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Application of Seismic Monitoring and Numerical Modelling in the Assessment of Possibility of Seismic Event Occurrence in the Vicinity of Ore Remnant

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Abstract: Seismic and rockburst hazard is one of the basic problems associated with deposit exploitation in many underground mines. Rockbursts are responsible for many mining accidents, and their effects, which include damaged excavations, destroyed equipment and machinery, generate financial losses and disrupt the operational continuity of the mining facility. Dynamic phenomena occurrence is one of the major natural hazards in Polish underground copper mines in the Legnica-Glogow Copper Belt (LGCB). The degree of seismic hazard in the LGCB results, among others, from the great depth of the copper deposit exploitation, high-strength rock layers in the roof strata and the ability of rock mass to accumulate elastic energy, as well as from an increasing amount of mining works to be carried out in difficult geological and mining conditions, for instance in the vicinity of remnants. The purpose of this paper is to show the influence of ore remnant on the possibility of seismic event occurrence by seismic activity analysis and numerical modelling. The possibility of using numerical modelling to back-calculate the occurrence of a seismic event due to sudden shear rupture is also presented. Analyses were conducted for the case study of the Polkowice-Sieroszowice Polish underground copper mine for the room-and-pillar mining system with room deflection. For the selected mining field, quantitative analysis of seismic activity was performed in connection with the assessment of the mining situation in this field. The location of tremor epicentres in the context of the existing geological and mining situation was also analysed, with special attention paid to the impact of remnants and dynamic phenomena in their vicinity. Subsequent investigations focused on the back analysis of deposit exploitation by room and pillar mining system with roof deflection in the selected mining field. Numerical simulations were conducted in a plane deformation state by means of Phase2 v. 8.0 software, which is based on the finite element method. The results of seismic and numerical analyses show that undisturbed rock remnants may have a negative impact on the seismic and rockburst hazard in the mining field. The analyses also show that on the edge of a rigid remnant, sudden fracturing of roof strata may occur, as a result of exceedance of shear strength (shear rupture). This may cause a high-energy mining tremor, and under appropriate conditions, may result in a rockburst phenomenon.

1. Introduction

The assessment of seismic events occurrence is very important for the design of safe exploitation in deep underground mines. Seismic tremors are caused by disturbing the stability of rock mass. As a
result, the potential energy is released from the rocks. Small part of this energy is transformed into seismic energy, which propagates from the focus of the tremor in the form of elastic waves [1, 2]. Rockbursts are a special type of mining tremors. In 1966, research conducted in mines located in Republic South Africa proved that each rockburst is accompanied by a mining tremor, while only a part of mining tremors causes rockbursts [3]. A rockburst results in a sudden damage or destruction of the excavation along with all the consequences involved [1, 2].

Polish copper ore mines of the LGCB region experienced mining tremors and rockbursts already during the first years of ore exploitation. High level of seismic activity is influenced by geological, mining and organizational factors. The most important factors include increasing mining depth, which translates into increased in-situ stress, as well as into the presence of discontinuity planes and of high-strength lime and anhydrite rocks in the roof, which show a tendency towards rockbursts. Roof rocks have high compression strength and therefore they are able to accumulate elastic energy and release it suddenly [4]. The mining factors which influence dynamic phenomena include: mining method, roof control method, mining face parameters and whether mining production is performed in constrained geological and mining conditions, inter alia in the presence of ore remnants.

Remnants are typically small irregular blocks of ground surrounded by mined-out areas in such a way that their exploitation is impossible or uneconomical [5]. In-situ observations and scientific research indicate that remnants negatively influence the risk of tremors and rockbursts, and as a result they pose a threat to mining works performed within the affected range. Rigid remnants present in mined-out area, constitute zones of high stress concentrations, which cover both the bed and the rock layers below and above the remnant [6, 7]. In the case when the dimensions allow such a situation, when the stress value in the remnant exceeds the remnant’s strength, the remnant may be crushed and – if the conditions are particularly unfavourable – a strain rockburst may occur [8, 9]. Such remnants may also cause the roof layers to collapse and eventually, as the distance to the mining face increases, lead to high-energy tremors [10, 6].

2. Case study – D-IE panel in Polkowice-Sieroszowice mine

2.1 Presentation of the D-IE panel

The case study of seismic activity in the rock mass and of numerical calculations was performed for the D-IE panel owned by the Polkowice-Sieroszowice Polish copper ore mine located in the LGCB. It was a closing field – production started in it in March 2005 and was performed in the vicinity of large mined-out areas present on both sides. Mineralization in the field was present in the lower part of the Zechstein carbonate succession and in the roof part of the Rotliegend and included: gray sandstone, quartz sandstone, fine-grained sandstone, cupriferous shale (clay and dolomite-clay) as well as streaky, dark gray, cryptocrystalline dolomite. The roof was formed of rock layers being part of the Zechstein carbonate succession, and the immediate floor comprised grey Rotliegend sandstone. The deposit extended in the NW-SE direction, and the dip (2-3°) towards NE. The deposit in the D-IE panel is located at a depth of approximately 1000 m. Average wall length is 500 m and the mined height varies between 2.0 m and 2.8 m. Working area width is typically between 4 and 5 strips. The rock mass showed small tectonic involvement and the deposit was classified with 3rd rockburst hazard degree. Until November 2008, the panel was mined using the room and pillar system with roof deflection and with an operating closing pillar (further: J-UGR-PS), and the room and pillar system with roof deflection and with drifts and airways driven in the workings (further: J-UGW-PS). In 2008, the operating closing pillar was removed and further extraction was performed with the room-and-pillar system with roof deflection (further: J-UG-PS) and with the J-UGW-PS in the right wing of the mining front. The deposit was mined with the use of technological pillars situated in perpendicular to the mining front and having basic dimensions of 6×8 m (J-UGR-PS and J-UG-PS). In 2007, due to problems with maintaining the roof's stability, a deposit remnant with a width of approx. 40 m was separated, between the extracted P-38 strip and strip P-33 [11].
2.2. Analysis of seismic activity of the rock mass in the D-IE panel

The D-IE panel showed high seismic activity. Between 01/01/2003 and 31/12/2011, a total number of 854 seismic events was recorded in the field, including 231 high-energy phenomena (Figure 1). The opening cutting in the D-IE panel was performed at a moderate (in relation to the mining conditions) seismic activity level. However, with growing production, a systematic increase in the number of tremors was recorded. In 2006, the indicators reached their maximum levels. In December 2006, a seismic event was recorded, which had a very high energy, in the E8 class, and which significantly affected the stability of the roof in the central part and in the right wing of the field. The reconstruction of the mining front was started with strips P-34-P-37, but eventually increasing problems with the roof necessitated forming a remnant 40 m in width.

![Figure 1. Yearly distribution of seismic activity in the D-IE panel for the period of 2002-2011 [11]](image)

In 2007, rockburst risk remained at high level and mining works consisted mainly in restoring the front on the right wing of the D-IE panel. As a result, mining production declined by almost 300% in comparison to 2006. This reduction was also reflected in the level of seismic activity. In 2007, the number of dynamic phenomena decreased by 60% in relation to the previous year, and seismic energy release dropped by 82%. Still, a total number of 61 seismic events were recorded in 2007, and high-energy tremors accounted for 31% of them. Instruments recorded 2 tremors in the E7 energy class and 3 tremors in the E6 class. The epicentres were located mainly along the undisturbed rock edges (which were the result of interrupted exploitation) and in the vicinity of a fault located in the area and having an approximately 0.5-1.5 m throw (Figure 2). The first event, having an energy of $10^7$ J was recorded on 13 March and caused stress relief in the rock mass. The second event had an energy of $4.4 \times 10^7$ J and was recorded on 04/10/2007. It was induced by blasting performed on the left wing of the front, in the area of the restoration works (Figure 2). This event did not affect the mining excavations. Figure 3 shows the mechanism of the epicentre of the E7 event, which was recorded in October 2007. The
geophysical analysis of the tremor (using the seismic moment tensor inversion method to define the mechanism of the tremor's focus) shows rock mass displacement on the reverse fault in the SW direction, towards the mined-out areas. This plane runs in the direction approximately consistent with the mining front line.

![Figure 2](image1.png)

**Figure 2.** Locations of the epicentres of dynamic phenomena in the D-IE panel in 2007, with the indicated area of the mining front under reconstruction and the area of rock remnant under formation

![Figure 3](image2.png)

**Figure 3.** Solution to the mechanism of tremor focus recorded on 04/10/2007: for the full tensor [11]

In December 2008, a very strong tremor in the rock mass, having energy equal to $6.1 \cdot 10^7$ J, led to a spontaneous rockburst in the right wing of the D-IE panel (Figure 4a). The rockburst caused a partial stress relief in the area and decrease of seismic activity in the subsequent months. A total number of 19 seismic events were recorded in 2008: 15 in the E5 energy class, 3 in the E6 class and 1 in the E7 class. The seismic events were located mainly on the right wing of the D-IE panel, in the active area of the mining front. This fact may be attributed to the modification of the border of mined-out areas operated by the Rudna I mining region in the vicinity of the right wing of panel D-IE or to the influence of the ore remnant. Figure 4a shows that the epicentres of many tremors recorded in 2008 are located on the edge of the undisturbed rock in the remnant or in the vicinity.

In 2009, the front line was developed in D-IE panel uniformly between the undisturbed rock in D-3E in the left wing and along the mined-out areas of the Rudna mine in the right wing of the field. During this period, production from the field was intensified. A total number of 95 seismic events were recorded in 2009, and high-energy tremors accounted for 31% of them. Instruments recorded 3 E6 tremors and 2 E7 tremors. Two tremors, an E6 and an E7, caused rock mass relaxation. The epicentres of high-energy dynamic phenomena were located mainly in the right wing of the panel, in
the vicinity of the mined-out areas in the Rudna. No phenomenon was observed in the surroundings of the ore remnant (Figure 4b).

In 2010, the mining front in the D-IE panel was located at a significant distance from the remnant. 147 tremors were recorded, 28 of which had high energy. 5 E6 and 5 E7 seismic events were recorded. Thus, the year 2010 was marked by a significant rockburst hazard level. 4 events affected the mining excavations: 1 spontaneous rockburst and 3 relaxations. In 2010, the epicentres of approximately 76% seismic events were located in the vicinity of the mining front. Figure 5 indicates that the epicentres of high-energy tremors were located both in the right and in the left wing of the panel. A significant number of phenomena having lower energies were located in the mined-out areas. 1 E3 tremor was recorded in the area affected by the remnant.

![Figure 4](image)

**Figure 4.** Locations of the epicentres of dynamic phenomena in the D-IE panel in: a) 2008, b) 2009

![Figure 5](image)

**Figure 5.** Locations of the epicentres of dynamic phenomena in the D-IE panel in 2010

2.3. Parameters and assumptions of the model

Numerical analyses of how the ore remnant influences the possibility of a seismic event were performed using the Phase2 v. 8.0 software based on the Finite Element Method. The application enables using the Finite Element Method to perform numerical analyses in a triaxial stress state and in plane strain state. The behaviour of the rock mass was described with an elastic-perfectly-plastic model with softening. 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 (Figure 6). The assumed rock mass structure was based on the geological exploration performed in the analysed mining field. Vertical stress was applied to the top edge of the model, to compensate for the load of the overlying rock. It was assumed that the top edge of the plate will be subjected to stress equal to 17.657 MPa, which corresponds to the value of vertical stress determined for the analysed region. The calculations included the unit weight of the rock layers. Displacement boundary conditions were set at plate edges. A finite element mesh was constructed of 3-node triangular elements.

The calculations were performed in steps, simulating a room-and-pillar mining system with roof deflection and with parameters characteristic for the analysed mining field (64 calculation steps). The first step involved the conditions in the rock mass prior to developing any workings. The second step consisted in the cutting of the undisturbed rock into technological pillars 8 m in width. In subsequent steps, the size of the technological pillars was reduced to the size of residual pillars (3 m) and successive technological pillars were formed. The deposit was cut into strips 6 m in width. The numerical simulations were based on an assumption that the working area width is of 5 strips. The ore remnant 40 m in width was formed when the life of face was approx. 460 m (step no. 30 in the numerical model), forming strip P-38 outside the risk area. Figure 6 shows the calculation scheme.

Figure 6. Calculation scheme for the D-IE panel (ore remnant 40 m in width)

Rock mass parameters assumed for the numerical analyses were determined using the Hoek-Brown classification based on the results of laboratory tests performed on rock samples collected from the
geological exploration holes drilled in the investigated region (Table 1). 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. In order to obtain optimal representation of actual conditions, the values of lowered parameters were selected by iterations so that the numerically calculated convergence values remained as close as possible to the results of in-situ convergence measurements.

Table 1. Rock mass parameters adopted for numerical modelling in an elastic-plastic model with softening

| Location         | Rock type                  | $h$ [m] | $E_s$ [MPa] | $v$ [-]  | $\sigma_t$ [MPa] | $c$ [MPa] | $\phi$ [°] | $c_{res}$ [MPa] | $\phi_{res}$ [°] | $\delta$ [°] |
|------------------|----------------------------|---------|-------------|----------|----------------|----------|-----------|----------------|----------------|-------------|
| Roof             | Main anhydrite             | 100.0   | 41.110      | 0.24     | 0.746          | 6.967    | 38.66     | 1.393          | 36.73          | 2.00        |
|                  | Clay-anhydrite breccia     | 10.0    | 7.100       | 0.18     | 0.093          | 2.507    | 39.06     | 0.501          | 37.11          | 2.00        |
|                  | Basic anhydrite            | 73.0    | 40.010      | 0.25     | 0.765          | 7.146    | 38.66     | 1.429          | 36.73          | 2.00        |
|                  | Calcareous dolomite I      | 15.0    | 44.980      | 0.24     | 2.933          | 12.085   | 39.00     | 2.417          | 37.05          | 2.00        |
|                  | Calcareous dolomite II     | 2.0     | 87.440      | 0.27     | 4.715          | 19.895   | 39.00     | 3.979          | 37.05          | 2.00        |
| Mined Deposit    | Mined height               | 2.7     | 25.240      | 0.21     | 0.825          | 8.424    | 39.31     | 1.350          | 37.35          | 2.00        |
| Height           | Quartz sandstone I         | 8.2     | 4.260       | 0.15     | 0.057          | 1.538    | 39.06     | -             | -              | -           |
|                  | Quartz sandstone II        | 194.5   | 3.220       | 0.13     | 0.043          | 1.160    | 39.06     | -             | -              | -           |

The symbols used in the above table are as follows: $h$ – thickness of rock layers, $\rho$ - volume density, $R_c$ – rock sample strength to uniaxial compression, $R_e$ – tensile strength of the rock sample, $E_s$ – longitudinal modulus of elasticity, $v$ – Poisson's ratio, $\sigma_t$ - tensile strength of the rock mass, $c$ – cohesion coefficient, $\phi$ – internal friction angle, $\delta$ – dilatancy angle, $c_{res}$ – residual cohesion coefficient, $\phi_{res}$ – residual internal friction angle.

2.4. Numerical modelling results and discussions

The assessment of the possibility of seismic event occurrence in the vicinity of ore remnant was performed on the basis of vertical stress distribution $\sigma_t$ and the range of the yielded element zones. The analyses covered the behaviour of ore remnants and of the surrounding rock mass in the successive steps of the simulated exploitation using room-and-pillar system with roof deflection.

The results of numerical calculations indicate that as the mining front is reconstructed (calculation step no. 35, when the life of face is 560 m – approximately 60 m from the remnant edge), a yielded zone occurs rapidly (during one calculation step) in the roof, above the edge of the analysed remnant (Figure 7). A lateral damage line in the roof is formed at the left edge of the remnant and is inclined at 60° towards the exploited area. The line was created mainly due to exceeded shear strength (Figure 7).
Numerical simulations demonstrated that inside the analysed 40 m remnant, yielded zones may be found only at the edges, and their range increases in successive exploitation steps. The remnant remains stable even in the case of maximum face life of 900 m (approximately 400 m from the edge). The range of yielded zones is at a maximum of 3.5 m (Figure 8).

**Figure 7.** Range of yielded zone for the life of face: a) 550 m (approximately 50 m from the remnant edge) – calculation step no. 34, b) 560 m (approximately 60 m from the remnant edge) – calculation step no. 35

**Figure 8.** Range of yielded zone inside the 40 m wide ore remnant for the face life of 900 m (approximately 400 m from the edge) – calculation step no. 59
Analyses of vertical stress $\sigma_y$ distribution in the vicinity of the 40 m remnant left in the D-IE panel indicate that the remnant concentrates stresses and affects the mass rock in its vicinity. Elevated stress zones propagate from the remnant centrically, both in the roof and in the floor. The violent destruction in the roof above the remnant edge (calculation step no. 35) resulted in the disturbance of the vertical stress $\sigma_y$ distribution at the left remnant edge and in reduced values of vertical stresses $\sigma_y$ in the yielded zone (Figure 9). Inside ore remnant, vertical stresses $\sigma_y$ reach highest values at a distance of approximately 2 m from the edge, and they decrease towards the centre of the remnant. Maximum stress values are found at the left remnant edge, on the side of mined-out areas (Figure 10).

![Figure 9. Vertical stress $\sigma_y$ distribution for the life of face: a) 550 m (approximately 50 m from the remnant edge) – calculation step no. 34, b) 560 m (approximately 60 m from the remnant edge) – calculation step no. 35](image)

![Figure 10. Vertical stresses $\sigma_y$ inside the 40 m remnant for the life of face: 550 m (approximately 60 m from the remnant edge) – calculation step no. 34, 560 m (approximately 60 m from the remnant edge) – calculation step no. 35, 900 m (approximately 400 m from the remnant edge) – calculation step no. 59](image)

3. Conclusions
The occurrence of dynamic phenomena is one of the leading problems in many underground mines, among others in Polish copper ore mines of the LGCB region. The results of seismic and numerical analyses show that undisturbed rock remnants may have a negative impact on the seismic and rockburst hazard in the mining field.
The paper presents the back analysis of deposit exploitation by room and pillar mining system with roof deflection in the D-IE panel. The numerical analyses also showed that during the reconstruction of the mining front, the roof may have suddenly and violently collapsed at the edge of the rigid remnant, on the side of the D-IE panel's mined-out areas, leading to a high-energy seismic event caused mainly by the exceeded shear strength. The mechanism of the phenomenon is approximately similar to the in-situ observations and seismic analyses performed in the D-IE panel. It may be concluded that numerical calculations simulated the possibility of a high-energy, E7-class event, which was recorded in October 2007 at the edge of the formed ore remnant and which had a nature of a reverse fault (Figure 11).

The results of numerical modelling performed for the D-IE panel indicate that the 40 m wide ore remnant should remain stable even when mining exploitation is advanced. Damage may occur only in the zones at the walls. It should not pose a threat of strain burst or pillar burst. Analyses of vertical stress $\sigma_y$ distribution inside the 40 m ore remnant lead to a conclusion that the concentrations of stresses $\sigma_y$ occur at remnant edges, while in the central part of the remnant they do not exceed the value of approximately 75 MPa, even if the mining front is located at a significant distance from the edge (approximately 400 m).

Back calculations performed as part of this work allow determining the conditions in which a dynamic phenomenon may occur.

Figure 11. Location of the epicentre of an E7 seismic event recorded in October 2007 at the edge of the formed remnant and the presumable mechanism of this phenomenon

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