Influence of the Roof Movement Control Method on the Stability of Remnant

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Abstract. In the underground mines, there are geological and mining situations that necessitate leaving behind remnants in the mining field. Remnants, in the form of small, irregular parcels, are usually separated in the case of: significant problems with maintaining roof stability, high rockburst hazard, the occurrence of complex geological conditions and for random reasons (ore remnants), as well as for economic reasons (undisturbed rock remnants). Remnants left in the mining field become sites of high stress values concentration and may affect the rock in their vicinity. The values of stress inside the remnant and its vicinity, as well as the stability of the remnant, largely depend on the roof movement control method used in the mining field. The article presents the results of the numerical analysis of the influence of roof movement control method on remnant stability and the geomechanical situation in the mining field. The numerical analysis was conducted for the geological and mining conditions characteristic of Polish underground copper mines owned by KGHM Polska Miedz S.A. Numerical simulations were performed in a plane strain state by means of Phase 2 v. 8.0 software, based on the finite element method. The behaviour of remnant and rock mass in its vicinity was simulated in the subsequent steps of the room and pillar mining system for three types of roof movement control method: roof deflection, dry backfill and hydraulic backfill. The parameters of the rock mass accepted for numerical modelling were calculated by means of RocLab software on the basis of the Hoek-Brown classification. The Mohr-Coulomb strength criterion was applied.

1. Introduction

Remnants of undisturbed rock are frequently left behind in underground mines as a result of performing mining operations. These remnants are unworked deposit fragments left in mining fields due to, inter alia: significant threat to roof stability, increased risk of rockburst, complex geological conditions, or random incidents [1-4].

Experience to date suggests that in the case of underground mining, a remnant left in order to isolate the reconstructed mining face from the disturbed rock mass allows stabilizing the situation locally, but the rigid remnant disturbs the geomechanical system in the mining field and causes ore loss. Additionally, remnants of undisturbed rock may induce high-energy seismic phenomena in the mining field and may pose a threat to the works performed in the area.

Remnants are locations where high stress values are concentrated. In the case when the stress value in the remnant exceeds the remnant’s strength, the remnant may fail and – if the geomechanical conditions are unfavourable – a strain rockburst may occur. Remnants of undisturbed rock may also affect rock mass in the area. Such remnants may cause roof layers to collapse above their edges (and thus promote high-energy rockbursts – shear rapture) [4-8].

In order to investigate how a roof movement control method influences ore remnant stability, numerical analysis was performed for the geological and mining conditions characteristic of Polish
copper mines owned by KGHM Polska Miedz S.A. The analysis was performed in a plane strain state, using Phase 2 v. 8.0 software. A remnant of undisturbed rock, 40 m in width, was analysed in in the subsequent steps of the simulated room and pillar mining system. Numerical simulations were performed for three roof movement control methods used in Polish copper mines: roof deflection, dry backfill and hydraulic backfill.

2. Numerical modelling

2.1. Description of the analysed region
The numerical analysis of the influence of roof movement control method on remnant stability were performed for a model mining field. The calculations were based on a generalized lithological structure of the Legnica-Glogow Copper Belt. The roof was assumed to be formed in a rock layer of high rigidity and strength, while the floor was assumed to consist of sandstone having significantly lower strength parameters. The simulations in the mining field were based on an assumption that excavation is performed in dolomite and sandstone. The ore in the mining field was assumed to be extracted using the room and pillar system, and when the life of face was approx. 460 m, a remnant was formed, 40 m in width. The analysis included three methods for roof movement control: roof deflection, dry backfill and hydraulic backfill.

2.2. Assumptions behind numerical modelling
The numerical calculation of the influence of roof movement control method on the stability of the 407m ore remnant was performed using the Phase2 v. 8.0 software. The application enables using the finite element method to perform numerical analysis in a triaxial stress state and in plane strain state. An elastic model of rock mass was adopted. The medium was assumed to be uniform and isotropic. The Coulomb-Mohr failure criterion was chosen as the measure of rock mass effort. The model for calculations comprised a plate with lithology layers which form the rock mass in Polish copper ore mines (figure 1).

![Figure 1. Calculation scheme with remnant of 40 m in width](image-url)
Vertical pressure of 17.657 MPa was applied to the top edge of the model, to compensate for the load of the overlying rock. The calculations included the unit weight of the rock layers. Displacement boundary conditions were set at plate edges:
- bottom edge of the model – no vertical displacement,
- side edges of the model – no displacement in direction perpendicular to edge surface.

A finite element mesh was constructed of 3-node triangular elements. In the central part of the plate, in the vicinity of the workings, the mesh was thickened, in order to increase the accuracy of calculations.

The calculations were performed in steps, simulating ore extraction in the room and pillar system (64 calculation steps). The first step involved the conditions in the rock mass prior to developing any workings. In the second step, the rock mass was divided into technological pillars having dimensions as shown in Table 1. In the subsequent steps, the size of the technological pillars was reduced until they reached a residual width and then successive technological pillars were formed. The rock mass was divided into pillars by strips having dimensions as shown in Table 1. The numerical simulations were based on an assumption that the working area width is of 5 strips. The ore remnant was formed when the face life was approx. 460 m (step no. 30 in the numerical model).

### Table 1. The numerical model geometry of the analysed mining field.

| Mining system         | Main pillar width | Residual pillar width | Excavation height | Strip width under the roof | Side wall inclination angle | Working area width |
|-----------------------|-------------------|-----------------------|-------------------|----------------------------|---------------------------|-------------------|
| room and pillar       | 8                 | 3                     | 3.5               | 6                          | 10                        | 5 strips          |

In the Legnica-Glogow Copper Belt mines, the technological pillars are expected to work in the post-critical state. The yield of pillars achieved by lowering their strength and strain parameters. The values of the lowered parameters were determined in the so-called backward analysis, by performing a given number of numerical simulations, so as the calculated values of vertical displacement for selected points approximated the actual values. The numerical analysis of the model field was based on an assumption that in the Legnica-Glogow Copper Belt mines maximum vertical displacement caused by using the room and pillar mining system with roof deflection are approx. 70% of the mined deposit thickness. In the case when the excavated space is liquidated using dry backfill, the maximum vertical displacement was assumed to be approx. 35% of the mined deposit thickness, while in the case of hydraulic backfill, the displacement was assumed at approx. 20%. Numerical simulations allowed adjusting the parameters of technological pillars and residual pillars to each of the roof movement control methods, so that the vertical displacement values for a mined deposit of 3.5 m in height was at the following levels: roof deflection – 2.5 m, dry backfill – approx. 1.23 m, hydraulic backfill – approx. 0.7 m.

Table 2 shows rock mass parameters adopted for the elastic model, for the Coulomb-Mohr criterion.

### Table 2. Rock mass parameters adopted for the numerical calculation of elastic model.

| Location              | Rock type       | $h$ [m] | $E_s$ [MPa] | $\nu$ [-] | $\sigma_t$ [MPa] | $c$ [MPa] | $\phi$ [''] |
|-----------------------|-----------------|---------|-------------|----------|-----------------|---------|----------|
| ROOF                  | Anhydrite       | 200.0   | 41,110      | 0.24     | 0.75            | 7.00    | 38.66    |
| MINED DEPOSIT HEIGHT  | Dolomite-Sandstone | 3.5   | 24,910      | 0.21     | 2.00            | 8.84    | 39.00    |
| FLOOR                 | Sandstone       | 202.7   | 3,220       | 0.13     | 0.05            | 1.16    | 39.06    |

The symbols used in the above table are as follows: $h$ – thickness of rock layers, $E_s$ – longitudinal modulus of elasticity, $\nu$ – Poisson ratio, $\sigma_t$ – rock mass tensile strength, $c$ – cohesion coefficient, $\phi$ – internal friction angle.
3. Analysis of the results of numerical calculations

The influence that the roof movement control method has on the behaviour of the 40 m wide ore remnant and on the geomechanical situation in the mining field was analysed on the basis of vertical stress pattern $\sigma_y$ and of rock mass strength factor $S_f$ in an elastic medium. The calculated displacement values were used to verify the numerical models. The analysis covered the behaviour of ore remnants and the effort of the neighbouring rock mass over the succeeding steps of the simulated room and pillar mining system, for three roof movement control methods: roof deflection, dry backfill, and hydraulic backfill.

When analysing vertical stress maps $\sigma_y$ in the succeeding mining steps, for the face life of 300 m, 600 m (approx. 100 m from the edge of the remnant) and 900 m (approx. 400 m from the edge of the remnant), an observation can be made that regardless of the roof movement control method, the remnant concentrates stress and acts on the neighbouring rock layers in both the roof and the floor. The range of this influence and the magnitude of stress in the vicinity of the remnant increase in the succeeding steps of the simulation, as the mining face progresses. When the distance above and below the remnant increases, its influence decreases and the values of vertical stress tend to their original levels (figure 2).

![Figure 2](image_url)

**Figure 2.** Distribution of vertical stress $\sigma_y$ in the analysed mining field for the life of face: a) 300 m - 19 calculation step, b) 600 m (approx. 100 m from the edge of the remnant) - 38 calculation step, c) 900 m (approx. 400 m from the edge of the remnant) - 59 calculation step
The results of the numerical simulations indicate that the levels of internal stress in the remnant and in its vicinity, as well as the influence range of the remnant largely depend on the roof movement control method. In the case when the extracted space is liquidated using roof deflection method, vertical stress $\sigma_y$ in the vicinity of the remnant reach maximum values and its influence range is greatest. The results of the calculations suggest that the limiting of roof displacement in the mining field by using dry or hydraulic backfill causes a significant decrease in the range of influence and in vertical stress values $\sigma_y$ (figure 3).

![Figure 3](image)

**Figure 3.** Distribution of vertical stress $\sigma_y$ in the analysed mining field for the face life of 900 m (approx. 400 m from the edge of the remnant) – calculation step 59, a) roof deflection, b) dry backfill, c) hydraulic backfill

The analysis of the distribution of rock mass strength factor $S_f$ in the succeeding simulation steps for the three roof movement control methods allows an observation that the 40m wide remnant helps stabilize locally the geomechanical situation in the mining field by improving the stability of the immediate roof in the neighbouring excavations (figure 4). An additional observation can also be made, that with dry or hydraulic backfill, the range of unstable zone can be limited significantly, especially in the roof over the excavations on the left side of the remnant.
Figure 4. Distribution of strength factor $S_f$ in the analysed mining field for the face life of 900 m (approx. 400 m from the edge of the remnant) – calculation step 59, a) roof deflection, b) dry backfill, c) hydraulic backfill

The analysis of the results of vertical stress simulations $\sigma_y$ inside the 40 m wide ore remnant in an elastic medium allows an observation that regardless of the roof movement control method, concentrations of vertical stresses $\sigma_y$ occur on the edges of the remnant and decrease towards the middle of the remnant (figures 5, 6). Unlike the vertical stress $\sigma_y$, the strength factor $S_f$ reaches its lowest values on the edges and increases towards the middle of the remnant (figures 7, 8). Values of strength factor $S_f$ below 1, as observed on remnant edges, indicate that the strength of the material in these areas (excavation walls) may be exceeded and a fractured zone or a zone of plastic flow may appear. The values of stress $\sigma_y$ and the values of strength factor $S_f$ on the edges and inside the remnant largely depend on the roof movement control method employed in the mining field.

The edges of the 40m wide and 3.5 m high remnant show stress $\sigma_y$ values in the range 170-440 MPa for roof deflection, 110-270 MPa for dry backfill, and 80-200 MPa for hydraulic backfill. Inside the remnant, vertical stress $\sigma_y$ values for analogical methods are approx. 100 MPa (roof deflection), 65 MPa (dry backfill) and 50 MPa (hydraulic backfill) (figures 5, 6).
Strength factor $S_f$ on the edges of the remnant is below 1.0 for distances smaller than approx. 1 meter from the edge, regardless of the roof movement control method. Outside this zone, in the undisturbed rock remnant, the $S_f$ factor is above 1.0: its maximum values are 1.71 for hydraulic backfill, 1.63 for dry backfill and 1.53 for roof deflection (figures 7, 8).

4. Conclusions

Highly advanced mining production in many underground mines causes an increasing number of mining works to be conducted in difficult geological and mining conditions, inter alia in the zones influenced by remnants of undisturbed rock. Remnants are locations of concentrated stress and they affect the layers of mass rock both in the roof and in the floor. Remnants may therefore have a negative impact on the occurrence of dynamic phenomena, including high-energy tremors and rockbursts. When the stress value in the remnant exceeds the remnant’s strength, the remnant may fail and – if the geomechanical conditions are unfavourable – a strain rockburst may occur. The roof layers may also suddenly and violently collapse on the edge of the rigid remnant, leading to a high-energy...
rockburst. The level of stress in remnants, as well as their stability depend inter alia on the geological and mining conditions in a given mining field, and on the roof movement control method used in this field.

The results of numerical modelling performed for the geological and mining conditions characteristic of Polish copper mines owned by KGHM Polska Miedz S.A. show that regardless of the roof movement control method, the remnant is a zone of concentrated stress and acts on the rock mass in the vicinity. Ore remnants act on the neighbouring rock layers of both the roof and the floor. In the stress concentration zones, higher stress values propagate in the roof and in the floor centrally from the remnant.

Figure 6. Graph of vertical stress $\sigma_y$ in the 40m wide remnant for the life of face 900 m (approx. 400 m from the edge of the remnant) - calculation step 59 - roof deflection, dry backfill, hydraulic backfill
Figure 7. Distribution of strength factor $S_f$ in the analysed mining field for the life of face 900 m (approx. 400 m from the edge of the remnant) - calculation step 59, a) roof deflection, b) dry backfill, c) hydraulic backfill

Figure 8. Graph of strength factor $S_f$ in the 40m wide remnant for the life of face 900 m (approx. 400 m from the edge of the remnant) - calculation step 59 - roof deflection, dry backfill, hydraulic backfill

As the distance from the remnant increases, its influence decreases and the values of vertical stress tend to their original levels. The greatest range of the influence exerted by the left remnant of undisturbed rock and the highest values of stress in the vicinity of the remnant are observed in the case of roof deflection method. Limiting roof displacement in the mining field (by using dry or hydraulic backfill) causes a decrease of vertical stress values $\sigma_y$ in roof rock layers, and a decrease in the influence range of the left remnant. In the case when liquidation is performed using dry backfill or hydraulic backfill method, strength factor $S_f$ in unstable zones over undisturbed rock remnants has higher values than those observed in the case of liquidation by roof deflection. Simulations performed for the model field also indicate that the limiting of roof displacement in the mining field by using dry or hydraulic backfill causes a decrease in vertical stress values $\sigma_y$ and an increase in strength factor $S_f$ inside the undisturbed rock remnants.

Optimal selection of roof movement control method may limit the pressures generated in the remnant by roof rock layers, and thus limit the risk of strain rockburst. Such selection will also
positively influence the stability of the remnant left in the mining field, as well as the stability of the mass rock in the vicinity.

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