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Ensuring Sustainability of Preparatory and Permanent Mining Workings in Deep Mines of Bump-hazardous Deposits

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This article is focused on solving the urgent problems of ensuring sustainability of mining workings in deep mines of bump-hazardous deposits by selecting and defining the types and efficient parameters of timbering, based on the author's many years of theoretical and experimental studies in the mines of JSC "Sevuralboksitruda". In order to characterize the state of outcrops of loose mining workings, the criterion of strain of the roof and the sides of the working was proposed, on the basis of which the selected categories that characterize the stress-strain behavior of the outcrops of mine workings with regard to dynamic forms of rock pressure manifestation at great depths. Depending on the workings outcrops stability criterion, recommendations have been developed on types and parameters of earthquake-proof timbering.

Key words: Mine, mine workings, rock-bump hazardous deposits, earthquake-resistant timbering, criterion of stability, rocks massif, steel-and-polymer rod, drift size.

In recent years, a steady growth in aluminum consumption has been noticed in Russia and in the world market, associated with the development of a wide range of high-tech, knowledge-intensive branches of industry.

Increasing aluminum production requires intensive development of the resource base and developing more and more new deposits, usually at great depths in difficult mining and geological conditions. In Russia, the main resource base of the aluminum industry are the mines on the Northern Ural bauxite mine basin, where mining is performed at a depth of 900-1000 m, and design and development of new horizons at depths of as much as 2000 m is planned.

At great depths, mining and geological conditions of mining deposits get dramatically complicated, dynamic forms of rock pressure manifestations are increased[1-2].

However, selecting and determining the types and rational parameters of timbering with regard to geological and mining conditions, providing reliable maintenance of workings during the whole period of their operation, safety of mining operations and the regularity of enterprise operation pace become urgent.

To solve this problem, specialists of the Mining University in cooperation with employees of JSC "Sevuralboksitruda" (JSC "SUBR")

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performed many theoretical and experimental studies, which helped to develop the "Instruction on selecting timbering for preparatory and capital mining workings of JSC "Sevuralboksitruda".

Methodology

For describing the state of loose excavation outcrops, the instruction proposes the criterion of workings roof and sides (P_v) tension, which expresses the ratio of the calculated tensions acting on the elements of the working to the estimated strength of rocks (3,4):

$$P_v = \frac{\sigma \cdot K_1 \cdot K_2 \cdot K_3}{R \cdot K_c \cdot \xi_\partial} \quad (1)$$

where σ is the tension in an intact rock massif normally to the longitudinal axis of the working, MPa;

K1 is the coefficient of tensions concentration due to the working;

K2 =K'2·K"2·K"'2 is the rate of tension change: due to the influence of other working -s (K'2), tectonic disturbances (TD) - (K"2) and room work - (K"'2);

K3 is the coefficient of additional tensions concentration caused by dynamic phenomena in the massif;

R is the average resistance of the rocks in the sample top the monoaxial compression during short-time loading, MPa;

Ks is the coefficient of structural weakening of the massif due to fracturing and webbing;

ξd is the coefficient of reducing resistance of the rock under repeated dynamic loading due to weakening of ties along cracks and to the fatigue phenomena[5].

The tensioning is defined as the sum of static and dynamic tensions with regard to their concentration around the working, while the calculated strength takes into account the structural weakening of the massif due to fracturing and to the dynamic phenomena.

The source data for calculating stability of the workings outcrops and making passports for timbering therein were:

a) The name and the purpose of a working, its size, service life, depth from the surface, layout relative to the ore body, the azimuth of the direction (taken in accordance with the project of preparation of or opening of the horizon);

b) Properties of the rock massif in the area of the working: lithological types of rock and their varieties, the average resistance to monoaxial compression value the sample, characteristic of jointing, presence of stratification and clay layers, water-bearing nature and resistance to the factors of weathering, angle and azimuth of the fall, strength of layers (set), characteristics of tectonic disturbances with indication of the attitude;

c) Data of the regional and local forecasts of shock hazard of the part of the rock massif in consideration[6-8].

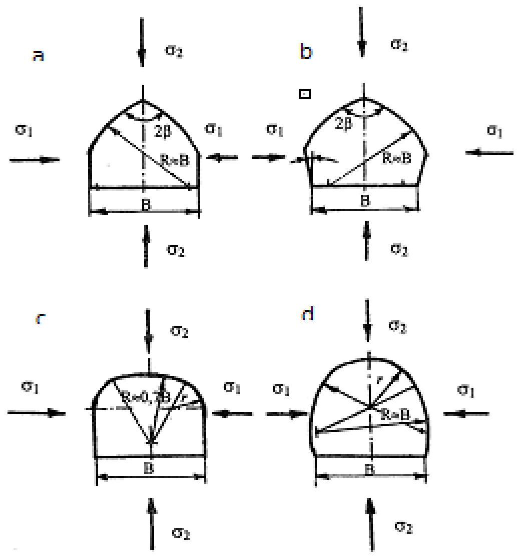
For workings made in the ore massif and the superincumbent bed, original data should be complemented with information about the structure and capacity of bauxite ore, its class and subclass of stability, textural-structural features.

The region experiences the non-equal-component stress field. The maximum principal stress (σ_{sh}) is oriented in the sublatitudinal direction with deviations of up to ± 250 from the horizontal plane, the minimum stress - in the submeridional (σ_m). The principal stress close to the vertical (σ_v) has an intermediate value. The ratio of σ_{sh}: σ_v: σ_m, according to the performed studies, is different for different mining fields[9].

The shape of working cross-section is chosen with regard to the orientation of the maximum strains in the rock massif and the excavation direction. In excavations made transversely to the direction of the maximum principal stress, the rectangular-tabernacular cross-sectional shape (Fig.1, a) is preferred if the vertical stress does not cause the limit condition in the walls of the working. Trapezoidal-tabernacular shape (Fig. 1, b) increases the stability of the walls[10].

In case of inclined (to the horizon) direction of the maximum principal stress in the massif, asymmetrical tabernacular (Fig. 2, a) or inclined ellipsoid (sectoral, Fig. 2, b, c) cross-sectional shapes are to be used, by placing the inclined axis of the tabernacle or of the sector at 90° ± 10° angle to the direction of maximum stress σ_{sh}. (11)

For the limit values of the stresses s_B, the shape of section (Fig. 2, c) is more effective in terms of resistance. In case of inclined bedding of the rock massif, it is advisable to make the working



a - rectangular-tabernacular; b - trapezoid - tabernacular; c - rectangular - domed; d - u-shaped

Fig.1. Reasonable shapes of workings cross-sections in vertical and horizontal direction of the principal normal stresses

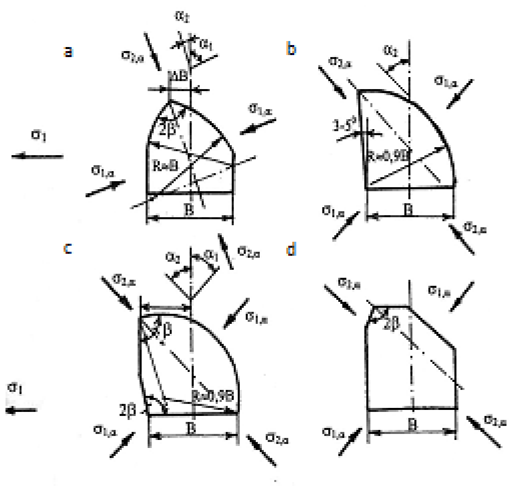


Fig. 2. Reasonable shapes of workings cross-sections in case of inclined direction of the principal normal stresses: a - rectangular-tabernacular asymmetric (Δ=0.1-0.3); b, c - sectoral (Δ=0.3 to 0.5); d - trapezoidal non-equilateral

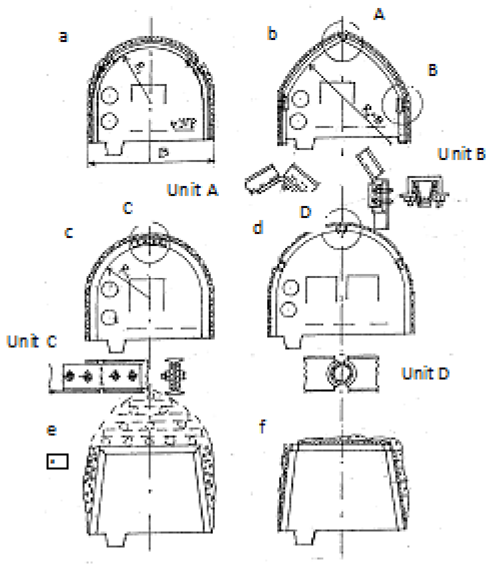


Fig. 3. Support frame timbering: a - arched of special interchangeable profile (SVP); b - tabernacular roof of SVP; c - arched made of double-tee semiarches; d - arched 5-articulate from a double-tee; e - trapezoidal wooden; f - mixed wood and metal with articulated beam of double-tee

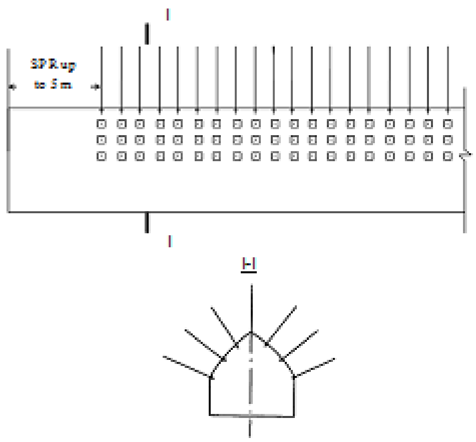


Fig. 4. Fastening of capital mining workings of stability category III in the area of high seismic activity. SPR timbering along the roof (l_w = 1.8 m, placement grid 1.0×1.0 m), reinforced with 0.3×0.3 m support plates

of polygon (oblique trapezoidal) cross section (Fig. 2, d).

Since the angle of inclination from the maximum horizontal principal stress σ_{sh} is usually a floating point value (10°...30°) within a mine field, and even within the length of a single working, the possibility should be provided for prompt changing of the shape of the cross section with regard to the natural formation of the contour during excavation, or the experience of maintaining other excavations in the area of a mine field.

If the cracks are oriented relative to the outline of the working, the working located in the direction of the greatest principal stress at the depth below the critical one, should have symmetrical arched cross-section (Fig. 1 c, d). The outline of the dome (the dome of semicircular or lowered shape) is chosen with regard to the experience in maintaining excavations at a certain site of the mine field.

In the areas with disturbed unstable rock, the shape of the cross-section of workings is determined by the design of the timbering.

Table 1. Criteria of stability of workings outcrops

Category and state of rock stability 1	Criterion of tension P_v 2	Justification of criteria 3	Rock state, geological features, forms of rock pressure manifestations 4
Category I - highly stable state	<1.2	The strains in the massif are less than or slightly (1.2 times) exceed the design strength of rock with regard to the weakening factors. Considering the restraining effect of the face in an excavation, it can be understood that the active tensions do not exceed the long-term strength of the rocks and the area around the working, the area of inelastic deformations is not formed, and the state of rocks on the working contour is stable.	The working contour is stable throughout its whole life. Separate flaws are possible in the face after blasting. The rock is massive, crack-free and lowly crumbling.
Category II - limit state	1.21-1.6	The strains in the massif are 1.21÷1.6 times higher than the design strength of rock with regard to the weakening factors. Taking into account the probabilistic nature of determining the initial values in calculation of P_v, and assuming normal distribution of random variables, taking into account the "three-sigma rule", range of P_v = 1.21÷1.6 can be taken as valid for assessing the limit state of rock outcrops, where formation of inelastic deformation zone or brittle fracturing of rocks in the marginal zone starts. Thus, the limiting condition is the "transition zone" from stable to unstable state of rock outcrops.	The contour of the working is stable for at least 12 hours after outcropping. Rock flaws and fractures are observed after blasting. Rock disturbance on the contour of the working is negligible and fade fast. The rock is moderately fractured (no more than one system of cracks).
Category III - unstable state	1.61-3.0	The strains in the massif are 1.61÷3.0 times higher than the design strength of rock with regard to the weakening factors. In these circumstances, a zone of inelastic deformation is formed around the workings, and rock deformation and flaw formation is observed, which gets eventually stabilized.	The contour of the workings remains stable for not more than 12 hours after outcropping. Deformation of rocks and flaw formation start after blasting. Growth of deformations is stabilized after 1 to 2 weeks. Moderately and massively fractured rock, no more than two cracks systems are developed.
Category IV_1 - very unstable state	3.01-4.5	In this category, the strains in the massif are considerably (3 and more times) higher than the design strength of rock with regard to weakening factors.	The contour of the workings remains stable for not more than 6 hours after outcropping. Rock flaws and caving after blasting are observed. Rock destruction and deformation does not fade for a long time (up to 6 months). Massively fractured rock with at least three cracks systems.
Category IV_2 - very unstable state	>4.5	In this range of P_v values, there are intense forms of rock pressure manifestations around the workings, not fading for a long time, and there are fractured rocks in the zone of inelastic deformations.	The contour of the working is stable for at least 3 hours after outcropping. Deformations of rocks and cavings can persist up to 6 months or more. Massively fractured, layered, sometimes fragmented rock.

RESULTS

The type and parameters of timbering are chosen on the basis of the calculated values of the P_v indicator that characterizes the category of workings outcrops stability. With that, 4 categories that characterize the stress-strain state of the mine workings outcrops with regard to the dynamic forms of rock pressure manifestations are determined[5,12].

Choosing the type and parameters of timbering for preparatory workings in deep mines In choosing the type and parameters of timbering, the modification principle was used, which makes it possible to increase the bearing capacity of the reinforcing timbering when geological conditions in the ongoing excavations are changed.

In the tables, the following designations are used:
SPR - Steel-Polymer Rod;

Table 2. Timbering parameters for field preparatory workings

P_v value, category and the state of rock stability	Types and parameters of timbering		Peeling the timbering from the face before blasting
	Permanent	Temporary	
1	2	3	4
P_v<1.2 Category I - highly stable rock state	Regular timbering is not required. SPR may be installed in locations of cutter breaks.	Not required	-
P_v=1.21-1.6 Category II - limit state	2.1 SPR l_w =1.35 m, cs =1.0×1.0 m; 1.2×1.2 m in the workings up to 5.4 m wide. In workings over 5.4 m wide, SPR l_w =1.8 m, cs=1.2×1.2 m. Use (100×100) ÷ (150×150) mm support plates. Auxiliary workings with cross section up to 6.5 m², where constant presence of people is excluded, may be unsupported with timbering at the command of the chief engineer of the mine.	SPR of permanent timbering	From the spacing of installation of timbering to 2.5 m in accordance with the certificate of the timbering
P_v =1.21-1.6 Category III - unstable state	3.1 SPR l_w=1.35 m on a 1.0×1.0 m grid with B<5.4 m. In workings over 5.4 m wide, SPR l_w =1.8 m on a 1.0×1.0 m grid. In local areas, 3.0-4.0 cm of gunite or shotcrete, 3.0-4.0 mm of "Techflex" may be used. SPR may be reinforced with support plates with size 300×300 mm, slabs of timber or segments of a t=0,06 m board. "Strip" type metal plates may be used for lagging.	SPR of permanent timbering	From the spacing of installation of SPR to 2.5 m. Determined by the certificate of timbering depending on geological conditions
P_v =3.01-4.5 Category IV_1 - a very unstable state	4.1 SPR l_w =1.35 m on a 0.8×0.8 m grid; 1.0×1.0 m in the workings up to 5.4 m wide. In workings over 5.4 m wide, SPR l_w =1.8 m on a 0.8×0.8, 1.0×1.0 m grid. Anchors are to be installed with support plates (0.25×0.25) ÷ (0.3×0.3) m or with other reinforcing elements.	SPR of permanent timbering	No more than the spacing of SPR installation
	4.2 Suspended timbering of wood or metal beams on rail shoulders with full lagging of roof with wood and backfilling voids, together with SPR l_w =1.35 m on a 1.0×1.0 m grid.	SPR lw=1.35 m on a 1.0×1.0 m grid.	No more than the spacing of SPR installation
	4.3 Wooden timbering of TQS staggered or solid.	TQS frame set	No more than the spacing of timbering
P_v >4.5 Category IV_2 - a very unstable state	4.4 SPR l_w =1.8 m on a 0.8×0.8 m grid with lagging of half-round logs or with the use of 0.25×0.25 or 0.3 x 0.3 m support plates. If workings width is less than 5.4 m, SPR l_w =1.35 m may be used on a 0.8×0.8 m grid with reinforcing elements (acc. to p. 7.4 of the instruction).	SPR of permanent timbering	No more than the spacing of timbering
	4.5 Metal arch timbering made of SVP with spacing of timbering 0.5 -1.0 m. Lacing of wood, concrete or metal grid. In workings up to 5.4 m from SVP-17-27, and in the workings of more than 5.4 m - SVP-27-33.	SPR 1.35÷1.8 m (1,0×1,0 m)	No more than the spacing of timbering
	4.6 SPR l_w =1.8 m on a 0.8×0.8 m or 0.7×0.7 m grid with metal or synthetic grid lagging together with a coating of shotcrete t=4.0-5.0 cm thick, or Techflex" t=4.0-5.0 mm.	SPR of permanent timbering	No more than the spacing of timbering

Table 3. The type and parameters of timbering in capital mining workings

P_v value, category and state of rock stability	Types and parameters of timbering: Permanent	Temporary	Peeling the timbering from the face before blasting
1	2	3	4
P_v<1.2 Category I - highly stable rock state	Regular timbering is not required. Depending on the geological conditions at individual sites, SPR l_w =1.35 m, the coating shotcrete t=2.0-3.0 cm or Techflex" t=2.0-3.0 mm may be used.	Not required	-
P_v=1.21-1.6 Category II - limit state	2.1 SPR l_w =1.35 m on a 1.0×1.0 m grid with B<5.4 m. In workings over 5.4 m wide, SPR l_w =1.8 m on a 1.0×1.0 m grid. Coating of shotcrete t=2.0-3.0 cm or Techflex" 2.0-3.0 mm thick.	SPR of permanent timbering	SPR from the installation spacing up to 2.5 m. Shotcrete or "Techflex" up to 2.5 m.
	2.2 SPR l_w =1.35 m or 1.8 m on a 1.0×1.0 ÷ 0.9×0.9 m grid. At separate sites, in places of rocks deformation - additional coating, spraying or shotcrete t=2.0-3.0 cm. "Techflex" t=2.0-3.0 m may be used.	SPR of permanent timbering	SPR from the installation spacing up to 2.5 m. Shotcrete, gunite or «Techflex» up to 2.5 m.
P_v=1.21-1.6 Category III - unstable state	3.1 Workings up to 5.4 m wide SPR l_w =1.35 m on a 1.0×1.0÷0.8×0.8 m grid, more than 5.4 m wide - SPR l_w =1.8 m on a 1.0×1.0 m grid. Roof bolting may be reinforced with 0.25 x 0.25÷0.3×0.3 m support plates, a metal strip, synthetic or metal bars. In rocks that are subject to destruction under the action of atmospheric air - additional solid coating of gunite t=3.0-4.0 cm or "Techflex" t=2.0-3.5 mm.	SPR of permanent timbering	From the spacing of installation of anchors to 2.5 m
P_v=3.01-4.5 Category IV□ - a very unstable state	4.1 In case of B<5.4 m SPR l_w =1.35 m on a 0.8×0.8 m grid. If workings width B> 5.4 m wide, SPR l_w =1.8 m on a 1.0×1.0 m grid. Various reinforcing elements may be used.	SPR of permanent timbering	Not more than the spacing of installation of anchors
	4.2 In case of B<5.4 m SPR l_w =1.35 m on a 1.0×1.0 m grid. In case of B<5,4 m SPR l_w =1.8 m on a 1.0×1.0 m grid with metal or synthetic grid lagging together with a coating of shotcrete t=4.0-5.0 cm thick, or "Techflex" t=4.0-5.0 mm.	SPR of permanent timbering	Not more than the spacing of installation of anchors
	4.3 SPR l_w=1.8 m on a 0.8×0.8÷0.7×0.7 m grid together with shotcrete t=4.0-5.0 cm or "Techflex" t=4.0-5.0 mm.	SPR of permanent timbering	Not more than the spacing of installation of anchors
	4.4 Metal arch timbering made of SVP with spacing 1.0 m with lagging of roof and sides with concrete slabs or metal grid.	Frames of arch support	No more than the spacing of timbering
P_v>4.5 Category IV□ - a very unstable state	4.5 SPR l_w =1.8 m on a 0.8×0.8 m or 0.7×0.7 m grid with metal grid lagging together and a coating of shotcrete t=4.0-5.0 cm thick, or "Techflex" t=4.0-5.0 mm.	SPR of permanent timbering	Not more than the spacing of installation of anchors
	4.6 Metal arch timbering made of SVP with spacing 1.0 m with lagging of roof and sides with concrete slabs or metal mesh.	Frames of arch support	No more than the spacing of timbering
	4.7 Monolithic concrete or reinforced concrete timbering not less than 0.2 m thick	SPR l_w =1.35 m c_a = 0.8×0.8 m	Not more than the spacing of installation of anchors

Table 4. Parameters of the "Techflex" coating in combination with anchor timbering

Name of timbering	Parameters if timbering: II stability category		III stability category		IV stability category	
Anchors installation grid, m×m	1.2×1.2	0.9×0.9-1.0×1.0	1.0×1.0	0.8×0.8-0.9×0.9	(0.9×0.9)-(1.0×1.0)	0.7×0.7-0.8×0.8
Polymeric coating thickness, mm	3.0-3.5	2.0-3.0	3.0-4.0	2.0-3.0	5.0-5.5	4.0-5.0

TQS - three-quarter set;
B - width of the working, m;
l_w - full length of the anchor rod;
c_s - spacing of anchors placement, m;
n_s - density of anchors placement, pcs/m²;
t - thickness of shotcrete or "Techflex".

Timbering for field preparatory workings is chosen according to Table 2, and for mining workings - to Table 3.

In Tables 2 and 3, the "roof" is the surface of the outcrop above the spring in workings of arched cross section shape, in case of tabernacular shape - above the base of the "tabernacle".

DISCUSSION

In defining the grid for placing anchors, one should take into account the following ratios of density n_s and spacing for placing anchors (c_s):

Anchors spacing cs, m	1.2×1.2	1.1 x 1.1	1×1	0.9×0.9	0.8×0.8	0.7×0.7
Density of anchors arrangement n_s, pcs/m²	0.7	0.83	1.0	1.2	1.56	2

Grid of anchors placement along the contour can be square or rectangular with the distance between rows of anchors along the axis of the working and along the perimeter in the range between 0.7 and 1.2 m. The following key sizes of anchors are recommended: bar diameter 16-20 mm, length - 2.5, 1.8 and 1.35 m. In case of hanging metal lagging grid, it is possible to use anchors 0.6 m long made of deformed steel bars 18 mm in diameter with support plate made of sheet steel.

Peeling of the timbering from the face is determined by the certificate of the timbering and is chosen on the basis of the geological structure of the massif, geotechnical and geomechanical conditions, rock stability in completed workings, or results of pilot testing of experimental timbering certificates.

The unified safety rules do not regulate design of the temporary timbering and peeling from the face. Depending on geological conditions, the parameters of the temporary timbering, according to the unified safety rules, are established by the certificated of timbering[13].

Tables 2 and 3 in columns 3 and 4 show the recommended design of temporary timbering and its peeling from the face, with respect to the average conditions of mining operations at the mines of SUBR.

Recommendations about parameters of the temporary timbering and its peeling from the face are stated before blasting. In most variants, elements of temporary timbering are used for temporary timbering. In rocks of II-III stability category, peeling from the face up to 2.5 m is allowed. In rocks of stability category IV_1 and IV_2 peeling of temporary timbering from the face should not exceed the spacing of timbering.

Peeling of the timbering from the face is determined by the certificate of the timbering and is chosen on the basis of the geological structure of the massif, geotechnical and geomechanical conditions, rock stability in completed workings, or results of pilot testing of experimental timbering certificates[14].

For permanent timbering in the area around the face of the working, new polymer coating "Techflex" is used, which gains up to 40% of strength within 6 hours, and enhances stability of the outcrops. When using metallic or synthetic grid lagging and shotcrete, peeling of permanent timbering from the face can reach 10-50 m depending on rock stability[15].

"Techflex" is an elastic cement-and-latex coating with high breaking strength (4-5 MPa) and adhesive properties that consists of a liquid polymer component (latex) and cement powder, which are mixed at the volume ratio 2:1 using a pneumatic pump, and applied onto the surface by spraying. The material forms an elastic protective and supporting coating that increases strength of the massif around the contour by eliminating the damaging effects of rocks cracking and delamination, as well as disturbances caused by the atmospheric phenomena (presence of moisture, oxidation, etc.).

In combination with anchor timbering, depending on rock stability, the following parameters of the coating are used for installation of timbering in workings are recommended (see Table 4).

Couplings of workings are to be timbered with SPR with complete filling of the holes with polymer concrete using reinforcing elements in accordance with the criteria of rock stability (tables 2, 3).

In inclined couplings (access crosscuts, overrunning branch, ring-shaped workings in underground infrastructures, etc.), if the width of the working is more than 5.4 m, SPR l_w =1.8 m is to be used.

"T" - shaped and cross-shaped couplings of workings are to be fastened with anchors l_w =1.8 m. In each of the coupling workings, at the length equal to its width, SPR l_w =1.8 m is to be installed. In case of further excavation, parameters of the timbering are to be chosen with regards to geological conditions in Table 2.

In rocks of III and IV stability categories, it is possible to install "Suspension" (Bush) made of 4-5 steel-polymer anchors 2.5-3.5 m long along the roof in the centre of workings coupling, as instructed by the chief engineer of the mine.

Supports timbering (Fig.3) should be used in massively fractured or crushed rocks of IV stability category (Tables 2, 3) that are prone to weathering out and precipitation, as well as in important workings around the shaft station with long service life. (16, 17)

Inter-frame spaces should be lugged with wooden lugs of half-round, round logs or boards, if the lifetime of the working is below 3 years, and with metal, grid and concrete lugs, if the age of the working is over 3 years.

When supporting timbering is used for coupling of workings, it should be anchored in strict accordance with the mining and geological conditions. Timbering should be chosen according to Tables 2 and 3.

The accepted parameters of the timbering of couplings of workings may be adjusted on the basis of practical experience and new research. (18, 19)

Figure 4 shows one of the options for earthquake-proof timbering - steel and polymer rods 1.8 m long with the 1.0×1.0 m placement grid reinforced with 0.3×0.3 m support plates. (20)

CONCLUSION

Practical experience of using "Instructions for choosing timbering for preparatory and mining workings in mines of OJSC "Sevuralboksitruda" proved the effectiveness of the proposed technical solutions for ensuring stability of workings and helped to reduce costs of timbering in preparatory and mining workings, as well as to improve safety of mining operations. These recommendations can be used by companies and organizations involved in design, construction and operation of underground workings in mines or with the hazard rock bursts, and the information contained in the article may be useful for educational, scientific, and engineering and technical personnel of enterprises, organizations, research and design institutes who deal with the issues of installation and maintenance of timbering in workings in bump hazardous rocks of ore deposits.

With regard to transferring to new development horizons in bump-hazardous deposits of deep mines, and changes in geological conditions, perspectives of further scientific research in this area are the improvement geomechanical approaches to assessing stability of mine workings and outcrops and justification of earthquake-resistant designs of timbering in development of bump-hazardous deposits.

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