Numerical simulation of the possibility of seismic event occurrence in hard rock mine

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Abstract. This article presents the problem of seismic and rockburst hazard in underground hard rock mines. Types of rockbursts and their mechanisms as well as the causes of dynamic phenomena are discussed. The possibility of using numerical modeling to simulate the occurrence of a high-energy tremor, as a result of sudden shear rupture, is also shown. Results of numerical simulations are presented for a model mining field in a hard rock mine at high depth, in which the deposit is mined in a room-and-pillar mining system. General geological and mining conditions characteristic for Polish underground copper mines in Legnica-Glogow Copper Mining District belongs to KGHM Polska Miedz S.A. were adopted in the models. The typical lithological cross-section of the polish copper mines is characterized by rigid, high-strength rock layers in the roof, capable of accumulating elastic energy, while layers with much lower strength parameters are present in the floor. In the analyzed mining field, the remaining undisturbed rock, with a width of 40 m, was left. Numerical simulations were conducted in a plane strain state by means of Phase2 v. 8.0 software. An elastic-plastic model with softening was accepted for the rock mass. The results of numerical modeling showed that sudden (one computational step in the model) collapse of roof strata may occur over the excavated space on the edge of the remaining undisturbed rock, as a result of exceedance of shear strength, above all. This may cause a very high-energy tremor, and under the appropriate conditions, may result in the rockburst phenomenon.

1. Introduction

Despite the broad application of various preventive methods, seismic and rockburst hazards remain the primary hazards in many hard rock mines around the world, including: South Africa, Canada, China, Australia, Sweden and Poland. Seismic and rockburst hazard is one of the major issues in polish underground copper mines [1, 2]. There are many classifications of rockbursts in the literature but essentially, two types of dynamic phenomena are distinguished. The first is directly associated with stopes, while the second is linked to primary tectonic discontinuities [3]. Rockbursts of the first type most frequently occur close to excavations. They are the result of stress redistribution around the excavations and the formation of stress concentration zones. Rockbursts of this type are characterized by the fact that the location where their effects manifest overlap with the location where rock is destroyed and where the hypocenter of causative tremors are located. The following may be considered as belonging to this group of rockbursts [4]: strain bursts, pillar bursts and face bursts. Dynamic phenomena related to tectonic discontinuities include rockbursts caused by fault activation or initiated by the sudden formation and propagation of fractures in undisturbed rock as a result of exceedance of shear strength (shear rupture) [4, 5].
Shear rupture bursts have been observed in many underground hard rock mines, including in RSA [4, 5]. According to [4], sudden fracturing of undisturbed rock as a result of exceedance of shear strength is one of the most important mechanisms generating very high-energy mining tremors and major rockbursts. Roof strata fractures form most often near edges, old gobs, boundaries between backfill mining and retreat mining, or in the direct vicinity of the mining front.

Research for the purpose of understanding the nature of dynamic phenomena in hard rock mines, determining tremor and rockburst mechanisms, and developing new methods for predicting, evaluating and preventing such hazards is being conducted at many research centers. Methods of assessing rock mass condition applied at hard rock mines include: geological determination of rockburst risk on the basis of the properties of the deposit and surrounding rock, mining seismology, rock mass pressure measurements and underground observations, seismo-acoustic method, seismic methods, analytical methods etc.

Geomechanical studies concerning the origin of dynamic phenomena in underground mines were initially based on empirical methods, ad hoc theories and hypotheses, and on analytical methods (yielding a closed-form solution). The complexity of phenomena occurring in the rock mass meant that obtaining a closed-form solution to geomechanical problems was very difficult and required the application of many assumptions that simplified the problem significantly. Thanks to the development of computer modeling and simulation techniques, numerical methods are widely used to solve geomechanical problems. These methods make it possible to analyze nearly any geometry, taking into account different models of material behavior under load, spatial changes in the rock medium's properties, the specific initial stress field, dynamic load, etc. Numerical methods significantly expand research capabilities related to analysis of seismic phenomena in underground mines, including identification and verification of mining tremor and rockburst mechanisms. Numerical modeling provides the capability of: identifying potential rockburst hazard zones in advance, predicting the hazard risk in every part of the rock mass, even in inaccessible parts, and identifying the conditions under which a dynamic phenomenon may occur [6]. The results of numerical simulations are used to plan and design mining works in mining fields at risk of rockbursts [7] and facilitate selection of the proper methods of combating this hazard. Attempts at using numerical methods for analysis of seismic phenomena are widely described in the literature [8-13].

Mining operations disturb the primary situation in the rock mass and directly interfere with the natural environment. About sustainable development initiatives and problems can be found in [14, 15]. In-situ observations performed in the polish underground copper mines and scientific research indicate that remnants negatively influence the seismic hazard [2, 13]. A remnant left in the mining field stabilizing the situation locally, but the large remnant disturbs the geomechanical system in the mining field. This article presents the results of numerical simulations conducted for a model mining field with geology characteristic for deep underground copper mines mined according to the room-and-pillar mining system, in which remnant with a width of 40 m was left behind. These research, which take into account the generalized situation characteristic of LGCB mines, are a continuation of research previously carried out for one of the mining fields located in the Polkowice-Sieroszowice mine [13].

2. Numerical modeling

2.1. Characteristics of the area of research
Numerical modeling was conducted for a model mining field in a hard rock mine at high depth (approx. 1000 m), in which the deposit is mined in a room-and-pillar mining system with roof deflection. In the analyzed mining field, when the length of the front amounts to approx. 460 m, remaining undisturbed rock with a width of 40 m was separated. Calculations were conducted for generalized geological and mining conditions characteristic of underground copper ore mines located in southwestern Poland in the Legnica-Glogow Copper Belt - owned by KGHM Polska Miedz S.A.,
within the area of the geological unit known as the Presudeten Monocline. A generalized structure of the rock mass in the LGCB region was used. It was assumed that the roof is a rigid rock layer with high strength, and the floor is made up of sandstones with significantly lower strength parameters.

2.2. Characteristics of numerical modeling
Numerical calculations were conducted in a plane deformation state by means of Phase2 v. 8.0 software. The behavior of the rock medium was described by an elastic-plastic model with softening. The Coulomb-Mohr strength criterion was applied as the measure of the rock mass's effort. The numerical model was a plate in which the rock strata making up the rock mass were accounted for (Figure 1). The upper edge of the model was subject to vertical load representing the action of the overburden (17.657 MPa). The unit-weight of rock layers was accounted for in calculations. It was assumed that the values of horizontal stresses are equal to vertical stresses (hydrostatic state of initial stresses). Displacement boundary conditions were set on the edges of the plate. At the bottom edge of the model – no vertical displacements, and on side edges – no displacements in the direction perpendicular to the surface of the edge. A finite element mesh consisting of 3-node triangular elements was applied.

**Figure 1.** Computational scheme for the model mining field (remnant with a width of 40 m)

Computations were performed in steps, simulating operation according to the room-and-pillar mining system with roof deflection (64 computational steps). The first step covered the situation in the rock mass before excavation of mining headings. The second step involved cutting into undisturbed rock and formation of technological pillars with the width of 8 m. In the next steps, the size of technological pillars was reduced to residual dimensions (3 m in width) and successive technological pillars were formed. Working in the deposit was performed in strips 6 m in width. In numerical simulations, a width of opening of the workspace equal to 5 strips was accounted for. In the analyzed
mining area, the remnant that was designated for separation when the front length was approx. 460 m (30th computational step in the numerical model) was accounted for.

2.3. Parameters of rock mass accepted for numerical modeling

The parameters of the rock mass accepted for numerical modeling were determined on the basis of the Hoek-Brown classification and presented in Table 1.

| Location | Name of rock    | \( h \) [m] | \( \rho \) [kg/dm\(^3\)] | \( E_s \) [MPa] | \( v \) [-] | \( \sigma_f \) [MPa] | \( c \) [MPa] | \( \phi \) ['] | \( c_{res} \) [MPa] | \( \phi_{res} \) ['] |
|----------|----------------|-------------|-----------------|----------------|----------|-----------------|----------|-----------|----------------|----------------|
| roof     | anhydrite      | 200.0       | 2.90            | 41 110         | 0.24     | 0.75            | 7.00     | 38.66     | 1.40           | 36.73          |
| deposit  | dolomite-sandstone | 3.5       | 2.63            | 24 910         | 0.21     | 2.00            | 8.84     | 39.00     | 2.21           | 37.05          |
| floor    | sandstone      | 202.7       | 1.95            | 3 220          | 0.13     | 0.05            | 1.16     | 39.06     | -              | -              |

In LGCB mines, the aim is for technological pillars to work in a post-critical state. In numerical simulations, increased yielding of pillars was introduced by reducing strength and strain parameters. In numerical analyses of the model area, it was accepted on the basis of the literature [16] that under the conditions in LGCB copper ore mines, maximum vertical displacements caused by mining of the deposit according to the room-and-pillar system with roof deflection, amount to approx. 70% of the deposit's thickness. Numerical simulations were conducted, which enabled selection of the parameters of technological and residual pillars, so that the vertical displacement values for a deposit with a height of 3.5 m were at the following levels: approx. 2.5 m.

2.4. Analysis of numerical modeling results

Based on numerical simulations the distribution of vertical stresses and areas of yielded elements among other things, were determined and analyzed in successive steps of exploitation. Numerically computed displacement values were used to verify numerical models (model calibration). The behavior of the rock mass in the analyzed area was tracked in successive steps of simulated mining operations.

By analyzing area of yielded elements, it can be observed that their reach grows in successive steps of simulated operations, particularly above the gob areas (Figure 2a-2f). This indicates progressing disintegration of roof layers above the gobs. The reach of the damaged area above operational excavations amounts to approx. 2 m. Inside the separated remnant of undisturbed rock with a width of 40 m, yielded areas only present near its edges, and their reach grows in successive steps of operations. At a front length of 900 m (approx. 400 m from the remnant edge), this reach amounts to approx. 2.5 m. This indicates that strength is exceeded and damaged zones are formed on the edges of the remnant, while its internal part remains stable.

The results of numerical simulations have demonstrated that, during simulation of the mining front, in the 35th computational step, when its length amounts to 560 m (approx. 60 m from the remnant edge), a yielded zone in the roof is formed suddenly (in one computational step) above the edge of the remnant with a width of 40 m (Figure 2d). The transverse line of destruction in the roof formed near the left edge of the remnant and is inclined at an angle of approx. 60° in the direction of the area that had already been mined out. It formed as a result of exceedance of shear strength, above all (Figure 3). Simulation results indicate that sudden collapse of roof strata may occur on the edge of the remnant above the space that has been mined out, which may generate a very high-energy tremor and induce the rockburst phenomenon under the appropriate conditions. In the analyzed mining field, after the
roof strata collapse phenomenon had occurred above the remnant edge, its internal part remained stable.

a)  

b)  

c)  

d)
By analyzing the map of vertical stresses $\sigma_y$ in successive steps of operations (Figure 4a-4f), it can be observed that, before the remnant of undisturbed rock is left behind, the stress concentration zone was present in front of the advancing mining front, and separation of a rigid remnant disrupted the geomechanical situation in the mining area. The remnant became a place where stresses were concentrated, acting on rock strata in both the roof and the floor found in its vicinity. Elevated stress zones are distributed centrally from the remnant in the roof and floor, and the reach of the action of...
the remnant and the value of stresses in its surroundings grow in successive steps of simulated mining as the front advances. As the distance from the remnant grows, its action decreases and vertical stress values tend towards the initial state. The occurrence of sudden destruction in the roof above the remnant edge (in the 35th computational step) caused disruption of the distribution of vertical stresses $\sigma_y$ near the left edge of the remnant as well as a reduction of their value in the yielded zone (Figure 4d).
Figure 4. Distribution of vertical stresses $\sigma_y$ in the model mining field for front lengths: a) 300 m – 19th computational step, b) 520 m (approx. 20 m from remnant edge) – 32nd computational step, c) 550 m (approx. 50 m from remnant edge) – 34th computational step, d) 560 m (approx. 60 m from remnant edge) – 35th computational step, e) 600 m (approx. 100 m from remnant edge) – 38th computational step, f) 900 m (approx. 400 m from remnant edge) – 59th computational step

Inside the remnant, vertical stresses $\sigma_y$ reach the greatest values at a certain distance from its edge, and their value decreases in the direction of the remnant's center (Figure 5). The maximum values of these stresses occur near the left edge of the remnant, from the side of gobs. For front lengths of 520 m (approx. 20 m from the remnant edge – 32nd computational step), 550 m (approx. 50 m from the remnant edge – 34th computational step), 560 m (approx. 60 m from the remnant edge – 35th computational step), 600 m (approx. 100 m from the remnant edge – 38th computational step) and 900 m (approx. 400 m from the remnant edge – 59th computational step), these stresses amount to,
respectively, 165 MPa (front length of 520 m), 215 MPa (front length 550 m), 227 MPa (front length 560 m), 234 MPa (front length 600 m) and 282 MPa (front length 900 m) at a distance of approx. 2 m from the left remnant edge. Inside the remnant, vertical stresses \( \sigma_y \) for analogous front lengths amount to, respectively, approx. 50 MPa (front length 520 m), 60 MPa (front length 550 m), 65 MPa (front length 560 m), 70 MPa (front length 600 m) and 90 MPa (front length 900 m) (Figure 5). Vertical stress \( \sigma_y \) values near edges and inside of the remnant grow in successive steps of operation.

![Figure 5. Vertical stresses \( \sigma_y \) inside the 40-m-wide remnant for front length: 520 m (approx. 20 m from remnant edge) – 32nd computational step, 550m (approx. 50 m from remnant edge) – 34th computational step, 560 m (approx. 60 m from remnant edge) – 35th computational step, 600 m (approx. 100 m from remnant edge) – 38th computational step, and 900 m (approx. 400 m from remnant edge) – 59th computational step](image)

3. Conclusions
Tremors and rockbursts occur in many hard rock mines around the world. Assessment of the hazard risk and analysis of the possibility that a dynamic phenomenon will occur are a very important aspect of designing safe mining under rockburst hazard conditions. The application of numerical methods significantly expands research capabilities related to analysis of seismic phenomena. Numerical modeling enables advance identification of potential rockburst hazard zones and prediction of the hazard state, while back analyses make it possible to determine the conditions under which a dynamic phenomenon may occur as well as to identify its potential mechanism.

Numerical modeling was applied in this study by means of Phase2 v. 8.0 software in order to determine the influence of remnant on the occurrence of dynamic phenomena in a mining field in a hard rock mine at high depth, mined according to the room-and-pillar system. Numerical analyses have demonstrated that a remnant with a width of 40 m left in this mining field should remain stable even in the case of significant advancement of mining and should not pose as hazard of stress-induced rockburst. Only side wall zones may be destroyed. However, numerical simulations also showed that sudden roof fracturing may occur during restoration of the mining front on the edge of a rigid remnant, from the side of gob, leading to a high-energy mining tremor as a result of exceedance of shear
strength, above all. The core of the remnant remained intact. These results confirm [17] conjecture that the deciding factor affecting occurrence of high-energy dynamic phenomena in the vicinity of remnants (stabilizing pillars) is the reach of destruction along their edges. He also acknowledged that the presence of shear stress concentrations on pillar edges should also be a significant parameter in pillar design.

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