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Stress-strain state research of rock mass during open-pit mining of minerals

Abstract. Sustaining the stability and load-bearing capacity of open-pit mine slopes is a critical and complex condition for the transition to open-pit-to-underground mining methods. For this reason, the research in this study aimed to provide a geomechanical justification for the stability of the technological elements of the open-pit-to-underground mining complex. This justification, conducted using a developed model, aimed to determine the influence on the formation of the rock mass's stress-strain state, exemplified by the quarries of the Kryvyi Rih mining and processing plants. In this work, mathematical and numerical methods were applied to predict the influence of the open pit on subsequent underground extraction, including the finite element method, as well as statistical and factor analysis. Additionally, to investigate the stress-strain state of the rock mass surrounding the depleted open pit, the software "Ansys, Inc. Products 2019 R3" was used. It was established that the magnitude of the maximum vertical displacements of the pit slope increases from 13-14 mm on the upper benches at depths of 30-45 m from the ground surface to 60-63 mm on the lower benches at depths of 270-300 m at the bottom of the depleted pit. The dependence of the magnitude of the maximum vertical displacements of the pit slope elements on the depth of excavation is described by a logarithmic function. It was also established that the stress magnitude ranges from 0.7-1.2 MPa at the pit bottom to 4.6-4.9 MPa beneath the pit floor at the depth of the future underground stopes. The dependence of the magnitude of the maximum stresses in the rock mass beneath the pit floor on depth is described by an exponential function. The calculations made it possible to obtain quantitative data on the change in the stress state of the rock mass depending on depth. The practical significance of the work lies in using these indicators to ensure a safe and effective transition to underground mining technology

Keywords: open-pit mine; geomechanical justification; integrated mining; dependence; modelling

Introduction

Safe and efficient transition from open-pit to open-pit-to-underground and purely underground mining technology depends on geomechanical processes within the rock mass. An understanding of these processes is crucial for ensuring accident-free mineral extraction in open-pit mines where underground operations are conducted beneath them. The most complex and difficult-to-predict phenomena are deformations of the open-pit fields, which are worked using the open-pit-to-underground method. The presence of open-pit slopes

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influences the propagation of deformations from underground operations and leads to the development of specific failure mechanisms.

M. Kimour *et al.* (2023) indicated that the occurrence of ground surface displacements and deformations during underground mining differs significantly, even within a single deposit. This is particularly noticeable at mines extracting the upper horizons of steeply dipping ore bodies. The behaviour of the rock mass is non-linear and time-dependent, which, when combined with natural factors such as fracturing, rock inhomogeneity, and others, introduces elements of randomness into deformation prediction. The nature of ground surface deformations during ore body extraction depends on the dimensions of the worked-out space, specifically its extent and depth. If the dimensions of the extraction beneath the open-pit floor are sub-critical relative to the depth of the ore body, the overlying barren rock forms a stress arch, which redistributes the load to the undisturbed rock mass. In this scenario, deformations do not reach the ground surface or the pit surface at all, causing only minor, localised displacements. When the dimensions of the worked-out area, particularly the strike length or total length, reach super-critical values relative to depth, the overlying rock mass no longer creates a stable arch; it collapses, and deformations propagate to the ground or pit surface. According to research by O. Ivasivka *et al.* (2023), this leads to the formation of a subsidence basin, gradual ground subsidence, surface collapses, or slope and bench failures of the open pit.

M.N. Bagde (2021) noted that the ratio of critical dimensions to depth depends on multiple factors. These include the physico-mechanical properties of the rocks, their fracturing, the dip angle of the ore body, and the selected mining method. An example of such a method is the use of cemented backfill to fill the worked-out space. Subsequently, in the hanging wall, zones of collapse or funnel formation, terraces, followed by cracks, and finally gradual subsidence are formed. This sequence reflects the progressive dampening and change in the nature of deformations as one moves away from the epicentre of the underground extraction influence towards the hanging wall. This is a result of the hanging wall being prone to more active displacement and subsidence towards the worked-out space due to gravity and mining-induced stresses. Thus, the mechanism described by O. Kulikovska *et al.* (2024) leads to the deformation and failure of the hanging wall, from the most intense manifestations near the underground stoping area to more gradual ones at the periphery of the zone of influence. With further extraction, the zone of gradual subsidence moves into the hanging wall of the ore body. In its place, cracks and terraces appear, and collapses in the form of funnels are formed on the ground surface. The former funnels merge into several groups, creating larger collapses that extend towards the hanging wall of the rock mass.

Determination of stable slope angles for the open-pit-to-underground mining level is performed by a calculation method. For instance, to determine the limit stability of slopes during the transition from open-pit to open-pit-to-underground mining, Y. Shen *et al.* (2024) propose a methodology based on using a rock mass displacement indicator. In this methodology, the displacement indicator is used as a criterion because excessive displacements or their rate of development are a direct indication that the rock mass is losing its integrity, significant deformations are occurring, and it is approaching a state of failure or is beyond the limits of acceptable deformation for the safe preservation of the pit slope. An algorithm also exists for determining the limit stability of slopes during the transition from open-pit to open-pit-to-underground mining, according to the methodologies concerning the Hannivske quartzite deposit in Kryvbas. According to this methodology, the calculation of stable slope angles is carried out with a safety factor of 1.3. This value is a design criterion for stability, considered sufficient to ensure the safety and reliability of the slopes under the conditions of the Hannivske deposit. As noted by N. Zuievska *et al.* (2023), this takes into account the properties of the quartzites, depth, hydrogeology, etc. The development of ground surface displacements with physical destruction and collapse during the transition from open-pit to open-pit-to-underground mining is dangerous and requires the implementation of safe transitional technologies. Such technologies prevent the development of any disturbances to the pit slopes during the transition to integrated mining of minerals within the existing open-pit area. Therefore, ensuring the stability and load-bearing capacity of pit slopes are important conditions for mining deposits using the open-pit-to-underground method.

The aim of the work was to study the stress-strain state of the rock mass to justify its load-bearing capacity and the stability of the pit slopes and underground workings during their combined extraction. For this purpose, using a developed model, the influence of open-pit mining on the stress-strain state of the rock mass during the transition to underground operations was determined.

Materials and Methods

Mathematical modelling was used as a tool for finding optimal solutions. Its essence lies in the iterative or analytical modification of input parameters. At each stage, the influence of these changes on associated technological characteristics was assessed to ultimately find the extreme maximum or minimum value of the objective function. Regarding the specific task of mathematical modelling, a phased change in parameters was carried out. These parameters characterise the direction of development of the open-pit and open-pit-to-underground mining operations, the change in the structure of comprehensive mechanisation at the quarry, and their influence on the intensity of ore production (the production capacity of the open-pit and open-pit-to-underground operations) in the combination zone. The developed mathematical model represents a set of numerical parameters that describe the geological and technological features of both the open pit and the mine field. This model links these parameters with one another, and its main goal is to maximise mineral extraction.

The research was conducted using the quarries of the Kryvyi Rih mining and processing plants as an example. The selection of these quarries was relevant, as it is here that the problems of deep open pits during the transition to underground mining, complex mining and geological conditions (strong but fractured quartzites), and the presence of large volumes of worked-out spaces make the issues of ensuring the stability and load-bearing capacity of the pit slopes urgent and complex. A model was presented for the research that corresponded to the average statistical dimensions of the Kryvbas quarries (Razumova *et al.*, 2021). The model was based on averaged data from the Kryvyi Rih mining and processing plants, such as Nothern, Inhulets, and Central. It also corresponded to the optimal dimensions of open pits in developed mining countries that have transitioned from open-pit to underground or integrated methods of mineral deposit extraction.

Initial geometric data for the open-pit model included a final depth of 300 m. The average height and width of the bench were 15 m. The total width of the open pit at the top, at ground level, was approximately 2,000 m, while its bottom width, corresponding to the thickness of the ore body, averaged 80 m. Mathematical methods were used in the work to create models that predicted how open-pit mining influenced subsequent underground mining. Specifically, numerical modelling methods and finite element analysis were used. To increase the accuracy of the modelling, the physico-mechanical properties of heterogeneous rocks and the technological features of the stoping operations were taken into account. The data obtained from the model were analysed using statistical and factor analysis methods, which allowed for the assessment and minimisation of risks.

To investigate the stress-strain state of the rock mass surrounding the depleted open pit, the software "Ansys, Inc. Products 2019 R3" was applied. This powerful tool, which is based on the finite element method, made it possible to model the behaviour of the rock mass under the load of the overlying barren rock. To investigate the stress-strain state of the rock mass surrounding the open pit using the "Ansys, Inc. Products 2019 R3" software, the following stages had to be performed. First of all, a three-dimensional geometric model had to be created. The model included the open pit and the adjacent rock mass. After the model was created, it had to be divided into smaller elements, specifically, meshed. The process of building a mesh for the deposit model consisted of discretisation; that is, the complex three-dimensional volume of the rock mass, the ore body, and the rocks in the pit slopes was divided into a large number of small finite elements.

During the modelling of the rock mass deposit between the existing and the designed open-pit mine, the model's mesh division was a key element for conducting a numerical analysis of the stress-strain state. Effective modelling required a substantiated choice of mesh element type, which corresponded to the physics and geometry of the problem, as well as the selection of element size, which ensured the necessary accuracy, especially in critical zones, with acceptable computational power. As part of the modelling methodology, mesh densification was applied in critical areas. This allowed for more detailed results in locations of greatest interest, such as in the corners formed at the bottom of the open-pit.

Unstructured meshing has been an indispensable tool for modelling complex geology, with its quality and accuracy achieved through appropriate refinement in specific zones and the use of higher-order elements. While it was necessary to refine the mesh in areas of concentration, it was critically important to ensure a smooth transition from a fine mesh to a coarser one at a certain distance from the concentrator itself. The software suite "Ansys, Inc. Products 2019 R3" had special tools and settings to control the rate of change in element size between adjacent regions, for instance, the element size growth rate. According to research by M. Tomova & A. Kisyov (2024), adherence to the rule of a smooth mesh transition is one of the factors that ensures its high quality and, consequently, the reliability of the stress and strain field modelling results.

If the mesh size was significantly reduced, for example, to 2 m, the process of meshing the model and the calculation itself took an excessive amount of time on a personal computer with 16.0 GB of RAM. For efficient modelling, a minimum of 32 GB of RAM or more is recommended. The quality of the mesh directly affected the accuracy of the results. Next, it was necessary to define material properties, loads, and boundary conditions. For the research, average mining conditions were adopted, with corresponding geo-mining and technical parameters for integrated open-pit-to-underground mining. Specifically, magnetitic quartzites are characterised by a high Young's modulus value (35,000 MPa) and a significant bulk density (3,400 kg/m^3). Their compressive strength (120 MPa) significantly exceeds their tensile strength (12 MPa), and the Poisson's ratio is 0.25.

Based on L. Jiangnan & X. Kuangdi (2023), for the calculation of the rock mass stress-strain state, variants of the classic open-pit-to-underground mining scheme for magnetitic quartzites were adopted, representing average conditions for the transition from open-pit to underground mining. After configuring all parameters, the calculation was initiated. The calculation program solved the system of equations to determine the distribution of stresses and strains throughout the entire rock mass. Typically, this analysis was conducted in stages, simulating the sequence of rock extraction. A three-dimensional model covering 60 m along the Z-axis was chosen for the simulation to most accurately reproduce the interaction conditions of the open-pit and underground complexes. Although the model was three-dimensional, two-dimensional cross-sections were used for analysing and visualising key patterns of the stress-strain state. This made it possible to present the main research results more clearly, without excessive detail.

Elements along the bottom and side boundaries of the model were fully fixed to prevent their movement. Gravitational loading and the pressure from the rock mass were taken into account in the model. These loads were applied to all elements to simulate realistic physical conditions. The calculation results were provided in the form of visualised maps of stress, deformation, and safety factor distributions. By analysing this data, it was possible to identify the most hazardous zones where the probability of failure is highest. The relationship between the maximum magnitude of vertical displacements and the depth of pit excavation was established by means of regression analysis, performed on the basis of the obtained modelling data.

Results

The application of mathematical methods is the most widespread. The availability of personal computers allows for the modelling and calculation of a large number of variant models in a relatively short period (Mehnert *et al.*, 2022). Based on a numerical analysis of the model, performed using the finite element method, it was established that any medium in which the natural balance has been altered strives to gradually restore it, transitioning to a new stable state. According to research by M. Karlsmo *et al.* (2024), this process is determined by Le Chatelier-Braun's principle. The time during which the medium returns to a new stable state is referred to as the relaxation period of the disturbed rock mass. Typically, at the bottom of an open-pit mine, the occurrence of deformations, subsidence, and cracks can be observed, and with significant extraction scales at a shallow distance to the bottom, even localised collapses or cave-ins directly within the bottom contours. The pit bottom is a free surface, making it sensitive to additional stresses and deformations (Kalinichenko, 2020).

Changes in the stress state were expected on the pit's contours and slopes, leading to a reduction in their stability. The underground workings activated existing tectonic disturbances (faults, cracks) within the slopes and initiated the development of new failure mechanisms (displacements of individual blocks, bench collapses, general slope failures), particularly in the hanging wall where mass movement was more intense. As shown in Figure 1, the entire hanging wall slope of the pit is failing under the influence of underground mining. It is in this zone that terraces, cracks, and zones of gradual subsidence are apparent. These are the visible signs of the influence of underground operations on the pit slope's surface.

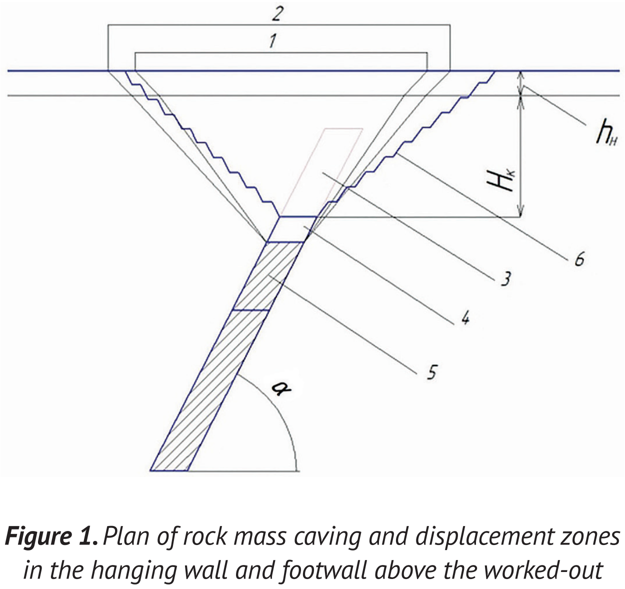

Figure 1. *Plan of rock mass caving and displacement zones in the hanging wall and footwall above the worked-out space of a deposit mined using an integrated method*

Notes: *1, 2 – accordingly, zone of ground collapse and ground subsidence above the worked-out underground space; 3 – contour of the deposit being mined by open-pit method; 4 – worked-out part of the deposit by underground method; 5 – part of the deposit subject to underground mining only; 6 – contour of the open pit in the form of benches;* $H_к$ *– final depth of the open pit; α – dip angle of the deposit; hн – thickness of the overburden*

Source: *developed by the author*

The zone of subsidence in the hanging wall extends beyond the pit contours, forming a subsidence basin on the ground surface with characteristic settlements and cracks, the scale of which depends on the dimensions of the excavation at depth and the distance to the surface. As underground mining operations deepen, the zones of collapse and subsidence move completely beyond the pit contours, leading to its physical destruction and collapse. Figure 1 illustrates the scale of the rock collapse and subsidence zones in the hanging wall and footwall of the deposit during combined open-pit-to-underground mining. Accordingly, the degree of their influence on the pit and the ground surface can be observed, which depends on a multitude of factors: the depth, dimensions, and shape of the stope, the physico-mechanical properties of the rocks, the presence and effectiveness of backfilling the worked-out space, as well as the sequence of block excavation (Ivadilinova *et al.*, 2023).

Even in more complex numerical methods, such as the finite element method in "Ansys, Inc. Products 2019 R3", where the stress-strain state was analysed and material strength criteria were applied at each point, the final stability assessment was also based on comparing the acting stresses (especially shear stresses) with the shear strength of the rocks at various points in the rock mass. The safety factor was calculated, or a stability analysis was performed by progressively reducing the rock strength parameters until a state of failure was reached, which was also essentially a determination of the safety factor. During the transition from open-pit to open-pit-to-underground mining operations, the necessity to consider the potential influence of underground mining was added to determine the magnitude of possible deformations of the pit slopes and surface. Induced deformations and altered stresses were superimposed on and interacted with the pre-existing stress-strain state caused by open-pit excavation, namely the open pit itself. This was not simply a linear sum of influences but a complex non-linear interaction that intensified negative phenomena.

Based on the properties of the magnetite quartzites, the geometry of the underground stopes was modelled with a stope inclination angle of 45 degrees and a bench height of 90 m. Figure 2 presents the overall initial calculation scheme for the option with mineral extraction conducted exclusively by the classical open-pit method. The figure is a visualisation of the finite element mesh used to model the stress-strain state of the rock mass around the open pit. The image demonstrates how the model space, which included the open pit and the adjacent rock mass, was divided into small elements (a mesh). This is a key stage of preparation for numerical calculations.

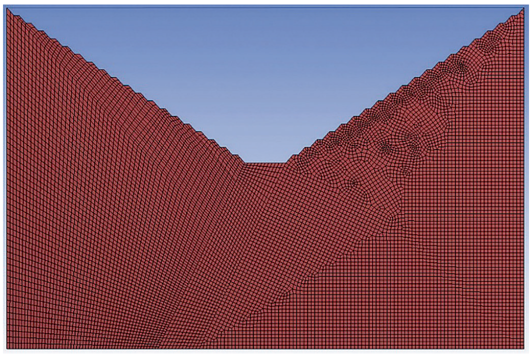

Figure 2. *Initial calculation model for the classical open-pit mining of minerals*

Source: *developed by the author*

Such a calculation scheme was applied to research different types of mineral deposits. For this purpose, the corresponding physico-mechanical properties of the minerals and host rocks were used in the calculations. Figure 3 presented the deformation magnitudes on the contour of the worked-out open pit depending on the depth of the working horizon, and in the undisturbed rock mass on the calculated contours of the future stopes during the transition to a combined open-pit-to-underground mining technology. The figure visualised the distribution of deformations (isolines) in the rock mass after the pit had been mined. This is a direct result of modelling and analysing the stress-strain state. The coloured lines in the figure were deformation isolines. They show how the intensity of deformations changed at different depths and locations within the rock mass. The figure clearly shows that the largest changes in deformation occurred specifically in the zone of the upper pit slopes and at its bottom. These areas were the most critical in terms of potential deformations and failures.

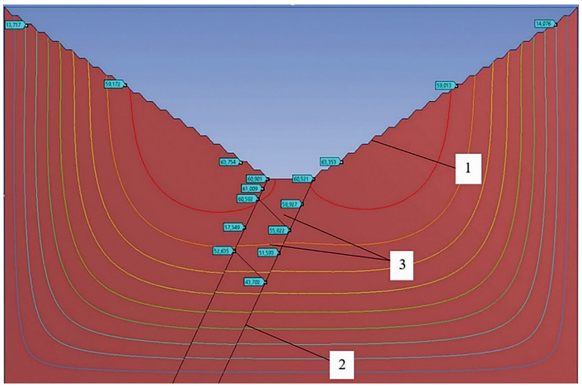

Figure 3. *Results of calculations of rock mass deformation during open-pit mining of minerals*

Notes: *1 – open pit contour; 2 – ore body; 3 – contours of the future first and second stage stopes, respectively*

Source: *developed by the author*

The results of calculations for the magnitude of maximum vertical displacements in the rock mass showed that the maximum vertical displacements of the pit slope's benches increased with increasing pit depth, from 13-14 mm on the upper benches at depths of 30-45 m from the ground surface to 60-63 mm on the lower benches at depths of 270-300 m at the bottom of the depleted pit. The results of the studies, presented in figures, were key to understanding the baseline stress-strain state of the open-pit area before or without the influence of underground mining. They allowed for the identification of red isolines in the upper parts of the slopes and at the pit bottom, which corresponded to larger deformation values. In these same areas, it was also visually confirmed that the rock mass was experiencing the greatest compression or tension, which were the zones of deformation concentration. Additionally, the figure enabled a clear assessment of how the pit influenced the entire volume of the rock mass, not just its immediate sections.

Such figures provided a clear understanding of the rock mass's reaction to open-pit excavation and served as a starting point for further analysis during the transition to the open-pit-to-underground method, as the influence of underground mining was superimposed on this baseline stress-strain state. The dependence of the magnitude of the maximum vertical displacements of the pit slope elements (benches) on the depth of the examined area from the ground surface is presented in Figure 4. This figure demonstrates the dependence of the maximum vertical displacements of the pit slope on the depth of its excavation.

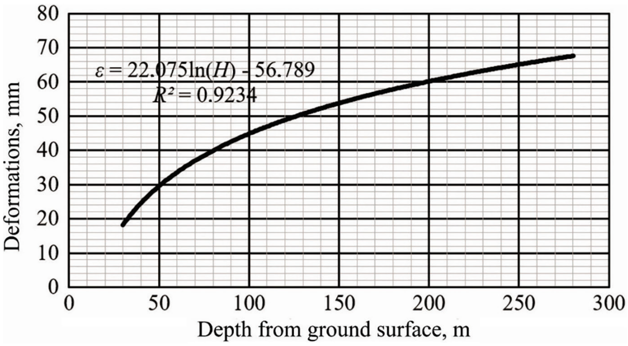

Figure 4. *Dependence of the magnitude of maximum vertical displacements of pit slope elements on the depth of excavation*

Source: *developed by the author*

The graph shows that as the excavation depth increases, so does the magnitude of vertical displacements on the pit slope. However, this increase is not linear; it follows a logarithmic pattern, which is confirmed by the regression equation on the graph. This indicates that the largest deformations occur during the initial stages of deepening, while at significant depths, the rate of deformation increase slows down. This logarithmic relationship is typical for mining operations and is explained by Le Chatelier-Braun's principle. According to this principle, disturbances are significant at initial depths, and the rock mass reacts sharply, causing a rapid increase in deformations. The data analysis carried out made it possible to establish a relationship with a high coefficient of determination, which is described by the following logarithmic equation:

$$\varepsilon = 22.075\ \ln(H) - 56.789;$$
$$R^2 = 0.9234, \qquad (1)$$

where ε – magnitude of the maximum vertical displacements of the pit slope, in mm; H – depth of the horizon (bench) from the ground surface, in m; R – magnitude of the coefficient of determination.

Figure 5 presents the results of calculations for stress magnitude in the rock mass during mineral extraction exclusively by open-pit mining. The location of the isolines with cold colours (blue) at the pit bottom and near its slopes indicates a low magnitude of stresses in these specific areas. The figure visually illustrates how the gravitational load was redistributed from the pit slopes to the internal sections of the rock mass. An analysis of the stress distribution at depth also allowed the influence of the open pit on future underground stopes, which were planned for extraction beneath its floor, to be assessed.

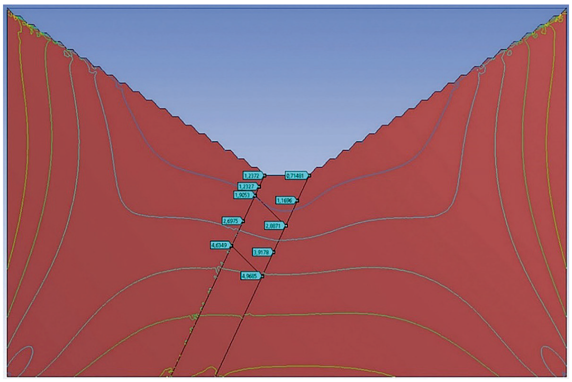

Figure 5. *Results of stress magnitude calculations in the rock mass during open-pit mining of minerals*

Source: *developed by the author*

Based on the research conducted, the magnitude of stresses in the rock mass beneath the open-pit floor increases from the ground surface at the bottom of the pit into the depth of the rock mass. In a natural, undisturbed rock mass, geostatic vertical stresses from the self-weight of the overlying rocks increase with depth. When the pit was created, a significant volume of rock was excavated. This led to a redistribution of the natural stress field. Directly on the pit floor and in the near-surface part beneath it, stresses are significantly reduced (unloaded) compared to the initial geostatic stresses, as the overlying rock mass has been removed. However, deeper into the rock mass from the pit floor, the influence of the unloading zone diminishes. Stresses gradually begin to recover and approach the values of natural geostatic stresses. Thus, at a certain depth beneath the pit floor, stresses become greater again and continue to increase with the depth of the deposit. The magnitude of stresses ranged from 0.7-1.2 MPa at the pit floor to 4.6-4.9 MPa beneath the pit floor at the depth of the future underground stopes for the second stage of mining. Figure 6 presents the dependence of the magnitude of stresses in the rock mass beneath the pit floor at the depth of the future underground stopes for the first and second stages of mining.

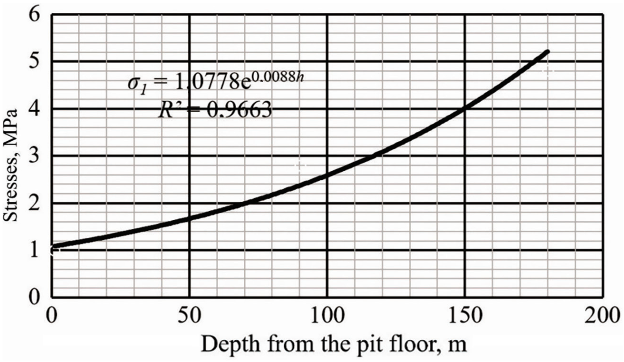

Figure 6. *Dependence of the maximum stresses in the rock mass beneath the pit floor on the depth of the future underground stopes*

Source: *developed by the author*

The graph shows a key finding of the modelling: stresses increase with depth, but this increase is not linear. Stresses grow following an exponential law, which is confirmed by the equation obtained from the regression analysis. This indicates that the influence of stresses becomes increasingly pronounced as depth increases. This relationship allows for the prediction of the rock mass's stress state at various depths. This is critical for planning underground stopes and selecting an appropriate mining technology to ensure safe operations. The relationship identified by the research is described by the exponential function of the form:

$$\sigma_1 = 1.0778e^{0,0088h}; \quad R^2 = 0.9663, \tag{2}$$

where σ_1 – magnitude of the maximum stresses in the rock mass, MPa; h – depth of the future underground stopes from the pit floor, m; R – magnitude of the coefficient of determination.

The obtained dependence is confirmed by studies conducted for similar conditions, for example, in the work of H. Luo *et al*. (2024). The reliability of the results is confirmed by the fact that the error margin does not exceed 12-15%, which is an acceptable value for geomechanical research. The obtained results make it possible to visualise the distribution of stresses, stress concentration zones, and deformations in the rock mass. This allows for the analysis of the influence of various mining technologies on rock mass stability, leading to the selection of the most effective solutions. Therefore, the calculations make it possible to obtain quantitative data on the change in the stress state depending on depth. This underscores the critical importance of these indicators for ensuring a safe and effective transition to underground mining technology.

Discussion

M. Zhe & M. Zhuoqian (2024) conducted analytical and field studies on the stability of rock slopes along a high-speed motorway that were prone to landslides. The authors used "Rocscience" software to evaluate these slopes. The results of the numerical modelling were in full agreement with the field observations, confirming the high risk of slope failure, especially during rainfall and earthquakes. The paper made an important contribution to mining geomechanics as it confirmed that the geometric parameters of slopes and external factors (water saturation, seismicity) are critical for their stability. It demonstrated the effectiveness of the software for predicting rock mass behaviour and preventing dangerous situations, which fully aligns with the demands regarding stresses and deformations. The presence of water in rock cracks and pores reduces their strength and increases pore pressure, which leads to a weakening of the rock mass. An increase in the groundwater level or heavy rainfall causes landslides and collapses, which directly affects the stability of the pit slopes and underground stopes. Earthquakes or even microseismic activity, for example from explosions, create dynamic loads that sharply increase stresses in the rock mass. This destroys existing stress arches or causes rock bursts and collapses, especially in weakened areas between open-pit and underground mining. Ignoring these factors leads to an underestimation of risks and, as a result, to catastrophic failures that threaten human life and infrastructure. Therefore, in geomechanical research, an analysis is obligatorily conducted with consideration of the hydrogeological and seismodynamic conditions of the working area. Studies concerning the transition from open-pit to underground mining are particularly sensitive to these factors, as it is precisely here that new zones of stress concentration are created, and the old rock mass of the open pit receives additional load. The commonality in the obtained results is the confirmation of the critical influence of external factors on the stability of the rock mass and the effectiveness of numerical modelling methods, whereas the difference lies in the fact that M. Zhe & M. Zhuoqian (2024) focused on slopes along a motorway, while this study focused on the specific issues of open-pit-to-underground mining of deposits.

Stress analysis using "SolidWorks Simulation" is a study that demonstrates the effectiveness of using software to analyse the behaviour of components under various loads, as presented by M. Yazeed *et al*. (2023). The paper highlights the power and importance of using modern software for engineering analysis. It shows that such tools are an effective alternative to complex manual calculations and allow for the visualisation and analysis of results with high accuracy. This work demonstrates that effective and precise tools exist for modelling the stress-strain state of a rock mass, which are key for this type of research. However, this published work demonstrates the effectiveness of mathematical modelling using various types of software on personal computers. Common to both studies is the confirmation of the effectiveness and key role of modern software for modelling the stress-strain state, but the difference lies in one case focusing on stress analysis in engineering components, while this study applied the approach to the specific problem of mining geomechanics.

B.O. Taiwo *et al*. (2023) noted that the state of pit slopes was influenced by explosive works used during extraction, as blasts were one source of localised seismicity affecting the rock mass's stress-strain state. The authors used a combination of geotechnical methods, monitoring, and data analysis to assess how blasts caused microcracks, which weakened the rock and increased the risk of collapses. This work highlighted the importance of considering not only static but also dynamic stresses when analysing rock mass stability. It confirmed the need to account for seismic factors in the pit during the transition from open-pit to underground mining. The results obtained in the current work align with the finding that dynamic loads from drilling and blasting are a key factor influencing the stress-strain state of the rock mass. The difference, however, lies in the fact that the original study focused on analysing the stability of pit slopes, whereas this research applied these findings to geomechanical processes under conditions of combined mining.

O.V. Kalinichenko (2020) noted that to determine changes in the stress-strain state of a rock mass when creating underground voids, analytical modelling with effective computer software is necessary. Particular attention is paid to methods for controlling the stress-strain state, which ensure stability and safety. The research findings contain recommendations and methodologies that prevent collapses, the formation of subsidence basins, and other negative geomechanical phenomena. This is directly related to the influence of worked-out space dimensions on surface deformations, as this dissertation developed a scientific basis for understanding and controlling geomechanical processes. The results of that study had an approximately similar error to the results of this research. What both works have in common is the application of software for modelling and analysing the stress-strain state to enhance mining safety. The difference is that the author focused on the creation of underground voids and workings, whereas this study focused on the interaction between open-pit and underground mining.

In the published work, Y. Lu *et al*. (2024) proposed an analysis of open-pit slope deformations and failures resulting from the combined influence of blasting operations and rainfall. The authors emphasised that although these factors are common, their combined effect has rarely been studied. An integrated approach, which included using finite difference method modelling to investigate slope response mechanisms, was used to study a large-scale landslide that occurred at a mine in China. The paper is relevant as it confirmed that to fully understand the behaviour of the rock mass, it is not enough to study only internal factors, such as stresses from mining. It is necessary to consider external factors, such as hydrogeology and dynamic loads, which made it an ideal complement to the results of this study on the open-pit-to-underground transition. The two studies similarly confirm the need to consider factors of natural and man-made origin for a comprehensive stability analysis, while the difference lies in the fact that one focused on open-pit slopes and this study focused on the interaction of the depleted open-pit with the surrounding rock mass.

The research results in the paper by M. Marchelli *et al*. (2023) are practical, as they provided specific tools for the preliminary design of open-pit geometry and risk assessment. This study confirmed that proper planning and consideration of the geomechanical properties of the rock mass significantly increased work safety. It also emphasised that every element of the open pit, from the bench to the overall geometry, was crucial for preventing dangerous situations. Both works used a single approach of applying geomechanical calculations for improving the safety of mining operations, but the difference lies in the fact that one focused on specific tools for designing open-pit geometry, while this research focused on the problem of subsequent combined mining.

In the paper by A. Driouch *et al*. (2023), it was proven that numerical modelling is an extremely important tool for selecting the safest and most effective mining sequence. It was also emphasised that the correct choice of mining methods is crucial for managing the stress-strain state of the rock mass, especially in conditions with weak rocks. The results obtained from both studies converge on the key factor being the necessity of applying numerical modelling to select effective mining methods. However, the difference lies in the fact that one study focused on choosing a mining sequence in weak rock conditions, whereas this research concentrated on geomechanical processes in a combined mining operation.

In mining science, a number of calculation schemes and methodologies are applied to determine the stability of open-pit slope elements. As stated by E.B. Gridina *et al*. (2020), a common feature of all existing calculation schemes is the comparison of shear and retaining forces acting along the weakest surface. This principle is used to calculate the factor of safety, which is the most common indicator of slope stability. The factor of safety is defined as the ratio of the total sum of retaining forces or moments, depending on the methodology, resisting movement along the surface, to the total sum of shearing forces or moments that tend to cause movement along this surface. A common feature of all existing calculation schemes is the comparison of shearing and retaining forces to determine the factor of safety, which is considered a classic approach, whereas this study considers the application of this principle in the context of open-pit mining, which is its distinctive feature.

A.G. Irwan & I.T. Wiati (2023) noted that the stability parameters of pit slopes obtained by calculation require adjustment as they do not reflect all factors that occur in the rock mass at each specific deposit during its development. The main parameters of the pit slope, such as its inclination angle and height, are determined by taking into account the main influencing factors, which include: the physico-mechanical properties of the rocks; the structural features of the rock mass and the deposit's structure; the dimensions and shape of the open pit; hydrogeological conditions; technological influence (the effect of drilling and blasting operations, external loads on the slope, particularly the close proximity of waste dumps, and so on); and the duration of the open pit's operation. A key shared conclusion is the confirmation that the calculated stability parameters require adjustment to account for a multitude of factors, whereas the difference lies in the fact that attention was focused on general parameters, while this study analyses the influence of the open pit on the rock mass.

Thus, the analysis of scientific sources and the results of the modelling confirm that assessing the stability of the rock mass around a depleted open pit requires a comprehensive approach. It has been established that stability parameters calculated by standard methods are insufficient, as they do not account for the combined influence of hydrogeological, seismodynamic, and technological factors. Therefore, to ensure the stability of the pit slopes and underground workings during their combined extraction, it is necessary to apply numerical modelling methods that allow all these factors to be taken into account for an accurate prediction of the stress-strain state.

Conclusions

The conducted research made it possible to perform a geomechanical justification for the stability of the elements of the open-pit mining complex. The obtained results confirmed the fundamental regularities of the rock mass's stress-strain state and provided a quantitative assessment of its behaviour. The research established that the magnitude of the maximum vertical displacements of the pit slope on its benches increased with increasing pit depth, from 13-14 mm on the upper benches at depths of 30-45 m from the ground surface to 60-63 mm on the lower benches at depths of 270-300 m at the bottom of the depleted pit. It was established that the dependence of the magnitude of the maximum vertical displacements of the pit slope elements on the depth of excavation was described by a logarithmic function with a high coefficient of determination. The results of the calculations made it possible to establish that the magnitude of stresses in the rock mass beneath the pit floor increased from the ground surface at the bottom of the pit into the rock mass according to an exponential law. It was established that the stress magnitude ranged from 0.7-1.2 MPa at the pit bottom to 4.6-4.9 MPa beneath the pit floor at the depth of the future underground stopes. During the research, it was established that stresses in the rock mass beneath the pit floor increased with depth. The results obtained confirmed that vertical geostatic stresses increased with depth, which was caused by the weight of the overlying rocks. However, upon the creation of the pit, a significant portion of these rocks was removed, leading to a redistribution of the initial stress field. The conducted studies showed that the stresses directly at the pit bottom and in the near-surface zone beneath it significantly decreased, which indicated the unloading of the rock mass. Nevertheless, with an increase in depth, the influence of this zone decreased. The stresses began to gradually recover and approached the initial geostatic values, continuing to increase further down the dip of the deposit. The performed analysis demonstrated zones of stress concentration on the pit slopes, as well as zones of unloading in the near-surface rock mass beneath its bottom. The obtained dependencies were confirmed by research performed for analogous conditions. The reliability of the results was confirmed by the fact that the error magnitude did not exceed 12-15%, which was an acceptable value for geomechanical studies. The obtained results were the basis for further work planning for the transition to underground mining. In further research, a focus is planned on studying key parameters to ensure the stability of the rock mass during the excavation of Chambers I, II, and III. The main objects of analysis will be changes in the distribution of stresses and deformations in the rock mass, as well as the mutual influence of the chambers on the overall stability of the rock mass around the pit.

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Conflict of Interest

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References

[1] Bagde, M.N. (2021). Ore and backfill dilution in underground hard rock mining. *Journal of Mining Science*, 57(6), 995-1005. doi: 10.1134/s1062739121060120.

[2] Driouch, A., Ouadif, L., Lahmili, A., Belmi, M.A., & Benjmel, K. (2023). Geotechnical modeling of the method for mining cobalt deposits at the Bou Azzer Mine, Morocco. *Mining of Mineral Deposits*, 17(1), 51-58. doi: 10.33271/mining17.01.051.

[3] Gridina, E.B., Rudakov, M.L., & Rumiantseva, A.M. (2020). Evaluation of stability of sides of quarries and dumps on the basis of a risk-oriented approach. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 4, 47-52. doi: 10.33271/nvngu/2020-4/047.

[4] Irwan, A.G., & Wiati, I.T. (2023). Reconstruction of natural slope stability by limit equilibrium methods and finite element methods. *Dinamika Teknik Sipil: Majalah Ilmiah Teknik Sipil*, 16(2), 43-49. doi: 10.23917/dts.v16i2.23276.

[5] Ivadilinova, D.T., Issabek, T.K., Takhanov, D.K., & Yeskenova, G.B. (2023). Predicting underground mining impact on the earth's surface. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 1, 32-37. doi: 10.33271/nvngu/2023-1/032.

[6] Ivasivka, O., Hevpa, Z., & Dyakiv, V. (2023). Activation of karst-fall phenomena within the mining district of Mine No. 2 and its impact on the state of infrastructure facilities and living conditions of residents. *Visnyk of the Lviv University. Series Geology*, 37, 42-55. doi: 10.30970/vgl.37.04.

[7] Jiangnan, L., & Kuangdi, X. (2023). Open-pit and underground combined mining. In K. Xu, (Ed.), *The ECPH encyclopedia of mining and metallurgy*. Singapore: Springer. doi: 10.1007/978-981-19-0740-1_348-1.

[8] Kalinichenko, O.V. (2020). *Development of scientific principles for controlling the stress-strain state of rock mass during underground excavation*. (Doctoral dissertation, M.S. Polyakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Dnipro, Ukraine).

[9] Karlsmo, M., Hosaka, T., & Johansson, P. (2024). Le Chatelier's principle enables stable and sustainable aqueous sodium/magnesium-ion batteries. *Journal of Materials Chemistry A*, 12(7), 4029-4036. doi: 10.1039/d3ta06826a.

[10] Kimour, M., Boukelloul, M.L., Hafsaoui, A., Narsis, S., Benghadab, K.M., & Benselhoub, A. (2023). Geomechanical characterization of rock mass rating and numerical modeling for underground mining excavation design. *Journal of Geology, Geography and Geoecology*, 32(1), 67-78. doi: 10.15421/112308.

[11] Kulikovska, O., Stupen, R., & Kolodiy, P. (2024). Cartographic and analytical model of the formation of the failed relief in a large mining region. *Spatial Development*, 10, 482-497. doi: 10.32347/2786-7269.2024.10.482-497.

[12] Lu, Y., Jin, C., Wang, Q., Li, G., & Han, T. (2024). Deformation and failure characteristic of open-pit slope subjected to combined effects of mining blasting and rainfall infiltration. *Engineering Geology*, 331, article number 107437. doi: 10.1016/j.enggeo.2024.107437.

[13] Luo, H., Wang, Z., Liu, K., Qiao, L., & Qing, L. (2024). Stress-strain state zoning model and novel large deformation classification method for squeezing tunnels. *Engineering Failure Analysis*, 164, article number 108711. doi: 10.1016/j.engfailanal.2024.108711.

[14] Marchelli, M., Peila, D., & Giacomini, A. (2023). Rockfall in open pit mines: Management of the pit geometry and protection measures design. *International Journal of Rock Mechanics and Mining Sciences*, 170, article number 105551. doi: 10.1016/j.ijrmms.2023.105551.

[15] Mehnert, M., Oates, W., & Steinmann, P. (2022). Numerical modeling of nonlinear photoelasticity. *International Journal for Numerical Methods in Engineering*, 24(7), 1602-1619. doi: 10.1002/nme.7177.

[16] Razumova, K.M., Temchenko, O.A., Maksymov, S.V., & Maksymova, O.S. (2021). Research of duration influence of loading and unloading operations on the use efficiency of technological motor transport on open pit iron mines. *Science and Transport Progress*, 6(96), 24-38. doi: 10.15802/stp2021/256794.

[17] Shen, Y., Feng, Z., Zhou, D., & Zhang, B. (2024). Different rock failure precursors using displacement coordination coefficient. *Environmental Earth Sciences*, 83, article number 490. doi: 10.1007/s12665-024-11814-9.

[18] Taiwo, B.O., Yewuhalashet, F., Ogunyemi, O.B., Babatuyi, V.A., Okobe, E.I., & Orhu, E.A. (2023). Quarry slope stability assessment methods with blast induced effect monitoring in Akoko Edo, Nigeria. *Geotechnical and Geological Engineering*, 41, 2553-2571. doi: 10.1007/s10706-023-02414-8.

[19] Tomova, M., & Kisyov, A. (2024). Applications and advantages of geophysical methods in underground mining. *Annual of the University of Mining and Geology "St. Ivan Rilski"*, 67, 184-188. doi: 10.5281/zenodo.13762777.

[20] Yazeed, M.A.A., Abdullah, A.A., Muhab M.F.A.-G., & Mithun, V.K. (2023). Stress analysis using solidworks simulation. *EPRA International Journal of Multidisciplinary Research (IJMR)*, 9, 28-35. doi: 10.36713/epra14295.

[21] Zhe, M., & Zhuoqian, M. (2024). Stability analysis of rock slope based on rocscience software. *Civil Engineering*, 13(7), 1152-1157. doi: 10.12677/hjce.2024.137124.

[22] Zuievska, N., Shaidetska, L., Kosenko, T., & Hutsuliak, Z. (2023). Application of engineering measures for the stabilization of the soil slope. *Collection of Research Papers of the National Mining University*, 73, 187-196. doi: 10.33271/crpnmu/73.187.

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Дослідження напружено-деформованого стану гірського масиву при видобутку корисних копалин відкритим способом

Анотація. Забезпечення стійкості та несучої здатності бортів кар'єрів це актуальна та складна умова для відпрацювання родовищ відкрито-підземним способом. У зв'язку з цим метою досліджень в роботі було геомеханічне обґрунтування стійкості технологічних елементів відкрито-підземного комплексу гірничих робіт. Це обґрунтування, проведено за допомогою розробленої моделі, мало на меті визначення впливу на формування напружено-деформованого стану масиву на прикладі кар'єрів Криворізьких гірничо-збагачувальних комбінатів. У даній роботі для прогнозування впливу кар'єру на подальший підземний видобуток були застосовані математичні та чисельні методи, зокрема метод скінченних елементів, а також статистичний та факторний аналіз. Крім того, для дослідження напружено-деформованого стану гірського масиву навколо відпрацьованого кар'єру було використано програмне забезпечення «Ansys, Inc. Products 2019 R3». Встановлено, що величина максимальних вертикальних зсувів борта кар'єру збільшується з 13-14 мм на верхніх горизонтах (уступах) на глибинах 30-45 м від денної поверхні до 60-63 мм на нижніх уступах на глибинах 270-300 м на дні відпрацьованого кар'єру. Залежність величини максимальних вертикальних зсувів елементів борта кар'єру від глибини розробки описується логарифмічною функцією. Було встановлено, що величина напружень коливається від 0,7-1,2 МПа на дні кар'єру до 4,6-4,9 МПа під дном кар'єру на глибині розташування майбутніх підземних очисних камер. Залежність величини максимальних напружень у гірському масиві під дном кар'єру від глибини описується експоненціальною функцією. Розрахунки дозволили отримати кількісні дані про зміну напруженого стану гірського масиву в залежності від глибини. Практична значимість роботи полягає у використанні цих показників для забезпечення безпечного та ефективного переходу до підземної технології розробки

Ключові слова: кар'єр; геомеханічне обґрунтування; комплексна розробка; залежність; моделювання