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THE ISSUE OF DETERMINING THE SIZE OF MAIN EXCAVATIONS PROTECTIVE PILLARS IN DEEP UNDERGROUND COPPER MINES

PROBLEMATYKA WYZNACZANIA WIELKOŚCI FILARÓW OPOROWYCH WYROBISK KAPITALNYCH W GŁĘBOKICH KOPALNIACH RUD MIEDZI

This article describes stability issues of main excavations in deep copper mines in Poland, from the perspective of mining work safety. To protect main transportation and ventilation routes, parts of rock are left untaken to form so-called protective pillars. The problem was to determine the size of main excavations protective pillars in deep underground copper mines in which provide stability of main excavations. The results of numerical simulations of the stability of protective pillars under specific geological and mining conditions are presented, covering: underground depth and width of protective pillar, number, size and layout geometry of protected excavations, as well as the impact of parameters of surrounding gob areas. Problem was solved applying numerical simulations based on the finite element method which were performed in a plane state of strain by means of Phase2 v. 8.0 software. The behavior of the rock mass under load was described by an elastic-plastic model. The Mohr-Coulomb criterion was used to assess the stability of the rock mass. The results of numerical modeling have practical applications in the designing of protective pillars primarily in determining their width. These results were used to prepare new guidelines for protective pillars in Polish copper mines in the Legnica-Glogow Copper District.

Keywords: protective pillars, main excavations stability, deep underground copper mines, numerical modeling

W artykule opisano problematykę stateczności wyrobisk kapitalnych w głębokich kopalniach rud miedzi w Polsce, która jest bardzo ważnym zagadnieniem w aspekcie bezpieczeństwa prowadzonych robót górniczych. W celu ochrony głównych dróg komunikacyjnych i wentylacyjnych pozostawia się fragmenty calizny tworzące tak zwane filary oporowe. Następnie przedstawiono wyniki symulacji numerycznych stateczności filarów oporowych w określonych warunkach geologiczno-górniczych ich użytkowania, które objęły: głębokość zalegania i szerokość filara, liczbę i wielkości oraz geometrię rozmieszczenia wyrobisk chronionych, a także oddziaływanie parametrów pól zrobów w otoczeniu. Symulacje numeryczne wykonano w płaskim stanie odkształcenia za pomocą programu Phase2 v. 8.0, w oparciu o metodę elementów skończonych. Zachowanie górotworu pod obciążeniem opisano modelem sprężysto-plastycznym.

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Zastosowano kryterium wytrzymałościowe Coulomba-Mohra. Wyniki modelowania numerycznego mają zastosowanie praktyczne przy projektowaniu filarów oporowych. Zostały wykorzystane przy opracowaniu nowych wytycznych dla filarów ochronnych w polskich kopalniach rud miedzi w Legnicko-Głogowskim Okręgu Miedziowym.

Słowa kluczowe: filary oporowe, stateczność wyrobisk kapitalnych, głębokie kopalnie rud miedzi, modelowanie numeryczne

1. Introduction

Main development excavations in the structure of the deposit in underground exploitation of bedded or pseudo-bedded deposits must be designed so that these excavations can be maintained for a long time when exploitation is performed up to boundaries. Due to the variety of applications that these excavations must perform (ventilation, transport of personnel and material) in Polish copper mines in the Legnica-Glogow Copper District (the Rudna mine and the Polkowice-Sieroszowice mine), they are designed in multi-heading configurations (bundles). In copper ore mining, the number of functional excavations in such a configuration ranges from 3 to 5, depending on the depth of the main excavation, the cross-section of individual excavation, and assigned applications. Due to the increasing depth of exploitation and extended length of air intake and exhaust channels, it is also expedient to separate ventilation functions by making lines only for air intake or exhaust in a bundle. To maintain such multi-heading configurations for a long time, protective pillars (undisturbed rock) with a width that ensures bearing of additional pressure from the rock mass, must be left on both sides of main excavations.

In the first years of operation of copper mines in the Legnica-Glogow Copper District, protective pillars with a width of 100-150 m were left behind to provide stability of main excavations, and this width increased as time went on, from 250 up to 600 m (particularly at greater depths). Currently, according to relevant regulations (*Regulation…*, 2016), protective pillars in Polish copper mines must have a width of at least 350 m. This value results from the necessity of ensuring expected safety conditions in the future, during exploitation with area collapse (upon pillar removal).

In relation to exploitation of the copper ore deposit in the Legnica-Glogow Copper District, at a depth of over 1200 m below ground level in the Deep Glogow Mine Region and planned exploitation of the deposit in the Bytom Odrzanski and Retkow areas, which is at an even greater depth than the areas in which mining is currently being performed, the target structure of development excavations at deposit level is of great significance. This structure constitutes the minimum required scope of excavations providing access to the deep deposit. Maintenance of their long-term stability and function will ensure the safety of the mining crew on haulage routes and in regions where work is performed as well as the reliability of the copper ore transport system and will enable effective ventilation of regions where work is planned. Besides work performed to provide access to new parts of the deposit, optimal use of existing shafts and ventilation infrastructure is a precondition for the realization of this undertaking. This is why it has been necessary to verify currently applicable guidelines concerning protective pillar size for main excavations by means of numerical methods. A broad research program was conducted in 2015, on the foundation of the scientific description: "*Development of guidelines for determining protective pillars and principles of securing and maintaining their applications in the mines of KGHM Polska Miedz S.A.*" (Butra et al., 2015).

2. Protective pillar stability

The weight of the overburden (p_z) and the weight of the rock making up semi-beams around the protective pillar have an impact on stress distribution in it. Protective pillars left behind after extraction of the rock around them become a stress concentration site, which has an unfavorable effect on the stability of functional excavations and on the rock burst hazard risk when a pillar's geometry is improperly designed. These hazards may occur while the pillar is performing its applications and/or during its removal at the final stage. Improperly designed geometry of the protective pillar may also pose a hazard to mining work performed within the range of its interaction. Stress distribution in the protective pillar and its immediate vicinity was formulated by Antoni Salustowicz (Fig. 1), a Polish scientist, by means of equations based on Budryk's bending theory of beams on elastic foundations (Salustowicz, 1955).

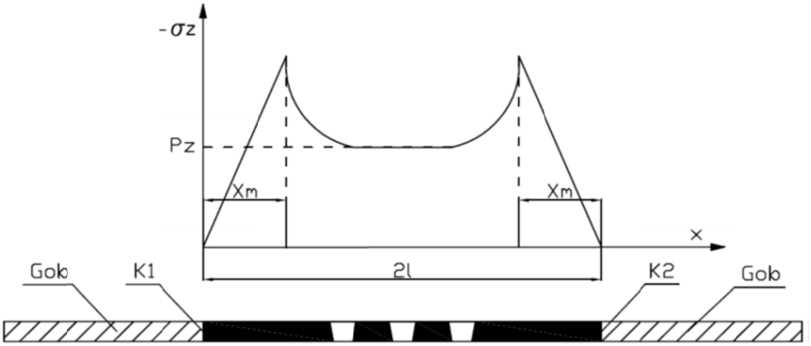

Fig. 1. Interaction of surrounding gob on a protective pillar (Salustowicz, 1955)

Figure 1 shows that, if the protective pillar has an appropriately large width of $2L$, thentwo areas of maximum stress are present on its edges, at a distance of x_m from edges K_1 and K_2. As the width of the protective pillar decreases, superposition of stresses may occur, and in extreme cases, when $2L = 2x_m$, these stresses are summed up. If this is the case, stresses reach very high values, up to $4p_z$. In turn, excessive splitting of a protective pillar with excavations or improper design of the geometry of large-size pillars within the protected bundle will cause growth of stress concentration in the side walls of excavations and enlargement of damaged zones. This inevitably leads to loss of stability of excavations, and in consequence, to loss of its functionality. For this reason, for bundles of main development excavations to the deep deposit, it must be planned to leave rock undisturbed on their edges, with a width that ensures their stability. The geometry of large-size pillars in bundles must be provided that will ensure their work in elastic phase throughout the entire period for which the bundle will be used.

Pillar failure modes are widely described in the literature (Brady & Brown, 2006; Alejano et al., 2017) and presented in the figure 2.

In Polish copper mines, carbonate and anhydrite formations are characterized by high strength properties, and when they lie above exploited areas, they generate high additional loads on protective pillars. This is why it is assumed that stress concentration in protective pillars in Polish copper mines depends on: depth of deposit, the width of the pillar, number and size, as

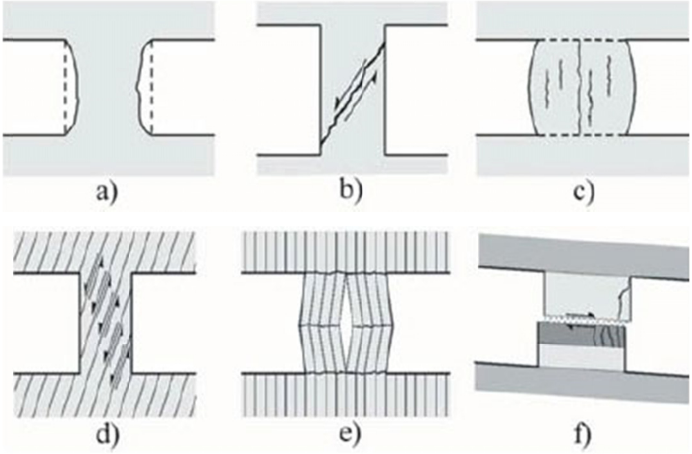

Fig. 2. The pillar failure modes: a) spalling from the pillar surfaces, b) shear fracturing, c) internal axial splitting of the pillar, d) pillar yielding due to slipping on the fractures, e) buckling (Alejano et al., 2017)

well as the geometry of the arrangement of protected excavations and on the parameters of gob areas (width, height of deposit and roof movement control method) in the vicinity of pillars. Stress concentration around main excavations has a direct impact on their stability. The rock mass may become overstressed and a damaged zone may form due to excessive stress concentration near the excavations. Rock encompassed by this zone exhibits a tendency to separate from the rock mass and shift, leading to rockfalls in protected functional headings, which is visible in the protective pillars in the Rudna mine and the Polkowice-Sieroszowice mine.

From an organizational perspective and in order to ensure maximum driving progress, the optimal number of development headings excavated at the same time is 3. From a geomechanical perspective, these excavations should be made symmetrically relative to the axis of the future protective pillar. When it is necessary to excavate a 5- or 7-heading bundle, additional excavations should be made in second order, with preservation of symmetry relative to the longitudinal axis of the future protective pillar. The roof of development excavations should be made up of a layer with strength properties ensuring long-term stability. This is why it is necessary to correctly identify the geological structure and strength/deformation properties of roof rock at the driving stage. It is advisable to apply resin-grouted bolts of a length of at least 1.6 m as the primary bolting in long-term excavations (*Regulations*…, 2017). Uncovered bolt elements are to be protected against corrosion. In the case of a deteriorated roof, additional bolting is to be applied with long bolts and corrosion-resistant mesh lagging (including standing support, locally).

Excavations in the bundle are linked by cross-cuts as driving progresses. Cross-cuts are successively dammed with ventilation dams in order to achieve fresh air supply as close to faces as possible. The distance between cross-cuts varies, ranging between 40 and 100 m depending on ventilation conditions. It should be attempted to provide a distance of approx. 100 m between cross-cuts. Only in the case of difficulties in providing proper climate conditions may the distance between cross-cuts be 50 m. In particular, greater distances of extreme cross-cuts, from at least 106 m (for 50 m minimum distance between cross-cuts) to 200 m and more (Figs 3 and 4) are to be ensured for extreme excavations in bundles supplying fresh air to the deep deposit (in contact with excavations performing other functions in the bundle). Excavating headings in the bundle in two phases (3 headings in first phase) may facilitate achieving such distances in extreme excavations.

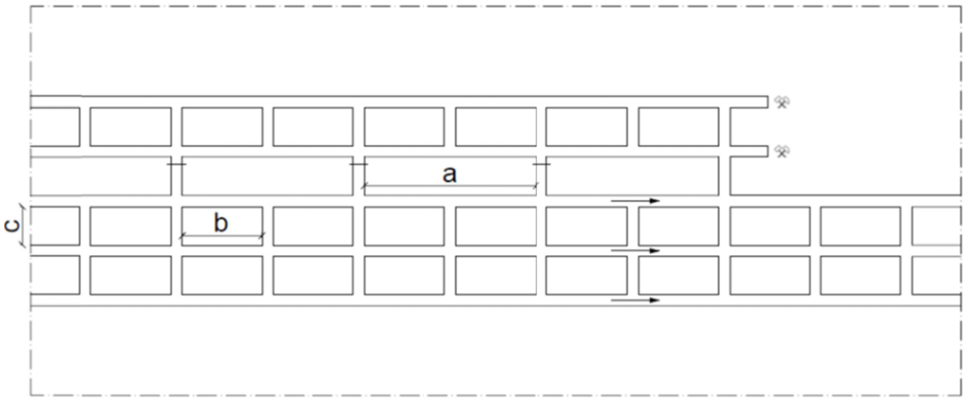

Fig. 3. Method of excavating extreme headings in a five-heading bundle, the minimum length of the pillar: a = 106.0 m, b = 50.0 m, the minimum width of the pillar: c = 20.0 m (Butra et al., 2015)

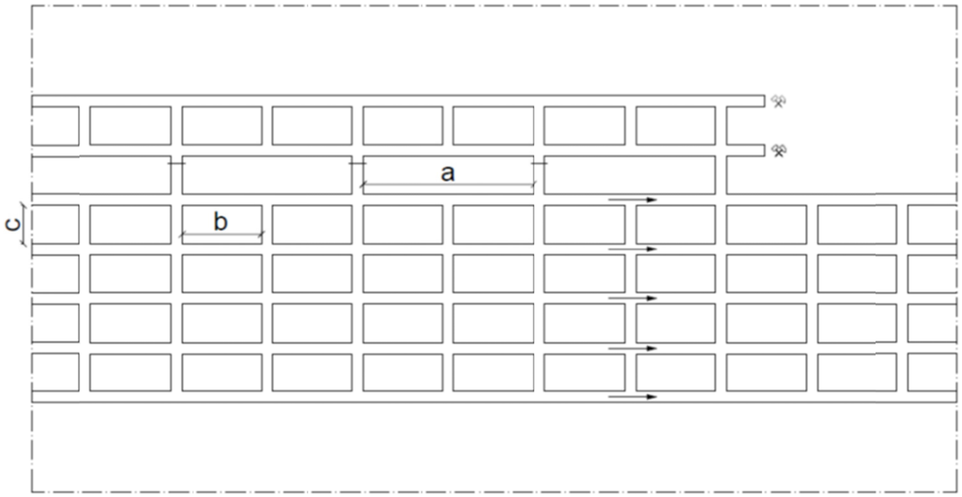

Fig. 4. Method of excavating extreme headings in a seven-heading bundle, the minimum length of the pillar: a = 106.0 m, b = 50.0 m, the minimum width of the pillar: c = 20.0 m (Butra et al., 2015)

The distance (in protective pillar) between excavations in a bundle also depends on geological and mining conditions, ranging between 18 and 40 m. Distance below 18 m might not ensure long-term work of large-size pillars in elastic phase (even at 3.5 m height of development excavations) at the stage where protective pillars carry additional loads from the overburden rocks from surrounding gob areas.

3. Methods: numerical analysis of protective pillar stability

Geomechanical analysis of the stability of protective pillars was conducted for geological and mining conditions in the region of the bundle of main inclines H-10÷H-17c and the bundle of roadways T,W-169 located in Polish underground copper mine in the Legnica-Glogow Copper District. These excavations were driven by blasting. All excavations had trapezoidal profile, with side walls inclined at an angle of 10° and width under the roof of 6 m.

Geomechanical parameters of rock in the analyzed region were determined on the basis of results of laboratory tests conducted on rock samples in KGHM Cuprum CBR sp. z o.o. rock mechanics laboratory. Samples for geomechanical tests were collected from geotechnical boreholes. The geological structure of the region subject to analysis is diverse. The main roof is composed of anhydrites and dolomites, which are characterized by high strength and strain properties. The deposit (a face) in mining headings is made up of dolomites and sandstones, and sandstones with varied strength properties are dominant in the floor layer of headings. RocLab 1.0 software (Rocscience, 2007) and Hoek-Brown classification were applied to determine the parameters of the rock mass (Hoek, 1994; Hoek & Brown, 1997; Hoek & Marinos, 2000; Hoek et al., 2002).

Numerical simulations of protective pillar stability were conducted by means of Phase2 v. 8.0 software (Rocscience, 2013) in a triaxial stress state of a plane strain state based on the finite element method (FEM). Numerical analyses were conducted by describing the rock mass with an elastic-plastic model (Table 1). It was assumed that the medium is homogeneous and isotropic. The Mohr-Coulomb strength criterion was applied to judge the stability of the rock mass. It is described by the formula:

$$\sigma_1 = \sigma_3 \cdot \frac{1+\sin\varphi}{1-\sin\varphi} + \frac{2c\cdot\cos\varphi}{1-\sin\varphi} \tag{1}$$

where: σ_1, σ_3 are maximum and minimum stress at failure, φ is internal friction angle, c is cohesion.

The stability was analyzed for protective pillars with widths of 400 m and 450 m, situated at a depth of 1300 m. In both cases, simulations were performed for a bundle of 5 and 7 excavations, accounting for variants of pillar width between excavations: 24 m and 28 m, and after that, simulation was performed for pillars with a width of 20 m. In every case that was analyzed the numerical model was a rectangular plate. The rock layers building up the rock mass were taken into consideration in every plate. The accepted structure of the rock mass resulted from a geological survey conducted in the region subject to analysis.

Calculations were performed step-by-step, simulating the excavation of 5 or 7 mining headings and accounting for the progress of exploitation in their vicinity. The first step covered the situation in the rock mass before excavation of mining headings. The second step was based on excavating mining headings with the dimensions presented in table 2. In the following steps, the progress of exploitation according to the room-and-pillar system with roof deflection near excavations was simulated (on both sides of the protective pillar), accounting for a protective pillar with a width of 400 m or 450 m. Numerical simulations were conducted for two variants of exploitation: in the direction “away from pillar” and “toward pillar”.

TABLE 1

Parameters of the rock mass accepted for numerical modeling in an elastic-plastic medium according to the Mohr-Coulomb criterion in the analyzed region

Location	**Name of rock**	h **[m]**	ρ **[kg/dm^3]**	E_{rm} **[MPa]**	v **[-]**	σ_t **[MPa]**	c **[MPa]**	φ **[^{o}]**	δ **[^{o}]**	c_{res} **[MPa]**	φ_{res} **[^{o}]**
Roof	Anhydrite	190.0	2.93	29,750	0.24	0.647	6.046	38.66	2.00	6.046	38.66
	Calcareous dolomite I	10.0	2.76	52,910	0.24	3.356	13.827	39.00	2.00	13.827	39.00
Deposit	Calcareous dolomite II	0.6	2.80	65,850	0.25	4.073	16.783	39.00	2.00	16.783	39.00
	Calcareous dolomite III	0.2	2.73	35,830	0.22	2.490	10.261	39.00	2.00	10.261	39.00
	Quartz sandstone I	2.7	2.34	8,650	0.19	0.182	3.630	40.54	2.00	3.630	40.54
Floor	Quartz sandstone II	3.0	2.36	7,330	0.20	0.161	3.210	40.54	2.00	3.210	40.54
	Quartz sandstone III	197.0	2.03	2,460	0.13	0.035	0.954	39.06	2.00	0.954	39.06

Marking in above table: h is thickness of rock strata, ρ is volume density, E_{rm} is longitudinal elasticity modulus, v is Poisson's ratio, σ_t is tensile strength of rock, c is cohesion, φ is angle of internal friction, δ is dilation angle, c_{res} is residual cohesion, φ_{res} is residual angle of internal friction.

TABLE 2

Geometry of numerical models

Width of protective pillar [m]	**Number of excavations in bundle [-]**	**Width of pillar between excavations [m]**	**Height of excavation [m]**	**Width of excavation under roof [m]**	**Width of excavation near floor [m]**	**Angle of inclination of side walls [°]**
400 or 450	5 or 7	20.0, 24.0 or 28.0	3.5	6.0	4.8	10

In numerical simulations, the upper edge of the model was subject to vertical load representing the action of the overburden. It was assumed that a stress equal to 24.309 MPa would be present at the level of the plate's upper edge, which corresponds to the value of vertical stress determined for the analyzed region based on data from the profile of the GG-1 shaft. The self-weight of rock layers was considered in calculations. It was assumed that vertical stresses change with depth and originate from the force of gravity, while the values of horizontal stresses are equal to vertical stresses (hydrostatic stress state). Displacement boundary conditions were set on the edges of the face:

- lower edge of the model – no vertical displacements,
- side edges of the model – no horizontal displacements.

A finite element mesh consisting of 3-node triangular elements was applied in the analyzed numerical models. The element mesh was concentrated at the center of the face in order to improve the accuracy of numerical simulations. An example scheme of simulation of a protective pillar with a width of 400 m, 5 excavations in the bundle, and pillar width between headings equal to 24 m for exploitation performed in the direction "away from pillar", has been presented in figure 5.

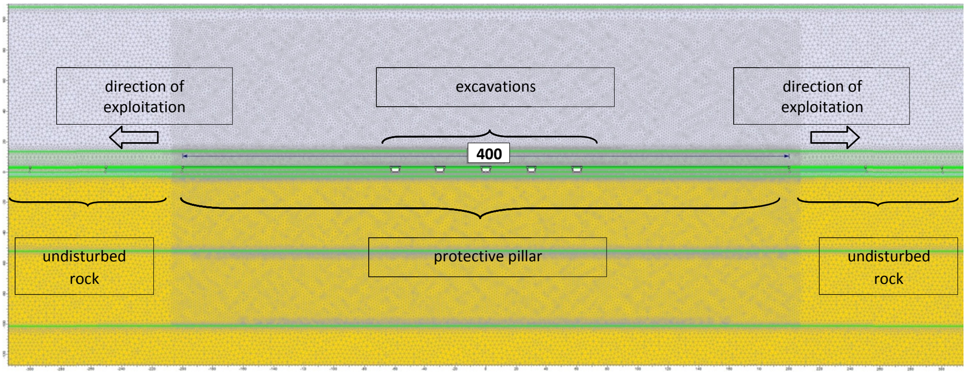

Fig. 5. Simulation of the stability of a protective pillar with a width of 400 m, 5 excavations in the bundle, and pillar width between excavations equal to 24 m, exploitation performed in the direction "away from pillar"

4. Results of numerical simulations

Based on numerical simulations conducted for the analyzed region areas of yield elements were determined for each numerical model. The behavior of protective pillars with widths of 400 m and 450 m under the influence of interactions arising from exploitation performed in their vicinity was analyzed. By analyzing yield areas, it can be noted that:

- protective pillars with widths of 400 m and 450 m should remain stable, only zones near pillar edges may be damaged, the maximum yield area near the edge of a protective pillar with a width of 400 m amounts to approx. 1.7 m (Fig. 6), and near the edge of a protective pillar with a width of 450 – approx. 1.5 m (Fig. 7),
- pillars with widths of 24 m and 28 m, situated between excavations, should also remain stable, and yield areas are only present near the edges of pillars up to a depth of approx. 1.5 m,
- rock strength may be exceeded around excavations (in the roof, floor and in side walls), and damaged areas may form (Figs 6 and 7), and yield zone in the roof comes up for every analyzed case does not exceed the value of approx. 1.72 m, in the floor – approx. 2.12 m, and in side walls – approx. 1.5 m,
- yield zones in the vicinity of excavations, above all, in the roof, grows in successive steps of simulated exploitation (meaning a growing gob area near the protective pillar), covering the maximum area at a panel length of 450 m.

By comparing yield zones around excavations in protective pillars, it was observed that increasing the width of the protective pillar up to 450 m does not significantly reduce the yield areas in either the roof or the floor of excavations (Figs 6 and 7). Differences in the size of damaged areas in the roof and floor reach several centimeters at the most. Numerical simulations also demonstrated a lack of significant differences in the size of yield zones between bundles of 5 and 7 excavations in the protective pillar. However, increasing the number of excavations in the protective pillar to 7 usually caused a slight increase in the yield areas around excavations.

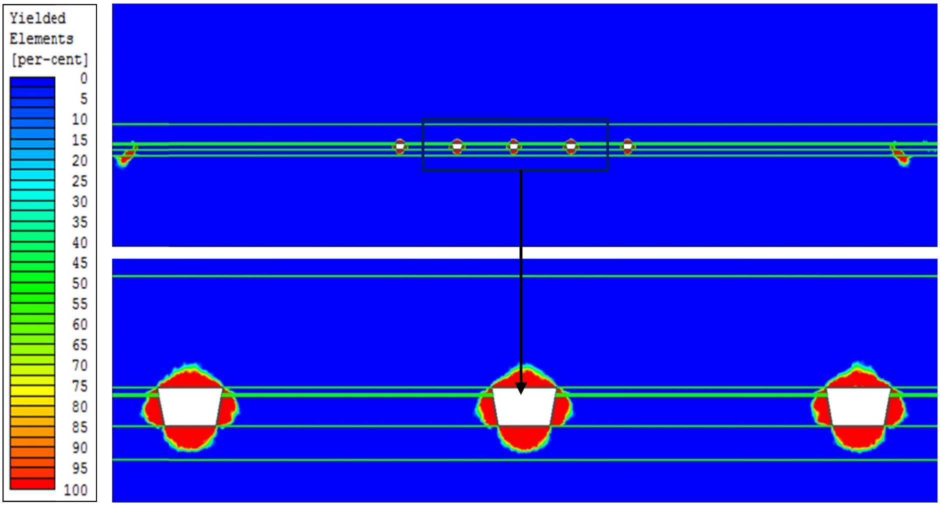

Fig. 6. Yield zones in the region of a protective pillar with a width of 400 m, 5 excavations in the bundle, and pillar width between excavations equal to 24 m, exploitation performed in the direction "away from pillar", panel length 450

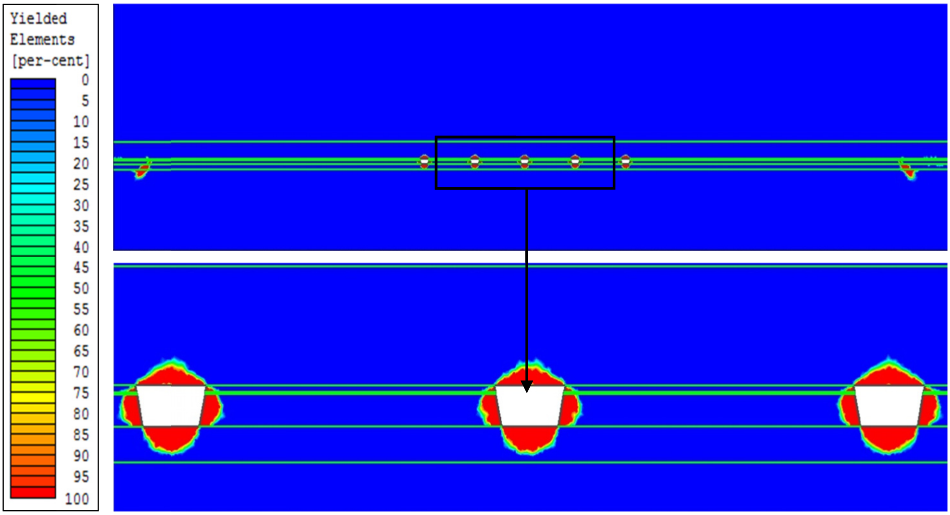

Fig.7. Yield zones in the region of a protective pillar with a width of 450 m, | 5 excavations in the bundle, and pillar width between excavations equal to 24 m, exploitation performed in the direction "away from pillar", panel length 450 m

Analysis of the yield zones around excavations in the protective pillar showed that increasing the width of the pillar between excavations from 24 m to 28 m, as well as reduction to 20 m, usually caused a slight increase in the size of yield zones in the roof and floor of excavations. These differences were small, on the order of several centimeters.

The results of numerical simulations of yield zones around headings situated within the protective pillar are concurrent for the two variants of exploitation (in the direction "away from pillar" and "toward pillar"). In the case of exploitation performed in the direction "toward pillar", greater growth of the yield zone is visible in the roof of excavations in successive stages of deposit extraction. The damaged zone nearly reaches its full size of 1.5-1.6 m at a panel length of 400 m (10th simulation step). In the case of exploitation in the direction "away from pillar", the full size of the yield zone in the roof (1.6-1.7 m) occurs suddenly at a panel length of 450 m (11th simulation step).

4. New guidelines for protective pillars

Conducted numerical simulations made it possible to develop new guidelines for protective pillars in Polish copper mines in the Legnica-Glogow Copper District. Guidelines were verified on the basis of underground observations conducted in existing excavations at a depth of over 1000 m below ground level. In deep mines, it was proposed that:

- the number of excavations (including main excavations) in the protective pillar cannot be greater than 7 (would be nice to know why here),
- the cross-section area of the main excavation in the pillar may not be less than 18 m^2,
- the width of large-size pillars in the bundle may not be less than 20 m,
- excavations in the protective pillar are to be designed in a configuration symmetrical relative to the pillar's axis,
- for pillars at a depth up to 1200 m, the width of the protective pillar should be at least 350 m,
- for pillars at a depth up to 1400 m, the width of the protective pillar should be at least 400 m,
- it should be attempted to ensure a distance of approx. 100 m between cross-cuts in large-size pillars in the bundle. In particular, for extreme excavations in bundles supplying fresh air to the deep deposit (in contact with excavations serving other functions), a distance of approx. 200 m is to be ensured between cross-cuts,
- when extracting the deposit near the protective pillar, its edges (boundaries) are to be made more flexible.

In addition, rules for safeguarding functional excavations in protective pillars were developed:

- functional excavations in the protective pillar are to be protected with resin-grouted roof bolting selected on the basis of applicable regulations and guidelines (*Regulations*…, 2017),
- geotechnical boreholes for determining the roof class are to be situated near the excavated bundles of development headings,
- in the event of a change of geological and mining conditions in the region or symptoms of roof instability, the roof class is to be verified, and if necessary, different roof bolting is to be selected (does not apply to situations related to local anomalies in geological structure),
- it is advisable for intersections of main excavations in the protective pillar to be additionally protected with bolts of increased length (the Chief Mining Engineer decides on this matter),

- uncovered bolt elements are to be protected against corrosion, and in the case of a deteriorated roof, additional bolting is to be applied with long bolts and corrosion-resistant mesh lagging (including standing support, locally).

5. Summary

Protective pillars left behind after extraction of the rock around them become a stress concentration site, which has an unfavorable effect on the stability of functional excavations and on the rockburst hazard risk when a pillar's geometry is improperly designed. As a result, excessive splitting of a protective pillar with excavations or improper design of the geometry of large-size pillars within the protected bundle will cause growth of stress concentration in the side walls of excavations and enlargement of damaged zones. This inevitably leads to loss of stability of main excavations, and in consequence, to loss of functionality. For this reason, for bundles of main development excavations to the deep deposit, it must be planned to leave rock undisturbed on their edges, with a width that ensures it will take over pressure from the roof layers forming cantilever beams around it (after extraction the deposit in its surroundings).

A geometry of large-size pillars in bundles must be provided that will ensure their work in elastic phase throughout the entire period for which the bundle will be used. Besides long-term stability of excavations protected by protective pillars and continuous monitoring of: the technical condition of excavations and the condition of the ventilation network as well as its planned and coordinated expansion, adherence to the guidelines and rules in question in Polish copper mines located in the Legnica-Glogow Copper District is to ensure preservation of all required parameters and function in cases where changes in the target structure are required. These changes may be justified by growing knowledge about the deposit or by new technical or organizational solutions.

Based on conducted numerical simulations and underground observations in existing excavations, new guidelines for protective pillars in Polish copper mines as well as rules for support functional excavations in protective pillars were developed.

Numerical simulations confirmed that a protective pillar with a width of 400 m, in which the analyzed excavations are situated, should remain stable and ensure stability of the immediate roof in mining excavations. Results of numerical simulations demonstrated that the material's strength may be exceeded on the edges of the protective pillar, and a yield zone may form. The maximum size of the yield zone in the roof of excavations situated within the protective pillar amounts to approx. 1.72 m.

Increasing the number of excavations in the protective pillar from 5 to 7, as well as increasing the width of the pillar between excavations from 20 m to 28 m, did not result in significant differences in stress distribution or size of yield zones around excavations. Values of principal stresses σ_1 and σ_3 as well as the reach of yield zones grow in successive steps of simulated exploitation as the gob area in the vicinity of the protective pillar increases.

The results of numerical simulations showed that the values of principal stresses σ_1 and σ_3 and the yield zones within the protective pillar largely depend on the value of roof displacements above the gob areas in the pillar's vicinity and on the width of gob areas next to the pillar. Optimal selection of roof movement control method may limit loads in the protective pillar induced by roof layers and improve the stability of excavations situated within the pillar.

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