Assessment of the Influence of Technological Risk Factors on the Undercut Parameters When Mining Kimberlite Using Block Caving

A A Kovalenko¹, O V Petrova², Yu D Mambetova³

¹Director of Mirninsky GOK, PJSC ALROSA, Molodezhny lane, 3, Mirny Republic of Sakha (Yakutia), 678174, Russia
²Candidate of Technical Sciences, Associate Professor of the Department of Development of Mineral Deposits, FSBEI HE "Magnitogorsk State Technical University named after G.I. Nosova, Lenin Ave., 38, Magnitogorsk, 455000, Russia
³Candidate of Technical Sciences, Associate Professor of the Department of Development of Mineral Deposits, FSBEI HE "Magnitogorsk State Technical University named after G.I. Nosova, Lenin Ave., 38, Magnitogorsk, 455000, Russia

E-mail: prmpi@magtu.ru, mambetova_yuliya@bk.ru

Abstract. The use of block caving to mine ores and rocks of kimberlite deposits in Yakutia (Udachnaya, Yubileynaya Mir pipes) will ensure high economic efficiency and productivity, reduce damage to diamond crystals due to non-explosive technology of mining. At the same time, block caving creates high technological risks associated with the essence of the technique itself, as well as the mining, engineering and geological specifics of kimberlite deposits. To ensure the effectiveness of the block caving method and planned progression of block caving, it is necessary to assess the influence of technological risk factors at the stage when caving parameters are determined to reduce the consequences during the whole life cycle of the mine.

1. Introduction

The world experience of mining using block caving demonstrates that this method can be successfully applied to mine ores in various geological and climatic conditions. The examples are El Teniente mines (Chile); Premier, Finch, Koffiefontein (South Africa); North Parks (Australia), Henderson (USA), and others. This allows using this mining method in the underground mining of kimberlite deposits in Yakutia — Mir, Yubileinaya and Udachnaya pipes [1-5]. The advantages of block caving for kimberlite mining are its high productivity allowing to replenish the corresponding retired open-pit mining capacity at an adequate pace, low production costs compared to other mining methods, as well as the ability to reduce damage to diamond crystals due to the non-explosive mining technology.

An analysis of the scientific and methodological literature on block caving methods showed that their effectiveness is mainly determined by the tendency of rocks to cave in by themselves and have stable fragmentation of the rock mass, which largely depends on the required undercut parameters, based on the hydraulic radius (hereinafter, HR) obtained by the results of the rock mass stability assessment using Lobshire, Matthews-Potvin, Mavdley and other methods [6-11]. Inaccurate undercut parameters determined at the design stage will become risk factors for insufficient fragmentation during operation. Insufficient fragmentation by itself will become a risk factor for failure to achieve the required...
performance and accidents from rock and air blasts, uncontrolled breakthrough of water (sludge), which can lead to unexpected shutdowns, and in some cases the loss of block reserves. Therefore, to ensure the required fragmentation and planned progression of block caving, it is necessary to assess the influence of technological risk factors when determining the block caving method parameters to reduce the consequences during the whole life cycle of the mine.

2. Study of technological risk factors

Analysis of the technological risk structure in methods of mining using block caving of ores and host rocks showed that its main factors at the design stage are:
- difference in the properties of the ore and host rock masses;
- spread of data range for ore and host rock masses;
- accuracy of properties determined for the rock mass.

The study of technological risk factors and their influence on the mining method parameters is especially relevant for mining of kimberlite deposits in Yakutia using the block caving method due to the specifics of mining and geological conditions complicating the implementation of this technology, which are characterized by permafrost, the occurrence of ore bodies in the zone of direct contact with water-bearing rocks, presence of mined-out quarry areas subject to thawing leading to the formation of sludge in the quarry bottom, occurrence of oil and bitumen, etc. [12-16].

The influence of physical and mechanical properties of the rock mass on the hydraulic radius was assessed using mathematical modeling of the effects of fracturing, strength and tension of the rock mass for the conditions of underground mining of the Udachnaya, Yubileinaya and Mir pipes by block caving of ores and host rocks using the data presented in Table 1. [17-20]

Table 1. Physical and mechanical properties of the mountainous area with kimberlite deposits in Yakutia for assessment of their impact on HR calculated by the Lobshir method [6, 20, 21].

| Parameters                        | Deposit          |
|-----------------------------------|------------------|
|                                   | Mirkimberlites | host rocks | Udachnaya kimberlites | host rocks | Yubileynaya kimberlites | host rocks |
| Bulk density, $\rho$, t/m$^3$     | 2.26-2.78       | 2.10-3.08  | 2.27-3.2              | 2.15-3.01  | 2.33                    | 2.44-2.61  |
| Compressive strength, $s_{cs}$, MPa | 16.1-45.1     | 0.9-161    | 3.87-6.2              | 2.1-174.1  | 1.73-5.65               | 6.7-152    |
| Tensile strength, $\sigma_t$, MPa | 1.9-4.2        | 0.21-29    | 0.5-4.6               | 0.8-12.1   | 0.78-1.43               | 0.4-15.7   |
| Protodyakonov strength index      | 2.0-5           | 2.0-8      | 2.5-4.5               | 2-5        | 5-6                     | 2-6        |
| Number of joint sets              | four joint sets | four joint sets | three joint sets | three joint sets | three joint sets | three joint sets |
| Fracture density, fractures per m | from 2-3 to 5-10 | from 3 to 10 | from 1-3 to 4-6        | 2-4        | 1.0-6.2                 | to 3-4     |

The analysis of data presented in Table 1 showed a significant difference in the properties of the ore and host rock masses, leading to different HR values at which effective cave-in will occur. Generally, the HR value is usually calculated during the design stage from the average values of the ore mass properties without considering the differences in the properties of ore and rock masses, which can result in no caving of rock mass occurring after the caving of ore mass, the formation of air gaps leading to
accidents from uneven depletion of quarry walls, uncontrolled breakthrough of sludge from the quarry space, air blasts.

The dispersion of data for the ore and host rock masses determines a wide range of HR values, both for the rock and ore masses, which complicates the choice of the specific single value during design. The practice of choosing the maximum HR value (hereinafter referred to as HR$_{\text{max}}$) both for the rock and ore masses leads to a significant increase in capital costs due to large undercut area, which according to (Butcher, 2018) amounts to 79-90% of the total investment [22] and a high probability of ore cave-in, leading to a high level of technological risk during operation. Thus, using HR$_{\text{max}}$ leads to the following disadvantages:

- block caving of ores due to the high fragmentation rate, which leads to the destruction of ore extraction tunnels;
- destruction of supports of the extraction points due to stress concentration resulting from the large area of undercut;
- drilling a significant amount of tunnels before the actual mining is commenced and, as a consequence, a delay with the actual ore mining.

The adoption of the HR value based on the average values of the physical and mechanical properties of the mass (hereinafter referred to as HR$_{\text{av}}$) at the design stage may also be insufficient when the block caving of an area (interlayers) of hard rocks is achieved, which will lead to a halt (delay) of the fragmentation process and, as a consequence, a slowdown or lack of ore caving. Therefore, rock mass pre-conditioning technologies shall be foreseen during the design stage in order to ensure the required physical and mechanical properties of the rock mass and its effective caving. To do this, it is necessary to assess the influence of different factors on the HR value, which is used to determine undercut parameters.

The HR$_{av}$ values for the conditions of Udachnaya, Yubileinaya and Mir pipes were 11, 7 and 10 m for the ore mass, respectively, as well as 13, 13 and 12 m for the mass, respectively, which corresponds to the size of a rectangular undercut with the dimensions of sides a and b given in Table 2 [23].

### Table 2. Dimensions of horizontal undercuts for kimberlite deposits in Yakutia.

|                      | Udachnaya | Yubileinaya | Mir |
|----------------------|-----------|-------------|-----|
|                      | per ore   | per rock    | per ore | per rock |
| Hydraulic radius HR$_{av}$ | 11        | 13          | 7     | 13       | 10     | 12    |
| Undercut width, m    | 45        | 50          | 30    | 50       | 40     | 50    |
| Undercut length, m   | 43.04     | 54.17       | 26.25 | 54.17    | 40     | 46.15 |
| Undercut area, m$^2$ | 1936.96   | 2708.3      | 787.5 | 2708.3   | 1600   | 2307.7|

The calculation results showed that a larger undercut area is required for the cave-in of the rock mass than for the ore mass by 1.4, 3.4 and 1.44 times for the Udachnaya, Yubileinaya and Mir pipes, respectively, which indicates high technological risks of effective caving at ore-rock contact, as well as host rocks, following the caving of the ore mass.

When determining the undercut parameters, not only the difference in the rock and ore mass properties shall be considered, but also a significant range of their values.

It was found that the main factors affecting HR are the ultimate compressive strength, stress state and the fracture density of the rock mass. Figure 1 shows the dependence of the hydraulic radius on the abovementioned factors for the Udachnaya pipe conditions. The influence of the factors is identical for Mir and Yubileynaya kimberlite pipes.
The analysis of physical and mechanical properties of the rock mass of the Udachnaya pipe showed that the fracture density of the ore mass varies in the range from 1 to 6 fractures per m, and of the host rock mass — from 2 to 4 fractures per m, while with the fracture density increase the value of hydraulic radius decreases. Analysis of the graph shown in Figure 1a shows that at a fracture density below 3 fractures per m for ore and rock masses, the HR value will not be enough to ensure block caving, which requires the fracture density of at least 3 fractures per m for uniform caving of ores and rocks, as well as the need for development of ground control methods to change the fracture density.

The range of ultimate compressive strength variation for Udachnaya pipe ore is 5–90 MPa, which is two times lower compared to rocks (4–180 MPa), while the HR value increases with an increase in the ultimate compressive strength of ore and rocks. Figure (1b) shows that if the ultimate compressive strength of the ore mass is in the range of 50-90 MPa, HR value is not sufficient for effective block caving, while the planned progression of block caving at the ore-rock contact will happen at the ultimate compressive strength of the rock mass of 4–50 MPa. This indicates the need to design methods for controlling the rock mass strength aimed at softening the rock mass to initiate the process of its block caving.

For the Udachnaye deposit mining conditions, it is assumed that the stress state coefficient of the mass varies in the range from 0.6 to 1.2 for both the ore and rock masses. The stress state coefficient value above 1 causes difficulties in the block caving process, and therefore it is necessary to ensure a decrease in the stress state coefficient of the rock mass to 1 and below.

Thus, it was found that certain methods for controlling physical and mechanical properties shall be provided in order to ensure uniform and effective caving of ores and rocks. The results of studies aimed...
at assessing the impact of physical and mechanical properties of the rock mass on HR are presented in Table 3.

**Table 3.** Physical and mechanical properties of the rock mass required for uniform block caving at HR$_{av.ore}$

| Required properties               | Udachnaya pipe | Yubileynaya pipe | Mir pipe |
|-----------------------------------|----------------|-----------------|----------|
| Fracture density, fractures per m | 22 min         | 3-4 min         | 6-7 min  |
| Ultimate compressive strength, MPa| 45 max         | 19 max          | 30 max   |
| Stress state coefficient          | 0.85-1         | 0.6-1           | 0.8-1    |

Analysis of the combined effect of factors on HR in order to identify their significance showed that the most significant factors affecting the ore mass HR are the fracture density, while for the rock mass HR — stresses in the mass for the conditions of the Udachnaya pipe deposit (Figure 2).

**Figure 2.** Influence of fracture density, tension and ultimate compressive strength on HR for the conditions of the Udachnaya pipe for: a — ore mass; b — rock mass.

For Yubileynaya pipe conditions, the most significant factor affecting HR for ore and rock masses is fracture density, while for the rock mass HR — the mass stress state. For Mir pipe conditions, respectively, for the ore mass — the fracture density and stress state, and for the rock — stress and strength.

Analysis of the simulation results showed that for effective caving of ore and rock masses, pre-conditioning of the mass is required, aimed at increasing the fracture density of the ore mass and reducing the tension of the rock mass, which will allow effective caving at the ore-rock contact even if they differ significantly.

For the purpose of operational control of the required properties of the rock mass at the reserves exploitation stage, empirical dependences of HR on the fracture density, strength and stress state of ore and rock masses were established by approximating the results of mathematical modeling for the conditions of underground mining of kimberlite deposits in Yakutia using block caving method with a confidence value $R^2 = 96$:

$$HR = m_1 \cdot f + m_2 \cdot t + m_3 \cdot \sigma + a$$  \hspace{1cm} (1)

$$\text{where } a, m_1, m_2, m_3 - \text{ constants determined using the data of economic and mathematical modeling of multiple linear regression, which have the following values:}$$
- for ore mass: $a=1.59$, $m_1=0.085$, $m_2=-1.04$, $m_3=9.33$;
- for rock mass: $a=0.5$, $m_1=0.048$, $m_2=-1.25$, $m_3=12.2$.

3. Evaluation of results

For the conditions of further underground mining of the Udachnaya pipe of ALROSA PJSC, a comparison was made of undercut parameters calculated using $HR_{\text{max}}$ and $HR_{\text{av}}$. In the first case, the undercut parameters were calculated based on $HR_{\text{max}}$, taking into account a margin of $10\% = 18$ m. To ensure uniform caving process, the double undercut is adopted as the undercut type. In the second case, the undercut parameters were calculated using $HR_{\text{av}} = 11$ m along with the development of engineering solutions for the pre-conditioning of the mass aimed at changing the significant physical and mechanical properties established by the results of mathematical modeling to the required values.

The world experience in mining using block caving methods has shown that the most effective direction for pre-treatment of the rock mass is hydraulic fracturing, which ensures a more uniform and directed change in the rock mass mechanical properties, as well as excludes large area overhangs. Hydraulic fracturing is also widely used as one of the degassing methods. [24-26] According to research by R.G. Jeffrey, A. van As, et al., hydraulic fracturing via a single well is capable of creating fractures in a radius of 50 m and more [22], based on the experience of the Northparkes mine. At the same time, hydraulic fracturing allows to increase the fracture density of the block by 1.5-2 times. According to the research, hydraulic fracturing wells for creating fractures must be drilled across the direction of the minimum stresses [27.28].

For the conditions of underground mining of Udachnaya pipe using block caving method, the $HR_{\text{av}}$ value is 11 m, for which the required fracture density of the mass will be 6 fractures per m according to relationship (1). To ensure the required fracture density, pre-conditioning of the rock mass is carried out using the proposed directional hydraulic fracturing, which will allow changing the fracture density of the rock mass to the required value — from 3 to 6 j/m and ensure efficient and uniform block caving of ores and rocks.

The comparative assessment of the effectiveness of alternative undercut parameters is presented in Table 3. The following assumptions were made for the calculation: extraction and access tunnels are identical, the specific volume of pre-commissioning works is the same.

| Table 4. Engineering and economic comparison of technological solutions. |
|--------------------------------|-----------------|-----------------|
| | $HR_{\text{max}}$ | $HR_{\text{av}}$ |
|--------------------------------|-----------------|-----------------|
| Hydraulic radius, m | 18 | 11 |
| Undercut parameters, m: | | |
| width | 70 | 45 |
| length | 74 | 43 |
| height | 10 | 10 |
| Preparatory-development operations, m$^3$ | 103600 | 19350 |
| Drilling cost, million rubles | 362.6 | 67.725 |
| Length of hydraulic fracturing wells, m | - | 100 |
| Number of wells | - | 7 |
| Well drilling cost, rubbles per m | - | 5000 |
| Drilling horizon penetration, million rubles | - | 3.5 |
| Block treatment cost, rub | 362.6 | 71.225 |

The results of comparison of alternative engineering solutions' efficiency showed that the block treatment costs at $HR_{\text{av}}$, including hydraulic fracturing costs, are more than 5 times lower than the block treatment costs at $HR_{\text{max}}$, including the costs of a double undercut.
4. Conclusions

Thus, further development of kimberlite deposits in Yakutia using block caving methods is associated with high technological risks due to method specifics, along with certain mining, engineering and geological conditions. To ensure the mining efficiency of the kimberlite deposits in Yakutia by block caving, the undercut parameters shall be determined as accurately as possible at the design stage, taking into account the technological risk factors — the difference in ore and rock properties, as well as the wide dispersion of values physical and mechanical properties of the rock mass. Comparison of the undercut parameters calculated from the values of HR_{max} and HR_{av} showed that taking the undercut value calculated using HR_{av} at the design stage along with the block pre-conditioning will reduce the cost of drilling and ensure effective caving process.

5. References

[1] Hartley W K 1981 Changes in Mining Methods in the Kimberl y Mines of DeBeers Consolidated Mines Ltd, RSA Block Caving to Caving, in Design and Operation of Caving and Sublevel Stopping Mines (Ed: D R Stewart) pp 3-16
[2] Kuzmin E V, Uzbekova A R 2005 Self-destruction: The path of development Mining magazine 8 pp 69 –71
[3] Wooa K S, Eberhardt E, Elmo D and Stead D 2013 Empirical investigation and characterization of surface subsidence related to block cave mining International Journal of Rock Mechanics & Mining Sciences 61 pp 31–42
[4] Bartlett P J and Croll A M 2000 Cave mining at Premier Diamond Mine. Proceedings MassMin Brisbane (Ed: G Chitombo) Australasian Institute of Mining and Metallurgy: Melbourne pp 227-234
[5] Dawson L R 1995 Developing Australia’s first block caving operation at Northparkes Mines - Endeavour 26 Deposit Proceedings 61h Underground Operators' Conference, Kalgoorlie, Australasian Institute of Mining and Metallurgy: Melbourne pp 155-164
[6] Kuzmin E V, Uzbekova A R 2006 Self-destruction of ores in underground mining: a textbook (M.: Publishing house of the Moscow State Mining University) 283 p
[7] Eremenko V A, Aimbinder I I, Patskevich P G and Babkin E A 2017 Assessment of the state of the rock mass at the mines of the Polar Division of OJSC MMC Norilsk Nickel GIAB 1 pp 5-17
[8] Kuzmin E V, Uzbekova A R 2004 Rating classifications of rock massifs: prerequisites for creation, development and scope GIAB 4 pp 201-202
[9] Laubscher D H, Jacubec J 2000 The MRMR Rock Mass Classification for jointed rock masses Foundations for Design (Brisbane) pp 475-481
[10] Jacubec J, Laubscher D H 2000 The MRMR rock mass rating classification system in mining practice (Brisbane) pp 413-421
[11] Brown E T 2002 Block caving geomechanics (Australia) 515 p
[12] Summers J 2000 Analysis and Management of Mining Risk, in Proceedings MassMin 2000 G Chitombo (ed) 29 October to 2 November 2000 (Brisbane, Australia) Australasian Institute of Mining and Metallurgy (Melbourne) pp 63–79
[13] Heslop T G 2000 Block caving—controllable risk and fatal flows In: Proceedings of MassMin (Brisbane, Australia) pp 437–454
[14] Summers J 2000a Risk assessment within CaveBase Report by CGSS, Berkshire, UK, to International Caving Study JKMRC and Itasca Consulting Group (Inc: Brisbane)
[15] Boyarko G Yu 2003 Strategic sectoral risks of the mining industry Domestic geology 4-5 pp 28-32
[16] Montyanova A A, Trofimov A V, Rumyantsev A E, Vilkishyn V B, Nagovitsin Yu N 2019 Experience and efficiency of using plasticized filling mixtures Vestnik MGTU im. G.I. Nosov T 17 1 pp 18-25
[17] Tishkov M 2018 Evaluation of caving as mining method for Udachnaya underground diamond mine project Proceedings of the Fourth International Symposium on Block and Sublevel Caving pp 835-846

[18] Sklyarov E V, Alekseev S V, Egorov K N and others Features of the development of primary diamond deposits in difficult mining and geological conditions of the eastern sector of the Arctic Fundamental research of the RAS Presidium

[19] Kuzmin E V, Uzbekova A R 2005 Application of self-caving systems in kimberlite ore conditions (GIAB) 8 pp 211 - 214

[20] Savich I N 2004 Scientific substantiation of technological solutions at underground mining of kimberlite deposits: dissertation ... Doctors of technical sciences: 25.00.22 (Moscow) 304 p

[21] Technological regulations for the design of the development of the Udachnaya pipe deposit up to elevation -680m in two versions of the development system with forced collapse and self-collapse (043-17 / 10) (LLC Uralmekhanobr) 387 p

[22] Jeffrey R G, van As A, Zhang X, Bunger A P, Chen Z R 2018 Measurement of hydraulic fracture growth in a naturally fractured orebody for application to preconditioning Caving 2018 – Y Potvin and J Jakubec (eds) pp 647-662

[23] Uzbekova A R 2004 Substantiation of parameters of self-destruction of kimberlite ores during their underground mining Autorefer. on sois. ... Ph.D. by spec. 25.00.22 (Moscow) 24 p

[24] Klishin V I, Lekontsev Yu M and Sazhin P 2006 The Experimental studies of the redistribution of the reference pressure in the longwall during forced landing of the roof GIAB 3 pp 339-347

[25] Sazhin P V 2004 Investigation of the influence of mechanical properties of seals on the direction of development of the initiating gap GIAB 7 pp 254–258

[26] Sainsbury B, Sainsbury D and Carrol D 2018 Back-analysis of PC1 cave propagation and subsidence behaviour at the Cadia East mine Caving 2018 – Y Potvin and J Jakubec (eds) pp 167-178

[27] Butcher R J, Fallon M 2011 Block caving strategic risks in Y Potvin (ed.) Proceedings of the Fourth International Seminar on Strategic versus Tactical Approaches in Mining Australian Centre for Geomechanics (Perth) pp 359-366

https://doi.org/10.36487/ACG_rep/1108_29_Butcher

[28] Flores-Gonzalez G 2019 Major hazards associated with cave mining: are they manageable in J Wesseloo (ed.) Proceedings of the First International Conference on Mining Geomechanical Risk Australian Centre for Geomechanics (Perth) pp 31-46

https://doi.org/10.36487/ACG_rep/1905_0.3_Flores-Gonzalez