Reduction of the Ore Losses Emerging within the Deep Mining of Bauxite Deposits at the Mines of OJSC «Sevuralboksitruda»

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Abstract. This article considers the issues associated with the deep mining of bauxite ores. A need for effective development of Russian aluminum mineral resource base requires companies to reduce the ore losses emerging while moving to the deeper mining, which is characterized by sophisticated geological, technical and geodynamic mining conditions. In this article we have revealed the changing patterns of the inter-chamber pillars’ stress state and stability taking into account the influence of various mining and geological factors. Based on the mine data and the results of numerical experiments performed with the use of PRESS 3D URAL software, this research has revealed that at the depth of more than 700-800 m inter-chamber pillars enter the supercritical mode of deformation and have minimal bearing capacity. Failure to take into account the supercritical mode of deformation leads to the significant losses of ore in pillars reaching 30-50%. At the same time, the ore losses can be reduced to 15-25% by considering the residual strength and supercritical deformation of the pillars while designing their parameters. The economic result would be achieved by improving the design process of mining operations, providing increased safety of mining operations along with losses reduction leading to to increase in production volumes.

1. Introduction

Annually, about 65% of Russian high-quality bauxite is being mined at the fields of the Severouralsk bauxite basin, developed by OJSC «Sevuralboksitruda» (OJSC «SUBR»). The program objectives of the «Development Strategy of Russian Metallurgical Industry for the Period up to 2020» require OJSC «SUBR» to increase the producing capacity of bauxite mining. At the same time, a need for effective development of Russian aluminum mineral resource base requires companies to reduce the ore losses emerging while moving to the deeper mining, which is characterized by sophisticated geological, technical and geodynamic mining conditions [1], [2].

Bauxite ores are considered to be very valuable: given the existing extraction ratio, an increase of 1% in the ore output gained through the reduction of ore losses results into increase of 0.7% in the company’s revenue from the sales of mineral concentrate. Such proportion can be obtained under the context of aluminum price stability. However, similar to other non-ferrous metals, aluminum prices show significant price volatility averaging around 20% and in some periods exceeding 50% [3]. During the period of 2007-2019, the prices have varied within a corridor of $1.500 - $3.300 per ton, however, starting from 2016 the London Metal Exchange show steady increase of the aluminum prices.
amounting to $1,870 per ton (as of 1\textsuperscript{st} February 2019). In this regard, the reduction of ore losses leads to a non-linear increase in revenue resulted from both growth of volumes and increase in prices [4].

OJSC «SUBR» develops the bauxite fields with difficult geological and technical conditions where the marginal part of the ore deposit may be under elastic or supercritical deformation depending on the physical and mechanical properties of the bauxite ore. Elastic deformation of the marginal part of the ore deposit emerges when the ore contains strong and solid types of bauxite, such as variegated or jasper-like. The supercritical deformation of the marginal part of the ore deposit is due to the presence of less solid, soft and friable types of bauxite, for example, easily soiled and non-easily soiled red bauxite. It is important to determine accurately the mode of deformation of the marginal part of the ore deposit as it helps to determine the stressed state of the panel pillars (inter-chamber pillars) at the moment of their creation.

It is well known that under the context of deep mining it is recommended to calculate the parameters of the inter-chamber pillars using the pressure-arch hypothesis in order to reduce the ore losses. According to this hypothesis the only pressure that is to be assumed while designing the parameters of the inter-chamber pillars is the one exerted on them by the hanging layer within the pressure-arch. At the same time, the strength of the inter-chamber pillars is taken into account without a decrease caused by the destruction of the pillars, thus, leading to the underestimation of their cross-section area. For more strong and solid types of bauxite ores (variegated and jasper-like bauxites), this error is insignificant due to the technological limitation determining the minimum possible width of the inter-chamber pillars at the level of 3 m. However, artificial overestimation of the strength of inter-chamber pillars consisting of the softer types of bauxite ores (non-easily soiled red bauxite and, especially, red easily soiled bauxite) leads to complete loss of their load-bearing capacity and, as a result, to the destruction of both inter-chamber pillars and backs. In this regard local adjustment of the inter-chamber pillars’ parameters based on the experimental test data is introduced as a preventive measure. However, its effectiveness has dramatically decreased in the context of the ubiquitous destruction of the inter-chamber pillars at the depth of 600-700m, a phenomenon that required scientifically sound geomechanical study to determine the reasonable parameters of the inter-chamber pillars taking into account their supercritical deformation.

2. Research objective

Seeking to increase the operational efficiency of deep mines this study aims to analyze the ore losses emerging under various loading modes of inter-chamber pillars within the process of underground mining of ore deposits with complex geological structure.

3. Methods

We have performed analysis of existing methods to determinate the inter-chamber pillars’ parameters developed by various researchers such as V.D. Slesarev [5], G.E. Gulevitch [6], V.V. Sokolovskiy [7], S.G. Avershin [8], Y.A. Modestov [9], K.V Ruppeineit [10], L.D. Shevyakov [11], S.V. Vetrov [12], V.F. Trumbachev [13], V.R. Rakhimov [14], G.L. Fisenko [15], Zh.S. Erzhanov [16], A.K. Chernikov [17], V.A. Eremenko [18], M.I. Potapchuk [19], etc. This analysis has shown that all the methods draw on the ultimate true breaking strength of the rock applying the pressure-arch theory. Analysis of the foreign experience of determining the parameters of the inter-chamber pillars presented in the works of Tournaire [20], Hoek & Brown [21], Pritchard & Hedley [22], Tavakoli[23], Maybee [24], H. Shimada [25] and others has shown that the loading surface of the pillars is determined by the impact of the total weight of the supported hanging layer column with further consideration of safety margin coefficient.

The PRESS 3D URAL software was applied to do ex ante assessment of the stability of inter-chamber pillars in the mined-out space under the context of the pillar mining system D.V. Sidorov [26], D.V. Sidorov & T.V. Ponomarenko [27], D.V. Sidorov & M.I. Potapchuk [28]. This software enables users to solve spatial problems of elasticity theory taking into account the natural and man-caused compliance properties of the ore deposit and pillars. The PRESS 3D URAL software involves
three main blocks: 1) processing of initial geological and technical documentation with further creation of a database containing the input data of all the facilities: geometric dimensions (width, length and height of development workings, chambers and pillars); 3D-layout of the stopes (workings of different purposes) and load-bearing ore elements (ore deposit, pillars of various purposes); physical and mechanical properties of the hanging rocks (roof) of the stopes and workings of various purposes as well as ore elements; parameters of the tectonic disturbances and boundary conditions; 2) numerical and analytical calculation; ; 3) processing of the results for visualization and analysis.

The numerical method of boundary integral equations included in the processor unit of the PRESS 3D URAL software enables users to calculate the stresses emerging into the inter-chamber pillars taking into consideration a wide range of mining, geological and engineering factors: various geometrical dimensions of stopes and pillars, various location of construction units in respect to the boundaries of the mined-out space, various physical and mechanical properties of enclosing rocks and ore, thickness of the ore deposit, parameters of the tectonic disturbances and the thickness of relieve slot. The stability of the inter-chamber pillars is calculated through the working stresses using an analytical method. The numerical experiments included the calculations performed for 1) different spans of the mined-out space; 2) different number of fulfilled rows of inter-chamber pillars; 3) different cross-section areas of pillars \( d \) varying from 3.0 m to 10.0 m; 4) different heights of pillars \( m \) varying from 0.5 m to 10.0 m; 5) different ratios of elastic modulus of pillars and enclosing rocks \( E_p/E_r \) varying from 0.2 to 10.0. The back span of the stopes \( l_b \) was taken in accordance with the real data from the mine, in average equal to 5.0 m - 5.2 m.

4. Results

The study examines the impact of the depth of mining on the stress occurring in the pillars being focused on the main types of bauxite ore mined at the field: red easily soiled, red non-easily soiled and variegated bauxite. The analysis of the obtained results shows that at the depth of more than 600-700 m inter-chamber pillars lose their load-bearing capacity even when the mined-out space is of insignificant size. This conclusion is supported by the numerous assessments performed by the experts of OJSC “SUBR” and aimed at evaluating the current state of mines and elements of mining structures.

Figure 1a represents the distribution of the load-bearing pressure emerging in the marginal part of ore deposit prior to the inter-chamber pillars’ creation. Practical experience shows that the distance to the point of maximum load-bearing pressure is usually around 1–2 m. The value of the load-bearing pressure is often equal to 2-3\( \gamma H \). If the marginal part of ore deposit is not in a rock-bump hazardous state, the inter-chamber pillars are designed without implementing special preventive measures aimed at unloading. Due to the creation of supporting pillars, the loads removed from the ground of the chambers are redistributed to the marginal part of ore deposit as well as to the supporting pillars, thereby, loading them. Figure 1b represents the distribution of the load-bearing pressure emerging in the marginal part of the ore deposit and supporting pillars after their construction. Figure 1b shows that there is an elastic core with the width of \( d = (a_1 + a_2) \) emerging inside the pillar and, consequently, such pillars would have sufficiently high load-bearing capacity. In this case, drawing on the Tournaire-Sheviakov theory (1884, 1962), the parameters of the solid support pillars can be calculated using the value of allowable stresses. Seeking to increase the operational efficiency of deep mines this study aims to analyze the ore losses emerging under various loading modes of inter-chamber pillars within the process of underground mining of ore deposits with complex geological structure.
The numerical evaluation of the stress-strain state of the columnar inter-chamber pillars located at the depth of more than 600-700 m was conducted for the various sizes of the mined-out spaces within the stopes. Such evaluation shows that the vertical stresses emerging inside the pillars exceed their breaking-down point, thus, causing their destruction. Usually the inter-chamber pillars exist in the mine in a form of truncated pyramids connected by the smaller bases (in the form of an hourglass) or are destroyed in their original form by splitting into parts due to the cracks emerging in parallel to the effect of compressive loads. Figure 2a represents the distribution of load-bearing pressure emerging in the marginal part of ore deposit prior to supporting pillars’ creation. Practical experience and calculation results show that the distance to the point of maximum load-bearing pressure is usually 10–12 m (red easily soiled bauxite) and 6–8 m (red non-easily soiled bauxite). The load-bearing pressure is usually equal to $1.5 \pm 2 \gamma H$. Generally, if the marginal part of ore deposit is comprised of less strong and less solid types of bauxite, its material is characterized by natural compliance (compression). A $3 \pm 5$ m section of the marginal part of ore deposit located deeper in the solid than the outcrop is in a state of supercritical deformation that corresponds to the residual strength of bauxite. Under such context, the marginal part of ore deposit is in a non-rock-bump hazardous state, thus, the inter-chamber pillars are designed without implementing special preventive measures aimed at unloading. Figure 2b represents the distribution of the load-bearing pressure emerging in the marginal part of the ore deposit and supporting pillars after their construction.

Figure 2b shows that the pillar obtains the residual strength and the load-bearing pressure is usually around $2 \pm 3$ MPa. Therefore, such pillars will have a non-significant load-bearing capacity. In this regard, calculation of the parameters of supporting pillars consisting of less strong and less solid types of bauxite ores can be based on the residual stresses.
Figure 2. - Distribution of the load-bearing pressure in the supercritical mode of deformation: a - in the marginal part of the ore deposit; b - in panel (inter-chamber) pillars (1 – load-bearing pressure zone, 2 – marginal part of the ore deposit, 3 – panel pillar being designed, 4 – panel entry being designed, 5 – panel pillar, 6 – panel entry, \( \sigma_{\text{max}} \) – point of maximum load-bearing pressure, \( \sigma_0 \) – residual strength of the ore, \( X_i \) – distance between the marginal part of the ore deposit and point of maximum load-bearing pressure)

The results of the performed analysis show that starting from the depth of 600-700 m inter-chamber pillars lose their load-bearing capacity even when the size of mined-out space is insignificant (Figure 3). Doubling of the width of the inter-chamber pillars leads to a significant increase in their load-bearing capacity. At the same time, the inter-chamber pillars comprised of the typical varieties of bauxite ores (red easily soiled bauxite and red non-easily soiled bauxite) also lose their load-bearing capacity upon reaching a depth of 700-800 m, independently to the significance of the mined-out space. In this case, the destruction of the inter-chamber pillars consisting of less solid and less strong types of bauxite ores (red easily soiled bauxite and red non-easily soiled bauxite) will lead to additional loading and further destruction of the inter-chamber pillars comprised of more strong and solid types of bauxite ores (variegated bauxite).

Figure 3. - The deformation processes caused by the natural compliance (settling) of inter-chamber pillars

The increase in the shape ratio of the inter-chamber pillars to 1.5 or more ensures the stability of the inter-chamber pillars consisting of strong and solid bauxite ores (red non-easily soiled bauxite and variegated bauxite). At the same time, the inter-chamber pillars comprised of soft bauxite ores (red easily soiled bauxite) are being destroyed upon reaching the depth 600-700 m even when the size of mined-out spaces is insignificant, subsequently contributing to the destruction of more strong and solid inter-chamber pillars.

Drawing on the performed analysis of the stress state of columnar inter-chamber pillars under the context of traditional pillar mining system, we have built a diagram reflecting the dependence of ore losses occurring in the columnar inter-chamber pillars on the depth of mining (Figure 4).
Figure 4. Dependence of ore losses occurring in the inter-chamber pillars on the depth of mining for different types of bauxite ore (1 - variegated bauxite; 2 - red non-easily soiled bauxite; 3 - red easily soiled bauxite)

Analysis of the results presented in the Figure 4 shows that in the modern conditions of mining (deep mining) the ore losses calculated according to the Tournaire-Sheviakov method reach up to 30-50%. However, the ore losses may be reduced to 15-25% by taking into consideration the inter-chamber pillars’ supercritical deformation while designing their parameters (Figure 5).

Figure 5. Dependence of ore losses occurring in the inter-chamber pillars taking into account the residual strength (1 - variegated bauxite; 2 - red non-easily soiled bauxite; 3 - red easily soiled bauxite)

5. Conclusion
In this article we have revealed the changing patterns of the inter-chamber pillars’ stability and stress state taking into account the influence of various mining and geological factors. The established patterns enable us to conclude that at the depth of more than 800 m the inter-chamber pillars do not withstand the loads induced by the pressure of overlying rocks and, thus, get destroyed shifting to the residual strength regardless to the type of bauxite ore. The ore losses can be reduced to 15-25% by taking into account the supercritical mode of deformation of the inter-chamber pillars.

Such a significant decrease of ore losses would result into considerable growth of company’s revenue. At the same time, the production costs would not change, since the project of mine
development, the equipment and the labor intensity remain the same. The economic result would be achieved by improving the design process of mining operations Marinin M and Marinina O [29], providing increased safety of mining operations along with losses reduction leading to increase in production volumes. Due to the effect of operating leverage, profit growth would be non-linear, showing a faster growth rate rather than sales revenue. Likewise, taking into account the current pricing environment for aluminum, the profit growth rate would be even higher.

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