenti sigurnosti smanjuju se na 1,20, 1,05 i 1,18. Analiza posmičnih deformacija i ukupnih pomaka u stijenskoj masi pokazuje da vlaženje naglo smanjuje efektivnu čvrstoću te uzrokuje prijelaz mehanizama nestabilnosti s plitkih površinskih odrona na klizišta cijele etaže kopa. Dobiveni rezultati mogu poslužiti kao podloga za projektiranje radnih kosina i planiranje odvodnjavanja u sličnim uvjetima eksploatacije ležišta nanosnoga tipa.

Ključne riječi:
površinski kop, nanosno ležište, stabilnost kosina, numerička analiza, koeficijent sigurnosti

Author's contribution

Oleksandr Kovrov (Professor): conceptualization, investigation and numerical simulation, writing – original draft. **Borys Sobko** (Professor): data curation, formal analysis, resources, writing – review & editing
All authors have read and agreed to the published version of the manuscript.