Substantiation of Geotechnical Risk Assessment Criterion for Mining Systems with Uncontrolled Caving of Ore and Surrounding Formations

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Abstract. The high risk of technogenic accidents involving caving technologies due to the variability of the state of rock mass determines the parameters of variability taking into account geotechnical risks based on the knowledge of the rock mass obtained through continuous monitoring. The assessment of geotechnical risks in mining taking into account the increasing reliability of design data input obtained through mining exploration, additional research, and monitoring results can help promptly respond to possible dangers and their consequences. The suggested geotechnical risk assessment criterion helps determine the level of danger at every stage of block caving implementation and promptly develop actions to prevent these risks and reduce their dependency on the external and internal environment factors.

1. Introduction

Due to the aggravating mining conditions and high volatility of prices for mineral resources, mining companies express an increasing interest in highly productive mining systems involving uncontrolled caving and characterized by low operational costs comparable with open-cut mining costs. The global experience of using mining systems with uncontrolled caving [1-4] shows that they can be used at kimberlite pipes in Yakutia, as well as gold and porphyry copper beds to finish open-cut mining activities. The key restricting factors for their extensive use in our country include the insufficient knowledge of the rock mass, the variability of its parameters, and the lack of local practical experience in the implementation of design solutions, which explains the high risks associated with the implementation of uncontrolled caving technologies.

The biggest difficulty in block caving is initiating the caving of the rock mass. Its failure or insufficiency may threaten the implementation of the mining system and result in rock bumps and air blasts, uncontrolled flooding (mud) and result in serious accidents with death toll and huge supply losses [5-8]. The efficiency of fragmentation and subsequent caving is determined by the sufficiency of undercutting parameters that depend on the properties of the rock mass that can be very scattered...
and uncertain. We should also note that undercutting parameters are determined using different methods [9-13] based on the practical experience available, which increases the uncertainty of mining system parameter calculation. These facts explain high geotechnical risks both at the design stage and at the following implementation states of the block caving system.

2. Theoretical approaches

The assessment of risks associated with uncontrolled caving suggested by Heslop (2000) [14] and Summers (2000) [15] sets out a list of risk factors that is used as the main one, although it is not exhaustive:

- the reliability of mining and geological data used to determine the structure, shape, and parameters of the ore body;
- the reliability of mining-engineering data about the ore body and the rock mass including geological structures, structure heterogeneity, rock parameters, rock mass stresses, and groundwater geology that are used to assess the rock cavability and proneness to the initiation and spread of caving, fragmentation, caving type, work pace, and dilution.
- cavability of rocks is determined by the forecasting of hydraulic radius, the size, and area of undercutting.

The existing methodological approaches to risk assessment in the mining industry, such as the Australian national standard for the mining industry [14], CaveRisk risk assessment methodology for uncontrolled caving systems [13,15,16], etc. determine the procedures of identification, assessment, and risk management methods and required these procedures to be performed at all of the life cycle stages of the project taking into account the changing knowledge about its mining and geological implementation conditions. The project risk level, whose reliability determines the efficiency of its management, is determined using the point-score system, generally based on the assessments of external and internal experts, as well as their experience and perceptions of input data reliability and the correctness of calculations for the key process parameters. These methods do not include acceptable risk criteria but it allows for the use of the ALARP (as low as reasonably practicable) acceptable risk principle. An advantage of risk assessment is that it helps determine risk manageability levels based on ratings and unmanageability classes by adjusting the parameter points for risks (process, characteristics) using the control ratio. The hierarchic structure of every risk assessment block with the identification of primary and secondary factors allows for the risk assessment of different project options across all of the dependent factors. Generally, this method allows for an adequate project risk assessment via the assessment of input data completeness and reliability and the correctness of key caving mechanism modeling but it does not eliminate the risk of technogenic accidents because it is impossible to determine the input data with 100% accuracy. Therefore, it is necessary to assess the level of geotechnical risk to develop and implement rock mass parameter management actions to improve the efficiency and provide the security of block caving systems.

The existing geotechnical risk assessment methods for underground mining activities as a rule stop at the construction stage and aim at the reduction of risks associated with the collapse of underground structures as a result of unreliable rock mass parameter assessment. At the same time, the efficient implementation of mining systems with uncontrolled caving requires solving two opposite problems related to rock mass state. These are providing the stability of underground mines in the haulage level and the undercutting level and the sufficient fragmentation in the caving block while preventing sinkholes in the ground surface, which determines the relevance of geotechnical risk assessment at all of the technological solution implementation stages.

Therefore, at the current development stage of using block caving at all of the mining operation life cycle stages (design, construction, operation, and liquidation (conservation)), it is necessary to consider the following geotechnical risk factors:

- the reliability of input data used for the calculation of mining system parameter
- reliability of calculation methods and modeling results
- economic and non-economic consequences of geotechnical risk.
The consideration of the mentioned factors will help us assess the level of geotechnical project risks, determine the riskiest technological zones and promptly determine the rock mass property management methods.

3. Geotechnical risk assessment criterion for mining systems with uncontrolled caving

High levels of geotechnical risks restrict both decision-making concerning the use of mining systems with uncontrolled caving and help reduce the efficiency of their implementation at all of the life cycle stages (Figure 1).

![Figure 1. The relations between the parameters of mining systems with uncontrolled caving and rock mass parameters at different life cycle stages of block caving.](image)

The geotechnical risk of block caving systems is related to the state of the rock mass, whose volatility during uncontrolled caving may result in economic and non-economic negative effects on the productivity of block caving as a result of accidents, injuries, and personnel mortality. We understand the geotechnical risk of the mining system with uncontrolled caving as its probability rate and the significance of economic and non-economic consequences at all of the mining operation life cycle stages.

The primary source of geotechnical risk in mining systems with uncontrolled caving is the lack of insufficiency of uncontrolled caving due to the poor fragmentation of the rock mass, which is often explained by the insufficient undercutting parameters that are determined by the hydraulic radius value and initial mining and geological data.

Thus, at the design stage, the key geotechnical risk factors for mining systems with uncontrolled caving include:
- unreliability and sometimes insufficiency of initial mining and geological data;
- the differences between the ore and rock mass parameters;
- the scattering of data ranges for the ore and rock masses.

The reliability of initial mining and geological data can be increased and the prompt rock mass property management can be implemented using a dynamic assessment of geotechnical risks integrated with the technological processes and connected to the achieved indicators of production processes. We understand the dynamic assessment of geotechnical risks as the assessment of the sufficiency of a set of key technological parameters, processes, and characteristics for the efficient implementation of block caving that is implemented at all of the mining project life cycle stages taking into account the increasing reliability of mining and geological data on the rock mass, as well as technological parameters and processes.
Normally, the identification of mining system parameters during the design stage is carried out under high uncertainty, which explains the low probability of achievement of expected parameters during the subsequent implementation stages of the uncontrolled caving technology. The system of continuous rock mass state monitoring is a key area of geotechnical risk analysis at all of the life cycle stages of block caving. This system improves our understanding of the rock mass parameters and it increases the designing costs and initial capital investments, yet it helps promptly respond to the changes in rock mass changes via the development of relevant management methods (Figure 2).

![Figure 2. The dynamic assessment of geotechnical risks at various mining project life cycle stages.](image)

The suggested criterion (1) helps determine the level of geotechnical risks and promptly react to the changes in the rock mass properties at all of the uncontrolled caving technology implementation stages depending on the changing factors of the external and internal environment.

\[
\begin{align*}
\{ P^\text{technol} \} &= \{ P_i^\text{technol} ; \Pi_i^\text{technol} \} \\
P_i^\text{technol} &\leq P_i^\text{technol}_{\text{acc}}
\end{align*}
\]

where \( P_i^\text{technol} \) is the geotechnical risk assessment criterion for uncontrolled caving system at mining production life cycle stage \( i \); \( P_i^\text{technol} \) is the implementation stage of the mining production life cycle; \( B_i^\text{technol} \) is the probability of geotechnical risks for mining systems with uncontrolled caving at mining project life cycle stage \( i \); \( \Pi_i^\text{technol} \) are the economic and non-economic effects of geotechnical risks at the mining project life cycle stage \( i \); \( P_i^\text{technol}_{\text{acc}} \) is the acceptable geotechnical risk at the mining project life cycle stage \( i \).

The probability of geotechnical risks for mining systems with uncontrolled caving at the mining project life cycle stage \( i \) is determined by the integral probability of initial mining and geological data error taking into account the significance of the impact of physical and mathematical properties of the
mass on the hydraulic radius value, and the probability of rock mass caving failure or insufficiency (2).

\[
\begin{align*}
B_i^{\text{technol}} &= B_i^{\text{init}} + B_i^{\text{caving}}, \\
B_i^{\text{init}} &= (K_{\text{break}} \cdot B_i^{\text{break}}) + (K_{\text{join}} \cdot B_i^{\text{join}}) + (K_{\text{stress}} \cdot B_i^{\text{stress}}),
\end{align*}
\]

(2)

where \(B_i^{\text{init}}\) is the probability of initial data error at the mining project life cycle stage \(i\); \(B_i^{\text{caving}}\) is the probability of rock mass caving failure or insufficiency at the mining project life cycle stage \(i\); \(K_{\text{break}}\), \(K_{\text{join}}\), and \(K_{\text{stress}}\) are the significance coefficients for the rock mass breakdown point, jointing, and stress respectively; \(B_i^{\text{break}}, B_i^{\text{join}}, B_i^{\text{stress}}\) is the probability of calculation error for rock mass breakdown point, jointing, and stress respectively at the mining project life cycle stage \(i\).

The probability of input data error is determined by their reliability level and using probabilistic assessment methods: variation coefficient, percentiles, etc. [17]. The acceptable reliability level of the input data identified by Read and Stacey (2009) can be determined through the technological solution implementation stage [18-19]. Significance coefficients for the key rock mass parameters used in the calculation of the hydraulic radius, such as the rock mass breakdown point, jointing, and stress ratio, can be determined by the mathematical simulation of their impact on the hydraulic radius value based on the actual mining and geological data [23].

The probability of caving failure or insufficiency is determined by the hydraulic radius value using the modified Mawdsley diagram through its comparison with the rock mass stability indicator \(N\) (Figure 3).

Figure 3. Uncontrolled caving probability assessment depending on the values of \(N\) and the hydraulic radius [13].

The aggregate economic and non-economic effects of geotechnical risks associated with mining systems with uncontrolled caving will be determined by the individual risks values, the compliance with mineral wealth conservation requirements in terms of acceptable losses, and, as a result, the losses associated with additional capital and operational costs and idle times associated with the mitigation of technogenic emergencies and accidents. We suggest assessing the effects of technogenic
emergencies according to their levels, low, medium, or high, in line with the assessment criteria (Table 3). The reliability of effect assessment is determined using the actual data on the accident rate at the company, compliance with acceptable loss standards, and actual costs of technogenic emergency and accident mitigation. During the technological solution design stage, when decisions are made in strict accordance with the existing standards and regulations, it is acceptable to use the average effect level.

**Table 1.** The assessment of potential effects of geotechnical risks in mining systems with uncontrolled caving.

| Effect level | Technological risk effects criterion for mining systems with uncontrolled caving |
|--------------|----------------------------------------------------------------------------------|
|              | Individual risk Safety [20] | Environmental | Economic losses [13] |
|              | Cost of assets | Annual operational costs | Project stalling |
| Low          | \( \leq 1 \times 10^{-6} \) (for all) | Losses below the standard level | \( \leq 1 \% \) | \( \leq 5 \% \) | less than 1 month |
| Medium       | \( 1 \times 10^{-3} - 1 \times 10^{-6} \) for company employees | Losses within the acceptable range | 1-10 \% | 5-10 \% | 1-6 months |
| High         | \( \geq 1 \times 10^{-3} \) for company employees; \( \geq 1 \times 10^{-4} \) for residents | Losses above the acceptable levels | \( \geq 10 \% \) | \( \geq 10 \% \) | Over 6 months |

The assessment of geotechnical risks in mining systems with uncontrolled caving is performed following the map of geotechnical risk (Table 2) ranked by their levels: acceptable, controlled, and unacceptable. The acceptable and controlled risk levels correspond to the acceptable level of geotechnical risks. That being said, the controlled level of risks requires additional rock mass property management actions relevant to the implementation stage of the technological solutions. The unacceptable level of technogenic risks requires a review of uncontrolled caving mining system parameters or rejection of this mining system.

**Table 2.** Geotechnical risk level map for mining systems with uncontrolled caving.

| Technological risk probability, % | Effect level |
|----------------------------------|-------------|
|                                  | Low        | Medium | High      |
| \( \leq 50 \)                   | Acceptable | Acceptable | Controlled |
| 50-90                            | Acceptable | Controlled | Unacceptable |
| \( \geq 90 \)                   | Controlled | Unacceptable | Unacceptable |
The assessment of geotechnical risks shall be carried out taking into account the production process development dynamics as the mining and geological data, the actual standard loss values, and the industrial safety level become more accurate, which helps promptly implement the respective management actions.

4. Implementation

The assessment of geotechnical risks at the design stage for the mining systems with uncontrolled caving of ores and adjoining rocks for the stoping conditions of the Udachnaya kimberlite pipe [21,22].

![Figure 4. Udachnaya pipe stoping system.](image)

The Udachnaya pipe was open-mined to the depth of 325 m and then the underground mining stage began using the sublevel caving method. Block caving is the most desirable option in terms of technical and economic indicators. The design parameters of the block caving system are shown in the table.

**Table 3.** Determining the design parameters of block caving and the probability of geotechnical risks

| No. | Name                                      | Unit         | Value     |
|-----|-------------------------------------------|--------------|-----------|
| 1   | Compressive resistance                    | MPa          | 3-87.6    |
| 2   | Jointing                                  | joints/m     | 1–6       |
| 3   | Stress ratio                              | unit fractions | 0.6-1.2  |
| 4   | Hydraulic radius for average values       | m            | 11        |
| 5   | Undercutting area                         | m²           | 1936.8    |
The physical and mechanical properties of kimberlite and adjoining rocks are characterized by a significant scattering of the data [24], and they are different for the Western and the Eastern ore bodies, which explains the high levels of geotechnical risks associated with uncontrolled caving. To assess the reliability of undercutting parameters in block caving during the cleaning up of the Udachnaya pipe, we assessed the geotechnical risks for different input data reliability levels (Table 3).

Table 4. Block caving parameters.

| Initial data reliability, % | Geotechnical risk probability, % | Hydraulic radius, m | Undercutting area, m² | Block commissioning time, months | Required rock mass jointing, joints/m |
|-----------------------------|---------------------------------|---------------------|----------------------|-------------------------------|---------------------------------------|
| 30                          | 95                              | 8                   | 1147                 | 15                            | 2                                    |
| 50                          | 62                              | 11                  | 1785                 | 23                            | 3                                    |
| 60                          | 47                              | 12                  | 2247                 | 29                            | 4                                    |
| 70                          | 37                              | 13                  | 2550                 | 33                            | 4                                    |
| 80                          | 27                              | 13                  | 2521                 | 32                            | 5                                    |
| 85                          | 20                              | 13                  | 2724                 | 35                            | 5                                    |

The analysis of Table 4 data shows that the higher the reliability of input data is, the lower the probability of geotechnical risk is. Reducing the probability of geotechnical risks by 100% cannot be considered possible. Table 5 presents the data on the geotechnical risk level depending on the significance of their effects and the reliability of input data.

Table 5. Geotechnical risk level depending on the level of effects and input data reliability

| Input data reliability, % | Low-level effects | Medium-level effects | High-level effects |
|---------------------------|-------------------|----------------------|--------------------|
| 30                        | Acceptable        | Unacceptable         | Unacceptable       |
| 50                        | Controlled        | Unacceptable         | Controlled         |
| 60                        | Controlled        | Acceptable           | Controlled         |
| 70                        | Controlled        | Acceptable           | Controlled         |
| 80                        | Controlled        | Acceptable           | Controlled         |
| 85                        | Controlled        | Acceptable           | Controlled         |

The presence of an abandoned quarry that accumulates precipitations, as well as the presence of rifts, and the disposition for gas, oil, and bitumen ingress, the consolidation ability of kimberlite
facilitates the development of technogenic emergencies (air blasts, flooding) with high-level effects. Therefore, the reliability of input data during the calculation of block caving parameters for the Udachnaya pipe must be at least 60%.

5. Conclusions
The parameters of uncontrolled caving technologies should be determined taking into account the dynamic assessment of geotechnical risks and the formation of a relevant monitoring system for uncontrolled caving mining system parameters, as well as their further adjustment taking into account the increasing reliability of design data input obtained through mining exploration, additional research, and monitoring results, as well as the industrial safety levels.

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