Stress–strain analysis of rock mass during mining of protective pillar of vertical shaft

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Abstract. The implemented studies aim at the geomechanical assessment of safe mining, including safety pillars, within the limits of the protective pillar of shaft RESH in the Irtysh Mine, with estimation of influence exerted by stresses and strains on the rock mass, permanent excavations and ground surface. Slacked replenishment of the raw material resources makes re-extraction of ore reserves from pillars highly topical. It is found that ore loss in mining of the protective pillars reach 30% and above of total reserves at some deposits. Based on the analytical solutions and 3D FEM modeling in terms of the Irtysh Mine, the authors validate feasibility of safe partial extraction of ore reserves from the protective pillar of shaft RESH without aggravating effect on the shaft operation and on the ground surface. The feature of this study is using both specification documents and mathematical modeling, with regard to geology, structure and lithology of a deposit and rock mass, physical and mechanical properties and geometrical complexity of mine objects, which essentially improves studies into stability of underground openings and ground surface. It is found that the basic measure of safety in mining of the protective pillar of shaft RESH is establishing safety pillars.

1. Introduction

In mining one of the basic protective actions to shield access shafts from influence of stoping are protective pillars [1–5]. In the majority of operating mines, protective pillars hold up to 30% of proven ore reserves. Complication of geological conditions and decrease in available reserves in mining at deeper levels calls for new ways of replenishing raw material sources. In such situation, extraction of ore reserves from pillars, including protective pillars, is one of the options though the comprehensive elaboration and validation of proper engineering solutions is required [6–9].

Currently, the only safe approach to extraction of ore reserves from pillars is the cut-and-fill systems. On the one hand, these systems eliminate the adverse effect of strata pressure on permanent openings as well as hazardous deformation of ground surface. On the other hand, the unreasonable rise in cost of cemented backfill at the low and mean value of ore makes production inefficient. Thus, development of engineering on safe extraction of ore reserves from pillar is a critical mission [10–14].

This paper describes the packaged studies aimed to evaluate feasibility of partial extraction of ore reserves from a protective pillar by systems with backfill with only a row of safety pillars in terms of shaft RESH in the Irtysh Mine.

2. Geotechnical situation and solutions

In order to solve the preset problems, 3D parameter-oriented model was developed for the geotechnical situation in the area of shaft RESH, including opening on haulage horizons nos. 0–13,
mined-out stopes between horizons nos. 0–13, vertical access openings, rib pillars (RP), level pillars (LP) and safety pillars (SP).

Aiming to select the order and sequence of extraction of ore reserves from the protective pillar, 3 stoping scenarios were analyzed.

**Scenario 1**—stress–strain analysis and assessment of stress–strain influence on shaft RESH and ground surface in application of systems with sublevel stoping, shrinkage stoping, as well as in extraction of ore reserves from RP, LP and SP 3–5 by block caving with filling of open stopes on levels 10–13 within the boundaries of the protective pillar of shaft RESH and with establishing LP (Figure 1).

**Figure 1.** Scenario 1: extraction of ore reserves within the protective pillar of shaft RESH up to level 13 without SP, with LP established (the level spacing is 50 m).

**Scenario 3**—extraction of ore reserves from stopes, RP and within the protective pillar of shaft RESH in the depth interval of levels 9–13 with establishing SP 3, 4 and 5.

**Figure 2.** Scenario 3: Extraction of ore reserves from stopes, RP and within the protective pillar of shaft RESH in the depth interval of levels 9–13 with establishing SP 3, 4 and 5.
Scenario 2 (limit case)—sublevel stoping and shrinkage stoping, as well as extraction of reserves from RP, LP and SP by block caving with filling on levels 9–13 within the protective pillar of shaft RESH (extraction of ore reserves from the protective pillar in the depth interval of levels 9–13 with undermining of overlying stopes and ground surface).

Scenario 3 (similar to Scenario 2)—extraction of ore reserves from the protective pillar of shaft RESH in the depth interval of levels 9–13 with only SP 3, 4 and 5 left (Figure 2).

Figures 3 and 4 visualize the obtained results (stress distribution) per characteristics cross sections both vertically along and across the strike, and laterally on levels 9–13:
— in the center of SP across the strike (sections 1–3);
— across the strike along shaft RESH—section 2; along the strike—section II);
— across the strike in ventilation holes—sections 3 and 4, along the strike—sections I and III;
— in footwall rocks (section IV along the strike of the ore body).

Figure 3. Cross sections and plan views of the geomechanical model.

Figure 4. Vertical sections of geomechanical model for estimating influence of stoping and extraction of ore reserves from safety pillars on ground surface, RESH shaft and permanent openings on haulage levels.
Safe conditions of undermining of buildings, structures, utility services and shafts, as well as protection measure are determined and selected from the comparison of the estimated, permissible and critical values of strains in rock mass and on ground surface.

Given the known estimated, permissible and critical strains of ground surface, undermining of surface buildings and structures is allowable if:

— anticipated strains are less than permissible values—without constraints;
— anticipates strains exceed critical values—safety measures are required to be undertaken.

The basic research method is the finite element-based modeling of stresses and strains in rock mass [15–18]. The modeling assumed that: the axis $y$ was oriented vertically; the axis $z$—across the strike of the ore body; the axis $x$—along the strike (i.e. $\sigma_y = \gamma H$, $\sigma_z = q_z \sigma_y = 0.9 \gamma H$, $\sigma_x = q_x \sigma_y = 0.8 \gamma H$). Stability of rock mass was assessed based on the stress–strain analysis [19–24].

The mathematical modeling was added with analytical prediction of straining of undermined objects during extraction of ore reserves from the protective pillar of shaft RESH [25–27].

The maximum ground surface subsidence is calculated as:

$$
\eta_{\text{max}} = \frac{k_m \times k_x \times L \times D \times m}{(2H_0 + D_1)^2},
$$

where $k_m$, $k_x$ are the coefficients of physical and mechanical properties of rocks, rock mass structure an dip angle of the ore body, assumed to equal 0.43 and 1.0, respectively; $D_1$, $L$ are the sizes of the mined-out area along the dip, along the strike; $H_0$ is the occurrence depth of the ore body; $m$ is the net thickness of the mind-out void.

The anticipated strains in the rock mass and on the surface are calculated using the procedure of standard curves [28–31 in application at coal deposits. Displacement and deformation at any point of subsidence trough were calculated from the formulas:

$$
\eta = \eta_{\text{max}} \times S(z),
$$

$$
i = \pm \frac{\eta_{\text{max}}}{L_i} \times F(z),
$$

$$
\zeta = 0.5 a_0 \times \eta_{\text{max}} \times F(z),
$$

$$
\varepsilon = \frac{0.5 a_0 \times \eta_{\text{max}} \times F'(z)}{L_i},
$$

where $z = x/L$ is the relative coordinate of a point in the half-trough of subsidence; $x$ is the current coordinate of the point in the half-trough of subsidence, calculated from the trough center (point of the maximum subsidence); $L_i$ is the length of the half-trough of subsidence ($L_1$—up-dip, in footwall; $L_2$—downdip, in hanging wall); $S(z)$, $F(z)$ are the standard tabulated distribution functions of subsidence, inclination and horizontal displacements as well as horizontal compressive–tensile strains in the half-trough of subsidence, depending on the coordinate $z$; $i$ are the inclines; $\zeta$ is the horizontal displacement; $\varepsilon$ are the horizontal compressive–tensile strains; $a_0 = 0.3$.

The boundary angles were assumed as $\beta_{01} = 60^\circ$ (in footwall), $\beta_0 = 55^\circ$ (in hanging wall). The half-length of the subsidence trough in the footwall is $L_1 = 420$ m. The distance from the subsidence trough center to the mouth of shaft RESH is $x = 180$ m. Accordingly, the relative coordinate of shaft RESH mouth in the half-trough of subsidence is $z = 180/420 = 0.43$.

The values of the standard functions $S(z)$ and $F(z)$ for the preset $z$ are given in Table 1.

The horizontal displacements $\zeta$ of the mouth shaft toward the mined-out area are calculated from (4). The length of the curved section of the shaft as a result of the horizontal displacement toward the mined-out void is approximately assumed as: $l_i = 428$ m.
Table 1. Values of the functions \( S(z) \) and \( F(z) \).

| Object  | \( z \) | \( S(z) \) | \( F(z) \) | \( F(z) \) |
|---------|--------|-----------|-----------|-----------|
| Shaft RESH | 0.43   | 0.52      | 0.78      | 0.86      |

The vertical deviation of the shaft is found from the formula:

\[
i_v = \zeta / l_i
\]  

The allowable vertical deviation of the shaft is 1/5000 of the curved section length, i.e., \( i_v = 0.2 \text{ mm/m} \).
3. Results and analysis

From calculation, it is found that (Figure 5):

— remoteness of rock footwall drifts ensures their safety;

— LP on levels 7–12 in scenario 1 prevent critical strains in rock mass in the vicinity of shaft RESH;

— horizontal strains in rock mass around shaft RESH are not to exceed critical values;

— scenario 2 of extraction of ore reserves from the protective pillar (limit case in the interval of levels 9–13, with formation of downdip mined-out span 250 m long features increasing strains \( \varepsilon_z \) in rock mass around shaft RESH in the area of levels 5–8 and 13 (\( \varepsilon_z = 0.3 \times 10^{-3} \)) and decreasing \( \varepsilon_z \) at levels 9–11 from compressive to tensile (\( \varepsilon_z < 0.1 \times 10^{-3} \)). Thus, for the sake of safety, it is required to establish SP as temporarily inactive at early stage, to be extracted at later stage of mining;

— SP in scenario 3 positively influence the distribution and values horizontal normal strains \( \varepsilon_x \) and \( \varepsilon_z \) in rock mass around shaft RESH, especially on lower levels. The range of the horizontal strains \( \varepsilon_z \) contains no critical values in the area of shaft RESH.

The analytical calculation results are compiled in Table 2. The anticipated strains of the undermined ground surface are within the permissible limits, namely, the horizontal strains of ground surface nearby the mouth of shaft RESH are:

— 1.8 times lower than the permissible strains in the mine;

— 12–30 times less than the permissible strains for household, public and industrial buildings on ground surface.

Table 2. Rock mass deformation during mining within protective pillar of shaft RESH with filing of mined-out void by caving down to level 13.

| Description                                                      | Value  |
|------------------------------------------------------------------|--------|
| Maximum surface subsidence, m                                    | 0.54   |
| Half-length of subsidence trough up-dip (in footwall), \( L_1 \), m | 420    |
| Distance from subsidence trough center to shaft RESH mouth, \( x \), m | 180    |
| Relative coordinates of shaft RESH mouth in half-trough of subsidence, \( z \) | 0.43   |
| Function \( S(z) \)                                              | 0.52   |
| Function \( F(z) \)                                              | 0.78   |
| Function \( F'(z) \)                                             | 0.86   |
| anticipated subsidence at shaft mouth, m                         | 0.28   |
| Anticipated inclines at shaft mouth, \( i \), mm/m               | 1.00   |
| Horizontal displacement of shaft mouth, mm                       | 63     |
| Length of curved sections of shaft, \( l_i \), m                 | 428    |
| Vertical deviation of shaft axis, \( i_v \), mm/m                | 0.15   |
| Half-length of subsidence trough downdip (in hanging wall), \( L_2 \), m | 420    |
| anticipated horizontal deformations of ground surface at shaft mouth, mm/m | 0.16   |

4. Conclusions

Extraction of ore reserves from the protective pillar of shaft RESH with filling of mined-out void by caving rocks in the footwall and hanging wall of the ore body (no backfill technology) causes no hazardous deformation of the undermined objects on ground surface. This is conditioned by small thickness of the ore body (\( m \approx 2.0–4.0 \) m). For safe operation of shaft RESH during extraction of ore reserves from the protective pillar, it is required to establish safety pillars as temporarily inactive at early stage and to extract ore reserves from them at later stage with the obligatory continuous geomechanical monitoring.

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