Extraction of ore reserves from pillars in room-and-pillar mining

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Abstract. The geotechnical situation in mines using the open stoping methods is governed by complex geomechanical behavior of rock mass around rib and level pillars. The impact of rock pressure on underground excavations grows in this case, and dynamic events due rock pressure happen more often. The latter became the reason for implementing this research. In terms of steeply dipping ore bodies, safe mining of earlier left pillars is feasible. The best scenario for pillar extraction, considering their parameters, is caving to open and partly filled with overlying rocks stopes. The geomechanical calculations during justification of mining parameters during extraction of ore reserves from pillars have determined regular patterns in the stress–strain behavior of rocks mass, which contributes to qualitative and quantitative prediction of safe and feasible mining conditions. The zones of instability in structural elements of the geotechnology, including pillars, are detected. The author proposes the order and sequence of pillar caving to open and partly filled stopes at the admissible completeness and quality of extraction.

1. Introduction
Thick and medium-thick and steeply dipping ore bodies currently under mining mostly feature complicated geotechnical situation governed by accumulation of many rib and level pillars left during earlier mining operations. Considering volume of these pillars, need to add to mineral resource base and probability of dynamic events due to rock pressure (as pillars are commonly assumed as concentration zones of higher pressure), mines are faced with the need to extract ore reserves from these pillars.

First, it is required to justify efficiency of pillar mining and to select safe and feasible mining technology. The adversities in safe pillar mining are the absence of access to the pillars and high probability of partial or complete failure of pillars in the extremely difficult geological and geomechanical conditions.

Efficient prediction of integrity of various pillars is possible using multi-variate mathematical modeling of their stress–strain behavior in the given geotechnical structure of a mine and varied indexes of ore and rock mass quality within the range typical of the given deposit [1–6].

This approach promotes understanding of geomechanical behavior of pillars and stopes affected by them, as well as feasibility of safe extraction ore reserves from the pillars at minimum loss and dilution.

2. Sublevel stoping
The system of sublevel stoping is depicted in Figure 1.
Figure 1. Sublevel stoping: 1—level haulage drive; 2—sublevel haulage drive; 3 and 5—access under vent raise; 4 and 6—vent raise; 7—access under orepass; 8—orepass; 9—cutting cross drift; 10—lateral haulage drift; 11—trench cut; 12—loading entry; 13—discharge stope; 14—production blastholes; 15—shattering blastholes; 16—rib pillar; 17—stope.

An extraction panel is divided into sections 80–100 m long along the strike and into sublevels 20 m high along the dip. Each sublevel is divided into stopes 50–70 m long parted with rib pillars. This system is recommended for ore bodies to 18.0–25.0 m thick.

At the preparatory stage, in footwall rock mass, sublevel haulage drives are made, and cutting cross drift are driven from these drives along the boundary of the extraction panel. From the cross drifts, a trench cut and a lateral haulage drift are made at a spacing of 16–30 m. The angle of the trench walls is to be not less than 50°.

Before stoping, from the trench cut to the upper top of the ore body, a cut-off raise is made by two–three blasts; later on the cut-off raise is expanded into the cut-off opening to the full thickness of the ore body.

After formation of the cut-off opening, blasting is carried out from the trench cut by layers toward open space. Broken ore is discharged at the ends of the loading entries and, partly, from the trench cut. Ore haulage within the extraction panel is carried out using load–haul–dumpers ST-14 and LH-410 by AtlasCoppco, or similar. LHD machines haul ore to orepasses to be passed to the level haulage drive; there, ore is loaded to dump trucks using vibratory feeders.
3. Justification of mining parameters for pillars

Safe mining parameters were determined from variational 3D numerical modeling of the stress–strain behavior and stability of rocks in the structural elements of the geotechnology using the finite element method [1–3]. The developed 3D geomechanical model of the geotechnical situation represented the block parametric diagram of mining during extraction of ore reserves from stopes, rib pillars (RP) and level pillars (LP) subjected to horizontal forces in compliance with the effective tectonic stress state [4–8], with preservation of the actual infrastructure governed by accessing and preparation of the ore body. The tectonic model of the geomedium was chosen due to prevalence of this stress type over the other [4–8].

Figures 2 and 3 show zones of possible failure in RP in the section along the strike of the ore body depending on the pillar width, rock mass quality \( K_c \)—coefficient of structural weakening) and length of the stope at the ore body thickness \( m = 25 \) m, mining depth of 300–400 m the stope height \( h_{st} = 60 \) m. The computational domain showed a typical geotechnical situation during mining of a blind ore body, with mined-out and operating stopes, with regard to lithology of one of the actual mineral deposits in Russia.

![Figure 2](image1.png)

**Figure 2.** Damaged rock zones (Mohr–Coulomb criterion) in structural elements of stoping systems (along the central axes of stopes) depending on the width of rib pillars and jointing of rock mass at the ore body thickness \( m = 25 \) m with stopes with height and length of \( h_{st} = 60 \) m and \( L_{st} = 65 \) m, respectively.

![Figure 3](image2.png)

**Figure 3.** Damaged rock zones in RP, and in stope roof and floor at \( W_{RP} = 15 \) m, \( h_{st} = 60 \) m and \( L_{st} = 50 \) m.
It is found that under very high values of the effective horizontal stresses, depending on rock mass jointing, first an internal core of failure appears and grows up to the lateral boundaries of rib pillars; then rock failure starts in the roof and floor of stopes. Instability of overlying rock mass and bottom of the extraction panel takes place exclusively in a very poor, heavily jointed rock ass ($K_c$ under 0.2) and in case of long spans.

Consequently, in rock mass under tectonic stresses, owing to the excess of the natural horizontal stresses over the vertical stress $\gamma H$ by 2.5–5 times, integrity and stability of roof is preserved in stopes during excavation.

Figure 4 shows the curves of the minimum sizes of rib pillars, spans of stopes and degree of jointing in rock mass.

![Figure 4. Minimum size of rib pillars versus (a) stope span and (b) coefficient of structural weakening at ore body thickness $m = 25$ m, stope height $h_{st} = 60$ m and mining depth of 400 m.](image)

It is shown that mining safety in areas of higher density of joints can be reached through the stope span control. For instance, in rock mass with the structural weakening coefficient $K_c = 0.5$, the reduction in the length of the stopes from 70–65 m to 50–40 m, at the other structural parameters being equal, ensures stability of rib pillars and stope roof for the whole period of mining in the extraction panel and further allows safe extraction of ore reserves from the pillars.

According to the calculated data, in the limiting case, the maximum depth for application of open stoping in most deposits, as per the methods of selection and justification of mining systems and based on the geomechanical modeling [7, 8], is limited to 400–600 m. The mining system design parameters have the ranges below:

- Level height—40–60 m;
- Stope length—40–50 m;
- Stope height—40–60 m;
- Rib pillar width—10–15 m (mining depth to 400 m) and 15–20 m (mining depth below 500 m).

Considering practical experience of open stoping and geomechanical aspects of stability of rib pillars, level pillars and spans in the period of stoping, it is recommended to implement stoping with ore discharge via trench bottom in blind ore bodies to the height of no more than 2 levels initially. The width of rib pillars is limited to 10–12 and 15–20 m in medium- and heavily jointed rock mass, respectively.

As stoping is advanced, the number of RP and LP grows. The integrated analysis of mining situation in operating mines reveals feasibility of 3 geotechnical scenarios in the mine structure represented by pillars:

**Scenario 1**—open stopes, no caved rocks. In this case, considerable volumes of ore reserves can be extracted from rib and level pillars;
**Scenario 2**—stopes are filled with caved rocks more than by 40% of the stope height. In this case, rib pillars can be mined (at high loss and dilution) and level pillars can be extracted at higher economic efficiency by retreat mining.

**Scenario 3**—stopes are filled with caved rocks less than by 30% of the stope height. One of the acceptable technologies involves discharge of gangue and then extraction of ore reserves from rib and level pillars.

This study considered the most typical conditions of mining of pillars depending on the number of stopes extracted along the strike and limited by actual stoping from above and by extracted stopes of the lower lying level from below (Figure 5).

The proposed mathematical modeling variants, in conformity with the actual geological parameters (thickness, depth, sizes of stopes and pillars) and geotechnical conditions (many pillars and extracted stopes, orepasses and raises driven both in ore and dirt rock, advance direction of pillar mining—this information makes it possible to find loads on the pillars in case of increasing total span of stoping), allow more correct stress–strain analysis and assessment of integrity in pillars.

The numerical modeling yields that the most favorable situation in terms of stresses appears when orepasses and vent raises are driven in rock mass. As against the arrangement in ore, pillars are subjected to lower load and the induced stresses are not post-limiting. In this case of the field driving of ore passes, the probability of safe and complete extraction of ore reserves from pillars essentially grows.

With regard to the implemented geomechanical assessment, the order of pillar mining is (Figure 6): Stage I—simultaneous caving of two–three RP and LP to unfilled open stopes (it is required to leave an ore layer as a safety cushion); Stage II—after caving of RP (or concurrently) overlying
hanging wall rocks are caved in order to fill mined-out void with gangue rocks (for creation of the cushion of the wanted volume for mining safety at the lower lying levels).

After initial stage of open stoping in 2 levels, in medium and low grade ore, it is advised to transfer to the sublevel caving technology [9, 10]. In this case, RP and LP are extracted by bulk caving and caved overlying rocks offer a safety rock cushion for lower level mining (the safety cushion made of caved overlying rocks can protect mine from possible bumps).

For caving of overlying enclosing rocks to open stoping void, it is recommended to use a cutting cross drift driven in hanging wall with further drilling to be performed from this drift to the height not less than the height of the level. In this case, it is possible that extension zones appear nearby the hanging walls, which can favorably activate the caving process.

4. Conclusion
The low level of reproduction of mineral reserves and the lack of prompt preparation of extraction panels for mining forces mines to extract earlier left pillars. It is found that integrity of a geotechnical structure composed of pillars and mined-out stopes is governed by the applied mining system parameters, total span of stoping both horizontally and vertically, as well as by the degree of jointing (quality) of ore and rock mass under mining. The basic method to avoid impact of rock pressure on operating stopes is well-timed extraction of rib and level pillars subsequent to stoping with a lag not more than 2–3 extraction units on a level, with extraction of pillars on the upper level by 2–3 stopes ahead of pillars on the lower lying level.

The geomechanical analysis provides the order and sequence of extraction of rib and level pillar by systems with caving, which allows safe mining at acceptable indices of extraction completeness and quality.

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