energies

Article

Application of Hydraulic Backfill for Rockburst Prevention in the Mining Field with Remnant in the Polish Underground Copper Mines

Karolina Adach-Pawelus * and Daniel Pawelus

Faculty of Geoengineering, Mining and Geology, Wroclaw University of Science and Technology, 50-370 Wroclaw, Poland; daniel.pawelus@pwr.edu.pl
* Correspondence: karolina.adach@pwr.edu.pl

Abstract: In the polish underground copper mines owned by KGHM Polska Miedz S.A, various types of room and pillar mining systems are used, mainly with roof deflection, but also with dry and hydraulic backfill. One of the basic problems associated with the exploitation of copper deposits is rockburst hazard. Aa high level of rockburst hazard is caused by mining the ore at great depth in difficult geological and mining conditions, among others, in the vicinity of remnants. The main goal of this study is to investigate how hydraulic backfill improves the geomechanical situation in the mining filed and reduce rockburst risk in the vicinity of remnants. Numerical modeling was conducted for the case study of a mining field where undisturbed ore remnant, 40 m in width, was left behind. To compare the results, simulations were performed for a room and pillar mining system with roof deflection and for a room and pillar mining system with hydraulic backfill. Results of numerical analysis demonstrate that hydraulic backfill can limit rock mass deformation and disintegration in the mining field where remnants have been left. It may also reduce stress concentration inside or in the vicinity of a remnant, increase its stability, as well as prevent and reduce seismic and rockburst hazards. Hydraulic backfill as a local support stabilizes the geomechanical situation in the mining field.

Keywords: hydraulic backfill; remnant; seismic and rockburst hazard; numerical modeling; Polish copper mines

check for updates

Citation: Adach-Pawelus, K.; Pawelus, D. Application of Hydraulic Backfill for Rockburst Prevention in the Mining Field with Remnant in the Polish Underground Copper Mines. *Energies* **2021**, *14*, 3869. https://doi.org/10.3390/en14133869

Academic Editors: Krzysztof Skrzypkowski and Maxim Tyulenev

Received: 21 May 2021
Accepted: 18 June 2021
Published: 27 June 2021

1. Introduction

Seismic and rockburst hazards have represented primary hazards in Polish underground cooper mines since the beginning of ore exploitation in the region. The first strong seismic event, having a magnitude of 2.8, took place on 31 July 1972. With the progress of mining operations, the number and energy of tremors regularly increased and some of them caused rockbursts [1].

Dynamic phenomena occur as a result of rock mass destabilization, leading to the release of potential energy from rocks. Tremors are caused by mining works, which disrupt the original stress state of the rock mass [2,3]. A rockburst is a dynamic phenomenon caused by a mining tremor which leads to sudden and violent destruction or damage of the excavation along with all of the involved consequences [2,3]. Rockbursts are responsible for many mining accidents and damaged excavations. They generate financial losses and disrupt the operational continuity of the mining facility.

The literature knows many classifications of rockbursts (e.g., [4–6]). Essentially, two types of dynamic phenomena are distinguished. The first is directly associated with stopes, while the second is linked to primary tectonic discontinuities [4]. Rockbursts of the first type most frequently occur in the vicinity of excavations. They are the result of both stress redistribution around the excavations and the formation of stress concentration zones. The following may be considered as belonging to this group of rockbursts [6]: strain bursts, pillar bursts, and face bursts. Dynamic phenomena related to tectonic discontinuities include rockbursts caused by fault activation or initiated by a sudden formation and propagation of fractures in undisturbed rock as a result of exceeded shear strength (shear rupture) [6,7]. According to Ortlepp [6], shear rapture is one of the most important mechanisms generating very high-energy mining tremors and major rockbursts. Roof strata fractures occur most often near the edges, old gobs, boundaries between backfill mining and retreat mining, or in the direct vicinity of the mining front.

Both in-situ observations in the Polish underground copper mines and scientific research indicate that a high level of seismic and rockburst hazard is influenced by geological, mining, and organizational factors. The most important geological factors include: increasing depth of mining operations, high in-situ stress in the rock mass, lithology of the rock mass and its geomechanical parameters (very strong lime and anhydrite rocks in the roof layers), as well as tectonics and the thickness of the deposit. The compression strength of roof rocks is very high and therefore they are able to accumulate elastic energy and release it suddenly [1].

The mining factors affecting the dynamic phenomena are: the mining method and its geometry, the roof control method, mining face parameters, concentration of mining works, and whether mining operations are performed under constrained mining conditions [1]. Local stress concentration is the primary mining-related cause of rockbursts, and it can be caused by improperly selected mining systems or by an improper geometry of such a system. Seismic and rockburst hazard is also affected by an excessive concentration of mining works and an increasing scope of mining works performed under constrained conditions, which includes, among other things, mining operations in the vicinity of remnants.

Remnants are undisturbed, typically irregular fragments of the deposit in which mining operations are impossible, technically very difficult, or uneconomical. In-situ observations and scientific research indicate that, in the vicinity of rigid remnants, zones of high stress concentration are located. They cover both the deposit and the rock layers below and above the remnant [8–11]. When the stress values in the remnant exceed the strength of remnant, it may be crushed, and if the conditions are unfavorable, a pillar rockburst may occur [8,12]. Such remnants may also cause the roof layers to collapse above their edges and eventually lead to high-energy seismic events (shear rapture) [8,11,13]. Therefore, it is of great significance to find a way to improve safety of the works in the vicinity of remnants.

Mining practice shows that the roof control method also has an impact on the level of seismic activity recorded in the mining field. Due to the variety of special applications of backfills, there are different types and technologies. For example, cemented hydraulic backfill, which is widely used because it provides high strength and allows the use of waste rock from mining operations, as well as tailings from mineral processing plants as ingredients [14]. Moreover, hydraulic backfill and paste backfill are also used. Meanwhile, Li et al. [15] proposed filling the post-excavation space with waste rocks.

In accordance with the formal regulations currently in force in Poland, copper mines located in the Legnica-Glogow Copper Belt (LGCB), use hydraulic backfill in mining fields where the thickness of the deposit exceeds 7 m [16]. Backfill is also used to control rock mass movement and surface subsidence in order to protect cities or surface facilities located above the excavations.

Hydraulic backfilling is about preparing a backfilling mixture, consisting of granular material (most often backfill sand) and process water and its gravitational hydrotransport to the backfilled excavation (goaf). The mixture flows through the pipeline to the backfilled excavation, where sedimentation of the backfill takes place. The sediment remains in the goaf and constitutes a backfill, and the water through the clarifiers is directed to the mine's drainage system. Preparation of backfilling mixtures in copper mine installations at LGCB, with gravity pipeline hydrotransport and L-shaped geometric pipelines, is carried out by dosing backfilling material and process water. The backfilling technology is characterized by the following parameters:

- Density of backfilling mixture: 1480 kg/m^3
- Flow velocity of the mixture: 6.8 m/s
- Mixture flow rate: 660 m^3/h
- Unit pressure loss: about 1390 Pa/rm
- Average water consumption: 720 m^3
- Average backfilling time: 1.04 h
- Average start-up and rinsing time: 0.90 h

Many years of in-situ observations carried out in the polish copper mines, in the mining fields where hydraulic backfill was used for the liquidation of mined out areas, showed that both seismic activity and rockburst hazard decreased in these fields [17–19].

Scientific research also indicates that the application of backfill can help effectively control the movement deformation of rock layers and reduce stress concentration, thus helping such events as rockbursts as well as increasing the stability of excavations [9,20–29]. The backfilled roof is more stable, its vibrations are at a higher frequency and prove less dangerous, and the duration of the tremor is shorter. At the same time, backfill causes a reduction in the maximum vibration velocities of rock particles (ppv) and in maximum values of their acceleration (ppa) [30].

The development of computer modeling and simulation techniques has significantly expanded research capabilities related to the analysis of seismic phenomena potential in underground mines. Numerical modeling allows for identifying potential rockburst hazard zones, estimating rockburst hazard in every part of the rock mass, even in inaccessible parts, and identifying the conditions under which a dynamic phenomenon may occur [31–33].

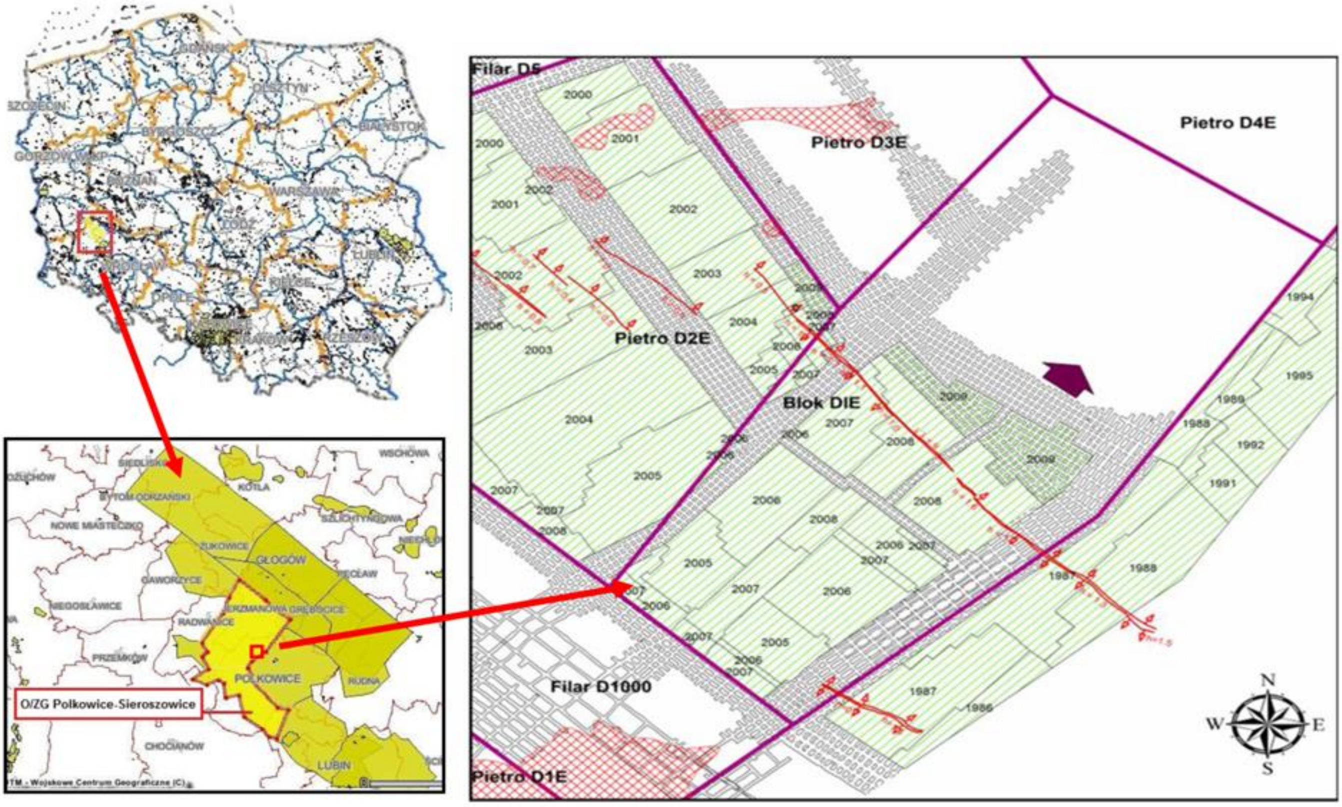
In this paper, numerical methods have been used to assess how hydraulic backfill can improve the geomechanical situation in the vicinity of a 40 m wide remnant, which was left behind in a mining field where a room and pillar mining system was used. Numerical simulations performed for the analyzed mining field where hydraulic backfill was applied in the excavations located in the vicinity of the remnant are a continuation of previous research [11,13] conducted for this mining field for the room-and-pillar system with roof deflection. The article includes a comparison of the results of numerical calculations performed for both cases. They can be used to improve the safety and efficiency of underground copper ore mining.

2. Case Study of a Mining Field with Remnant in a Polish Underground Copper Mine

Polish underground copper mines (Lubin, Rudna, and Polkowice-Sieroszowice) are located in the south-west part of Poland and belong to the Legnica-Glogow Copper Belt (LGCB) (Figure 1). The deposit is located in Permian formations, at the contact between dolomite-limestone, sandstone, rotliegend and lower zechstein series. Copper is found associated to sulfides, mainly: chalcocite, bornite and chalcopyrite. The copper deposit is developed in the form of a pseudo-stratum with variable thickness and low inclination (approximately 4°). It is present at a substantial depth of 600 m to 1400 m. A typical lithological cross-section of the LGCB region 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. The deposit is mined with the room and pillar system, mostly with roof deflection, but to improve the geomechanical situation, dry and hydraulic backfill are also used.

2.1. Geological and Mining Conditions of Research Area

The research area in this case study is one of the mining fields located in the Polkowice-Sieroszowice mine (Figure 1). The copper ore deposit is 2.0–2.8 m high, extends in the NW-SE direction, and dips (2–3°) toward NE. The depth of the deposit is approximately 1000 m. It includes mostly sandstone (gray, quartz, and fine-grained sandstone), cupriferous shale (clay and dolomite-clay), as well as dolomite (streaky, dark gray, cryptocrystalline). The roof is built of rock layers being part of the Zechstein carbonaceous series, and the floor is made of grey Rotliegend sandstone. The tectonics in the field is quite poor. One fault is located in the middle part of the mining filed and has an approximately 0.5–1.5 m throw [11].



(**a**) (**b**)

Figure 1. Location of the LGCB in Poland, location of the analyzed mining field in the Polkowice-Sieroszowice mine (**a**), analyzed mining field and location of the remnant (**b**).

Mining operations in the analyzed field started in March 2005 using a room-and-pillar system with roof deflection. The deposit was cut with rooms and strips into rectangular technological pillars with basic dimensions of 6 × 8 m, which were situated perpendicular to the line of the mining front. The excavations were in the shape of an inverted trapezoid, with the roof width equal to 6 m and the inclination angle of sidewalls 10°. Technological pillars were successively reduced to residual pillars, as the mining front progressed, and left in the mined-out area. In Polish copper mines, the size of technological pillars is selected in such a way that they progressively yield at the stage of separation from the deposit. The width of the working area was generally between 4 and 5 strips (Figure 2) [11].

Exploitation in the analyzed field was carried out in constrained mining conditions. In 2007, because of problems ensuring the roof's stability in the central part and in the right side of the field, a deposit remnant approximately 40 × 100 m was created, between strip P-38 and strip P-33 (Figure 2) [13].

2.2. *Seismic Activity Registered in the Vicinity of the Remnant during Room and Pillar Mining*

The analyzed mining field was characterized by a relatively high level of seismicity. Figure 3 presents yearly distribution of the number of mining tremors as well as seismic energy emissions for the period of 2002–2011. The greatest number of seismic events and the highest level of seismic energy emission were recorded in the field in 2006. In December 2006, a very high-energy, class E8 seismic event occurred. It seriously influenced the roof stability in the central part and in the right side of the field. The mining front was being reconstructed with strips P-34 ÷ P-37, but in August 2007 increasing problems with the roof necessitated stopping them, and the progress of the P-38 ÷ P-42 strips began. As a result, a remnant approximately 40 m in width was formed. While restoring the front in the right side of the field, on 13 March 2007, a seismic event having an energy of 10^7 J was recorded. Then, on 4 October 2007, the second event with an energy of 4.4×10^7 J occurred. The epicenters of these events were located in the vicinity of the remnant, while the epicenter of the tremor from October 2007, on the edge of the undisturbed rock remnant. The geophysical mechanism of this event shows rock mass displacement on the reverse fault in the SW direction (towards the gob areas). This surface runs in the direction approximately consistent with the mining front line.

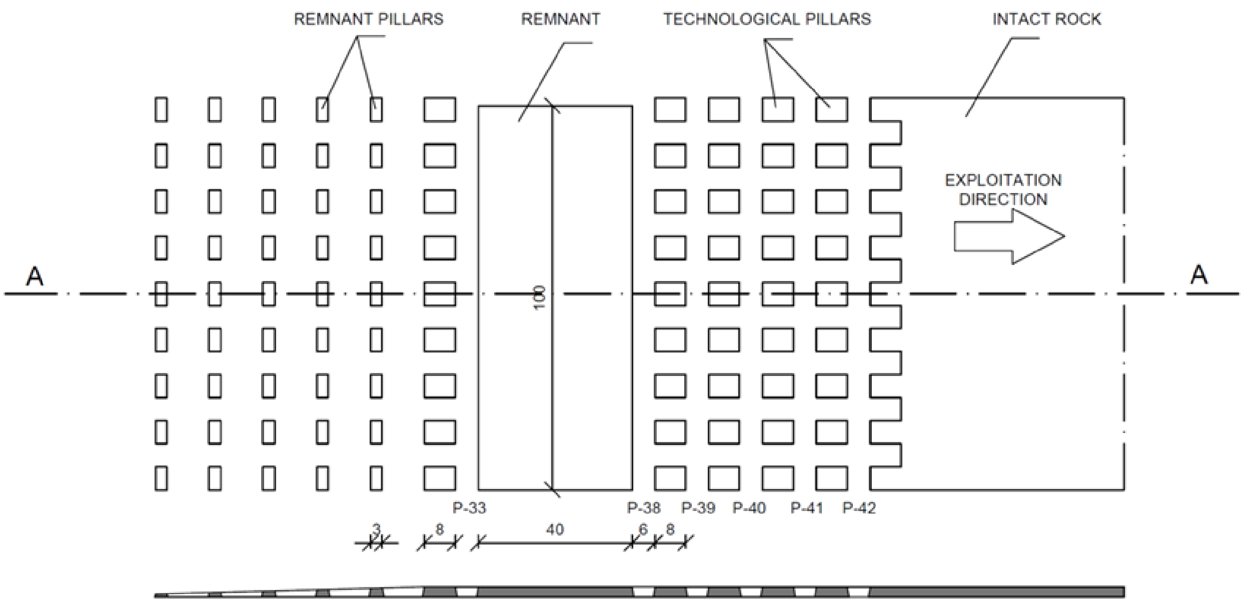


Figure 2. Analyzed mining field (room and pillar mining with roof deflection) and location of the 40 m wide remnant.

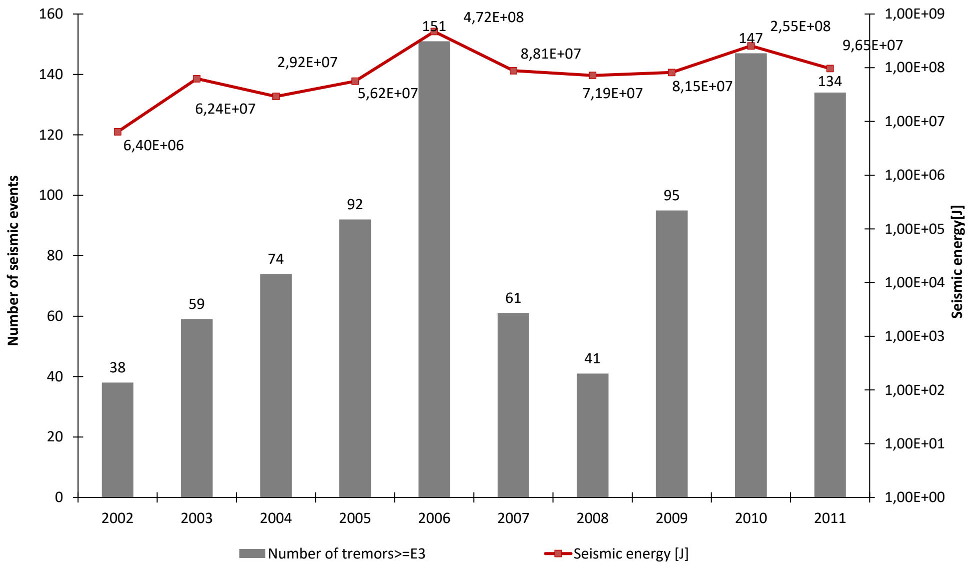


Figure 3. Seismic activity for the period of 2002–2011 in the analyzed field [13].

Moreover, numerical back analysis of the mining front reconstruction, deposit exploitation, and remnant behavior in the field also showed that the roof may have suddenly and violently collapsed at the edge of the rigid remnant, on the side of the field's gob areas, during the reconstruction of the mining front. It may cause a high-energy seismic event induced mainly by the exceeded shear strength [13] (Figure 4). The results of the analysis indicate a significant impact of the mining edge on the occurrence of dynamic phenomena that can be dangerous to the working crew. Therefore, it is of great significance to study the application of hydraulic backfill to reduce the risk and the tendency of seismic events in the working face nearby rock remnants.

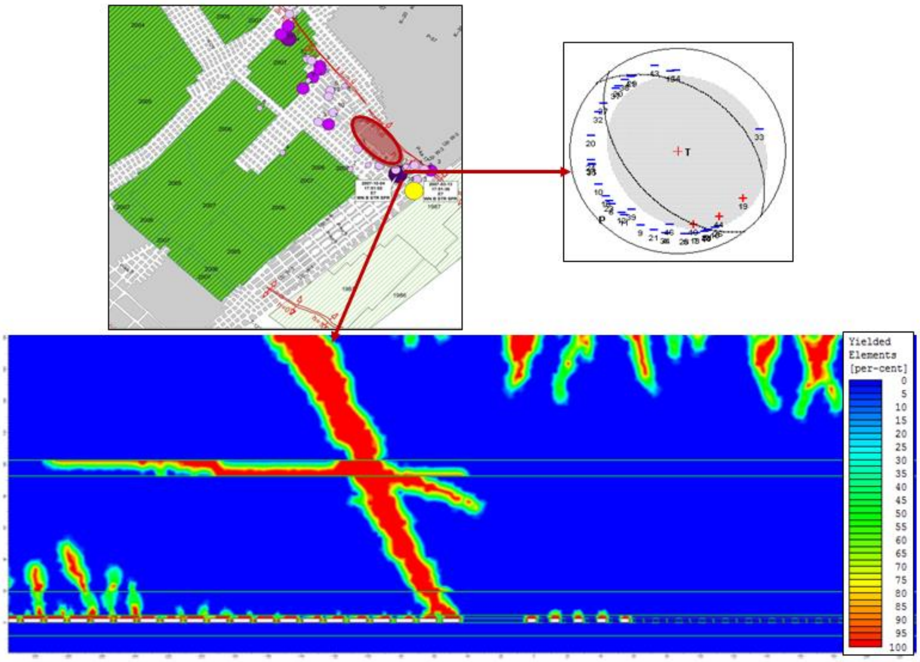


Figure 4. E7 seismic event which occurred in October 2007 at the edge of the created remnant with its probable mechanism [13].

3. Methods: Numerical Simulation of the Application of Hydraulic Backfill in a Mining Field with a Remnant

The numerical model of the analyzed field mined with the room and pillar mining system was created in the RS2 v. 9.0 finite element program in a plane strain state. With the use of adequate computational power, the 2D analysis allowed FEM analyses on a dense mesh, particularly in the vicinity of excavations and deposit remnants. Therefore, the problem could be approached globally, by analyzing a large model and simulating exploitation in the entire field. The model is constructed properly, as the simulation results correspond well to the measurement data related to the convergence of the excavations in the analyzed field.

In the first part of this research [11,13], a back calculation was performed in order to provide the model with a reflection of the actual situation observed in the analyzed mining field. In further calculation steps, the retreat room and pillar mining process was reconstructed in the deposit, based on the actual parameters of the mining system used in the analyzed field (sizes of the technological pillars and the residual pillars, dimensions of the excavation cross-sections, size of the working area, etc.). The numerical model also included a deposit remnant approximately 40 m in width between strips P-33 and P-38, which was formed, at a 460 m front length, by excavating strip P-38 outside the danger zone (31st calculation step). After the remnant of undisturbed rock had been separated, the field was further mined with the use of the room and pillar method with systematic retreat by roof deflection.

In the second part of the research, the use of hydraulic backfill in excavations adjacent to the remnant was proposed as a solution for limiting rock mass deformations (Figure 5).

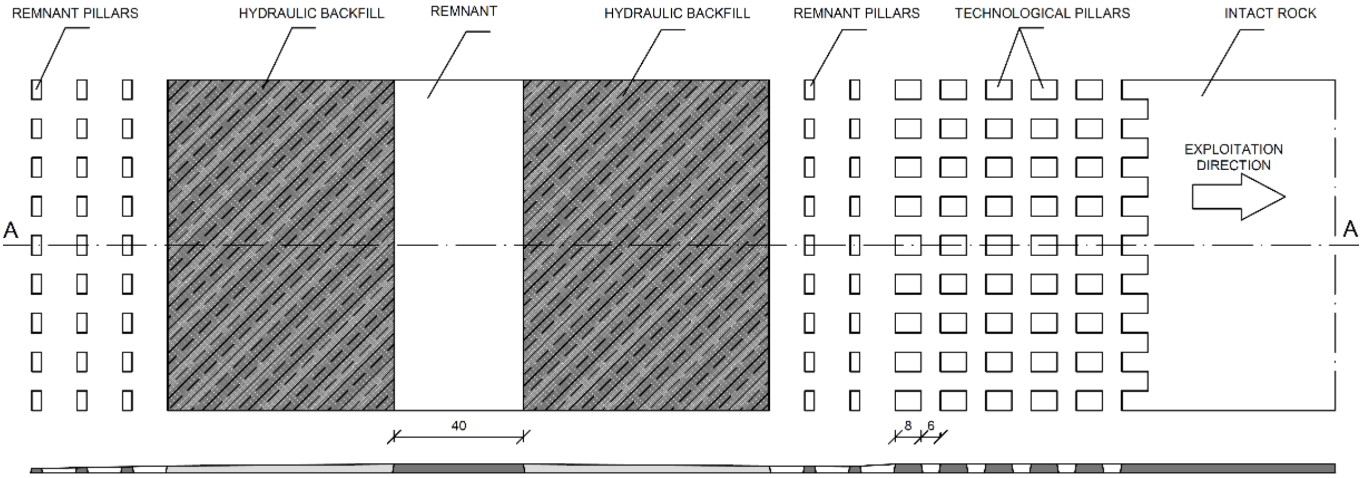


Figure 5. Scheme of room and pillar mining operations with the application of hydraulic backfill in the vicinity of the remnant.

The numerical model reflecting the actual situation observed in the analyzed mining field was modified. In the modified model, stepwise numerical simulations reflected the cutting of the deposit with the room and pillar method with roof deflection until strip P-33 was excavated, when the front length was approximately 460 m (30th step in the numerical model) (Figure 6a). The next (31st) step in the numerical model simulated the hydraulic backfilling of five strips (P-29–P-33) prior to excavating strip P-38 outside the danger zone (Figure 6b). In the next (32nd) step of the numerical model, strip P-38 was excavated to isolate (form) a deposit remnant 40 m in width. Steps 33–37 of the numerical model simulated the excavation of successive strips having a cross-section in the shape of an inverted trapezoid with the width of the excavation roof equal to 6 m and the inclination angle of sidewalls 10°. The rock mass was cut into technological pillars 8 m in width (Figure 6c). When the working area was 5 strips wide, as the front advanced, the mined-out area started to be systematically liquidated with the use of hydraulic backfill. The proposal included using hydraulic backfill to close the mined-out areas on the right side of the remnant, in the area from strip P-38 to strip P-43 (steps 38–42 in the numerical model). In steps 43–65, deposit exploitation in the analyzed field was continued with the use of the room and pillar method with roof deflection (Figure 6d). The rock mass was cut into technological pillars 8 m in width, which were subsequently reduced in size to remnant sizes, and further technological pillars were cut. The assumption concerning the width of the working area in the numerical simulations was 5 strips.

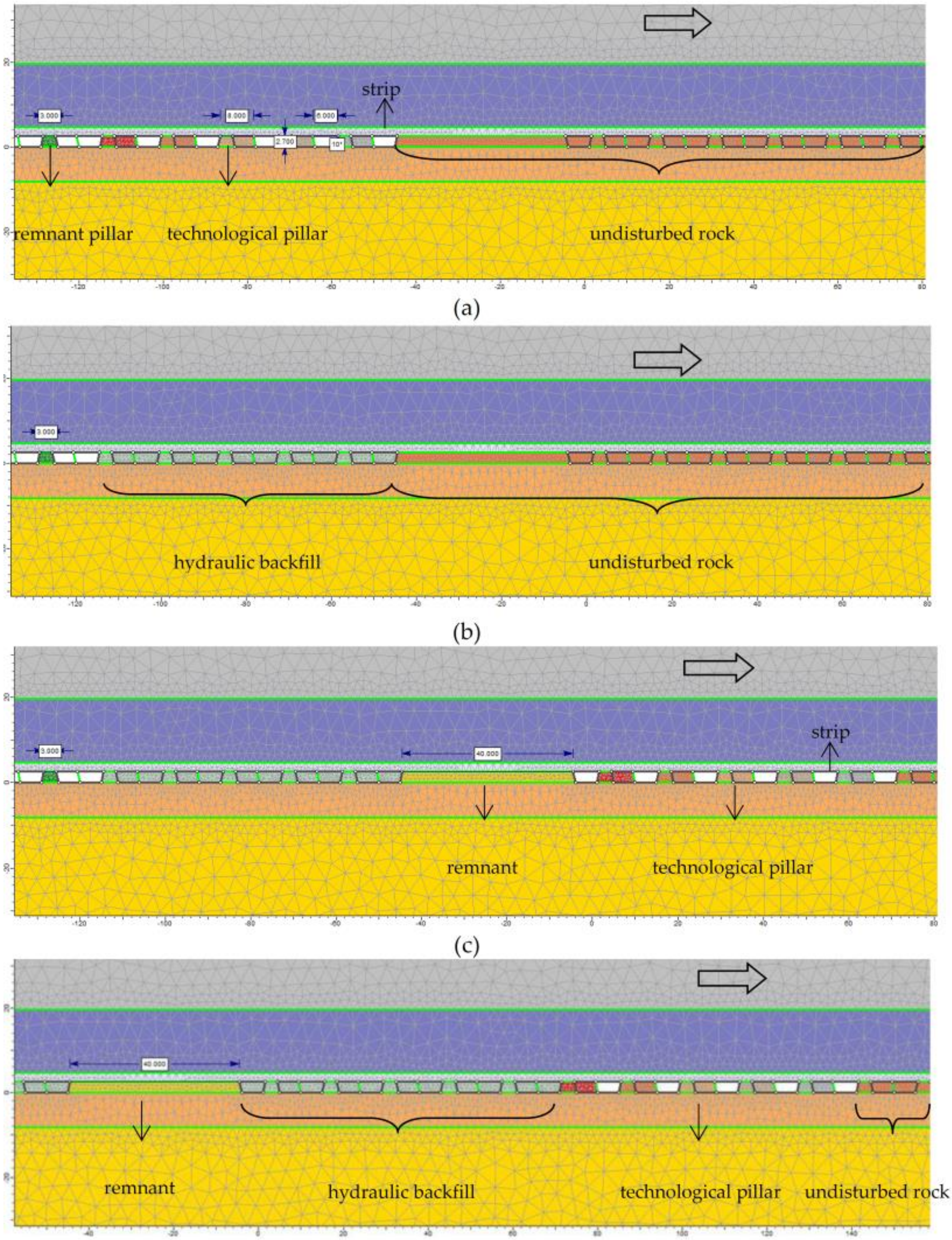
The numerical model was a plate in which the actual geological structure of the analyzed mining field was included (Table 1). Displacement boundary conditions were set in the model:

- Bottom edge of the plate: no vertical displacements
- Side edges of the plate: no horizontal displacements

The upper edge of the plate was loaded with a vertical stress of 17.657 MPa (vertical stress determined on the basis of data from borehole S-294). The self-weight of rock layers was accounted for in the calculations. The virgin horizontal stress was assumed to be equal to the virgin vertical stress (hydrostatic state of initial stresses). In the RS2 v. 9.0 computer program, rock mass was assumed to be homogeneous and isotropic, and the behavior of the rock mass was characterized by an elastic and an elastic–plastic model with softening. The Mohr–Coulomb strength criterion was applied.

As was mentioned before, the numerical model served to reconstruct the actual geological structure of the analyzed mining field. As in the first part of this research, the parameters of the rock mass (for the Coulomb–Mohr criterion) were determined on the basis of laboratory tests of rock samples from boreholes drilled in the analyzed region

(Mo-12 To-2, Mo-12 To-5 and Mo-11 To-3). The Hoek–Brown classification was used. The parameters of the rock mass are presented in Table 1.



(d)

Figure 6. Simulation of mining operations performed in the analyzed field: (**a**) step 30, (**b**) step 31, (**c**) step 37, (**d**) step 42.

Table 1. Rock mass parameters used in the numerical model of the analyzed region [11].

Location	Rock Type	h (m)	E_s (MPa)	v (-)	σ_t (MPa)	c (MPa)	ϕ (°)	c_{res} (MPa)	ϕ_{res} (°)	δ (°)
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	7100	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
Floor	Quartz sandstone I	8.2	4260	0.15	0.057	1.538	39.06	-	-	-
	Quartz sandstone II	194.5	3220	0.13	0.043	1.160	39.06	-	-	-

The symbols used in the above table are as follows: h—thickness of rock layers, E_s—longitudinal modulus of elasticity, v—Poisson's ratio, σ_t—tensile strength of the rock mass, c—cohesion coefficient, ϕ—internal friction angle, δ—dilatancy angle, c_{res}—residual cohesion coefficient, ϕ_{res}—residual internal friction angle.

The numerical model was built on a finite element mesh with 3-node triangular elements. In order to improve the accuracy of the numerical calculations, mesh density was increased in the central part of the model, in the vicinity of the excavations. The model has 81,864 elements and 41,289 nodes.

The parameters of the hydraulic backfill used in the model were determined iteratively and were based on a practical experience that, under the conditions of the LGCB copper mines, maximum vertical displacements due to the mining of the deposit with the room and pillar system with hydraulic backfill amount to approximately 15–20% of the deposit's thickness [34]. The detailed numerical model for the analyzed region is presented in Figure 7.

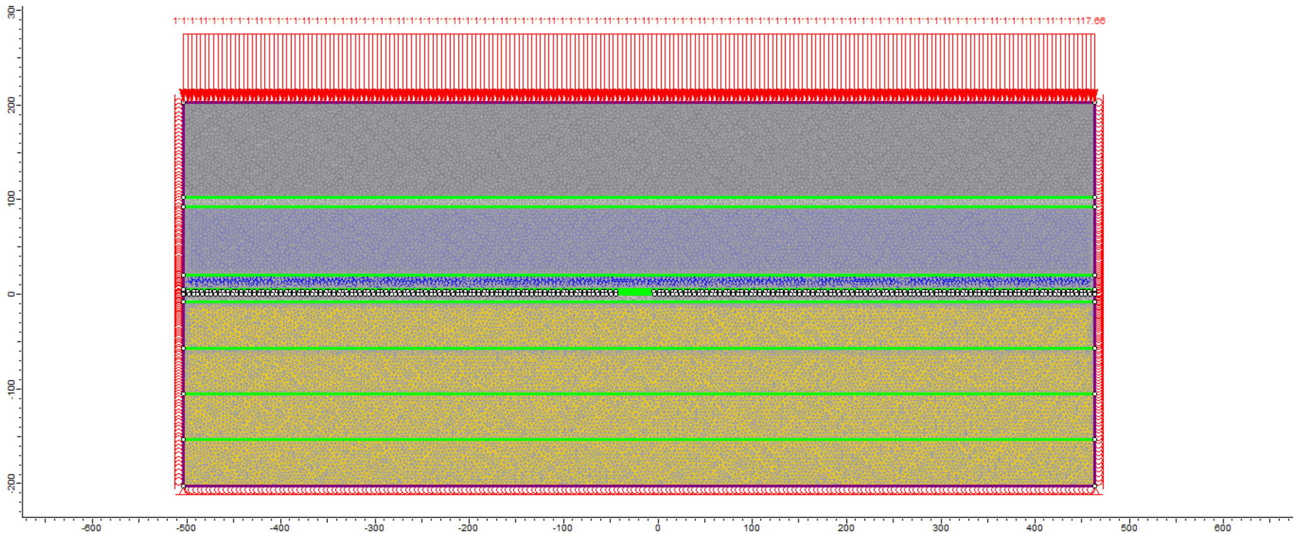


Figure 7. Numerical model for the analyzed region.

The model was validated on the basis of the convergence measurements of excavations driven in the analyzed mining field. The results from the in-situ convergence measurements were compared with the convergence values calculated by means of the numerical simulations. A very good correlation between the numerically calculated convergence and the measurement results may indicate that the model was built correctly (Figure 8).

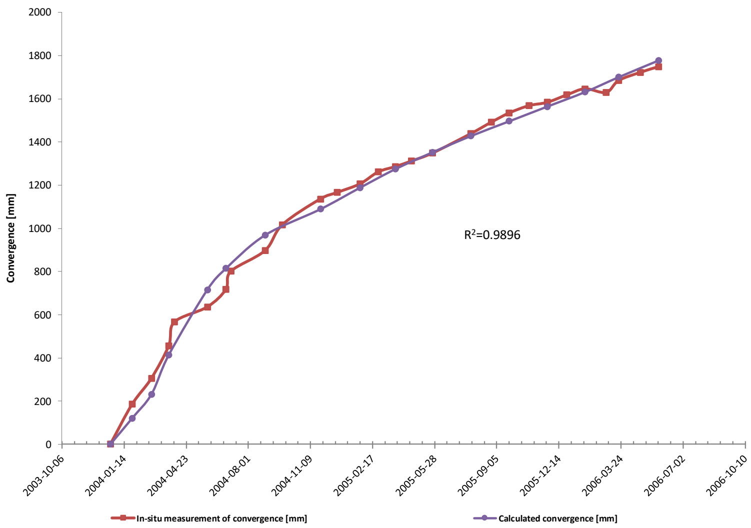


Figure 8. Matching between the results of the in-situ convergence measurements and the convergence values obtained using the numerical model.

4. Discussion

In order to investigate how the hydraulic backfill can improve the geomechanical situation in the vicinity of remnants, vertical stress σ_y distribution and yielded zones have been analyzed. The behavior of the remnant and of the rock mass in its vicinity was analyzed in the successive steps of the room and pillar mining system. The results of the numerical simulations conducted for the case of the mining field in which hydraulic backfill was used in the excavations located in the vicinity of the remnant have been compared with the results of the analysis performed in the previous research for the case of the room and pillar system with roof deflection.

The numerical simulation results for the analyzed mining field demonstrated that the application of hydraulic backfill in the excavations located in the vicinity of the remnant reduces deformations of roof strata generally in the entire mining field and mostly near the remnant.

The results of numerical simulations conducted in the first part of the research for the case of the room and pillar system with roof deflection showed that, in the 35th computational step, during the reconstruction of the mining front, when the fifth strip was created, a yielded zone suddenly (in one computational step) formed in the roof above the edge of the remnant (Figure 9a,b). The transverse line of destruction in the roof was formed near the left edge of the remnant and was inclined at an angle of approximately 60° in the direction of the gob area. These results indicate that a sudden fracturing and collapse of rigid roof layers may occur on the edge of the remnant, mainly due to the exceeded shear strength. This may cause a seismic event with high energy, potentially resulting in a rockburst phenomenon, if appropriate conditions are met [11].

The analysis of the area of the yielded elements numerically calculated in the second part of the research for the case with the room and pillar system with hydraulic backfill in the vicinity of remnant indicates that yielded zones in the field are smaller than in the case with roof deflection. Areas of yielded elements appear in particular above the gobs and they are observed to grow in the successive steps of the simulated room and pillar mining (Figure 10a,b). This indicates a progressing disintegration of roof layers above the mined-out areas. Moreover, in the case with hydraulic backfill, no yielded zone forms suddenly in the roof in the vicinity of the remnant edge over the entire period of mining operations (Figure 10b). A comparison between Figures 9 and 10 also shows that, in both of the analyzed cases, the remnant is stable. Yielded areas inside the remnant occur only near its edges. Their reach increases in the successive steps of the mining operations. After the reconstruction of the entire mining front (five strips on the right side of remnant), the reach of the yielded areas on the remnant edges does not exceed 2 m, while for a front distance of approximately 470 m from the remnant edge the reach of yielded areas reaches a maximum of approximately 3.5 m. During the reconstruction of the mining front, the yielded zones above the strips amount to approximately 2.0–2.9 m.

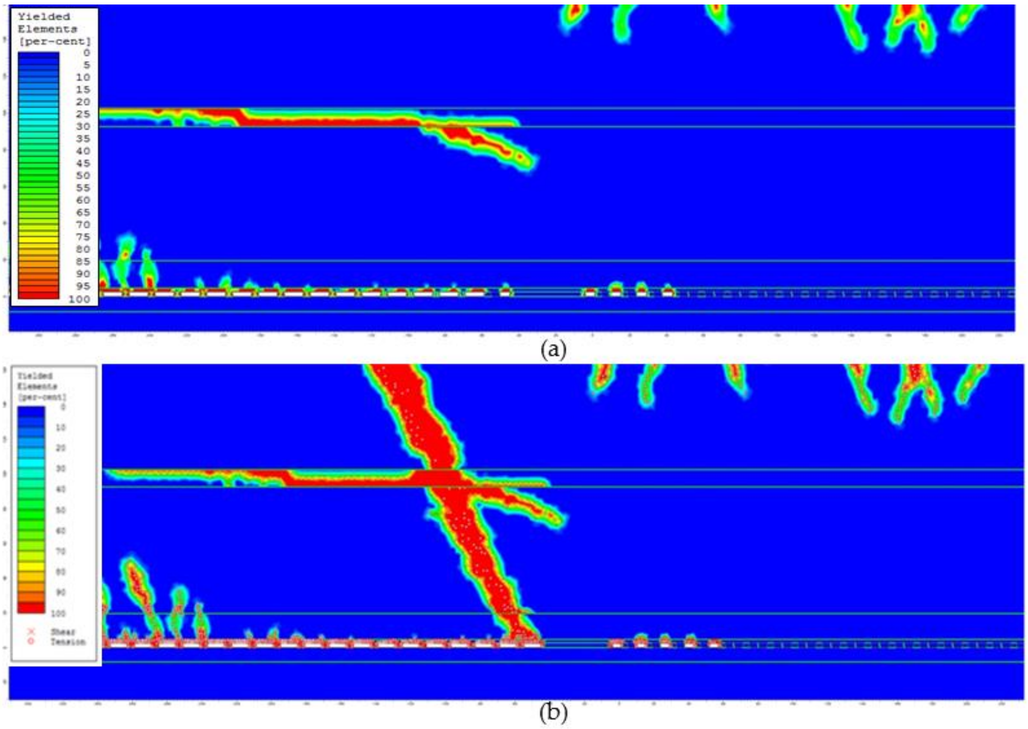


Figure 9. Yielded zones for mining front: (**a**) approximately 50 m from the remnant edge—34th calculation step, (**b**) approximately 60 m from the remnant edge—35th calculation step [11].

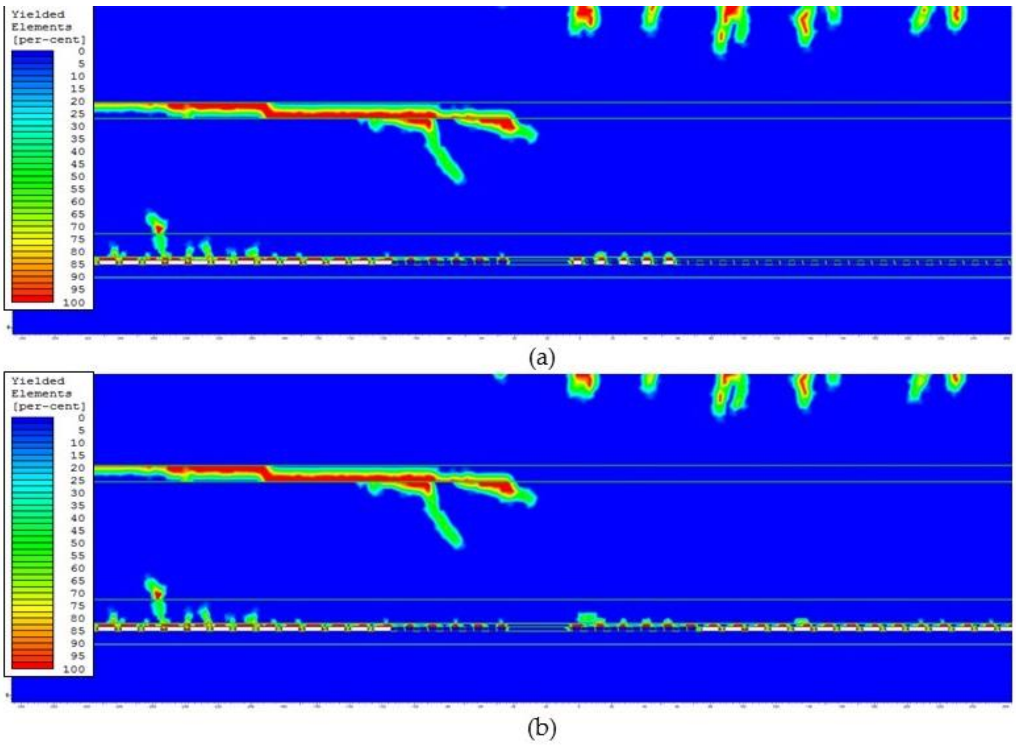


Figure 10. Yielded zones for mining front: (**a**) approximately 60 m from the remnant edge—36th calculation step, (**b**) approximately 470 m from the remnant edge—65th calculation step.

Figures 11–14 show the distribution of vertical stresses σ_y in the analyzed field for the room and pillar system with roof deflection (Figure 11) and with hydraulic backfill (Figures 12 and 13). It can be observed that stress concentration zones occur inside and in the vicinity of the remnant. A comparison between Figures 11 and 12 shows that the violent destruction in the roof above the remnant edge resulted in vertical stress redistributions near the left edge of the remnant and reduced the values of vertical stresses σ_y in the area of the yielded zone.

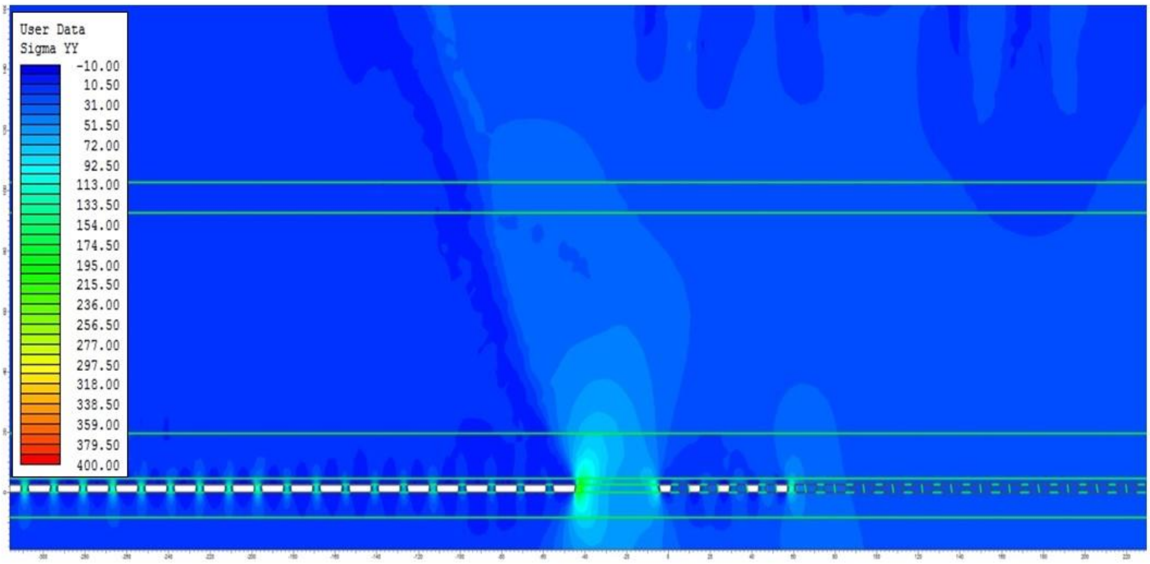


Figure 11. Distribution of vertical stresses σ_y for the front distance approximately 60 m from the remnant edge—35th calculation step [11].

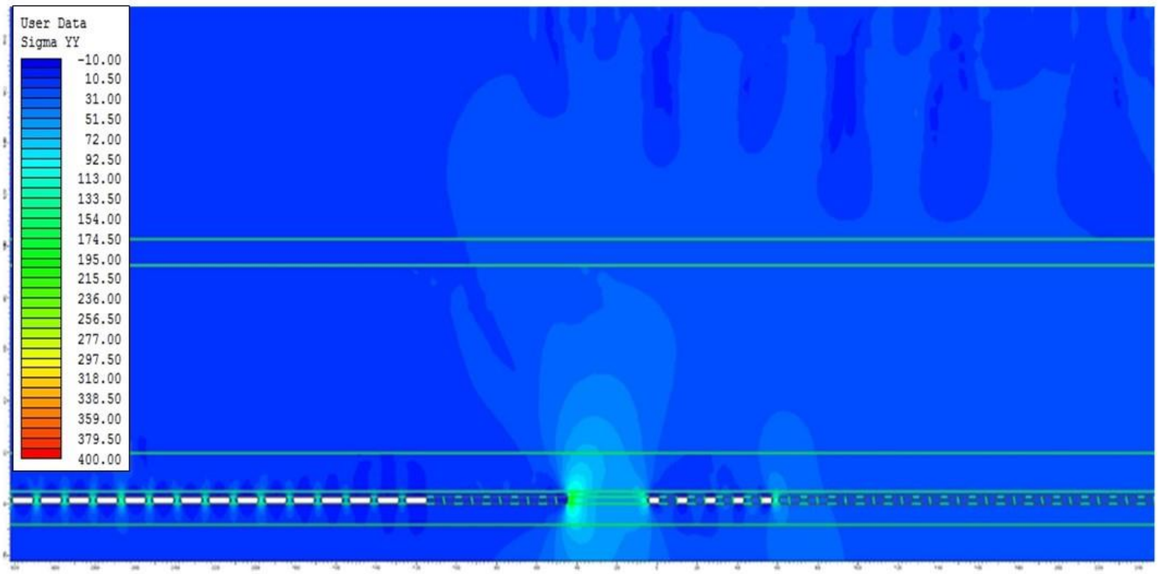


Figure 12. Distribution of vertical stresses σ_y for the front distance approximately 60 m from the remnant edge—36th calculation step.

Analyses of vertical stress σ_y distribution in the roof above the 40 m wide remnant (at distances of 5 m, 10 m, 20 m, and 40 m) for the room and pillar system with hydraulic backfill indicate that this remnant affects the roof layers. The maximum values of vertical stresses σ_y in the roof above the remnant (at distances of 5 m and 10 m) occur at a distance from the edge and are respectively equal to 5 m—120 MPa, 10 m—100 MPa. Their values decrease rapidly towards the level of approximately 20–25 MPa over the hydraulic backfill. With the increasing distance from the remnant, vertical stress σ_y values decrease and tend towards the initial stress state. In the roof layers at a distance of 20 m and 40 m above the remnant, the greatest values of vertical stress σ_y occur above its center (Figure 13). The impact range of the remnant and the values of vertical stresses in its surroundings increase in the successive steps of the simulated mining operations as the front progresses.

A comparison between the values of vertical stress σ_y in the roof 10 m above the remnant for the cases of the room and pillar system with roof deflection and with hydraulic backfill shows that the application of hydraulic backfill reduces the values of vertical stresses in the roof. The values of these stresses near the left edge of the remnant can be noticed to have decreased by a maximum of 20 MPa after the use of hydraulic backfill for the front distance of approximately 470 m from the remnant edge. Moreover, the difference in vertical stress σ_y between the roof deflection case and the hydraulic backfill case increases in the successive steps of the mining operations (Figure 14).

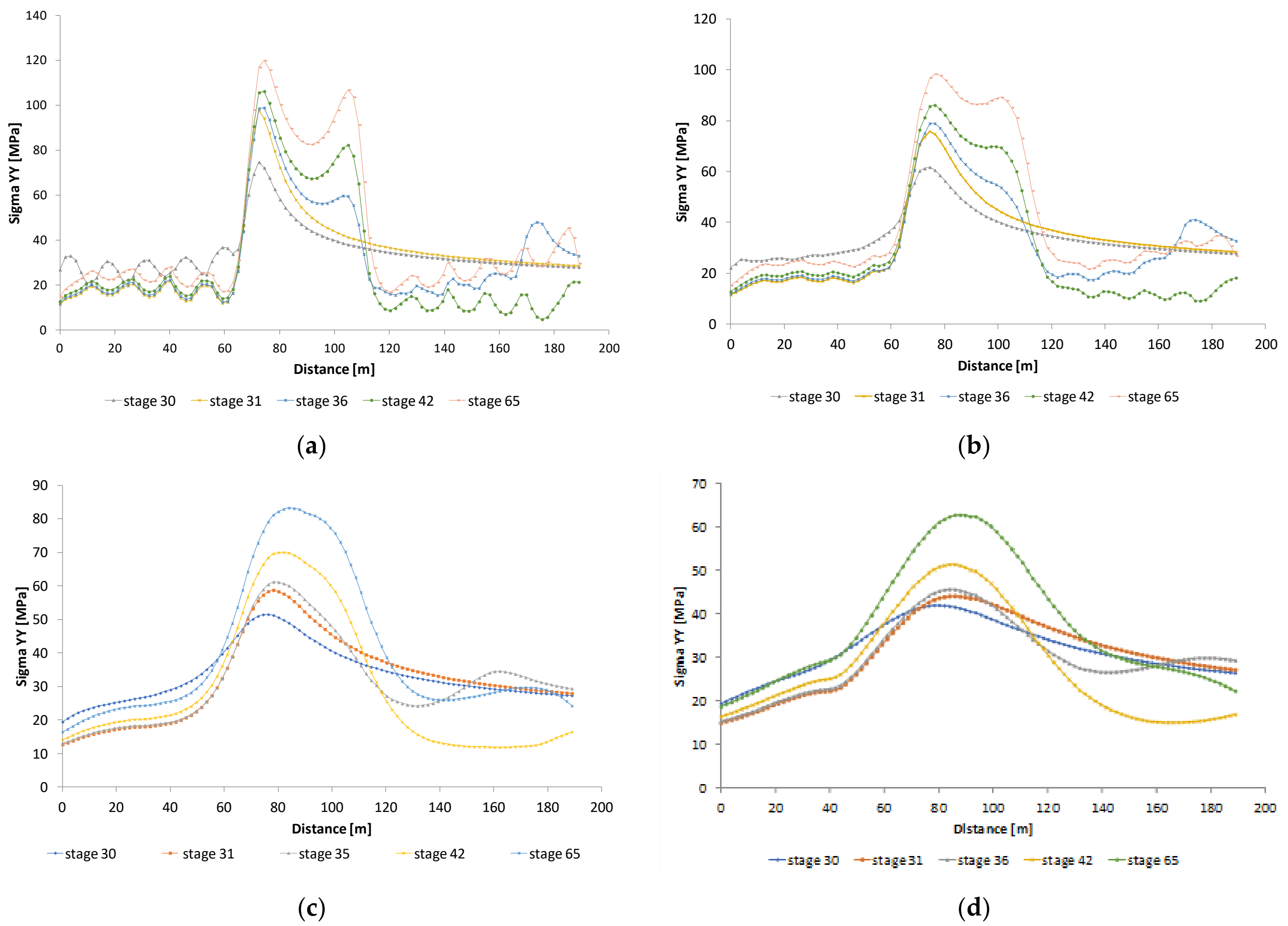


Figure 13. Vertical stress σy in the roof, for vertical distances of: (**a**)—5 m, (**b**)—10 m, (**c**)—20 m and (**d**)—40 m above the remnant.

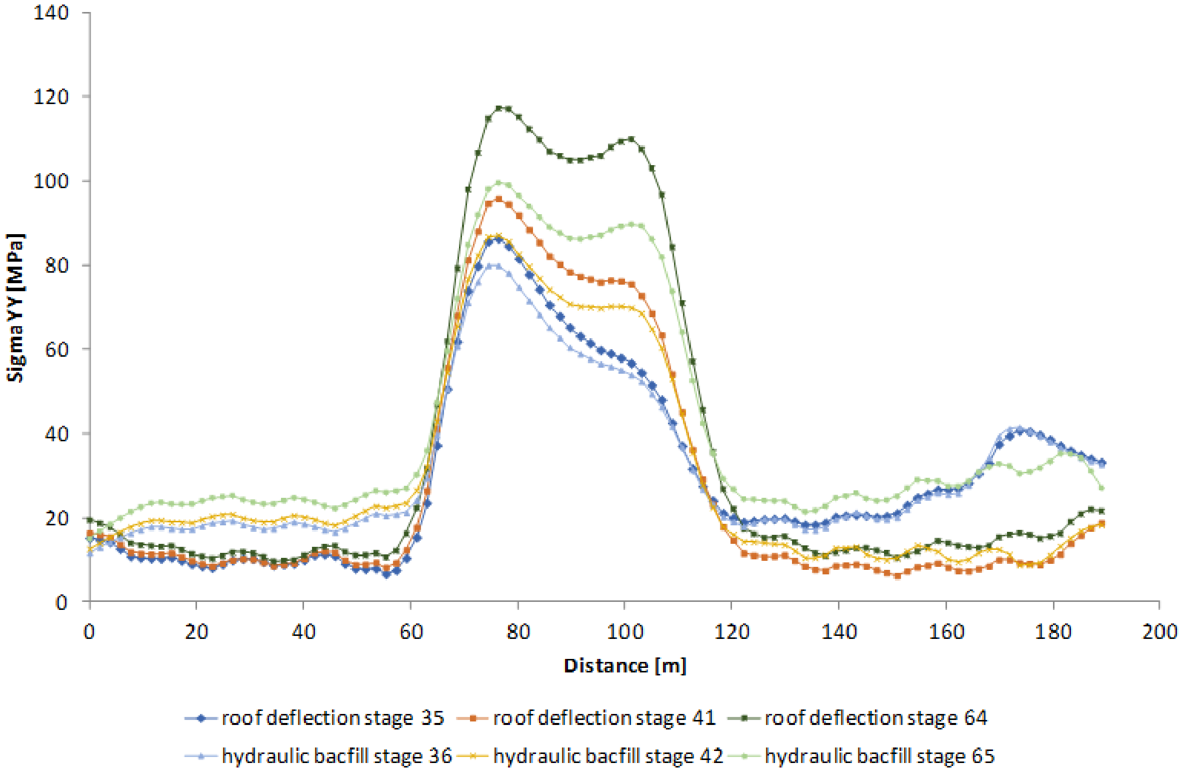


Figure 14. Comparison between vertical stresses σ_y in the roof layer 10 m above the remnant for the roof deflection case and the hydraulic backfill case, for the front distance of approximately: 60 m from the remnant edge—computational steps 35, 36, 146 m from the remnant edge—computational steps 41, 42), 470 m from remnant edge—computational steps 64, 65.

Figure 15 shows a comparison between the values of vertical stress σ_y inside the 40 m wide remnant for the cases of the room and pillar system with roof deflection and with hydraulic backfill. As can be seen, in both cases, the highest values of vertical stresses σ_y occur at a distance of approximately 2 m from its edge. Their values decrease towards the direction of the remnant's center. Moreover, the values of vertical stress σ_y inside the remnant increase in the successive steps of the mining operations. The maximum values of these stresses near the edge as well as in the center of the remnant can be noticed to occur in the case of the room and pillar mining system with roof deflection.

The greatest difference between vertical stress values σ_y inside the remnant in the cases of the room and pillar system with roof deflection and with hydraulic backfill occur on the right side of the remnant and is equal to 50 MPa for the maximum front distance of approximately 470 m from the remnant edge. Similarly, in the center of the remnant, the greatest difference between vertical stress values σ_y is noticed for the front distance of approximately 470 m from the remnant edge and is equal to 15 MPa.

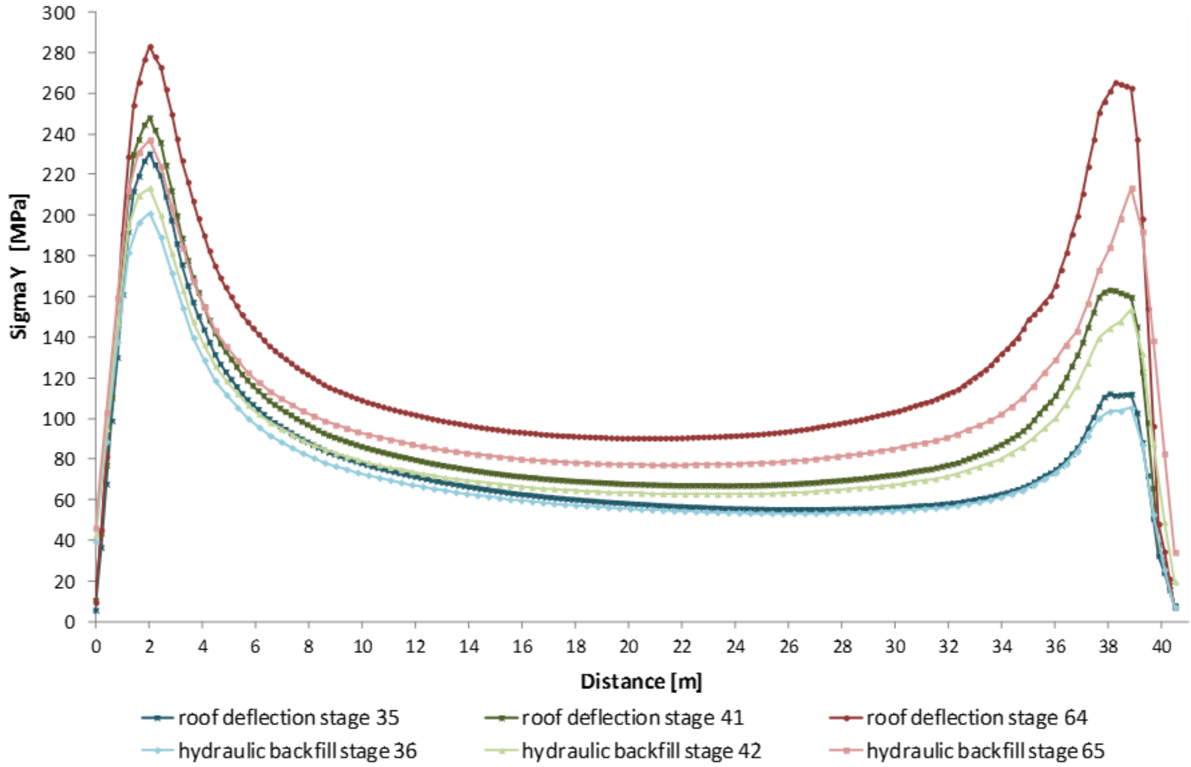


Figure 15. Comparison between vertical stresses σ_y inside the 40 m wide remnant for the roof deflection case and the hydraulic backfill case, for the front distance of approximately: 60 m from the remnant edge—computational steps 35, 36, 146 m from the remnant edge—computational steps 41, 42), 470 m from the remnant edge—computational steps 64, 65.

5. Conclusions

Due to a high level of mining concentration in Polish underground copper mines, mining works are very often carried out in difficult geological and mining conditions, resulting in high seismic and rockburst hazards. Frequent high-energy seismic events pose a threat to crews working underground. Therefore, optimal solutions should be found that will allow the extraction of copper ore deposits as safely and economically as possible. This paper focuses on the problem of the application of hydraulic backfill in excavations located in the vicinity of remnants, in order to improve the safety and efficiency of mining operations. The results of the numerical simulations allowed conducting a qualitative analysis and illustrating the occurrence of certain phenomena in the rock mass, in which copper ore is mined with the room and pillar systems.

The results of the numerical simulations performed for the case study (a mining field located in a Polish underground copper mine where undisturbed ore remnant 40 m in width was left behind) indicate that:

- The application of hydraulic backfill in the vicinity of the remnant strongly improves the geomechanical situation in the mining field, mostly by limiting rock mass deformation and disintegration in the mining field.
- In the case of hydraulic backfill, yielded zones in the field are smaller than in the case of roof deflection. They appear in particular above the gobs and increase in the successive steps of the simulated room and pillar mining.
- When the room and pillar mining system with roof deflection is used, sudden fracturing and collapse of rigid roof layers may occur on the edge of the remnant and cause a high-energy seismic event. In the case with hydraulic backfill, no yielded zone is suddenly formed in the roof in the vicinity of the remnant edge for the entire period of mining operations in the analyzed field.

– The application of hydraulic backfill also reduces the values of vertical stresses σ_y inside and in the vicinity of the remnant.

The results of the performed analyses indicate that the application of hydraulic backfill in the vicinity of the remnant has a number of very important advantages. It provides progressive roof deflection over the mined-out areas, which eliminates the formation of mining edges. Furthermore, it reduces stress concentrations at the remnant edges and prevents roof layers above edges from collapsing (which may result in high-energy tremors and rockbursts—shear raptures). It also increases the stability of the rock mass in the mining field reduces the stress concentration inside and near the remnant, thus limiting the risk of pillar rockburst. Further research based on numerical calculations showed that increasing the area of the backfill zone near the remnant would further improve stress distribution and reduce rock layer deformations in the mining fields.

The obtained results may facilitate decisions regarding the further development of mining works in areas affected by the presence of remnants and will allow for the verification of mining operation protocols and rockburst prevention methods. The results are also intended not only to improve the safety of mining operations carried out in the mining fields in which leaving a remnant is a necessity, but also to increase the efficiency of copper ore mining.

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.

Author Contributions: Conceptualization, K.A.-P.; methodology, K.A.-P. and D.P.; software, K.A.-P.; validation, K.A.-P.; formal analysis, K.A.-P.; investigation, K.A.-P.; resources, D.P.; data curation, D.P.; writing—original draft preparation, K.A.-P.; writing—review and editing, K.A.-P.; visualization, K.A.-P.; supervision, K.A.-P.; project administration, D.P.; funding acquisition, K.A.-P. All authors have read and agreed to the published version of the manuscript.

Funding: The research work was co-founded with the research subsidy of the Polish Ministry of Science and Higher Education granted for 2021.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Butra, J.; Kudelko, J. Rockburst hazard evaluation and prevention methods in Polish copper mines. *Cuprum Sci. Tech. J. Ore Min.* **2011**, *4*, 5–20.
2. Cook, N.G.W. Seismicity induced by mining. *Eng. Geol.* **1976**, *10*, 99–122. [CrossRef]
3. Ortlepp, W.D.; Stacey, T.R. Rockburst mechanisms in tunnels and shafts. *Tunn. Undergr. Space Technol.* **1994**, *9*, 59–65. [CrossRef]
4. Gibowicz, S.J.; Kijko, A. *An Introduction to Mining Seismology*; Academic Press: San Diego, CA, USA, 1994.
5. Kaiser, P.K.; McCreath, D.R.; Tannant, D.D. *Canadian Rockburst Support Handbook*; Geomechanics Research Centre: Sudbury, ON, Canada, 1996.
6. Ortlepp, W.D. *Rock Fracture and Rockbursts: An Illustrative Study*; SAIMM Monograph Series M9, 98; The S Af Inst of Min and Metall: Johannesburg, South Africa, 1997.
7. Ortlepp, W.D. Observation of mining-induced faults in an intact rock mass at depth. *Int. J. Rock Mech. Min. Sci.* **2000**, *37*, 23–436. [CrossRef]
8. Salustowicz, A. *Outline of Rock Mass Mechanics*; AGH Science and Technology Press: Krakow, Poland, 2019.
9. Adach-Pawelus, K. Influence of the roof movement control method on the stability of remnant. In *IOP Conference Series—Earth & Environmental Science, Proceedings of the World Multidisciplinary Earth Sciences Symposium, Prague, Czech Republic, 11–15 September 2017*; IOP Publishing Ltd: Bristol, UK, 2017; Volume 95, p. 042022. [CrossRef]
10. Adach-Pawelus, K. The influence of the geology of ore remnant on its behaviour in the mining field. In *Science and Technologies in Geology, Exploration and Mining 1.3, Exploration and Mining, Proceedings of the 18th International Multidisciplinary Scientific GeoConference, Albena, Bulgaria, 2–8 July 2018*; Curran Associates, Inc.: New York, NY, USA, 2018; Volume 18, pp. 1–10.
11. Adach-Pawelus, K.; Butra, J.; Pawelus, D. An attempt at evaluation of the remnant influence on the occurrence of seismic phenomena in a room-and-pillar mining system with roof deflection. *Studia Geotech. Mech.* **2017**, *39*, 3–16. [CrossRef]

12. Lenhardt, W.A.; Hagan, T.O. Observations and possible mechanisms of pillar associated seismicity at great depth. In *SAIMM, Johannesburg, South Africa, Symposium Series S10, Proceedings of the International Deep Mining Conference, Mbabane, Swaziland, 10–12 September 1990*; South African Institute of Mining and Metallurgy: Johannesburg, South Africa, 1990; pp. 1183–1194.
13. Adach-Pawelus, K. Application of seismic monitoring and numerical modelling in the assessment of the possibility of seismic event occurrence in the vicinity of ore remnant. In *IOP Conference Series—Earth & Environmental Science, Proceedings of the World Multidisciplinary Earth Sciences Symposium, Prague, Czech Republic, 3–7 September 2018*; IOP Publishing Ltd: Bristol, UK, 2019; Volume 221, pp. 1–10. [CrossRef]
14. Basarir, H.; Bin, H.; Fourie, A.; Karrech, A.; Elchalakani, M. An adaptive neuro fuzzy inference system to model the uniaxial compressive strength of cemented hydraulic backfill. *Min. Miner. Depos.* **2018**, *12*, 1–12. [CrossRef]
15. Li, M.; Zhang, J.X.; Jiang, H.Q.; Huang, Y.L.; Zhang, Q.A. Thin plate on elastic foundation model of overlying strata for dense solid backfill mining. *J. China Coal. Soc.* **2014**, *39*, 2369–2373.
16. Dz.U. 2017 poz. 1118. Ordinance of the Minister of Energy of 23 November 2016 on Detailed Requirements for Conducting Underground Mining Operations. Available online: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20170001118. (accessed on 23 June 2021). (In Polish)
17. Szpak, M. Impact of mining method cavity caused by the extraction under rockbursts hazard in chosen panels in Rudna—copper mine. *Cuprum Sci. Tech. J. Ore Min.* **2008**, *3*, 15–31. (In Polish)
18. Bartlett, S.; Burgess, H.; Damjanović, B.; Gowans, R.; Lattanzi, C. Technical Report on the Copper-Silver Production Operations of KGHM Polska Miedz, S.A. In the Legnica-Glogow Copper Belt Area of Southwestern Poland; Toronto, ON, Canada. 2013. Available online: https://kghm.com/en/technical-report-copper-silver-production-operations-kghm-polska-miedz-sa-legnica-glogow-copper-belt. (accessed on 23 June 2021).
19. Gogolewska, A.; Junik, P. Seismic hazard related to rate of face advance in Lubin copper ore mine. *Min. Sci.* **2013**, *20*, 87–99. (In Polish) [CrossRef]
20. Pariseau, W.G.; Kealy, C.D. Support potential of hydraulic backfill. In Proceedings of the 14th Symposium on Rock Mechanics, Pennsylvania, PA, USA, 11–14 June 1972; pp. 501–526.
21. Hassani, F.; Ouellet, J.; Servant, S. In situ measurements in a paste backfill: Backfill and rock mass response in the context of rockburst. In Proceedings of the Seventeenth International Mining Congress and Exhibition of Turkey, Ankara, Turkey, 19–22 June 2001; pp. 165–175.
22. Zhang, J.; Zhou, N.; Huang, Y.; Zhang, Q. Impact law of the bulk ratio of backfilling body to overlying strata movement in fully mechanized backfilling mining. *J. Min. Sci.* **2011**, *47*, 73–84. [CrossRef]
23. Xiaojun, F.; Qiming, Z.; Muhammad, A. 3D modelling of the strength effect of backfill-rock on controlling rockburst risk: A Case study. *Arab. J. Geosci.* **2020**. [CrossRef]
24. Li, J.; Yin, Z.Q.; Li, C.M. Waste rock filling in fully mechanized coal mining for goaf-side entry retaining in thin coal seam. *Arab. J. Geosci.* **2019**, *12*, 509. [CrossRef]
25. Feng, J.; Peng, H.; Shuai, G.; Meng, X.; Lixin, L. A roof model and its application in solid backfilling mining. *Int. J. Min. Sci. Technol.* **2017**, *27*, 139–143. [CrossRef]
26. Zhang, J.; Li, B.; Zhou, N.; Zhang, Q. Application of solid backfilling to reduce hard-roof caving and longwall coal face burst potential. *Int. J. Rock Mech. Min. Sci.* **2016**, *88*, 197–205. [CrossRef]
27. Skrzypkowski, K. Decreasing mining losses for the room and pillar method by replacing the inter-room pillars by the construction of wooden cribs filled with waste rocks. *Energies* **2020**, *13*, 3564. [CrossRef]
28. Huang, Y.L.; Zhang, J.X.; Zhang, Q.; Nie, S.J.; An, B.F. Strata movement control due to bulk factor of backfilling body in fully mechanized backfilling mining face. *J. Min. Saf. Eng.* **2012**, *29*, 162–167.
29. Li, M.; Zhang, J.X.; Liu, Z.; Zhao, X.; Huang, P. Mechanical analysis of roof stability under nonlinear compaction of solid backfill body. *Int. J. Min. Sci. Technol.* **2016**, *26*, 863–868. [CrossRef]
30. Hemp, D.A.; Goldbach, O.D. The effect of backfill on ground motion in a stope. In Proceedings of the 3rd Symposium Rockburst and Seismicity in Mines, Kingston, Ontario, 16–18 August 1993.
31. Kaiser, P.K.; Tang, C.A. Numerical simulation of damage accumulation and seismic energy release during brittle rock failure part II: Rib pillar collapse. *Int. J. Rock Mech. Min. Sci.* **1998**, *35*, 123–134. [CrossRef]
32. Wang, J.A.; Park, H.D. Comprehensive prediction of rockburst based on analysis of strain energy in rocks. *Tunn. Undergr. Space Technol.* **2001**, *16*, 49–57. [CrossRef]
33. Zhu, W.C.; Li, Z.H.; Zhu, L.; Tang, C.A. Numerical simulation on rockburst of underground opening triggered by dynamic disturbance. *Tunn. Undergr. Space Technol.* **2010**, *25*, 587–599. [CrossRef]
34. Piechota, S.; Cala, M.; Korzeniowski, W. Evaluation of the value of rock formation strengthening coefficient used for classification of roof in LGOM mines for different methods of gob liquidation. *Min. Rev.* **2006**, *9*, 1–8. (In Polish)