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Grapho-analytical optimization of ore drawing parameters from barrier pillars with field preparation in inclined deposits under caving conditions

D.K. Bekbergenov[1], R.K. Zhanakova[2*], M.N. Omiralin[1], S.A. Assylkhanova[2]
[1]*Mining Institute after D.A. Kunayev, Almaty, Kazakhstan*
[2]*Satbayev University, Almaty, Kazakhstan*
**Corresponding author:* *r.zhanakova@satbayev.university*

Abstract. This article presents the results of a grapho-analytical study aimed at optimizing technological parameters for ore drawing from barrier pillars (BP) in inclined ore deposits under caving conditions. The extraction of reserves remaining within barrier pillars is one of the most challenging tasks in underground mining, as it requires a balance between maximizing ore recovery and maintaining the geomechanical stability of the surrounding rock mass. Particular attention is paid to substantiating the rational spatial position of drill-haulage drifts (DDW) during field preparation in caving zones. The research methodology is based on geometric and grapho-analytical modeling of ore drawing processes under various mining and geological conditions. The study considers ore body thicknesses ranging from 6 to 12 m and dip angles from 15° to 51°. Several variants of left-asymmetric displacement of the DDW axis relative to the central axis of the barrier pillar were analyzed to determine their influence on ore recovery efficiency, ore losses, dilution, and the stress-strain state (SSS) of the surrounding rock mass. The results show that displacement of the DDW axis significantly affects both extraction performance and geomechanical safety. The rational displacement interval was found to be 1.5-2.0 m in the direction of the ore body dip. Further displacement leads to deterioration of the stress-strain state of the host rocks, reduction of the protective rock layer between the drift roof and the stoping floor, and the need for additional deepening of mine workings. Such modifications increase development volumes in waste rock and, consequently, mining costs. The effectiveness of asymmetric drift placement is most pronounced in deposits with dip angles up to 30°, whereas for steeper ore bodies with dip angles of 40-51°, its practical significance decreases due to the predominance of gravity-controlled ore flow. The obtained results provide a scientific basis for improving mining layouts and can be used in the design of underground mining systems to enhance ore recovery, reduce losses and dilution, and ensure geomechanical stability during the extraction of reserves from barrier pillars.
Keywords: *barrier pillar, inclined deposit, ore drawing, drill-haulage drift, caving zone, grapho-analytical modeling, stress-strain state.*

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1. Introduction

The effective extraction of mineral reserves remaining in barrier and panel-to-panel pillars is a critical issue for the mining industry of Kazakhstan. Recent studies show that the transition from open-pit to underground mining, especially in deposits with complex morphology, requires an in-depth analysis of geomechanical processes to ensure the stability of mine workings [1, 2]. During the repeated extraction of barrier pillars (BP) in caving zones of inclined deposits, the risk of rock mass destabilization increases, which necessitates the application of advanced monitoring and modeling methods [3, 4].

The fundamental aspects of ensuring the stability of open-pit slopes and underground structures have previously been considered using major deposits such as Vasilkovskoye and Akzhal as examples [2, 5]. It has been established that the accuracy of stress-strain state (SSS) prediction directly depends on the quality of geomechanical justification of mining system parameters [4, 6]. At the same time, minimizing ore losses and dilution remains a priority, as these factors determine the economic efficiency of production [7, 8].

Under the conditions of inclined deposits with dip angles of 15-51°, conventional approaches to the placement of preparatory workings are often insufficiently effective. Studies of ore drawing processes and the interaction between broken ore and caved rock indicate the need to optimize the spatial position of drill-haulage drifts (DDW). The use of modern support materials, including innovative shotcrete mixtures that improve stability under complex mining and geological conditions, also plays an important role in ensuring the long-term stability of such workings [9, 10].

The study of asymmetric field-preparation schemes is of particular scientific interest. Previous investigations of the SSS during repeated BP extraction have shown that the asymmetric arrangement of field workings makes it possible to shift zones of maximum stress concentration and thereby protect the structural elements of the mining layout [4]. In addition, high-energy methods of rock mass impact, such as hydraulic fracturing, provide additional opportunities for controlling the behavior of difficult-to-cave roofs [11].

In recent years, considerable attention has been paid to improving ore recovery technologies in caving mining systems [12, 13]. The efficiency of ore extraction from barrier pillars depends not only on the geological characteristics of the deposit, but also on the configuration of mine workings and the interaction between the fragmented ore mass and the surrounding rocks. Practical experience from underground mines shows that even minor changes in the location of production openings can significantly affect ore losses, dilution, and the overall economic performance of mining operations [14]. Therefore, the optimization of mining layouts remains an important scientific and engineering task.

The application of grapho-analytical methods provides an effective tool for investigating ore flow behavior under various mining and geological conditions. Unlike purely numerical approaches, grapho-analytical modeling enables the visualization of draw zones, the identification of stagnant areas, and the assessment of the influence of excavation geometry on extraction indicators [12, 15]. Such methods are particularly useful at the preliminary design stage, when rapid evaluation of several technological alternatives is required. Moreover, graphical models can serve as a basis for subsequent geomechanical analysis and engineering decision-making.

For inclined ore bodies, determining the optimal position of drill-haulage drifts is especially important, since gravity-driven ore movement is strongly affected by the deposit dip angle [13, 16]. As the dip angle increases, the geometry of ore flow zones changes considerably, which may influence both recovery efficiency and the stability of mining structures. Consequently, identifying rational displacement parameters for drill-haulage drifts is essential for achieving a balance between maximum ore recovery and geotechnical safety.

Despite the considerable amount of accumulated research data, issues related to the grapho-analytical optimization of left-asymmetric DDW displacement parameters for different ore body thicknesses of 6-12 m remain insufficiently studied. Therefore, the objective of this study is to determine rational parameters for the left-asymmetric displacement of drill-haulage drifts located beneath the barrier pillar and to assess their influence on ore recovery and geomechanical stability under various mining and geological conditions. The obtained results are intended to provide a scientific basis for optimizing field-preparation schemes and improving the efficiency of ore extraction from barrier pillars within caving zones.

2. Study area and proposed mining technology

Considering the current mining conditions at the Zhezkazgan deposit and the specific features of intact ore bodies located within the caving zone, the use of an underground mining technology based on a continuous caving system with end discharge of ore is proposed [3, 10]. This recommendation is based on the analysis of mining experience under similar geological and geotechnical conditions. Further testing of the proposed underground technology is planned at the Annenskaya mine of VZhR [4, 8, 11, 12].

According to the proposed technology, the extraction of intact ore bodies within the caving zone does not involve the formation of a conventional stoping chamber. Therefore, direct access of personnel and mining equipment to the unsupported stoping space is excluded. Safe mining operations are ensured by driving small-cross-section drill-haulage drifts (DDW), which allow the installation of rock bolts [13] and, where required, additional support using steel arch frames made of SVP-22 special profiles [9]. These workings provide access for drilling fan-shaped borehole patterns for ore breaking, as well as for loading and transporting the broken rock mass to the local ore pass.

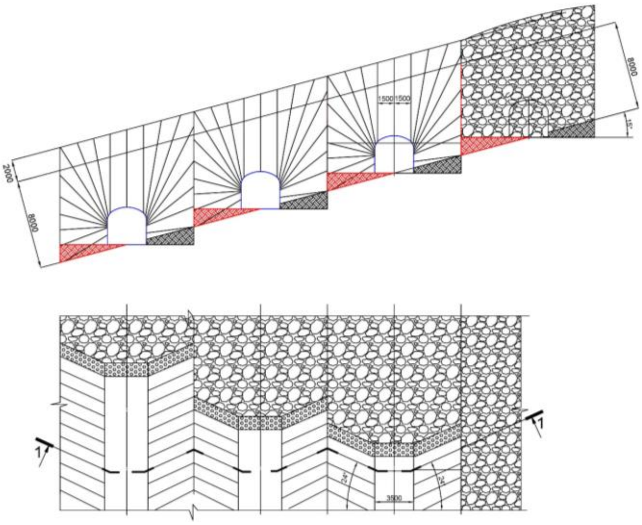

Figure 1. General view of the proposed technology for mining intact ore bodies using a continuous caving system with end discharge of ore mass within the caving zone: drilling pattern of fan-shaped boreholes in three planes and placement of the DDW along the ore–rock contact on the footwall side of the deposit

As shown in Figure 1, the proposed technological scheme is intended for inclined ore bodies with dip angles greater than 15° and thicknesses ranging from 6 to 12 m. The extraction block is formed along the strike of the ore body within a designated area up to 12 m wide. The DDW is driven along the ore–rock contact on the footwall side of the deposit. The drift is supported by rock bolts and, if necessary, by steel arch frames made of SVP-22 special profiles. Vertical fan-shaped boreholes are drilled from the roof and sidewalls of the DDW, while inclined fans are drilled to form a triangular undercut. After drilling, one fan of boreholes is blasted, followed by ventilation of the block. According to the end-discharge technology, the broken ore and host rock are then loaded and transported by self-propelled LHD equipment to the local ore pass.

The DDW is advanced section by section. Drilling-and-blasting operations are carried out in parallel with preparatory and cutting operations in subsequent DDW sections, while the broken rock mass is discharged accordingly. At the beginning of operations and throughout each working shift, all safety measures aimed at identifying and eliminating hazardous situations within the technological area must be strictly observed under the constant supervision of the shift foreman.

To extract reserves remaining in intact ore bodies, underground mining is therefore proposed using a continuous caving system with end discharge of ore and host rock [3, 10]. In this system, the block height is assumed to be equal to the ore body thickness, while the thickness of the caved ore layer is taken as equal to the line of least resistance of the blasted borehole fan. To reduce the seismic effect of blasting, one fan is detonated at short-delay intervals.

For preparatory operations, drill-haulage drifts are used for each panel within the block. Depending on mining and geotechnical conditions, the DDW may be driven either without additional support or with rock-bolt reinforcement combined with steel arch-frame support made of SVP-22 special profiles [9].

3. Research methods

The research methodology is based on grapho-analytical modeling aimed at justifying the rational parameters for the location of drill-haulage drifts (DDW) driven in the rock mass beneath the floor of barrier pillars (BP). The main focus of the study is to determine the rational magnitude of the left-asymmetric displacement of the DDW axis relative to the central axis of the BP. Such displacement makes it possible to adapt the technological scheme to the conditions of inclined ore bodies and to reduce the negative influence of the caving zone on the stability of preparatory workings.

To achieve this objective, a series of graphical models was developed for a wide range of mining and geological conditions. The variable parameters included ore body thicknesses of 6, 8, and 10 m at dip angles of 15°, 20°, and 30°. Particular attention was also paid to ore bodies with a thickness of 12 m, for which the range of analysis was extended to dip angles of 40° and 51°. This made it possible to evaluate changes in ore drawing conditions during the transition from gently inclined to steeply inclined ore bodies. During the modeling process, the displacement of the DDW axis relative to the BP axis was varied from 1 to 4 m with an increment of 1 m.

The optimization procedure was based on a comprehensive analysis of the geometry of the formed ore-drawing funnels and the corresponding slope angles of the caved rock mass. During graphical construction, the DDW positions were determined to ensure the most favorable relationship between ore recovery indicators and the safety of preparatory workings. Particular attention was paid to maintaining a stable stress-strain state (SSS) of the surrounding rock mass and preventing a critical reduction in the protective rock layer between the DDW roof and the floor of the stoping space.

At the final stage of the study, the obtained graphical solutions were generalized and the rational parameters of left-asymmetric DDW displacement were determined for different combinations of ore body thickness and deposit dip angle. These parameters were further used to substantiate the effectiveness of the selected geometric proportions of outlet workings during the repeated extraction of reserves from barrier pillars within the caving zone.

Thus, the proposed methodological approach makes it possible to compare alternative DDW displacement schemes, identify rational geometric parameters for different mining and geological conditions, and provide a basis for further graphical interpretation of the obtained optimization results.

4. Results and discussion

The grapho-analytical study was carried out to optimize the location parameters of drill-haulage drifts (DDW) driven in the rock mass beneath the floor of barrier pillars (BP). The analysis covered ore body thicknesses of 6, 8, and 10 m at dip angles of 15°, 20°, and 30°. In addition, for ore bodies with a thickness of 12 m, the study was extended to dip angles of 15°, 20°, 30°, 40°, and 51°. This made it possible to evaluate the influence of ore body geometry on the rational displacement of the DDW axis under different mining and geological conditions.

At the first stage, graphical models were developed for several variants of left-asymmetric DDW displacement relative to the BP axis. The displacement values were taken as 1, 2, 3, and 4 m in the direction of the ore body dip. An example of such graphical constructions for an ore body thickness of 6 m is shown in Figure 2. These schemes made it possible to compare the geometry of the formed ore-drawing funnels, the position of stagnant zones, and the relationship between the DDW roof and the floor of the stoping space.

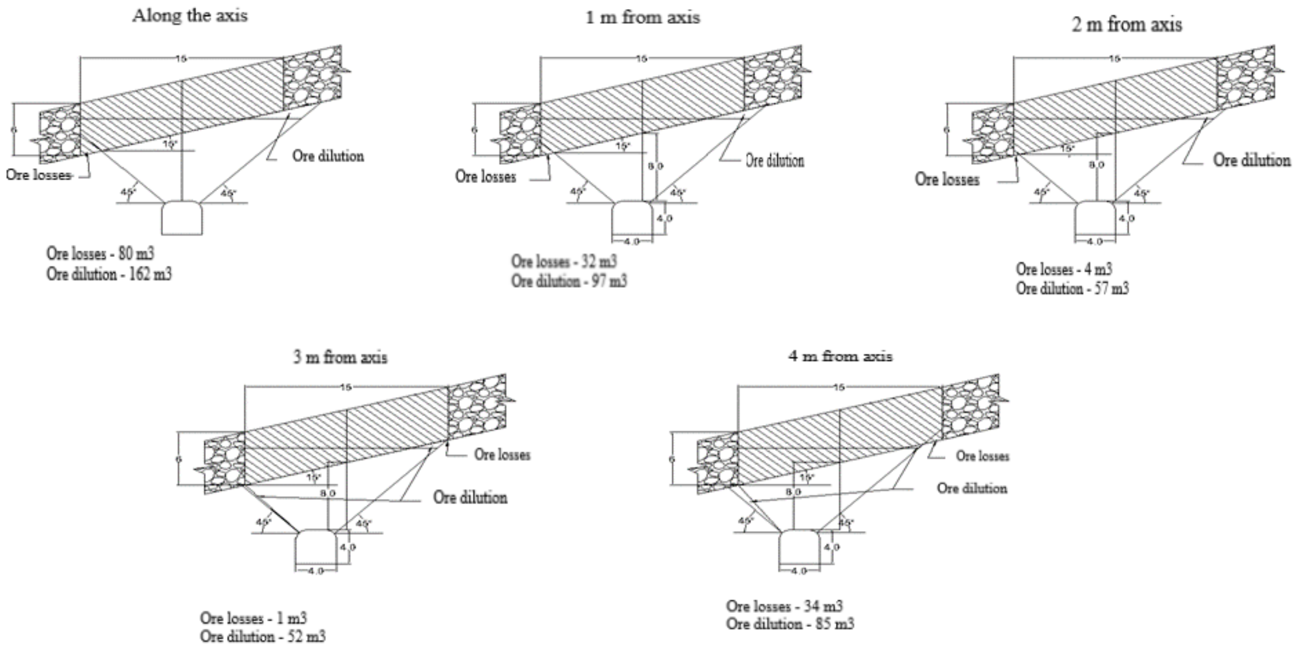

Figure 2. Graphical representations for optimizing left-asymmetric DDW displacement relative to the BP axis with shifts of 1, 2, 3, and 4 m during the repeated extraction of reserves from the BP for an ore body thickness of 6m

The obtained graphical results show that the displacement of the DDW axis has a nonlinear influence on the efficiency of ore drawing. A small displacement of 1 m does not always provide a sufficient correction of the ore flow geometry in inclined deposits, especially when the dip angle causes noticeable asymmetry in the movement of the broken ore mass. In contrast, excessive displacement of 3-4 m leads to distortion of the ore-drawing funnel, displacement of stagnant zones, and an increased risk of ore losses and dilution. Therefore, the DDW position cannot be selected only on the basis of maximum approach to the ore body; it must also take into account the stability of the surrounding rock mass and the preservation of a sufficient protective layer above the working.

The most favorable results were obtained when the DDW axis was shifted by approximately 1.5-2.0 m from the BP axis in the direction of the deposit dip. Within this interval, the geometry of the ore-drawing funnel remains technologically acceptable, while the protective rock layer between the DDW roof and the floor of the stoping space is not critically reduced. This provides a rational balance between ore recovery, dilution control, and geomechanical stability of preparatory workings.

Based on the graphical analysis, a left-asymmetric DDW shift of 2 m from the BP axis was adopted as the rational technological solution for the considered inclined deposits with dip angles up to 30°. The corresponding optimized parameters are presented in Figure 3a-f.

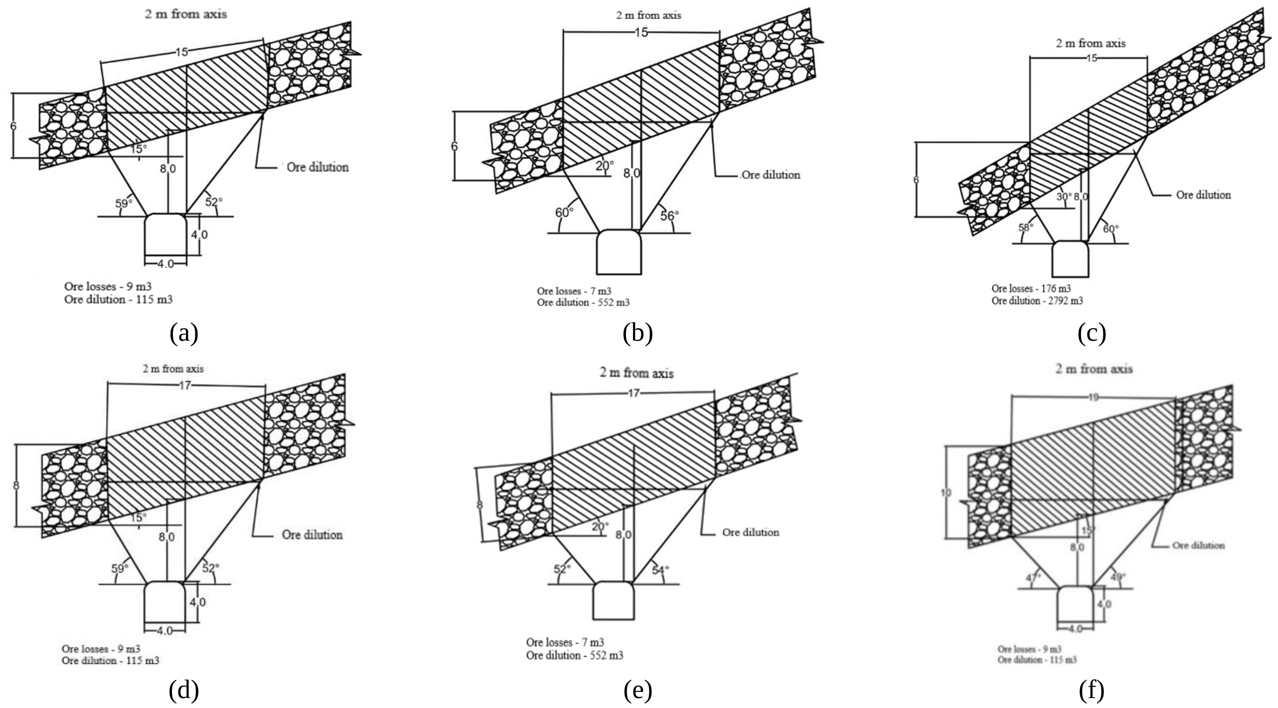

Figure 3. Optimal technological parameters for a left-asymmetric DDW shift of 2 m from the BP axis and the corresponding slope angles of the waste-rock outlet funnel: (a) ore body thickness of 6 m and deposit dip angle of 15°; (b) ore body thickness of 6 m and deposit dip angle of 20°; (c) ore body thickness of 6 m and deposit dip angle of 30°; (d) ore body thickness of 8 m and deposit dip angle of 15°; (e) ore body thickness of 8 m and deposit dip angle of 20°; (f) ore body thickness of 10 m and deposit dip angle of 15°

The comparison of the graphical schemes confirms that the practical efficiency of left-asymmetric DDW placement is most pronounced for inclined ore bodies with dip angles of 15-30°. Under these conditions, the ore mass movement is affected both by gravity and by the spatial configuration of the outlet workings. Therefore, a rational shift of the DDW axis makes it possible to improve the formation of the drawing funnel and reduce the probability of stagnant zones in the broken rock mass.

At the same time, an increase in DDW displacement beyond 2 m is not technologically justified in most of the considered cases. Although such displacement may locally modify the ore drawing conditions, it causes an unfavorable approach of the DDW roof to the floor of the stoping space. This reduces the thickness of the protective rock layer and may destabilize the stress-strain state (SSS) of the surrounding rock mass. If a shift greater than 2 m is required, additional vertical deepening of the DDW becomes necessary. Such a solution can partially restore geomechanical safety, but it also increases the volume of development in waste rock and, consequently, the cost of mining operations.

For steeply inclined ore bodies with dip angles of 40° and 51°, the influence of asymmetric DDW displacement decreases. Under these conditions, gravity-controlled ore flow becomes dominant, and the drawing process tends toward a more symmetrical vertical discharge pattern. As a result, the practical significance of shifting the DDW from the BP axis is reduced, while the additional costs associated with asymmetric preparation become less justified.

Thus, the results of the grapho-analytical study confirm that the rational displacement of the DDW axis depends on the combined influence of ore body thickness, deposit dip angle, ore-drawing funnel geometry, and the geomechanical condition of the surrounding rock mass. For the considered mining conditions, the most reasonable technological solution is a left-asymmetric DDW shift of 1.5-2.0 m, with 2 m adopted as the optimal design value for deposits with dip angles up to 30°.

5. Conclusions

Based on the conducted grapho-analytical study, rational parameters for the left-asymmetric displacement of drill-haulage drifts during the repeated extraction of reserves from barrier pillars in inclined ore bodies were substantiated. The analysis considered the combined influence of ore body thickness, deposit dip angle, ore-drawing funnel geometry, and the geomechanical stability of preparatory workings.

It was established that the displacement of the DDW axis relative to the BP axis has a nonlinear effect on ore drawing conditions. Insufficient displacement does not fully compensate for the asymmetric movement of the broken ore mass in inclined deposits, whereas excessive displacement distorts the geometry of the drawing funnel, increases the probability of stagnant zones, and may lead to higher ore losses and dilution.

The rational interval of DDW displacement was determined to be 1.5-2.0 m from the BP axis in the direction of the ore body dip. This interval provides the most favorable balance between ore recovery, dilution control, and preservation of a stable stress-strain state of the surrounding rock mass. For practical design purposes, a left-asymmetric shift of 2 m can be adopted as the optimal technological parameter for inclined ore bodies with dip angles up to 30°.

It was shown that a DDW shift greater than 2 m is generally not advisable without additional vertical deepening of the working. Although such deepening may improve the geomechanical position of the drift, it increases the volume of development in waste rock and therefore leads to higher mining costs. The efficiency of the proposed asymmetric preparation scheme decreases as the deposit dip angle increases. For steeply inclined ore bodies with dip angles of 40-51°, gravity-controlled ore flow becomes dominant, and the need for DDW displacement from the BP axis is significantly reduced. Therefore, the proposed recommendations are most applicable to inclined deposits with dip angles of 15°–30°.

The obtained results can be used to improve field-preparation schemes, increase ore recovery, reduce dilution, and maintain the geomechanical stability of workings during barrier pillar extraction.

Author contributions

Conceptualization: BDK, ZRK; Data curation: BDK, ZRK; Formal analysis: OMN; Funding acquisition: ZRK, OMN; Investigation: BDK; Methodology: ZRK, OMN; Project administration: BDK; Resources: ZRK, OMN; Software: BDK, ZRK, OMN; Supervision: BDK, ZRK, OMN; Validation: ZRK, OMN; Visualization: BDK, ZRK; Writing – original, draft: BDK, ZRK, OMN; Writing – review & editing: ZRK, OMN, ASA. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Еңіс кен денелерін опырылу жағдайында далалық дайындау кезінде тосқауыл кентіректерден кенді шығару параметрлерін графоаналитикалық оңтайландыру

Д.К. Бекбергенов[1], Р.К. Жанакова[2*], М.Н. Омиралин[1], С.А. Асылханова[2]

[1]Д.А. Қонаев атындағы Тау-кен институты, Алматы, Қазақстан
[2]Satbayev University, Алматы, Қазақстан

**Корреспонденция үшін автор: r.zhanakova@satbayev.university*

Аңдатпа. Мақалада опырылу жағдайында еңіс кенді шоғырлардағы тосқауыл кентіректерден (ТК) кен шығарудың технологиялық параметрлерін оңтайландыруға бағытталған графоаналитикалық зерттеу нәтижелері ұсынылған. Тосқауыл кентіректерде қалдырылған қорларды игеру жерасты кен өндірудегі ең күрделі міндеттердің бірі болып табылады, өйткені ол кенді барынша толық алуды және қоршаған тау жыныстары массивінің геомеханикалық тұрақтылығын сақтауды қатар қамтамасыз етуді талап етеді. Опырылу аймақтарында далалық дайындау кезінде бұрғылау-жеткізу қазбаларының (БЖҚ) ұтымды кеңістіктік орналасуын негіздеуге ерекше назар аударылған. Зерттеу әдістемесі әртүрлі тау-кен-геологиялық жағдайларда кен шығару процестерін геометриялық және графоаналитикалық модельдеуге негізделген. Қуаты 6–12 м аралығындағы кен денелері және 15°-тан 51°-қа дейінгі құлау бұрыштары қарастырылды. Кенді алу тиімділігіне, шығындарға, құнарсыздануға және қоршаған тау жыныстары массивінің кернеулі-деформацияланған күйіне (КДК) әсерін анықтау мақсатында БЖҚ осін тосқауыл кентіректің орталық осіне қатысты сол жақ асимметриялық ығыстырудың бірнеше нұсқалары талданды. Нәтижелер БЖҚ осінің ығысуы кенді алу көрсеткіштеріне де, геомеханикалық қауіпсіздікке де айтарлықтай әсер ететінін көрсетеді. Ығыстырудың ұтымды аралығы кен денесінің құлау бағыты бойынша 1.5–2.0 м құрайды. Ығыстыруды одан әрі арттыру жанас жыныстардың КДК-нің нашарлауына, қазба төбесі мен тазарту кеңістігінің табаны арасындағы қорғаныш тау жынысы қабатының азаюына, сондай-ақ тау-кен қазбаларын қосымша тереңдету қажеттілігіне әкеледі. Мұндай өзгерістер бос жыныстар бойынша қазба жүргізу көлемін ұлғайтып, тиісінше кен өндіру шығындарын арттырады. Қазбаларды асимметриялық орналастырудың тиімділігі құлау бұрыштары 30°-қа дейін болған жағдайда анағұрлым айқын байқалады, ал құлау бұрыштары 40–51° болатын тік кен денелері үшін оның практикалық маңызы кен массасының гравитациялық ағынының басым болуына байланысты төмендейді. Алынған нәтижелер дайындау сұлбаларын жетілдірудің ғылыми негізін қалыптастырады және тосқауыл кентіректерден қорларды игеру кезінде кенді алуды арттыру, шығындар мен құнарсыздануды азайту, сондай-ақ қазбалардың геомеханикалық тұрақтылығын қамтамасыз ету мақсатында жерасты игеру жүйелерін жобалауда қолданылуы мүмкін.

Негізгі сөздер: *тосқауыл кентірек, еңіс кен денесі, кенді шығару, бұрғылау-жеткізу қазбасы, опырылу аймағы, графоаналитикалық модельдеу, кернеулі-деформацияланған күй.*

Графоаналитическая оптимизация параметров выпуска руды из барьерных целиков при полевой подготовке наклонных залежей в условиях обрушения

Д.К. Бекбергенов[1], Р.К. Жанакова[2*], М.Н. Омиралин[1], С.А. Асылханова[2]

[1]*Институт горного дела им. Д.А. Кунаева, Алматы, Казахстан*
[2]*Satbayev University, Алматы, Казахстан*

**Автор для корреспонденции:* r.zhanakova@satbayev.university

Аннотация. В статье представлены результаты графоаналитического исследования, направленного на оптимизацию технологических параметров выпуска руды из барьерных целиков (БЦ) в наклонных рудных залежах в условиях обрушения. Извлечение запасов, оставленных в барьерных целиках, является одной из наиболее сложных задач подземной разработки, поскольку требует обеспечения баланса между максимальным извлечением руды и сохранением геомеханической устойчивости окружающего породного массива. Особое внимание уделено обоснованию рационального пространственного положения буродоставочных выработок (БДВ) при полевой подготовке в зонах обрушения. Методика исследования основана на геометрическом и графоаналитическом моделировании процессов выпуска руды при различных горно-геологических условиях. Рассмотрены мощности рудных тел от 6 до 12 м и углы падения от 15° до 51°. Проанализированы несколько вариантов левоасимметричного смещения оси БДВ относительно центральной оси барьерного целика с целью определения их влияния на эффективность извлечения руды, потери, разубоживание и напряженно-деформированное состояние (НДС) окружающего породного массива. Результаты показывают, что смещение оси БДВ существенно влияет как на показатели извлечения, так и на геомеханическую безопасность. Рациональный интервал смещения составляет 1,5-2,0 м в направлении падения рудного тела. Дальнейшее увеличение смещения приводит к ухудшению НДС вмещающих пород, уменьшению защитного породного слоя между кровлей выработки и почвой очистного пространства, а также к необходимости дополнительного заглубления горных выработок. Такие изменения увеличивают объем проходки по пустым породам и, соответственно, повышают затраты на добычу. Эффективность асимметричного расположения выработок наиболее выражена при углах падения до 30°, тогда как для более крутых рудных тел с углами падения 40-51° его практическое значение снижается вследствие преобладания гравитационно обусловленного потока рудной массы. Полученные результаты формируют научную основу для совершенствования схем подготовки и могут быть использованы при проектировании подземных систем разработки с целью повышения извлечения руды, снижения потерь и разубоживания, а также обеспечения геомеханической устойчивости выработок при отработке запасов из барьерных целиков.

Ключевые слова: *барьерный целик, наклонная залежь, выпуск руды, буродоставочная выработка, зона обрушения, графоаналитическое моделирование, напряженно-деформированное состояние.*

Publisher's note