Validation of variants and structural parameters for mining systems for thin ore bodies

SA Shchukin*, AI Konurin** and SA Neverov***
Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: *s.shukin@ngs.ru; **akonurin@yandex.ru; ***nsa_nsk@mail.ru

Abstract. The current mining of thin and steeply dipping ore bodies features depth down to 700–1100 m below ground surface, increased dimension of various-purpose pillars and, as consequence, higher mineral loss and overall degradation of mining efficiency. In connection with this, it is urgent to find new mining systems as well as scientific approaches to validation of safe parameters of geotechnologies such that, depending on geological and geomechanical conditions, as well as on mineral value, minimize geotechnical risks and maintain competitiveness of production. The aim of this study is to determine safe parameters of open stoping technology for thin ore bodies in terms of the Irtysh complex ore mine. The key research methods are production planning and mathematical (numerical) stress–strain analysis and stability of structural elements in underground mines. The calculated parameters of pillars and stopes for open stoping ensure operating stoping in areas of steeply dipping or inclined ore bodies. Application of 3D mathematical modeling to geological and geomechanical conditions of an operating mine greatly expands the range of approaches and knowledge in complicated problem solving, which proves reliability and correctness of the results obtained for specific nonrecurring geotechnical situations.

1. Introduction
Shallow mining of thin ore bodies, including the early phase, widely uses room-ad-pillar method with empty space left open for some time [1–7]. High mining intensity, minimal material inputs and labor cost, structural simplicity and applicability to ore bodies of different morphological and geological complexity are the major advantages of this geotechnology. In the meanwhile, the depth of mining steadily increases and geomechanical situation worsens, which calls for new engineering solutions towards reliable ground control (elimination of dynamic events in the form of rock bursts) and competitiveness of low-value minerals [1, 4, 6–7].

For instance, the Irtysh complex ore deposit contains both steeply dipping (75–85°) and gently dipping (30–45°) site traced down to a depth of 1100 m. The thickness of the ore bodies is less than 6 m and averages 2–5 m. The ore and enclosing rocks possess essentially different physical and mechanical processes. The footwall rocks have the hardness $f = 3–6$ on Protodyakonov’s scale while the hanging wall rocks have $f = 7–9$; in the zones of dislocations and weathering, $f$ ranges from 2 to 3. The hardness of ore is much higher: $f = 10–16$.

The structural parameters of room-and-pillar systems should be justified for application at the depths of 700–800 depending on rock mass quality. This problem is relevant in our days.
2. Research method

Within this study towards validation of safe parameters for the room-and-pillar technologies to be applied in the conditions of the Irtysh deposit, the problem on stresses and strains of rock mass depending on its quality at the depth of Level 13 \((H = 730 \text{ m})\) was solved.

The 3D elasticity problem was solved using the finite element method [8–16]. The design features of the mining system variants are presented in Figs. 1–3.

Figure 1 depicts the shrinkage stoping system with classic parameters: the height of a level is 50 m; the length of a panel along the strike is 50 m; the width of a rib pillar (RP) is 10 m; the length×height of a stope is 40×37 m; the height of the crown×bottom is 5×8 m; the height of a level pillar is 13 m; the spacing of the orepasses is 7 m; the up/down distance between the vent cross cuts is 8 m.

A feature of this geotechnology consists in filling of mined-out void with broken ore (interim storage). A part of this ore (to 30%) is extracted as a result of shattering before breaking of a new layer, which creates a free space to 2 m high between the storage and intact ore mass. The upward mining is carried out by panels toward the decreasing crown pillar. After breaking in stopes has been finished, the overall discharge of shrinkage ore is accomplished [1].

![Figure 1](image1.png)

**Figure 1.** Shrinkage stoping (m = 4 m—thickness of the ore body): 1—haulage drift; 2—haulage cross heading; 3—ventilation drift; 4—ventilation cross heading; 5—scraper drift; 6—orepasses; 7—ventilation and service raise; 8—vent cross cuts.

The basic parameters of these technologies to be substantiated are the RP width \((B_{RP})\), heights of crown and bottom pillars \(CP\) and \(BP\) (\(h_{CP}\) and \(h_{BP}\)) as well as the stope span \((L_s)\).

Figure 2 shows the sublevel caving system [1, 17–21]. It structurally analogous to the above described system. A panel is divided into stopes and temporal ore pillars. Depending on thickness and variability of an ore body, every 10–16 m along the strike, sublevel drifts are made and connected to the vent raise. Mining is carried out by levels, and an upper level is always a few slices ahead of a lower sublevel. As stoping advances, breaking of reserves in \(CP\) and \(BP\) is performed.

Owing to similarity of the systems, the basic parameters are assumed as in the shrinkage stoping. The crown pillar was subjected to sublevel caving during stoping in the above-lying panel. As in case of the shrinkage stoping system, the sizes of \(CP\) and \(BP\), as well as the stope length are to be validated.
Figure 2. Sublevel stoping system (m = 6 m): 1, 2—haulage drift and cross heading; 3, 4—ventilation drift and cross heading; 5—scraper drift; 6—orepasses; 7—ventilation and service raise; 8—drilling drifts.

Figure 3. Room-and-pillar system at (a) preparation stage and in (b) actual mining (m = 3 m): 1, 2—haulage drift and cross heading; 3, 4—ventilation drift and cross heading; 5—panel raise; 6, 7—undercuts 1 and 2; 8, 9—scraper drifts 1 and 10; 10, 11—orepasses 1 and 2; 12—man way; 13—vent cross cuts; 14—panels; 15—temporary chain pillar (TCP); 16—crown pillar CP; 17—temporary columnar pillars.
Flat sites of the ore body are mined by the room-and-pillar method in single layer [1, 7] (Figure 3). In this method, a panel is split up-dip into two parts with two scraper undercuts. Nearby the panel raises, temporary chain pillars TCP 3–4 m wide are left. Two access subpanels are developed from the scraper undercuts and then connected by vent cross cuts. Between the access subpanels, rooms 7 m wide are cut. Mining is retreat, top-downward, with leaving of columnar pillars.

Considering structural characteristics of this technology, mining safety was evaluated depending on the width of TCP ($B_{TCP}$), diameter of columnar pillars ($d_P$) and stope span ($L_S$) (see Figure 3).

The geomechanical models developed for the numerical experimentation characterize mining with discussed systems under conditions of the Irtysh deposit.

The distribution of the induced stresses and strains in the structural elements of the geotechnologies was determined from the system of equations:

--- equilibrium
\[ \sigma_{ij} + p_{ij} = 0, \]  
--- Cauchy
\[ \varepsilon_{ij} = 0.5(u_{i,j} + u_{j,i}), \]  
--- Hooke’s law
\[ \sigma_{ij} = 2G\varepsilon_{ij} + \lambda\theta\delta_{ij}, \]  
and the boundary conditions which are the initial natural stresses:
\[ y gH \sigma = 0.97, \]  
\[ q_x H \sigma = 0.8, \]  
\[ q_z yz \sigma = 0, \]  
\[ u_{x,y,z} = 0. \]  

where $\sigma_{ij}$ are the stress tensor components ($\sigma_x$, $\sigma_y$, $\sigma_z$ and $\tau_{xy}$, $\tau_{xz}$, $\tau_{yz}$ are, respectively, vertical and horizontal normal and shear stresses); $p_{ij}$ are the bulk forces; $\gamma$ is the density of rocks; $g$ is the gravitational deceleration; $\varepsilon_{ij}$ are the strain tensor components ($\varepsilon_x$, $\varepsilon_y$, $\varepsilon_z$ and $\varepsilon_{xy}$, $\varepsilon_{xz}$, $\varepsilon_{yz}$ 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); $\theta = \varepsilon_x + \varepsilon_y + \varepsilon_z$ is the relative volumetric strain; $G$ and $\lambda$ are the Lamé parameters
\[ G = \frac{E}{2(1+\mu)}, \lambda = \frac{E\mu}{(1-2\mu)(1+\mu)}; \]  
$\delta_{ij}$ is the Kronecker delta; $q_x, q_z$ are the lateral earth pressure coefficient; $\mu$ is Poisson’s ratio.

Stability of pillars was estimated by the Mohr–Coulomb criterion [22–29]. The zones of critical state in rock mass were identified using the safety factor ($K_S$) determined from the equation of straight-line envelope of limit Mohr’s circles:
\[ K_S = \frac{\sin \phi(\sigma_{max} + \sigma_{min} + 2C\times ctg\phi)}{\sigma_{max} - \sigma_{min}} > 1, \]  

where $\sigma_{max}$ and $\sigma_{min}$ are the maximal and minimal principal stresses, respectively; $C$ and $\varphi$ are the cohesion and internal friction angle. The value of $K_S$ less than one points at the possible damaged rock zones.

3. Calculation results and analysis
The calculation results are depicted as instability zones in structural elements of the geotechnologies depending on rock mass quality ($K_S$ is the structural weakening factor). The computation accepted $K_S = 0.5, 0.3$ and 0.1 for good, fair and poor rock mass, respectively.

Figure 4 shows the zones of critical state in the elements of the shrinkage stoping technology for section I–I. It is fond that due to the increased compressive and shear stresses, the weakest and most instable zones are the roof of empty stopes, edges of rib pillar, upper part of the panel bottom at the level of ore passes (bottom pillar between orepasses) and sidewalls of the ventilation cross heading nearby stoping. The rock mass quality has an essential influence on the strength of rocks. The medium- and heavily jointed rock masses suffer from active expansion of damaged rock zones in footwall and hanging wall of the open stopes.

Thus, for mining safety at great depths (700–800 m), it is mandatory to increase the sizes of the rib and crown pillar to 12 and 8 m, respectively.
Figure 4. Possible damaged rock zones in structural elements of shrinkage stoping by the Mohr–Coulomb criterion in section I–I in Figure 1.

The similar results are demonstrated in Figure 5 for the sublevel stoping system. According to calculated data, at the depth of 700–800 m, RP 10 m wide and CP 5 m high fail to ensure required safety of stoping even in good rock mass. Owing to high concentrations of the compressive and shear stresses in poor rock mass, the crown pillar starts failing from the center toward its sides, over the entire cross section. The same situation is observed in RP. In this case, it is required to increase sizes of these pillars: \( B_{RP} = 12 \) m; \( h_{CP} = 8 \) m.

It has been found that the increase in RP width to 12 m and in the height of the crown (CP) to 8 m improves their stability. The major damaged rock zones appear at the pillar edges being in contact with open stopes. Nonetheless, the application range of this system directly depends on the rock mass quality. It is safe to use this technology in fair and good rock masses, with involvement of support and reinforcement.

Figure 5. Possible damaged rock zones in elements of sublevel stoping system by the Mohr–Coulomb criterion for section I–I in Figure 2 at \( K_S = 0.1 \).

Figure 6. Possible damaged rock zones in elements of room-and-pillar system by the Mohr–Coulomb criterion for section I–I in Figure 3b at \( K_S = 0.3 \) and \( d_P = 3–5 \) m.
In Figure 6, the stability of pillars in the single-layer room-and-pillar system is assessed. It has been found that the columnar pillars with a diameter of 3 m are incapable to ensure safety of the panel roof and fail even in good rock mass. The increase in the pillar diameter to 5 m improves the pillar stability, and the application range of the technology expands to fair rock masses. At the preparation stage, the worst conditions are observed in the ventilation cross heading and haulage drift in the influence zone of upper level stoping. The temporary chain pillars are also instable in medium and heavily jointed rocks.

4. Conclusions
1. The application range of geotechnologies under conditions of the Irtysh deposit is mostly limited by the factor of rock mass quality.
2. In the variants of shrinkage stoping and sublevel stoping, the width the the temporal level pillar at level 13 should be not less than 12 m; the height of the crown and bottom pillars should be not less than 8 and 10 m.
3. For safe deep-level (700–800 m) mining of inclined ore bodies in fair rock masses by room-and-pillar, the columnar pillar should have a diameter not less than 5 m, the width of the temporary chain pillar should be not less than 6 m, the span of the stope across and along the strike (distance between the edges of the pillars) should be not more than 4.5 and 5.0 m, with obligatory support systems in stopes in the influence zone of mined-out panels.
4. In the heavily jointed rock mass, the discussed systems of mining, event with effective parameters, will be incapable to ensure required safety and need further studies and substantiation in terms of the size of pillars and spans.

Acknowledgements
This work was supported by the Ministry of Education and Science of the Russian Federation, Grant of the Russian Federation President to support young Russian scientists–candidates of sciences, Grant No. MK-6827.2018.5.

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