

Review Article

Economic assessment of the impact of rock mass water content on open-pit slope stability and mining safety

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ABSTRACT

The aim of this study is a comprehensive analysis of the effect of rock mass water saturation on its geomechanical condition, open-pit wall stability, and mining safety. The research methods include theoretical analysis, systematisation of scientific literature, and analytical methods of rock mechanics. The paper examines the mechanism by which groundwater and surface water impact the stress-strain state of the rock mass, including the generation of pore and hydrostatic pressure, hydraulic wedging of fractures, and the deterioration of physical and mechanical properties under water saturation. Based on Terzaghi's effective stress principle and the Mohr–Coulomb strength criterion, it is shown that an increase in pore pressure reduces the effective normal stress component, cohesion, and friction angle, thereby degrading slope stability. It is established that an increasing degree of water saturation reduces the slope stability factor from 1.40–1.55 (for a dry mass) to 0.90–1.10 (for a heavily saturated mass), which corresponds to a transition to a limiting or unstable state. The influence of water saturation on the blast energy transfer mechanism in contour blasting is also considered: the presence of water in blast holes increases the depth of the disturbed zone from 0.5–1.0 m to 1.0–1.8 m and the fracture radius from 1.2–1.6 m to 1.5–2.3 m. The results substantiate the need for special geomechanical and technological solutions for mining operations in waterlogged conditions.

Keywords: Contour blasting, geomechanics, open-pit wall stability, pore pressure, rock mass water saturation, stability factor, Terzaghi principle

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INTRODUCTION

The development of mineral deposits by open-pit mining is accompanied by a constant change in the stress-strain state of the rock mass. This change is caused by the formation of the mined-out space, the redistribution of natural stresses, and alterations in the geomechanical conditions of the rock strata.^[1] As mining operations progress, the established equilibrium of the rock mass is disturbed, its stress state is restructured, zones of stress concentration appear, and man-made fractures and areas of potential stability loss are formed.

The water saturation of the rock mass has a significant impact on the condition of benches and pit walls.^[2] Groundwater and surface water affect the physical and mechanical properties

of rocks, reducing their strength and creating conditions for the development of deformation processes. The influence of water manifests not only in a change in the strength characteristics of the rock mass but also in the activation of filtration processes, a reduction in effective stresses, and a deterioration of slope stability. Collectively, these factors have a significant impact on the safety and efficiency of open-pit mining operations.

The main ways in which water saturation influences the geomechanical state of the rock mass are shown in Figure 1.^[3]

Purpose of the Study

The objective of this study is a comprehensive analysis of the mechanism by which the water content of a rock

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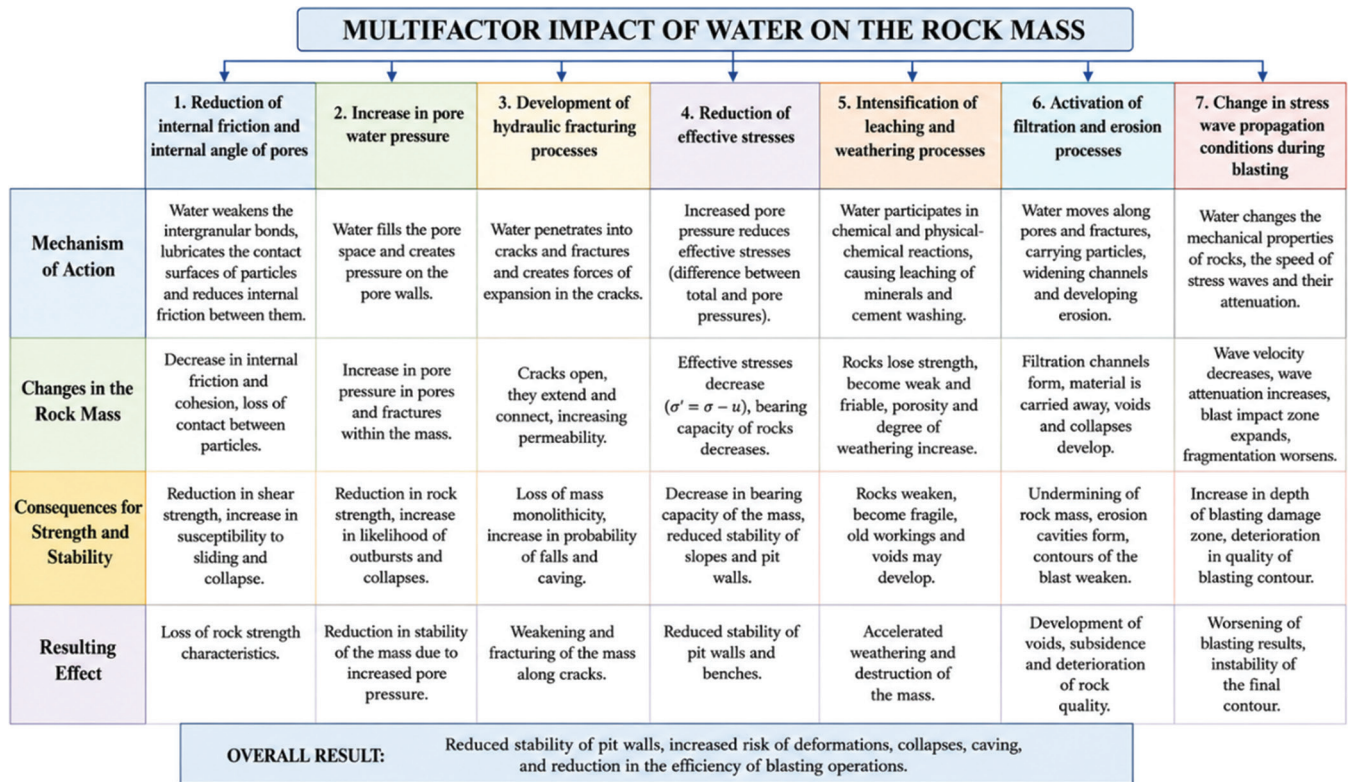


Figure 1: A diagram of the multifactorial influence of water content on the geomechanical state of the rock mass and the stability of pit walls

mass influences its geomechanical state, pit wall stability, and the safety of open-pit mining operations. The research objectives include: analyzing the factors that contribute to the waterlogging of the pit rock mass; assessing the influence of pore and hydrostatic pressure on the stress-strain state of the rock; analyzing the change in the stability factor under water saturation; and studying the specifics of blast energy transfer in waterlogged conditions.

Problem Discussion

The water saturation of the rock mass is determined by a combination of natural and anthropogenic factors that variously affect the hydrogeological state of the open-pit mine. The water saturation of an open-pit mine rock mass is governed by several main factors, each with its own source and mode of impact. Atmospheric precipitation, in the form of infiltrating rainfall and snowmelt, moistens the upper part of the rock mass. Groundwater, originating from aquifers, raises the pore water pressure within the mass. Tectonic discontinuities such as fractures and faults increase the hydraulic conductivity of the rocks. Anthropogenic fractures, produced by drilling and blasting operations, create seepage (filtration) pathways through which water can migrate. Surface water bodies, including rivers, streams, and reservoirs, cause inundation of the slopes and saturation of their toe. Finally, process water, associated with irrigation

and dust suppression, contributes additional saturation of the rock mass.^[4]

The most complex hydrogeological conditions form in fractured and tectonically disturbed rock masses.^[5] In such conditions, groundwater movement occurs predominantly through a system of natural fractures, lithological contacts, and fault zones, which promotes localized moisture accumulation, an increase in the degree of rock water saturation, and a reduction in the stability of the pit walls.

The degree to which water saturation affects the stability of the open-pit mine mass is largely determined by the structural state of the rocks and the intensity of their fracturing.^[6] The degree of rock mass fracturing largely determines both the way groundwater seeps through the mass and its overall stability. When fracturing is low and the spacing between fractures exceeds 1.0 m, seepage remains localized, and the rock mass retains high stability. With a moderate degree of fracturing, where fracture spacing ranges from 0.3 to 1.0 m, seepage becomes well developed, and stability drops to a moderate level. At a high degree of fracturing, with spacing of 0.1 to 0.3 m, seepage turns intensive, and the stability of the rock mass is noticeably reduced. Finally, under very high fracturing, where fracture spacing is <0.1 m, seepage becomes pervasive throughout the mass and its stability falls to a low level. As

can be seen, an increase in the degree of fracturing of the rock mass is accompanied by an increase in water permeability and a decrease in its stability.^[7]

MATERIALS AND METHODS

The object of this study was the processes of change in the geomechanical state of the pit wall rock mass under various degrees of water saturation characteristic of deep open-pit mine conditions. The study was carried out in four sequential stages.

The first stage involved an analysis of published results from 2021 to 2025 on field observations and laboratory studies concerning changes in the physical and mechanical properties of water-saturated rocks. The analysis used data on granodiorites, diorites, syenites, limestones, and argillites.

In the second stage, a theoretical analysis of the influence of pore pressure changes on the stress-strain state of the rock mass was performed using Terzaghi's principle of effective stress and the Mohr–Coulomb strength criterion. These relationships were used to qualitatively explain the mechanism by which the stability of the rock mass decreases as its degree of water saturation increases. Numerical calculations for a specific open-pit mine were not performed as part of this work.

In the third stage, an analysis of published research results was conducted on the change in the slope stability factor under various hydrogeological conditions.

In the fourth stage, a comparative analysis was performed on published experimental studies of controlled blasting in dry and water-saturated rock masses, with an assessment of the depth of the damaged zone and the fracture radius. The obtained results are systematized in the form of tables and diagrams.

To theoretically describe the influence of pore pressure on the stress-strain state of the rock mass, Terzaghi's effective stress principle is used:^[8]

$$\sigma' = \sigma - u, \quad (1)$$

where σ' – is the effective stress, MPa; σ – is the total stress, MPa; and u – is the pore water pressure, MPa.

To theoretically analyze the change in shear strength, the Mohr–Coulomb strength criterion is used:^[8]

$$\tau = c + (\sigma - u) \tan \varphi \quad (2)$$

where τ – is the shear strength, MPa; c – is the rock cohesion, MPa; and φ – is the angle of internal friction, deg.

Hydrostatic pressure is described by the well-known expression:^[8]

$$P_w = \gamma_w h, \quad (3)$$

where P_w – is the water pressure, MPa; γ_w – is the specific weight of water, kN/m³; and h – is the height of the water column, m.

To characterize slope stability, a stability coefficient is used, defined by the expression:^[8]

$$\hat{E}_{stab} = \frac{\Sigma R}{\Sigma T} \quad (4)$$

where ΣR – is the sum of the retaining forces preventing the displacement of the rock mass; ΣT – is the sum of the shearing forces causing a loss of stability.

In this study, the above relationships are used not to perform engineering calculations for a specific site, but to provide a theoretical basis for the mechanisms of how water content affects the geomechanical state of a rock mass. The further discussion is based on a comparison of results published in contemporary Russian and international studies.

RESULTS AND DISCUSSION

Based on an analysis of published experimental data and theoretical relationships,^[1-6] it was established that an increase in the degree of water saturation is accompanied by a decrease in effective stresses in the near-contour zone of the rock mass. An increase in pore pressure reduces the resistance of rocks to shear deformation, which deteriorates slope stability.

The penetration of water into the pore space and fracture system alters the stress state of the rock mass by generating pore pressure. An increase in water pressure within the pore space and fracture system leads to a redistribution of stresses and a reduction in their effective component, which is borne by the rock skeleton. As a result, the load-bearing capacity of the rock mass decreases, its resistance to shear deformation diminishes, and the probability of stability loss in the near-contour zones increases.

An increase in pore pressure leads to a decrease in the effective normal stress component, which determines the shear stability of the rock mass. One of the main consequences of water saturation is the deterioration of the physical and mechanical properties of the rocks. To illustrate the nature of the change in strength characteristics, Table 1 provides a summary of published experimental data presented in works.^[9-12]

Table 1: Change in rock strength characteristics upon water saturation

Rock	Dry strength, MPa	Water-saturated strength, MPa	Strength reduction, %
Granodiorite	160–180	130–150	10–18
Diorite	140–170	115–140	12–20
Syenite	120–150	95–120	15–22
Limestone	80–120	55–90	20–35
Argillite	50–80	25–45	35–50

It should be noted that the given values are generalized ranges obtained by various authors for rocks of similar lithological composition. The specific values depend on the mineralogical composition of the rocks, the degree of fracturing, water saturation, and the testing conditions.

As can be seen in Table 1, sedimentary and argillaceous rocks exhibit the greatest sensitivity to the effects of water. Igneous rocks are also subject to a noticeable decrease in strength properties during prolonged water saturation.

Hydrostatic pressure, which arises in pores, fractures, and structurally weakened zones of rocks, has a significant influence on the stability of water-saturated rock masses.^[10] Hydrostatic pressure increases in proportion to the height of the water column. In the conditions of deep open-pit mines, this effect is significantly amplified due to the increasing depth of excavation and the intersection of aquifers. The effect of water on the geomechanical state of rocks is sequential in nature [Figure 2].^[1-3]

To assess the influence of water saturation on slope stability, a generalization of published research results^[11-14] concerning the change in the stability factor under varying degrees of rock mass water content was performed. The summary data are presented in Table 2.

As can be seen from Table 2, an increase in the degree of water saturation leads to a successive decrease in the slope stability factor. The operational practice of deep open-pit mines shows that an increase in the water saturation of the rock mass can reduce the stability factor by 15–40%.^[11-14] A decrease in the stability factor, from a geomechanical point of view, indicates a transition of the near-contour rock mass from a stable to a limit and unstable state, accompanied by scree, collapses, and landslides.

The influence of water saturation is of particular importance in the contour blasting of boreholes.

In water-saturated conditions, the presence of water in boreholes, pores, and natural fractures ensures a more efficient

Table 2: Influence of the degree of water saturation on the slope stability factor

Degree of water saturation	Stability factor
Dry rock mass	1.40–1.55
Low water saturation	1.25–1.40
Medium water saturation	1.10–1.25
High water saturation	0.90–1.10

transfer of blast energy to the surrounding rock mass, as water is significantly less compressible than air.^[15]

Table 3 presents a summary of published results from experimental studies on the influence of water saturation on rock mass failure parameters during contour blasting.^[13-16]

The presented ranges reflect the results of various experimental studies and are provided for a comparative assessment of how water content influences the rock mass failure parameters. They are not the results of our own experimental research.

Therefore, when designing contour blasting parameters in water-saturated conditions, it is necessary to regulate the distribution of blast energy and limit the depth of the man-made impact, which can be achieved using combined inert stemming.^[16]

Economic consequences of reduced open-pit wall stability. Water saturation of the rock mass has a complex effect not only on the geomechanical state of the near-wall zone but also on the economic performance of the mining enterprise. A decrease in slope stability is accompanied by an increased probability of deformations, spalling, and local collapses, which leads to higher operating costs, lower mining productivity, and an increased cost of mineral extraction. Therefore, assessing the economic consequences of deteriorating open-pit wall stability is an important stage in selecting rational measures to manage the hydrogeological regime of the mine field.

Economic damage from reduced slope stability consists of several interconnected components, including the costs of rectifying the consequences of deformations, restoring process infrastructure, organizing additional dewatering and drainage measures, as well as losses caused by forced equipment downtime and reduced production volumes. In the general case, the total economic damage can be represented as follows:^[17]

$$U_{\Sigma} = U_{res} + U_{dt} + U_{dw} + U_{ti} + U_{di} \quad (5)$$

where U_{res} – is the cost of restoring damaged sections of pit walls and benches, in monetary units; U_{dt} – is the loss due to mining equipment downtime, in monetary units; U_{dw} – is the cost of pumping and drainage of the pit field, in monetary units; U_{ti} – is the cost of restoring the pit's transport infrastructure,

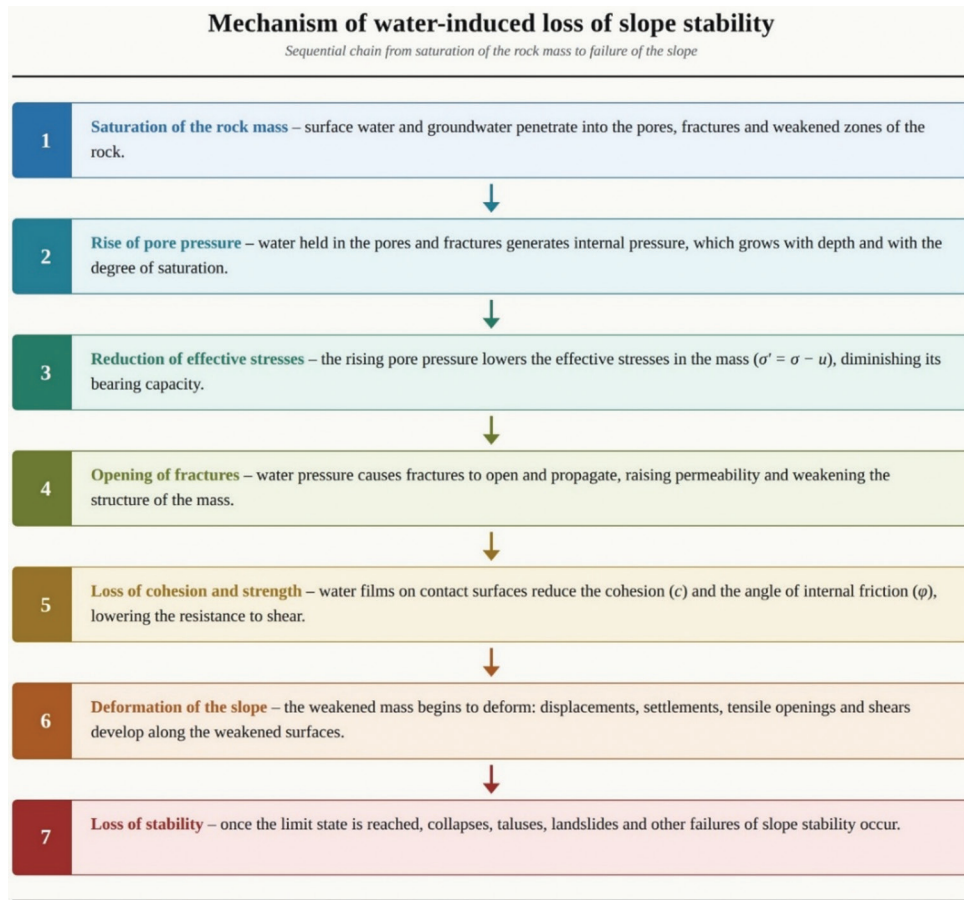


Figure 2: A diagram of the mechanism by which water content influences the geomechanical state of a rock mass, developed by the authors based on the analysis of^[1-3]

Table 3: Influence of water saturation on rock mass failure parameters during contour blasting

Parameter	Dry rock mass	Water-saturated rock mass
Depth of the disturbed zone, m	0.5–1.0	1.0–1.8
Fracture radius, m	1.2–1.6	1.5–2.3
Backbreak	Low	Increased
Stability of the perimeter rock mass	High	Reduced
Probability of spalling	Low	High

in monetary units; U_{dil} – is the economic loss caused by ore dilution and reduced extraction volumes, in monetary units.

It follows from expression (5) that a reduction in slope stability affects virtually all main elements of the production process. The magnitude of each component is determined by the specific mining-geological and hydrogeological conditions of the deposit, the mining depth, the scale of deformations, and the adopted open-pit mining technology.

The most significant losses are those associated with the disruption of normal quarry operations. If signs of stability loss appear, drilling, blasting, excavation, and transport activities are temporarily suspended until an engineering survey of the hazardous area is completed. The economic damage from equipment downtime can be estimated using the following expression:^[17]

$$U_d = C_h \cdot T_d \quad (6)$$

where C_h – is the average cost per hour of operation for the mining and transport equipment complex, c.u./h; T_d – is the total duration of forced downtime, h.

Furthermore, economic efficiency is significantly impacted by the need to perform additional mining work after rockfalls and local collapses. Clearing work sites and restoring haul roads requires repeated excavation and transport of the rock mass, which leads to an increase in the consumption of fuel, electricity, and operating materials. The additional costs can be determined as follows:^[17]

$$U_a = V_a \cdot C_m, \quad (7)$$

where V_a – is the volume of additional mining work, m^3 ; C_m – is the unit cost of excavating and transporting 1 m^3 of rock mass, c.u./ m^3 .

Under conditions of high-water content, a significant share of operating expenses comes from measures to control the hydrogeological regime of the open-pit mine. These include operating pumping stations, installing surface and deep drainage systems, drilling dewatering wells, and conducting hydrogeological monitoring. Despite the increase in current costs, implementing these measures makes it possible to significantly reduce the likelihood of emergency situations and lessen the total economic damage.

The greatest impact on the company's economics is the need to change the open-pit parameters when slope stability is reduced. A decrease in the design slope angle leads to an increase in the stripping ratio and a growth in the volume of overburden removal. This is accompanied by an increase in costs for drilling, blasting, loading, hauling, and dumping of waste rock, which directly affects the production cost of the mineral.

Additional losses arise from the deterioration in the quality of the extracted ore. The development of deformations is accompanied by the mixing of the mineral with waste rock, an increase in dilution, and a loss of reserves. As a result, the volume of rock mass to be processed increases, the content of the valuable component decreases, and the costs of crushing, grinding, and concentration rise. Consequently, a deterioration in the stability of the pit wall rock mass leads not only to an increase in current operating costs but also to a decrease in the economic return of the entire production complex.

A reduction in the stability of open-pit walls produces a chain of operational and economic consequences across the whole production process. Local scree and slope failures require the clearing of work areas and re-excavation of the collapsed rock mass, which increases the operating costs of mining. Damage to transportation routes calls for the restoration of roads, berms, and drainage facilities, adding to the costs of infrastructure repair and maintenance. Forced equipment downtime, caused by the stoppage of drills, excavators, and dump trucks, lowers productivity and drives up mining costs. A reduction of slope angles increases the volume of stripping operations, which in turn raises the stripping ratio and the overall mine development costs. Dilution and loss of the mineral, resulting from a decline in the quality of the extracted ore, increase processing costs and reduce profit. The increased water content of the rock mass necessitates the organization of water removal and drainage, thereby raising the costs of dewatering and engineering protection. Finally, enhanced geomechanical monitoring, involving geodetic surveying and instrumental control, entails

additional operating expenses. This summary was compiled based on an analysis of works.^[1-16]

As can be seen from the above, reduced stability of pit walls has a complex impact on the company's economic performance. The most significant damage is not associated with the implementation of preventive measures, but with mitigating the consequences of emergency deformations, which are accompanied by equipment downtime, additional volumes of overburden removal, and a decrease in the quality of the mined ore. In this regard, the timely implementation of measures for dewatering, installing drainage systems, monitoring the hydrogeological regime, and optimizing contour blasting parameters should be considered economically justified investments that reduce total operating costs and increase the efficiency of open-pit mining.

Thus, an economic assessment shows that ensuring the stability of pit walls is not only a necessary condition for industrial safety but also one of the most important factors in improving the technical and economic efficiency of a mining enterprise. Implementing a set of preventive engineering measures makes it possible to reduce the probability of emergencies, decrease non-productive costs, ensure the stable operation of the mining and transport complex, and increase the economic efficiency of deposit development.

CONCLUSION

The analysis shows that the water saturation of the rock mass should be considered not only as a hydrogeological factor but also as a significant geomechanical one that substantially affects the stress-strain state of the near-contour zone and the stability of pit walls. The penetration of water into pores, cracks, and surfaces of weakness is accompanied by a complex of interconnected processes: an increase in pore and hydrostatic pressure, a decrease in effective stresses, hydraulic fracturing, a deterioration of rock strength properties, and the formation of decompaction zones. The combination of these phenomena leads to the weakening of the rock mass, the intensification of fracturing, and a decrease in resistance to deformation and failure, which manifests as the development of local displacements, rockfalls, and other forms of stability loss.

It has been found that an increase in water saturation reduces the slope stability factor from 1.40–1.55 (for a dry rock mass) to 0.90–1.10 (for a highly waterlogged rock mass), while the strength characteristics of several rock types decrease by 10–50%. The most unfavorable conditions are observed when intersecting aquifers, during the development of man-made fracturing after drilling and blasting, and when conducting contour blasting in water-filled boreholes.

The problem becomes particularly significant during contour blasting of water-filled boreholes, when water becomes an active component in the charge-water-rock system interaction. This increases the depth of the disturbed zone from 0.5–1.0 m to 1.0–1.8 m and the fracture radius from 1.2–1.6 m to 1.5–2.3 m. The results obtained indicate that reducing the water saturation of the rock mass helps to increase the stability of pit walls, decrease the likelihood of accidents, and reduce additional costs associated with mitigating the consequences of slope deformation, organizing dewatering, and restoring operational infrastructure. Therefore, measures to manage the hydrogeological regime can be considered a factor in improving the economic efficiency of open-pit mining operations.

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