Approaches to Calculating Loads on Interchamber Pillars under Incomplete Undermined Conditions

P A Glebova
Laboratory of Rock Mechanics, Mining Institute of the Ural Branch of the Russian Academy of Sciences, 78a Sibirskaya street, Perm 614007, Russian Federation
E-mail: polina.glebova@mi-perm.ru

Abstract. The paper uses mathematical modeling to calculate loads on interchamber pillars under incomplete undermined conditions by using the room and pillar system at great depths and by retaining rigid barrier pillars. The approaches are based on the method of the fictitious pillars, as well as the method of forming a rock pressure arch in the incompletely undermined area. The unloading effect of the barrier pillars on the interchamber pillars is shown, the distribution of vertical loads is obtained, and the height of the rock pressure arch is calculated.

1. Introduction
The use of the room and pillar system with rigid barrier pillars is preferable for the development of potash and salt deposits at depths of 1,000 meters and more.

The system with the barrier pillars makes it possible to reduce the load on the interchamber pillars, decrease the loss of minerals, as well as localize failures within one area in case of destructions of the interchamber pillars.

There are a lot of studies about mechanisms of load distributions between pillars. Most of them are based on the hypothesis of an arch formation under the mined section [1, 2, 3]. The authors use various techniques, which do not always coincide with experimental data [4]. As shown by field measurements, the unloading of interchamber pillars in a system with barrier pillars can reach 80 % [5, 6].

To further evaluate the load redistribution between the pillars of different rigidity and bearing capacity values, two approaches are presented based on the method of the fictitious pillars and the method of forming the rock pressure arch in an incompletely undermined zone.

2. Conditions for load redistribution in a system with barrier pillars
Undermining conditions are divided into complete and incomplete ones. If pillars are located in a completely undermined zone, they carry the load of the whole weight of a rock pillar from the top of the deposit to the earth's surface (figure 1). If pillars are located in an incompletely undermined zone, the pillars carry only a part of the weight load of a rock stratum lying under a certain arch (figure 2). In this case, the rest of the load refers to the edge part of the undermined rock mass.

Undermining conditions for the earth's surface can vary depending on the mining and geological conditions of a particular field’s development. In engineering, they are characterized by the ratio of the length of the mined-out space (L) to the depth of mining (H). When $L \geq 1.4H$ and $L < 1.4H$, the conditions of the complete and incomplete undermining are respectively fulfilled [7].
Conditions of a field’s undermining are critical for the rock pressure control using barrier pillars. Compared to interchamber pillars, wide barrier pillars have increased rigidity and bearing capacity. By retaining pillars with various rigidity values, it is possible to create conditions for the incomplete undermining for interchamber pillars, which will lead to their unloading. Thus, the interchamber pillars will be loaded only with the rocks of the under-arch part, and the remaining load will be distributed on the barrier pillars (figure 3) [8].

**3. Computational parameters**

The research focused on studying a chamber block bounded by the axes of symmetry of the barrier pillars (figure 4). The modeling was carried out with the calculated parameters presented in table 1. Here $B$ is the width of the barrier pillars (BP); $L$ is the distance between the barrier pillars, $b$ is the width of the interchamber pillars (ICP); $a$ is the width of the chambers, $n$ is the number of paths of the stopes, $H$ is the depth of mining.

| BP | ICP | ICP | ICP | ICP | ICP | ICP | ICP | BP |
|----|-----|-----|-----|-----|-----|-----|-----|----|
| $B/2$ | $b$ | $a$ | $L$ | $B/2$ |
Table 1. The computational parameters.

| B, m  | a, m | b, m | n  | H, m |
|-------|------|------|----|------|
| 29.9  | 6.0  | 4.2  | 8  | 1120 |

Average load $P$ on the interchamber pillar was determined depending on the weight of the pillar of rocks with the height $H_1$, limited by the axes of symmetry of the chambers adjacent to the pillar:

$$P = \frac{\gamma \cdot H_1 \cdot (a + b)}{b}$$

(1)

It should be noted that in the completely undermined area within the considered parameters, the average load on the pillars is calculated to be 62 MPa. This value will be required for a comparative analysis of the results presented for different approaches.

4. Approaches to estimating loads on interchamber pillars

4.1. Calculations based on the method of fictitious pillars

The first version of modeling was based on the so-called method of fictitious pillars [9]. The approach consisted in creating the unloading effect of the barrier pillars by specifying the soil response along their cross section in the form of vertical distributed load [10]. The soil response $q$ was defined as the maximum load that the barrier pillars carry after the destruction of all interchamber pillars:

$$q = \frac{\gamma \cdot H \cdot (B + L)}{B}$$

(2)

Mathematical modeling was carried out in an elastic formulation for plane strain conditions. The numerical implementation was carried out by the finite element method [11]. The design scheme is shown in figure 5.

![Figure 5. The computational scheme.](image)

The average load $P$ on the pillar was determined by the vertical stresses $\sigma_y$ acting on the roof of the pillar. The simulation results presented in figure 6 showed that the maximum load falls on the central pillar, and decreases as it approaches the barrier pillars. The unloading of the central pillar between the chambers reaches 56%. In this case, there is complete unloading of the extreme interchamber pillars. Thus, it can be assumed that the interchamber pillars are under pressure from rocks within a certain arch. The maximum arch height was determined as:

$$d = \frac{P_c \cdot b}{\gamma \cdot (a + b)},$$

(3)

where $P_c$ is the average load on the central interchamber pillar. According to the computation results, within the set parameters, the arch height was $d = 453$ m.
4.2. Calculations based on the method of formation of the rock pressure arch in the zone of the incomplete undermining

The modeling calculations were based on field measurements [12]. The author assessed the effect of the combined use of flexible and supporting rigid pillars during the development.

The concept of LTD (load transfer distance) is introduced, which sets conditions for undermining the earth’s surface. With the mined-out area $L \geq 2LTD$, the pillars are in the zone of the complete undermining (figure 7), taking the load from the entire rock mass. In the case of $L < 2LTD$, conditions of the incomplete undermining are created, in which the interchamber pillars in the system with the barrier pillars take the load from the weight of rocks within a certain arch (figure 8). The rest of the load is redistributed to the barrier pillars.

$LTD$ is approximated by a function of the mining depth $H$ [12]:

$$LTD(H) = \begin{cases} 
-13.72 + 0.373H - 0.000269H^2, & H \leq 554.9 \text{ m} \\
0.086H + 62.78, & H > 554.9 \text{ m} 
\end{cases} \tag{4}$$

During the complete undermining ($L \geq 2LTD$), the rock pillar height is calculated using the formula [12]:

$$d = \frac{H}{4LTD} \left(8LTDl - 4l^2\right), \tag{5}$$

where $l$ is the distance to the barrier pillar (figure 7). In case when $L < 2LTD$ with two barrier pillars, the arch is considered to be parabolical. The maximum height of the arch is confined to the center of the mined-out space (figure 8). In this case, to calculate the height of the arch, it is necessary to have calculations (4) and (5) in the complete undermining conditions when $l = \frac{L}{2}$ by distributing the load from the interchamber pillars to one barrier pillar. Further, the obtained height of the arch $d$ is taken as a new mining depth and then the calculations are repeated to distribute the load on the second barrier pillar.

![Figure 7. The complete undermined area when $L \geq 2LTD$.](image)
Numerical modeling was carried out for the focus of this work to quantify loads on the interchamber pillars and the height of the arch. The computational scheme is shown in figure 9, where $d$ is the height of the rock pressure arch, $N_i$ is the weight of the rock pillar supported by the interchamber pillar (ICP-$i$, $1 \leq i < n$, $n$ is the number of chambers).

The arch boundary was described by a quadratic function $y(x) = -0.195x^2 + 15.07x$, where $x$ is the distance to the left barrier pillar. $N_i$ was calculated as $(0 < x_i < L, 1 \leq i < n, n$ is the number of chambers):

$$N_i = \gamma \int_{x_i}^{x_{i+1}} y(x) \, dx$$  \hfill (6)

The average load $P_i$ acting on the interchamber pillar (ICP-$i$) was found as:

$$P_i = \frac{N_i}{b}$$  \hfill (7)

According to the calculation results, the height of the rock pressure arch under the incomplete undermining conditions was $d = 292$ m. The loads acting on the interchamber pillars are presented in table 2. The unloading effect of the central interchamber pillar reaches 72 %. The edge pillars are unloaded by 90 %.

**Table 2.** The distribution of vertical loads.

| Pillars | ICP-1 | ICP-2 | ICP-3 | ICP-4 | ICP-5 | ICP-6 | ICP-7 |
|---------|-------|-------|-------|-------|-------|-------|-------|
| $P$, MPa | 6.5   | 12.7  | 16.4  | 17.6  | 16.4  | 12.7  | 6.5   |
5. Conclusion
As a result of using the mathematical modeling methods, we analyzed the load redistribution between the pillars under the incomplete undermining conditions. The room and pillar system is considered for the development of the barrier and interchamber pillars. Approaches based on the method of the fictitious pillars, as well as the method of the rock pressure arch formation in the zone of the incomplete undermining were taken as modeling options.

The obtained results reflect the unloading effect of the barrier pillars on the interchamber pillars. Under the incomplete undermining conditions, the interchamber pillars carry only a part of the total weight of the rock pillar up to the surface and stay within a certain arch. The unloading effect of the central interchamber pillar was 56 – 72 %. For each version of the simulation, the height of the rock pressure arch acting on the interchamber pillars was calculated. Despite the fact that the results of the approaches have discrepancies, the obtained estimates seem to be quite correct, though they need to be refined based on field experimental studies.

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