Extraction of ore reserves from undermined protective pillar under open pit bottom

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Abstract. One of the problems in ore mining is untimely preparation of ore reserves for extraction. Eventually, mining efficiency drops. Aiming to replenish quickly depleting reserves, mining of various-purpose pillars is undertaken. For this reason, studies into safe mining of pillars are relevant and essential. For instance, for a gold mine in ground conditions of pronounced geological and structural uncertainty, for the sustained short- and-medium-term production, a method was validated and proposed for extraction of ore reserves from the undermined crown pillar left under the open pit bottom. In the framework of this research, a geomechanical model of an ore deposit has been developed in the form of a conceptual flow chart of mining of a crown pillar under an open pit bottom at the preserved production infrastructure condition by surface and underground mining. 3D numerical modeling uses the finite element method. The calculations find that underground mining of the undermined protective pillar under the open pit bottom, due to considerable jointing of the steeply dipping ore body, is limited by expansion of wide possible rock damaged zones up to the ground surface.

1. Introduction
Many currently operating mines are faced with the problem of preparing ore reserves for extraction. One of the efficient ways of replenishing depleted reserves and sustaining project capacity of a mine can be mining of various-purpose timely inactive pillars in the existing underground infrastructure [1–5]. For instance, for a gold mine in ground conditions of pronounced geological and structural uncertainty, for the sustained short- and-medium-term production, a method was validated and proposed for extraction of ore reserves from the undermined crown pillar left under the open pit bottom. Thus, the problem is relevant and needs to be studied further [6–11].

In connection with this, this paper discusses geomechanical assessment of safe extraction of ore reserves from an undermined and overmined pillar under an open pit bottom.

2. Research methods and engineering solutions
Within this research, a 3D geomechanical model has been developed in the form of a conceptual parametric flow chart of mining a pillar under an open pit bottom, subjected to loading by equal forces conforming with hydrostatic stress field, with preservation of the current infrastructure conditioned by operation of surface and underground mines (Figure 1) [12–17].

Modeling, stress–strain analysis and stability calculation of the protective pillar between the surface and underground mines were performed in the framework of elasticity (linear stress–strain dependence) in three dimensional space using the finite element method [18–23].
Figure 1. Computational domain $R$ with basic parameters for modeling stress state and stability of rock mass in geotechnical structure of a deposit.

The evolution of stresses and strains in the computational domain $R$ is described by the system of equations below:

- Static relations
  \[ \sigma_{ij,j} + pF_i = 0, \]  

- Geometric relations
  \[ \epsilon_{ij} = 0.5(u_{i,j} + u_{j,i}), \]  

- Physical relations
  \[ \sigma_{ij} = 2G\epsilon_{ij} + \lambda\theta\delta_{ij}, \]  

- and boundary conditions:
  \[ \begin{align*}
  \sigma_y(0,x,z) &= \gamma g H = 0, \quad \tau_{xy}(0,x,z) = \tau_{yz}(0,x,z) = 0; \\
  u_y(L_y,x,z) &= 0, \quad \tau_{xy}(L_y,x,z) = \tau_{yz}(L_y,x,z) = 0; \\
  \sigma_z(0,x,y) &= q\sigma_y, \quad \tau_{xz}(0,x,y) = \tau_{zx}(0,x,y) = 0; \\
  u_z(L_z,x,y) &= 0, \quad \tau_{xz}(L_z,x,y) = \tau_{zx}(L_z,x,y) = 0; \\
  \sigma_z(L_z,z,y) &= q\sigma_y, \quad \tau_{xz}(L_z,z,y) = \tau_{zx}(L_z,z,y) = 0; \\
  u_z(0,z,y) &= 0, \quad \tau_{xz}(0,z,y) = \tau_{zx}(0,z,y) = 0;
  \end{align*} \]  

where $\sigma_{ij}$ are the stress tensor components ($\sigma_x$, $\sigma_y$, $\sigma_z$ and $\tau_{xy}$, $\tau_{xz}$, $\tau_{yz}$ are, respectively, vertical, horizontal normal and shear stresses); $pF_i = \gamma g \delta_{ij}$ are the bulk forces; $\gamma$ is the density of rocks; $g$ is the gravitational deceleration; $\epsilon_{ij}$ are the strain tensor components ($\epsilon_x$, $\epsilon_y$, $\epsilon_z$ and $\epsilon_{xy}$, $\epsilon_{xz}$, $\epsilon_{yz}$ are, respectively, the vertical and horizontal principal linear and angular strains); $u_i$ are the displacement vector components ($u_x$, $u_y$, $u_z$ are the vertical and horizontal displacements); $\theta = \epsilon_x + \epsilon_y + \epsilon_z$ is the relative volumetric strain; $G$ and $\lambda$ are the Lamé parameters; $\delta_{ij}$ is the Kronecker delta; $q_x$, $q_z$ are the lateral earth pressure coefficient; $H$ is the depth of mining.

Geomechanical assessment required solution of a multivariate problem of mining advance:

---Scenario 1 provides extraction of ore reserves from the protective pillar by upward cut-and-fill system at different stages of stoping (4 stages) near the open pit bottom by sublevel caving;

---Scenario 2 assumes mining of the protective pillar sublevel stoping with cemented backfill (2 stages).

The solution assumed that backfill imposes a certain load and has cohesion with ore body and enclosing rock mass.

Scenario 1 has 4 stages described below.
Stage 1: extraction of two layers (one with backfill, another as open stoping). The ore pillar thickness is \( \approx 25.0–30.0 \text{ m} \);
Stage 2: Extraction of half-height of the pillar by slice mining. The pillar thickness is \( \approx 15.0–20.0 \text{ m} \);
Stage 3: Slice open stoping ≈ 4.5–5.0 m, preparation of the rest pillar 15 m high for sublevel caving;
Stage 4: Sublevel caving of the rest pillar 15 m high with stoping advancing to the middle of the ore body along the strike.

Scenario 2 involves 2 stages below.
Stage 1: Half-height mining by stoping with cemented backfill. The rest pillar ≈ 15.0–18.0 m high is prepared for open stoping with rib pillars (RP);
Stage 2: Mining of the rest pillar ≈ 15.0–18.0 m high is prepared for open stoping with rib pillars (RP). The open stope size along the strike is assumed to 10 m, the width of RP is 3–5 m.

The numerical calculation results are shown in profiles oriented across (sections 1–3) and along (section 4) the strike of the ore body (Figs. 2–4). Stage 2/2 in Scenario 2 means Stage 2 with vertical cut for the stress–strain analysis made along RP nearest to the open stope.

Figure 2. (a) 3D image of profiles in geomechanical assessment of underground mining of protective pillar; (b) plane view of sections for stress–strain analysis and stability estimation of rock mass.

Figure 3. Sections for Scenario 1, Stage 2.

The estimate criterion was the stability factor by the Mohr–Coulomb theory [24–31]:

\[ K_m = \frac{2C \cos \phi + (\sigma_1 + \sigma_3) \sin \phi}{(\sigma_1 - \sigma_3)}, \]  

(5)

where \( C \) is the cohesion, MPa; \( \sigma_1 \) and \( \sigma_3 \) are the maximal and minimal principal stresses obtained from the elastic solution, MPa; \( \phi \) is the internal friction angle, deg. The values of \( K_m \) less than one characterize possible damaged rock zones. The values of the mechanical characteristics of rocks (cohesion and internal friction angle) in (5) were assumed with regard to the structural weakening factor of rocks \( (K_s) \).
3. Results and analysis
The generalized modeling results in the considered mining scenarios are presented as the comparative estimate by mining stages in the protective pillar under the open pit bottom (Figs. 5 and 6).

The analysis of geotechnical situation in mining of the protective pillar by Scenario 1 shows that:
- at the initial stage of mining (Stage 1 with backfilling of the first layer), there are no wide zones of possible instability in rock mass around the stoping and pillar. An exception is the north area where the pillar instability is predicted with damaged rock zone expanding up to the ground surface. Isolated damaged rock zones localize in the roof of the stopes and development and entry faces, near the open pit bottom and in the level pillars, which, irrespective of the mining stage, are the zones of higher stress concentration, which makes them the most vulnerable elements of the geotechnology;
- mining according to stage 2 essentially deteriorates the geomechanical situation. The zones of possible instability are predicted far and wide in the influence zone of the protective pillar, capturing the interface zone and almost whole hanging wall of the ore body, especially when $K_s = 0.15–0.25$;
− in mining the half-height of the protective pillar (20 m high) by horizontal upward cut-and-fill, the critical strain zones are predicted across the whole volume of the protective pillar and its interface zone, capturing stopes in the influence zone of underground mine;
− mining according to stage 4 is unallowable irrespectively whether the sublevel caving system or mining with backfill is used.

Figure 6. Distribution of maximal shear stresses $\tau_{\text{max}}$ and predicted zones of instability in rock mass within the considered geotechnical structure for Scenario 2 in section 1: 2–2/2 mean mining stage 2.

Similarly, the analysis of geotechnical situation in mining of the protective pillar by Scenario 2 shows that:
− the rest 15–18 m-high part of the ore pillar adjoining immediately the open pit bottom falls in the zone of probable failure in stoping according to stage 1. The vast zone of post-limit deformation is located in the hanging wall of the ore body and expands up to the ground surface. The highest instability is predicted in the roof of stopes, with considerable failure unavoidable. This stage of stoping is assumed as the limit case close to the emergency situation in the mine;
− mining at the bottom of the open pit (top of the protective pillar) by open stoping with rib pillars (stage 2) is unallowable due to unsafety. The latter is conditioned by total instability of geotechnical structure of the protective pillar.

The insignificant differences in distributions of stresses and stability in the ore body and rock mass in Scenarios 1 and 2 at the final stages (accordingly, stages 4 and 2) are explained by different strength and deformation characteristics of backfill. However, these differences have no considerable influence on the zones and nature of possible damage in elements of the geotechnical structure of the protective pillar.

It is worthy of mentioning that no stresses induced in the main body of ore and rock mass are limiting relative to its deformation and strength characteristics. Nonetheless, considering rock mass quality, the rock mass tends to the limit stage in terms of tension and shearing, towards the worst situation.

Thus, for Scenario 1, the geomechanically safest stage is slice stoping of two layers in the protective pillar (Figure 7, stage 1), when thickness of the pillar is not less than 25–30 m. In all other variants, the geotechnical situation generated by gradual extraction of ore reserves from the pillar is unallowable due to initiation and expansion of possible damaged rock zones. Under such conditions, safe mining of the pillar is only possible by the open pit method (deepening of the pit).

Extraction of the rest part of the protective pillar by open stoping with leaving rib pillars (stage 2) in Scenario 2 is unallowable due to considerable zones of instability in the elements of the
geotechnical structure (rib pillars, around the open stopes, in footwall and in hanging wall), with expansion up to the ground surface. Therefore, as above, the safest approach to extraction of reserves from the protective pillar is the open pit mining method.

4. Conclusions
1. It has been found that underground mining of the undermined protective pillar under the open pit bottom in the steeply dipping ore body, due to its poor quality, is limited by expansion of vast damaged rock zones up to the ground surface.
2. Under conditions of the pronounced geological and structural uncertainty of the rock mass, the suggested method to extract ore reserves from the protective pillar under the bottom of an open pit is the open pit mining.

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