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Provision of Stability of Development Mining at Yakovlevo Iron Ore Deposit

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Abstract:

This article discusses solution of urgent problem of stability provision of development mining at Yakovlevo iron ore deposit (Russia) by means of selection and determination of types and rational parameters of support on the basis of theoretical and experimental studies described here. In order to characterize the state if static stability of unsupported mining we propose the stress criterion of mining elements (roof and sidewalls), on the basis of which the categories are highlighted characterizing possible stability states of mining rocks and forms of rock pressure manifestation. Depending on the value of stability criterion of mining outcropping the recommendations have been developed on selection of types and parameters of support of development mining in ore body.

Keywords: deposit, mine, iron ore, ore body, development mining, stability estimation.

INTRODUCTION

Yakovlevo iron ore deposit is one of the largest in terms of proven resources of premium ores with pure iron content in the ore up to 70% and low content of harmful impurities (sulfur, phosphorus, etc.).

The deposit is characterized by complex hydrogeological and mining conditions. Thick steep deposit is comprised of (up to 50%) loose and semi-loose ores with uniaxial compression strength from 0.3 MPa to 3 MPa and existence of high pressure water bearing strata.

The deposit structure is synclinal fold, the west wing of which coincides with Yakovlevo tape of ferrous quartzite. Inclination of strata, forming the deposit, is north–eastward, monoclinal, the dip angle is 60-70º, the strike is north–westward at the azimuth angle of 320º.

Rich iron ores are product of weathering of ferrous quartzite. The form continuous sheet-like deposits with the width in the range from 200 m to 600 m. Their thickness varies from 20 m to 250 m and even higher.

The ore deposit is of varied configuration. Carbonatization occurring in the ore deposit results in development of dense hard ores coinciding with upper part. The zone of loose ores spreads mainly in the thickest mineralization areas in middle part of the deposit.

The deposit sidewall is comprised of phyllitic quartz–sericite chlorite–sericite shale, the footwall is comprised of sediments of sand/shale series. Vast field of plagiogranite is located in the deposit footwall в.

Folded structures with rock discontinuity are distinctly observed in hanging (eastern) wall of Yakovlevo deposit. The fractures are of oblique-slip fault type and form numerous crushing zones. In south–east the structure is complicated by tectonic disturbances. The rich iron ores are characterized by intensive jointing, deconsolidation and loading-out, leading to loss in mining stability [1-5].

The rock inrush in development mining is illustrated in Figs. 1 and 2.

Taking into account the complicated essence of hydrogeological and mining conditions, an urgent problem is provision of stability of development mining in ore body at all stages of mining operations.

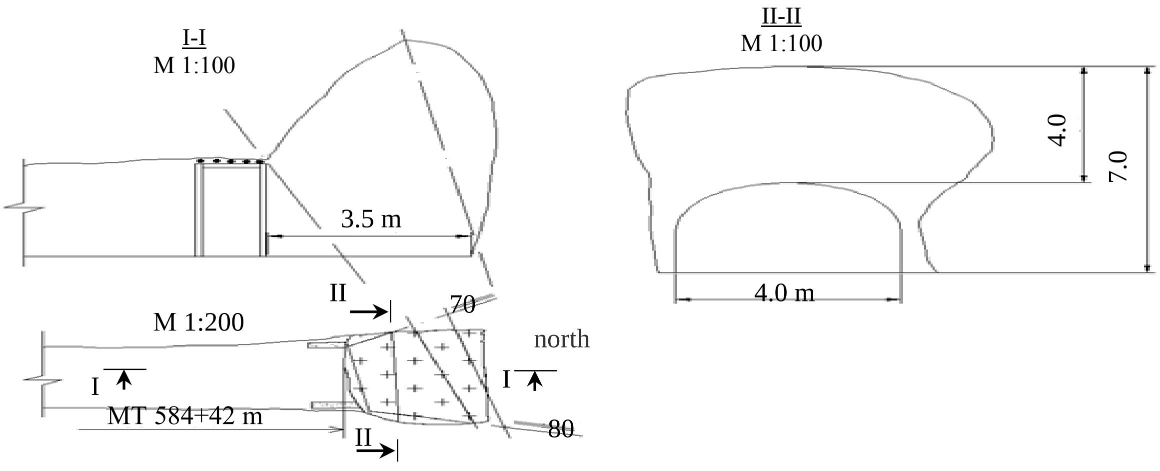

Figure 1. Schematic view of rock inrush generation in haulage crosscut No. 7, level: 425 m.

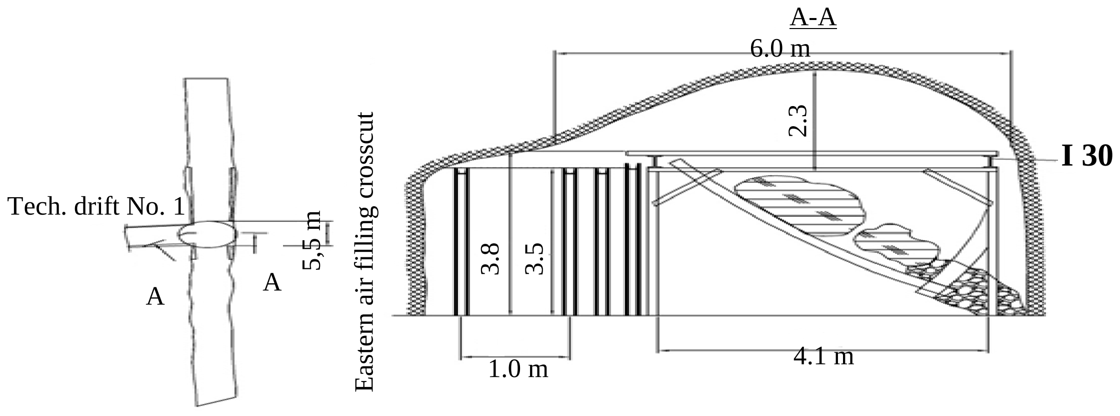

Figure 2. Schematic view of rock inrush at junction of eastern air-filling crosscut and technological drift No. 1 (Level: 370 m)

In this regard estimation of stability of ore outcropping and reasonable selection of types and parameters of mining supports corresponding ti geological and mining conditions of the deposit is highly important problem.

EXPERIMENTAL

Aiming at estimation of mining at Yakovlevo deposit the experts of Saint Petersburg Mining University (hereinafter referred to as Mining University) together with surveying group of Yakovlevo deposit, OOO Metal-Group developed procedure and examined the state of mining using the simples instrumental observations [6].

The acquired data were summarized as follows:

- designation and purpose of mining, inner dimensions, operation lifetime, depth (level) from surface, layout with regard to ore body, its boundaries and finished mining, inclination angle and orientation of mining;
- properties of ore body at the mining site;
- data on forecasted dynamics of formation of influence cone at the mining site including its operation lifetime;
- mining data on ore body were supplemented by data on variety of ores and intermediate rocks along the mining route, distances from mining to rocks of footwall and sidewall along normal, as well as data on geological structures capable to create load-out effect at mining site in the field of natural vertical and horizontal stresses;
- data on field mining located in ore contact zones of footwall and sidewall with ore body were supplemented with data on distance from mining site to contact of ore body with rocks.

While summarizing the information, the data on physicomechanical properties of rocks and ores were based on generalized values obtained at different times upon development of Yakovlevo deposit by VIOGEM, VNIMI institutes, Mining University and geological service of the deposit (Table 1).

Table 1. Physicomechanical properties of rich iron ores for deposits of Kursk Magnetic Anomaly

Rocks			Natural moisture, %	Density of mineral portion, g/cm3	Density, g/cm3	Matrix density, g/cm^3	Porosity, %	Porosity index	Ultimate compressive strength, MPa kgf/cm^2
Rich iron ores	Residual, weathering crust	Hard rock, solid	0.40-5.53	3.80-4.22	3.49-5.10	3.37-3.76	≤ 16.72	≤ 0.128	65.4-357.1 654.0 -3571.0
		Hard rock, weak	3.26-7.00	3.53-4.94	2.43-3.67	2.95-3.50	8.90-25.34	0.197-0.411	20.7-29.8 206.9-298.5
		Semi-rock	6.00-15.00	3.20-4.62	2.99-4.00	2.64-3.29	21.00-36.00	0.212-0.404	3.4-8.7 34.1-87.0
		Semi-loose and loose	14.13-44.00	3.83-5.50	2.40-3.50	2.32-3.17	28.20-57.00	0.651-0.735	0.1-1.2 1.0-12.1

	Sedimentary, redeposited	Hard rock, solid	2.00-4.54	3.93-4.11	3.64-3.93	3.47	2.20-16.31	0.093-0.101	$\frac{84.3-125.2}{843.0-1252.0}$
		Hard rock, weak	6.00-7.96	3.40-4.99	2.77-3.31	2.50-3.10	7.40-26.56	0.360-0.610	$\frac{14.9-29.8}{148.9-298.0}$
		Loose	-	4.00-4.04	2.85-2.90	-	29.60	-	-

The strength of rich iron ores significantly depends on stratification and water saturation. Coefficients of correction of physicomechanical properties upon water saturation are summarized in Table 2 [7]. The calculations should be based on the minimum value of strength of ores and rocks in Tables 1 and 2.

Table 2. Coefficients of correction of physicomechanical properties of rich iron ores upon water saturation * (data by Mining University)

Type of rich iron ores	Ultimate compressive strength, $R_{\text{comp,}}$ MPa		Shear strength parameters				Young modulus, MPa	
			across stratification		along stratification			
	across stratification	along stratification	cohesion, MPa	internal friction angle, degrees	cohesion, MPa	internal friction angle, degrees	across stratification	along stratification
In natural state								
Semi-loose	$\frac{1.94-4.59}{3.26}$	3.03	$\frac{0.40-1.4}{0.95}$	$\frac{18-34}{25}$	-	-	$\frac{200-878.3}{444.8}$	-
Loose*	$\frac{1.23-2.16}{1.5}$	$\frac{0.43-0.72}{0.61}$	$\frac{0.41-0.72}{0.5}$	23	$\frac{0.15-0.25}{0.18}$	20	$\frac{20-45}{31}$	-
In water saturated state								
Semi-loose	$\frac{1.43-3.33}{2.4}$	2.23	$\frac{0.28-1.00}{0.66}$	$\frac{10-19}{14}$	-	-	$\frac{64.0-204.0}{102.5}$	-
Loose	$\frac{0-1.26}{0.61}$	$\frac{0-0.64}{0.42}$	$\frac{0-0.53}{0.22}$	0-9	$\frac{0-0.28}{0.16}$	0-8	$\frac{8.5-23.5}{10.1}$	-
Coefficient of decrease in strength and strain properties of ores upon water saturation, $\xi_{\hat{a}}$								
Semi-loose	0.74	0.74	0.69	0.56	-	-	0.23	-
Loose	0.4	0.68	0.45	0.39	0.88	0.4	0.32	-

* - The coefficients define the ratio of the parameter of water saturated sample to that in natural state.

While estimating the mining stability the coefficient of structural loosening K_c of host ores and rocks was determined in accordance with Regulations SNiP II-94-80 by data of quantitative analysis of fracturing of ore body in the places of designed mining positions on the basis of engineering and geological survey with regard to levels of ore loosening [8].

Table 3 summarizes the data on K_c values proposed by VIOGEM, SNiP II-94-80 and recommended by Mining University for estimation of stability of rock and ore outcropping.

Table 3. Coefficients of structural loosening of ores and rocks between the levels 370 m and 425 m (data by VIOGEM)

Designation of ores and rocks	Size of structural blocks, m	VIOGEM	SNiP II-94-80	Recommended	
				Drilling and blasting	Mining machine
Iron mica martite ores and martite ores, loose	< 0.1	-	0.2	0.3	0.4
Iron mica martite ore, chloritized, medium density	0.1	0.13	0.4	0.4	0.6
Chlorite limonite martite ore, dense	0.13	0.15	0.4	0.5	0.7
Iron mica martite ore, carbonatized, dense	0.2	0.22	0.4	0.5	0.7
Hydrohematite martite ore, fine, hard	0.25	0.3	0.4	0.5	0.7
Chlorite sericite ferrous shale	0.2	0.2	0.4	0.4	0.7
Ferrous quartzite, martite iron mica	0.42	0.3	0.4	0.6	-
Granitic rocks	0.6	-	0.6	0.6	-
Weathered granitic rocks	0.4	-	0.4	0.4	-
Phyllite, aleurolite	0.4	-	0.4	0.4	-

Note: numerator – variation range; denominator – average.

Upon determination of the properties of stressed state of ore body the vertical stresses in footwall and sidewall should be calculated as follows:

$$\sigma_V = K\gamma H \qquad (1)$$

where: γ is the average rock density up to ground level, MN/m^3; H is the mining depth from ground level, m; K is the coefficient of concentration of vertical stresses in ore body (Table 4).

The horizontal stresses in footwall and sidewall are calculated as follows:

$$\sigma_H = \lambda \sigma_V , \qquad (2)$$

where λ is the coefficient of horizontal stress determined experimentally or by the equation:

$$\lambda = tg^2 \frac{90 - \varphi}{2} , \qquad (3)$$

where φ is the angel of internal friction.

Table 4. Coefficients of concentration K of vertical stresses in ore body

Level		Horizontal distance from contact with ore body, m				
		0	10	20	30	50
-365 м	footwall	1.22	1.15	1.1	1.0	1.0
	sidewall	1.5	1.4	1.3	1.1	1.0
-425 м	footwall	1.15	1.1	1.05	1.0	1.0
	sidewall	1.53	1.4	1.3	1.1	1.0

The vertical and horizontal stresses in ore body were determined experimentally or by mathematical simulation with consideration for decrease in natural stresses due to dewatering of ore body and its loading-out by host rock bodies.

RESULTS

On the basis of computer aided simulation of stress–strain state of ore body the values of vertical and horizontal stresses were obtained for the levels: – 365 m, - 425 m (Fig. 3). The problem was solved in plane (2D) variant with accounting for own weight of dewatered ore body [9-12].

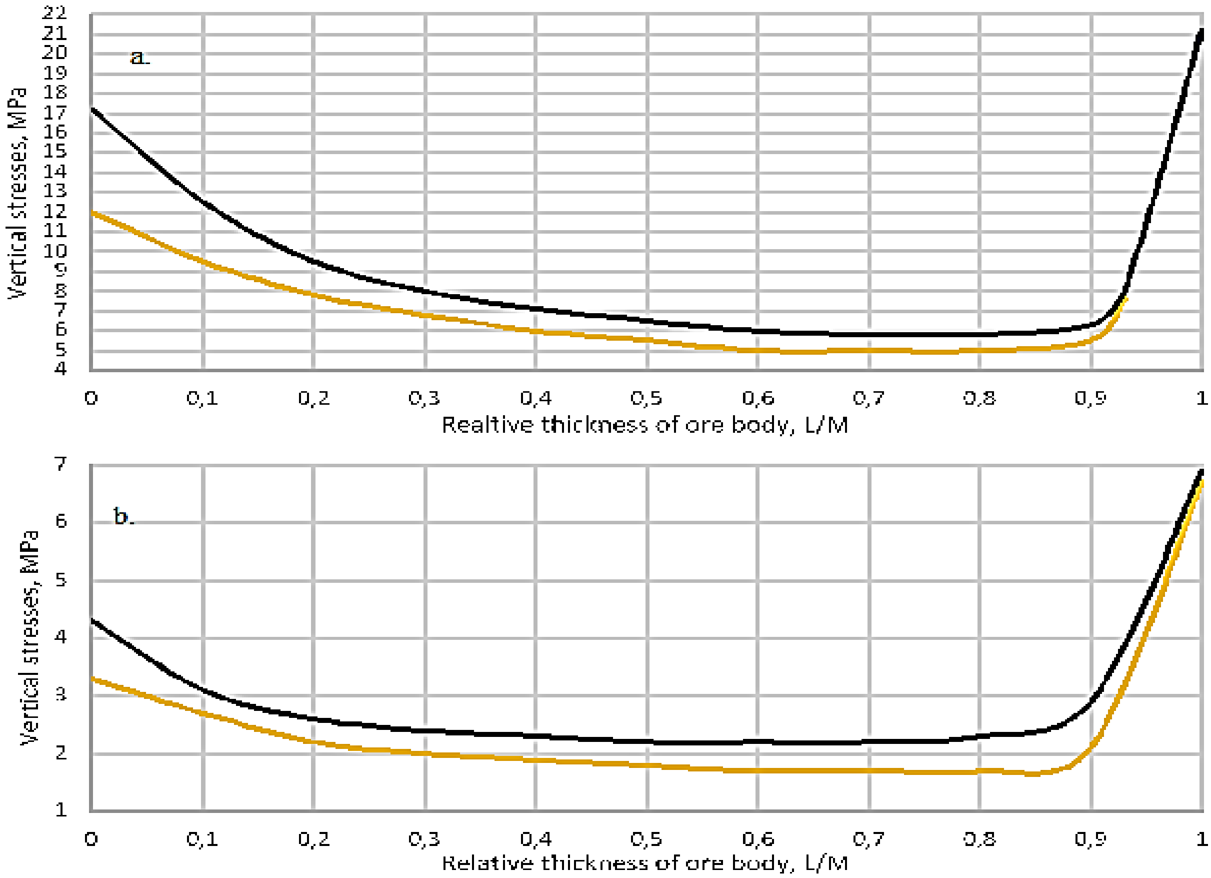

Figure 3. Distribution of vertical (a) and horizontal (b) stresses in ore body of Yakovlevo mine: — - level: 365 m; — - level: 425 m. L – horizontal distance from footwall to sidewall, m; M – horizontal thickness of ore body, m.

It was proposed to estimate the state of static stability of unsupported mining by stress criterion of mining elements (roof and sidewalls), expressing the ratio of calculated stresses (numerator) to calculated strength (denominator) [13-15]:

$$\Pi_{\mathrm{m}} = \frac{\sigma \cdot K_1 \cdot K_2}{R \cdot K_c \cdot \xi_{\mathrm{w}}}, \qquad (4)$$

where σ is the vertical and horizontal stresses in ore body at mining site, MPa;

K_1 is the coefficient of stress concentration as a consequence of mining (Table 5);

$K_2 = K_2^{'} \cdot K_2^{''}$ is the coefficient of variation of stresses as a consequence of influence of other mining $K_2^{'}$ and second working $K_2^{''}$ (Table 6);

R is the average value of resistance against uniaxial compression upon short term loading, MPa (Tables 1 and 2);

K_c is the coefficient of structural loosening of ore body due to natural and technogenic fracturing, stratification and microheterogeneity upon drilling and blasting and machine mining (Table 3);

ξ_w is the coefficient considering for decrease in ore and rock strength due to water saturation equaling to the ratio of ultimate strengths in water saturated and natural states (Table 2).

The K_1 values for mining of ridge type in cross section are summarized in Table 5. The given values of K_1 should be increased by 0.1 for mining of trapezoid and square angled configuration of cross section.

Table 5. Coefficients of stress concentration (K_1)

Designation of rocks and ores	Square-angled ridge and ridge	
	walls	roof
Quartzite, shale	1.8	1.5
Hydrohematite ores	1.33	1.25
Martite loose ores	1.25	1.15
Iron mica martite ores, loose	1.25	1.15
- medium dense and dense	1.35	1.25

The coefficient of stress concentration $K_2^{'}$ due to mutual influence of parallel mining sites is determined as a function of distance between the mining sites and their normalized diameter (Table 6) [16].

Table 6. Coefficients of stress concentration $K_2^{'}$

Ratio of distance between the mining centers to normalized mining diameter $2R_0$	1.25	1.5	2.0	2.5	3.0	3.5
Coefficient $K_2^{'}$	1.8	1.45	1.2	1.1	1.07	1.05

The normalized radius for mining sites of non-circular configuration is as follows:

$$R_0 = \sqrt{\frac{S_{\text{sink}}}{\pi}}, \quad (5)$$

where S_{sink} is the surface area of mining cross section in sinking, m^2.

The coefficients of stress concentration $K_2^{'}$ at junctions of horizontal mining sites determined with accounting for deformation non-linearity of ore body are summarized in Tables 7 and 8.

The distance between the axes of oblique angled mining hunctions (Fig. 4, a; Table 8) is:

$$m = l \cdot \sin\alpha , \quad (6)$$

where α is the angle between the axes of mining junctions; l is the mining length from junction center to the considered cross section.

The zone of mutual influence of mining sites for square-angled junction is $L_0 = 4R_0$, and for oblique angled junction is $L_0 = 4\,R_0/\sin\alpha$, where R_0 is the normalized radius of mining junction (Fig. 4).

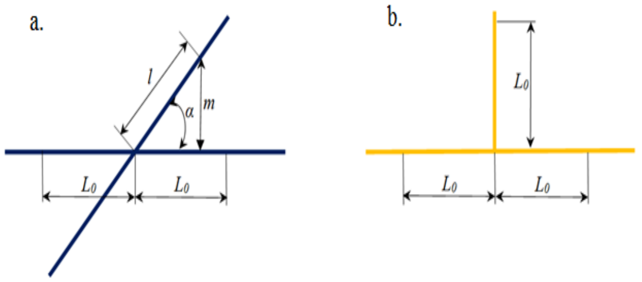

Figure 4. Schematic view of mining junctions: a – unilateral oblique angled; b – unilateral square angled.

Table 7. Coefficients of stress concentration $K_2^{'}$ in sidewalls of square-angled junction

Distance between axes of mining junction in the area of their mutual influence (in fractions of normalized radius of influencing mining)	Junction type	
	Unilateral	Bilateral
1.0	1.33	1.49
1.5	1.19	1.29
2.0	1.13	1.19
3.0	1.08	1.1
4.0	1.05	1.08

Table 8. Coefficients of stress concentration $K_2^{'}$ in sidewalls of oblique-angled junction

Distance between axes of mining junction in the area of their mutual influence (in fractions of normalized radius of influencing mining)	Junction type	
	Unilateral	Bilateral
1.0	1.42	1.63
1.25	1.31	1.47
1.5	1.24	1.37
1.75	1.20	1.30
2.0	1.17	1.25
3.0	1.10	1.15
4.0	1.07	1.10

The coefficient K''_2, considering for support pressure in the area of influence of second working, are determined by several factors: mining position with regard to second working front, distance of mined-out space, strength and deformability of ore body, structure of roof rocks, existence of dead zones, and others.

The K''_2 values should be selected by experimental data, and if they are unavailable for mining in one layer of ore body, according to Table 9.

Table 9. Coefficients of stress concentration K''_2 as a function of influence of second working

Distance between center of second mining to the considered cross section of mining (in fractions of normalized radius of second mining)		1.0	1.25	1.5	1.75	2.0	2.5	3.0
Mining areas	roof	1.28	1.15	1.07	1.02	1.0	1.0	1.0
	sidewalls	1.33	1.25	1.19	1.16	1.13	1.1	1.08

The Π_m value was determined separately for mining roof and sidewalls, possible condition of stability and rock pressure manifestations were estimated (Table 10) [17].

Table 10. Stress intensity criterion of mining element Π_m and possible states of rock stability of mining

No.	Π_m, category and state of rock stability	Models of body deformation and rock stability in un-supported mining
1.	$\Pi_m<1.0$ Category I - stable state	Prelimit linear and non-linear deformation. Mining contour is stable, possible occurrence of single flaws and inrushes.
2.	$\Pi_m=1.0\div1.3$ Category II - limit state	Near-contour area of body transfers into limit state.
3.	$\Pi_m = 1.3 \div 3.0$ Category III - unstable state	Areas of non-elastic deformations are formed around mining sites.
4.	$\Pi_m > 3.0$ Category IV - highly unstable state	Areas of non-elastic deformations and rock cavities are formed around mining sites

DISCUSSIONS

Taking into consideration possible forms of rock pressure manifestation for different categories of mining stability, rational configurations of cross section were recommended. In hydrohematite ores and ore body it is recommended to apply square-angled ridge and ridge configuration of mining cross section [18,19].

In ore body the square-angled configuration of mining cross section is selected. Optimum ratio of ridge height to its width in ores of natural humidity should be selected in the range from 0.42 to 0.46; in water saturated ores to 0.68. Such ratios were obtained on the basis of field observations of stability of mining contour in rich ores.

Development mining, which according to procedures of preparation of mining site are intended for cutting of drilling stations of crosscut, are allowed for processing by trapezoid cross section. The trapezoid configuration simplifies support designs for junctions with stations and crosscuts.

In host rocks the configuration of cross section of field mining is square-angled ridge with lowered ridge, its height is *1/3* of its width. The ridge curvature radii depend on the mining width B: for central arch $R=0.64B$, for side arches $r=0.26B$ [20].

On the basis of data analysis of field observations obtained upon surveying of mining conditions with consideration for strength, structure and deformation properties of Yakovlevo deposit the recommendations on selection of type and parameters of supports of development mining were developed for various stability categories of outcroppings, see Table 11.

Table 11. Types and parameters of supports of development mining in ore body

No.	Π_m, category and state of rock stability	Types and parameters of permanent support
1.	$\Pi_m<1.0$ Category I - stable state	1. Permanent support is not required. Regular inspections of mining state with roof cleaning in the areas of flaw occurrences. 2. At the sites of possible flaw occurrence: rock bolting, Swellex or SPSh rock bolts, 1.8 m in length with pad plates and metallic mining mesh. Bolting mesh: from 0.9×0.9 to 1.1×1.1 m.
2.	$\Pi_m=1.0\div1.3$ Category II - limit state	1. Roof bolting with metallic mining mesh at mining roof and sidewalls. Swellex or SPSh rock bolts, 1.8 m in length with pad plates and metallic mining mesh. Bolting mesh: from 0.7×0.7 to 1.0×1.0 m. The distance from lower row of bolts to mining ground up to 1.2 m. 2. Metallic arched compressible support, KMP-AZ type, SVP profile with metallic mining mesh and backfilling of near-support space. Arch step: 1.0 m. 3. Metallic frame trapezoid support, SVP, with metallic mining mesh, A-P, A- III0 10 + 12 mm. Frame step: 0.75 m.
3.	$\Pi_m = 1.3 \div 3.0$ Category III - unstable state	1. Metallic arched compressible support, KMP-AZ type, SVP-22 and SVP-27 profile with metallic mining mesh and backfilling of near-support space. Arch step: 0.75 m to 1.0 m. 2. Metallic frame trapezoid support, SVP-22 and SVP-27, metallic mining mesh at mining roof and sidewalls. Frame step: 0.5-1.0 m. 3. Integrated roof bolting with boards and metallic mining mesh at mining roof and sidewalls. Swellex or SPSh rock bolts, 1.8 m in length. Bolting mesh: from 0.7×0.7 to 0.8×0.8 m. The distance from lower row of bolts to mining ground up to 1.0 m.
4.	$\Pi_m > 3.0$ Category IV - highly unstable state	1. Metallic arched support with welded metallic mining mesh and backfilling of near-support space. Protecting support. Distance between arches: 0.5-0.75 m. Support elements: SVP-22, SVP-27 with pad plates for legs. Inter-frame couplings (legs, cross bar). 2. Metallic arched support, SVP-22 and SVP-27, with welded metallic mining mesh and backfilling of near-support space. Protecting support. Frame step: 0.5 m. Pad plates for legs, 3-4 inter-frame couplings. 3. In the areas of tectonic disturbances, in the contact areas of loose and dense ores and in the areas of significant water inflow: metallic arched support with advance timbering.

The survey results of mining sites and calculations of stress criterion demonstrated good agreement between actual condition of mining sites and data in Table 11.

The obtained results were used for arrangement of Guidance on selection of type and parameters of supports of permanent and development mining at Yakovlevo deposit.

CONCLUSIONS

The obtained results were used for arrangement of Guidance on selection of type and parameters of supports of permanent and development mining at Yakovlevo deposit.

The Guidance has been approved and now it is used upon development mining at Yakovlevo iron ore deposit.

Field experience of application of the guidance demonstrated efficiency of the proposed engineering solutions on provision of stability of development mining and made it possible to reduce costs for supports as well as to improve mining safety.

The developed recommendations can be applied by companies performing design, construction and operation of underground mining of iron ore deposits; they can be practical for researchers and engineers involved in development of mining supports.

Further challenges of the work can include development of new and improvement of existing geomechanical approaches to estimation of mining stability of initially developed levels of rich iron ore deposits with consideration for variations in mining and hydrogeological conditions, as well as development of new support designs.

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