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INFLUENCE OF REMNANT SIZE ON THE GEOMECHANICAL SITUATION AND SAFETY IN THE MINING FIELD BASED ON NUMERICAL MODELING

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Abstract: Great problem associated with the Polish underground mining is doing the mining operations at an increasing depth in difficult geological and mining conditions, among others, in the area of remnant impact. The problem with remnants and its effect on the rock mass behavior is an important issue in the Polish underground hard coal mines and copper mines. The main goal of the paper is to investigate how the different sizes of remnants affect the geomechanical situation in the mining field. Numerical simulations were conducted for the case study of a mining field with a room and pillar mining system, where undisturbed remnants 10, 20, 40, 60, 100, and 200 m in width, were left behind. Results of numerical analysis demonstrate that the size of remnant has a great influence on the stress distribution and rock mass stability in the mining field. As the width of the remnant decreases, the values of vertical stress σ_y both inside the remnants and in its surroundings increase and reach very high values for narrow remnants. In contrast to the vertical stress σ_y, the strength factor S_f decreases as the width of the remnant decreases. Simulations show also that leaving a large remnant in the form of a stabilizing pillar, improves the stability of the roof in the mining field but for remnants with high widths an unstable zone might be formed in the roof layers above the edge of the remnant at the goaf side which may cause sudden fracturing and collapse of rigid roof layers on the edge of the remnant. The results achieve in this paper can be utilized to enhance the safety and efficiency of underground mining.

Keywords*: *size of remnant; stability of the rock mass; FEM simulations; room and pillar mining system

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1. INTRODUCTION

Since underground copper mining in Poland has exceeded 1200 m below the surface, operations are frequently significantly influenced by difficult geology and mining conditions. Due to the issues related to the rock mass instability and the occurrence of dynamic phenomena deposit remnants are left in the mining field as a stabilizing pillars. Irregular remnants very often stabilize locally the situation in the field, enhancing the roof stability. However, rigid remnant may cause deposit losses and disturbs the geomechanical situation in the entire surroundings, and thus constitutes a new threat to mining works and mining crew. Mining practice, numerous observations and measurements as well as scientific research carried out globally (Lenhard and Hagan 1990; Lenhard 1992; Durrheim et al. 1998; Singh 2005; Singh et al. 2006; Spottiswoode and Drummond 2014; Wagner 2019, Feng and Wang 2020; Wang et al. 2021) and in Poland (Salustowicz 2019; Adach-Pawelus 2018; Adach-Pawelus and Pawelus 2021; Burtan and Chlebowski 2022) indicate that in several situations zones of high stress concentration are located in the vicinity of remnants. They cover both the remnants and the rock layers below and above them (Salustowicz 2019; Adach-Pawelus 2018; Adach-Pawelus and Pawelus 2021). When the stress values inside the remnants exceed the strength of the remnant, it may be crushed, and a pillar rockburst may occur (Lenhard 1992; Salustowicz 2019; Adach-Pawelus and Pawelus 2021). Remnants with appropriate width may also cause the roof layers to collapse above their edges and eventually lead to high-energy seismic events (shear rapture) (Lenhard and Hagan 1990; Durrheim et al. 1998; Ortlepp 2000; Salustowicz 2019; Wagner 2019, Adach-Pawelus et al. 2017; Adach-Pawelus and Pawelus 2021). Furthermore, remnant coal pillars, left in the upper seams, during multi-seam coal mining, can readily lead to stress concentrations in the deeper seam, creating operational difficulties in the lower coal seam. Extracting of the deeper seam may destabilize the upper residual coal pillar, leading also to dynamic events (Zhu and Tu 2017; Feng and Wang, 2020; Zhang et al. 2020).

Moreover scientific research concerning remnants indicates that the types of rocks forming remnants and their geomechanical parameters influence the behavior and stability of the remnant (Adach-Pawelus 2018), as well as roof control method affects the rock mass behavior around remnants (Adach-Pawelus and Pawelus 2021). Mining experience indicates that the size of remnant also has an great impact on the rock mass stability and level of seismic activity recorded in the mining field.

In Poland, the issue of the impact of remnants on the surrounding rock mass was examined using analytical methods by Salustowicz (2019), who assessed the stress distribution within the remnants and their surroundings. He demonstrates that if a remnant has a certain width of *2l*, two stress concentration zones appear at its edges, positioned at a certain distance from them. As the remnant’s width decreases, stresses become superimposed at its edges, and in an extreme scenario, they are summed and may reach very high values. In the appropriately narrow remnant, maximum compression stress is located at its center and is equal to (Salustowicz 2019):

$$\sigma_z = -\left(2 \cdot \frac{2k}{\sqrt{3}} + \frac{2k}{\sqrt{3}} \cdot \frac{l}{h}\right), \tag{1}$$

where:

- l – half of pillar (remnant) width
- h – half of remnant height
- $2k$ – yield point.

The strength of a remnant is strongly affected by its dimensions. When the remnant's strength is exceeded, it may be crushed and in the case of wide remnants, critical stress will have a much greater value than for narrow remnants (Salustowicz 2019).

Destruction of the remnants on a large scale with different shapes and dimensions under varying geological and mining conditions were analyzed in the Republic of South Africa mines (Lenhard and Hagan 1990; Lenhard 1992; Durrheim et al. 1998; Singh 2005; Singh et al. 2006). Lenhardt and Hagan (1990) identified four mechanisms that can induce seismic events near remnant. They found that the relatively narrow protective pillars could be crushed due to the applied loads. But, in terms of larger pillars, with a sufficiently high stress concentration, slip may occur on one or two shear planes located under the pillar edges. Lenhardt (1992) also indicated that that the presence of shear stress concentrations on pillar edges should also be a significant parameter in pillar design.

Researchers are still exploring the best approaches to assess the stability of remnants and their impact on the surrounding rock mass. Advances in computational methods and numerical modeling have greatly enhanced research possibilities associated with the rock mass behavior and stability analyses in underground mines. Numerical simulation has a wide range of applications in underground mining. It allows, e.g., for: identifying stress concentrations zones in the rock mass, assessing underground excavations stability under different stress conditions and the designing of their support (Kudełko and Bodlak 2020; Pawelus and Butra 2024; Adach-Pawelus and Pawelus 2021; Wang et al. 2022; Skrzypkowski et al. 2022), simulating designing and testing parameters of different mining methods (Blachowski and Ellefmo 2012; Zhang et al. 2020; Xu et al. 2022; Xiaojun et al. 2020) as well as identifying potential rockburst hazard zones and assessment of seismic and rockburst hazard (Adach-Pawelus et al. 2017; Adach-Pawelus 2018; Adach-Pawelus and Pawelus 2021; Wang 2020; 2022), moreover analyzing of mining salt deposits with backfill and the determining of the backfilling influence on the dynamics of deformation of the undermined rock mass (Rybak et al. 2022) or analyzing of adapting powered roof support to diverse mining and

geological conditions (Szurgacz and Brodny 2020), etc. Nowadays the influence of remnants on the surrounding rock mass and stability of undisturbed remnant pillars in underground mining worldwide are often analyzed on the basis of numerical methods (e.g., Adach-Pawelus 2018; Adach-Pawelus and Pawelus 2021; Adach-Pawelus et al. 2017; Feng and Wang 2020; Zhang et al. 2020; Watson et al. 2007; Peng and Wancheng 2012).

In this study, numerical modeling have been applied to evaluate the impact of remnant size on the geomechanical conditions and surrounding rock mass in the mining field where the part of undisturbed deposit, as a stabilizing remnant pillar was left because of the problems with maintaining the roof stability in the field. Analyzes were carried out for the room and pillar mining system with roof deflection, which is often used the polish underground copper mines. Geological conditions applied in the model are characteristic for the Fore-sudetic Monocline, located south-west part of Poland. Numerical simulations performed for the six remnant widths: 10, 20, 40, 60, 100, and 200 m are a continuation of previous research (Adach-Pawelus 2018) carried out for this mining field for the 40 m wide remnant for different geology and geomechanical parameters of ore remnant. It is highly important to identify a method to enhance the safety of operations near remnants. Therefore, the results achieve in this paper and determining the optimal size of the remnant that can be left in the mining field can be utilized to enhance the safety and effectiveness of underground copper ore extraction. Further research need to be performed on the prediction and prevention of the potential stability loss in the future.

2. MINING AND GEOLOGICAL CONDITIONS CHARACTERISTIC FOR A POLISH UNDERGROUND COPPER MINES

The research in this case study focuses on conditions typical of polish underground copper mines operated by KGHM Polska Miedz S.A., within the Legnica-Glogow Copper Belt (LGCB). Three underground copper mines: Lubin, Rudna and Polkowice-Sieroszowice are situated in the southwestern region of Poland (Fig. 1). The deposit represents a section of the Fore-Sudetic Monocline, found within Permian formations at the contact between dolomite-limestone, sandstone, rotliegend and lower zechstein series. Copper occurs in association with sulfides, primarily: chalcocite, bornite and chalcopyrite. The copper deposit is formed as a pseudo-stratum with variable thickness, ranges from several dozen centimeters to several meters and low inclination (approx. 4°). Copper deposit with an average thickness of 3.45 m and a copper content of 2.09% is present at a substantial depth of 600 m to 1400 m (Paździora 2019).

The roof consists of rock layers that are part of the Zechstein carbonate series, while the floor is composed of grey Rotliegend sandstone. A typical lithological profile of the LGCB region features rigid, high-strength rock formations in the roof, primarily dolomites and anhydrites, which have the ability to accumulate elastic energy. In contrast, the floor contains sandstone layers with significantly lower strength parameters. The copper ore deposit is extracted using the room and pillar method with roof deflection, and in some cases, dry and hydraulic backfill is applied to enhance geomechanical stability.

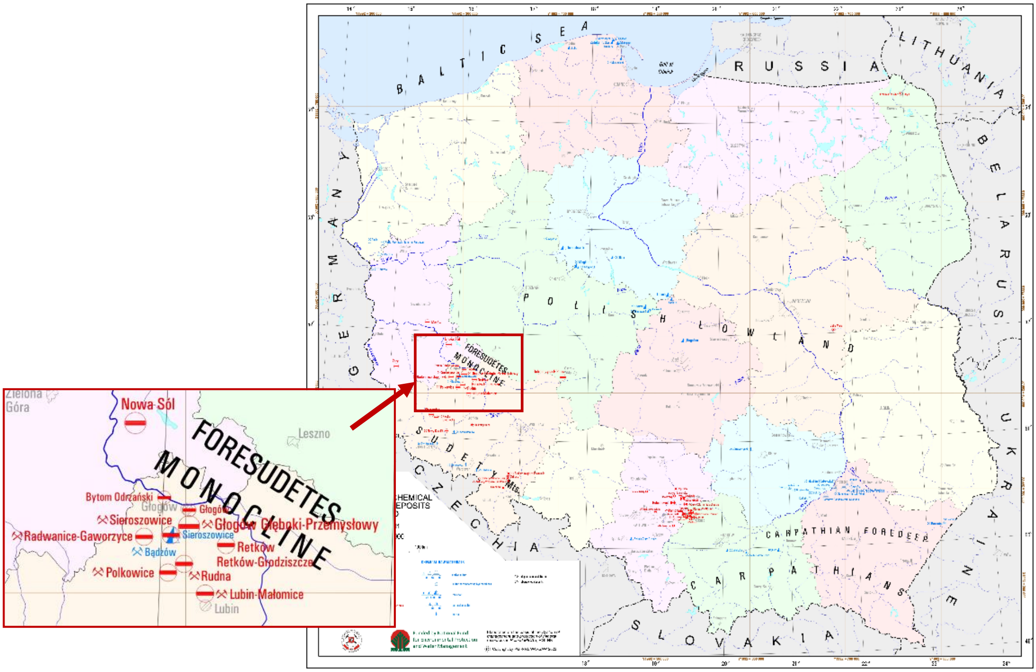


Fig. 1. Location of the copper deposit and mines in Poland
(based on: Polish Geological Institute, 2024)

In the room and pillar mining system with roof deflection, the deposit is cut with rooms and strips, forming rectangular technological pillars with dimensions designed depending on the geological and mining conditions in such a way that they progressively yield as they are separated from the deposit. Technological pillars are often oriented perpendicular to the mining front. The excavations have an inverted trapezoidal shape, with varying roof widths and sidewalls inclined at an angle of 10°. As mining progresses, technological pillars are systematically reduced to residual pillars and left in the goaf area (Fig. 2). The currently used mining system allows to obtain from 75% to even 90% of the deposit ore (Paździora 2019).

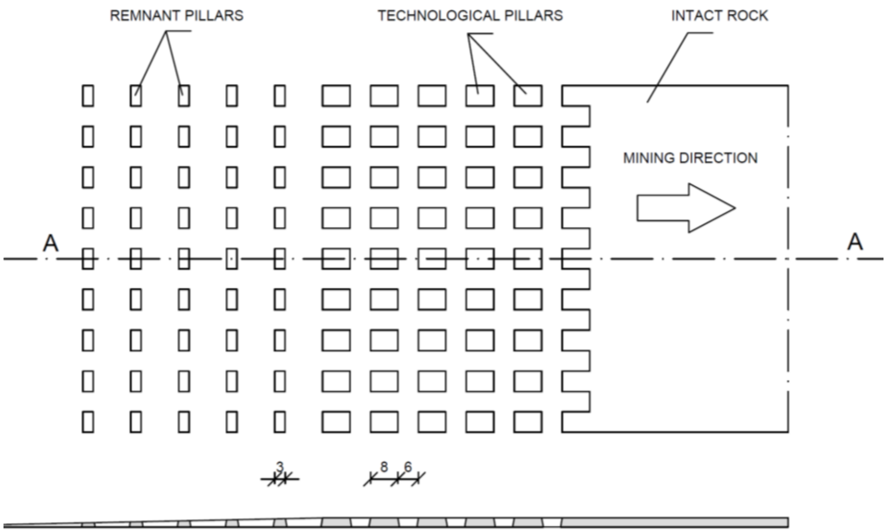


Fig. 2. Room and pillar mining system with roof deflection

3. METHODS: NUMERICAL SIMULATION OF A DIFFERENT SIZE OF REMNANT IN A MINING FIELD

The numerical calculations of the influence of remnant size on the geomechanical situation in the mining field were performed using RS2 v. 9.0 finite element program in a plane strain state. In this instance, a 2D analysis was selected as it enabled FEM simulations on a fine mesh, especially around excavations and deposit remnants. Therefore, the problem could be approached globally, by analyzing a large model and simulating exploitation in the entire field. Results obtained numerically correspond well with the mining observations and in-situ measurements of the convergence of the excavations in the polish copper mines.

To find the impact of remnant size on the geomechanical situation in the mining filed numerical simulation of room and pillar mining system with roof deflection was analyzed. It was assumed that a deposit remnant was separated due to problems with maintaining the roof's stability in the central part of the field. Five variants of remnant width were analyzed (Fig. 3):

- 10 m
- 20 m
- 40 m
- 60 m

– 100 m
– 200 m.

In the each model, the characteristic parameters of the room and pillars mining system with roof deflection (J-UG-PS) are implemented. The chosen parameters are shown in Table 1. In the Legnica-Glogow Copper Belt mines the rooms and strips have a characteristic shape of an inverted trapezoid.

Table 1. The room and pillar mining system parameters used in the model

Remnant width [m]	*h* [m]	Pillar high [m]	Technological pillar width [m]	Residual pillar width [m]	Working area	Roof control method
10	1000.0	3,5	8	3	5 strips	roof deflection
20						
40						
60						
100						
200						

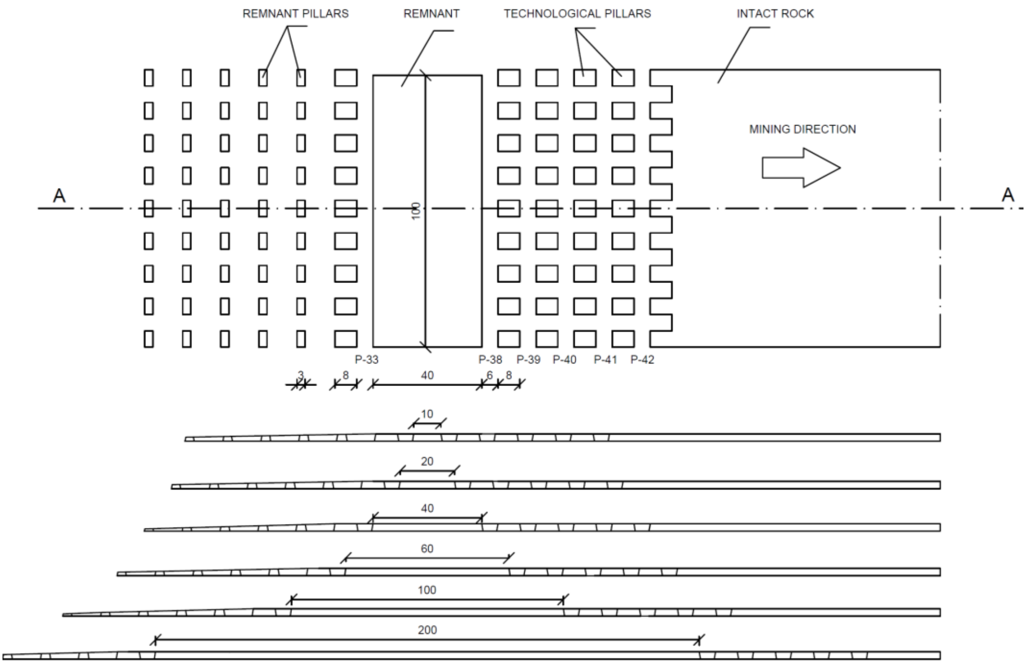


Fig. 3. Mining field where the room and pillar mining system with roof deflection is used and 6 variants of remnant width: 10, 20, 40, 60, 100, and 200 m are left behind

To simulate mining the copper deposit with the room and pillars mining system with roof deflection, the calculations were performed in steps (64 calculation steps). The initial stage involved the conditions in the rock mass prior to developing any workings (Fig. 4). In the second step, the rock mass was divided into technological pillars, each 8 m wide. As the process advanced, these pillars were progressively reduced to remnant pillar sizes, while additional technological pillars were formed. When the working area reached a width of five strips. The ore remnant was formed when the face distance was approx. 460 m (30th in the numerical model). In the following (31st) step of the numerical model, a strip was excavated to establish a deposit remnant. Steps 32–37 of the numerical model simulated the excavation of consecutive strips, characterized by an inverted trapezoidal cross-section, a roof width of 6 meters, and sidewalls inclined at an angle of 10°.

In this study, numerical model was a plate with lithological layers typical of the rock mass found in Polish copper mines. A generalized geological structure of the LGCB region was applied, assuming that the roof consists of a rigid, high-strength rock layer, while the floor comprises sandstones with considerably lower strength properties. The rock mass parameters are detailed in Table 2.

As mentioned before, due to the high seismic risk and the occurrence of dynamic phenomena that have effects in the mining excavations, the technological pillars in the LGOM mines are expected to operate in the post-critical state. In the numerical model, pillar yielding was simulated by reducing their strength and deformation parameters. The values of these reduced parameters were determined through a backward analysis, involving multiple numerical simulations to ensure that the computed vertical displacement values at selected points closely matched the actual measurements. The numerical analyses of the model field was conducted under the assumption that the maximum vertical displacement in the LGOM mines due to the use of the room and pillar system with roof deflection is approximately 70% of the mined deposit thickness. The parameters of both the technological pillars and the residual pillars were calibrated for the room and pillar system with roof deflection on the basis of numerical simulations.

The calculations were performed using an elastic model of rock mass, assuming the medium to be homogeneous and isotropic. Rock mass stability was assessed using the Coulomb-Mohr failure criterion.

Table 2. Rock mass parameters used in the numerical model

Rock type	h [m]	E_s [MPa]	σ_t [MPa]	c [MPa]	ϕ [°]	V [–]
Anhydrite	200.0	41,110	0.75	7.00	38.66	0.24
Sandstone-Dolomite	3.5	24,910	2.00	8.84	39.00	0.21
Sandstone	202.7	3,220	0.05	1.16	39.06	0.13

The symbols used in the above table are as follows: h – thickness of rock layers, E_s – longitudinal modulus of elasticity, σ_t – tensile strength of the rock mass, c – cohesion coefficient, ϕ – internal friction angle, ν – Poisson's ratio.

A vertical load of 17.657 MPa was applied to the upper boundary of the model to account for the weight of the overlying rock layers. The calculations considered the unit weight of the rock strata. Displacement boundary conditions were defined at the plate edges (Fig. 4):

– bottom boundary of the model – no vertical displacement,
– side boundaries of the model – no displacement in horizontal direction.

The finite element mesh consisted of 3-node triangular elements. To enhance the accuracy of the numerical computations, the mesh density was increased in the central region of the model, particularly near the excavations.

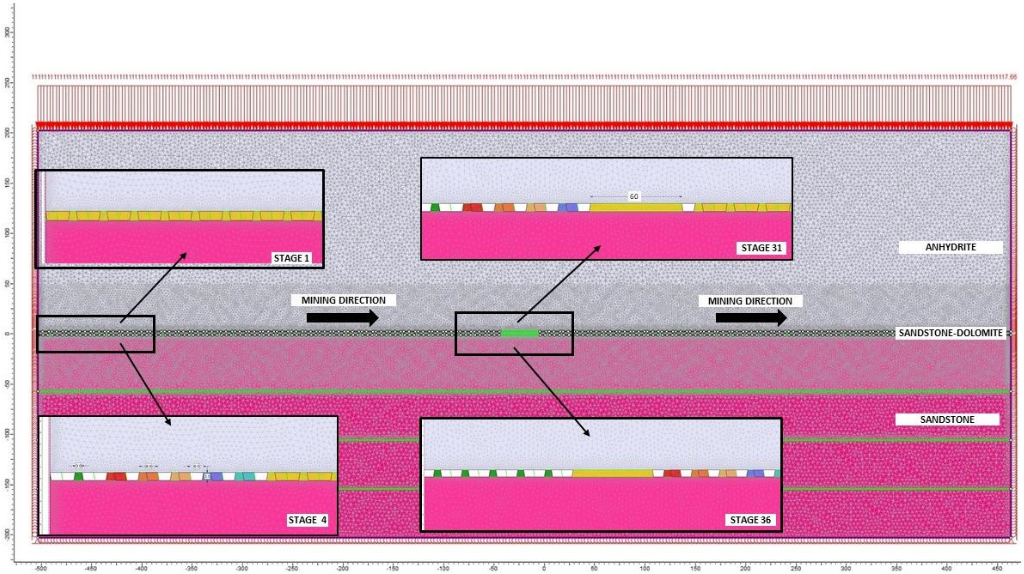


Fig. 4. Numerical model for the remnant width 60 m

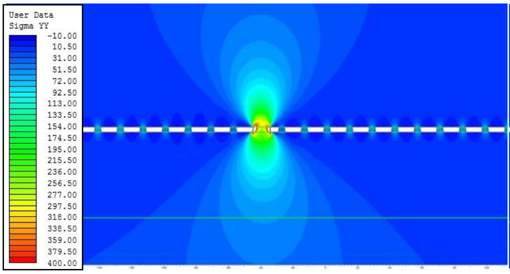
4. DISCUSSION

To investigate how the size of the deposit remnant can influence the geomechanical situation in the mining field, vertical stress σ_y distribution and strength factor S_f have been analyzed. The behavior of the rock mass near the remnant was examined at the successive steps of the mining operation by room and pillar system.

The numerical simulation results conducted for 6 different size of remnant: 10, 20, 40, 60, 100, and 200 m, demonstrated that the size of deposit remnant left in the mining filed have a great influence on the vertical stress σ_y distribution and rock mass stability.

The results of vertical stress σ_y distribution showed that in the successive steps of the room and pillar mining system, leaving a stiff remnant can disturb the geomechanical situation in the mining field. The remnant is a place of stress concentration and affects both the layers in the roof and the floor that are located in its vicinity.

The range of remnant impact and values of vertical stress σ_y in its surroundings increase in the successive steps of simulated mining exploitation. As the width of the remnant increases, the values of vertical stress σ_y in its surroundings decrease, while the range of its impact increases (Fig. 5).



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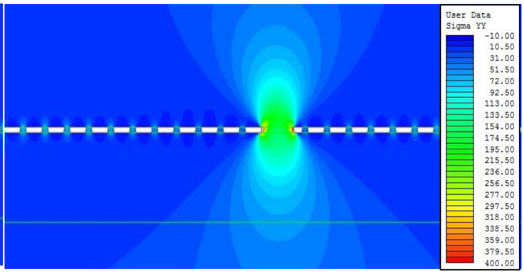

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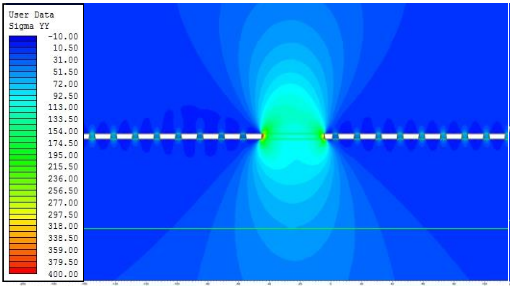

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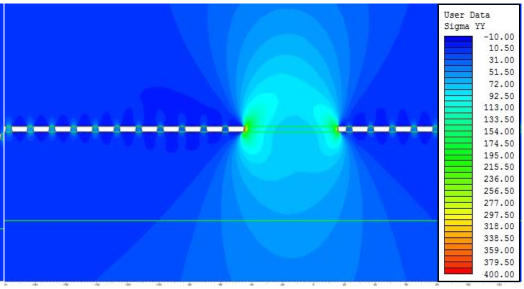

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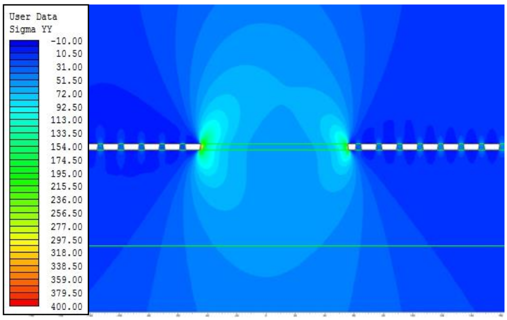

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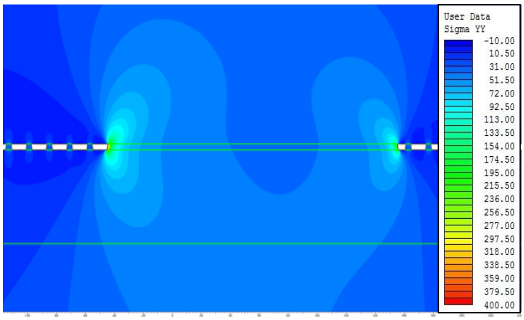
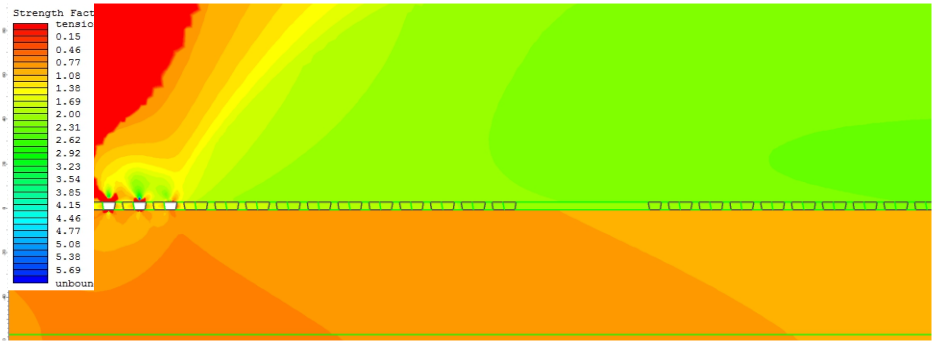


f)

Fig. 5. Distribution of vertical stresses σ_y for the front distance approximately 400 m from the remnant edge – 59th calculation step for different remnant width: a) 10 m, b) 20 m, c) 40 m, d) 60 m, e) 100 m, f) 200 m

The analysis of the strength factor S_f distribution in the mining field for the various remnant widths showed that the remnant stabilizes locally the geomechanical situation in the mining field. Remnant becomes an additional support point for the roof layers, which cause a slow progressive roof deflection over the mined-out areas. Leaving a large remnant in the form of a stabilizing pillar, which separates the mining workings from the disturbed part of the rock mass, improves the stability of the roof in the workings located in its vicinity, outside the previously endangered area (Fig. 6).



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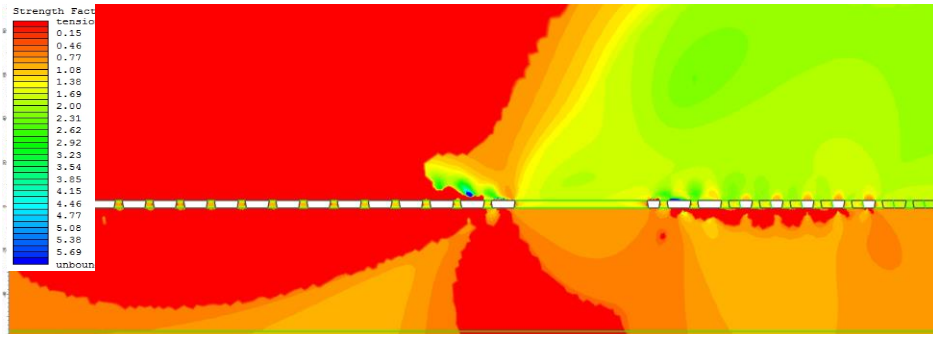

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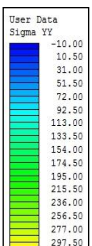


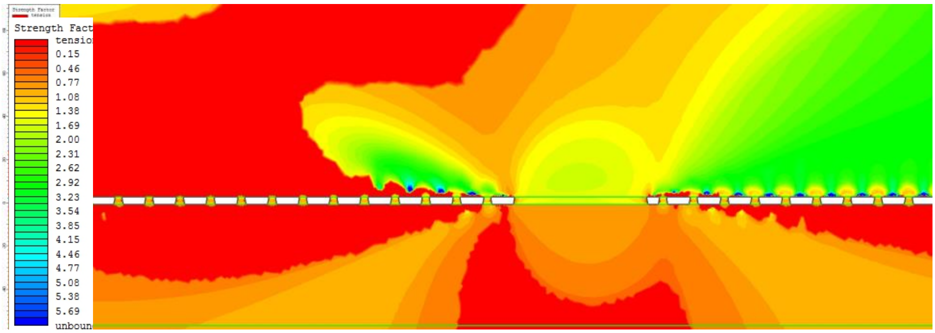
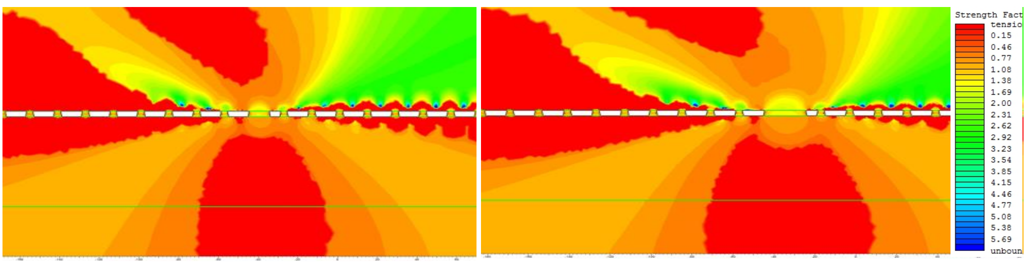
c) 

Fig. 6. Distribution of strength factor S_f for the front distance approximately:
a) 300 m – 19th calculation step, b) 620 m (100 m from the remnant edge) – 38th calculation step,
c) 920 m (400 m from the remnant edge) – 59th calculation step

The distribution of the strength factor S_f in the roof above remnants of different widths (especially 40, 60, 100, and 200 m) indicated that in each case an unstable zone is formed in the roof layers above the edge of the remnant at the goaf side (S_f values slightly greater than 1.0). The values of the S_f within this zone decrease with the successive steps of the mining progress. In the case of narrow remnants with a width of 10 and 20 m, the unstable zone in the roof occurs above the central part of the remnant. For a large front distance of approx. 470 m from the remnant edge, the strength factor S_f in these zones may have values lower than 1. These results indicate that a fracturing and collapse of rigid roof layers may occur on the edge of the remnant, mainly due to the exceeded shear strength (Figs. 6 and 7).



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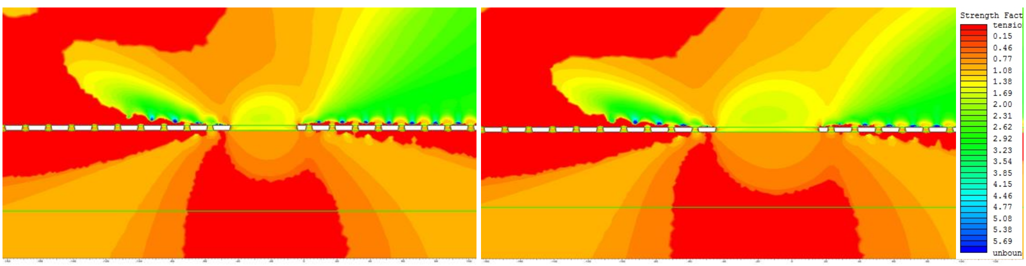

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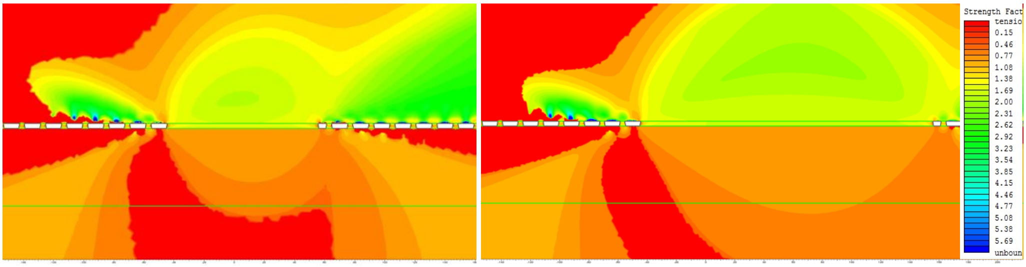

e) f)

Fig. 7. Distribution of strength factor S_f for the front distance approximately 400 m from the remnant edge – 59th calculation step for different remnant width: a) 10 m, b) 20 m, c) 40 m, d) 60 m, e) 100 m, f) 200 m

Analyses of vertical stress σ_y distribution inside the 10, 20, 40, 60, 100, and 200 m wide remnant for the room and pillar system indicate that regardless of the size of the remnant, the vertical stress σ_y concentration occurs at the edges of the remnant and decreases towards the center of them. The vertical stress σ_y, both at the edges and inside the remnant, increases with decreasing its width. The greatest increase in vertical stress σ_y was observed in the case of remnants with a width of 10 and 20 m. In analyzed mining field (for mining front distance approx. 400 m from the edge of the remnant), the vertical stress σ_y inside the remnant increases from approx. 35 MPa (for a 200 m wide remnant), up to approx. 120 MPa (for a 20 m wide remnant) and up to approx. 200 MPa (for a 10 m wide remnant) (Fig. 8).

Moreover, it can be observed that in the case of remnants with a width of 10, 20, 40, and 60 m, when the distance of the mining front from remnant edge is quite long, the vertical stress σ_y inside the remnant reach very high values, while inside the remnants with a width of 100 and 200 m, the vertical stress σ_y reach values close to the virgin stress or operational stress occurring in a given mining field (Fig. 8).

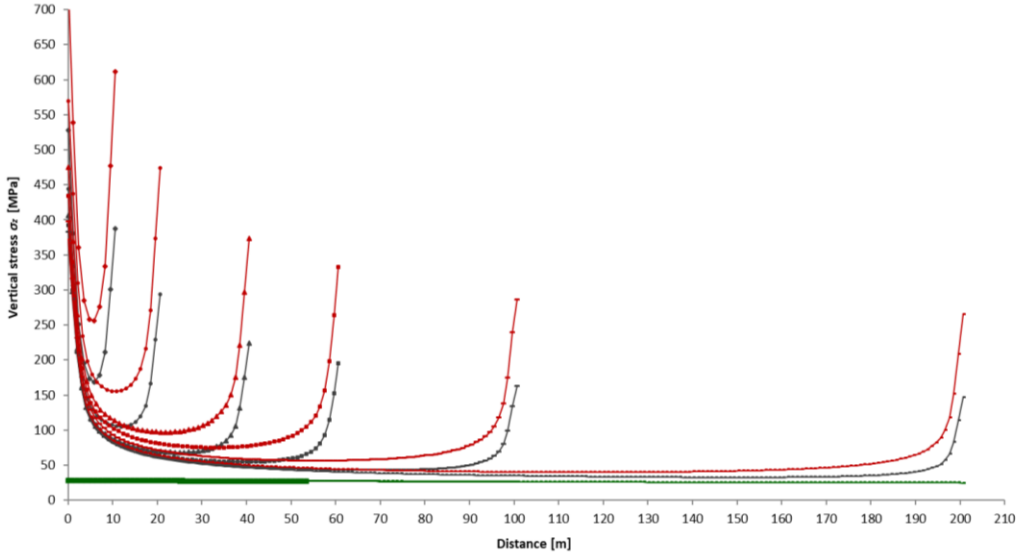

Fig. 8. Comparison between vertical stresses σ_y inside the remnant of different size: 10, 20, 40, 60, 100, and 200 m

In contrast to the vertical stress σ_y, the strength factor S_f reach its lowest values at the edges and increases towards the center of the remnant. Values of the strength factor S_f less than 1 at the edges of the remnants indicate that in the vicinity of their edges (excavation sides) the strength of the material may be exceeded and a yielded or fractured zone may be formed. The values of the vertical stress σ_y, on the edges and inside the remnant increase gradually with the advancement of the mining front, while the strength factor S_f decreases (Fig. 9).

The values of the strength factor S_f decrease as the width of the remnant decreases. In the analyzed field (for the front distance approximately 400 m from the edge of the remnant), the strength factor S_f decreases from a maximum value of 1.85 (for a 200 m wide remnant) to 1.39 (for a 10 m wide remnant) (Fig. 9).

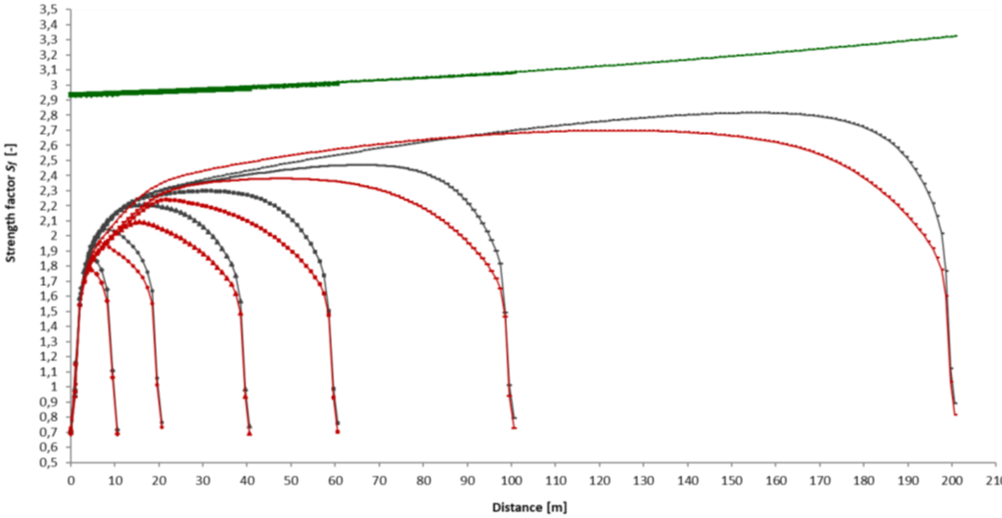

Fig. 9. Comparison between strength factor S_f inside the remnant of different size: 10, 20, 40, 60, 100, and 200 m

5. CONCLUSIONS

In Polish underground copper mines, mining works are very often carried out in difficult geological and mining conditions. The most dangerous natural hazards for mining crews working underground are seismic and rockburst hazard as well as rockfall hazard. Thus, the most effective solutions should be identified to enable the extraction of copper ore deposits in the safest and most cost-efficient way. This study addresses the issue of the copper ore extraction the mining field were due to difficult geological and mining conditions deposit remnant as a stabilizing pillar has been left. To analyze the influence of remnant size on stress distribution and rock mass stability in the mining field numerical simulations using RS2, Rocscience software were performed for the case study (a mining field with geological and mining conditions characteristic for the underground copper mines located in Poland).

The results of the numerical calculations allowed conducting a qualitative analysis and illustrating the occurrence of certain phenomena in the rock mass, in which copper ore is mined in polish underground copper mines with the room and pillar systems.

The results of the numerical analysis indicate that the size of the remnant left in the mining field has a great influence on the stress distribution and rock mass stability:

– as the width of the remnant decreases, the values of vertical stress σ_y both in-

side remnants and in its surroundings increase and reach very high values for remnants 20 and 10 m width,
- regardless of the size of the remnant, the vertical stress σ_y concentration occurs at the edges of the remnant and decreases towards the center of them,
- in contrast to the vertical stress σ_y, the strength factor S_f reaches its lowest values at the edges and increases towards the center of the remnant. It means that the strength of the material at the remnant edges (excavation sides) may be exceeded and a yielded zones may be formed. Moreover the values of the strength factor S_f decrease as the width of the remnant decreases.
- leaving a large remnant in the form of a stabilizing pillar, improves the stability of the roof in the mining field but for remnants with high widths an unstable zone might be formed in the roof layers above the edge of the remnant at the goaf side which may cause sudden fracturing and collapse of rigid roof layers on the edge of the remnant.

The numerical analysis results obtained for the case study showed that proper design of stabilizing deposit remnant size is very important in order to improve the safety and efficiency of mining operations. Otherwise, rigid narrow remnants may cause the risk of pillar rockburst, or in case of large remnants, mining edges may be formed and risk of shear raptures occurs.

Further research is needed on predicting and preventing potential stability loss in the future.

Further research will include a 3D model of the analyzed field and a comparison of the obtained results with the results of the 2D analysis and analysis of the different remnants' size built of different rock types and its influence on the seismic and rockburst hazard. Moreover, it will include determining the optimal size of the remnant that can be left in the mining field and verification of mining operation rigors and rockburst prevention methods.

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