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Research and application of polynomial models in the development of an automated geological and mine surveying support system for open-pit mining

Abstract. The relevance of the research was determined by the necessity to improve the accuracy and efficiency of geological and mine surveying operations under conditions of complex geological structures and limited resources for field investigations. The development and implementation of automated software enabled the prompt analysis of large data volumes, optimisation of the testing network, and reduction of exploration costs. The aim of the research was the development of software for polynomial models of curves and surfaces with a proposed simplified algorithm for implementing the least squares method. The desktop application software was developed in Microsoft Visual Studio 2019 using the Microsoft Foundation Classes library. The mobile application was developed in Android Studio. For 3D graphics, the OpenGL library with shaders was employed, ensuring high operational performance. Parameters for evaluating the adequacy of the model were defined, as standard standalone packages provided insufficient objectivity. It was demonstrated in automated mode that the Lagrange polynomial represents a particular case of the developed polynomial model in curve construction. Furthermore, the interpolation method for surface construction was improved by incorporating spatial variability of indicators through the use of autocorrelation functions. During the construction of autocorrelation functions, spatial variability was assessed based on autocorrelation coefficients between values at adjacent control points, as well as the critical correlation radius, which made it possible to evaluate the predictive potential beyond the polynomial construction zone. The application of critical correlation radius in the automated geological and mine surveying system for analysing the testing network of all boreholes (exploratory and blasting) was described. It was noted that the network parameters should reflect the natural variability of the studied indicators. In cases where the deposit depth exceeded the bench height, the feasibility of predicting qualitative characteristics based on the results of blasting boreholes located above the mineral deposit was considered, allowing for a significant reduction in the scope of costly exploratory works. It was established that the multi-module automated geological and mine surveying system had been developed and implemented over many years in open-pit mines, particularly

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at the Erdenet enterprise (Mongolia), which develops a copper-molybdenum deposit. The results of the conducted research were utilised in the educational process and in the automated geological and mine surveying system for planning and managing mining operations in open-pit environments

Keywords: regression model; autocorrelation function; least squares method; Lagrange method; frame model; critical correlation radius; indicatrix

Introduction

Under conditions of increasingly complex subsurface geological structures, limited resources for fieldwork, and the necessity for prompt engineering decision-making, emerged an urgent need for the implementation of automated tools for analysing geological and mine surveying information. The enhancement of the efficiency of such operations was directly associated with the use of modern mathematical methods and software, which enabled a reduction in exploration costs and an improvement in the reliability of forecasts. Particular attention was paid to the advancement of spatial interpolation models adapted to real-world environments, where the indicators exhibit complex variability, and traditional statistical methods proved insufficiently effective.

Regression analysis, as highlighted by D. Mountgomery *et al*. (2021), represented a powerful statistical instrument widely applied in the natural, technical, and socio-economic sciences. I. Pardoe (2021) emphasised the role of the coefficient of determination R^2 as a key metric for assessing a model's capacity to explain the variation of the target variable. Meanwhile, the studies of I. David *et al*. (2020) demonstrated that traditional adequacy criteria could be complemented by new ones, such as median squared error prediction and robust model efficiency, which better accounted for the presence of extreme or leading data.

According to the findings of S. Lapach (2025), the least squares method (LSM) remained one of the most effective techniques for parameter estimation in regression analysis, particularly in the presence of large data scatter. It was also emphasised that under conditions of heteroscedasticity, various methods produced significantly different results, and the choice of model ought to be based on the characteristics of the dataset. This was supported by the research of V.V. Khlivnyi & C.V. Bazilo (2023), which substantiated the appropriateness of using the Fisher criterion and the multiple correlation coefficient R^2 for verifying the informativeness of metamodels.

In the field of geoinformation modelling, an essential aspect involved the consideration of spatial autocorrelation. As demonstrated in the works of P. Bidiuk *et al*. (2020), effective modelling of temporal and spatial processes was achieved through the application of the Box-Jenkins methodology as well as intelligent approaches that allowed for the refinement of regression model structures. These approaches ensured high modelling accuracy through the analysis of autocorrelation and partial autocorrelation functions.

Special attention was paid to the issue of interpolation model accuracy. In the study by O. Prokaza & O. Kuznetsova (2022), it was justified that high model significance could be attained through the inclusion of a greater number of relevant factors. At the same time, the insufficient significance of individual parameters was attributed to the influence of random disturbances and unaccounted variables. In the context of improving model accuracy, the approach of J. Bell (2020) appeared appropriate, where in unique orthogonal polynomial estimators were proposed to strike a balance between minimising the mean squared error and ensuring result stability under dynamic conditions.

Despite existing achievements, the automation of assessing the spatial variability of geological indicators using critical correlation radius, and their integration with interpolation models, remained insufficiently explored. Likewise, limited attention had been given to the possibilities of predicting the qualitative characteristics of mineral resources based on limited or indirect data, particularly from blasting boreholes. The research focused on the development of automated software for constructing polynomial models of curves and surfaces, incorporating spatial autocorrelation and evaluating the boundaries of reliable forecasts beyond the zone of direct measurements. The aim of the study was to construct polynomials $y = f(x)$ and $z = f(x, y)$, which most accurately described the dependency of the resultant indicator on the selected factor.

Materials and Methods

A simplified algorithm for implementing the LSM in the construction of polynomial models $y = f(x)$ and $z = f(x, y)$ was proposed. This approach eliminated the need for calculating partial derivatives, as presented in the textbook by E. Manoukian (2021), where the procedure was described in detail. The task was reduced to the elementary formulation of a system of linear equations based on the proposed algorithm. As outlined in the textbook by V.M. Horbachuk & O.I. Kushlyk-Dyvulska (2023), this system was solved using the Gaussian elimination method. The adequacy of the polynomial model was subsequently evaluated. This study introduced enhancements to polynomial models and provided an assessment of their accuracy, along with interpolation methods that accounted for indicator variability in constructing surfaces using polynomial and frame-based models.

Mathematical modelling is typically conducted in various standalone software packages. These tools are often difficult to integrate as components within larger systems, particularly in the context of automated generation of input data and transmission of results within a system. Furthermore, such packages usually offer insufficient assessment of model adequacy. Within the geological and mine surveying software (GMSS) module, the following methods for curve construction were implemented: 1) Polynomial method (based on the least squares method); 2) Lagrange polynomial; 3) Cubic spline interpolation; 4) Hermite spline interpolation; 5) Bézier curves; 6) B-splines. For surface modelling, the following methods were developed: 7) Polynomial method (based on the least squares method); 8) Interpolation method (grid-based and frame-based); 9) B-splines (NURBS surfaces); 10) Nearest neighbourhoods (polygons).

In methods 2 to 4, the curves strictly passed through the control points. Methods 5 and 6 ensured that the curves passed exactly through the first and last points. In many cases, these constraints were unnecessary. However, for solving a range of problems, the involvement of all control points in curve and surface construction was essential. These conditions were satisfied in polynomial models. Nevertheless, these models did not account for values located between adjacent points, which significantly affected the evaluation of model adequacy. This factor had to be considered when assessing the spatial variability of indicators during borehole testing for the selection of test networks, reserve estimation, and ore body delineation along quarry horizons. An example of generating a curve polynomial $y = f(x)$ could be found in Microsoft Excel, although such tools typically failed to provide any evaluation of variability between control points.

The article proposed methods for evaluating model adequacy, ensuring a more accurate selection of a polynomial model. Similar to time series, polynomial construction was considered under the condition $x_{i+1} > x_i$. Particular attention was given to the B-spline method (methods 6 and 9), where a dynamic controllable model was formed through the adjustment of weights at the control points. This method was implemented in the construction of the open-pit surface based on the coordinates of bench edges. The GMSS had been continuously expanded and improved, both in terms of software and calculation accuracy. This fully applied to the curve and surface modelling module, which was employed in tasks such as assessing spatial variability of indicators, resource estimation (both operational and complete), ore extraction accounting, forming the information base for mining planning and management, and modelling of the deposit and open-pit contours.

In its initial implementation, O. Zelensky & V. Lysenko (2022) introduced the GMSS module at the Erdenet enterprise (Mongolia), which develops a copper-molybdenum deposit. The new version was developed for the conditions of an iron ore deposit, using the example of the Southern Mining and Processing Plant (Southern MPP). In this context, significant improvements in software and mathematical support were made by O. Zelensky (2023). To construct the polynomial model, an array of control points was utilised, generated either automatically from shuffled or sequential data. A sinusoidal function was selected for forming sequential data due to its continuous, periodic, and smooth nature, without phase shift as observed in the cosine function. Based on the sine function, a clear relationship between data values was identified, resulting in a high level of model adequacy. This visibly demonstrated the relevance of the developed indicator system.

To determine the acceptable level of model adequacy, dozens of test scenarios were conducted, allowing the identification of deviation levels from standard indicators. The number of points *N* did not directly influence the performance of the system, but it was taken into account when constructing the model and determining the maximum degree of the polynomial. The desktop application software for constructing polynomial models was developed in C++ using the Microsoft Foundation Classes (MFC) library. Model visualisation was performed with the OpenGL library. User interaction was facilitated through the graphical interface of the MFC application. Peripheral devices such as a keyboard and mouse were employed for parameter control, as further detailed in the Results section. Users were provided with the ability to adjust the polynomial degree and the number of control points. All computational algorithms were implemented manually by the authors, without reliance on additional libraries. To support comprehensive research execution, a mobile application for the Android operating system was also developed (Zelensky, 2023), offering functionality similar to the desktop version. The article provided an in-depth investigation of the polynomial method and the Lagrange polynomial, while other methods were described in the works of O. Zelensky (2023) and O. Zelensky & V. Lysenko (2022).

Results

When constructing curves, it is necessary to determine such a function $y = f(x)$ that most accurately characterises the dependence of the resulting indicator on the chosen factor. To obtain a polynomial curve, the LSM was used, which ensures the minimisation of the sum of squared deviations of the given indicators from the resulting curve. The following formula was used (1):

$$\sum_{i=1}^{n} \left(y_i - \hat{y}_i\right)^2 \rightarrow min, \qquad (1)$$

where y_i – the actual value of the resulting indicator; $\hat{y}_i$ – the computed value of the indicator; n – the number of observations. In general, the curve formula has the following form (2):

$$f(x) = A_0 + A_1x + A_2x^2 + \ldots + A_M^M, \text{ or, } f(x) = \sum_{i=0}^{M} A_i xi, \quad (2)$$

where M – the degree of the polynomial. Obtaining A_i by the least squares method is reduced to solving a system of linear equations consisting of $M+1$ linear algebraic equations (3):

$$\begin{cases} a_{00}A_0 + a_{01}A_1 + *** + a_{0M}A_M = b_0 \\ a_{10}A_0 + a_{11}A_1 + *** + a_{1M}A_M = b_1 \\ ***************************** \\ a_M A_0 + a_{M+1}A_1 *** + a_{2*M}A_M = b_M. \end{cases} \quad (3)$$

When determining the coefficients a_{ij} and b_{ij}, the literature often provides a rather complex solution algorithm. O. Zelensky & V. Lysenko (2022) proposed a simple method for obtaining these coefficients using the formula (4):

$$a_{ij} = \sum_{k=1}^{n} x_k^{i+j}; \; b_i = \sum_{k=1}^{n} x_k^i \cdot y_k, \quad (4)$$

where x_k, y_k – the coordinates of the input control points; n – the number of control points.

Further, solving the system of linear algebraic equations using classical methods is not difficult, that is, obtaining the values of the coefficients A_i. In the program developed by the authors, the Gauss method was used. For the study of the polynomial curve, the sine wave $y = sin(x)$ in the range from -3π to 3π was used as the source data. The input data is the number of control points N. In this case, the value of the control points (y) starts from the point $x = -3\pi$, $y = 0$. Then y is determined by increasing the argument x by 6π / $(N-1)$. Naturally, the last point will have the value $y = 0$, $x = 3\pi$. The obtained control points are used in two variants: sequential data and shuffled data.

In the first case, the sequence of control point formation was described above, in the second – their order is randomly changed. Figure 1 shows the dialog window for generating input data to build two polynomials. The number of control points for the first calculation is 9, and for the second – 101. In this case, the data is not "shuffled". The location of the control points is shown in Figure 2.

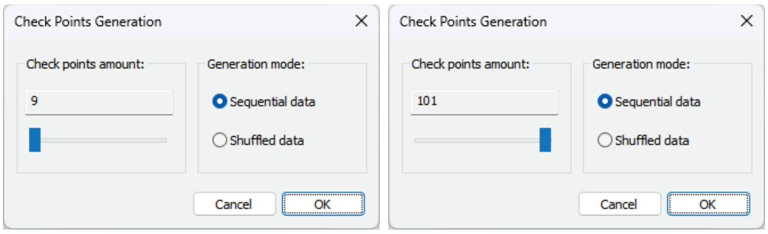


Figure 1. *Message box for generating input data*

Source: *software developed by the authors*

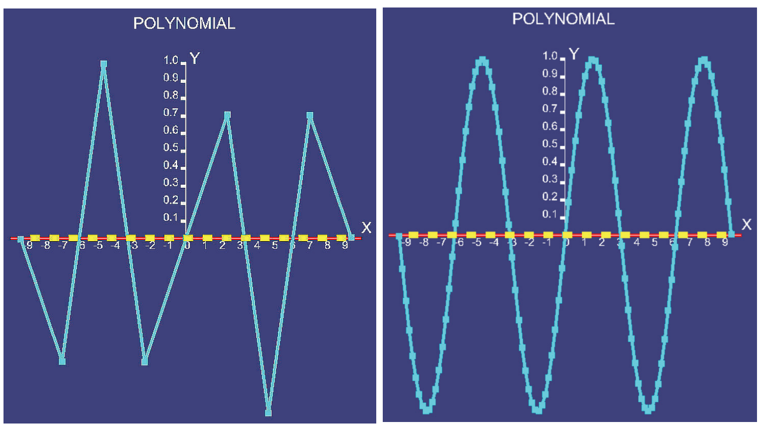


Figure 2. *Location at 9 and 101 point*

Source: *software developed by the authors*

In Microsoft Excel, the degree of correspondence between the model and the real data is determined by the coefficient of determination, R^2. In other words, this is a measure of the model's accuracy. R^2 is calculated using formula (5):

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}; \; \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i, \quad (5)$$

where n – the number of input data points; y_i and $\hat{y}_i$ – the actual and predicted values of the indicator.

If $R^2 = 1$, this corresponds to a perfect model in which all observation points lie exactly on the regression line – that is, the sum of squared deviations is zero. If $R^2 = 0$, there is no relationship between the variables in the polynomial model, and instead, the mean of the observed values can be used to estimate the output variable. A model with R^2 in the range of 0.5 to 0.8 is considered satisfactory. If $R^2 > 0.8$, the model is regarded as highly reliable. Values below 0.5 indicate that the model is ineffective. A polynomial passes through all control points when its degree is maximal – that is, one less than the number of input data points. Figure 3 presents an 8th-degree polynomial for 9 control points.

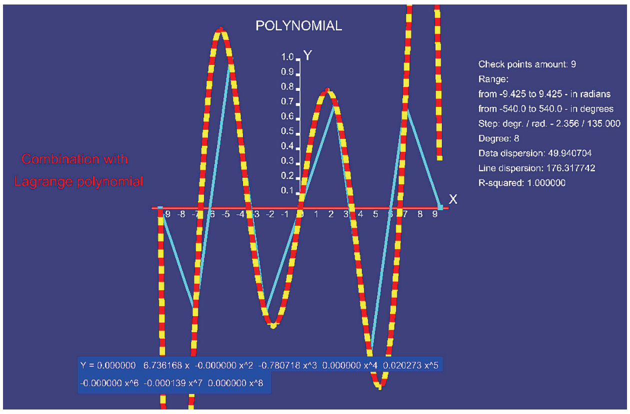


Figure 3. *Polynomial of degree 8*
Notes: *below is the equation of polynomial of degree 8*
Source: *software developed by the authors*

As shown in Figure 3, the polynomial passes through all control points, and in this case $R^2 = 1$. However, the use of such a polynomial is impractical due to sharp fluctuations between the control points. In this case, it is proposed to compare the variances of the data and the curve using formula (6):

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(X_i - \bar{X})^2. \qquad (6)$$

These values are presented in Figure 3. Here, the variance of the input data is 49.9, and the estimated variance of the curve (based on the function values at increasing arguments with a fixed step) is 176.3. In this case, even though $R^2 = 1$, adopting such a model would be incorrect. Therefore, in addition to R^2, the variance ratio should be considered. It is proposed that the acceptable difference in variances should not exceed 20%, although this may vary depending on the specifics of the domain under study. Figures 4 and 5 show 7th- and 10th-degree polynomials constructed for 40 input points.

It was visually evident that the 10th-degree polynomial model proved to be more effective. This was also confirmed by quantitative evaluation. As observed from the data presented in Figures 4-5, the variance of the input data equalled 50. The variances of the 7th- and 10th-degree polynomials amounted to 32.2 and 48.4, respectively. The deviations of the variances of the 7th-degree and 10th-degree polynomials from the variance of the input data (k_7 and k_{10}) were determined as follows:

For the 7th-degree polynomial:
$k_7 = (50 - 32.2)/50 \cdot 100 = 35.6\%$

For the 10th-degree polynomial:
$k_{10} = (50 - 48.4)/50 \cdot 100 = 3.2\%$

The value of k_{10} was significantly below 20% in comparison to k_7.

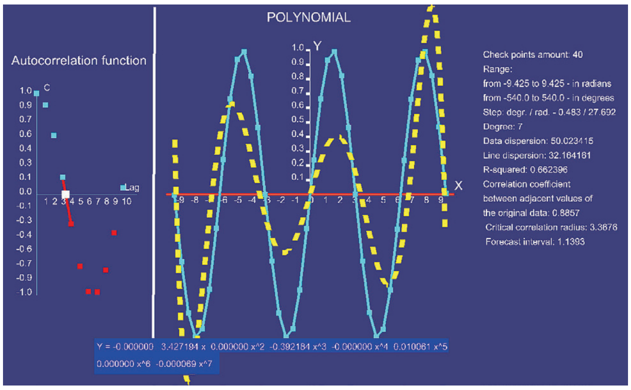


Figure 4. *Polynomial of degree 7*
Source: *software developed by the authors*

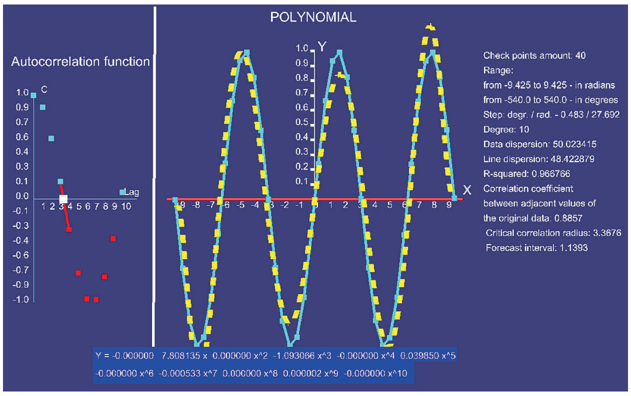


Figure 5. *Polynomial of degree 10*
Source: *software developed by the authors*

As shown in Figure 5, the same input data were used ($N = 40$, degree = 10), but they were arranged in a random order. These were generated by selecting the "Shuffled data" option in the dialogue window (Fig. 1). In this case, the polynomial variance ratio equalled (Fig. 6): $k_{10} = (50 - 16.2)/50 \cdot 100 = 67.6\%$. Such a model could not be considered acceptable.

As previously indicated, a polynomial passed through all N control points if its degree equalled $N - 1$. This was demonstrated in Figure 3, which presented an 8th-degree polynomial for 9 control points. The curve was represented by a line comprising alternating red and yellow segments. In this case, the constructed polynomial fully coincided with the Lagrange polynomial.

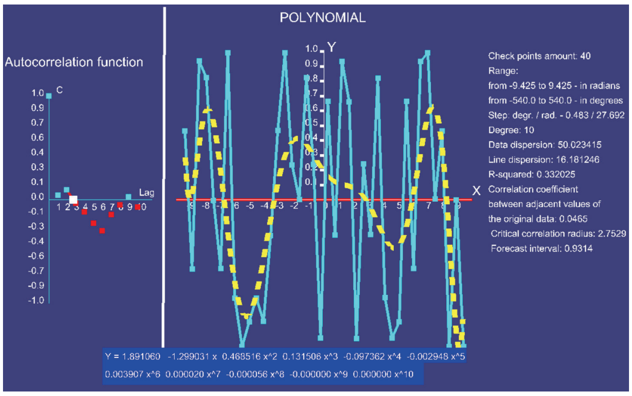


Figure 6. *Polynomial of degree 10 ("shuffled data")*
Source: *software developed by the authors*

This polynomial strictly passed through all control points. This result indicated that the constructed polynomial was sufficiently universal for any given degree and, in particular, coincided completely with the Lagrange polynomial when the degree equalled $N - 1$. In the Lagrange polynomial, for $N + 1$ numbers (x_0, y_0), (x_1, y_1), ..., (x_n, y_n), there existed a unique polynomial of degree N such that (7):

$$L(x) = \sum_{i=0}^{n} y_i\, l_i\,(x), \tag{7}$$

where $l_i(x)$ was defined by formula (8):

$$l_i(x) = \\ = \prod_{j=0, j \neq i}^{n} \frac{x - x_j}{x_i - x_j} = \frac{x - x_0}{x_i - x_0} \cdots \frac{x - x_{i-1}}{x_i - x_{i-1}} \cdot \frac{x - x_{i+1}}{x_i - x_{i+1}} \cdots \frac{x - x_n}{x_i - x_n}. \tag{8}$$

For any $i = 0, \ldots, n$, the polynomial l_i had a degree of n and satisfied the condition (9):

$$l_i(x_j) = \begin{cases} 0, & j \neq i, \\ 1 & j = i. \end{cases} \tag{9}$$

Hence, $L(x)$ was a linear combination of the polynomials $l_i(x)$ and had a degree of no more than n, while also satisfying $L(x_i) = y_i$. During the study of polynomial models, an important indicator for evaluating spatial variability was examined. For this purpose, the autocorrelation function (ACF) was utilised. Quantitatively, the ACF could be measured using autocorrelation coefficients. The ACF was a function $r_m = f(m)$, where r_m represented the autocorrelation coefficient between the initial sequence of control points and the sequence shifted relative to the initial one by a lag of m. For example, the initial sequence included n numbers. In this case, $n = 8$ with the following values: 5, 8, 1, 9, 4, 6, 9, 10. For a shift $m = 1$, the autocorrelation coefficient (degree of association) was determined between $n - m$ pairs of numbers: 5, 8, 1, 9, 4, 6, 9 – 8, 1, 9, 4, 6, 9, 10. For $m = 2$, the autocorrelation coefficient was determined between $n - m$ pairs: 5, 8, 1, 9, 4, 6 – 1, 9, 4, 6, 9, 10, and so forth. Thus, in constructing the ACF, the values of r_m (autocorrelation coefficients for increasing m) were used. The value of r_m was determined by formula (10):

$$r_m = \frac{\sum_{i=0}^{n-m}(x_i - \bar{x}_1)(x_{i+m} - \bar{x}_2)}{\sqrt{\sum_{i=0}^{n-m}(x_i - \bar{x}_1)^2 (x_{i+m} - \bar{x}_2)^2}}, \tag{10}$$

where $\bar{x}_1$ – the arithmetic mean of the initial sequence (from the first to the $n - m$ elements), and $\bar{x}_2$ – the arithmetic mean of the "shifted" sequence (from the m-th to the n-th elements).

It was noted that with each increment of lag m by one, the number of value pairs used to calculate the ACF coefficient decreased by one. Therefore, the maximum lag (m) was usually recommended to be equal to $n/4$. The ACF reached its maximum value of 1 at $m = 0$ (indicating full self-correlation of the series), and equalled 0 when the initial sequence and its shifted counterpart were uncorrelated. The faster the autocorrelation function decreased with increasing m, the weaker the autocorrelation was, and vice versa. The ACF gradually decreased and intersected the abscissa axis at a distance r_k from the origin. The parameter r_k was referred to as the critical correlation radius. At the initial shift ($m = 1$), r_1 was defined as the autocorrelation coefficient between values at adjacent control points. When $r_1 > 0.7$, a consistent trend in the variation of the studied parameter was observed. When $r_1 \leqslant 0.7$, the dataset was considered a set of random, independent variables. Figures 4-6 illustrated the autocorrelation functions and their corresponding critical correlation radius. The number of control points equalled 40. Figures 4 and 5 employed identical input data; therefore, the results of the autocorrelation analysis were also identical: the autocorrelation coefficient between adjacent values in the input data was $r_1 = 0.88$; the critical correlation radius equalled $r_k = 3.36$. In Figure 6, using the same 40 input values but arranged in random order, the results were as follows: $r_1 = 0.039$, $r_k = 1.78$.

Three factors were identified as determining the adequacy level of the polynomial model: 1) the coefficient of determination, which depended on the degree α; 2) the ratio of the variances between the curve and the control points; 3) the autocorrelation between adjacent values in the input data (r_1). Among these, the second and third factors were of greatest significance. Moreover, these factors were interrelated. The model was considered effective when $r_1 > 0.7$ and the ratio of the variances between the curve and input data was less than 20%. While r_1 depended solely on the input data, the variance ratio depended on the selected polynomial degree α.

When evaluating the spatial variability of indicators, the critical correlation radius r_k, as described by O. Zelensky & V. Lysenko (2022), was regarded as an important parameter. This value allowed for the estimation of forecast capability beyond the polynomial construction range. The application of r_k was further examined within the GMSS system. For many years, the GMSS system, as part of an automated quarry management system, had been implemented in non-ferrous and iron ore deposits. In this context, the input data mainly comprised the coordinates from borehole collar surveys, bench edges, tracks, and other objects, as well as the results of blast hole testing and both detailed and operational exploration.

Implementation experience demonstrated that at non-ferrous deposits, blast hole testing was carried out almost comprehensively, i.e. for all boreholes. The critical correlation radius r_k, determined in the study of variability of total copper content (Cu_{tot}) in the porphyry copper ores of the Erdenet GMSS, were presented in Table 1. In this case, the network of blast and exploration boreholes revealed the natural characteristics of the studied parameters along the quarry horizons, as the correlation radius exceeded the testing intervals. In terms of deposit depth, the critical correlation radius was significantly less than the bench height (15 m), indicating the appropriateness of forecasting quality parameters based on blast hole test data from the overlying horizon for the purpose of operational resource estimation under conditions of limited exploration data availability. This approach allowed for significant cost reduction in conducting expensive exploration operations.

Table 1. *Critical correlation radius for Cutotal (in meters)*

Test Network	By the area of the deposit		By depth
	along the strike	across the strike	
By blast borehole, 8×8	24 ± 7	20 ± 12	120 ± 20
By exploration borehole, 30×60	130 ± 40	100 ± 40	

Source: *developed by the authors on the basis of their own research*

Anisotropy is present, and to evaluate it, an indicatrix in the form of an ellipse is used, which illustrates the variability of parameters in different directions. The indicatrix is constructed based on the critical correlation radius in various directions. Figure 7(a) shows the autocorrelation function and the corresponding indicatrix. The use of indicatrices to assess the variability of a key parameter in the mining face-based on blast hole testing data from the digital model of the deposit-allows for a reduction in fluctuations of the parameter in the ore flow by selecting the mining direction along the major axis of the indicatrix. In Figure 7(b), the arrow indicates the direction of the least variability, which is the proposed mining direction.

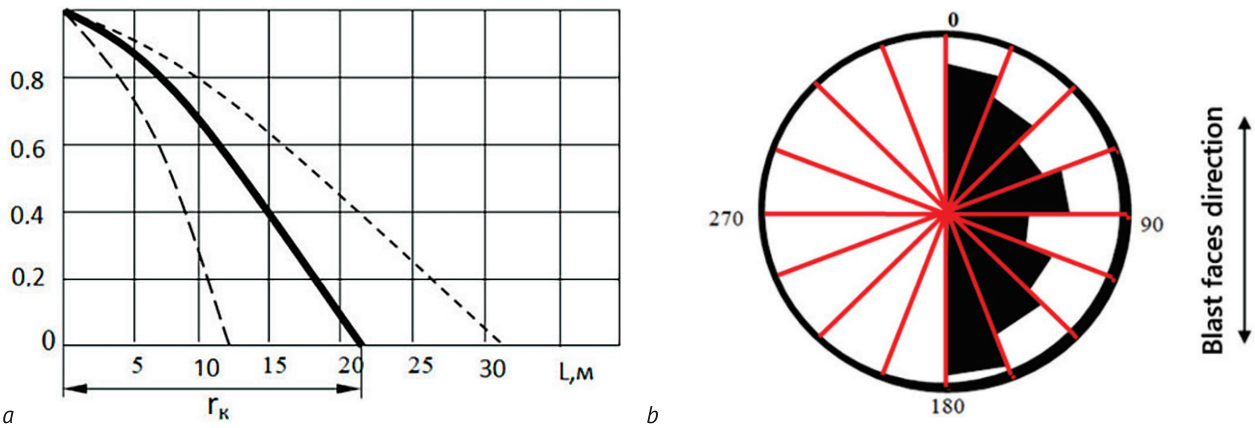
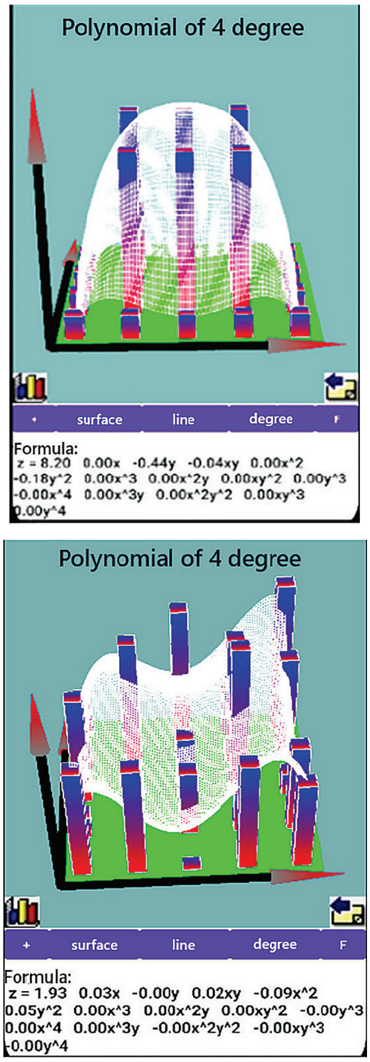


Figure 7. *Indicators of variability of indicators*

Notes: *a – autocorrelation function; b – indicatrix*

Source: *software developed by the authors*

The construction of a surface based on a polynomial model is presented in the works of O. Zelensky (2023). These works also provided a simplified algorithm for implementing the least squares method. The core of the algorithm is minimising the sum of squared deviations of the function $z = f(x, y)$ from the input data. Figure 8 shows two degree-4 polynomials (surfaces) based on 25 input data points. In Figure 8(a), model adequacy can be assessed using the coefficient of determination. However, this is a specific case where the indicator values change smoothly. In cases of more complex variability, a second indicator must be used: the deviation between the variance of the input data and the variance of the fitted surface. This is evident in the example shown in Figure 8(b). A detailed selection of surface construction methods requires further research.



a

b

Figure 8. *Building a surface with a polynomial of degree 4*
Notes: *a – sequential data; b – shuffled data*
Source: *software developed by the authors*

The construction of a surface within a specified contour by pit horizons is carried out as follows. The user defines a contour that is covered with a regular grid of a given step size. At each grid node Z_A, the indicator value is interpolated based on test data from the nearest boreholes. The algorithm for finding these nearest boreholes is described in the work of O. Zelensky & V. Lysenko (2022). The indicator value at a node is determined using the inverse distance method (11):

$$Z_A = \frac{\sum_{i=1}^{N} Z_i \cdot d_i^{-\alpha}}{\sum_{i=1}^{N} d_i^{-\alpha}}, \qquad (11)$$

where α – the interpolation power (usually $\alpha = 2$); d_i – the distance between the node and the i-th closest borehole; Z_i – the indicator value at the i-th borehole; N – the number of nearest boreholes to the node.

This well-known formula does not account for the natural component of indicator variability. This can be addressed by incorporating the indicatrix, which reflects the presence of critical correlation radius in all directions. In this case, the inverse distance method is refined as follows (12, 13):

$$Z_A = \frac{\sum_{i=1}^{N} Z_i \cdot d_i^{-\alpha ot_i}}{\sum_{i=1}^{N} d_i^{-\alpha ot_i}}, \qquad (12)$$

$$ot_i = \frac{r_{ki}}{r_{kmax}}, \qquad (13)$$

where r_{ki} – the critical correlation radius in the i-th direction; r_{kmax} – the maximum critical correlation radius.

One of the modules of the developed automated GMSS for the conditions of the Southern MPP includes an interpolated 3d model, shown in Figure 9. The user defines a contour, which is covered with a regular grid with a defined step size *sh*. For each grid node, rectangular prisms are constructed, with heights equal to the interpolated Fe_{mag} values, and the base being a square with side length *sh*. The coordinates *x*, *y* of the square's centre correspond to the *x*, *y* coordinates of the grid node. An alternative to the interpolation model is a wireframe model (Fig. 10), where interpolated values are simply connected by straight lines.

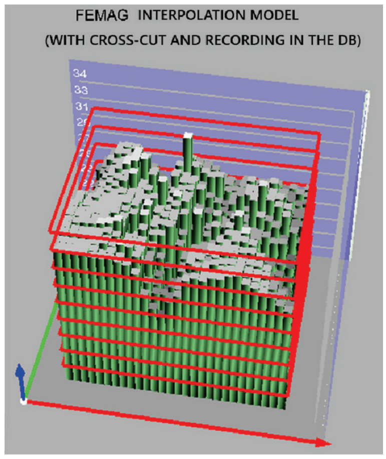


Figure 9. Interpolation model of Fe_{mag} variability
Source: *software developed by the authors*

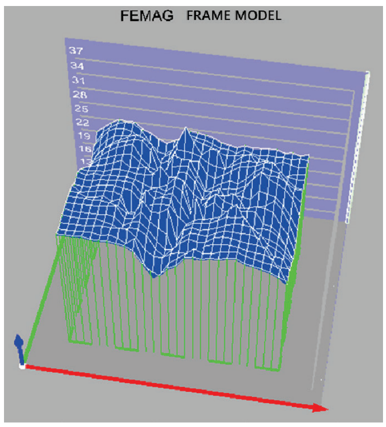


Figure 10. *Wireframe model of* Fe_{mag} *variability*
Source: *software developed by the authors*

Particular attention within the conducted study was devoted to the assessment of the adequacy of a polynomial model reflecting the relationship between input and output data in forecasting tasks. The results obtained during the experiments confirmed the necessity of a more thorough analysis of both the accuracy of the models themselves and the interpretability of the resulting coefficients, taking into account the spatial and statistical properties of the data.

One of the fundamental tools for assessing model quality was the coefficient of determination (R^2), which is used, in particular, within the Microsoft Excel software environment. However, its application was not always sufficient for adequate evaluation, especially in cases involving spatial or temporal variability of data between control points. In this study, the problem was partially addressed through additional analysis of spatial variability by means of the autocorrelation function and variance ratio, which enabled the assessment of model smoothness and stability in the intervals between known values. This approach shared common features with the method of statistical modelling of random fields proposed by Z. Vizhva *et al*. (2023), where emphasis was likewise placed on accounting for structural heterogeneity and constructing adequate realisations to supplement incomplete data. The distinction lay in the application area (geophysics versus general-purpose regression modelling); however, the approach to handling the spatial components of the data was conceptually similar.

At the same time, as noted by B. Sencer (2024), Excel possesses significant limitations in regression analysis, particularly concerning the assessment of non-linear models. The author pointed to the systematic overestimation of the coefficients of determination in the case of non-linear functions approximated as linear. In this study, such issues were addressed through the use of R^2, root mean square error, and mean absolute error calculations within an external environment, which allowed the avoidance of misleading conclusions typical for Excel's built-in functions. Hence, the obtained results confirmed the need for a critical evaluation of standard statistical analysis tools, especially in the context of complex models. An alternative perspective was presented by U. Srilakshmi *et al*. (2024), who, working in the field of predictive modelling in healthcare, proposed an innovative approach to improving the efficiency of linear regression models by reducing the dimensionality of variables. Unlike traditional methods, this approach involved a preliminary transformation of input data, which significantly reduced the sum of squared errors. The research described in this article did not involve prior dimensionality reduction; however, the influence of the random component on model accuracy was taken into account. Moreover, both studies indicated the advantage of using non-parametric methods in cases where classical assumptions were violated.

To support this, reference may be made to the conclusions of W. Laverty & I. Kelly (2021), who compared the least squares method with the non-parametric Kendall and Theil approach. In cases where data exhibited heteroscedasticity or asymmetry, the latter method provided high estimation efficiency. In the cases considered in this article, some datasets displayed signs of non-normality, making the application of adaptive or non-parametric modelling approaches particularly relevant. This aligned with the findings of O. Tkachenko (2021), who proposed an approach for adaptive regression parameter estimation using higher-order statistics. Such an approach enabled the adjustment of models to real data violating Gaussian assumptions, which were not accounted for in classical regression analysis within Excel. These considerations were further supported by the conclusions of D. Tadashi *et al*. (2024), who focused on the development of local polynomial models of software reliability. Although the applied domain differed, their approach to polynomial degree control and adaptive forecasting was highly relevant in terms of modelling complex dependencies in data. The idea of using semi-parametric models could also be adapted within general regression tasks to achieve greater flexibility in model construction.

In the study by O. Zorin & V. Palahin (2023), a new approach to the statistical processing of RZ-signals was proposed, based on the use of moment-cumulant models for describing the fine structure of random processes. Although the subject area differed slightly, the proposed method involved constructing polynomial stochastic solvable rules with coefficient optimisation based on a moment criterion. The practical implementation and testing of such algorithms became possible through MATLAB tools, which were detailed in the work of O. Romanyuk *et al*. (2024). The MATLAB environment provided the necessary functionality for implementing numerical methods, system modelling, and visualisation of results, which was critically important for evaluating the effectiveness of new reception methods under complex noise conditions. This once again highlighted the importance of polynomial models and their feasibility of implementation across various programming environments or mathematical software packages.

Thus, the comparative analysis of the results of the study presented in this article with existing approaches in the literature enabled several important generalisations to be drawn. Standard analytical tools, such as Microsoft Excel, remained limited in the context of evaluating complex models, particularly in cases of non-linear or adaptive regression. Spatial or statistical data analysis between control points allowed for improved modelling accuracy, as confirmed both in this study and in the works of other authors. The application of adaptive and non-parametric approaches, such as those proposed by W. Laverty & I. Kelly (2021), O. Tkachenko (2021), and U. Srilakshmi *et al*. (2024), opened new possibilities for improving model accuracy, especially when classical statistical assumptions were violated. The development of more sophisticated models, including semi-parametric or local polynomial types, enabled effective modelling of complex systems, with wide-ranging applications not only in engineering or economics, but also in healthcare, software reliability, and geophysics.

In summary, it may be stated that the effective application of methods for assessing the adequacy of polynomial models under modern conditions required a comprehensive approach, combining classical techniques with adaptive methods, the use of new spatial data processing tools, and non-parametric statistical approaches. The obtained results confirmed the potential for further research into the improvement of model quality assessment, taking into account the spatio-temporal heterogeneity of data, which had become particularly relevant in interdisciplinary areas of mathematical modelling application.

Conclusions

The article presented a study of polynomial functions $y = f(x)$ and $z = f(x, y)$ of a given degree. The implementation of the polynomial model was based on the method of least squares. Due to the complexity of the task, a simplified algorithm was proposed, which reduced the problem to solving a system of linear equations. The adequacy of the polynomial model was assessed using integrated packages of the coefficient of determination R^2, as implemented in Microsoft Excel. However, this assessment remained limited, as it did not take into account the nature of the curve's behaviour between control points. This significant drawback was addressed by two additional indicators. The first indicator involved the ratio of the variances of the input data and the curve points. The second indicator comprised the assessment of spatial variability of indicators using an autocorrelation function. All studies described in the article were carried out in an automated mode, which considerably simplified the process and enabled the simulation of a substantial amount of data for obtaining results. An example included the construction of a polynomial curve of a selected degree α, equal to one less than the number of control points (N - 1). In this case, the curve passed precisely through the control points. An identical curve was obtained using the Lagrange method. When constructing the autocorrelation function, the assessment of spatial variability of the indicator was determined by the autocorrelation coefficient between values at neighbouring control points, as well as by the critical correlation radius r_k, which enabled the evaluation of the forecasting capability beyond the constructed polynomial. In the automated HMSS system, critical correlation radius was used for assessing the test network across all boreholes (exploratory and blasting). The parameters of the network had to reflect the natural characteristics of the studied indicators.

In the case of non-ferrous metals, tests were generally conducted on blasting boreholes. If the deposit depth exceeded r_k, i.e. the height of the bench, it was considered appropriate to forecast the qualitative indicators based on test data from blasting boreholes of the overlying horizon. This significantly reduced the need for costly exploratory operations. Based on r_k values in different planar directions, an indicatrix was constructed. Its use enabled the implementation of interpolation and framework models that accounted for the spatial variability of indicators. The construction of curves and surfaces was performed for both desktop and mobile applications and was successfully implemented at non-ferrous and iron ore deposits as part of an automated geological and mine surveying system. Future research prospects involved improving spatial forecasting algorithms using surfaces as an example, and integrating the software with artificial intelligence for adapting results to various geological and technical conditions.

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Conflict of Interest

None.

References

[1] Bell, J.W. (2020). Polynomial least squares multiple-model estimation: Simple, optimal, adaptive, and practical. *SN Applied Sciences*, 2, article number 1964. doi: 10.1007/s42452-020-03439-x.

[2] Bidiuk, P.I., Demkivskyi, Y.O., & Demkivska, T.I. (2020). Method of development of heteroskedastic processes models. *Bulletin of the Kyiv National University of Technology and Design. Technical Science Series*, 142(1), 19-26. doi: 10.30857/1813-6796.2020.1.2.

[3] David, I.J., Adubisi, O.D., Ogbaji, O.E., Eghwerido, J.T., & Umar, Z.A. (2020). Resistant measures in assessing the adequacy of regression models. *Scientific African*, 8, article number e00437. doi: 10.1016/j.sciaf.2020.e00437.

[4] Horbachuk, V.M., & Kushlyk-Dyvulska, O.I. (2023). *Probability theory and mathematical statistics*. Kyiv: Igor Sikorsky Kyiv Polytechnic Institute.

[5] Khlivnyi, V.V., & Bazilo, C.V. (2023). Influence of operating parameters of hydroabrasive cutting of various materials on the accuracy of observing the cutting width. *Bulletin of Cherkasy State Technological University*, 28(2), 38-49. doi: 10.24025/2306-4412.2.2023.280719.

[6] Lapach, S.M. (2025). Conflict of user accuracy requirements and regression model indicators. *Mathematical Machines and Systems*, 2025(1), 91-102. doi: 10.34121/1028-9763-2025-1-91-102.

[7] Laverty, W.H., & Kelly, I.W. (2021). Exploring the effects of assumption violations on simple linear regression and correlation using Excel. *American Journal of Theoretical and Applied Statistics*, 10(4), 194-201. doi: 10.11648/j.ajtas.20211004.13.

[8] Manoukian, E.B. (2021). *Mathematical nonparametric statistics*. Hoboken: Taylor & Francis Group.

[9] Mountgomery, D.C., Peck, E.A., & Vining, G.G. (2021). *Introduction to linear regression analysis* (6th ed). Hoboken: John Wiley & Sons, Inc.

[10] Pardoe, I. (2021). *Applied regression modeling* (3d ed.). Hoboken: John Wiley & Sons, Inc.

[11] Prokaza, O.I., & Kuznetsova, O.V. (2022). Construction of mathematical models of evaporation plant by experimental-statistical method. *Visnik of the Volodymyr Dahl East Ukrainian National University*, 271(1), 36-40. doi: 10.33216/1998-7927-2022-271-1-36-40.

[12] Romanyuk, O.N., Romanyuk, O.V., & Tsikhanovskaya, O.M. (2024). Information support for economic disciplines. In *Proceedings of the XVII international scientific and practical conference of the information technologies and automation – 2024* (pp. 393-396). Odesa: Odesa National University of Technology.

[13] Sencer, B. (2024). On the pros and cons of using Excel for regression analysis. *Turkish Journal of Agriculture – Food Science and Technology*, 12(s2), 2234-2241. doi: 10.24925/turjaf.v12is2.2234-2241.6931.

[14] Srilakshmi, U., Manikandan, J., Thanmayee, V., Abhinav, G., Tharun, K., & Saideep, D. (2024). A new approach to computationally-successful linear and polynomial regression analytics of large data in medicine. *Journal of Computer Allied Intelligence*, 2(2), 35-48. doi: 10.69996/jcai.2024009.

[15] Tadashi, D., Siqiao, L., & Okamura, H. (2024). Local polynomial software reliability models and their application. *Information and Software Technology*, 166, article number 107366. doi: 10.1016/j.infsof.2023.107366.

[16] Tkachenko, O.M. (2021). *Polynomial methods and tools for estimating regression parameters using Non-Gaussian error models*. (Doctoral dissertation, Cherkasy State Technological University, Cherkasy, Ukraine).

[17] Vizhva, Z., Demydov, V., & Vizhva, A. (2023). Statistical modeling of random fields with Gaussian correlation function for magnetometry data analysis. *Bulletin of Taras Shevchenko National University of Kyiv: Geology*, 3(102), 81-87. doi: 10.17721/1728-2713.102.

[18] Zelensky, O. (2023). Construction surface using desktop and mobile applications. *Scientific and Practical Journal "Economics and Technical Engineering"*, 1(1), 87-102. doi: 10.62911/ete.2023.01.01.07.

[19] Zelensky, O.S., & Lysenko, V.S. (2022). Improvement of automated contouring of ore grades along the horizons of ore quarries. *Journal of Kryvyi Rih National University*, 55, 15-24. doi: 10.31721/2306-5451-2022-1-55-15-24.

[20] Zorin, O., & Palahin, V. (2023). Adaptive system for receiving data by bipolar discrete signals in information and measurement systems in asymmetric non-Gaussian noise. In *International scientific conference of the information technologies and computer modelling* (pp. 181-182). Ivano-Frankivsk: Vasyl Stefanyk Precarpathian National University.

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Дослідження та використання поліноміальних моделей при розробці автоматизованого геолого-маркшейдерського забезпечення гірничих робіт у кар'єрі

Анотація. Актуальність дослідження зумовлена потребою в підвищенні точності та ефективності геолого-маркшейдерських робіт в умовах складної геологічної будови та обмежених ресурсів для польових досліджень. Розробка та впровадження автоматизованого програмного забезпечення надали змогу оперативно аналізувати великі обсяги даних, оптимізувати мережу випробувань і зменшити витрати на розвідувальні роботи. Метою дослідження була розробка програмного забезпечення поліноміальних моделей кривих і поверхонь із запропонованим спрощеним алгоритмом реалізації методу найменших квадратів. Програмне забезпечення для десктопного додатку розроблено в середовищі Microsoft Visual Studio 2019 на базі бібліотеки Microsoft Foundation Classes. Мобільний додаток розроблено в середовищі Android Studio. Для роботи з 3D-графікою застосовується бібліотека OpenGL з використанням шейдерів, що забезпечує високу продуктивність експлуатації. Було визначено параметри для оцінки адекватності моделі, яка в стандартних автономних пакетах недостатньо об'єктивна. В автоматизованому режимі показано, що поліном Лагранжа є окремим випадком розробленої поліноміальної моделі при побудові кривих. Крім того, вдосконалено інтерполяційний метод при побудові поверхні. При цьому враховується просторова мінливість показників з використанням автокореляційних функцій. При побудові автокореляційних функцій було здійснено оцінку просторової мінливості показника на основі коефіцієнтів автокореляції між значеннями у сусідніх контрольних точках, а також критичного радіуса кореляції, що дало змогу оцінити потенціал прогнозування за межами зони побудови полінома. Було описано застосування критичних радіусів кореляції в автоматизованій системі геолого-маркшейдерського забезпечення для аналізу мережі випробувань усіх свердловин (вибухових і розвідувальних). Було зазначено, що параметри мережі мають відображати природну варіативність досліджуваних показників. У випадках, коли глибина покладів перевищує висоту уступу, було розглянуто доцільність прогнозування якісних характеристик за результатами випробувань вибухових свердловин, розташованих вище залягання корисної копалини, що дозволяє суттєво скоротити обсяги дорогих розвідувальних робіт. Було встановлено, що багатомодульна автоматизована система геолого-маркшейдерського забезпечення протягом багатьох років удосконалюється та впроваджується на кар'єрах, зокрема на підприємстві «Ерденет» (Монголія), яке розробляє мідно-молібденове родовище. Результати проведених досліджень використано у навчальному процесі та в автоматизованій системі геолого-маркшейдерського забезпечення при плануванні та керуванні гірничих робіт у кар'єрі

Ключові слова: регресійна модель; автокореляційна функція; метод найменших квадратів; метод Лагранжа; каркасна модель; критичний радіус кореляції; індикатриса

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Assessment of the impact of soil water saturation at the Malyshevske deposit on the stability of quarry structures

Abstract. A high groundwater level and significant wettability of ore sands at the Malyshevske deposit create substantial risks for the stability of foundations, base soils, and structures within the quarry field. The study of these factors is critically important for ensuring the safety and reliability of mining and construction facilities. The objective of the paper was to determine the physical and mechanical properties and to assess the influence of ore sands on the stability of foundations, base soils, and structures within the quarry zone of the Malyshevske deposit, as well as to develop recommendations for their stabilisation. A comprehensive set of research methods was applied, including hydrogeological, geophysical, hydraulic analyses, and mathematical calculations. The investigation of hydrogeological conditions was used to identify the groundwater level and its impact on structural stability. Testing of ore sands was conducted to determine their physical and mechanical characteristics, including permeability and filtration properties. Key factors affecting foundation stability in high moisture zones were identified. Recommendations were developed to increase the bearing capacity of base soils and foundations through drainage systems, soil injection stabilisation, and the use of special materials with low permeability. The actual average filtration coefficient of ore sands at the Malyshevske deposit was determined using the piezometric head method. For the first time in this region, integrated measures were proposed that include a combination of drainage and filtration systems to reduce groundwater levels, along with mathematical modelling to forecast the impact of these changes on the stability of quarry structures. The study has considerable practical significance for the design and operation of quarries under conditions of elevated groundwater levels and high soil moisture saturation. The proposed methods and measures allow for effective risk reduction associated with fluctuations in groundwater levels and ensure the stability of quarry structures, which in turn enhances the safety of mining operations and reduces maintenance costs for engineering facilities

Keywords: hydrogeology; groundwater; wettability; drainage; soil stabilisation; safety

Introduction

The stability of foundations and bases under complex hydrogeological conditions is a critically important factor for the safe operation of industrial and construction facilities within the quarry area. The high groundwater level and considerable wettability of ore sands at the Malyshevske deposit pose significant engineering challenges, directly affecting the reliability of structures and the safety of personnel working in the

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extraction zone. Deformation of water-saturated soils in an open-pit environment can lead to subsidence, uneven settlement of foundations, loss of bearing capacity of structures, and the development of landslide processes. This poses a threat both to the integrity of infrastructure and to the lives of workers located within the hazardous zone. Additional negative factors include atmospheric precipitation, the hydrodynamic impact of filtration flows, seismic loads, and seasonal fluctuations in the groundwater level, which may lead to uncontrolled deformations and emergency situations.

D. Babets *et al*. (2020) studied the impact of water saturation on the strength characteristics of sedimentary rocks. They found that increased moisture significantly reduces rock strength, which may cause deformation and failure of structures founded on such soils. This highlighted the importance of considering water saturation in the design of foundations and other engineering structures. H.N. Ngugi *et al*. (2021) examined the effect of soil moisture variation on deformation and differential settlement of frame structures in the Nairobi area. They concluded that moisture changes can lead to significant differential settlement, negatively affecting building stability and integrity. This study underlined the importance of moisture control in soils to ensure structural stability.

L. He *et al*. (2024) analysed the mechanisms of destabilisation and landslide prevention technologies in open-pit mines with soft interlayers under the influence of rainwater infiltration. They found that water infiltration into such layers significantly reduces their strength, which can result in landslides and collapses. The authors proposed a set of measures to improve slope stability, including drainage systems and soil reinforcement. V. Ivanov *et al*. (2020) studied the role of water in the stability of shallow landslides, based on experimental tests. They found that increased soil moisture reduces its strength and increases the risk of landslides. The researchers emphasised the need to consider hydrogeological conditions when assessing slope stability and designing engineering measures.

The researchers J. Ślusarek & M. Łupieżowiec (2020) analysed the influence of soil moisture on the stability of buildings situated on slopes. They concluded that increased moisture could lead to a reduction in soil strength and foundation deformation, negatively affecting the structural stability of buildings. The authors recommended the use of drainage systems and waterproofing to minimise the adverse effects of moisture. The scientists M. Maknoon & M. Aubertin (2021) studied the use of terracing to improve the stability of mine waste embankments. They found that the creation of terraces reduces the rate of water infiltration and enhances slope stability. This research highlights the importance of structural solutions for managing water saturation in mining dumps. The researchers Y. Abramov *et al*. (2022) conducted a study aimed at substantiating an experimental method for determining fluid percolation parameters in bulk materials. They identified key relationships between infiltration rate and the physical and mechanical characteristics of porous media. This study is valuable for assessing the water permeability of ore sands at the Malyshevske deposit, which is an important factor in evaluating the stability of quarry structure foundations.

The scientist T.K. Tokunaga (2020) proposed a simplified Green-Ampt model for assessing soil permeability and predicting infiltration processes. The researcher studied water filtration mechanisms in porous media and concluded that it is necessary to take capillary effects into account when modelling hydrogeological conditions. These findings can be applied to forecasting soil behaviour under quarry conditions with high moisture levels. The research by V. Oliinyk *et al*. (2022) was dedicated to developing a method for the experimental determination of water infiltration parameters in soil. The authors demonstrated that the structure of the pore space and the moisture content significantly affect the water penetration rate, which may be useful for evaluating potential risks of foundation base erosion under quarry conditions.

Thus, the analysis of scientific literature indicated that previous studies have mostly focused on the physicochemical properties of ore sand components, methods for their determination, and the influence of these characteristics on technological processes. Despite the considerable body of scientific research, the comprehensive impact of ore sand water saturation on the stability of quarry structures at the Malyshevske deposit remains insufficiently explored. Systematic studies that combine hydrogeological, mechanical, and mathematical aspects of structural stability forecasting are lacking. The issue of developing effective measures for stabilising foundations and bases under high moisture conditions remains particularly relevant. In this context, the aim of the study was to determine the physical and mechanical properties of ore sands and assess their influence on the stability of bases, foundations, and structures within the quarry zone of the Malyshevske deposit. As part of the study, recommendations were also developed for soil stabilisation and groundwater level reduction using drainage systems and specialised construction materials.

Literature Review

To assess the stability of structures under quarry conditions, it is necessary to consider the effects of soil water saturation, changes in their physical and mechanical properties, as well as environmental aspects associated with mining waste. Research in this area covers a wide range of issues, from soil mechanics and geotechnical fundamentals to slope stability analysis and long-term environmental risks. This review considered recent scientific studies that highlighted these aspects and are important for understanding the processes affecting the safety of construction and operation of engineering structures in mining regions.

M. Zotsenko *et al.* (2004), in their textbook on engineering geology, examined soil mechanics, the fundamentals of foundation and basement structure design. The authors provided a detailed analysis of the physical and mechanical properties of soils and their interaction with the surrounding environment. This work serves as an important theoretical basis for assessing the stability of building structures in areas with a high level of soil water saturation, particularly under mining conditions. Professor V. Suiarko (2019) investigated engineering geology and geotechnical fundamentals, focusing on the mechanical properties of soils, their stability, and their use in the design of foundations and structures. The author emphasised the importance of hydrogeological analysis to ensure the stability of geotechnical structures. This study is a valuable resource for assessing the impact of high groundwater levels on construction safety, which is directly related to the subject matter of this work. B. Vriens *et al.* (2020) underlined the importance of sustainable management of mining waste to prevent adverse hydrogeochemical processes that may affect the environment and soil stability. Their study also pointed to the necessity of monitoring and controlling emissions from waste as a vital aspect of mine safety. This research is significant as it provides an assessment of the impact of waste on soil stability and suggests measures to minimise negative consequences. B.O. Otunola & O.O. Ololade (2020) investigated the properties of clay minerals, which can significantly enhance the processes of removing heavy metals due to their adsorption characteristics. Their findings highlighted the importance of using clays for soil stabilisation and for reducing the concentration of pollutants in hydrogeochemical systems. This is particularly relevant in areas containing mining waste, where heavy metals may affect the ecological balance and the structural stability of constructions.

Y. Taha *et al.* (2021) studied the environmental behaviour of concrete produced using mining waste, in particular its ability to leach toxic elements. This research made it possible to assess the long-term environmental risks associated with the use of waste materials in construction, and the impact of such materials on infrastructure stability in mining regions, where soil stability is critically important for operational safety. G. Yang *et al.* (2023) examined the stability of slopes composed of water-sensitive shales under different moisture conditions. They noted that moisture significantly alters the physical and mechanical properties of soils, which can lead to landslides and slope failures. This study is essential for assessing the impact of meteorological factors, particularly precipitation, on quarry slope stability and the safety of mining operations.

L. Shu *et al.* (2024) emphasised that moisture significantly affects the mechanical properties of materials, particularly the strength of gas shales. Their study showed that fluctuating moisture conditions may result in a reduction in material strength, which is an important factor when assessing the stability of geotechnical structures. These findings are key to the subject of this research, as they help to determine the influence of moisture on the stability of soils and structures, especially under the high groundwater levels typical of mining environments. A general analysis of the literature indicated that the stability of soils and materials under mining conditions is largely influenced by moisture content, hydrogeochemical processes, and the use of mining waste in construction. All of these factors are critically important for ensuring the safety of mining operations, and the studies reviewed provide valuable data for managing risks, maintaining structural stability, and ensuring environmental safety in complex hydrogeological conditions.

Materials and Methods

The engineering protection of territories and buildings from natural hazards is regulated by normative documents, in particular DBN V.1.1-46:2017 (2017) and DBN A.2.2-1:2021 (2021), which include requirements for environmental impact assessment and the prevention of landslides and collapses. However, these regulations do not provide specific recommendations for ensuring the stability of foundations and structures under complex hydrogeological conditions, such as those found at the Malyshevske deposit, characterised by a high groundwater level. The Malyshevske titanium-zirconium ore deposit is located in an area of an active aquifer, and its geological structure includes highly permeable hydrophilic sands, which significantly complicates mining operations and necessitates detailed analysis of the stability of foundations and structures. Within the scope of this research, the physical and mechanical properties of ore sands and their hydraulic conductivity were analysed, allowing the assessment of the influence of groundwater on the stability of quarry slopes. A comprehensive approach was used, combining hydrogeological investigations, geophysical measurements, and experimental determination of water filtration parameters through ore sands.

To obtain reliable data on the hydraulic conductivity of the ore sands under investigation, experimental tests were conducted in a specialised laboratory of the Technical Control Department (TCD) at the Vilnohirsk Mining and Metallurgical Plant (MMP). The tests were carried out using one of the most widely applied methods – the hydraulic head analogy – which consists in measuring the time required for water to pass through a specific layer of ore sands.

According to the described methodology, the following stages were completed:

1. Sample preparation. The selected samples of ore sands were standardised by particle size and density.

2. Formation of a hydraulic system. Water was passed through the ore sand sample under hydrostatic pressure, implemented by creating a hydraulic head.

3. Measurement of filtration time. The time interval required for water to pass through the sample was recorded.

4. Calculation of hydraulic conductivity. The calculation was performed based on the obtained experimental data using a formula that takes into account the hydraulic radius and other parameters.

To calculate the hydraulic conductivity, Darcy's law was used, which describes the relationship between the velocity of fluid flow through a porous medium and the hydraulic pressure gradient. Darcy's formula is expressed as:

$$Q = -K \cdot A \cdot \left(\frac{dh}{dx}\right), \quad (1)$$

where Q – fluid flow rate through the test section, m^3/s; K – hydraulic conductivity coefficient, m/s; A – cross-sectional area of the sample, m^2; $\frac{dh}{dx}$ –hydraulic pressure gradient.

The calculation was carried out for each sample, considering the different content of components in the ore sands. Since hydraulic conductivity depends on the size and shape of particles, porosity, and the presence of clay inclusions, all possible factors were taken into account in the calculations. Initial research data: water flow rate – $l/s = m^3/s$; cross-sectional area – m^2. To calculate hydraulic pressure based on the height of the water column, the following equation was used:

$$P = \rho g h, \text{ Pa}, \quad (2)$$

where ρ – density of water, 1,000 kg/m^3; g – acceleration due to gravity, m/s^2; h – height of the water column, m.

Results

To ensure the uninterrupted operation of mining activities within the quarry, industrial and auxiliary structures are located, each performing an important technological or infrastructural function. The main facilities are listed in Table 1.

Table 1. *Industrial and auxiliary structures of the quarry*

Structure	Functionality
Crushing and screening complexes	Primary processing of extracted ore, ensuring continuation of the technological process
Conveyor and transport galleries	Efficient transfer of raw materials between key production units
Pumping stations	Drainage of mine and quarry water, prevention of its uncontrolled accumulation
Power infrastructure (substations, transformer units, power transmission lines)	Provision of stable power supply to all quarry facilities
Control rooms and maintenance facilities	Coordination of mining equipment operation and its technical maintenance
Storage facilities for various purposes	Safe storage of materials, including structural stability of foundations
Administrative and sanitary-domestic buildings	Creation of comfortable working conditions for personnel, operation of laboratories and control units

Notes: *the listed facilities are located within Quarry No. 7, whose raw material base is the Malyshevske placer deposit*
Source: *compiled by the author based on original research*

Each of these structures must comply with heightened requirements for stability and safety, taking into account the complex engineering and geological conditions of the quarry environment. Ensuring the reliability of these facilities under challenging geotechnical conditions is essential for minimising the risk of accidents and protecting the lives of personnel working within the quarry (Popov & Popova, 2022). Therefore, particular attention should be given to the development of effective measures for waterproofing, drainage, soil stabilisation, and deformation monitoring.

The Malyshevske deposit belongs to alluvial placers and is characterised by a complex stratigraphic structure that includes several main geological layers:

- quaternary deposits – loams, sandy loams, and sands that form the upper layer, with a thickness ranging from 3 to 15 m;
- neogene deposits – located beneath the Quaternary layer and composed of clayey sandstones, loams, and thin layers of clay. The thickness of this layer varies from 10 to 30 m;
- sarmatian sands – containing a high concentration of heavy minerals, including ilmenite, rutile, and zircon. This is the primary mining layer, with a thickness ranging from 5 to 25 m;
- precambrian crystalline rocks – comprising granites, gneisses, and quartzites that form the basement of the deposit. Due to their high density and low hydraulic conductivity, these rocks influence the formation of aquifers.

The structural features of the deposit determine the uneven distribution of ore sands and the variability of their physical and mechanical properties. A detailed understanding of the geological structure allows for optimisation of extraction activities and the development of measures to mitigate the impact of groundwater on slope stability, road washouts, and related hazards. One of the key factors influencing the stability of quarry slopes is the degree of water saturation in the rock mass and the dynamics of both underground and surface water. Figure 1 presents a diagram of the aquifer systems and the processes contributing to the waterlogging of the quarry field.

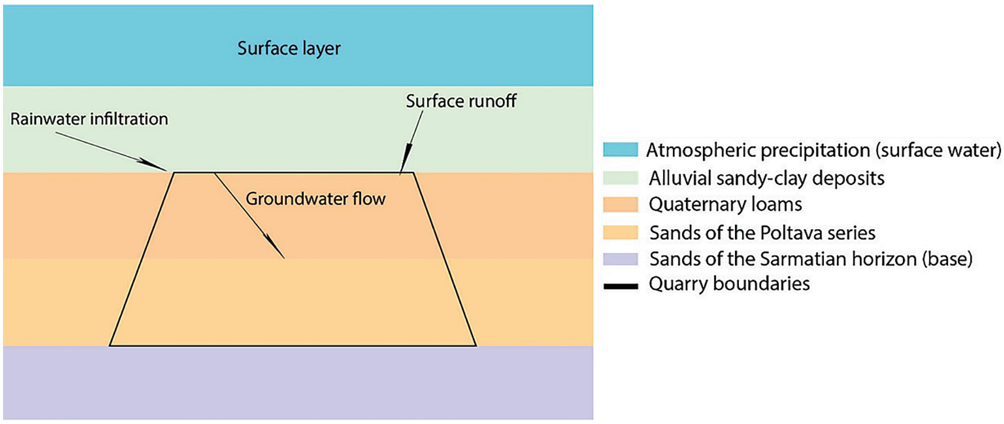

Figure 1. *Schematic representation of aquifers and waterlogging of the quarry field*
Notes: *the diagram illustrates the processes of quarry waterlogging, including surface runoff, rainwater infiltration, and subsurface flow. Colour coding indicates the main geological horizons that affect the hydrogeological conditions of the deposit*
Source: *developed by the author based on hydrogeological studies by S. Vasylenko (2015)*

The waterlogging scheme illustrates the key hydrogeological processes that determine the operating conditions of the mining site. Figure 1 presents the following main factors:

1. Surface runoff – atmospheric precipitation falling on the quarry slopes, causing erosion processes, landslide formation, and increased load on the drainage system.
2. Rainwater infiltration – the penetration of precipitation into aquifers, which alters groundwater levels and increases the risk of flooding within the quarry space.
3. Subsurface flow – water movement through aquifers, which determines the saturation level of rock masses and, in turn, affects the stability of quarry slopes.

An analysis of the hydrogeological conditions of the Malyshevske deposit revealed a complex structure of aquifers that directly affect quarry operation and mine safety. It has been established that the groundwater level lies at a depth of 10-25 m from the surface and experiences seasonal fluctuations, rising in spring and falling in summer. At the same time, chemical analysis of groundwater indicated increased aggressiveness, particularly due to high concentrations of sulphates and chlorides, which cause corrosion of metal structures. A significant level of mineralisation (1.5-3.5 g/l) has also been identified, creating additional challenges for drainage and necessitating the implementation of water treatment technologies (Solodovnik & Yakymenko, 2021). The hydrogeological features of the deposit significantly influence the stability of rock masses. The high moisture content of the ore sands contributes to the development of landslides, and the softening of overburden rocks due to wetting complicates material transport and mining operations. Elevated moisture levels in the rock mass require constant water removal to maintain quarry slope stability.

Effective management of the quarry's water balance can be achieved through a combination of technical solutions. The use of drainage wells reduces groundwater levels and localises areas of excessive moisture, while open drainage ditches collect surface runoff and prevent flooding of operational zones. Filtration systems using sand and gravel materials contribute to water purification, improving drainage performance. Additional protection of production areas from infiltration is ensured by waterproofing barriers such as geomembranes and bentonite mats. The results obtained emphasise the need for an integrated approach to regulating the quarry's water regime. Implementing modern monitoring technologies and groundwater level control will not only improve the efficiency of developing the Malyshevske deposit but also minimise the risks associated with waterlogging processes. However, to ensure the stability of mining operations, it is essential not only to manage the water balance but also to assess the physical and mechanical properties of the rock masses, which determine their stability under changing hydrogeological conditions.

Investigating the strength, hardness, and other physical and mechanical parameters of the rock masses at the Malyshevske (Samotkanske) placer deposit of ilmenite-rutile-zircon sands makes it possible to evaluate their capacity to maintain structural integrity under saturation and mining-induced loads. Given the mineralogical composition of the ore sands, which includes quartz (on average 75%) and clay minerals (approximately 20%), as well as other heavy ore minerals such as leucoxenised ilmenite, leucoxene, rutile, zircon, kyanite-sillimanite, staurolite, tourmaline, and chromite, the main factors influencing their hydraulic conductivity can be identified. The general physical and mechanical characteristics of ore sands containing these minerals are presented in Table 2.

Table 2. *General overview of the physico-mechanical characteristics of ore sands, considering their composition and the content of major minerals*

Characteristic	Ore sands
Chemical composition	Quartz (SiO_2) – approximately 75%; clay minerals – around 20%; other heavy minerals (leucoxenised ilmenite, leucoxene, rutile, zircon, kyanite-sillimanite, staurolite, tourmaline, chromite) – remainder
Hardness (Mohs)	From 7 (quartz) to varying values for other minerals
Density (g/cm³)	Depends on sand composition, typically around 2.65 g/cm³ (as in quartz)
Colour and appearance	Varies from light brown to yellowish-white or red, depending on impurities and minerals; texture ranges from fine-grained to coarse-grained
Magnetic properties	Absent or very weak, although certain heavy minerals may exhibit magnetic behaviour

Notes: *the characteristic values may vary depending on the specific deposit and bedding conditions of the sands. The data are provided for typical samples with a dominant quartz content*

Source: *developed by the author based on laboratory studies and analysis of literature sources by V. Biletskyi (2004) and the US Geological Survey (2020)*

The composition of ore sands directly affects their strength, wear resistance, and technological properties. At the same time, an important aspect is not only the general characteristics of the ore mass, but also the properties of each type of mineral contained in the rock. Ilmenite ores, whose main component is $FeTiO_3$, exhibit high resistance to corrosion processes and are widely used in the production of titanium and its alloys, pigments, and abrasive materials. Rutile ores (TiO_2) are key sources of titanium compounds used in various industries, including pigment production, ceramics, and titanium alloys. Zircon ores containing $ZrSiO_4$ are applied in the manufacture of ceramics, glass, abrasives, and special alloys. For a deeper understanding of the differences between these types of ores and their mechanical behaviour, a comparative analysis of their physico-mechanical characteristics has been carried out, with the results presented in Table 3.

Table 3. *Comparative overview of the physico-mechanical characteristics of three different types of ores: ilmenite, rutile and zircon*

Characteristic	Ilmenite ore	Rutile ore	Zircon ore
Chemical composition	$FeTiO_3$	TiO_2	$ZrSiO_4$
Hardness (Mohs)	5-6	6-6.5	6.5-7
Density (g/cm³)	4.7-4.8	4.2-4.3	4.6-4.7
Color and appearance	variable, metallic lustre, crystalline or granular structure	black or dark brown, metallic lustre, crystalline structure	various colours, crystalline structure, metallic lustre
Fusibility	variable texture	variable texture	variable texture
Magnetism	magnetic	non-magnetic	non-magnetic

Notes: *the presented characteristics are average values for typical samples and may vary depending on the conditions of occurrence and metamorphic processes*

Source: *developed by the author based on laboratory analyses and geological research data by B. Sobko & M. Chebanov (2018)*

The physico-mechanical properties of ore sands largely determine the characteristics of their hydraulic transportation, the choice of technological equipment, and its service life. In calculations of hydraulic transport, such parameters are taken into account as the density of the material, its porosity, wettability, solubility, granulometric composition, grain shape, hydraulic coarseness, abrasiveness, and grindability during transportation. One of the key factors determining the hydraulic conductivity of ore sands is the quartz content, as this mineral has high permeability. With an increase in the proportion of quartz in the sands, their filtration capacity also increases. The filtration coefficient of quartz sands depends on the granulometric composition, degree of compaction, and other factors, and according to reference data, has the following average values:

- coarse-grained quartz sand: 10^{-2} – 10^{-3} m/s;
- medium-grained quartz sand: 10^{-3} – 10^{-4} m/s;
- fine-grained quartz sand: 10^{-4} – 10^{-5} m/s.

Clay minerals also significantly affect hydraulic conductivity, especially in cases of the formation of clayey inclusions, which reduce the porosity and permeability of the material. At the same time, other heavy ore minerals may possess different properties: some of them are permeable, while others considerably decrease the water conductivity of the environment. Overall, the hydraulic conductivity of ore sands is the result of the interaction of all these components, and its values can vary considerably depending on local conditions and the mineralogical composition of the material. This characteristic plays an important role in the mining and construction industries, as it determines the possibilities for effective water drainage, rock stability, and technological parameters of processing. Specialised testing methods are used for the precise determination of the hydraulic conductivity of ore sands, including the evaluation of the filtration coefficient and water permeability tests. Measurements are usually carried out in units of the filtration rate of liquid through the material, such as metres per day or centimetres per hour.

The calculated values of hydraulic pressure for each case (2), and the following values were obtained:

$$P_1 = 1{,}000 \cdot 9.81 \cdot 0.192 \approx 1{,}886.8 \text{ Pa};$$
$$P_2 = 1{,}000 \cdot 9.81 \cdot 0.182 \approx 1{,}785.7 \text{ Pa};$$
$$P_3 = 1{,}000 \cdot 9.81 \cdot 0.196 \approx 1{,}923.1 \text{ Pa};$$
$$P_4 = 1{,}000 \cdot 9.81 \cdot 0.185 \approx 1{,}818.2 \text{ Pa};$$
$$P_5 = 1{,}000 \cdot 9.81 \cdot 0.182 \approx 1{,}785.7 \text{ Pa}.$$

From formula (1), the hydraulic conductivity coefficient K is expressed through known parameters:

$$K = -\left(\frac{Q}{A}\right) \cdot \left(\frac{dx}{dh}\right). \quad (3)$$

The calculation is performed for each of the five samples, taking into account that each sample has a different component content:

$$K_1 = -\left(\frac{0.01}{1}\right) \cdot 1{,}886.79 = 5.3 \cdot 10^{-6} \text{ m/s};$$
$$K_2 = -\left(\frac{0.01}{1}\right) \cdot 1{,}785.71 = 5.6 \cdot 10^{-6} \text{ m/s};$$
$$K_3 = -\left(\frac{0.01}{1}\right) \cdot 1{,}923.08 = 5.2 \cdot 10^{-6} \text{ m/s};$$
$$K_4 = -\left(\frac{0.01}{1}\right) \cdot 1{,}818.18 = 5.5 \cdot 10^{-6} \text{ m/s};$$
$$K_5 = -\left(\frac{0.01}{1}\right) \cdot 1{,}785.71 = 5.6 \cdot 10^{-6} \text{ m/s}.$$

Since the filtration coefficient K is a positive quantity, its absolute value is taken into account. For the generalised analysis, the average value is calculated. The obtained result is converted into metres per day:

$$Kser = 5.44 \cdot 10^{-6} \cdot 86{,}400 = 0.47 \text{ m/day}. \quad (4)$$

The obtained average value $Kser = 0.47$ m/day indicates the generalised rate of water filtration through the studied material and takes into account all conducted experiments. The study made it possible to obtain quantitative indicators of the hydraulic conductivity of the ore sands of the investigated site. The results can be used for further modelling of hydrodynamic processes in the deposit and optimisation of technological solutions during mining operations. The schematic of the experimental setup is shown in Figure 2.

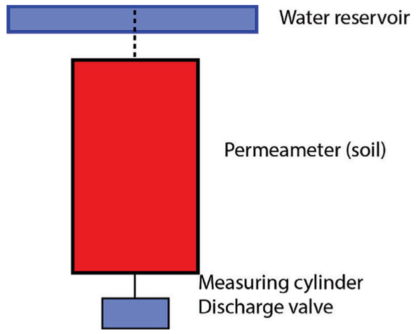

Figure 2. *Diagram of the experimental setup for testing soil permeability by the constant head method (Constant Head Permeability Test)*

Notes: *water reservoir – maintains a constant water level to support a stable gradient; permeameter (soil) – sample of the investigated soil through which water passes; measuring cylinder – used to collect filtrate and measure water volume; outlet valve – regulates water outflow and ensures controlled flow*

Source: *developed by the author based on the methodology for soil permeability testing*

The research results showed that the main safety risks in the quarry are associated with the high hydraulic conductivity of the ore sands, which leads to excessive saturation of the pit walls and can cause landslides. Increased water saturation of the rocks reduces their strength, affecting the stability of the slopes. Saturation of mining transport routes complicates the movement of equipment due to road erosion. The conducted studies of filtration coefficients for various ore sand samples allowed the determination of the average permeability of the rocks, which significantly affects drainage and water removal. Hydrogeological conditions are an important factor for mining safety. A high level of saturation causes a reduction in the bearing capacity of the rocks, which can lead to collapses. Water-saturated soils create problems for ore transportation and the operation of hydraulic monitors due to changes in water pressure.

To minimise the impact of saturation, it is necessary to apply drainage systems, control groundwater levels, and stabilise slopes to avoid critical changes in the quarry structure. High hydraulic conductivity promotes water penetration through ore sands, which requires additional water removal measures. In open-pit quarries, an effective water drainage system helps prevent flooding that could halt operations. Slope stability remains a critical factor, as water flows through porous layers can cause landslides and collapses. This is especially important for the development of ore sands, where soil stability is necessary for the safety of personnel and equipment. Increased moisture complicates material transportation and creates risks for quarry operations.

Saturation of the quarry working zones is caused by atmospheric precipitation and aquifers. The alluvial aquifer covers part of the deposit area but does not significantly affect the overall water inflow. The Quaternary aquifer is more widespread and can cause difficulties due to water-saturated clays, especially during the winter period. The Poltava aquifer overlies the ore sands, but its level remains stable.

As a result of saturation, the rocks become moist, complicating the operation of machinery, particularly in winter. Freezing of water-saturated ore sands on equipment increases energy consumption and requires frequent maintenance. Loss of slope stability due to moisture can cause landslides, posing danger to workers. The volumes of water inflow reach significant levels, necessitating systematic water removal. Moistening of working surfaces increases the risk of injuries, while landslides can damage equipment and communications. To reduce risks, a set of measures was proposed: installation of drainage systems to control water levels, soil reinforcement using cementation and silicatisation methods, application of geomaterials for sand stabilisation, and design of foundations with increased bearing area. This will contribute to improving work safety under complex hydrogeological conditions.

Discussion

The results of this study are consistent with the findings of previous research on the stability assessment of foundations and structures in complex hydrogeological conditions, particularly in mining environments. Several key studies have addressed similar issues, providing valuable insights into the influence of groundwater levels, soil permeability, and structural stability.

L.W. Abramson *et al*. (2001) conducted a comprehensive investigation of slope stability and stabilisation methods, emphasising the importance of groundwater management to prevent slope failures. Their study highlighted the role of appropriate drainage technologies, which corresponds with the conclusions of the present article, noting that a high groundwater level significantly affects the stability of foundations at mining sites such as the Malyshevske deposit. However, unlike the study by L.W. Abramson *et al*. (2001), which focused on general slope stabilisation methods, this study provided a more detailed specification of hydrogeological conditions and their impact on foundation stability. Y. Ait-khouia *et al*. (2023) studied sustainable management of mining waste through automated mineralogical and geochemical analysis. Their research demonstrated the importance of understanding the mineral composition of waste for assessing its geotechnical properties. The results obtained confirm their conclusions, as the analysis of the ore sands' composition and granulometric distribution played a key role in evaluating foundation stability. The main difference is that this study places greater emphasis on the impact of groundwater infiltration on these materials, rather than solely their composition.

Researchers B. Liu *et al*. (2020) investigated the effect of moisture on the mechanical and electrical characteristics of water-saturated sandstone during freezing. Their findings indicated that increased moisture content reduces material strength, making structures more prone to deformation. This observation aligns with the results obtained here, which show that higher moisture content in ore sands reduces foundation stability. However, whereas their study focused on frozen conditions, this study concentrates on variations in hydrogeological conditions throughout the year. O. Borziak *et al*. (2022) emphasised the importance of engineering-geological investigations for construction. They noted the necessity of detailed assessment of the physical and mechanical properties of soils and rocks prior to construction commencement. This study extended their conclusions by applying these principles to the conditions of the Malyshevske deposit, analysing the interaction between groundwater levels and soil stability in a high-moisture environment.

K. Guanira *et al*. (2020) proposed a methodological approach for the mineralogical characterisation of dumps from a skarn-type Cu (Au, Ag) deposit. Their work provided insights into the mineralogical properties influencing waste behaviour, which is similar to this study's investigation of ore sand composition. However, while their research predominantly focused on mineralogical characterisation for waste management, this study evaluated the impact of hydrogeological conditions on construction safety. N.N. Imam Robit *et al*. (2023) investigated the effect of moisture on the failure of bearing capacity in strip foundations on sandy loam soils. Their research demonstrated how increased moisture reduces soil strength, which corresponds with the results indicating that high groundwater levels adversely affect foundation stability. However, this study additionally incorporated hydrogeological monitoring and permeability testing to assess long-term risks to structures.

Researchers N. Saberi & B. Vriens (2024) studied the impact of moisture on the mineralogical and drainage properties of degrading mining waste. Their research demonstrated how changes in water saturation affect geotechnical properties over time, supporting the conclusions obtained here about the necessity of continuous groundwater monitoring to assess construction risks at mining sites. However, this study focused more on engineering solutions to mitigate these risks, whereas their research predominantly discusses mineralogical transformations. V. Shapoval *et al*. (2020) analysed slope stability considering excess pore water pressure. Their study emphasised the importance of accounting for excess pressure in geotechnical assessments, which was also considered in this study. However, unlike their work, which mainly concentrated on slope stability, this study extended the analysis to the stability of foundations under conditions of high groundwater levels.

D. Wang *et al.* (2022) investigated interactions between hydraulic fractures and natural fractures in mining conditions. Their research highlighted the role of hydraulic properties in determining fracture propagation, complementing the findings described here about groundwater flow through ore sands and its impact on structural stability. However, this study focused more on engineering measures needed to counteract these effects rather than on the fracture formation process itself. Scientists Y. Yao *et al.* (2025) presented a review of modern soil moisture monitoring technologies for slope stability assessment. Their research underlined the advantages of contemporary moisture monitoring systems for predicting slope failures, supporting the use of hydrogeological monitoring to evaluate seasonal groundwater fluctuations in this study. Although their study offered a broader overview of monitoring technologies, this study applied these concepts to a specific mining environment, emphasising their practical application in construction safety management.

In summary, the results of this study are consistent with the existing scientific literature regarding the impact of groundwater levels and soil moisture on the stability of foundations in mining conditions. The key contributions of this study include a detailed specific analysis of the Malyshevske deposit conditions, integration of hydrogeological monitoring with engineering assessments, and experimental evaluation of ore sands' permeability. These results highlighted the necessity of continuous monitoring and adaptive engineering solutions to ensure structural stability in highly moist mining environments.

Conclusions

The high groundwater level and significant moisture content of ore sands at the Malyshevske deposit present serious challenges to the stability of foundations, bases, and building structures. The presence of large amounts of water in the soil adversely affects the soil's bearing capacity, which can lead to increased settlements and create conditions for uneven structural deformations. This requires careful planning and the application of specific engineering solutions aimed at ensuring the long-term stability of structures.

One important aspect is the use of drainage systems that allow controlling the groundwater level and reducing its impact on structures. Additionally, to enhance foundation stability, it is advisable to apply geotechnical soil reinforcement and specialised foundation strengthening technologies capable of reducing the risks of deformation and destruction in the long term. It is equally important to consider dynamic loads and the impact of mining operations, as these factors can impose additional stresses on structures. The development of specialised foundation solutions that take these features into account is a necessary condition for ensuring the reliability of buildings under complex mining and geological conditions.

Thus, the application of comprehensive measures including drainage systems, soil reinforcement, and specialised foundation technologies is key to ensuring the stability and safety of structures at the Malyshevske deposit. Carefully planned engineering solutions can significantly reduce risks associated with adverse hydrogeological conditions and the impact of mining operations, thereby ensuring the reliability of structures over an extended period. The analysis of the physico-mechanical characteristics of ore sands confirmed their significant influence on mining safety. Hydraulic conductivity and moisture content are key risk factors that must be considered during the planning and operation of the quarry. Further research should be directed towards developing innovative methods for monitoring the condition of the quarry field and improving worker safety.

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Conflict of Interest

None.

References

[1] Abramov, Y., Basmanov, O., Oliinik, V., & Khmyrov, I. (2022). Justifying the experimental method for determining the parameters of liquid infiltration in bulk material. *Eastern-European Journal of Enterprise Technologies*, 4(10(118)), 24-29. doi: 10.15587/1729-4061.2022.262249.

[2] Abramson, L.W., Lee, T.S., Sharma, S., & Boyce, G.M. (2001). *Slope stability and stabilization methods*. New York: John Wiley & Sons.

[3] Ait-khouia, Y., Benzaazoua, M., Ievgeniia, M., & Demers, I. (2023). Moving towards sustainable mine waste rock management through automated mineral and geochemical analysis. *Journal of Geochemical Exploration*, 248, article number 107182. doi: 10.1016/j.gexplo.2023.107182.

[4] Babets, D., Kovrov, O., Moldabayev, S., Tereschuk, R., & Sosna, D. (2020). Impact of water saturation effect on sedimentary rocks strength properties. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 4, 76-81. doi: 10.33271/nvngu/2020-4/076.

[5] Biletskyi, V. (2004). *Concise mining encyclopedia* (Vol. 1). Donetsk: Donbass.

[6] Borziak, O., Liutyi, V., Romanenko, O., & Podtelezhnikova, I. (2022). *Engineering and geological studies for construction*. Kharkiv: Ukrainian State University of Railway Transport.
[7] DBN A.2.2-1:2021. (2021). *Composition and content of environmental impact assessment (EIA) materials*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=98038.
[8] DBN V.1.1-46:2017. (2017). *Engineering protection of territories, buildings, and structures from landslides and collapses: General provisions*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=72096.
[9] Guanira, K., Valente, T.M., Ríos, C.A., Castellanos, O.M., Salazar, L., Lattanzi, D., & Jaime, P. (2020). Methodological approach for mineralogical characterization of tailings from a Cu (Au, Ag) skarn type deposit using QEMSCAN. *Journal of Geochemical Exploration*, 209, article number 106439. doi: 10.1016/j.gexplo.2019.106439.
[10] He, L., Shang, Y., Lei, X., & Li, G. (2024). Destabilization mechanism and prevention technology of open-pit mine slope with soft interlayer under rainfall infiltration conditions: A case study. *Mining, Metallurgy & Exploration*, 41, 859-873. doi: 10.1007/s42461-024-00941-3.
[11] Imam Robit, N.N., Md Nujid, M., Md Nor, N.S., Tholibon, D.A., & Mukhlisin, M. (2023). Investigation moisture content effect on bearing capacity failure of strip footing rested on silty sand soil based on crack characteristics assessment using non-destructive test. *Procedia Structural Integrity*, 47, 597-601. doi: 10.1016/j.prostr.2023.07.064.
[12] Ivanov, V., Arosio, D., Tresoldi, G., Hojat, A., Zanzi, L., Papini, M., & Longoni, L. (2020). Investigation on the role of water for the stability of shallow landslides – insights from experimental tests. *Water*, 12(4), article number 1203. doi: 10.3390/w12041203.
[13] Liu, B., Sun, Y., Wang, B., Han, Y., Zhang, R., & Wang, J. (2020). Effect of water content on mechanical and electrical characteristics of the water-rich sandstone during freezing. *Environmental Earth Sciences*, 79(10), article number 236. doi: 10.1007/s12665-020-08991-8.
[14] Maknoon, M., & Aubertin, M. (2021). On the use of bench construction to improve the stability of unsaturated waste rock piles. *Geotechnical and Geological Engineering*, 39, 1425-1449. doi: 10.1007/s10706-020-01567-0.
[15] Ngugi, H.N., Shitote, S.M., & Ambassah, N. (2021). Effect of variation in moisture content on soil deformation and differential settlement of frame structures in Nairobi area and its environs. *The Open Construction and Building Technology Journal*, 15, 106-128. doi: 10.2174/1874836802115010106.
[16] Oliinyk, V., Basmanov, O., & Mykhailovska, Yu. (2022). Method for experimental determination of liquid infiltration parameters in soil. *Problems of Emergency Situations*, 2(36), 15-25. doi: 10.52363/2524-0226-2022-36-2.
[17] Otunola, B.O., & Ololade, O.O. (2020). A review on the application of clay minerals as heavy metal adsorbents for remediation purposes. *Environmental Technology & Innovation*, 18, article number 100692. doi: 10.1016/j.eti.2020.100692.
[18] Popov, V., & Popova, A. (2022). Combined tunnel type floodgates for road facilities. *Modern Technologies, Materials and Structures in Construction*, 19(2), 60-71. doi: 10.31649/2311-1429-2022-2-60-71.
[19] Saberi, N., & Vriens, B. (2024). The effects of water content on mineralogical and drainage quality dynamics in weathering mine waste rock. *Minerals Engineering*, 214, article number 108791. doi: 10.1016/j.mineng.2024.108791.
[20] Shapoval, V., Shashenko, O., Hapieiev, S., Khalymendyk, O., & Andrieiev, V. (2020). Stability assessment of the slopes and side-hills with account of the excess pressure in the pore liquid. *Mining of Mineral Deposits*, 14(1), 91-99. doi: 10.33271/mining14.01.091.
[21] Shu, L., Xie, L., He, B., & Zhang, Y. (2024). Comparison of the sample preparation strategies and impacts on the tensile strength of gas shale with variable moisture conditions. *Energies*, 17(10), article number 2327. doi: 10.3390/en17102327.
[22] Ślusarek, J., & Łupieżowiec, M. (2020). Analysis of the influence of soil moisture on the stability of a building based on a slope. *Engineering Failure Analysis*, 113, article number 104534. doi: 10.1016/j.engfailanal.2020.104534.
[23] Sobko, B., & Chebanov, M. (2018). Influence of physical and mechanical properties of soils on cut width of a dragline while truck loading. *Collection of Research Papers of the National Mining University*, 55, 112-119.
[24] Solodovnik, T., & Yakymenko, I. (2021). Problems and methods of drinking water purification in the systems of decentralized water supply. *Bulletin of Cherkasy State Technological University*, 26(2), 63-81. doi: 10.24025/2306-4412.2.2021.239703.
[25] Suiarko, V. (2019). *Engineering geology (with the basics of geotechnics)*. Kharkiv: V.N. Karazin Kharkiv National University.
[26] Taha, Y., Benarchid, Y., & Benzaazoua, M. (2021). Environmental behavior of waste rocks based concrete: Leaching performance assessment. *Resources Policy*, 74, article number 101419. doi: 10.1016/j.resourpol.2019.101419.

[27] Tokunaga, T.K. (2020). Simplified green-ampt model, imbibition-based estimates of permeability, and implications for leak-off in hydraulic fracturing. *Water Resources Research*, 56(4), article number e2019WR026919. doi: 10.1029/2019WR026919.

[28] US Geological Survey. (2020). *Mineral commodity summaries*. Reston: U.S. Geological Survey. doi: 10.3133/mcs2020.

[29] Vasylenko, S. (2015). *Geological structure, formation conditions, and ore-bearing capacity of the Motronivske-Annivske titanium-zirconium placer deposit*. (Doctoral dissertation, Institute of Geological Sciences of the National Academy of Sciences of Ukraine, Kyiv, Ukraine).

[30] Vriens, B., Plante, B., Seigneur, N., & Jamieson, H. (2020). Mine waste rock: Insights for sustainable hydrogeochemical management. *Minerals*, 10(9), article number 728. doi: 10.3390/min10090728.

[31] Wang, D., Taleghani, A.D., & Yu, B. (2022). Height effect on interactions between the hydraulic fracture and natural fractures. *Geofluids*, 2022(1), article number 4642326. doi: 10.1155/2022/4642326.

[32] Yang, G., Chen, Y., Liu, X., Yang, R., Zhang, Y., & Zhang, J. (2023). Stability analysis of a slope containing water-sensitive mudstone considering different rainfall conditions at an open-pit mine. *International Journal of Coal Science & Technology*, 10, article number 64. doi: 10.1007/s40789-023-00619-z.

[33] Yao, Y., Fan, J., & Li, J. (2025). A review of advanced soil moisture monitoring techniques for slope stability assessment. *Water*, 17(3), article number 390. doi: 10.3390/w17030390.

[34] Zotsenko, M., Kovalenko, V., Yakovliev, A., Petrakov, O., Shvets, V., Shkola, O., Bida, S., & Vynnykov, Yu. (2004). *Engineering geology. Soil mechanics, foundations, and basements*. Poltava: National University "Yuri Kondratyuk Poltava Polytechnic".

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Оцінка впливу водонасичення ґрунтів Малишевського родовища на стійкість конструкцій кар'єру

Анотація. Високий рівень ґрунтових вод і значна змочуваність рудних пісків Малишівського родовища створюють значні ризики для стійкості основ, фундаментів та конструкцій на кар'єрному полі. Дослідження цих факторів є критично важливим для забезпечення безпеки та надійності гірничих і будівельних споруд. Метою роботи було визначення фізико-механічних властивостей та оцінка впливу рудних пісків на стійкість основ, фундаментів і конструкцій у зоні кар'єру Малишевського родовища, а також розробка рекомендацій щодо їх стабілізації. У роботі застосовано комплекс різноманітних методів дослідження, зокрема гідрогеологічні, геофізичні, гідравлічні, та математичні розрахунки. Використано дослідження гідрогеологічних умов для визначення рівня ґрунтових вод та їхнього впливу на стабільність конструкцій. Здійснено випробування рудних пісків для визначення їх фізико-механічних характеристик, зокрема водопроникності та фільтраційних властивостей. Встановлено ключові фактори, що впливають на стабільність фундаментів у зонах підвищеної вологості. Розроблено рекомендації щодо підвищення несучої здатності основ і фундаментів за допомогою дренажних систем, ін'єкційного зміцнення ґрунтів та використання спеціальних матеріалів з низькою водопроникністю. Визначено фактичне середнє значення коефіцієнта фільтрації рудних пісків Малишевського родовища за допомогою методики водонапірного стовпа. Вперше для даного регіону запропоновано інтегровані заходи, що включають комбінацію дренажних і фільтраційних систем для зниження рівня ґрунтових вод, а також математичне моделювання для прогнозування впливу цих змін на стабільність конструкцій кар'єра. Робота має значну практичну значимість для проектування та експлуатації кар'єрів в умовах підвищеного рівня ґрунтових вод та високої вологонасиченості ґрунтів. Запропоновані методи і заходи дозволяють ефективно знижувати ризики, пов'язані зі зміною рівня ґрунтових вод, і забезпечити стабільність кар'єрних конструкцій, що в свою чергу дозволить підвищити безпеку гірничих робіт та знизити витрати на обслуговування інженерних споруд

Ключові слова: гідрогеологія; ґрунтові води; змочуваність; дренаж; стабілізація ґрунтів; безпека

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Overview of technologies and prospects for underground uranium mining

Abstract. The relevance of research into underground uranium mining is underpinned by the growing demand for a stable supply of nuclear raw materials for atomic energy, which is regarded as a key factor in ensuring energy security amid the ongoing global energy crisis. Given the scarcity of high-grade ores and the necessity to exploit low-grade deposits, particular attention is drawn to the implementation of advanced leaching technologies directly within underground ore blocks. The objective of this study was to investigate and assess the efficiency of underground block leaching for uranium, considering the geological conditions of Ukrainian deposits, and to evaluate its prospects for enhancing the economic performance of mining enterprises. The research employed methods including analysis of the geological and structural features of ore deposits, simulation of leaching processes, and techno-economic assessment of block leaching under the specific conditions of Ukrainian uranium-bearing formations. A comparative analysis was conducted between conventional uranium mining techniques and advanced underground leaching technologies. The principal findings demonstrated that underground block leaching significantly reduces the costs associated with mining and processing of low-grade uranium ores, minimises environmental impact, and enhances the profitability of mining operations. Furthermore, the study confirmed that the geological and hydrogeological conditions of Ukraine's uranium deposits are favourable for the implementation of this technology. The application of block leaching facilitates the expansion of the raw material base by incorporating low-grade and substandard ores that were previously not considered for industrial exploitation. The practical value of the study lies in its potential to enhance the economic efficiency of mining enterprises, reduce mining and processing costs, and mitigate the adverse effects on the environment. The implementation of underground block leaching will contribute to the sustainable development of Ukraine's uranium industry

Keywords: underground block leaching; mining-chemical technology; uranium deposits; low-grade ores; nuclear energy

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Introduction

Ensuring a stable supply of uranium raw materials is a strategically critical objective for nuclear energy. As nuclear power remains one of the world's primary electricity sources, the demand for high-quality nuclear fuel continues to grow. However, conventional uranium mining techniques such as open-pit and underground mining pose substantial economic and environmental challenges. The depletion of high-grade uranium ores necessitates the exploration of more efficient and environmentally friendly mining methods. Underground block leaching is one such method enabling the utilisation of low-grade and sub-standard ores while minimising environmental impact and reducing mining costs.

Modern underground leaching technologies, particularly of the block type, enable the efficient exploitation of low-grade deposits, a factor highly relevant to the Ukrainian uranium industry (IAEA, 2019). L. Guihe & Y. Jia (2024) further highlighted that *in-situ* leaching is the most efficient uranium recovery method. This approach not only significantly lowers ore processing costs but also ensures minimal environmental impact compared with conventional mining techniques. They additionally emphasise the necessity of detailed hydrogeological assessment prior to implementation to mitigate lixiviant loss.

R. Jin *et al.* (2023) analysed the formation patterns of uranium deposits in large sedimentary basins, concluding that hydrogeological conditions, rock porosity, and mineralogical composition of the ore body are the principal determinants of underground leaching effectiveness. The authors emphasised that in low-permeability formations, leaching parameters should be adapted to optimise the process efficiency. Y. Zhou *et al.* (2020) investigated the recovery of uranium from sandstone deposits by underground acid leaching, demonstrating that sulphuric acid concentrations of 3-5% significantly enhance uranium yield, and that dissolution kinetics depends on mineral composition and permeability. M. Donskyi *et al.* (2023), in their analysis of geological features of Ukraine's uranium deposits, found that many of the deposits contain albitites that are well suited for underground leaching. However, the authors emphasised the imperative of rigorous hydrogeological monitoring to prevent lixiviant migration into groundwater.

V. Verkhovtsev *et al.* (2023a) assessed the environmental risks associated with underground uranium leaching in Ukraine, identifying potential lixiviant migration into aquifers and the necessity of controlling chemical reactions within leaching blocks, and recommending real-time monitoring systems. In a separate study, V. Verkhovtsev *et al.* (2023b) evaluated recent technological advances in uranium ore processing in Ukraine, asserting that combining leaching with downstream hydrometallurgical treatment can significantly increase uranium yields while reducing losses of valuable components.

O.A. Lysenko & A.Kh. Bakarzhyiev (2019) reviewed the Ukrainian uranium sector's current state and prospects, concluding that while most deposits show leaching potential, but further research is needed to evaluate its effectiveness across diverse geological settings. Additionally, the authors recommended refining regulatory frameworks to stimulate sector development. Similarly, the World Nuclear Association's (2023) report highlighted the pre-eminence of underground leaching among uranium mining techniques, underscoring its capacity to mitigate environmental impact and lower mining costs compared with conventional underground mining methods.

Despite considerable progress in underground leaching research, unresolved issues remain concerning the long-term hydrogeological impact of this technology and associated environmental risks. Furthermore, the optimisation of leaching parameters for diverse uranium ore types, particularly under Ukrainian geological conditions, remains understudied. Consequently, this study aimed to evaluate the effectiveness of underground leaching for Ukrainian uranium deposits, considering their specific geological-structural and hydrogeological characteristics, and to determine optimal process parameters.

Materials and Methods

This study was underpinned by a comprehensive analysis of scientific and technical literature, reports by international organisations, statistical datasets, and the findings of prior research in the field of uranium ore mining and processing, with a particular focus on underground block leaching (UBL) technologies.

The State Enterprise "Eastern Mining and Processing Plant" (SE "SkhidGZK"), Ukraine's primary and Europe's largest uranium producer, was selected as a key case study for this research. The enterprise exploits deposits characterised by complex mining and geological conditions and relatively low uranium content (0.02-0.06%), often composed of albitite ores. Its operational experience and deposit characteristics provide a valuable contextual basis for assessing the broader applicability of UBL in Ukraine. To evaluate the effectiveness of the UBL technologies for uranium ores, international best practices were reviewed. These included: the application of leaching techniques in geologically challenging deposits in Australia; technologies adapted to ore bodies hosted in dense hard-rocks in Canada; automated leaching monitoring systems employed in Kazakhstan; and techno-economic considerations presented at a French symposium on block leaching. The comparative analysis encompassed technological flowsheets, process parameters, economic performance indicators, and environmental implications.

A wide range of sources was systematised, including peer-reviewed scientific publications, doctoral theses, technical reports, and documentation from international agencies such as the IAEA (2019), UNECE (2019), NEA (2022), and World Nuclear Association (2023). A critical examination of existing scientific methodologies and their relevance to the research topic was undertaken. Conventional uranium mining techniques (underground and open-pit) were contrasted with the UBL method using techno-economic and environmental criteria. Analytical assessments were performed to evaluate geological, hydrogeological, technological, and economic prerequisites for effective implementation of UBL in Ukrainian uranium deposits.

The methodological framework for this study incorporated key scientific research methods, analysis and synthesis. Analysis was applied to meticulously examine various aspects of the UBL technology, geological characteristics of the deposits, economic factors, and environmental consequences. Synthesis facilitated the integration of the obtained data to form a comprehensive understanding of the method's advantages, its limitations and prospects for its implementation in Ukraine. For instance, the mineralogical composition of the ores (uranite, pitchblende, coffinite, brannerite) and the host rocks (albitites) was analysed to assess their suitability for sulphuric acid leaching. A comparative analytical method was also used to evaluate conventional uranium ore mining technologies compared with the UBL method, particularly in terms of production cost, mining efficiency, environmental impact, and occupational safety. Ukraine's experience was contrasted with leading international practices from Australia, Canada, Kazakhstan, and France. Finally, a system-based approach enabled the assessment of the implementation of UBL as an integrated system, considering the interrelationship of geological, technological, economic, and environmental factors.

While this study did not encompass original numerical simulations, it was underpinned by an extensive review of previously published leaching process models. These models aided in understanding the dynamics of chemical reactions between leaching solutions and the ore body, and the influence of hydrogeological conditions on process efficiency. Being analytical in nature, this study did not incorporate original fieldwork or laboratory experiments conducted by the authors. Instead, the research focused on in-depth interpretation of available geological-structural data on Ukrainian uranium deposits, particularly those within albitite formations. Previous laboratory and pilot-scale leaching trials were also studied, including investigations into diffusion and filtration dynamics within ore bodies. Supplementary relevant data were sourced from academic articles, technical reports, and institutional databases.

Primary research materials included monographs and academic articles by Ukrainian, Canadian, Chinese, and Kazakh scientists, doctoral theses, and data on the geological structure, mineralogical composition (including uraninite, pitchblende, coffinite, and brannerite within albitite rocks), and hydrogeological conditions of Ukrainian uranium deposits. Information on properties of leaching solutions and their interactions with ores was also used. The study of co-leaching of uranium and radium allowed for the consideration of the impact of accompanying processes on overall recovery efficiency (Bai *et al.*, 2023). This study analysed the key indicators such as uranium content in ores (e.g. % U_3O_8), uranium recovery rates, leaching rates, ore permeability and porosity, filtration coefficients, and process duration. Economic indicators, including production cost, capital and operational expenditures, profitability, and cost reduction potential were also examined. Attention was paid to environmental indicators, including the mitigation of negative environmental impact, waste minimisation, as well as to physical and mechanical properties of ores and host rocks, operational safety.

This study primarily relied on the consolidation and interpretation of findings, methodologies, and approaches presented in existing scholarly literature. Conclusions and recommendations are supported by numerous academic and technical publications. Data were extracted from authoritative information sources and the official websites of international organisations such as the UNECE (2019), NEA (2022), IAEA (2023), and World Nuclear Association (2025), providing up-to-date statistics, analytical insights, and overviews of uranium industry technologies. This methodological approach ensured a robust and reproducible assessment of the UBL technology and its prospects for deployment in Ukraine.

Results and Discussion

The characteristics of uranium deposits in Ukraine, coupled with the accumulated exploitation experience and global uranium mining practices highlight the promising potential of a mining-chemical technology: leaching uranium from stockpiled ores within underground stope blocks (IAEA, 2022). NEA (2022) reports the average global uranium content in industrial ores at approximately 0.22% U_3O_8. Ukrainian deposits, as noted by O.A. Lysenko & A.Kh. Bakarzhyiev (2019), often exhibit significantly lower uranium grades, typically 0.02-0.06%. This necessitates that the Ukrainian uranium industry specifically adapt its mining technologies to these low-grade ores. Given the current production costs for natural uranium concentrate in Ukraine and the prevailing market price, the profitability of mining and processing operations remains critically low. This creates a difficult situation: current mining and processing methods are highly capital- and labour-intensive, yet they are applied to ores that are predominantly low- or sub-economic grade. Conventional underground mining and subsequent hydrometallurgical processing at centralised plants remain in use in 2025 and are only economically viable for high-grade ore bodies. Therefore, enhancing profitability requires the implementation of novel, cost-effective technologies for mining and processing low- or sub-economic grade ores. A particularly promising approach is the mining-chemical technology of underground leaching from monolithic hard-rock ores, which involves creating artificial permeability within the ore massif. V.I. Lyashenko *et al*. (2024) indicate that UBL technology retains competitiveness even under conditions of low uranium content.

Compared to conventional hard-rock mining techniques, mining-chemical technologies offer several advantages: the elimination of expensive, labour-intensive and hazardous ore handling operations, the 70-75% reduction in the volume of ore haulage to the surface, the prevention of underground void formation, decreased dependence on rail transport for ore transportation and reduced tailings management costs. The NEA (2022) and the World Nuclear Association (2025) report similar advantages at uranium deposits in Australia, where underground leaching minimised damage to surface ecosystems while ensuring highly efficient recovery of valuable components. Mining-chemical technologies for uranium recovery enable the exploitation of previously sub-economic or sub-standard ore reserves. Preliminary estimates suggest that bringing such ores in production could expand the raw material base of Ukrainian uranium mines by a factor of 1.4-1.6. According to V. Verkhovtsev *et al*. (2023b), UBL offers several advantages including reduced transportation costs, diminished environmental impact, enhanced profitability, and the incorporation of sub-standard ores into production.

Y. Yang *et al*. (2023) demonstrated that the utilisation of CO_2 and O_2 in underground leaching processes can reduce greenhouse gas emissions, thereby mitigating the environmental impact of UBL. Canadian researchers R. Jin *et al*. (2023) underscored the criticality of assessing hydrogeological conditions for the successful implementation of UBL. The study by E.C. Reinisch & B.G. Henderson (2023) on Canadian UBL experience in dense hard-rocks highlighted that leaching efficiency depends on the permeability achieved through prior blasting. Additionally, ore body morphology plays a crucial role in UBL performance. L. Meng *et al*. (2024) note that hydrogeological assessment and leaching potential evaluation must become mandatory components of the planning phase. Operational practices from Australia and Canada suggest that combined approaches may be feasible for Ukrainian uranium mines wherein conventional mining methods are applied to balance reserves, and UBL is reserved for sub-economic, sub-standard and isolated ore deposits.

The deposits currently exploited by the SE "SkhidGZK" – Vatutinske, Michurinske, Tsentralne, and Novokonstantynivske – are located within Precambrian formations of the Ukrainian Shield, overlain by 30-50 m thick Cenozoic loose sediments. Uranium-bearing bodies are associated with metasomatically altered albitites. These albitites, being as dense as the surrounding metamorphic rocks, formed impermeable monoliths during ore genesis, thus presenting conditions conducive to UBL. Their high density, low permeability, and comprehensively studied post-ore fracturing are advantageous for the implementation of this technology. Within the mentioned deposits, blocks prepared for leaching may be conceptually likened to sealed vessels filled with porous, permeable ore. Solution leakage is limited, particularly if blocks are situated beyond fractured zones. The uranium minerals present include uraninite, pitchblende, coffinite, and brannerite. Of these, the first three dissolve readily in sulphuric acid solutions when an oxidant is present. While brannerite typically demonstrates resistance to leaching, it does not occur in its pristine state in Ukrainian deposits; rather, it manifests as decomposed fine aggregates of uranium oxides and silicates with titanium and iron oxides. Consequently, ores containing brannerite exibit leaching characteristics comparable with those containing uraninite and pitchblende.

Thus, Ukraine possesses a sufficient resource base for UBL, as the mineralogical composition and properties of ores across all deposits are favourable for this technology's application. This technology is particularly suited for the development of individual ore bodies within deposits that consist of low-grade and sub-economic uranium ores, individual fragments of deposits with losses within fractured zones that cannot be mined by other technologies, and small deposits at shallow depths. A detailed analysis of the geological structure, mineral composition, and mining-geological conditions of uranium deposit formation in sodium metasomatites indicates that, based on a combination of characteristics, they are favourable for UBL.

The solubility of uranium compounds in sulphuric acid solutions is primarily determined by the form in which uranium is present within the ore. Like other elements in the Earth's crust, uranium may occur either as discrete mineral phases or as isomorphic impurities within the crystal lattices of other minerals. Typically, uranium incorporated as an isomorphic impurity exhibits poor solubility, whereas uranium occurring in its own distinct mineralogical forms dissolves readily in sulphuric acid solutions. From this perspective, ores from albitite-hosted uranium deposits are deemed highly amenable to leaching, as uranium in these formations is predominantly occurs as discrete minerals such as uraninite, pitchblende, brannerite, coffinite, and various uranium hydroxides. Of particular importance to the dissolution process is the oxidation state of uranium in these compounds. Minerals containing uranium in the hexavalent state exhibit significantly greater solubility in sulphuric acid solutions. The chemical equation for this reaction is as follows:

$$UO_{3(s)} + 2H^{+}_{(aq)} \rightarrow UO^{2+}_{2(aq)} + H_2. \quad (1)$$

Tetravalent uranium minerals, prevalent in the ores of albitite-hosted deposits, exhibit slow reactivity with sulphuric acid solutions. However, under practical block leaching conditions, the dissolution process is significantly accelerated by the presence of trivalent iron ions in the productive solutions. These ions are released into solution from iron-bearing dark-coloured minerals such as chlorite, biotite, phlogopite. The reaction can be represented by the following equation:

$$UO_{2(s)} + 2Fe^{3+}_{(aq)} \rightarrow UO^{2+}_{2(aq)} + 2Fe^{2+}_{(aq)}. \quad (2)$$

Thus, uranium contained in albitite-hosted ores – composed predominantly of uraninite, pitchblende, and brannerite (minerals in which uranium is present in the tetravalent state) – readily dissolves under block leaching conditions. This is facilitated by the presence of ferric iron ions, which are leached by sulphuric acid from the host rocks. During underground mining operations that incorporate drilling and blasting, seismic shockwaves are generated within the rock massif. Stress release tends to occur preferentially along pre-weakened tectonic zones that commonly host ore mineralisation. This process induces the opening of microfractures where ore mineralisation is concentrated, thereby enabling productive leaching solutions to access the ore minerals. Given that ore blasting during the preparation of block leaching rooms is typically performed without a compensatory space, the seismic energy from blasting exerts a more pronounced impact on the ore material, significantly increasing the extent of microfracture development. Thus, the combination of ore genetic features and the specific block leaching preparation method results in the formation of an artificially permeable zone within the leaching block. In this zone, the bulk of ore minerals are exposed to acidic solutions through an interconnected network of fractures and microfractures.

The physical and mechanical properties of uranium ores and their transformation under following sulphuric acid exposure are of critical importance for the leaching process. The presence of clay minerals in the input ore, or their intensive formation due to acid exposure severely mitigate permeability and filtration characteristics, potentially leading to the cessation of block leaching operations. However, P. Goyal *et al.* (2024) highlight that the application of modern chemical reagents can significantly enhance the dissolution rate and completeness of uranium recovery, thereby boosting the economic efficiency of the process. A detrimental factor for block leaching is ore compaction, defined as the tendency of loosened ore to self-compress and reduce permeability due to physicochemical interactions with oxygen and acidic solutions.

The ores and host rocks of the deposits exploited by the SE "SkhidGZK" are composed of considerably strong albitites with natural bulk densities of 2,650-2,660 kg/m³ and loosened densities of 1,660 kg/m³. Due to the minimal carbonate content and complete absence of clays, these ores are not prone to compaction. The porosity of blasted ore reaches up to 37%, which supports high permeability, and the leached ore massif maintains stable filtration characteristics throughout the block leaching process. From both a technological and environmental perspective, the success of block leaching operations is critically dependent on inundation of the deposit and permeability of host rocks. High inundation leads to dilution of productive solutions, thereby increasing acid consumption and diminishing economic viability. Furthermore, excessive permeability in host rocks can result in solution losses, uranium migration, and aquifer contamination by sulphates and other leachate components.

Challenges associated with controlling the permeability of the ore massif and preventing the leakage of productive solutions underscore the need for advanced monitoring systems. B. Yang *et al.* (2023) highlight that uranium adsorption by sandstones beyond the leaching zone can compromise environmental safety, thereby requiring enhanced hydrogeological monitoring during block leaching operations. As demonstrated in the study by B. Tsoy *et al.* (2021) on the application of this technology in Kazakhstan and Canada, the integration of automated monitoring systems can lead to significant improvements in both the efficiency and safety of leaching processes.

The uranium-bearing crystalline host rocks in uranium deposits consist of albitites, albitic-microcline rocks, granites, migmatites, and gneisses. Their mineralogical composition is primarily feldspars (90%), quartz (up to 30%), and mafic minerals (e.g., aegirine, chlorite, phlogopite, riebeckite, epidote, biotite), which may account for 15-20%. These formations are naturally water- and acid-resistant, rendering natural leaching unfeasible. Consequently, artificial permeability zones with filtration coefficients of several metres per day should be generated by blasting. M. Stupnik *et al.* (2020) confirmed that the stress-strain state induced by blasting at the SE "SkhidGZK" deposits enhance microfracture development, thereby improving artificial permeability for block leaching.

The substantial filtration coefficient gradient at the interface between the rock massif and an artificially permeable zone prevents productive solutions from filtration into undisturbed crystalline rocks. Only diffusion processes occur across this boundary. Laboratory and pilot-scale studies demonstrated that the maximum depth of diffusion penetration for productive solutions into undisturbed host rock at albitite deposits does not exceed 0.2 m. These findings confirmed that the natural geological and hydrogeological conditions of Ukrainian uranium deposits provide reliable containment of leaching solutions within artificially created permeable zones, ensuring minimal dilution and loss while protecting aquifers from contamination.

In their report at the 1970 São Paulo symposium, M. Harel & P. Suqier (1970) addressed the technical and economic aspects of block leaching. They provided a comparison with conventional mining methods and described the specific techniques for the preliminary destruction of the ore massif. The blasted ore was stockpiled with an average uranium content of 0.102 conventional units. The amount of ore in the stockpile was 2,540 t, and the uranium recovery rate was 82.5%. The method of leaching from a preliminary destructed ore mass in underground blocks proved to be promising based on its techno-economic indicators. Subsequently, a significant portion of the uranium at one of the mines was planned to be recovered using this method. Extensive experimental research on block leaching of uranium ores was also undertaken by Canadian scientists. X. Luo *et al.* (2022) demonstrated that leaching can be successfully applied to steeply dipping ore bodies, while B. Tsoy *et al.* (2021) noted that shallow-dipping bodies may lead to suboptimal solution distribution in blasted ore. Infiltration leaching processes are characterised by a rapid increase in uranium content in the initial stages of spraying, followed by a decline after reaching a peak. During the final stage, uranium concentrations remain low and stable for a prolonged period. Theoretically, this behaviour is attributed to the molecular diffusion of uranium from dispersed mineral phases to the surface of solid ore fragments or the ore massif – a conclusion corroborated by empirical results from block leaching operations, Figure 1.

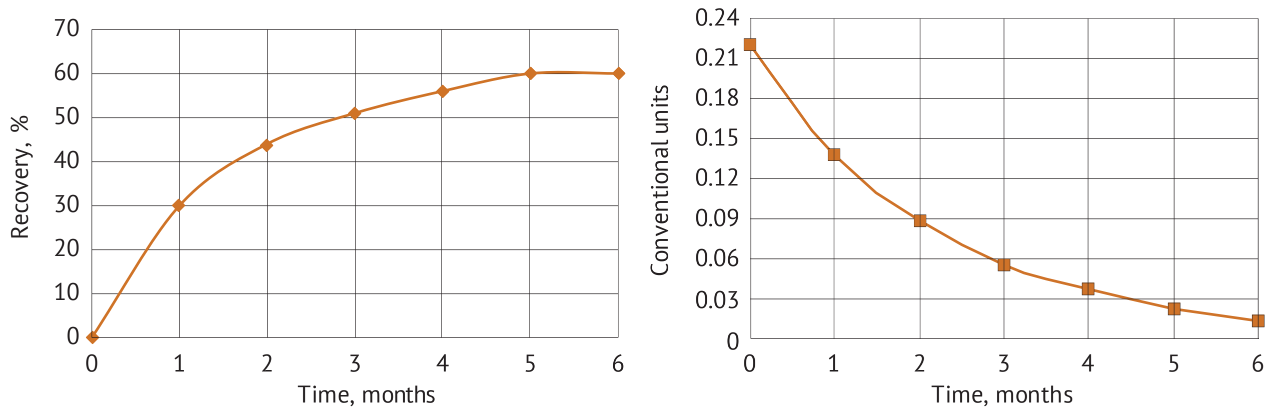

Figure 1. *Variation in uranium leaching indicators as a function of process duration*
Source: *P.M. Kucha (2013)*

Under conditions of lixiviant application to blasted ore, uranium minerals in a readily soluble state dissolve first. This is followed by the leaching of uranium from minerals remaining on the surfaces of rock fragments, and finally from impregnated zones. These specific characteristics of uranium leaching from stockpiled ore masses in blocks were successfully used to manage and optimise the underground leaching process, thereby enhancing its efficiency. The analysis of accumulated experience from enterprises engaged in block leaching revealed several technical, economic, and social advantages of this method. Primarily, it allows for the expansion of the raw material base of mining enterprises through the inclusion of low-grade uranium deposits, including significant reserves of sub-economic and sub-standard ores. It also contributes to labour productivity per unit of final product, improves working conditions and occupational safety, and mitigates the environmental impact.

These advantages of block leaching contribute to lower production costs, improved profitability of enterprises, and enhanced competitiveness of the final product. According to the IAEA (2023), the implementation of combined approaches for the extraction of balance and sub-standard ores will facilitate process optimisation and cost reduction. The economic efficiency of UBL is a key factor in its implementation. Research indicates that this method can reduce uranium production costs and improve operational profitability. The analysis by K. Yussupov *et al.* (2024), which examined the economic parameters of uranium deposits in Ukraine, confirms the feasibility of applying block leaching to low-grade deposits. The cost-benefit evaluation revealed that the cost of uranium obtained from underground leaching is 30% lower than that from conventional underground mining. Moreover, the use of advanced reagents can mitigate the consumption of chemical agents and enhance metal recovery, positively impacting the financial performance of enterprises.

The economic analysis indicates that achieving total uranium recovery from solutions at a level of 75-80% compared with that obtained via conventional underground mining is sufficient to ensure competitiveness. When advantages of block leaching – specifically, reduced losses, the inclusion of low-grade and sub-standard ores in development, and lower mine preparation costs – are considered, an acceptable overall recovery rate may be as low as 65-72%

or less. The review of experience and outcomes from mining-chemical uranium recovery technologies revealed three main directions for the effective use of leaching from stockpiled ores in blocks. The first is the recovery of balance reserves and existing sub-economic ores left after mining the deposit when their extraction by conventional means is unprofitable. The second is a combined mining-chemical scheme for uranium deposit development that integrates conventional methods for mining balance reserves with chemical recovery of sub-economic, sub-standard ores and individual ore bodies. The third is utilising block leaching as a principal method for developing both balance and sub-standard ores.

Under the specific conditions of Ukrainian uranium deposits, the second technological approach is entirely feasible. This would allow for uranium recovery from *in-situ* stockpiled ores, if not entirely, then from a significant proportion of balance reserves in run-of-mine, sub-economic and even off-balance ores. This would contribute to securing a stable uranium supply for nuclear energy needs, enhance the industry's competitiveness, and support sustainable economic development. UNECE (2019) underscores the necessity to modernise uranium resource utilisation strategies, including the implementation of UBL to ensure sustainable development of the industry in Ukraine.

Conclusions

The UBL technology for uranium ores presents a promising trajectory for the development of the mining industry, as it combines economic efficiency with a mitigated environmental impact. The findings of this study confirmed that the geological and hydrogeological conditions of Ukrainian deposits are conductive for the implementation of this technology. This allows for a substantial reduction in both extraction and processing costs, as well as the minimisation of environmental pollution. To sustain the competitiveness of the technology, the total uranium recovery rate from solutions of 75-80% is typically required. Nevertheless, considering the comprehensive benefits of UBL (reduced material losses, the capacity to exploit low-grade and sub-standard ores, and lower mine preparation costs), an acceptable total recovery rate can make 65-72% or even less, while retaining economic viability.

A primary economic benefit of UBL is the significant reduction in operational expenditure. Research demonstrates that uranium produced via underground leaching incurs production costs that are approximately 30% lower than those of conventional underground mining. This substantial cost saving directly enhances the profitability and competitiveness of enterprises operating in the uranium sector, particularly those processing low-grade ores. UBL also optimises the mining process by reducing the volume of ore that needs to be brought to the surface by 70-75%. This considerable decrease obviates several costly, labour-intensive, and hazardous operations associated with conventional ore handling, including ore drawing, haulage, and surface handling. Consequently, this also mitigates expenditures on rail transport to processing facilities and on the long-term maintenance of tailings facilities.

Future research should focus on the development and justification of specific geological-technological models tailored to Ukrainian deposits. These models should aim to practically achieve and optimise key performance indicators for UBL identified in this analysis, which include a potential 30% reduction in production costs, a 1.4-1.6-fold expansion of the mineral resource base, and uranium recovery rates of 65-80%. Based on these findings, the implementation of underground block leaching will enhance the efficiency of Ukraine's uranium mining industry and guarantees a stable supply of nuclear raw materials for the energy sector.

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Conflict of Interest

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References

[1] Bai, Z., Zhao, X., Zhang, J., Wu, F., & Tang, Q. (2023). Optimisation of uranium-radium co-leaching from uranium ore. *Journal of Radioanalytical and Nuclear Chemistry*, 332, 1841-1845. doi: 10.1007/s10967-023-08892-7.

[2] Donskyi, M.O., Syomka, V.O., Sukach, V.V., Ivanov, B.N., Bondarenko, S.M., & Belskyi, V.M. (2023). The features of distribution of uranium of albitites of the Novokostiantynivka and the Partyzanske deposits. *Geochemistry and Ore Formation*, 44, 14-32. doi: 10.15407/gof.2023.44.014.

[3] Goyal, P., Sengupta, A., Srivastava, A., Mukherjee, S., Rout, V.V., & Mohapatra, P.K. (2024). *In-situ*-generated fluoride-assisted rapid dissolution of uranium oxides by ionic liquids. *Inorganic Chemistry*, 63(8), 3275-3284. doi: 10.1021/acs.inorgchem.3c04075.

[4] Guihe, L., & Jia, Y. (2024). A review of *in situ* leaching (ISL) for uranium mining. *Mining*, 4(1), 120-148. doi: 10.3390/mining4010009.

[5] Harel, M., & Suqier, P. (1970). *Report of France at the international symposium on uranium extraction from uranium ores and other sources No. M 154/4*. Retrieved from https://inis.iaea.org/records/en147-9nm12.

[6] IAEA. (2019). *Uranium production cycle selected papers 2012-2015*. Retrieved from https://surl.lt/pqceiz.

[7] IAEA. (2022). *Recent developments in uranium exploration, production, and environmental issues*. Retrieved from https://www-pub.iaea.org/MTCD/Publications/PDF/te_1463_web.pdf.

[8] IAEA. (2023). *Advances in uranium ore processing and recovery from non-conventional resources*. Retrieved from https://www.iaea.org/publications/3542/advances-in-uranium-ore-processing-and-recovery-from-non-conventional-resources.

[9] Jin, R., Yu, R., & Miao, P. (2023). Basin uranium mineralization law. In *Geological background of sandstone-type uranium deposits in Ordos Basin, Northwest China* (pp. 325-356). Singapore: Springer. doi: 10.1007/978-981-19-6028-4_5.

[10] Kucha, P.M. (2013). *Substantiation of technology and parameters of underground mining operations during block leaching of uranium from rock ores*. (Doctoral thesis, Kryvyi Rih National University, Kryvyi Rih, Ukraine).

[11] Luo, X., Zhang, Y., Zhou, H., He, K., Zhang, B., Zhang, D., & Xiao, W. (2022). Pore structure characterization and seepage analysis of ionic rare earth orebodies based on computed tomography images. *International Journal of Mining Science and Technology*, 32(2), 411-421. doi: 10.1016/j.ijmst.2022.02.006.

[12] Lyashenko, V.I., Dudar, T.V., Stus, V.P., & Shapovalov, V.A. (2024). Improvement of combined technologies for underground block leaching of metals from off-balance and substandard ores. *Environmental Safety and Natural Resources*, 52(4), 5-27. doi: 10.32347/2411-4049.2024.4.5-27.

[13] Lysenko, O.A., & Bakarzhyiev, A.Kh. (2019). State and prospects of the uranium raw material base of Ukraine. *Mineral Resources of Ukraine*, 1, 11-17. doi: 10.31996/mru.2019.1.11-17.

[14] Meng, L., Ning, H., Jiang, W., Sheng, Y., Wang, W., & Tang, C. (2024). Comprehensive study on hydrogeological conditions and suitability evaluation of *in situ* leaching for sandstone-hosted uranium deposit in Erlian Basin. *Water*, 16(19), article number 2785. doi: 10.3390/w16192785.

[15] NEA. (2022). *Uranium 2021: Resources, production, and demand*. *Paris: OECD Publishing*.

[16] Reinisch, E.C., & Henderson, B.G. (2023). Spatio-temporal analysis and volumetric characterization of interferometric synthetic aperture radar-observed deformation signatures related to underground and *in situ* leach mining. *Journal of Applied Remote Sensing*, 17(4), article number 044511. doi: 10.1117/1.JRS.17.044511.

[17] Stupnik, M., Kalinichenko, V., Fedko, M., Kalinichenko, O., & Hryshchenko, M. (2020). The study of the stress-strain state of the massif in mining uranium at "VOSTGOK" deposits. *E3S Web of Conferences*, 166, article number 03006. doi: 10.1051/e3sconf/202016603005.

[18] Tsoy, B., Myrzakhmetov, S., Yazikov, E., Bekbotayeva, A., & Bashilova, Y. (2021). Application of radio-wave geointoscopy method to study the nature of spreading the solutions in the process of uranium underground leaching. *Mining of Mineral Deposits*, 15(4), 1-7. doi: 10.33271/mining15.04.001.

[19] UNECE. (2019). *Redesigning the uranium resource pathway*. Geneva: United Nations.

[20] Verkhovtsev, V., Musich, O.G., Fomin, Y.O., & Demikhov, Y.M. (2023a). Bacterial leaching of balanced ores of albitite deposits of the Ukrainian Shield. *Mineralogical Journal*, 45(1), 72-82. doi: 10.15407/mineraljournal.45.01.072.

[21] Verkhovtsev, V., Sushchuk, K., Tyshchenko, Y., Meshcheryakov, S., & Koliabina, I. (2023b). Control of the environmental impact of uranium underground well mining (on the example of Mykhailivka polygenic deposit of the Ukrainian Shield). *Visnyk of Taras Shevchenko National University of Kyiv. Geology*, 101, 81-87. doi: 10.17721/1728-2713.101.12.

[22] World Nuclear Association. (2023). *In-situ leach (ISL) mining of uranium*. Retrieved from https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/in-situ-leach-mining-of-uranium.

[23] World Nuclear Association. (2025). *Uranium mining overview*. Retrieved from https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview.

[24] Yang, B., Cui, D., Meng, T., Lian, G., & Guo, H. (2023). Characteristics and influencing factors of uranium adsorption by sandstones outside an acid *in situ* leaching uranium mining area. *Environmental Earth Sciences*, 82, article number 532. doi: 10.1007/s12665-023-11230-5.

[25] Yang, Y., Zuo, J., Qiu, W., Wu, J., Que, W., Zhou, G., Liu, Z., & Wu, J. (2023). Assessment of the greenhouse gas footprint and environmental impact of CO_2 and O_2 *in situ* uranium leaching. *Acta Geologica Sinica (English Edition)*, 97(3), 986-994. doi: 10.1111/1755-6724.15058.

[26] Yussupov, K., Aben, E., Myrzakhmetov, S., Akhmetkanov, D., & Sarybayev, N. (2024). Increasing the efficiency of underground block leaching of metal. *Civil Engineering Journal*, 10(10), 3339-3349. doi: 10.28991/CEJ-2024-010-10-014.

[27] Zhou, Y., Li, G., Xu, L., Liu, J., Sun, Z., & Shi, W. (2020). Uranium recovery from sandstone-type uranium deposit by acid *in situ* leaching. *Hydrometallurgy*, 191, article number 105209. doi: 10.1016/j.hydromet.2019.105209.

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Огляд технологій та перспективи підземного видобутку уранової сировини

Анотація. Актуальність дослідження підземного видобутку урану зумовлена зростанням потреби у стабільному постачанні ядерної сировини для атомної енергетики, яка розглядається, як один із ключових факторів енергетичної безпеки в умовах глобальної енергетичної кризи. Враховуючи обмеженість високоякісних руд та необхідність розробки низькосортних покладів, особливу увагу привертає впровадження сучасних технологій вилуговування урану безпосередньо в підземних блоках. Метою роботи було дослідження та оцінка ефективності блочного підземного вилуговування урану з урахуванням геологічних умов родовищ України, а також визначення перспектив застосування цього методу для підвищення економічної ефективності гірничодобувних підприємств. У процесі дослідження використано методи аналізу геолого-структурних особливостей родовищ, моделювання процесів вилуговування, а також техніко-економічне оцінювання застосування блочного вилуговування в умовах українських родовищ. Застосовано порівняльний аналіз традиційних методів видобутку урану та новітніх технологій підземного вилуговування. Основні результати показали, що блочне підземне вилуговування дозволяє суттєво знизити витрати на видобуток та переробку низькосортних уранових руд, мінімізувати екологічний вплив на довкілля та підвищити рентабельність підприємств. Дослідження підтвердили, що геологічні та гідрогеологічні умови уранових родовищ в Україні є сприятливими для впровадження цієї технології. Застосування блочного вилуговування дозволяє розширити сировинну базу за рахунок залучення бідних та некондиційних руд, які раніше не розглядалися для промислової розробки. Практична цінність роботи полягає у можливості підвищення економічної ефективності гірничодобувних підприємств, зниженні витрат на видобуток та переробку руд, а також зменшенні негативного впливу на навколишнє середовище. Запровадження підземного блочного вилуговування сприятиме сталому розвитку уранової промисловості України

Ключові слова: блочне підземне вилуговування; гірничо-хімічна технологія; уранові родовища; низькосортні руди; ядерна енергетика

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Beneficiation of technogenic phosphorus-containing raw materials as a source of mineral fertilisers

Abstract. The relevance of this research arises from ongoing challenges related to rising raw material costs, geopolitical instability, and the complexity of processing phosphate rock ores with high impurity content. These factors underscore the need to develop efficient approaches for the beneficiation and processing of low-grade raw materials and waste as alternative sources of phosphorus. The aim of the study was to develop a technology for the beneficiation of technogenic phosphorus-containing materials to obtain phosphate rock concentrate suitable for fertiliser production. The research involved mineralogical, chemical, granulometric, and sedimentation analyses of the raw materials. Laboratory experiments included grinding, flotation, and magnetic separation. In addition, the properties of reagents for flotation-based beneficiation of phosphorus-containing materials were investigated. The study examined the potential for beneficiating technogenic phosphorus-containing materials derived from phosphate ore processing. Two laboratory-scale flowsheets – magnetic-flotation and flotation-magnetic – were tested, both enabling the production of commercial phosphate rock concentrate with a P_2O_5 content ranging from 18.7% to 21.5%, and phosphorus recovery of 69.5% to 93%. For the first time, the significance of surface tension energy at the three-phase boundary during flotation was established, justifying the use of an anionic collector, talactam, for the effective separation of francolite from quartz. Magnetic separation, both before and after flotation, was found to enhance francolite concentration while reducing the content of glauconite and iron-bearing minerals. It was also determined that preliminary classification of the feed material at a particle size threshold of 0.16 mm reduces sludge formation during disintegration. The resulting glauconite-rich products have potential applications in the production of potash fertilisers and green pigments, although further study is required. The practical significance of this work lies in the successful implementation of the developed beneficiation technology for technogenic phosphate raw materials, which enables the production of phosphate concentrate (23.18%) suitable for the manufacture of Grade III phosphate flour fertiliser, and a glauconite product (50.71%) applicable as an enterosorbent and a source of trace elements in compound animal feeds

Keywords: phosphorus; francolite; glauconite; magnetic separation; flotation

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Introduction

Phosphorus constitutes a key element in agriculture, forming a critical component of mineral fertilisers, including superphosphate, ammonium phosphate (amophos), and diammonium phosphate (diamophos). The sustainability of modern agro-industrial productivity cannot be maintained in the absence of phosphorus. However, phosphorus is a finite, non-renewable resource, with global reserves projected to be exhausted within the next 50-100 years. The resulting phosphorus deficit poses a direct threat to global food security. Consequently, intensive efforts have been directed towards the development of phosphorus recovery technologies from waste, wastewater, sludge, and phosphogypsum. Ukraine possesses no significant industrial deposits of natural phosphorus, necessitating the annual importation of over 800,000 tonnes of phosphatic fertilisers, primarily sourced from Morocco, Poland, China, and Lithuania. War, sanctions, and logistical constraints have had a marked impact on the accessibility of such imports. Attaining phosphorus self-sufficiency represents a strategic objective for Ukraine, aimed at reducing import dependency and enhancing agricultural autonomy. Ensuring a reliable supply of phosphate feedstock to Ukrainian producers of mineral fertilisers is a critical and pressing challenge. The successful resolution of this issue is vital to enabling the uptake of advanced phosphorus-processing technologies. Ukraine holds the potential to convert technogenic waste into a source of critical materials, thus reducing import reliance and entering the recycled phosphorus products market.

Within this context, research into efficient methods for processing phosphorite ores of varying degrees of enrichment is pertinent, with consideration of mineral composition, technological characteristics, and the potential for sustainable utilisation, has become increasingly relevant. Emphasis has therefore shifted towards the extraction of phosphates from tailings and low-grade ore deposits as secondary resources. Market instability, driven by geopolitical factors, rising raw material costs, and the inherent complexity of processing phosphorite ores with high impurity levels, necessitates the development of new strategies for resource utilisation, enrichment, and phosphate waste processing.

A. Proidak *et al*. (2021) identified that, due to political circumstances, Ukraine had encountered substantial challenges in supplying its fertiliser and ferrophosphorus plants with domestically sourced phosphorites and apatites. The authors conducted comprehensive studies on the mineral composition and metallurgical properties of phosphorite rocks, enabling an assessment of their suitability for the production of phosphorus-containing ferroalloys. S. Banerjee (2023) noted that the composition of phosphorite ores varies significantly depending on origin, with considerable diversity in structure, texture, and physicochemical properties. According to Y. Raiymbekov *et al*. (2023), approximately 20 million tonnes of low-grade phosphorites globally remain unprocessable under current technologies. The depletion of phosphorite deposits and the low content of phosphoric anhydride have contributed to declining global demand for phosphates, underscoring the need for advanced research on the enrichment and comprehensive utilisation of low-grade phosphates.

B. Wang *et al*. (2022) demonstrated that, due to their low phosphorus content and high proportions of accompanying materials (quartz, clay, calcite, dolomite, mica, feldspar, etc.), natural phosphate ores are unsuitable for direct application as fertilisers or for use as raw materials in phosphate fertiliser production. The efficient utilisation of phosphorites with medium or low phosphorus content is only feasible following preliminary treatment to achieve the requisite phosphorus concentration. Selection of an appropriate enrichment method depends on key parameters such as mineral texture, total phosphorus content, gangue composition, and, most importantly, the target phosphorus concentration as dictated by the intended application.

M. Sajid *et al*. (2022) reviewed phosphorite ore enrichment technologies aimed at achieving high-quality concentrates. Commonly employed enrichment techniques include flotation, electromagnetic separation, gravity separation, and magnetic separation. Global economic development has stimulated increasing demand for phosphorus-containing products. All existing high-grade phosphorite deposits have now been exhausted. This has necessitated the utilisation of low-grade phosphorites and off-spec phosphate raw materials, which remain underexplored and underutilised.

Y. Raiymbekov *et al*. (2020) provided an overview of low-grade phosphorite beneficiation practices in various countries, describing separation mechanisms during flotation enrichment and carbonate mineral decomposition using organic acids. The authors concluded that method selection depends on the mineralogical structure and chemical composition of the phosphorites. N. Abbes *et al*. (2020) enriched low-grade phosphate ore from Sra Ouertane (Tunisia) via thermal treatment, including calcination, quenching, and desliming. The applied treatment successfully increased the P_2O_5 content from 20.01 wt.% to 24.24 wt.% post-calcination and to 27.24 wt.% following quenching. Furthermore, enrichment of associated rare-earth elements (Ce, La, Nd, Pr, Sm, Y) was achieved, while the Cd concentration was significantly reduced from 30 mg/kg to 14 mg/kg.

M. Derhy *et al*. (2020) reported that flotation technology had been extensively studied due to its wide application in phosphorite enrichment, with various depressants and collectors deployed to remove calcite and silica from sedimentary phosphate ores. A single-stage flotation of either phosphate or calcite was found insufficient for producing high-quality concentrates. K. Zhantasov *et al*. (2024) established that approximately

55-60% of the phosphate ore extracted and crushed comprises fine fractions below 10 mm, which are unsuitable for conventional phosphate fertiliser production. Experimental results confirmed the high efficiency of mechanical activation for fine phosphorite fractions. The proposed innovative process differs fundamentally from existing methods, as mechanochemical activation enabled direct, acid-free, and waste-free conversion into mineral phosphate fertilisers

U. Ryszko *et al.* (2023) highlighted that enrichment processes generate substantial volumes of waste. The processing and reuse of such phosphorus production waste is currently expanding, with the goal of producing scarce products. The integration of magnetic separation and flotation methods in the enrichment of phosphorite ore waste enables the recovery of concentrates suitable for the production of mineral fertilisers. The objective of the study was to investigate the mineralogical, chemical, granulometric, and sedimentological composition and technological properties of the feedstock, thereby developing a magnetic-flotation enrichment process for technogenic phosphorus-containing materials, capable of yielding concentrates and products suitable for fertiliser production.

Materials and Methods

A total of 18 small mineralogical samples of technogenic phosphorus-containing material were submitted to Kryvyi Rih National University for examination. A composite technological sample was prepared from these for use in process development studies. Chemical analysis was employed to determine the elemental and oxide composition of the material, including the content of primary components (P_2O_5, CaO, SiO_2, Fe_2O_3) and impurities affecting process properties and the suitability of concentrates for fertiliser production. Mineralogical analysis identified the constituent minerals (apatite, quartz, glauconite, etc.), which was critical for assessing the material's processing behaviour and selecting effective treatment methods.

Particle size distribution was determined through granulometric analysis, which established the optimal conditions for crushing, grinding, and enrichment, given the significant influence of size fraction on separation efficiency and recovery. Sedimentation analysis, based on the settling rate of fine particles in liquid, enabled precise estimation of particle sizes below 0.05 mm, which are known to affect material behaviour in aqueous and hydraulic enrichment processes. A technological analysis was conducted to evaluate the material's suitability for beneficiation, including laboratory-scale magnetic and flotation enrichment trials and assessment of concentrate quality indicators (e.g. yield, P_2O_5 content), forming the basis for the proposed processing flowsheet.

The composite sample was washed and classified into size fractions: +1.25, -1.25+0.5, -0.5+0.25, -0.25+0.16, -0.16+0.074, -0.074+0.044, and -0.044 mm. Representative subsamples of approximately 500 fragments were taken from each fraction using quartering, with 25% of fragments identified as free particles or composites for each mineral. Recalculation of composites into equivalent free particles was performed using a custom formula implemented in Microsoft Excel (Office XP). Grindability was evaluated using a standard method at grinding times of 5, 10, 20 and 40 minutes in a 7-litre laboratory ball mill under dry and wet conditions. The solid-to-liquid-to-ball ratio (S: L: B) was maintained at 1:0.33:10, and the mill charge was 1.6 kg (Biletsky *et al.*, 2020). Further sample preparation involved grinding to 0.16 mm (the size of the phosphorite opening) in a laboratory ball mill (model 75A-ML, Horstal Plant, Ukraine).

Magnetic susceptibility was studied in the laboratory of the Department of Mineral Processing and Chemistry, Kryvyi Rih National University, using the ponderomotive method based on the Gouy technique, as described by V. Zdeshchyts & A. Zdeshchyts (2023). The Gouy method involves measuring the gravitational force on a sample with one end in a strong magnetic field and the other in a weak field. Laboratory-scale magnetic enrichment was conducted using a rotary separator (model 259-CE, MAGNIS R&D Centre, Luhansk, Ukraine) equipped with a high-intensity magnetic field. Two materials were processed: raw material ground to 100% minus 0.16 mm (70% of class minus 0.074 mm) and the froth product from flotation.

Material with 70% of -0.074 mm and 30% solid content was fed into the separator's working zone, consisting of 200 mm high grooved plates. The matrix loading was 0.2 g/cm^3. A scalping rotor, operating at one-third the magnetic induction of the axial rotors, removed magnetic particles from the plates, enhancing the recovery of iron-containing components in the magnetic product. Magnetic field induction ranged from 0.6 to 1.2 T.

Flotation tests were conducted in a mechanical-type flotation machine (model 237 FO, SCMA Lab, Kryvyi Rih, Ukraine) with cell volumes of 0.5, 1.0, and 1.5 litres, air flow rate of 1 L/m^3 of slurry, and impeller speed of 26.7-28.3 s^{-1}. Test samples weighed 200, 400, or 600 g; closed-cycle tests used 150, 350, or 500 g. The flotation feed consisted of deslimed material (0.02 mm), ground to 100% of -0.16 mm, and the non-magnetic product from magnetic separation. Reagent selection and dosage followed standard phosphorite flotation practices and previous research (Oliinyk *et al.*, 2023). Anionic collectors were used: crude tall oil soap (CTOS) and talactam (RCONH $(CH_2)_5$ COONa), a condensation product of tall oil with sodium salt of amino carboxylic acid. Sodium silicate acted as a depressant, and soda ash adjusted the pH (ranging from 8.7 to 10.5). Slurry solids content during agitation was 26%; mixing time was 3 minutes. Reagent consumption (kg/t): collectors – 0.5-1.7; depressants – 0.4-0.7; pH regulators – 0.5-0.8.

Optimal parameters from single flotation tests were refined in closed cycles using recirculated water, including primary, scavenger, and three to four cleaner flotation stages. Decantation was employed to obtain recycled water; tap water was used in process trials. Collector flotation activity was assessed via surface tension measurement using the ring detachment method, based on the force required to detach liquid adhering to a ring. Additionally, the impact of slurry temperature on flotation performance using talactam was studied, as this reagent is a condensation product of tall oil and amino carboxylic acid sodium salt.

Sedimentation analysis of slimes was conducted using a gravimetric method, based on differential settling velocities of particles of varying size and mineral composition. The methodology of sedimentation analysis was based on the differences in settling time of mineral particles of varying grain sizes. The essence of the method consisted in determining the variation in substance concentration at a specific depth of the suspension. During the experiments, the equal-settling coefficient for mineral particles was taken into account. The material was classified into grain size classes. For the calculation of settling time of mineral particles for each grain size class, terminal settling velocities were determined. The terminal settling velocities for the classes with a maximum grain size of 0.033 mm were calculated using Stokes' formula:

$$u = \frac{2\Delta\rho g a^2}{9\mu}, \qquad (1)$$

where u – is the particle settling velocity, m/s; $\Delta\rho = \rho_s - \rho_f$ – is the difference in densities of the dispersed phase and the medium, respectively, kg/m^3; g – is the acceleration of gravity, m/s^2; μ – is the viscosity of the medium, PaS (0.0001 Pa×s); a – is the particle radius, m.

During the planning of experiments, the settling time for the selected vessel was determined as the ratio of the height between the vessel markings to the calculated terminal settling velocities of the material. Distilled water was used during the experiments. In the course of sedimentation analysis using this method, samples were taken from a specific depth of the suspension at different time intervals from the start of the experiment, and the mass concentration of the substance in each sample was determined. With knowledge of the particle size and the settling height, the sampling time was calculated. The difference in mass concentrations between individual samples indicated the relative content of particles of the respective fractions in the analysed suspension. The calculations took into account the density of the solid phase in the relevant suspension: 3,800 kg/m^3 for intermediate products and an average of 2,600 kg/m^3 for waste. The settling time of a particle in the suspension (t_s) was estimated as the time required for the particle to travel a distance equal to the vessel height (H):

$$t_s = \frac{H}{u}. \qquad (2)$$

Sedimentation analysis of the suspension by the gravimetric method was carried out using an apparatus consisting of a 1 dm^3 cylinder, a stirrer, and a Robinson pipette, which enabled sampling of the liquid at a constant level. A weighed portion of material of a specific grain size class (-0.045 + 0 mm) was placed into the vessel filled with water. The previously calculated settling time was then measured, after which the non-settled material was decanted. The experiment was repeated with the addition of clean water until the liquid above the lower mark became transparent.

Results

The results of the study on the influence of surface tension magnitude as a function of reagent concentration were presented in Figure 1.

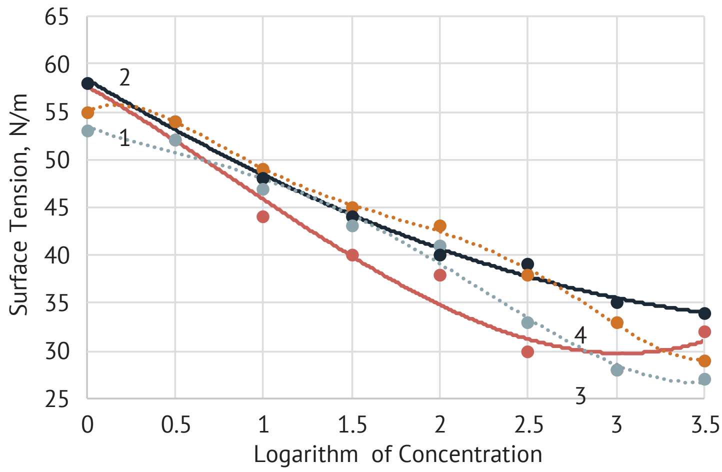

Figure 1. *Surface tension as a function of reagent concentration*

Notes: *1 – Talactam solution in tap water; 2 – CTOS solution in tap water; 3 – Talactam in technical water; 4 – CTOS in technical water*

Source: *authors' development*

All four reagents demonstrated typical surfactant behaviour: surface tension decreased with increasing reagent concentration, confirming their capacity to accumulate at phase interfaces and reduce surface energy. In tap water, talactam produced a gradual reduction in surface tension, with the critical micelle concentration (CMC) observed around a logarithmic concentration of ≈2.5, beyond which the curve plateaued. Surface tension reduction was moderate in this case.

In contrast, talactam in process water achieved a significantly deeper reduction in surface tension – from 60 mN/m to approximately 30 mN/m within the studied concentration range (logarithmic concentration 0 to 2.5) – followed by a gradual yet substantial decline. This behaviour was attributed to strong interactions with process water, likely influenced by the presence of calcium ions and trace impurities. Initial surface tension was slightly higher (~58-60 mN/m). In both tap and process water, CTOS exhibited less efficiency than talactam, confirming talactam in process water as the most effective surfactant within this series, due to its consistent and substantial reduction of surface tension. Water type significantly influenced activity, with process water enhancing performance due to coagulation effects. The kinetics of optical density variation for talactam in tap water are shown in Figure 2.

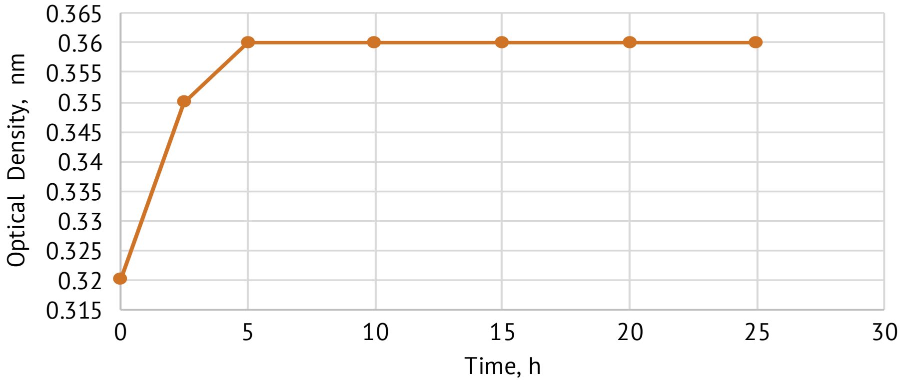

Figure 2. *Kinetics of optical density change for talactam in tap water*
Source: *authors' development*

A sharp increase during the initial 5 hours indicated active processes of dissolution, dispersion, or interaction between talactam and water components. Stabilisation occurred around 0.360 nm after 5 hours, indicating that the system had reached equilibrium. Stability up to 25 hours indicated the physicochemical resistance of talactam in tap water following the initial activation/dissolution process. The observed increase in optical density was likely due to one or more of the following: dissolution or swelling of the polymer, reactions with ions or impurities, or self-aggregation of molecules. Changes in optical density – an important indicator of surfactant system stability and interactions with aqueous environments – depended on reagent concentrations (Fig. 3).

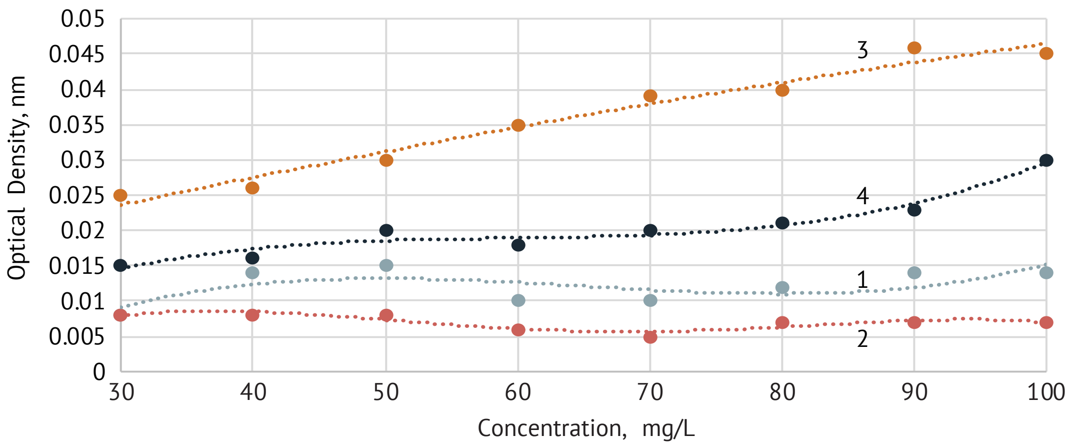

Figure 3. *Change in optical density of talactam dependent on reagent concentrations*
Notes: *1 – Talactam solution in tap water; 2 – CTOS solution in tap water; 3 – Talactam solution in recycled water; 4 – CTOS solution in recycled water*
Source: *authors' development*

Observations on talactam behaviour in recycled versus tap water revealed that in recycled water, optical density increased most significantly with increasing concentration, reaching ~0.045 nm at 100 mg/L. This suggested active particle aggregation and the presence of colloids or impurities interacting with talactam. In tap water, optical density remained stable, with a slight peak at 40-50 mg/L. Subsequent plateauing or decline likely indicated solubility limits and stabilisation, or reduced aggregation. In recycled water, CTOS also showed increased optical density, albeit to a lesser extent than talactam, suggesting partial aggregation inhibition or lower absorbance. In tap water, CTOS exhibited minimal changes, with optical densities in the 0.005-0.01 nm range – indicating the most stable behaviour in this environment, likely due to absence of particle aggregation. Thus, talactam in recycled water demonstrated a strong tendency to aggregate, leading to increased optical density and improved collector performance, as confirmed in subsequent trials. The chemical composition of the composite technogenic phosphorus-containing sample is shown in Table 1. The average P_2O_5 content was 10.55%, with SiO_2 at 35.65%, total Fe at 7.5%, CaO at 18.82%, and Al_2O_3 at 5.3%. These oxides served as key evaluation criteria for phosphorite and glauconite products.

Table 1. *Chemical composition of technogenic phosphorus-containing raw material (average values)*

Material	Components, %															
	P_2O_5	MgO	CaO	SiO_2	Al_2O_3	Fe_{total}	FeO	Fe_2O_3	TiO_2	Na_2O	K_2O	MpO	F	S_{total}	CO_2	SO_3	LOI
Sample	10.55	2.02	18.82	35.65	5.3	7.5	1.0	10.1	0.19	0.33	2.75	0.45	1.85	1.34	2.42	0.9	0.355

Source: *authors' development*

Mineralogical analysis revealed that the primary phosphorus-bearing mineral, francolite, constituted 21.8% of the sample. The sample was characterised by a significant content of glauconite (38.6%) and iron hydroxides (7%). It also contained heterogeneous clay material (9.1%) and gypsum (2.1%). The liberation characteristics of the minerals are illustrated in Figure 4.

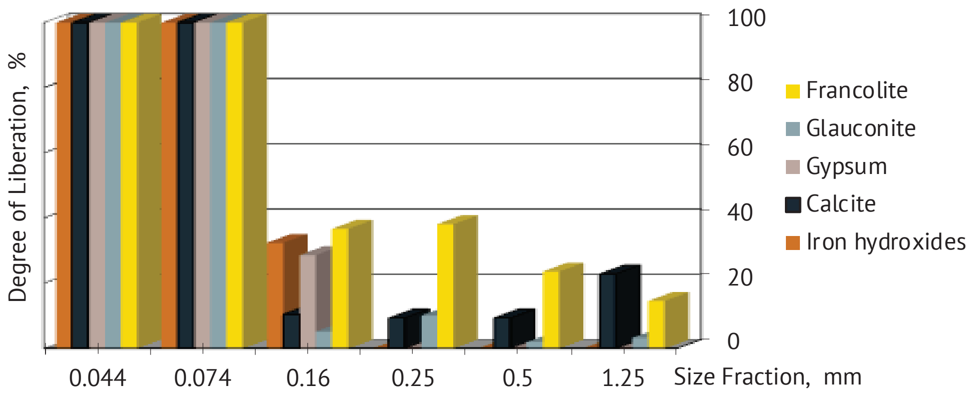

Figure 4. *Mineral liberation in the grain size classes of the initial sample*

Source: *authors' development*

Mineralogical analysis of classified material showed that the +1.25 mm fraction comprised 15.7% free particles and 84.3% composites. Among the free particles were francolite, clay mineral, glauconite, calcite, and palaeoresidue. Rich composites (with >50% of a single mineral) outnumbered poor ones (≤50 %) – 52.7% vs. 31.6%. Rich composites were primarily composed of glauconite, francolite, and clay mineral. Palaeoresidue occurred only as free fragments.The -1.25 + 0.5 mm fraction consisted of 82.2% composites (34.2% rich, 28.1% poor). Rich composites contained glauconite, francolite, and clay mineral. In contrast to previous fractions, iron hydroxides and hydromicas no longer exhibited a predominance of rich composites. Free particles (17.8%) included the same minerals found in coarser fractions, with quartz appearing as an additional free component.

The -0.5 + 0.25 mm fraction contained 20.5% free particles and 79.5% composites. Free particles included the same components observed in coarser fractions. Rich composites significantly exceeded poor ones (67.5% vs. 12.0%). No poor magnetite composites were detected. The -0.25 + 0.16 mm fraction comprised 17.6% free fragments and 82.4% composites. All previously identified minerals were present among the free fragments, with the exception of magnetite. The gap between rich and poor composites widened to 71.2% and 11.2%, respectively. Beginning with the -0.16 + 0.074 mm fraction and continuing to finer sizes, all particles were fully liberated.

The distribution of minerals across size classes was non-uniform. The -0.5 mm fractions were the most enriched in francolite, due to the low selectivity of fine-grained ore enrichment. Grinding to -0.16 mm resulted in sharp reductions in coarse fractions and a marked increase in fines. Fine grinding maximised mineral liberation at 0.16 mm, though it generated a significant volume of slimes. Hence, pre-classification using classifiers and hydrocyclones prior to grinding is recommended. The formation rate of the minus 0.16 mm fraction is shown in Figure 5, with rapid formation occurring within the first 16 minutes, followed by a sharp decline.

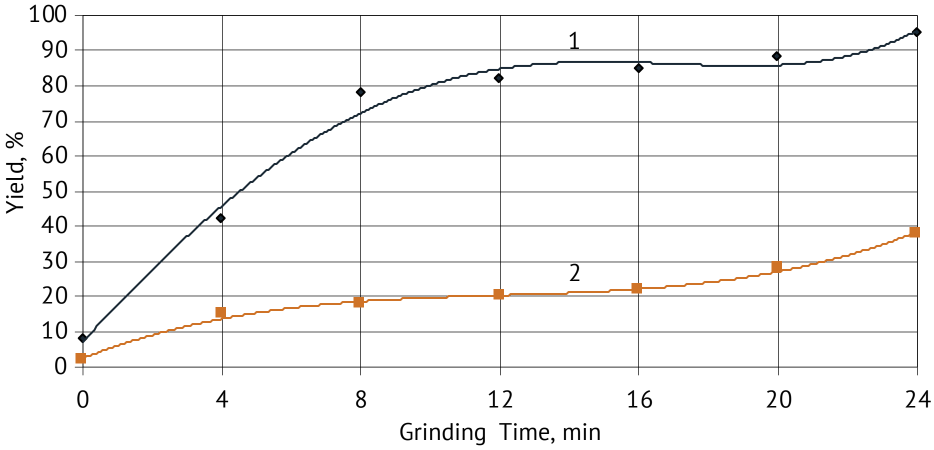

Figure 5. *Kinetics of formation of -0.16 mm and -0.044 mm size fractions during sample grinding in a ball mill*
Notes: *1 – Formation curve of the -0.16 mm size fraction; 2 – Formation curve of the -0.044 mm size fraction*
Source: *authors' development*

Formation of the <0.16 mm fraction followed a polynomial equation with an approximation reliability of 0.9894:

$$R^{+} = 0.0008\,t^{4} - 0.0236\,t^{3} - 0.188\,t^{2} + 10.743\,t + 7.1234, \qquad (3)$$

where R^{+} – retained portion on the 0.16 mm sieve, %; t – grinding time, min. Formation of the -0.044 mm fraction followed a polynomial with approximation reliability of 0.9954:

$$R^{+} = 0.0082\,t^{3} - 0.2969\,t^{2} + 3.871\,t + 2.4762, \qquad (4)$$

where R^{+} – retained portion on the 0.044 mm sieve, %; t – grinding time, min.

Detailed mineral-petrographic analysis of screened products clarified the grinding mechanism. The first phase involved intense disintegration of aggregates, liberating francolite grains. This was followed by disaggregation of intergrowths and grinding of liberated mineral grains. Due to its low hardness, francolite was prone to overgrinding and transitioned into the -0.044 mm fraction. During the study of raw material comminution, it was established that, in order to increase the degree of mineral intergrowth liberation, release of phosphorite and glauconite, and to reduce the content of refractory slimes, a closed grinding circuit with high circulating loads had to be employed.

Sedimentation analysis of post-grinding slimes demonstrated that the P_2O_5 content in the +0.02 mm and -0.02 mm fractions was evenly distributed, allowing the +0.02 mm fraction to be included in enrichment processes and thereby increasing overall P_2O_5 recovery in the final product. The material, with slimes removed (-0.02 mm), was subjected to magnetic and flotation enrichment. Chemical analysis confirmed the sample as a high-carbonate feedstock with elevated iron content. Studies of magnetic susceptibility showed that glauconite and siderite exhibited weak magnetic properties, while phosphates and quartz were non-magnetic. The difference in susceptibility between glauconite/siderite and quartz/phosphates was sufficient for selective recovery in a high-intensity magnetic field.

The mineral distribution in magnetic separation products was found to be independent of feed composition, with magnetic products enriched in glauconite, iron hydroxides, and magnetite in varying ratios. Grinding to -0.16 mm did not significantly reduce phosphorus losses in magnetic products, indicating an isomorphic association between glauconite and phosphate. In non-magnetic products, an increase in non-magnetic mineral phases (calcite, quartz, clay, barite, palaeoresidue) was observed, depending on the material fed into the separator. The presence of these phases in magnetic products resulted from intergrowths with iron-rich minerals. Francolite was detected in both magnetic and non-magnetic products, mainly as intergrowths with glauconite. The distribution of minerals in the products of magnetic separation of the ground ore was presented in Figure 6.

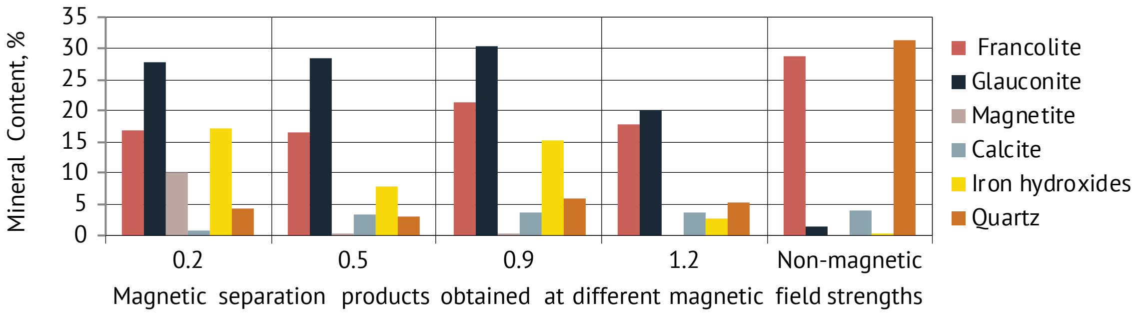

Figure 6. *Mineral Distribution across magnetic separation products of raw material ground to 100% passing 0.16 mm*
Source: *authors' development*

The clay mineral content in magnetic products of ground materials increased from 3.3% to 19.2% with rising magnetic field induction (0.2 T to 1.4 T). In non-magnetic products, the content reached 30.0 – 44.0%. In intermediate products, content varied from 12.2% to 20.1%. Glauconite distribution in magnetic products peaked at 75.4% at 0.9 T and then declined to 52.2% at 1.4 T. In non-magnetic products, glauconite content was 1.3%.

Magnetic separation of ground feedstock enabled glauconite to be separated into a distinct product. However, due to residual francolite in magnetic products, additional separation of the flotation froth was performed. In the non-magnetic product, francolite content was 28.8%, compared to 16.6-21.2% in magnetic products. Magnetic separation of the froth product improved the francolite concentration in the flotation fraction by removing glauconite. At 0.9 T, the magnetic field reduced total iron content in the froth phosphate product from 8-11% to 2-3%. Analysis of the flotation froth product from material ground to 100% -0.16 mm showed that the P_2O_5 content in the phosphorite concentrate ranged from 18.7% to 21.5%, with P_2O_5 recovery in the froth product ranging from 69.5% to 93%. The relationship between P_2O_5 content and collector dosage (talactam and CTOS) is shown in Figure 7.

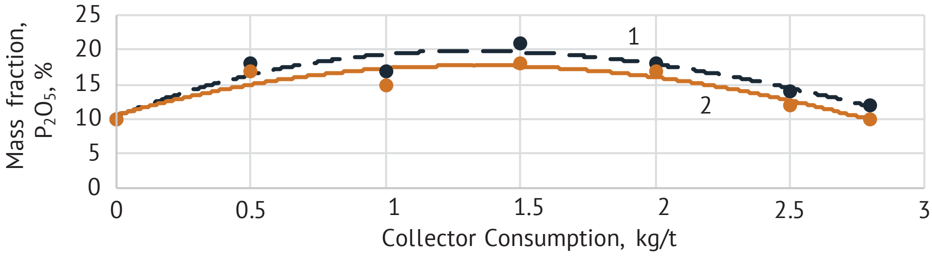

Figure 7. *Dependence of mass fraction of phosphorus on collector consumption*
Notes: *1 – Talactam; 2 – CTOS*
Source: *authors' development*

Analysis of the flotation results of the ore indicated that the mass fraction of P_2O_5 in the concentrate varied from 15.7 to 21.0%. The dependence of phosphorus oxide recovery in the concentrate on the collector consumption (tall oil amide and CTOS) was presented in Figure 8.

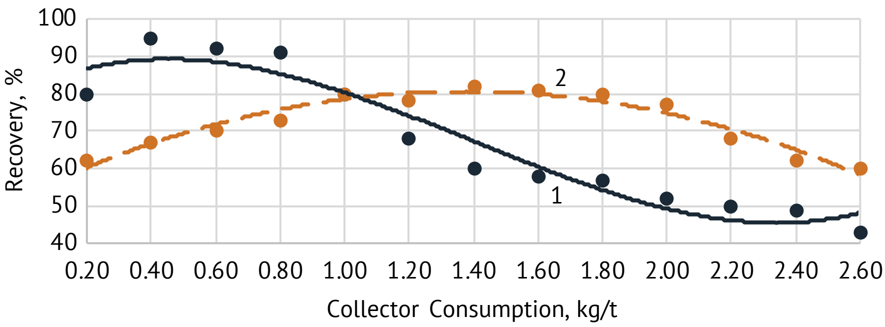

Figure 8. *Dependence of phosphorus oxide recovery into concentrate on collector consumption*
Notes: *1 – Talactam; 2 – CTOS*
Source: *authors' development*

Analysis of the flotation results of the ore demonstrated that P_2O_5 recovery in the concentrate varied from 93% to 69.5%. Further analysis demonstrated that increasing collector dosage above 2.0 kg/t impaired selectivity, causing not only phosphate but also quartz to report to the froth. With minimal collector dosage, P_2O_5 content increased sharply while yield decreased. As collector dosage increased, concentrate yield rose but quality declined. Talactam consumption was 40% lower than CTOS. Thus, talactam demonstrated superior collecting performance and selectivity, and was selected as the primary reagent in the recommended scheme. The results of the study on the influence of temperature on the selectivity of the flotation beneficiation process of technogenic phosphorus-bearing material were presented in Figure 9.

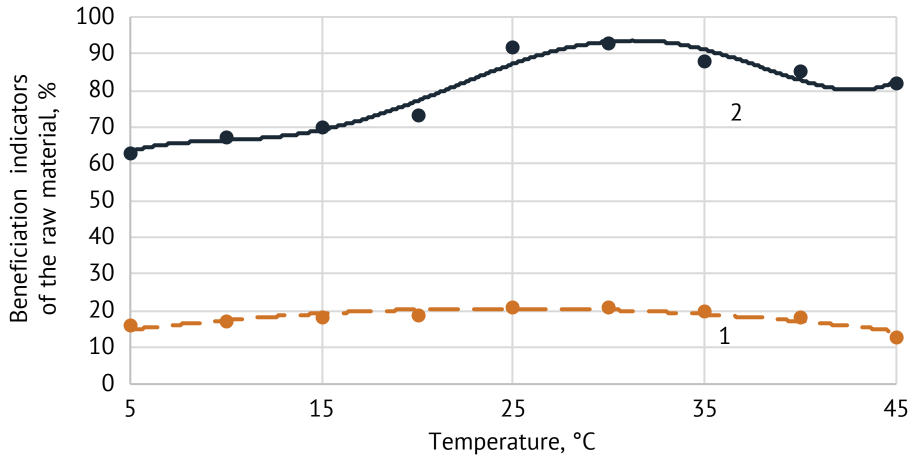

***Figure 9.** Dependence of beneficiation performance indicators of phosphorus-containing technogenic raw material on pulp temperature*

***Notes:** 1 – change in mass fraction of phosphorus oxide in concentrate; 2 – change in phosphorus oxide recovery into concentrate*

***Source:** authors' development*

Analysis of the research results revealed that during beneficiation of the sample within the temperature range of 5 to 45°C. Low temperatures negatively impacted technogenic phosphorus-containing material recovery due to reduced bubble attachment strength on a mineral surface. At a suspension temperature in the range 0-15°C, P_2O_5 recovery in the concentrate was 20-60%, with P_2O_5 content at 15-18%. Using CTOS under the same conditions yielded only 10-30% recovery at 12-16% P_2O_5. Talactam mitigated the negative impact of low temperatures. Between 20°C and 35°C, recovery increased to 93%, with P_2O_5 content at 20-21%.

Mineralogical analysis of flotation products from material ground to 100% -0.16 mm showed that glauconite (39.9-46.7%), iron hydroxides (4.2-6.9%), gypsum, and barite concentrated in the cell product. The froth product exhibited a 3-5-fold increase in francolite content – an advantageous outcome. However, clay mineral, quartz, calcite, and palaeoresidue were also present. These may be removed during chemical treatment. The froth product is recommended for further magnetic separation to eliminate glauconite and enhance phosphorite concentrate quality. The cell product represented tailings of the process, with P_2O_5 content at 4.25%. In flotation tests using the non-magnetic product (100% of the -0.16 mm size class; P_2O_5 content: 12.93%), a phosphorite concentrate with 21% P_2O_5 was obtained, meeting third-grade phosphorite flour standards, with a yield of 47.03%. P_2O_5 recovery in the froth was 76.41%. The cell product had 5.76% P_2O_5.

Based on the conducted research, two variants of the beneficiation flowsheet were developed: magnetic-flotation and flotation – magnetic, both providing the production of phosphorite concentrate and glauconite product. The results of ore beneficiation under laboratory conditions according to the proposed flowsheets were presented in Table 2.

***Table 2.** Results of beneficiation of technogenic phosphorus-containing raw material*

Flowsheet operation	Product name	Yield, %	Mass share, %		Recovery, %	
			P_2O_5	F_{total}	P_2O_5	Fe_{total}
Option 1						
Magnetic Separation	Magnetic (Glauconite Product)	50.71	8.24	12.07	39.60	81.60
	Non-magnetic	49.29	12.93	2.80	60.40	18.40
Flotation	Concentrate	23.18	21.0	1.70	46.15	5.25

Table 2. Continued

Flowsheet operation	Product name	Yield, %	Mass share, %		Recovery, %	
			P_2O_5	F_{total}	P_2O_5	Fe_{total}
	Tailings	26.11	5.76	3.78	14.25	13.15
	Feed	100.0	10.55	7.50	100.0	100.0
Option 2						
Flotation	Concentrate Middlings	41.92	19.28	5.98	76.60	33.40
	Tailings	58.08	4.25	8.60	23.40	66.60
Magnetic Separation	Magnetic (Glauconite Product)	18.79	17.20	10.60	30.64	26.56
	Concentrate	23.12	20.97	2.22	45.96	6.84
	Feed	100.0	10.55	7.5	100.0	100.0

Source: *authors' development*

According to the first variant, magnetic beneficiation of the ground material to 100% of the -0.16 mm size class was proposed at the beginning of the flowsheet. This enabled the removal of iron-bearing minerals from the phosphorus-bearing product and, consequently, reduced the amount of material fed to flotation. Magnetic separation yielded a glauconite concentrate with a mass fraction of P_2O_5 of 8.24% and 4.07%, and a phosphorite concentrate with a mass fraction of P_2O_5 of 21.0%. In the second variant, magnetic beneficiation was applied to the concentrate obtained from flotation of the ground material. Magnetic separation produced a glauconite concentrate with a mass fraction of P_2O_5 of 17.2%, and a phosphorite concentrate with a mass fraction of P_2O_5 of 20.97%. Therefore, the first flowsheet variant (magnetic – flotation) proved to be more efficient and offered several advantages. Firstly, it allowed a 50.71% reduction in flotation load due to early recovery of the glauconite product during the initial stage of processing the technogenic phosphorus-bearing material. Secondly, phosphorus recovery in the concentrate was higher by 0.19%.

Discussion

The obtained results were compared with those presented in scientific publications addressing similar aspects of natural and technogenic phosphorite ore beneficiation. The choice of enrichment methods in these studies was largely determined by the mineral composition of the initial feedstock.

H. Amar *et al.* (2022) demonstrated that the increasing demand for phosphate ore, driven by the depletion of high-grade reserves, has rendered the mining and processing of low-grade phosphates a necessity for sustainable production. The phosphate industry, identified as a major contributor of mining waste, consists of three main operational stages. The first involves ore extraction and separation from accompanying minerals and was sent to the beneficiation plant. In the second process, phosphate rock was concentrated using physical and chemical beneficiation methods. The resulting phosphate concentrate was then delivered to processing plants for the production of phosphoric acid and various types of fertilisers. Enrichment generates substantial volumes of tailings composed of fine fractions, which represent an environmental burden and disrupt landscapes. Numerous studies have examined sedimentary low-grade phosphate deposits (<16% P_2O_5) to raise phosphate quality to market specifications (~30% P_2O_5). Applied processes have ranged from simple mechanical treatments (crushing, grinding and classification) to complex operations such as flotation and leaching. Pre-enrichment stages have included attrition, scrubbing, washing, and desliming to eliminate clays and fine silicates. Flocculation was found to be highly effective, achieving sedimentation levels of 81.3% in just 15 seconds using anionic flocculants. Polyacrylamide flocculants showed superior performance, achieving 37 times faster sedimentation than natural settling.

R. Dabbebi *et al.* (2023) explored the reuse of phosphate mine waste (PMW) across various sectors. Their study highlighted the potential of PMW as raw material for multiple applications within sustainable management frameworks. The authors emphasised that the variable mineralogical composition and elemental content of PMW, dependent on deposit origin and enrichment methods, made it suitable for diverse uses. Secondary utilisation of phosphate waste is a complex process requiring detailed examination of the physical and mineralogical properties of tailings. The most efficient phosphate recovery method identified was direct flotation using anionic fatty acid collectors. PMW was also recognised as a rich source of heavy metals and rare-earth elements (REEs). Elements such as Cd, Cr, Mn, Mo, Ni, Pb, U, V, and Zn, along with phosphorus, were extracted from phosphate slimes. Zinc and nickel were successfully recovered via leaching. REEs were most effectively recovered using flotation.

In a study by J. Guo *et al.* (2024), it was emphasised that the successful beneficiation of phosphate ore containing phosphates, apatite, calcite, and dolomite was based on a thorough understanding of its mineralogy, mineral surface properties, distribution, and mineral liberation. Due to the relatively low P_2O_5 content and high impurity levels, most ores were unsuitable for direct acidulation and required pre-enrichment to produce suitable concentrates. Applied methods included flotation, attrition cleaning, desliming, electrostatic separation, magnetic separation, gravity concentration, and calcination. In direct flotation, anionic collectors were used differentially, with optimum pulp alkalinity at pH 9.5 maintained by Na_2CO_3. Phosphate ores (53-63 μm) from Rajasthan and Madhya Pradesh (India) underwent two-stage high-gradient magnetic separation following calcination and flotation. The use of sodium oleate and sodium metasilicate yielded a final concentrate containing 31.5% P_2O_5 and 8.8% SiO_2, with an overall P_2O_5 recovery of 65.0%.

A. Kareeva *et al*. (2023) investigated Chilisai low-grade phosphorites through a comprehensive study of their physicochemical properties. Techniques employed included chemical and energy-dispersive analysis, FTIR spectroscopy, X-ray diffraction, and mineralogical analysis. The presence of glauconite, a hydromica composed of iron and aluminium silicate, quartz, and potassium oxides, was identified alongside dolomite. The latter was often misidentified as calcite; however, its crystal structure, with calcium and magnesium ion mobility along three axes, enabled distinction. The results offered new insights into the unique characteristics of Chilisai phosphorites, such as REE traces and ion mobility in glauconite and dolomite, which are critical for identifying novel phosphorus-bearing feedstocks.

A. Mahmoud *et al*. (2024) studied low-grade phosphate ore from Abu Tartur in Egypt's New Valley Governorate. Estimated at 980 million tonnes at 30% phosphate content, it is one of the country's largest deposits. Phosphate extraction was performed using gravity, magnetic, and flotation enrichment. Chemical composition (P_2O_5, CaO, SiO_2, SO_2, Fe_2O_3) was determined via X-ray diffraction. The flotation process was negatively affected by fine fractions <0.074 mm, prompting mechanical impurity removal using modern classifiers. This improved P_2O_5 content from 21.27% to 22.38%. Magnetic separation with a Dings cross-belt separator increased P_2O_5 content to 25.25% with 90.3% recovery. Flotation of the non-magnetic product using a mixed reagent system (oil and oleic acid) produced a concentrate with 28.29% P_2O_5 and 86.14% recovery.

X. Zhang *et al*. (2022) developed an effective desilication method for siliceous phosphate ore. MLA and SEM-EDS microscopy characterised mineral components and morphology. The effect of Falcon centrifuge parameters (rotation speed, water pressure, feed rate) on separation efficiency was evaluated. Orthogonal experimental design was used to establish a predictive model. Laboratory tests confirmed that at 64.73 Hz, 0.012 MPa, and 30.51 mL/s, maximum P_2O_5 recovery of 86.02% was achieved at 27.45% P_2O_5. Most valuable mineral loss occurred in the -0.045 mm fraction. Optimisation experiments identified 0.045-0.09 mm as the optimal particle size range. By implementing these recommendations, flotation feed optimisation reduced grinding costs.

M. Derqaoui *et al*. (2021) reviewed reagents for direct froth flotation of low-grade phosphates. Mixed collectors were found to provide better apatite selectivity and recovery than fatty acids, which required selective depressants. Apatite flotation efficiency was shown to depend not only on reagent type but also on adsorption mechanisms and solution chemistry. Surfactants such as dodecylaspartate and dodecylglutamate, containing two and three carbon atoms between carboxyl groups respectively, exhibited micellisation coefficients 4-5 times higher than dodecylglycinate. Hydrogen bonding promoted denser molecular packing at the air – water interface and within micelles. Formation of intermolecular complexes led to lower surface tension. Internal chelation was advantageous for calcium-bearing surfaces. While dodecylaminomalonate and dodecylaspartate showed strong adsorption on hydroxyapatite, dodecylglutamate adsorbed weakly. On non-specific surfaces, the three surfactants displayed similar adsorption behaviour.

Analysis of the current study in comparison with previous works confirmed the relevance of technogenic phosphorus-containing feedstock beneficiation and validated the proposed process flowsheet, comprising: closed-circuit grinding with high circulating loads to minimise slime formation; high-intensity magnetic separation to reduce flotation load; flotation using a complex anionic collector (talactam) to ensure selectivity and performance.

Conclusions

The conducted research confirmed the effectiveness of utilising phosphorite ore processing waste to produce concentrates suitable for the manufacture of third-grade phosphorite flour. The glauconite products obtained following francolite removal were found suitable for use in the production of potassium fertilisers and green pigments.

It was established that fine grinding of technogenic phosphorus-containing material resulted in significant slime formation. To minimise this, disintegration should be preceded by classification using hydrocyclones and classifiers, with a particle size cut-off of 0.16 mm. Experimental studies demonstrated that magnetic separation of feed material with 100% -0.16 mm reduced total iron content in the non-magnetic product from 8-11% to 2-3%, while increasing P_2O_5 content by a factor of 1.18-2.63.

Flotation trials demonstrated the possibility of producing phosphorite concentrates with P_2O_5 contents ranging from 18.7% to 21.5% and recoveries between 69.5% and 93%. Magnetic separation of flotation froth products enabled partial enhancement of francolite concentration in the froth fraction and a significant reduction in glauconite and iron hydroxide content. However, the advisability of magnetic separation post-flotation should be confirmed via detailed techno-economic assessments, incorporating downstream chemical processing considerations.

Based on the processing of technogenic phosphorus-containing samples with initial P_2O_5 contents of 10.55% and 5.45%, market-grade phosphorite concentrates were obtained with P_2O_5 contents of 18.7-21.5% and recoveries of 69.5-93%.

Two laboratory-verified flowsheet variants were developed for feedstock enrichment: magnetic-flotation and flotation-magnetic. Both enabled production of phosphorite concentrate and glauconite product. In the first variant, magnetic separation performed at the head of the circuit, produced glauconite concentrates with P_2O_5 contents of 8.24% and 4.07%, and phosphorite concentrate with 21.0% P_2O_5. In the second variant, magnetic separation followed flotation, producing glauconite concentrate with 17.2% P_2O_5 and phosphorite concentrate with 20.97% P_2O_5.

For the first time, it was demonstrated that, during technogenic phosphorus-containing material flotation, interfacial surface tension energy at the interfaces of the three-phase system must be considered. This finding substantiates the recommendation of talactam, an anionic collector, for the selective separation of francolite from quartz, and defines the optimal operational conditions for the technological process. The questions examined in this study require further investigation. The results obtained are consistent with findings in related research and may serve as a foundation for more in-depth exploration of REE recovery from technogenic phosphorus-containing materials.

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Conflict of Interest

None.

References

[1] Abbes, N., Bilal, E., Hermann, L., Steiner, G., & Haneklaus, N. (2020). Thermal beneficiation of Sra Ouertane (Tunisia) low-grade phosphate rock. *Minerals*, 10, article number 937. doi: 10.3390/min10110937.

[2] Amar, H., Benzazoua, M., Elghali, A., Hakkou, R., & Taha, Y. (2022). Waste rock reprocessing to enhance the sustainability of phosphate reserves: A critical review. *Journal of Cleaner Production*, 381(1), article number 135151. doi: 10.1016/j.jclepro.2022.135151.

[3] Banerjee, S. (2024). *Research note: Phosphate ore grades and concentrates from igneous and sedimentary phosphate rocks and their associated mining operations*. Kingston: Queen's University.

[4] Biletsky, V.S., Oliynyk, T.A., Smirnov, V.O., & Skliar, L.V. (2020). *Fundamentals of mineral enrichment techniques and technologies*. Kyiv: Lira-K Publishing House.

[5] Dabbebi, R., Perumal, P., & Mukanna, S. (2023). Management and valorisation of phosphate beneficiation slime: A critical review. *International Journal of Environmental Science and Technology*, 20, 11763-11776. doi: 10.1007/s13762-023-04901-0.

[6] Derhy, M., Taha, M., Hakkou, Y., & Boulif, M. (2020). Review of the main factors affecting the flotation of phosphate ores. *Minerals*, 10(12), article number 1109. doi: 10.3390/min10121109.

[7] Derqaoui, M., Aarab, I., Abidi, A., Yacoubi, A., El Amari, K., Etahiri, A., & Baçaoui, A. (2021). Review of the reagents used in the direct flotation of phosphate ores. *Arabian Journal of Geosciences*, 15, article number 49. doi: 10.1007/s12517-021-09293-4.

[8] Guo, J., Li, B., Peng, H., & Tao, C. (2024). Recovery of phosphors by beneficiation technology. *Journal of Composites and Biodegradable Polymers*, 12, 7-15. doi: 10.12974/2311-8717.2024.12.02.

[9] Kareeva, A., Bolysbek, A., Nazarbek, U., Abdurazova, P., & Raiymbekov, Y. (2023). Comprehensive study of physico-chemical properties of low-grade phosphate raw materials. *Engineering Journal of Satbayev University*, 145(1), 25-31. doi: 10.51301/ejsu.2023.i1.04.

[10] Mahmoud, A., Atrees, M.Sh., Mohamed, S.T., & Abdeldayem, S.M. (2024). Comparative study of phosphate concentrate from Abu Tartur phosphate rocks from the Egyptian Western Desert obtained from the froth flotation and hydrolytic operations. *Bulletin of Faculty of Science, Zagazig University (BFSZU)*, 2, 24-33. doi: 10.21608/bfszu.2024.217480.1317.

[11] Oliinyk, T., Skliar, L., Kushniruk, N., Holiver, N., & Tora, B. (2023). Assessment of the efficiency of hematite quartzite enrichment technologies. *Inżynieria Mineralna*, 1(1(51)), 33-44. doi: 10.29227/IM-2023-01-04.

[12] Proidak, A., Gasyk, M., & Proidak, Yu. (2021). Research into phosphate mineral composition and waste phosphorite ore. *Mining of Mineral Deposits*, 15(1), 96-102. doi: 10.33271/mining15.01.096.

[13] Raiymbekov, Y., Abdurazova, P., & Nazarbek, U. (2023). Thermodynamic analysis of enrichment of low-grade phosphate raw materials with organic acid. *Mining Magazine of Kazakhst*an, 5, 32-38. doi: 10.48498/minmag.2023.2017.5.005.

[14] Raiymbekov, Y., Besterekov, U., & Abdurazova, P. (2020). Review of methods for enrichment of phosphate raw materials in the world. *Bulletin of Karaganda University*, 98(2), 92-96. doi: 10.31489/2020Ch2/92-96.

[15] Ryszko, U., Rusek, R., & Kołodyńska, D. (2023). Quality of phosphate rocks from various deposits used in wet phosphoric acid and P-fertilizer production. *Materials*, 16(2), article number 793. doi: 10.3390/ma16020793.
[16] Sajid, M., Bary, G., Asim, M., Ahmad, R., Ahamad, M.I., Alotaibi, H., Rehman, A., Khan, I., & Guoliang, Y. (2022). Synoptic view on P ore beneficiation techniques. *Alexandria Engineering Journal*, 61(4), 3069-3092. doi: 10.1016/j.aej.2021.08.039.
[17] Wang, B., Zhou, Z., Xu, D., Wu, J., Yang, X., Zhang, Z., & Yan, Z. (2022). A new enrichment method of medium-low grade phosphate ore with high silicon content. *Minerals Engineering*, 181, article number 107548. doi: 10.1016/j.mineng.2022.107548.
[18] Zdeshchyts, V., & Zdeshchyts, A. (2023). Measurement of magnetic susceptibility of substances in the conditions of distance education. *Physical and Mathematical Education*, 38(4), 36-41. doi: 10.31110/2413-1571-2023-038-4-005.
[19] Zhang, X., Tao, Y., & Ma, F. (2022). Application of Falcon centrifuge in the separation of siliceous phosphate ore. *Particulate Science and Technology*, 40(8), 958-971. doi: 10.1080/02726351.2022.2027056.
[20] Zhantasov, K., Bazhirov, T., Kolesnikov, A., Toltebaeva, Z., & Bazhirov, N. (2024). Acid-free processing of phosphorite ore fines into composite fertilizers using the mechanochemical activation method. *Composite Science*, 8(5), article number 165. doi: 10.3390/jcs8050165.

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Збагачення техногенної фосфорвміщуючої сировини як джерела отримання мінеральних добрив

Анотація. Актуальність досліджень пов'язана з невирішеними питаннями зростання вартості сировини, геополітичної нестабільності та складності переробки фосфоритових руд із високим вмістом домішок, що обумовлює необхідність пошуку ефективних підходів до збагачення та переробки низькосортної сировини й відходів як альтернативних джерел фосфору. Мета дослідження – розробка технології збагачення техногенної фосфоровмісної сировини для одержання фосфоритового концентрату, придатного для виробництва добрив. При виконанні досліджень використано мінералогічний, хімічний, гранулометричний та седиментаційний аналізи складу сировини. При виконанні лабораторних експериментів використані подрібнення, флотація та магнітна сепарація. Досліджено властивості реагентів для розробки флотаційної технології збагачення фосфорвмісної сировини. У роботі досліджено можливості збагачення техногенної фосфоровмісної сировини, отриманої в результаті переробки фосфоритової руди. Запропоновано дві лабораторно апробовані технологічні схеми – магнітно-флотаційну та флотаційно-магнітну, що забезпечують одержання товарного фосфоритового концентрату з масовою часткою P_2O_5 від 18,7 до 21,5 % при вилученні фосфору 69,5-93 %. Уперше встановлено необхідність урахування енергії поверхневого натягу на межі розділення трьох фаз під час флотації, що дозволило обґрунтувати доцільність застосування аніонного збирача – талактаму – для ефективного розділення франколіту та кварцу. Проведення магнітної сепарації як до, так і після флотації сприяло підвищенню вмісту франколіту та зменшенню вмісту глауконіту і залізовмісних мінералів. Встановлено, що попередня класифікація сировини за граничною крупністю 0,16 мм дозволяє зменшити утворення шламів при дезінтеграції. Отримані глауконітові продукти можуть бути потенційно використані для виробництва калійних добрив та зелених пігментів, однак це потребує подальших досліджень. Практична значимість роботи полягає в тому, що впровадження у виробництво розробленої технології збагачення техногенної фосфоритової сировини дозволило отримати фосфатний концентрат в кількості 23,18 %, який придатний для виготовлення мінерального добрива – фосфатного борошна III-го сорту, та глауконітовий продукт в кількості 50,71 %, що використовується як ентеросорбент та джерело мікроелементів у складі комбікормів

Ключові слова: фосфор; франколіт; глауконіт; магнітна сепарація; флотація

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Investigation of the influence of dynamic loads on the fastening of underground mine workings

Abstract. In the context of the need to increase the energy resistance of underground fasteners under dynamic influence, the study was aimed at an experimental and analytical assessment of the mechanical behaviour of wooden structures, in particular, panels made of cross-glued wood, under the influence of impulsive loads. The purpose of the study was to establish the efficiency of using wood and cross-glued elements as energy-adaptive materials for fastening mine workings. The research methodology was based on laboratory modelling of explosive and seismic modes using stands and digital systems for fixing deformation parameters, considering normalised geometric conditions and the influence of humidity. The tests were carried out with samples prepared for the typical conditions of mine workings in Ukraine, taking into consideration of the geostructural characteristics of the regions of Dnipropetrovsk, Lviv, and Kirovohrad oblasts. It was recorded that cross-glued panels retained structural integrity after the action of pulses with an amplitude of up to 3.0 megapascals and a duration of 0.2 seconds, demonstrating a higher ability to dissipate energy compared to solid wood. It was found that the specific values of absorbed energy for the panels averaged 280-340 joules, and the residual deformation did not exceed 3.4%, which indicated the ability of the material to withstand repeated loads without loss of load-bearing capacity. The results of the study confirmed the feasibility of including cross-glued wood in the composition of fastening systems with high requirements for energy absorption. The practical significance of the obtained data lies in the possibility of modifying underground structures based on available wooden materials with predicted characteristics of adaptation to dynamic impacts

Keywords: residual deformation; impulsive load; dissipative capacity; orthogonal multilayer structure; geostructural conditions; quenching coefficient; wood anisotropy

Introduction

The increase in the intensity of mining operations at considerable depths is accompanied by an increase in the impact of dynamic loads on the elements of infrastructure support for the underground production cycle, primarily on fastening systems. Blasting operations, mining impacts, and anthropogenic seismic vibrations generate pulsed waves with a high amplitude and short-term load phase, which often exceed the limits allowed for conventional structures. In such conditions, it is necessary to use materials that can not only withstand instantaneous overloads, but also maintain the residual load-bearing capacity in the event of partial damage. This determines the relevance of the study of materials with dissipative and adaptive properties, in

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particular wood, and composites based on it – such as multilayer cross-laminated timber (CLT).

In the process of analysing current scientific sources devoted to the topic of dynamic loading in an underground mining environment, key approaches to assessing the influence of impulse factors on the structural stability of workings and the efficiency of technical equipment were identified. The study by F. Tahmasebinia *et al.* (2021) analysed the behaviour of combined fasteners in the dynamic load mode by numerical modelling, in particular, the limits of their plastic deformation were determined and the potential for energy absorption was estimated. J. Yao *et al.* (2021) demonstrated that rope lifting systems under ultra-deep mine conditions experience a significant impulsive load, which had a significant impact on the operation of equipment, especially in areas of uneven stress distribution.

H. Zhang *et al.* (2025) proposed an innovative *in-situ* method for strengthening the surrounding array by subsurface injection of reinforcing solutions, which reduced the amplitude of the vertical shock load, although the main focus was on macroscopic geomechanical effects. The study by J. Li *et al.* (2021) analysed the processes of rock instability under the influence of impulsive perturbation, based on which the researchers proposed a differentiated model of rock behaviour depending on the prestress level. Modelling by J.R. Huerta *et al.* (2022) allowed developing scenarios for the functioning of mining systems, considering variable dynamic factors, in particular, their impact on the probability of emergency degradation of individual fastening elements.

The study by D. Chepiga *et al.* (2024) established the stability of protective systems under static load under long-term operation, while experimentally proved the loss of efficiency under the influence of variable loads. S. Pysmennyi *et al.* (2023) conducted a stress-strain analysis of workings in coal mines, which allowed mapping areas of maximum risk of damage, indicating the need for adaptive fasteners to stabilise them. V.P. Shchokin *et al.* (2025) as part of monitoring the technical condition of mine shafts, they found the accumulation of deformations during operation, but stressed the dependence of the results on the type of load, which strengthened the argument in favour of considering the impulse factor. A. Neshchadymenko (2021) presented an effective method for determining the mechanical parameters of rocks using numerical modelling, which helped to construct scenarios for interaction with various types of fasteners. Ultimately, F. Seguel *et al.* (2021) developed a structural architecture of intelligent positioning subsystems that allows real-time coordination of technical equipment during blasting operations, although the study did not focus on energy absorption issues in structural materials.

Thus, a methodological gap was identified due to the lack of a systematic approach to evaluating wood, in particular CLT, as an active structural material for fastening under dynamic load conditions. The parameters of residual deformation of wood after the action of impulses, energy absorption in the short-term overload mode, crack resistance at variable humidity, and the mechanisms of layer-by-layer degradation in multicomponent structures of the CLT type were not established. There is also a lack of data on the interaction of wooden structures with the rock mass in a dynamically unstable environment. The identified limitations in the coverage of these aspects confirmed the need to direct further research to the experimental and analytical assessment of the effectiveness of wood in mining anchor systems.

The purpose of the study was to experimentally substantiate the feasibility of using solid wood and CLT as materials for energy-intensive adaptive fasteners in underground mine workings exposed to short-term impulsive loads. For its implementation, the following research tasks were formulated: to establish the characteristic parameters of dynamic load within the main geostructural regions; to carry out a comparative assessment of the mechanical characteristics of solid wood and CLT based on the results of laboratory tests; to analyse the influence of humidity, load direction, and number of layers on the functional stability of wooden structural elements in the mining environment.

Materials and Methods

The study was of an applied experimental and analytical nature and was conducted in Ukraine during January 2022 – March 2025. The main part of the experimental procedures was implemented based on a technical stand and test equipment at the M.S. Poliakov Institute of Geotechnical Mechanics NASU (n.d.). Analytical substantiation of the impulsive load parameters was carried out based on generalisations of the M.S. Poliakov Institute of Geotechnical Mechanics NASU, considering the geostructural conditions of coal and ore mines in Ukraine.

Materials for testing were solid coniferous wood – Scots pine (*Pinus sylvestris* L.) and European larch (*Larix decidua Mill.*), and three- and five-layer CLT panels made of the same wood. Solid wood samples had a rectangular cross-section of 60×60 mm and a length of 240 mm, with a humidity of 10-12%. The CLT panels were 120×120×400 mm in size. The sample was not random in nature and was created based on the criteria of structural uniformity, absence of visual defects, compliance with strength classes according to EN 338:2016 (2016). 32 samples were formed: 16 solid wood samples (8 for axial, 8 for transverse loading) and 16 CLT samples (8 three-layer and 8 five-layer), which corresponded to the structure of the load tests presented in the results. Experimental work with plants – both cultivated and wild – including the collection of wood material samples, was carried out in accordance with applicable institutional, national, and international ethical standards. Researchers adhered to the provisions of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

The tests were carried out using a DYN-PRESS 3000 hydraulic impact stand (Walter + Bai AG, Switzerland) and a VibroImpact V-32 vibration platform (L.A.B. Equipment Inc., USA), which provided an impulsive load with an amplitude of 2.5-3.0 mPa with a duration of 0.1-0.2 s. The Impaq LX-400 system (Dewetron GmbH, Austria) and the VIC-3D digital optical imaging system (Correlated Solutions Inc.) were used for digital fixation of strain parameters), and the acoustic emission registration system AE 9000 (Mistras Group, USA). Bench testing helped to record the residual deformation, the rate of crack development, and the amount of energy absorbed based on the "load – strain" curves. The specific energy intensity was calculated as the area under the "load – strain" curve normalised to the sample volume; the boundary strain was defined as the maximum elongation or compression in the peak load phase, and the dissipation factor was defined as the ratio of the area of the hysteresis loop to the accumulated potential energy. The tests were carried out in accordance with the provisions of FPREN 1995-1-1 (2025) and DIN 1052:2008-12 (2008), considering the methodological recommendations of the Technical University of Dresden (n.d.), DynaTTB models (Abrahamsen *et al.*, 2020) and experimental results of CLT panels published by A.G. Aljuhmani *et al.* (2025). The mechanical action on the samples reproduced the modes characteristic of blasting operations and anthropogenic seismic loads in mines.

The interpretation of the results was based on a generalisation of the values of residual deformation, the area under the "load – strain" curve, the dissipation factor, and the nature of crack propagation. All data were normalised according to the geometric parameters of the samples, and adjusted for the influence of humidity and load direction. The obtained dependences allowed quantifying the ability of wood, in particular CLT, to dissipate energy and maintain structural integrity under conditions of multiple impulsive impacts, which is relevant for the underground mining environment.

Results

Nature of dynamic loads in underground mining conditions

Dynamic loads that occur in an underground mining environment are characterised by an impulsive nature and are accompanied by a short-term change in the stress-strain state of rocks. The main sources of such loads are blasting operations, mining impacts and anthropogenic seismic vibrations. Their influence causes a local excess of the contact pressure limit values between the breed array and the fastening elements, which causes structural damage in the fixation zones and weakened sections of structures. In the case of repeated or cyclic impulses, fatigue damage is observed, which reduces the service life of fasteners and increases the probability of collapse of the array.

The intensity of dynamic loads largely depends on the spatial and geological parameters of the deposit, the depth of mining operations, the type of mineral, and the presence of tectonic fault zones. In particular, an increased level of seismic activity is recorded in the conditions of deep mining of coal and iron ore deposits in the Donetsk and Kryvyi Rih oblasts, which causes the need to use fasteners with increased depreciation capacity. Within regions with a lower level of tectonic activity, in particular, in Zakarpattia and the Nikopol basin, long-term but less intense fluctuations prevail, which require alternative constructive approaches. To identify areas with high concentrations of dynamic loads, it is advisable to spatially map the main coal and ore basins of Ukraine (Fig. 1). This mapping allows comparing the geographical location of deposits with industrial centres and structural and geological zones of violations, which is a necessary condition for assessing the risks associated with explosive, seismic, and anthropogenic impacts on underground anchorages. On this basis, technical solutions were developed aimed at improving the structural stability of fastening systems under variable dynamic load conditions.

Figure 1 shows the spatial configuration of the main coal deposits in Ukraine, in particular, anthracite and brown coal basins, and the localisation of the main production centres. The total volume of mining load is formed primarily in the areas of the Donetsk and Lviv-Volyn basins, where a high level of industrial load is combined with active exploitation of deep deposits. These regions are critical in terms of the frequency of mountain impacts and anthropogenic seismic vibrations, which leads to increased requirements for the energy and mechanical stability of fixing structures.

Of particular interest is the spatial overlap of the brown coal basin of central Ukraine with industrial nodes, in particular within Oleksandriia and Dnipro, where, despite the lower depth of development, regular anthropogenic dynamic disturbances are recorded. The spatial coverage shown in the figure also allows for a preliminary assessment of potential areas for expanding underground mining, considering the structural and geological characteristics of the massif. Such cartographic visualisation provides a basis for integrating the dynamic factor into design models of mechanical interaction of rocks and technical equipment.

The above information summarises the dynamic impact indicators typical for the five leading mining regions of Ukraine, including Donetsk coal basin, Lviv-Volyn basin, Kryvyi Rih iron ore district, Nikopol manganese basin, and Transcarpathian polymetallic region. For each of them, the range of amplitudes, the average impulse duration, and the annual frequency of dynamic events are analysed (Table 1). This systematisation creates the basis for a comparative assessment of the load level, which should be considered when choosing the type of fastening material and the corresponding geometry of its structural elements.

Figure 1. *Geographical location of coal basins and major mining areas of Ukraine*

Source: *compiled by the author based on O. Pasyuk & I. Stavchuk (2010)*

Table 1. *Parameters of dynamic loads in underground mine workings of various geostructural regions of Ukraine*

Geostructural region	Typical amplitude range, mPa	Impulse duration, s	Average frequency of manifestations (per year)	Load sources
Donetsk coal basin	2.0-3.0	0.05-0.2	40-60	Blasting operations, mining strikes
Lviv-Volyn coal basin	1.5-2.5	0.07-0.15	20-35	Blasting operations, local tectonic shifts
Kryvyi Rih iron ore region	2.5-3.5	0.04-0.1	50-70	Mining impacts, mass explosions
Nikopol manganese basin	1.0-2.0	0.06-0.12	10-25	Anthropogenic seismic vibrations
Transcarpathian polymetallic region	0.8-1.5	0.1-0.25	5-15	Weak tectonic impulses

Notes: *"Impulse duration" – represented as the average range of the main load phase; "Manifestation frequency" – average annual number of recorded dynamic events in workings; load sources are grouped according to the preferred impulse origin*

Source: *compiled by the author based on M.S. Poliakov Institute of Geotechnical Mechanics NASU (n.d.)*

The analysis of the indicators given in Table 1 showed the predominance of high levels of dynamic load within the Kryvyi Rih iron ore and Donetsk coal regions. Under these conditions, the impulse amplitude reaches 3.5 mPa, which requires the use of fastening materials with an increased ability to withstand instantaneous peak overloads. For the Transcarpathian polymetallic region and the Nikopol manganese basin, lower amplitude values were recorded, but an increase in the impulse duration combined with a reduced frequency causes the need for improved energy dissipation characteristics, which affects the choice of materials with the depreciation function.

The generalised dynamic impact parameters established for five geostructural regions varied in the following ranges: amplitude – from 0.8 to 3.5 mPa; impulse duration – from 0.04 to 0.25 s; frequency – from 5 to 70 events per year. The maximum values of intensity and repeatability were recorded in the Kryvyi Rih Oblast, where the cumulative effect of short-term but regular impulses was observed. But in the Zakarpattia Oblast, loads of a smaller amplitude with a longer time profile predominate, which creates other requirements for materials with increased ductility and viscosity. This range of loads determines the feasibility of adapting the type of structural material in accordance with a specific mining environment, considering the energy absorption capacity and the ability to recover elastically after impulse overload.

Comparison of the periodicity of dynamic events with the impulse duration indicates the predominance of the impulse mode with a high frequency of short overloads in regions such as Kryvyi Rih. This creates conditions for gradual depletion of the energy and mechanical resource of the material, which requires the introduction of components capable of multiple compensation of impulse action without loss of functional integrity. Thus, the comparative characteristics of georegions provide the basis for determining the requirements for fastening systems in a differentiated approach, which involves the use of wooden engineering materials with predicted elastic-strain response characteristics. To compare the behaviour of wooden materials under the action of an identical impulsive load, the nature of their deformation, types of destruction, and features of damage propagation were analysed. The main focus was on solid wood and CLT, which exhibited excellent energy absorption mechanisms due to structural features. Solid wood is characterised by anisotropic behaviour, while CLT provides localisation of damage within layers, which increases overall stability. Generalised characteristics are presented in Table 2.

Table 2. *Nature of deformation and types of destruction of fastening materials under the action of an impulsive load*

Material	Main type of deformation	Type of destruction	Propagation of damage	Residual load-bearing capacity (%)	Features of energy absorption
Solid wood	Stress deformation with delamination	Layer-by-layer cracking along the fibres	Linear (along the fibres)	40-60	Limited damping capacity, dependence on the direction of fibres
CLT	Layer-by-layer shear and absorption	Internal destruction of individual layers without loss of overall integrity	Dissipative (dispersed)	60-75	High multi-vector impulse absorption capacity

Notes: *residual load-bearing capacity – ability of the material to maintain resistance after the action of an impulsive load, as a percentage of the initial value. Dissipation refers to the ability of a material to dissipate energy without concentrating it in individual zones*
Source: *compiled by the author based on DIN 1052:2008-12 (2008), FPREN 1995-1-1 (2025), Technical University of Dresden (n.d.)*

Analysis of the data presented in Table 2 showed that solid wood, although it has limited rigidity, exhibits the ability to partially absorb energy due to deformation along the fibres. The main limitations of its use are anisotropy, which significantly reduces the efficiency of wood under complex or transverse loads, and increased sensitivity to moisture and structural heterogeneity. Compared to this material, CLT demonstrated multi-vector deformation behaviour due to the orthogonal arrangement of layers. Based on this configuration, energy is redistributed in the transverse and longitudinal directions, which avoids the development of through cracks and the destruction of the entire structure. The preservation of the load-bearing capacity was recorded even in cases of localised damage to one or more layers, which indicates the presence of an internal compensatory resource. The established properties give grounds to consider CLT as a potentially effective structural material for conditions of increased explosion hazard, high frequency of dynamic impulses, or seismic instability.

Indicators of the energy-mechanical behaviour of wooden materials show significant differences, which are reflected in the ability to absorb and dissipate impulse energy. Solid wood and CLT form various mechanisms of elastic compensation and quenching, which is crucial for ensuring the stability of fasteners in dynamically unstable mining environments. The most representative parameters for analysing the efficiency of materials in mining fastening systems are specific energy intensity, extreme deformation, quenching coefficient, and crack resistance, which integrally reflect their ability to elastic compensation and long-term preservation of load-bearing capacity. Generalised characteristics are presented in Table 3.

Table 3. *Comprehensive comparison of the energy and mechanical characteristics of solid wood and CLT under impulsive load conditions*

Parameter	Solid wood	CLT
Crack resistance	Medium (spread along the fibres)	High (localised within a single layer)
Specific energy consumption, kJ/m^3	80-110	100-135
Boundary deformation, %	10-14	12-8
Quenching coefficient (dissipation)	0.25-0.35	0.40-0.55

Notes: *crack resistance – ability of a material to limit the propagation of cracks after local overload; specific energy intensity – amount of energy that the material can absorb per unit volume until the moment of destruction; boundary deformation – maximum relative change in shape to the loss of elasticity; damping ratio – ratio of energy scattered during the impulse cycle to the maximum accumulated potential energy*

Source: *compiled by the author based on M.S. Poliakov Institute of Geotechnical Mechanics NASU (n.d.), Technical University of Dresden (n.d.), DIN 1052:2008-12 (2008), R. Abrahamsen et al. (2020), A.G. Aljuhmani et al. (2025)*

Analysis of the obtained parameters showed that solid wood provides only a moderate level of energy absorption, while its crack resistance remains limited due to the dominance of deformations along the fibres and a reduced ability to redistribute the load. Although the specific values of the quenching coefficient (0.25-0.35) and the maximum deformation (10-14%) allow wood to amortise the impulse action to a certain extent, the risks of penetrating destruction under transverse load remain high. However, CLT shows higher performance from all positions: the specific energy intensity reaches 135 kJ/m^3, the quenching coefficient – up to 0.55, and the maximum deformation – 18%, which indicates the ability of the material to effectively dissipate energy and maintain structural integrity even in the case of multiple dynamic impacts. The high level of crack resistance of CLT is conditioned by the orthogonal configuration of the layers, which prevents the development of cracks over the entire thickness of the element and provides a multi-vector stress dissipation path. This allows interpreting CLT as a structurally optimised material for conditions of explosive, seismically active or anthropogenic unstable mines, where it is especially important to ensure the stability of the attachment at short-term but intense impulses.

Structural properties of wood as a material for mining fasteners

Wood is used in mining as a structural material with a long service life, in particular, for the development of temporary, compensating, and shock-absorbing elements of fastening systems. This practice is conditioned by a combination of low density, elastic properties, and the ability to partially dissipate energy without forming rigid brittle fracture zones. The efficiency of wood is determined by such parameters as rock composition, internal structural uniformity, humidity, fibre orientation, and technological mode of processing. Coniferous species, in particular Scots pine (*Pinus sylvestris*) and European larch (*Larix decidua*), are characterised by a sufficient level of mechanical stability under conditions of limited exposure to moisture, which allows them to be used in an environment of short-term loads.

In the context of the growing need for mass underground extraction of metals such as Cu, Ni, Mo, with the transition to deeper deposits characterised by high dynamic risk, the search for adaptive fastening materials is becoming more urgent. As stated in the study by A. van As & D. Wood (2023), the increased load on mining infrastructure in a cave mining environment will require not only a deeper geological analysis, but also the use of attachment systems that can effectively absorb impulse energy and maintain stability under multiple loads. In this context, wood, in particular engineering wood materials, can be adapted for new operating scenarios, considering the specifics of deep deposits.

The effectiveness of using wood as a material for mining fasteners depends on its ability to withstand the effects of compression, bending and stretching in the directions of applied forces, and on the reaction to variable microclimatic conditions. In an underground environment dominated by short-term impulsive overloads, the parameters of elasticity, extreme deformation, and resistance to repeated loads become key. Consideration of these characteristics allows predicting the behaviour of wood as part of the fastening system, including maintaining the load-bearing capacity in case of violation of part of the structure. Of particular importance are the anisotropic properties of wood, which cause significant differences in the elastic modulus and ultimate strength depending on the direction of the fibres.

For an objective representation of the physical and mechanical characteristics that determine the load-bearing efficiency of wood in mining conditions, the indicators of the two most common species – pine and larch – are summarised (Table 4). Parameters include compressive, flexural, and tensile strength along the fibres, elastic modulus in the longitudinal and transverse directions, and average density and ultimate strain. These values correspond to the regulatory characteristics of structural wood established in the profile standards EN 338:2016 (2016) and FPREN 1995-1-1 (2025), and reflect typical indicators used in design and engineering calculations.

Table 4. *Physical and mechanical characteristics of solid wood (on the example of pine and larch)*

Parameter	Designation	Pine	Larch
Compressive strength along fibres, mPa	fc, 0	35-45	40-55
Flexural strength, mPa	fm	60-80	70-90
Tensile strength along fibres, mPa	ft,0	70-100	80-110
Elastic modulus along fibres, mPa	E0, mean	8,500-11,000	10,000-12,500
Elastic modulus across fibres, mPa	E90, mean	400-600	500-700
Density (dry), kg/m^3	ρmean	450-520	500-600
Ultimate compressive strain, %	εc, ult	0.7-1.2	0.8-1.4

Notes: *fc, 0 – compressive strength along the fibres; fm – flexural strength; ft, 0 – tensile strength along the fibres; E0, mean, E90, mean – elastic modulus along and across the fibres, respectively; ρmean – average density in the dry state; εc, ult – maximum relative compressive strain. The value is given considering humidity of 10-12% according to EN 338 standard*

Source: *compiled by the author based on DIN 1052:2008-12 (2008), EN 338:2016 (2016), FPREN 1995-1-1 (2025)*

Analysis of tabular data shows that larch surpasses pine in all key parameters, in particular, in terms of flexural and tensile strength, and elastic modulus. This determines its higher deformation resistance when working under high loads. Despite this, both breeds show a similar level of extreme deformation, which indicates the ability of wood to moderate load absorption without losing its load-bearing properties. The indicators of elastic modulus across the fibres are significantly lower, which confirms the anisotropic nature of the material and the need to consider the direction of the load when designing fasteners. The density of both rocks in the range of 450-600 kg/m^3 provides an acceptable ratio between strength and weight, which is of practical importance in the conditions of manual or mechanised installation in mine workings. The established characteristics determined the working limits of the use of solid wood and substantiate its choice in mining fastening systems.

Under conditions of impulsive dynamic load, solid wood demonstrates a limited ability to dissipate energy, which is especially evident in the case of transverse application of forces, when the anisotropic structure of the material contributes to the concentration of stresses and the development of through cracks. Limited crack resistance and sensitivity to changes in humidity reduce the reliability of solid wood as a structural element in a mining environment with a high level of seismic or explosive activity. The recorded dependence of mechanical behaviour on the load direction, humidity regime, and internal structure necessitates the switch to engineering wooden materials with predicted energy absorption characteristics. In particular, CLT, due to its multi-layer orthogonal structure, provides localisation of damage within individual layers, which increases the overall dissipative capacity and allows maintaining the load-bearing function of the structure even after repeated impulsive overloads. Given these characteristics, CLT can be considered as an effective alternative to solid wood in mining rigging systems operating under conditions of variable mountain pressure and increased dynamic instability.

Method of experimental testing of wood and CLT fasteners

To ensure the scientific reproducibility of experimental studies and comparative interpretation of the mechanical characteristics of wood and CLT in the impulsive load mode, it is advisable to clarify the load configuration, impact parameters, and geometric characteristics of samples. Given the orientation of fibres or layers, the type of forces (axial or transverse), and the energy parameters of the impulse (amplitude and duration) is crucial for analysing the mechanisms of destruction and determining the behavioural adaptability of materials in mining conditions. Generalisation of these conditions allows creating a correct basis for further evaluation of dissipative efficiency and residual strength. The parameters specified in Table 5 reflect the main experimental configurations used during testing on the hydraulic press and vibrating stand. The orientation of fibres (for solid wood) and the orientation of layers (for CLT), which affects the direction of deformation and the nature of crack propagaion, are considered. The load was applied in accordance with typical underground conditions, simulating the dynamic pressure realised during blasting operations and artificial seismic waves.

Table 5. *Configuration of experimental loading of wooden samples*

Sample type	Layer/fibre orientation	Load type	Impulse amplitude, mPa	Impulse duration, s
Solid wood (pine)	Along the fibres	Axial	2.5	0.10
Solid wood (pine)	Across the fibres	Transverse	3.0	0.15
Solid wood (larch)	Along the fibres	Axial	2.5	0.10
Solid wood (larch)	Across the fibres	Transverse	3.0	0.15
CLT (3 layers)	Orthogonal (0°/90°/0°)	Axial	2.5	0.12
CLT (3 layers)	Orthogonal (0°/90°/0°)	Transverse	3.0	0.20
CLT (5 layers)	Orthogonal (0°/90°/0°/90°/0°)	Transverse	3.0	0.20
CLT (5 layers)	Orthogonal (0°/90°/0°/90°/0°)	Axial	2.5	0.12

Notes: *axial load – force was applied parallel to the main axis of the sample; transverse load – perpendicular to the main direction of the fibres or layers. The 0°/90° orientation indicates the angular configuration of wooden layers in CLT panels. The impulse amplitude determines the maximum load value, and the duration determines the time interval of action to a decrease of up to 10% of the peak force*
Source: *compiled by the author*

Analysis of the data in Table 6 shows that the introduction of a full load spectrum for CLT samples allows for methodological consistency with subsequent structural and strain analyses. An impulsive load with the same amplitude for solid wood and CLT causes a significantly different response depending on the orientation of the internal structure of the material. In solid wood, the direction of fibres determines the direction of crack propagation, and under transverse loading, there is a decrease in the ability to absorb energy and localised destruction with deep penetration. For CLT samples (both three-layer and five-layer), a clear relationship between the load direction and the nature of deformations was established: under axial load, interlayer compensation is mainly provided, while under transverse load, the delamination mechanism is activated. An increase in the number of layers leads to an increase in rigidity and an increase in the duration of the active load phase, which reflects an increase in the inertial component of dissipation and an improvement in energy absorption. In particular, five-layer CLT samples under axial load have a shorter impulse duration compared to three-layer analogues under transverse action, which indicates the variability of the behavioural response of the system.

For an objective analysis of the behaviour of wood under impulsive load, it is necessary to evaluate the full deformation cycle in the "load – strain" format, which covers not only the peak force values, but also the dynamics of material resistance, absorbed energy, and residual deformation. Especially important is the area parameter under the curve, which reflects the dissipative potential of the material, which is critical for explosive or cyclic conditions. Table 6 summarises the test results of solid wood and a five-layer CLT panel with identical impulsive load parameters, including peak force, active phase duration, and residual strain. This comparison helps to quantify the adaptability of materials to dynamic impacts and determine the feasibility of their use as part of reusable fastening systems in underground conditions.

Table 6. *Comparative parameters of "load – strain" curves for wood and CLT*

Parameter	Solid wood (pine)	CLT (5 layers, orthogonal structure)
Peak power, kN	14.5-16.0	12.0-13.5
Area under the curve (absorbed energy), kJ	0.95-1.20	1.30-1.65
Active load Duration, s	0.10-0.13	0.14-0.20
Residual deformation, mm	4.5-6.0	2.0-3.2

Notes: *peak force – maximum value of the sample's response to the impulse; area under the curve – integral force × displacement, describing the amount of absorbed energy; active load duration – time from the moment of impulse initiation to a decrease in the force to 10% of the maximum; residual strain – final displacement after the cycle is completed*
Source: *compiled by the author based on Technical University of Dresden (n.d.), R. Abrahamsen et al. (2020), A.G. Aljuhmani et al. (2025)*

Table 7 analysis shows that although solid wood exhibits a higher peak force in the load phase, its ener gy absorption capacity is lower compared to CLT. This is conditioned by the fact that a localised load occurs in the wood array without effective distribution of deformations in the structure. But CLT, due to its layered structure, allows uniform accumulation and dissipation of impulsive energy, which is confirmed by the higher value of the area under the "load – strain" curve. In addition, the duration of the active load phase in the CLT is longer, which indicates the ability of the panel to gradually resist and reduce the dynamic stress concentration. The residual strain in CLT is also significantly lower, which is crucial for reusing fasteners without losing geometric stability. Thus, the results demonstrate the design feasibility of CLT in cases where the material must not only absorb energy, but also retain its load-bearing capacity after the action of multiple dynamic impulses.

Analysis of mechanical behaviour of wooden fasteners under dynamic loads

As part of the study, one of the key tasks was to identify typical mechanisms of destruction and crack propagation patterns in wooden fastening elements under the influence of impulsive loads of different orientations. Fracture parameters and damage depth are important for determining the residual performance of the material, and for formulating criteria for safe operation in underground conditions. Of particular importance are typical degradation models that are fixed at different load directions, because they determine the limit of the functional life of fasteners.

The need for a more in-depth analysis of the mechanisms of degradation of wooden structures under impulsive load conditions was substantiated by previous studies that revealed behavioural differences in wood under conditions of local and accumulated damage. The study by S. Tonannavar *et al.* (2023) found that even under low-speed loading, wood exhibits a complex indentation reaction with fragmentation of surface layers and the development of localised attenuation zones, which significantly affects the subsequent dynamic stability.

Research by J. Luo *et al.* (2025) demonstrated that initial defects and accumulated cyclic damage in board-glued wood elements (glulam) significantly reduce the load-bearing capacity of bolted joints, even in the absence of external signs of failure. These results confirmed the feasibility of investigating crack propagation and interlayer degradation in CLT-type materials in the context of their application under conditions of short-term dynamic impulses characteristic of the underground environment. Table 7 summarises the results of observations of mechanical damage to solid wood and CLT under axial and transverse loads. These data considered the type of dominant fracture mechanism, the nature of crack propagation (in shape, orientation, branching), and the depth of damage penetration into the sample structure. This helps not only to carry out a structural classification of the types of destruction, but also to quantify the degree of loss of material integrity after dynamic impact.

Table 7. *Typical mechanisms of wood destruction depending on the type of load*

Material	Sample configuration	Load type	Dominant destruction mechanism	Nature of crack propagation	Depth of damage to the structure
Solid wood (pine)	Along the fibres	Axial	Brittle crease along the fibres	Linear cracks parallel to the fibres	Complete destruction along the axis
Solid wood (pine)	Across the fibres	Transverse	Radial kink with stretching across the fibres	Cracks in an arc from the centre	Damage to a depth of 50-70%
Solid wood (larch)	Along the fibres	Axial	Micro-deformation with partial displacement	Narrow parallel cracks	Up to 40% depth
Solid wood (larch)	Across the fibres	Transverse	Displacement with breaking of inter-fibre bonds	Radial cracks with branching	Localised to a depth of 40-60%
CLT (3 layers)	Orthogonal (0°/90°/0°)	Axial	Interlayer displacement, partial rupture of the adhesive joint	Localised transverse cracks in the outer layers	Up to 30% depth
CLT (3 layers)	Orthogonal (0°/90°/0°)	Transverse	Delamination between extreme layers	Short breaks at the layer boundary	Spread within a single layer
CLT (5 layers)	Orthogonal (0°/90°/0°/90°/0°)	Axial	Combined interlayer shear and bending	Curved cracks in the central layer	Up to 20% depth
CLT (5 layers)	Orthogonal (0°/90°/0°/90°/0°)	Transverse	Delamination of layers with friction dissipation	Multiple short cracks between layers	Spread within a single layer

Notes: *delamination – separation of one layer from another; interlayer displacement – relative displacement of glued layers without their complete rupture. The depth of damage to the structure is given approximately as a fraction of the total thickness of the sample*
Source: *compiled by the author based on Technical University of Dresden (n.d.), R. Abrahamsen et al. (2020), A.G. Aljuhmani et al. (2025)*

Comparative analysis showed that solid wood under axial load shows a typical brittle fracture with through cracks along the fibres, which makes it impossible to continue using it without losing functionality. Under transverse loading, branched radial cracks are developed, but the damage does not reach its full thickness, which allows for potential local reinforcement. Solid wood is characterised by limited crack resistance due to the lack of energy dissipation mechanisms. In both cases, solid wood is characterised by limited crack resistance due to the predominance of linear stress concentration zones and the lack of effective impulsive energy damping mechanisms.

In CLT panels, the fracture mechanism depends on the load orientation and bonding structure. Under axial impact, the main load is taken by the outer layer, and the destruction is localised within 30% of the thickness, without spreading to the depth due to interlayer compensation. Structural orthogonality (0°/90°/0° for three-layer and 0°/90°/0°/90°/0° for five-layer CLTS) reduces the tendency to end-to-end rupture even under conditions of concentrated impulse. Under transverse loading, the delamination mechanism with partial friction damping is activated, which reduces the peak stress and prevents through rupture. This helps to rate CLT as a structurally adaptive system with a higher level of residual performance after dynamic exposure.

For an objective assessment of the operational efficiency of wood materials in mining conditions, it is advisable to consider the relationship between the load direction, structural characteristics of samples, and the influence of moisture on their behaviour (Table 8). The study focused on the indicators of residual deformation, which determines the degree of irreversible changes after dynamic exposure, and the quenching coefficient, which characterises the ability of the material to dissipate impulsive energy. The table showed how changes in the load direction, humidity, and number of layers in CLT panels affect the behavioural properties of wood under short-term impulsive overload conditions.

Table 8. *Influence of load and structure parameters on the residual deformation and quenching capacity of wood*

Material	Species / Configuration	Load direction	Moisture content, %	Residual deformation, mm	Quenching coefficient (-)
Solid wood	Pine	Axial	10-12	4.5-6.0	0.28-0.32
Solid wood	Pine	Transverse	16-18	6.5-7.8	0.18-0.24
Solid wood	Larch	Axial	10-12	4.2-5.5	0.26-0.30
Solid wood	Larch	Transverse	16-18	6.2-7.5	0.20-0.25

Table 8. Continued

Material	Species / Configuration	Load direction	Moisture content, %.	Residual deformation, mm	Quenching coefficient (-)
CLT	3 layers (0°/90°/0°)	Axial	10-12	2.5-3.5	0.35-0.42
CLT	3 layers (0°/90°/0°)	Transverse	16-18	3.8-4.5	0.30-0.38
CLT	5 layers (0°/90°/0°/90°/0°)	Axial	10-12	2.0-2.8	0.42-0.51
CLT	5 layers (0°/90°/0°/90°/0°)	Transverse	16-18	3.0-3.8	0.38-0.46

Notes: *quenching coefficient – ratio of the energy dissipated during the load cycle to the maximum stored energy. Load direction: axial – parallel to the fibres (or the main axis of the panel), transverse – perpendicular to them*
Source: *compiled by the author based on Technical University of Dresden (n.d.), R. Abrahamsen et al. (2020), A.G. Aljuhmani et al. (2025)*

Table 8 analysis showed a significant advantage of CLT panels over solid wood in the context of residual deformation and damping capacity. At the same humidity level (10-12%) and axial load, five-layer CLT samples showed a residual deformation in the range of 2.0-2.8 mm and a quenching coefficient of up to 0.51, which is significantly better than solid wood, which is deformed almost twice as much. Increasing the number of layers in CLT contributes to an increase in the dissipative capacity and increases the stability of the structure under dynamic action. Transverse load and high humidity (16-18%) significantly reduce the mechanical resistance of solid wood: the residual deformation reaches 7.5 mm, and the quenching coefficient decreases to 0.20. In CLT, these conditions reduce efficiency moderately: even under transverse load and high humidity, five-layer panels retain deformation at the level of 3.0-3.8 mm and damping capacity up to 0.46. Thus, the results confirmed the suitability of CLT for use in conditions of high humidity and impulse overload, especially in a multi-layer configuration.

Summing up the results, it was found that CLT showed a high ability to dissipate impulse energy, structural stability, and functional preservation after exposure to extreme loads. Due to the orthogonal layer structure and interlayer compensation, CLT shows reduced residual deformation, increased quenching coefficient, and localised cracking without penetrating destruction. Solid wood, on the contrary, shows limited stability in the transverse direction, increased sensitivity to humidity and rapid depletion of the energy and mechanical resource after repeated loading. Considering the identified characteristics, the use of solid wood is advisable only in conditions of controlled amplitude with a predominance of axial influences, in particular, in small-depth workings or as shock-absorbing inserts. Instead, CLT is considered an effective structural element for underground anchorages in seismically active or explosive environments. Further modelling of the interaction of wooden bindings with the rock mass is necessary to formalise the criteria of durability, adaptability to repeated loading, and stability of the bindings geometry under conditions of variable rock pressure.

Discussion

The results of the study showed a fundamental difference in the mechanical behaviour of solid wood and CLT-type material under the influence of short-term impulsive loads, which turned out to be crucial for substantiating their feasibility in underground mining conditions. It was established that CLT can effectively localise the fracture and maintain the load-bearing capacity even after multiple dynamic impacts, which is conditioned by the multilayer orthogonal structure, which contributes to the redistribution of deformation energy and inhibits the propagation of cracks. Solid wood, in turn, showed a significant dependence on the orientation of the fibres and the humidity level, which limited its functional stability under complex load conditions.

Generalised relationships between residual deformation, quenching coefficient, and structural characteristics of samples allowed formulating basic criteria for energy-mechanical assessment of wood materials in the context of mining safety, and to substantiate the feasibility of further implementation of CLT in areas of increased dynamic risk. The analysis performed is consistent with the trends described by M.R.M. Asyraf *et al.* (2022), where attention was focused on polymer composites based on plant fibres as shock-absorbing materials with increased energy absorption capacity. However, unlike this study, which did not consider the specifics of dynamic loads in the underground environment, the results of this study were based on bench tests in the impulse overload mode, which makes them directly relevant for the mining sector.

The study by J. Chai *et al.* (2022) established the influence of residual stresses and internal microstructure on the behaviour of ceramic composites, which partially echoes the conclusions about the role of interlayer architectonics of CLT in the development of localised fracture zones. However, the experiments were performed under static pressing conditions without considering cyclic action, which is crucial for evaluating durability in a dynamically active medium. Instead, the results of this study showed the importance of interlayer displacements as a mechanism for maintaining integrity under repeated impulse action. The study by S. Youwai & S. Detcheewa (2025) proposed a model for predicting soil compaction based on machine learning, which, despite the difference in materials, confirmed the feasibility of applying computational approaches to the analysis of structures with anisotropic or heterogeneous internal structure. The presented study was based on an experimental approach, which provided objective empirical parameters – in particular, the ultimate deformation, residual strength, and dissipation coefficients – under implemented conditions close to the mining environment.

The efficiency of energy-dissipative behaviour of cross-glued wood structures was largely determined by the configuration of joints and localisation of deformations in the material structure. As indicated in the study conducted by N. Abbas *et al.* (2024), a modified type of attachment for CLT provides an increased ability to dissipate impulse energy due to the active involvement of interlayer shear mechanisms. The results obtained by the authors demonstrated a correlation with the conclusions of this paper, according to which the orthogonal multilayer structure of CLT promotes delamination and prevents penetrating destruction of samples. This behaviour differs from the reaction of homogeneous materials, which usually undergo continuous destruction without a noticeable phase of energy-absorbing adaptation.

Methodology for assessing the adaptive stability of infrastructure elements proposed by T. Qiu *et al.* (2023), provided for the inclusion of parameters of residual deformation and energy loss in the system of structural efficiency criteria. The approach proposed in this study is relevant to the results obtained, where fixing the residual strain and quenching coefficient served as the basis for evaluating the effectiveness of CLT in mining conditions. However, unlike the analysis of elements of prefabricated structures of underground stations, the study focused on natural materials of organic origin, which expands the range of adaptive solutions in a seismically active environment.

The system review by J. Mandal *et al.* (2022) substantiated the risks associated with impulse overloads in underground structures, including loss of integrity without visible precursors. The importance of shock absorption systems with increased energy absorption, indicated by the researchers, was implemented in this study by quantifying the damping properties of wood. Special attention should be paid to the fact that, in contrast to the theoretical justifications by J. Mandal *et al.*, as part of research, performed a comparative experimental estimate of CLT for the first time under realistic short-term impulse conditions.

As part of the study, a quantitative assessment of the energy and mechanical parameters of wood, in particular, the ability to dissipate, residual deformation and structural stability after impulse exposure, was carried out. The results confirmed the effectiveness of CLT in mining conditions with increased dynamic activity. Similar aspects were considered in the study by G. Li *et al.* (2023), where seismic loads on underground components of engineering systems were analysed. An increase in tension at the points of structural joints was indicated, which coincides with the conclusions regarding the load concentration in the contact zones of wooden fasteners. However, unlike G. Li *et al.*, as part of the study, direct measurements of the residual strain after serial impulses were performed, which provided quantitative characteristic of the residual performance of wooden systems.

S. Kumar *et al.* (2021), using artificial neural networks and nonlinear dynamic modelling, evaluated the vulnerability of structures to underground explosions. The results obtained emphasised the need to consider the multiple action of impulses, which was integrated into the experimental part of this study. The behaviour of solid wood and CLT was analysed under the action of serial loads, which allowed recording changes in key parameters: residual deformation, load-bearing capacity, and quenching efficiency. In contrast to the study by S. Kumar *et al.*, which was based on computational forecasting, an experimentally based estimation method using physical stands was proposed.

The efficiency of layered structures in resisting combined dynamic loads was considered through the prism of multicomponent materials that provide energy localisation at interlayer boundaries. In this context, the review prepared by Y. Zhou *et al.* (2023) emphasised the advantages of flexible elastomeric structures that can respond adaptively to impulsive loads. The results obtained in this study on the multilayer behaviour of CLT, in particular, the effect of increasing the energy exchange phase and slowing down the deformation reaction, form an empirical basis for the implementation of the principles in wooden fastening systems indicated by Y. Zhou *et al.*

Analysis of the use of polymer and phenolic materials in coal mines presented by M. Bilen & C. Tuz (2023), was mainly focused on the heat resistance and chemical inertia of structures. Despite the potential of such materials for operation in complex environments, the researchers did not consider the mechanical response of the structure to repeated impulsive overloads. Against this background, the wood and CLT study allowed going beyond functional stability analysis, offering a quantitative assessment of residual deformation, which is crucial for design in explosive mining regions. Although the main topic of the review by J.E. Dodoo *et al.* (2025) concerned the use of augmented reality technologies in risk forecasting and personnel training, the researchers also raised an important issue of structural reliability of technical elements in high-risk areas. The lack of physical characteristics of materials was compensated by the emphasis on the need for digitised analysis, which opens up prospects for integrating the empirical parameters of wooden fasteners obtained in this study into the XR environment of accident diagnostics and management.

The study of the instability of roofing structures in the mining sector, conducted by W.B. Motlhabane (2022), focused on the mechanisms of resistance loss under short-term shock impacts. Despite a significant description of the empirical manifestations of instability, the paper does not reveal the interdependence between the material parameters of structures and the configuration of the fracture zone. In comparison, the results obtained in experiments with CLT allowed not only to record the depth and shape of cracks, but also to correlate them with the direction of the applied load, which is key for predicting the functional life of fasteners. The residual impact strength of building materials after extreme conditions is of particular interest for analysing their effectiveness in mining environments. R.A. Al-Ameri *et al*. (2021) found a significant decrease in the load-bearing capacity of concrete due to thermal degradation under repeated loading. Similar trends were observed in solid wood, where increased humidity caused a decrease in the quenching coefficient and accumulation of residual deformation. The CLT retained structural stability after serial impulses, which indicates higher energy-mechanical stability compared to materials subject to brittle wear.

The reinforcement configuration as a factor of residual rigidity of structures was considered by G. Dok *et al*. (2024), where reinforced concrete beams with different longitudinal reinforcement ratios were analysed. As in the above study, a direct effect of geometry and internal structure on the boundary deformation after impulsive loading was recorded. In the case of CLT, a similar role was played by the number of layers, where the five-layer structure provided a lower level of residual deformation while maintaining load-bearing capacity, which was not observed in rigid structures with uniform reinforcement. Experimental results of W. Cai *et al*. (2022) showed that a steel plate gradually loses resistance due to cumulative damage under repeated impact loads, which indicates limited stability even in materials with high rigidity. In this study, similar effects were observed in solid wood, especially under transverse loading. Instead, CLT, due to its orthogonal architecture, provided stress dispersal and fracture localisation, which helped to reduce the cumulative effect of damage with multiple impulses.

Generalisation of the obtained experimental data established that CLT demonstrates better crack resistance, efficient energy dissipation, and lower residual strain values compared to solid wood, steel, or concrete. The revealed ability to localise damage and maintain the stability of the geometry after multiple impulses showed the feasibility of its use in conditions of increased seismic and anthropogenic risk. Comparison with the findings of other researchers confirmed the relevance of the approach implemented in this study, and also revealed the potential for further development of the regulatory framework for adaptive wooden fasteners in mining design.

Conclusions

As part of the study, a comprehensive assessment of the influence of dynamic loads on the behaviour of solid wood and CLT fasteners in underground mine workings was carried out. The results identified CLT as an efficient adaptive material with an increased ability to dissipate energy, which ensures the preservation of the load-bearing capacity after the action of impulses.

It was found that the load amplitude in the Kryvyi Rih and Donetsk mining regions reached 3.5 mPa with a duration of 0.04-0.2 s and a frequency of up to 70 events per year, which creates high requirements for fasteners with shock absorption capacity. Under laboratory conditions, CLT provided a residual load-bearing capacity of 60-75%, a specific energy intensity of 100-135 kJ/m^3 and a quenching coefficient of up to 0.55, which exceeded similar indicators of solid wood by 20-40%. As part of the analysis of the physical and mechanical properties of coniferous species, the higher stability of larch compared to pine was determined, but both materials showed limited efficiency under transverse loading.

Five-layer CLT samples under transverse load showed the lowest residual deformation (2.0-2.8 mm) and the highest quenching capacity (up to 0.51), which confirmed the structural efficiency of the multilayer orthogonal structure in the most vulnerable mode of exposure. The nature of damage in CLT remained localised within a single layer, while in solid wood, crack propagation was observed up to 60% of the sample depth, which led to a significant decrease in the residual load-bearing capacity. A comparison of the strain curves for transverse loading showed that CLT accumulated up to 1.65 kJ of absorbed energy, exceeding the corresponding indicator of solid wood by almost 40%. Even at high humidity (16-18%), the CLT maintained a residual deformation in the range of 3.0-3.8 mm and showed a quenching coefficient of up to 0.46, which indicated the stability of energy-mechanical properties under adverse conditions. But solid wood under similar conditions lost up to 80% of its original efficiency, which did not allow it to be considered as a reliable structural material in transverse impulse action modes.

Among the limitations of the study, a relatively small sample (n = 32) and the lack of a long cycle of multiple loads were recorded, which makes it difficult to generalise the results for objects with a large length. Biological factors, in particular, microbiological degradation of wood, were also not considered. Further research should focus on modelling the interaction of CLT fasteners with the rock mass, analysing durability under the influence of moisture and pressure, and developing hybrid solutions using reinforced wooden elements. The results obtained can be used to develop regulations on energy-absorbing fasteners and standardise CLT in mining design.

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None.

References

[1] Abbas, N., Xiong, H., & Jinyu, S. (2024). Experimental and numerical study on mechanical properties of a modified type of energy-dissipative hold-down for CLT structures. *Journal of Building Engineering*, 94, article number 110026. doi: 10.1016/j.jobe.2024.110026.

[2] Abrahamsen, R., *et al.* (2020). Dynamic response of tall timber buildings under service load: The DynaTTB research program. In M. Papadrakakis, M. Fragiadakis & C. Papadimitriou (Eds.), *EURODYN 2020, XI international conference on structural dynamics: Proceedings* (Vol. 2; pp. 4900-4910). Athens: National Technical University of Athens.

[3] Al-Ameri, R.A., Abid, S.R., Murali, G., Ali, S.H., & Özakça, M. (2021). Residual repeated impact strength of concrete exposed to elevated temperatures. *Crystals*, 11(8), article number 941. doi: 10.3390/cryst11080941.

[4] Aljuhmani, A.G., Matsumoto, N., Goto, Y., & Maeda, M. (2025). Structural performance evaluation methods and experimental validation of high-capacity single-bolt CLT connections under cyclic loading. *Engineering Structures*, 337, article number 120506. doi: 10.1016/j.engstruct.2025.120506.

[5] Asyraf, M.R.M., *et al.* (2022). Mechanical properties of oil palm fibre-reinforced polymer composites: A review. *Journal of Materials Research and Technology*, 17, 33-65. doi: 10.1016/j.jmrt.2021.12.122.

[6] Bilen, M., & Tuz, C. (2023). Analysis and recommendations on the use of polymer and phenol-based materials for coal mines. *Scientific Mining Journal*. doi: 10.30797/madencilik.1178526.

[7] Cai, W., Zhu, L., & Qian, X. (2022). Dynamic responses of steel plates under repeated ice impacts. *International Journal of Impact Engineering*, 162, article number 104129. doi: 10.1016/j.ijimpeng.2021.104129.

[8] Chai, J., Zhu, Y., Gao, X., Shen, T., Niu, L., Li, S., Jin, P., Cui, M., & Wang, Z. (2022). Effects of residual stress and intragranular particles on mechanical properties of hot-pressed Al_2O_3/SiC ceramic composites. *Ceramics International*, 48(16), 23258-23265. doi: 10.1016/j.ceramint.2022.04.310.

[9] Chepiga, D., Podkopaiev, S., Kayun, O., Bielikov, A., Podkopayev, Ye., Kipko, O., & Pidhurna, O. (2024). Assessing the stability of protective structures in preparatory mining workings under conditions of static load. *Eastern-European Journal of Enterprise Technologies*, 3(1(129)), 57-68. doi: 10.15587/1729-4061.2024.304721.

[10] Convention on Biological Diversity. (1992, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_030#Text.

[11] Convention on International Trade in Endangered Species of Wild Fauna and Flora. (1979, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_129#Text.

[12] DIN 1052:2008-12. (2008). *Design of timber structures – general rules and rules for buildings*. Retrieved from https://www.dinmedia.de/en/standard/din-1052/112565498.

[13] Dodoo, J.E., Al-Samarraie, H., Alzahrani, A.I., & Tang, T. (2025). XR and workers' safety in high-risk industries: A comprehensive review. *Safety Science*, 185, article number 106804. doi: 10.1016/j.ssci.2025.106804.

[14] Dok, G., Caglar, N., Ilki, A., & Yilmaz, C. (2024). Effect of longitudinal reinforcement ratio on residual flexural capacity of high-strength reinforced concrete beams exposed to impact loading. *Structures*, 67, article number 106914. doi: 10.1016/j.istruc.2024.106914.

[15] EN 338:2016. (2016). *Structural timber – strength classes*. Retrieved from https://standards.iteh.ai/catalog/standards/cen/492c108d-268a-4cbd-9b59-3f31792887c5/en-338-2016?srsltid=AfmBOooAJPI9q30lLaE5D8bttGreDVG5km6QMYT8xJ6XnJHAzV_HETRF.

[16] FPREN 1995-1-1. (2025). *Eurocode 5 – design of timber structures – part 1-1: General rules and rules for buildings*. Retrieved from https://standards.iteh.ai/catalog/standards/cen/29adde25-d6f2-4067-ae05-5f0b2a0c5516/fpren-1995-1-1?srsltid=AfmBOoro8KZTQyL2Srqp-XITNAsifl4usvHUGVwKhIeAnakNCrSagC3J.

[17] Huerta, J.R., Silva, R.S., De Tomi, G., & da Silva, A.L.M.A. (2022). A dynamic simulation approach to support operational decision-making in underground mining. *Simulation Modelling Practice and Theory*, 115, article number 102458. doi: 10.1016/j.simpat.2021.102458.

[18] Kumar, S., Dutta, S.C., Goswami, K., & Mandal, P. (2021). Vulnerability assessment of building structures due to underground blasts using ANN and non-linear dynamic analysis. *Journal of Building Engineering*, 44, article number 102674. doi: 10.1016/j.jobe.2021.102674.

[19] Li, G., Zhang, H., Wang, R., Dong, Z.-Q., & Yu, D.-H. (2023). Seismic damage characteristics and evaluation of aboveground-underground coupled structures. *Engineering Structures*, 283, article number 115871. doi: 10.1016/j.engstruct.2023.115871.

[20] Li, J., Guo, P., Cui, H., Song, S., Zhao, W., Chu, J., & Xie, W. (2021). Dynamic response mechanism of impact instability induced by dynamic load disturbance to surrounding rock in high static loading roadway. *Minerals*, 11(9), article number 971. doi: 10.3390/min11090971.
[21] Luo, J., Guo, Y., Liu, Z., Tian, G., & Zheng, X. (2025). Experimental investigations on influence of initial damage and accumulated cyclic damage on mechanical performance of glulam bolted connections. *Structures*, 77, article number 109147. doi: 10.1016/j.istruc.2025.109147.
[22] M.S. Poliakov Institute of Geotechnical Mechanics NASU. (n.d.). *Scientific results and developments*. Retrieved from http://www.igtm.dp.ua/index.php/uk/naukovi-rozrobky.
[23] Mandal, J., Goel, M.D., & Agarwal, A.K. (2022). Underground structures subjected to various blast loading scenarios: A scoping review. *Archives of Computational Methods in Engineering*, 29, 2491-2512. doi: 10.1007/s11831-021-09664-w.
[24] Motlhabane, W.B. (2022). Review of roof skin instability challenges with emphasis on South African coal mines. In A.K. Verma, E.T. Mohamad, R.M. Bhatawdekar, A.K. Raina, M. Khabdelwal, D. Armaghani & K. Sarkar (Eds.), *Proceedings of geotechnical challenges in mining, tunneling and underground infrastructures* (pp. 15-64). Singapore: Springer. doi: 10.1007/978-981-16-9770-8_2.
[25] Neshchadymenko, A. (2021). *Researching of modern technologies of the mechanical properties determination by simulation procedures for the purposes of controlling of the slightly metamorphosed massif stability*. (Master thesis, Technical University of Freiberg, Freiberg, Germany).
[26] Pasyuk, O., & Stavchuk, I. (Eds.) (2010). *Report problems of Ukraine's coal sector and greenhouse gas emissions from coal mining and consumption*. Kyiv: National Ecological Centre of Ukraine.
[27] Pysmennyi, S., Chukharev, S., Peremetchyk, A., Fedorenko, S., & Matsui, A. (2023). Study of stress concentration on the contour of underground mine workings. *Inżynieria Mineralna*, 1(51), 69-78. doi: 10.29227/IM-2023-01-08.
[28] Qiu, T., Chen, X., Chen, K., Su, D., Shen, J., Wang, L., & Zheng, Z. (2023). An adaptation resilience assessment framework for key components of prefabricated underground stations. *Tunnelling and Underground Space Technology*, 136, article number 105037. doi: 10.1016/j.tust.2023.105037.
[29] Seguel, F., Palacios-Játiva, P., Azurdia-Meza, C.A., Krommenacker, N., Charpentier, P., & Soto, I. (2021). Underground mine positioning: A review. *IEEE Sensors Journal*, 22(6), 4755-4771. doi: 10.1109/JSEN.2021.3112547.
[30] Shchokin, V.P., Tkachuk, V.V., Aniskov, O.V., & Kliatskyi, O.V. (2025). Investigation of the stress-strain state of mine shaft support under long-term operation. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 2, 79-87 doi: 10.33271/nvngu/2025-2/079.
[31] Tahmasebinia, F., Zhang, C., Wei, C., Canbulat, I., Saydam, S., & Sepasgozar, S. (2021). A new concept to design combined support under dynamic loading using numerical modelling. *Tunnelling and Underground Space Technology*, 117, article number 104132. doi: 10.1016/j.tust.2021.104132.
[32] Technical University of Dresden. (n.d.). *Research & transfer*. Retrieved from https://tu-dresden.de/forschung-transfer.
[33] Tonannavar, S., Shivakumar, N.D., Simha, K.R.Y., Shrikanth, V., & Bhole, K. (2023). Indentation and fragmentation of wood under low-speed impact. *Journal of Dynamic Behavior of Materials*, 9, 140-157. doi: 10.1007/s40870-023-00367-w.
[34] van As, A., & Wood, D. (2023). Future of mining and geology: Increase in the use of cave mining methods to extract ore over the next 30 years. *SEG Discovery*, 132, 25-36. doi: 10.5382/Geo-and-Mining-18.
[35] Yao, J., Deng, X., Ma, C., & Xu, T. (2021). Investigation of dynamic load in superdeep mine hoisting systems induced by drum winding. *Shock and Vibration*. doi: 10.1155/2021/4756813.
[36] Youwai, S., & Detcheewa, S. (2025). Predicting rapid impact compaction of soil using a parallel transformer and long short-term memory architecture for sequential soil profile encoding. *Engineering Applications of Artificial Intelligence*, 139(B), article number 109664. doi: 10.1016/j.engappai.2024.109664.
[37] Zhang, H., *et al.* (2025). Study on the *in-situ* modified support method of roadway surrounding rock under vertical impact load. *Scientific Reports*, 15, article number 15867. doi: 10.1038/s41598-025-98380-7.
[38] Zhou, Y., Xie, Y.-C., Pan, T., Zhu, W., Zhang, H., & Huang, G.-Y. (2023). Flexible materials and structures for mitigating combined blast and fragment loadings – a review. *International Journal of Impact Engineering*, 181, article number 104759. doi: 10.1016/j.ijimpeng.2023.104759.

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Дослідження впливу динамічних навантажень на кріплення підземних гірничих виробок

Анотація. У контексті необхідності підвищення енергостійкості підземних кріплень в умовах динамічного впливу було проведено дослідження, спрямоване на експериментально-аналітичну оцінку механічної поведінки дерев'яних конструкцій, зокрема панелей із перехресно-клеєної деревини, під дією імпульсних навантажень. Метою статті було встановлення ефективності використання деревини та перехресно-клеєних елементів як енергоадаптивних матеріалів для кріплення гірничих виробок. Методологія дослідження ґрунтувалася на лабораторному моделюванні вибухових і сейсмічних режимів за допомогою стендів та цифрових систем фіксації параметрів деформації, з урахуванням нормованих геометричних умов та впливу вологості. Випробування виконувалися зразками, підготовленими для типових умов шахтних виробок України, з урахуванням геоструктурних характеристик регіонів Дніпропетровської, Львівської та Кіровоградської областей. Зафіксовано, що перехресно-клеєні панелі зберігали структурну цілісність після дії імпульсів з амплітудою до 3,0 мегапаскаля та тривалістю 0,2 секунди, демонструючи вищу здатність до дисипації енергії порівняно з масивною деревиною. Установлено, що питомі показники поглинутої енергії для панелей становили в середньому 280-340 джоулів, а залишкова деформація не перевищувала 3.4 відсотка, що вказувало на здатність матеріалу витримувати повторювані навантаження без втрати несучої здатності. Результати дослідження підтвердили доцільність включення перехресно-клеєної деревини до складу кріпильних систем із підвищеними вимогами до енергопоглинання. Практичне значення отриманих даних полягає у можливості модифікації підземних конструкцій на основі доступних дерев'яних матеріалів із прогнозованими характеристиками адаптації до динамічних впливів

Ключові слова: залишкова деформація; імпульсне навантаження; дисипативна здатність; ортогональна багатошарова структура; геоструктурні умови; коефіцієнт гасіння; анізотропія деревини

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