Development of the Digital Model for the Selection of Mine Working Support in Complex Mining and Geological Conditions

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Abstract. The methodological basis for the development of a multi-factor digital model for selecting efficient and safe mine working support for given mining and geological conditions on the basis of the assessment of rock mass stability conditions depending on its fracturing and stress state when mining iron ore deposits of Gornaya Shoria is presented. The need to solve fundamentally new problems related to the application of various types of support systems is due to the changeover of mines to ore mining at great depths and classifying deposits as liable to rock-bumps. It is a very important factor, because a decrease in the stability of workings is associated with a high level of stresses in the deep levels being worked out, increased by bearing pressure, which ultimately leads to an increase in the cost of maintaining them. The developed multi-factor digital model "EvrazrudaKrep", which is based on the results of the analysis of guidelines and instructions of the institutes such as All-Russian Research Institute of Mining Geomechanics and Survey, East Research Institute of Ore Mining, Mining Institute of Siberian Branch of Russian Academy of Science, T.F. Gorbachev Kuzbass State Technical University, as well as the mine working support experience in Russia and abroad, allows to quickly solve the problem of choosing a support and improving mining safety in complex mining and geological conditions.

1 Introduction

There are Temir-Telbes (Kaz, Kemerovo Region, Western Siberia, Russia) and Kondoma groups of iron ore deposits in Gornaya Shoria. The most promising are Kondoma group deposits - Tashtagol and Sheregesh (Fig. 1) [1].

In Tashtagol, stoping operations have reached a depth of 700 m, development works have reached 900 m and are carried out on five levels (–70)÷(–350) m, sinking operations are carried out on six levels of the mine. In the course of the year, more than 1,000 m of permanent workings, more than 2,000 m of development workings and about 3,000 m of entries are sunk, 2.5-3 million tonnes of ore are mined.

Mining operations at Sheregesh deposit are carried out at six levels of the mine (+525) – (+115) m. Stoping operations have reached a depth of 470 m, development works - 600 m.

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During the year, more than 2,000 m of development workings and more than 12,500 entries are sunk in the deposit. Up to 4.6 million tons of ore are mined [2, 3].

Deposits are classified as liable to rock-bumps [4].

It was found by the research of East Research Institute of Ore Mining that the maximum main stresses in Tashtagol and Sheregesh deposits have north-west direction and are 2.5-3 times greater than the roof strata weight γH.

In the course of the year, there are 3-4 bulk blasts with seismic energy of 10^8-10^9 J in the mines [2, 5].

Under these conditions, the choice of an effective type of mine working support during the sinking cycle, taking into account its subsequent operation, is the most important task for ensuring the required safety of geotechnology for mining iron ore deposits in Gornaya Shoria [6, 7].

2 Development of a digital model for the selection of mine working support

Long-term practice shows that the basic variables affecting the choice of a support are: the stability of rock and ore masses, the hardness factor *f* according to the Protodyakonov scale of hardness, the structural weakness rate K_{sw}, the average distance between fractures L_{av}, the size of the zone of inelastic strain of rock mass around a mine working l_B.

The stability of rocks and ores is determined by the strength characteristics of rock types, the intensity of fracturing and the original stress state of rock mass [8].

The original parameters are determined by the geological survey. The main changes in rock and ore fracturing, the propagation of joint systems, and their association with certain rock types are established. The degree of stability in disjunctive fault lines is due to the zones of crushing, shear, and foliation. Fault zones with poor case-hardening (clay material, carbonates, iron hydroxides, chlorite) are particularly hazardous (unstable).

When documenting by the geological service, it is necessary to identify areas of rock mass weakening associated with actively manifested superimposed carbonization processes and low-temperature hydrothermal metamorphism (carbonatization, chloritization, seritization, hematitization, and iron hydroxiding). It should be noted that silicification does not reduce the stability of rocks.

The stability of rock mass around a mine working is directly dependent on fracturing of rocks and ores. The main types of joint systems are continuous, discontinuous and chaotic. All fractures, dividing rock into blocks, ranging in size from ten centimeters to several meters, should be taken into account. Tine fractures within the block are not taken into account. To assess fracturing, it is necessary to determine the parameters of the main joint systems — width, type of filling (if any), angle of incidence [8]. By type of filling fractures are divided into three types:

– tight and welded fractures, fractures with quartz and quartz carbonate filling;

– fillings are products of low-temperature hydrothermal dynamo-metamorphism (chlorite, sericite, carbonate, hematite, iron hydroxides);

– fractures in fault lines with clay gauge; fractures in crushing zones with poor case-hardening (clay material, especially the watered one) and fractures in shear, and intensive foliation zones with milonitization and polish faults.

The effect of fracturing on the stability of rock mass around a mine working is taken into account by means of the structural weakness rate K_{sw} and the average distance between fractures L_{av}.

Several (at least 2-3) joint systems are found almost throughout the mine-take. The number of joint systems is determined in the face in three different segments horizontally and vertically in 2-3 m long segments, depending on the cross-section of working. The av-

erage distance between fractures is determined by the formula

$$L_{av} = \frac{1}{6}\left(\frac{L_1^h}{n_1^h} + \frac{L_2^h}{n_2^h} + \frac{L_3^h}{n_3^h} + \frac{L_1^v}{n_1^v} + \frac{L_2^v}{n_2^v} + \frac{L_3^v}{n_3^v} \right) \qquad (1)$$

where L_1^h and L_1^v – the distance between the extreme fractures in horizontal and vertical segments, m; n_1^h and n_1^v – the number of fractures in the horizontal and vertical segments.

As a rule, the average distance between fractures is taken according to the most intense fracturing.

Fracturing measurements are taken for all rock and ore types with a distance between areas of no more than 30-40 m along strike. Additional measurements are made in various structural units. The results of measurements are recorded in the book in the following form (Table 1).

Table 1. The measurement recording book.

Segment referencing	Rock, ore character-istic	The results of measurements											
		L_1^h	n_1^h	L_2^h	n_2^h	L_3^h	n_3^h	L_1^v	n_1^v	L_2^v	n_2^v	L_3^v	n_3^v

For example, ores and rocks of the Sheregesh deposit are characterized by the following fracture intensity parameters (Table 2).

Table 2. Rock and ore fracturing classification.

Mass fracture intensity	L_{av}, m	K_{sw}
Intensive fracturing	до 0,1	≤0,1
High fracturing	0,10–0,20	0,1–0,2
Medium fracturing	0,20–0,50	02–04
Below-medium fracturing, mostly tight fractures	0,50–0,60	0,5–0,7
Low fracturing, sparse tight fractures or lack thereof	>0,60	0,8–1,0

The changeover of the mines of Gornaya Shoria to mining ore bodies at great depths and classifying of parts of the deposits as burst-prone and liable to rock bumps caused the need to solve fundamentally new problems of the conditions of using different support types and systems [9, 10].

According to the deposits, there are workings that are outside and within the zone of stoping influence. Depending on the location of workings relatively to the direction of action of the main components, the stress field and the stability of workings will differ.

The original stress state of rock mass in quantitative terms is characterized by the values of vertical and horizontal stresses - along strike and transverse.

The deposits are characterized by gravitational and tectonic stress fields, in which the values of the horizontal stress components are greater than those of the vertical ones. These stresses are established in iron ore deposits (Table 3). In addition, each field has its own azimuth of the main horizontal stress component $A_{\sigma.max}$ [11].

Table 3. Parameters of gravitational and tectonic stress field in the deposits of Gornaya Shoria

Deposit	Outside the zone of stoping influence				Within the zone of stoping influence			
	σ_1	$\sigma_2 = \sigma_{max}$	σ_3	$A_{\sigma.max}$, degrees	σ_1	$\sigma_2 = \sigma_{max}$	σ_3	$A_{\sigma.max}$, degrees
Kaz	0,4 γH	2,4 γH	γH	85	2,5 γH	3,7 γH	γH	85
Tashtagol – to a depth of 890 m below 890 m	1,3 γH 1,8 γH	2,5 γH 3,0 γH	γH γH	320 350	3,5 γH	5 γH	γH	50
Sheregesh	1,4 γH	2,6 γH	γH	330	3,8 γH	5,2 γH	γH	48

The strength of enclosing rocks surrounding the mine workings is determined by effective tangential shearing stress.

Tangential shearing stress in the walls and the roof of workings can be found from the expression [11]:

$$\tau_{av} = 0{,}5\left(\sigma_{//} - \sigma_{\perp} + 2\frac{a_w}{h_h}\sigma_{//} \right) \qquad (2)$$

where $\sigma_{//}$, $\sigma_{\perp}$ – the value of the horizontal component of stress in rock mass, acting along and perpendicular to the axis of a working; a_w – width of working, m; h_h – height of a working, m.

In the case when the direction of a working coincides with the direction of the maximum horizontal component of stress, tangential stresses in the roof and the walls of a working are calculated respectively from the expressions

$$\tau_{av}^{r} = 0{,}5\left(\sigma_1 - \sigma_2 + 2\frac{h_h}{a_w}\sigma_1 \right) \qquad (3)$$

$$\tau_{av}^{w} = 0{,}5\left(\sigma_2 - \sigma_3 + 2\frac{a_w}{h_h}\sigma_3 \right) \qquad (4)$$

When the direction of a working coincides with the direction of the minimum horizontal component σ_1, tangential stresses in the roof and the walls of a working are calculated respectively from the expressions

$$\tau_{av}^{r} = 0{,}5\left(\sigma_2 - \sigma_3 + 2\frac{h_h}{a_w}\sigma_2 \right) \qquad (5)$$

$$\tau_{av}^{w} = 0{,}5\left(\sigma_2 - \sigma_3 + 2\frac{a_w}{h_h}\sigma_3 \right) \qquad (6)$$

where σ_1 – the minimum horizontal component of stress; σ_2 – the maximum horizontal component of stress, σ_3 – vertical component of stress; $\sigma_3 = \gamma H$.

Tangential shearing stress in the roof and the walls of workings located at an angle to

the maximum horizontal component of stress is obtained by the formula

$$\tau_{av} = \sqrt{\frac{\tau_{min.av}^2}{1 - \varepsilon_э^2 \cos^2}} \tag{7}$$

where $\tau_{min.av}$ – the minimum tangential shearing stress in the roof and in the walls of working; ε – eccentricity – geometrical locus; θ – the angle between the maximum horizontal component of stress and the axis of a working, measured from 0 to 90°.

Eccentricity is determined separately for the roof and the walls of a working from the ratio

$$\varepsilon^2 = 1 - \frac{\tau_{min.av}^2}{\tau_{max.av}^2} \tag{8}$$

where $\tau_{max.av}$ – tangential shearing stress in the roof and in the walls.

In the case when the width of a working is equal to its height, the minimum effective shearing stress for workings located at an angle to the minimum horizontal component of stress is defined as

$$\tau_{av} = \tau_{max.av} \cos(\theta) \tag{9}$$

The stability factor of mine workings is determined:
for the roof by

$$K_{stab} = \sqrt{\frac{[\tau_{av}]}{\tau_{av}^r}} \tag{10}$$

for the walls by

$$K_{stab} = \sqrt{\frac{[\tau_{av}]}{\tau_{av}^w}} \tag{11}$$

where $[\tau_{av}]$ – the ultimate shearing strength of enclosing rock, $[\tau_{av}] = K_{sw} [\sigma] \mu$; τ_{av}^w – the effective shearing stress in the roof of a working; τ_{av}^w – the effective shearing stress in the walls of a working; $[\sigma] = f \times 10$, MPa – the uniaxial compression strength of enclosing rock; μ – Poison's ratio; K_{sw} – the structural weakness rate. The K_{sw} value is determined by the distance between fractures (Table 4).

Table 4. The dependence of the structural weakness rate K_{sw} on rock (ore) fracturing L_{av}.

The distance between fractures L_{av}, m	The structural weakness rate K_{sw}
>1,5	0,9
1,5–1,0	0,8
1,0–0,5	0,6
0,5–0,2	0,4

After calculating the rock (ore) stability factor, the category of rock stability (Table 5), the design and parameters of mine support are determined.

Table 5. The category of rock (ore) stability.

Rock stability factor	Stability degree	Category of stability
>1	strongly stable	I
1,0–0,65	stable	II
0,65–0,45	medium stable	III
0,45–0,25	unstable	IV
>0,25	strongly unstable	V

When choosing a support, it is necessary to consider the category of rock-bump hazard in the deposit. According to the level of rock-bump hazard, the deposits or rock mass areas around workings are divided into two categories: "Hazard" and "No hazard". The category "Hazard" corresponds to the stress state of rock mass around a mine working, at which a rock bump may occur. The category "No hazard" corresponds to a non-hazardous state and does not require measures against rock bump.

3 Results

Based on many years of research and methodological analysis of the interrelationships of parameters during sinking and operation of mine workings under conditions of stress-strain state and rock bump hazard of iron ore deposits in Gornaya Shoria, the multi-factor digital model "EvrazrudaKrep" was developed to select the type of support and its possible detachment depending on the deposit depth, the categories of rock mass stability and the cross-section of a working [12] (Fig. 1)
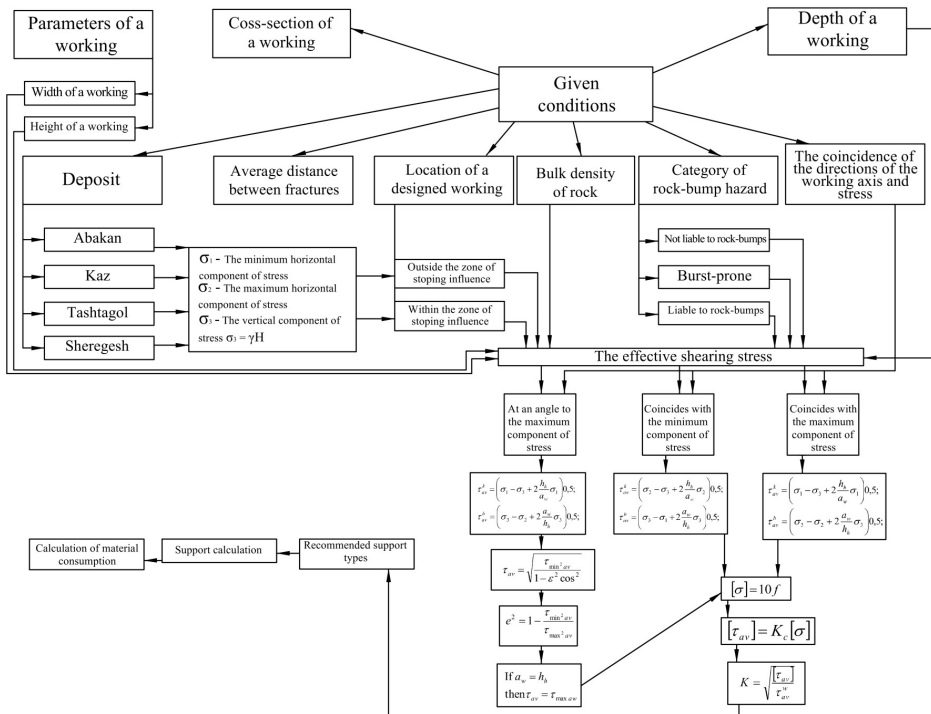

Fig. 1. The multi-factor digital model "EvrazrudaKrep".

The multi-factor digital model "EvrazrudaKrep" is based on the results of the analysis of recommendations and guidelines of the institutes such as All-Russian Research Institute of Mining Geomechanics and Survey, East Research Institute of Ore Mining, Mining Institute of Siberian Branch of Russian Academy of Science, T.F. Gorbachev Kuzbass State Technical University, as well as the experience of using different support types in the Gornaya Shoria mines and other iron ore deposits, including foreign ones. The stability of rocks and ore is determined by the method developed by Siberian Branch of Russian Academy of Science, as it takes into account the stress state of rock mass of a particular deposit. This is a very important factor, because a decrease in the stability of workings is associated with a high level of effective stresses in deep levels being worked out, increased by bearing pressure, increased rock bump hazard of rock mass, which ultimately leads to an increase in the cost of maintaining them.

4 Conclusions

For automated designing of the support construction, electronic models of fastening of mine working supports, mine support systems (cross-section and longitudinal sections, lining units, materials and consumption of materials) were developed. The electronic layout of the support construction design includes: a title page, a sheet - a list of persons informed of and acknowledged; mining geotechnical and engineering data and a report on the rock bump hazard of rock mass, necessary for the automated search for a rational support option; printout results of processing the specified conditions by the "EvrazrudaKrep" program, graphic material.

Using this program, "Methodological guidelines for mine working support and support state monitoring at the "Evrazruda" mine were developed and put into effect by order No. 305 of April 25, 2013 [11]. The manual allows to quickly address the issues of choosing the mine support system in changing mining geological and geodynamic conditions when driving a working, as well as to improve the safety of sinking operations when mining rock-bump hazardous iron ore deposits of Gornaya Shoria.

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