SUBSTANTIATION OF STABLE CROWN SHAPES IN IRON ORE MINING

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Krivbass rich iron ores are mined by stoping at the depths of 1200-1450 m, preliminary development reaching 1600 m. Increased rock pressure decreases stability of mine workings, in particular stopes and compensating rooms, affecting stability of the most vulnerable element - exposed crowns of underground workings [1-8]. Due to this, the problem of stability of exposed stope and compensatory room crowns gains considerable importance when designing stopes at great depths.

Determining regularities of rock pressure impacts on the crown stability depending on its shapes, mining depths and iron ore hardness, therefore, will facilitate choosing and substantiating crown shapes.

The *Ansys 16.0* based finite element technique is applied to calculate stress and strain as well as triangulation with a 2 m side is performed to build stress and strain diagrams.

The computation process is conducted concurrently, including creation of a stiffness matrix, solution of linear equations, calculation of results when processing with memory sharing and distributing. The component synthesis mode, the analysis of the cyclic symmetry, submodelling techniques facilitate work with large models and systems that represent the stress-strain state of rocks.

The applied technologies parameters and the stoping sequence are considerably impacted by the stress-strain state of rocks, i.e. information on the character and values of active stresses in the massif, reasons of their changes during stoping enables enhancing the applied flow sheet and developing new ones, choosing optimal parameters and sequence of stoping.

The experiment consists in creating models with horizontal, tent, vaulted and inclined crown shapes the dip of which varies within a wide range.

The values of caved rock pressure on the ore massif P_1, P_2 and P_3 represent mining conditions of Krivbass deposits and correspond to mining at the depths of 1200, 1450 and 1700 m.

Physical and mechanical properties of the ore and waste ore studied are given in Table 1.

Table 1

Physical and mechanical properties of ore and waste ore

Parameters	Units	Ore				Rock			Waste rock
		1P *f*=3-5	*2P* *f*=4-6	*3P* *f*=5-7	*4P* *f*=6-8	*1П* *f*=4-6	*2П* *f*=5-7	*3П* *f*=8-10	
Young modulus	MPa	22000	25000	28000	32000	22000	33000	40000	5000
Volume weight	kg/m^3	3700	3650	3600	3500	2800	2900	3000	2400
Compressive resistance	MPa	30	40	50	60	45	55	80	5
Ultimate tension stress	MPa	3	4	5	6	4.5	5.5	8	0.3
Poisson ratio	–	0.30	0.28	0.26	0.25	0.26	0.24	0.24	0.25

Table 2 presents values of rock pressure on the ore massif corresponding to mining conditions of Krivbass deposits.

Table 2

Parameters of rock pressure on the ore massif

Parameters	Unit of meas.	P_1	P_2	P_3
Rock pressure on massif: vertical / lateral	MPa	7.0/2.5	8.5/3.0	10.0/3.5

When studying the stress-strain state of the ore massif special attention is paid to shapes of stopes and to shapes of stope crowns in particular, stope sizes being assumed equal for comparison purposes.

The calculated stress fields values (MPa) for various crown shapes are given below.

Principal stress values in stopes with horizontal crowns are distributed according to the classical law of stress distribution in rocks. The maximum compressive stresses are seen in the corners of stopes whereas tension stresses are found in the central part of the crowns.

Being the most dangerous, tension stresses are the most frequent reason for destructive manifestations of rock pressure that affect mining engineering elements.

The value of tension stresses in a stope crown not exceeding the ultimate tension stress of the ore massif, the crown remains stable, especially in ores with low fracturing. The value of tension stresses in a stope crown exceeding the ultimate tension stress of the ore massif, the crown is predictably unstable and tends to form local falls or be completely destroyed.

The maximum stresses values in horizontal crowns of stopes σ_1 depend on the mining depth H_p and the corresponding value of rock pressure various iron ore hardness are described by the polynomial equations:

– for ore hardness f=4–6

$$\sigma_1 = 2 \cdot 10^{-6} H_p^2 - 0{,}0128 H_p + 3{,}056 \text{ , MPa;}$$

– for ore hardness f=5–7

$$\sigma_1 = 2 \cdot 10^{-6} H_\mathrm{p}^2 - 0{,}0132 H_p + 2{,}836 \text{ , MPa;}$$

– for ore hardness f=6–8

$$\sigma_1 = 2 \cdot 10^{-6} H_\mathrm{p}^2 - 0{,}0124 H_p + 1{,}076 \text{ , MPa.}$$

The adaptive index of maximum stresses in horizontal crowns of stopes σ_1 depending on the mining depth H_p and various iron ore hardness can be determined by the expression, MPa:

$$\sigma_1 = \left(-4{,}4394\ \ln\left(f_p\right) - 1{,}6208\right) \times$$
$$\times \left(2{,}2727 \cdot 10^{-7} H_p^2 - 1{,}4545 \cdot 10^{-3} H_p + 0{,}3472\right).$$

Principal stress values in stopes with tent crowns are distributed in the following way. As the result of crown contour transformations, principal stress inversion is observed.

The stress-strain state of the tent crown massif experiences decreased compressive stress values and no tension stresses.

The dependency of maximum stresses in tent crowns of stopes σ_1 on the mining depth H_p and the corresponding value of rock pressure for various iron ore hardness is described by the logarithmic equations:

- for ore hardness f = 4-6

$$\sigma_1 = 28{,}804 \ln\left(H_p\right) - 172{,}05,$$

where σ_1 is the maximum stress value in tent crowns, MPa;

H_p is the mining depth, m;

- for ore hardness f = 5-7

$$\sigma_1 = 28{,}804 \ln\left(H_p\right) - 171{,}05;$$

- for ore hardness f = 6-8

$$\sigma_1 = 25{,}858 \ln\left(H_p\right) - 148{,}3.$$

The following expression enables determining the universally adaptive index of maximum stresses in tent crowns of stopes σ_1 depending on the mining depth H_p and the corresponding rock pressure value for differentiated iron ore hardness, MPa:

$$\sigma_1 = \left(-0{,}1354\ f^2 + 3{,}0691\ f + 19{,}873\right) \cdot \left(0{,}9001\ \ln\left(H_p\right) - 5{,}3766\right).$$

Based on the obtained results and fundamental laws, it is possible to conclude that tent shapes of crowns possess commensurately much higher stability as compared with horizontal exposures.

The following regularities result from calculating values of maximum stresses in vaulted stopes depending on the mining depth and rock pressure values for various iron ore hardness.

The crown maximum stresses vary depending on the value of rock pressure and the vaulted crown curvature.

The most stable crowns are the vaulted ones with the curvature radius equal to a half of the stope width.

The calculated maximum stresses σ_1 of rocks when forming a vaulted crown demonstrate that crown stress values vary depending on the rock pressure value and the crown curvature with the following dependencies.

Depending on ore hardness:

- for ore hardness f = 4-6:

$$\sigma_1 = 2{,}8804\ln(H_p) - 10{,}405,$$

where σ_1 is values of maximum stresses in vaulted crowns of stopes, MPa; H_p is the mining depth, m;

- for ore hardness f = 5-7:

$$\sigma_1 = 5{,}4662\ln(H_p) - 28{,}635;$$

- for ore hardness f = 6-8:

$$\sigma_1 = 5{,}2211\ln(H_p) - 27{,}72.$$

The numerical simulation results allow the conclusion that the vaulted shapes of stope crowns facilitate decrease of maximum stress values. The increase of the vault curvature radius causes the decrease of the compressive stress values on the crown center. At that, the maximum stress values are observed in the vault spring.

With the crown curvature radius going to infinite values, the vault center experiences tension stresses. In this case the conceptual pattern of stress distribution in the massif is identical to the strain-stress state of the horizontal crown massifs.

The following expression determines the average dependency of values of maximum stresses in vaulted crowns of stopes depending on their relative curvature radius:

$$R_o = \frac{l_{\text{кн}}}{2R_n},$$

where R_o is the relative vault curvature radius of stope crowns;

$l_{кн}$ is the normal width of the dead stope, m;

R_n is the crown curvature radios, m.

The dependency of values of maximum stresses in vaulted crowns of stopes on the vault curvature radius is described by the equation:

$$\sigma_{1R_o} = 6{,}636\ln(R_o) + 9{,}4 .$$

Multifactor experiments enable determining the universal adaptive index of maximum stresses in vaulted crowns of stopes σ_1 depending on the mining depth H_p, relative crown curvature radius R_o and iron ore hardness f, MPa:

$$\sigma_1 = (0{,}2880\ \ln(H_p) - 1{,}0405)\cdot(6{,}636\ \ln(R_o) + 9{,}4)\times$$
$$\times(-5{,}83\cdot 10^{-3} f^2 + 0{,}1325 f + 0{,}4582).$$

Dependencies of maximum stresses values in inclined crowns on the mining depth and the corresponding rock pressure values for various iron ore hardness enable the following results.

Maximum stress values in the crowns under study vary depending on rock pressure and the crown dip.

The calculated values of maximum stresses in inclined crowns of stopes σ_1 depend on the mining depth H_p and the corresponding value of rock pressure for various iron ore hardness f and are described by the logarithmic equations.

The determined dependencies are described by the following equations:

- for ore hardness f = 4-6

$$\sigma_1 = 12{,}144\ln(H_p) - 73{,}945,$$

where σ_1 is values of maximum stresses in inclined crowns, MPa;

H_p is the mining depth, m;

- for ore hardness f = 5-7

$$\sigma_1 = 12{,}634\ln(H_p) - 77{,}974,$$

- for ore hardness f = 6-8

$$\sigma_1 = 11{,}538\ln(H_p) - 70{,}707.$$

Dependency of values of maximum stresses in inclined crowns on the dip angle $\lambda_п$ of the inclined crown of the stope is described by the following polynomial expression:

$$\sigma_{1н} = -0{,}0031\lambda_n^2 + 0{,}5517\lambda_n - 9{,}1692\,,$$

where $\lambda_п$ is the dip angle of the inclined crown, degrees.

Results of the multifactor experiments allows determining the universal adaptive index of maximum stress values in inclined crowns of stopes σ_1 depending on the mining depth H_p, the crown dip and the corresponding iron ore hardness, MPa:

$$\sigma_1 = \left(1{,}0469\ln\left(H_\mathrm{p}\right) - 6{,}3746\right)\cdot\left(-0{,}0031\lambda_n^2 + 0{,}5517\lambda_n - 9{,}1692\right)\times$$
$$\times\left(0{,}2566\ln\left(\mathrm{f}\right) + 0{,}5836\right)$$

Simulation analysis results in the following. The increased mining depth causes considerable rock pressure growth. Therefore, when stoping at great depths, it is necessary to specify requirements for stability of exposed stopes and compensating rooms as well as for accuracy of designing construction units.

So, when mining rich iron ores by sublevel caving at Krivbass underground mines, it is advisable to make wider use of vertical and inclined compensating rooms.

The technology of mining panels with caving ore onto the tent-shaped compensating room should be applied as well.

Stope crown stability is a key requirement when mining rich ores by the room-and-pillar method. It is critical to use vaulted crowns that provide maximum stability in complicated geological and mining conditions.

Sufficiently complete research of the technology of forming vaulted crowns allows recommending the suggested methods for substantiating stable crown shapes at underground mines of the PrJSC “Sukha Balka”.

Rich iron ore deposits of “Frunze” and “Yubileynaya” underground mines, which are part of the PrJSC “Sukha Balka”, are characterised by iron content of 46%. Low-grade ores (magnetite and oxidized types of ferruginous quartzite) occur between the mines (site No.6).

The deposits of “Frunze” and “Yubileynaya” are made of rocks of Krivorozhskaya metamorphic series of the lower Proterozoic (PR1) and the Archean rocks (AR). There are seven ferruginous and seven schist levels altogether.

The Fifth and the Sixth ferruginous levels are the main ore bearing thicknesses of the iron ore deposits.

Apart from rich iron ore deposits of the Fifth and the Sixth levels, there are also minable magnetite quartzite deposits “Yuzhnaya” and “Severnaya” which are part of the magnetite quartzite areas between sites No.5 and No.6. Other ferruginous levels are of insignificant thickness, high degree of oxidation and, therefore, not minable.

The “Frunze” deposit in the V ferruginous level includes ore bodies of the underground mine “Zapadnaya of underground mine No.8”, “V-VIII Severnaya” and “Saksaganka of underground mine No.2”. Ore bodies “Diagonalnaya”, “I-III Yuzhnaya” and “Tsentralnaya” form the Sixth ferruginous level.

The ore bodies are pillar- and sheetlike in shape. The main and largest reserves are located in the Fifth ferruginous level. The ore bodies are mainly represented by martite metals. Gothite-hematite-martite, dispersed-hematite-martite, gothite-hematite ores are represented as “margins” of martite ores. The hardness ratio of martite ores varies from 3-4 to 11-13 points (Protodyakonov scale of hardness), that of the enclosing rocks is from 9-10 to 14-16 points.

The “Yubileynaya” deposit is located in the Fifth ferruginous level and contains ore bodies “Glavnaya” and “Shurfov 42-46”. The Sixth level contains ore bodies “Gnezdo 1-2”, “Gnezdo - 3” and “Tsybulko 76”.

The stock-, nest- and seemlike ore bodies are of 190-1530 m long along the strike. The horizontal thickness makes 2-42 m; the horizontal ore area is 750-30360 m^2. The ore bodies occur according to enclosing rocks and have a northeastern strike and a SW dip with the 50-60 ^{o} angle.

Weakly fractured stable hydrohematite quartzite and unstable fall-prone along sheeting planes gothite-hematite and quartz-chlorite schists make the footwall rocks. The hanging wall contains gothite-hematite and martite weakly fractured stable quartzite. The hardness ratio of the ores varies from 4-6 to 11-13 points (Protodyakonov scale of hardness), that of the enclosing rocks is from 5-6 to 11-13 points.

In accordance with the standard design “Mining systems for Krivbass underground mines” (NIGRI, 1986) and geological and mining conditions of the ore body occurrence and physical and mechanical properties of ores and enclosing rocks at “Yubileynaya” underground mine, the PrJSC “Sukha Balka”, the sublevel-stoping system with vertical rings of deep holes onto the horizontal compensating room should be applied to mining blocks.

Mining rich iron ores at the depth of over 1300 m at “Yubileynaya” underground mine with horizontal crowns in forming undercutting rooms is connected with problems of maintaining stable horizontal exposures.

At great depths, the growing rock pressure affects stability of horizontal compensating rooms. Possible failures of horizontal crowns result in deep holes’ integrity loss and, therefore, increased amount of oversize pieces of ore. The latter impairs rich ore drawing and extraction indices and increases mining costs.

In view of the above mentioned drawbacks and the current mining technology used at the mines, the authors recommend application of the vaulted crown.

A variant of the room-and-pillar system with formation of an vaulted crown of a stope when mining of blocks by stages recommended for the PrJSC “Sukha Balka” underground mines is given in Fig. 1.

As compared to horizontal exposures, the recommended vaulted crown of a stope is of increased stability and decreases the probability of casual failures.

Formation of a vaulted crown is performed through charging some of the deep blast holes within the contour of the future stope.

Simultaneously charged and blasted holes corresponds in number and layout to the stage of forming a vaulted crown of a stope.

In forming vaulted crowns in stopes, principal stress values are distributed according to the classical law of stress distribution in rocks.

The results of the Ansys 16.2.-based stress field calculations for various shapes of vaulted crowns are given below. The finite element size is 1 m, stress values on isolines are given in MPa.

The calculation results and isolines of principal stresses σ_1 in rocks during the second stage of forming a vaulted crown in the room-and-pillar variant recommended for the PrJSC “Sukha Balka” underground mines.

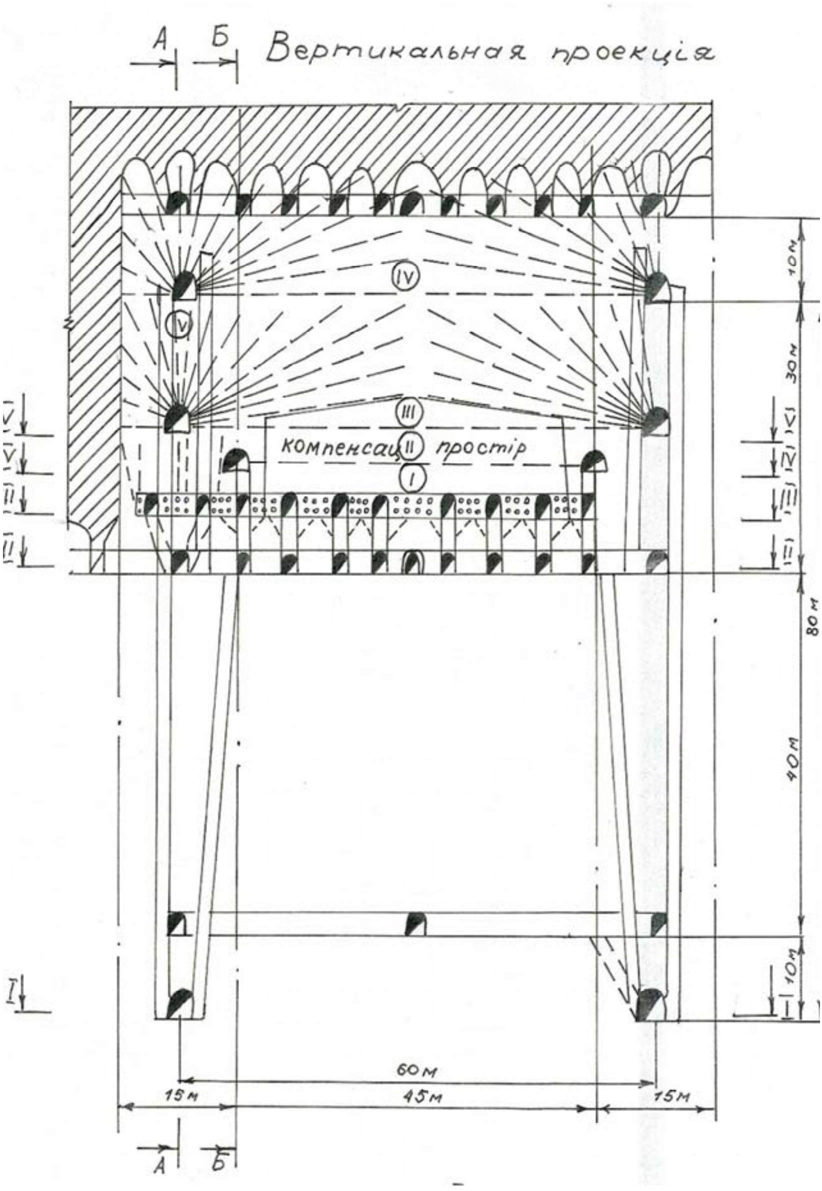

Fig. 1. A variant of the room-and-pillar system with formation of a vaulted crown: I, II, III, IV - stages of forming an vaulted crown of a stope

Calculations principal stresses σ_1 of rocks when forming a vaulted crown demonstrate that the value of stresses in the crowns vary depending on the rock pressure value and the curvature radius of the vaulted crown. The most stable are the vaulted crowns with the curvature radius equal to a half of the stope width.

Multifactor experiments enable determination of the universal adaptive indices of a value of maximum stresses in vaulted crowns of stopes σ_1 depending on the mining depth H_p, a relative crown curvature radius R_o and differentiated iron ore hardness f, MPa:

$$\sigma_1 = \left(0{,}2880 \ln\left(H_p\right) - 1{,}0405\right) \cdot \left(6{,}636 \ln\left(R_o\right) + 9{,}4\right) \times$$
$$\times \left(-5{,}83 \cdot 10^{-3} f^2 + 0{,}1325 f + 0{,}4582\right).$$

The calculations show that vaulted crowns of stopes experience tension stresses. The largest values of stresses are observed in the vault springs; however, they are far from being destructive.

In contrast to horizontal crowns, the central part of vaulted crowns sees almost no tension stresses that are considered the most dangerous for stope exposures.

Due to absence of tensile stresses in vaulted crowns of stopes, they possess increased stability, other factors being equal.

Compensating rooms and stopes with stable vaulted crowns will experience the decreased number of destroyed holes over the stope zone caused by possible partial or complete failure of crowns.

Undestroyed deep holes will enhance massif breaking indices due to increased quality of muck crushing and corresponding decrease of oversize yield. Increased quality of rock massif breaking will enable muck ore indices and broken rich ore extraction from stopes.

Thus, considerable rock pressure growth at great depths places special requirements on stability of exposed stopes as well as stability of crown exposures of stopes and compensating rooms when designing stopes.

Due to it, when mining rich iron ores by sublevel caving systems, wider application of vertical and inclined compensating rooms is recommended for Krivbass underground mines.

Tent and vaulted crowns are advisable when mining rich iron ores by the room-and-pillar systems at depths of over 1300 m to provide maximum stability under high rock pressure.

Use of vaulted crowns in the PrJSC “Sukha Balka” underground mines will enable decrease of losses of deep holes in crowns from 18-21% to 11-15%.

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