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Technical Note

An Analysis of the Impact of Mining Excavation Velocity on the Development of Gaseous and Gaseous Geodynamic Hazards in Copper Ore Mines

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Abstract: The hazards of gaseous geodynamic phenomena and rockbursts are among the most challenging to assess and classify. This perception arises from both a review of the literature and an examination of available instructions and regulations in underground mining facilities. The hazard of gaseous geodynamic phenomena in Polish copper ore mines only appeared in 2009, whereas these phenomena occur and are commonly described in other mining countries. In Polish copper ore mines, due to the room and pillar system in fields with lengths of about 460 m, very often parallel to neighboring fields, which together give a length of about 900 m, it is difficult to identify the location of gas traps due to the large size of the area. This paper presents an analysis of the influence of the velocity of the excavation on the possibility of escalating or reducing the described mining hazards. An analysis of the impact of excavation velocity on the state of gaseous geodynamic and roof fall hazards was conducted for two mining fields. For the considered mining fields, the hypothesis was formulated that an excavation velocity greater than or equal to 17 m/month positively influences a reduction in both gaseous geodynamic and roof fall hazards.

Keywords: geodynamic hazard; excavation velocity; room and pillar; underground copper excavation

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Citation: Gniewosz, M.; Stopkowicz, A.; Cała, M. An Analysis of the Impact of Mining Excavation Velocity on the Development of Gaseous and Gaseous Geodynamic Hazards in Copper Ore Mines. *Geosciences* **2024**, *14*, 54. https://doi.org/10.3390/geosciences14020054

Academic Editors: Chun Zhu, Yujun Zuo, Shibin Tang, Qian Yin and Jesus Martinez-Frias

Received: 22 December 2023
Revised: 7 February 2024
Accepted: 16 February 2024
Published: 18 February 2024

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1. Introduction

The world of mining is subject to many types of natural hazards, which occur with different scales and characteristics. Due to the depletion of easily accessible deposits, the mining industry is forced to undertake the exploitation of resources at increasing depths. This is associated with an increase in the associated natural risks. This trend can be seen in both coal and ore mining. It seems that the way of recognizing and, above all, classifying gaseous geodynamic hazards is one of the most problematic issues for both the scientific community and mining industry employees. This problem can be observed when analyzing the legal provisions and guidelines in force in mining countries. European countries, as well as China, rely on the parameters and their criterion values in general use, while the USA and Australia point to local mining–geological conditions. The hazard of gaseous geodynamic phenomena in Polish copper ore mines only appeared in 2009, whereas these phenomena occur and are commonly described in other mining, for example, in South Africa [1], China [2], Chile [3], and the USA [4].

Research dedicated to gaseous geodynamic hazards typically focuses on the analysis of individual cases. Hedlund [5] documented an extreme outburst of carbon dioxide that occurred on 7 July 1953 in a potash mine in former East Germany. Li and Hua [6] described an outburst in which over 2000 tons of oil-bearing sandstone were expelled along with 900,000 m^3 of gas in the air shaft of Haishiwan Colliery, China. Hedlund [7] presented a case study from the Menzengraben mine (former DDR), where an extreme outburst occurred in 1953, possibly involving several thousand tons of carbon dioxide.

In Polish copper ore mines, due to the room and pillar system in mining fields with lengths of about 460 m, very often parallel to the neighboring fields, which together give a length of about 900 m, it is difficult to identify the location of gas traps due to the large size of the area. The possibility of introducing a classification based on the categorization of factors influencing the possibility of a gaseous geodynamic phenomenon is currently being investigated. However, it should be remembered, that potential gas-destructive sites are characterized by specific features, such as increased porosity, fracturing, the occurrence of gas in floor rocks, and the reduced mechanical parameters of rocks in the immediate vicinity of the conducted exploitation. This makes it possible for other hazards to co-exist with the hazard of gaseous geodynamic phenomena, which have a direct impact on exploitation. These are the risk of rockfall from the roof, gas emanations into excavations, and water inflows from roof rocks. This paper presents an analysis of the influence of the velocity of the excavation on the possibility of increasing or reducing the described co-occurring hazards.

2. Methods for Describing and Classifying Rock and Gas Outburst Hazards in the World of Mining

It is recognized that there is no universal definition or classification that can be used to describe the gaseous geodynamical phenomena hazard [8].

The situation is unfortunately similar in the case of other mining hazards, such as rock-bursts or methane hazards. There are no uniform or universally recognized classifications of hazards in underground mining. Researchers might seek a method similar to the widely disseminated and universally used classification systems for rock mass, such as RMR, Q, or GSI. This article, therefore, focuses on one of the factors, mining exploitation velocity, for which a significant correlation has been demonstrated with the intensity of rock and gas outbursts hazard, as well as roof fall.

For example, in China, a risk classification that includes seven geological and twelve operational or design factors is used [9]. In the USA, rock outburst classification considers six contributing factors: depth of cover, pillar design, multiple seam interactions, geology, mining layouts, and the practices and past history of bursts [10]. In Poland, sixteen factors contributing to the hazardous state of coal mines exist. In addition, three methods are suggested to evaluate the real state of a coal burst hazard: the seismological method, the seismoacoustic method, and the drilling method. The way to solve the problem of gaseous geodynamical phenomena hazard is not yet determined.

Attempts have been made to introduce a classification of gaseous geodynamic hazards in copper ore mines [11]. The assessment of the hazard level related to gaseous geodynamic phenomena in an excavated corridor is based on the recognition of the rock mass in which the excavation will be performed (depth, lithology, tectonics, local disturbances), as well as on gas and endoscopic studies of the exploration borehole in the excavation. Based on conducted statistical studies, four significant groups of factors determining the possibility of potential hazards related to gaseous geodynamic phenomena have been identified. The first two groups pertain to the recognition of the rock mass, while the remaining two groups concern gas conditions and endoscopic studies in the exploration borehole, respectively.

In Polish copper mines, rock outbursts are a new natural hazard. So, there has not yet been an agreed-upon definition of the contributing factors that best describe the rock outburst hazard. One of the possible contributing factors that may have an impact on reducing the hazard, for example, the velocity of mining excavation, is described in this paper.

3. Description of Mining and Geological Conditions

An analysis of the velocity of mining excavation was carried out in two adjacent mining fields located in O/ZG Polkowice-Sieroszowice KGHM P. M S. A. These are fields SI XII/4 and SI-XII/5, and the length of the front line of each field is 460 m. These regions, following the legal regulations in force in Poland, have not been classified in any of the two categories of risk of gas and rock outbursts [12]. Due to the presence of rocks in the fields with properties that may lead to the appearance of a hazard, to improve safety, it was decided, in accordance with the technical design of exploitation [13], to drill ahead of the front lines.

Excavation in the analyzed fields is carried out with a room and pillar system, one-stage with roof deflection (JUGP-S). The depth of the deposit is in the range of 1100–1200 m. The basic dimensions of the pillars are 8 × 9 m. The fields are qualified to the first degree of rockburst hazard, and the average uniaxial compressive strength of the rocks in the mining face is 97 MPa. The size of the mining face, in which mining is carried out, is variable and depends on the parameters of the deposit, technological requirements, etc. However, it can be said that its range in both fields is between 2. 1 and 3. 4 m. The mining face is led in three layers: sandstone 0.3–1.5 m, slate up to about 0.4 m, and carbonates 0.7 to 3.0 m. The thickness of the carbonate series between the layer and the anhydrite is between 9 and 12 m [13]. The area of work is located on the border of a documented salt deposit lying above the layers of anhydrite.

The last measurements of the initial stress state in the mine were conducted in 2012. The estimated values of the vertical stresses are approximately $\sigma_v \cong 30$ MPa. The values of higher horizontal stresses are $\sigma_H \cong 1.1\ \sigma_v$, while the values of lower horizontal stresses are $\sigma_h \cong 0.8\ \sigma_v$. No observable effects of the influence of horizontal stress components on the stability of rooms and pillars were noted.

The analysis covers the period from the start of the operation in the first field SIXII/4 in January 2017 to October 2019. Based on the materials made available by O/ZG Polkowice-Sieroszowice, and based on previous experience, particular fragments of fields were selected for analysis. These are the fragments in which, during the excavation, there was an escalation of hazards co-occurring with the gaseous geodynamic phenomena, such as the local falling of roof rocks, gas emanations, and the water inflow from roof rocks.

Figure 1 shows the location of the selected fields in the mining area of "Sieroszowice" [14]. On the map, the zone determining the first level of the gas and rock outbursts is marked in red. The zone of the geological structure (Jakubowa Flexure), conducive to the occurrence of the gas hazard symptoms, is marked in blue. This is where the analyzed fields are located.

Figure 1. A map of the planned excavation in the areas of the projected hazard. Red circles—shaft location, orange line—salt deposit.

The map of the excavations (Figure 2) shows the range of the cut from the beginning of the excavation to 1 March 2020. The map includes marked disturbances (zones 1, 2, 3, and 4) that were recognized during the excavation. The disturbances do not coincide with the parts of the deposit excluded from exploitation due to the intensification of gas and the roof fall hazard symptoms.

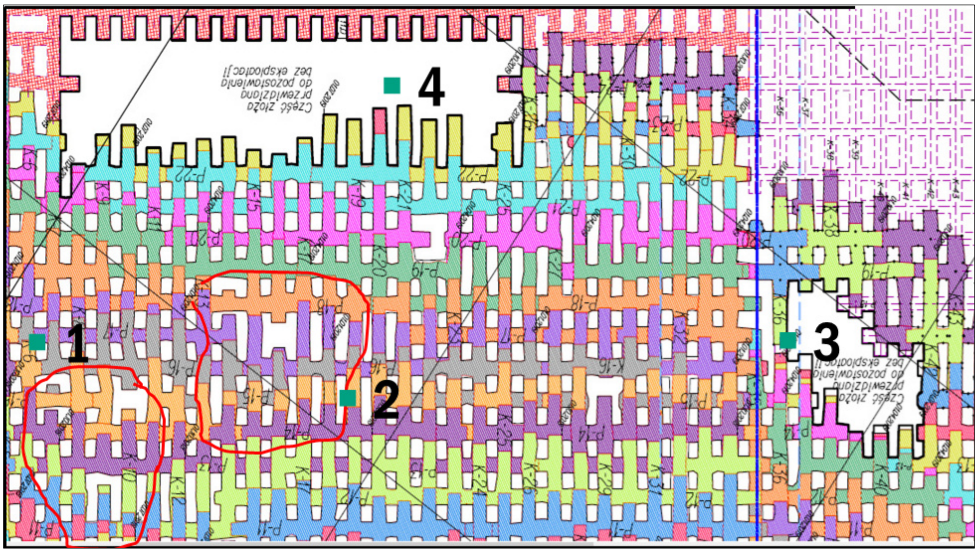

Figure 2. Sketch of the selected fragments of the fields, together with the progress of the individual excavation. White parts of the map signed in Polish mean parts of the mining field excluded from excavation. The colors represent the following months of excavation. The dotted lines symbolize the planned excavation of with room and pillar system.

4. The Velocity of Mining Excavation and Its Impact on Gaseous Geodynamic Hazard

The analysis of mining velocity was performed based on the calculation of the monthly progress of each room over its entire service life. Four fragments of the fields were analyzed in detail (Figure 3). These were selected to be analyzed in detail based on the largest scale of the symptoms of the gas and roof fall hazards. Each time, this led to the necessity to stop the works, redesign the inter-room pillars, and, in the worst cases, leave parts of the deposit without excavation. In the following tables (Tables 1–4), the velocity of the rooms in the selected sites is presented. Orange boxes in Tables 1–4 represent the low excavation velocity and green boxes the high one.

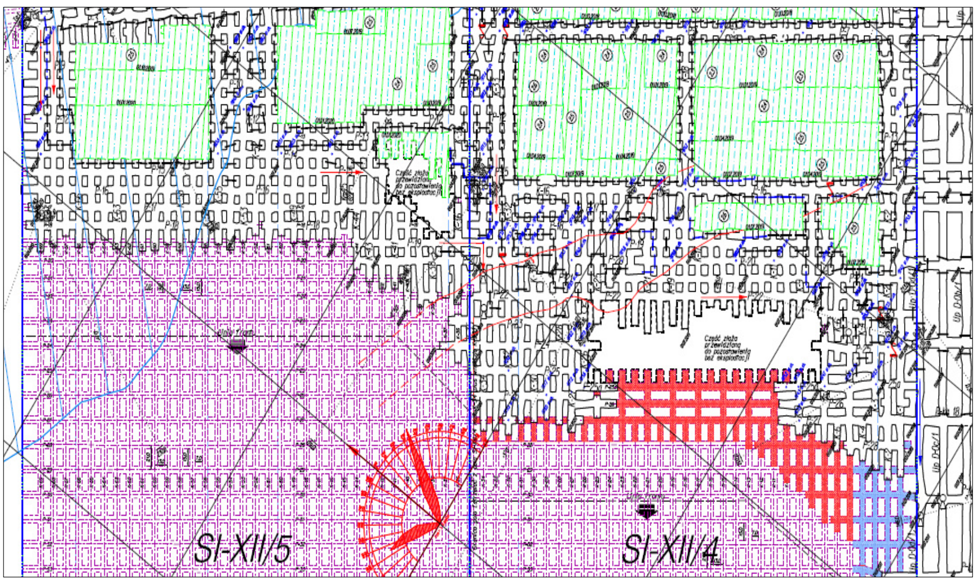

Figure 3. Sketch of the selected fragments of the fields, together with the progress of the individual excavation.

Table 1. The velocity of mining excavations at the front from room 7 to room 12 in the period from April 2018 to October 2018 m/month.

	Room					
	K-7	**K-8**	**K-9**	**K-10**	**K-11**	**K-12**
	[Meters/Month]					
18 April	20	20	13	12	7	20
18 May	18	25	26	8	3	5
18 June	12	6	15	28	8	8
18 July	7	12	5	5	26	23
18 August	22	10	11	5	16	17
18 September	14	11	4	19	9	17
18 October	25	19	22	23	23	18
Average velocity [meters/month]	16.9	14.7	13.7	14.3	13.1	15.4

Table 2. The velocity of mining excavations at the front from room 13 to room 20 in the period from June 2018 to March 2019 m/month.

Date	**K-13**	**K-14**	**K-15**	**K-16**	**K-17**	**K-18**	**K-19**	**K-20**
	[Meters/Month]							
18 June	15	-	-	-	-	-	-	-
18 July	5	14	15	20	34	28	33	20
18 August	20	10	29	30	28	19	22	26
18 September	22	40	24	24	21	21	22	29
18 October	18	12	12	16	17	14	16	16
18 November	25	6	14	9	10	10	17	15
18 December	14	23	9	18	7	15	10	5
19 January	30	12	22	2	26	20	12	18
19 Febuary	7	10	20	22	10	15	16	8
19 March	25	20	21	16	17	14	23	29
Average velocity [meters/month]	17.7	15.8	18.2	17.4	19.4	17.3	19.0	18.2

Table 3. The velocity of mining excavation from room 36 to room 43 in the period from December 2018 to September 2019.

	K-36	**K-37**	**K-38**	**K-39**	**K-40**	**K-41**	**K-42**	**K-43**
	[Meters/Month]							
18 December	10	19	18	17	22	27	36	26
19 January	16	24	24	25	14	14	6	19
19 Febuary	18	12	19	16	23	24	36	22
19 March	28	26	17	18	25	23	19	12
19 April	15	15	16	4	3	-	3	5
19 May	-	-	-	-	-	3	-	16
19 June	3	3	4	-	-	9	18	15
19 July	-	-	-	-	-	-	17	14
19 August	35	-	-	-	-	-	52	25
19 September	48	-	-	-	-	-	25	36

Table 4. The velocity of the excavations from room 7 to room 26 in the period from December 2018 to July 2019 [meters/month].

	K-7	K-8	K-9	K-10	K-11	K-12	K-13	K-14	K-15	K-16	K-17	K-18	K-19	K-20	K-21	K-22	K-23	K-24	K-25	K-26
	[Meters/Month]																			
18 December	23	16	24	25	19	31	14	23	9	18	7	15	10	5	7	10	15	17	6	17
19 January	13	10	10	9	5	12	30	12	22	2	26	20	12	18	13	22	11	20	16	12
19 Febuary	29	28	22	17	19	12	7	10	20	22	10	15	16	8	19	6	20	7	17	13
19 March	16	12	18	22	22	18	25	20	21	16	17	14	23	29	19	14	19	21	12	16
19 April	8	16	8	6	14	14	14	20	17	27	26	25	22	23	15	-	12	14	21	21
19 May	16	2	16	20	16	18	19	14	10	13	18	23	14	24	32	26	25	10	26	29
19 June	6	-	4	9	3	7	6	11	8	-	3	12	16	12	15	17	18	-	12	34
19 July	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10

The periodic decreases in the progress of the individual excavations can be observed in Table 1. It seems that the appearance of hazards is not affected by a velocity decrease in a single excavation in a short period, e.g., (K-7, July 2018). However, the visible deterioration of mining conditions, in this case, occurred after the velocity in the group of excavations from K-8 to K-10 had decreased over three months (from July to September—boxes marked in orange). Comparing Table 1 with the excavation progress map (Figure 3) shows that after a 3-month slowdown in September 2018, a decision was made to locally change the size of the pillars and not to excavate K-10 between P-12 and 13 [15].

Table 2 presents the scope of the mining velocity from K-13 to K-20 in which, due to the deterioration of the conditions, decisions were made to change the geometry of the pillars and not to make individual rooms (Figure 3). It can be seen in Table 2 that these periods coincide to a large extent with the decrease in the mining velocity throughout the field. After the period in which the velocity was maintained at a relatively high level above 20 m/month, there was a decrease in the velocity within the entire section of the field from October 2018.

It should be noted that the velocity decrease itself did not initially occur due to a drastic change in the mining and geological conditions. Rather, it resulted from the organizational and operational decisions and the availability of both technical and human resources. Such a conclusion may be formulated based on an analysis of the three elements combined: the excavation map (Figure 3), the mining velocity (Table 2), and the collective diagram (Figure 4).

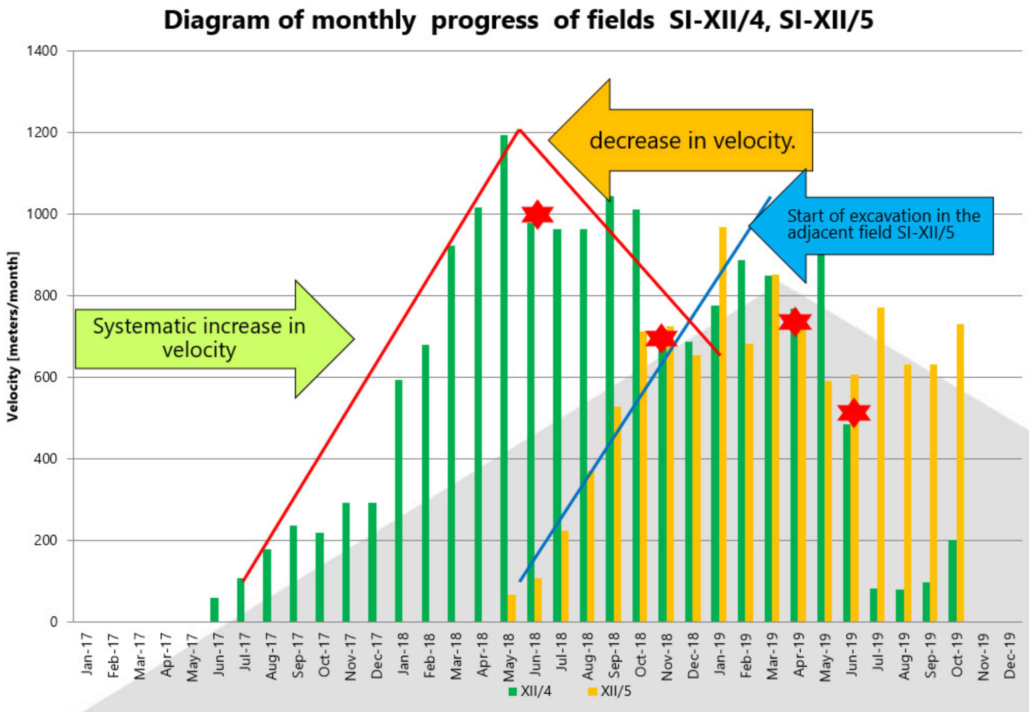

Figure 4. Diagram of the monthly velocity of the fields S-XII/4 and SI-XII/5. Red and blue lines are the limits of excavation velocity. Stars represent the moments of escalation of gas and the outburst hazard.

It should then be noted that the decrease in velocity in the analyzed fragment is at the same time associated with an increase in the mining velocity in the adjacent SI-XII/5 field. Taking into consideration the fact that the exploitation works were carried out using the same amount of machinery and human resources, we conclude that this results directly from the transfer of the technical resources to another field. The fact that the velocity has been falling since October 2018 is also important to note. The significant increase in the gas and the roof fall hazard, which led to the decision to increase the size of the pillars to

22 m and not to carry on with K-16 and 14 between P-16 and P-18, was made at the turn of December 2018 and January 2019 [15,16].

The velocity of K-15 and K-17 (which was used to bypass room 16) in January 2019 (over 20 m/month) is also significant. It can be seen here that with the involvement of an appropriate amount of technical possibilities, high velocity can be maintained in places where it previously amounted to 9 m/month, even when no significant changes in the mining and geological conditions occurred. Therefore, it seems reasonable to put forward the hypothesis that the limitation of mining velocity may lead to an escalation of hazards.

As it is known from the theory of rockbursts, an increase in the rate of development causes instability in the rock mass and the manifestation of dynamic phenomena [17]. However, in the two analyzed mining fields, no symptoms of increased rockburst hazards because of the acceleration of exploitation speed were observed.

Table 3 presents a case where, due to the mutual location of the two fronts of the SI-XII-4 and SI-XII/5 fields and the need to maintain an appropriate distance between them, the velocity in the SI-XII/5 field was first limited and then stopped. The mutual location of the fronts and the border between them is shown on the map (Figure 2). In June 2019, during an attempt to restart the analyzed section, because of the deterioration of mining conditions and an increase in the gas and outburst hazard, it was then decided to bypass the section of the field from K-36 to K-42 with strip 19 of K-34 and K-42 [15]. The velocity marked in green refers to the progress of the bypass with K-34 and K-42 (Figure 3). As in the cases described above, it can also be seen here that once the decision has been made and the technical and organizational measures have been applied, the field can carry out work effectively in the areas where the conditions have deteriorated.

This requires the appropriate use of the available means of movement, as in the example of room K-42, in which the progress in August was 52 m/month. Assuming an average advance of 2.8 m and 20 working days per month, all works related to the production cycle were performed in this excavation every day.

In Table 4, the period before the decision to exclude the largest part of the SI-XII/4 field, marked in Figure 2 with number 4, was analyzed. Table 4 shows the velocity in rooms 7 to 26 in the period immediately preceding the decision to shut down a part of the field. In the six months preceding the shutdown of the part of the field, no significant velocity drops covering more than one excavation in a period longer than one month were observed. This may indicate that a single incidental slowdown (probably related to local disturbances) in a small area does not contribute to the deterioration of the conditions. It was in May, when the slowdown occurred in several adjacent rooms, and on the 17 of June, when the H2S concentrations were exceeded, that a decision was made to exclude parts of the field from K-17 D-0d [15].

A key fact to note in the analysis of this case is that the inflow of gases and water to the excavations did not occur because of the progress of chambers from 7 to 26/P-22, but rather, it occurred because of the places preceding the front lines from 17 to 18/K-15 to 18, and from P-19 to 20/K-20 to 21. These are the locations analyzed in Table 2 where the slowdown and the change in the geometry of excavations took place. This leads to the conclusion that leaving unresolved problems at an earlier stage of the excavation may have a negative influence on the process of the excavation at a later stage.

The diagram (Figure 4) shows the distribution of the velocity of the excavations in each month in the SI-XII/4 and SI-XII/5 fields since the beginning of the operation. The green color indicates the velocity of SI field XII/4 in each month, while the orange color indicates the velocity of SI field XII/5. From June 2017 to May 2018, a systematic increase in the velocity in the SI-XII/4 field can be observed. In May 2018, the branch started the excavation of the adjacent field SI-XII/5. As the progress in this field increases, a decrease in velocity in the SI-XII/4 field can be observed. The chart shows the previously discussed moments of escalation of gas and the outburst hazard. It is now clear that they are not only related to the local velocity drops but also that they fit into the slowing down trends across the fields. The greatest total velocity in the SI-XII/4 field took place in May 2018 and amounted to approx. 1200 running m.

5. Summary

Taking into account the multitude of factors influencing the occurrence of the hazard of gas and rock outbursts, as well as the accompanying hazards, it is impossible to clearly state to what extent the velocity of the excavation front affects the possibility of the escalation of gas and the outburst threat. However, leaving aside other aspects and assuming that the mining and the geological conditions in the analyzed fields are similar, it can be concluded that the velocity of the excavation is not without significance.

Based on the analysis of Tables 1–4, it seems that the velocity above which the mining conditions in the excavations did not deteriorate is 17 m/month. To determine the values of velocity, it would be necessary to try to relate them to the geotechnical properties of the rocks in the given area and to determine the influence of the particular parameters. These tests, however, require a lot of research carried out directly during excavation, which must be carried out on different fields with different mining and geological characteristics. They are necessary to properly counteract the negative effect of the hazard of gas and rock outbursts and roof falls on the operations.

For this moment, it seems appropriate to carry out maintenance work not at a specific point during the progress but certainly in a continuous mode, without stopping in any particular parts of the fields. It should be however noted that this particular value of mining velocity is estimated only for the conditions of the two adjacent fields SI-XII/4 and SI-XII/5.

A bold hypothesis can also be formulated that each field extracted by the room and pillar system has its optimal minimum excavation velocity, which mitigates the risk of gas and rock outbursts as well as rock falls.

Author Contributions: Conceptualization, M.G., A.S. and M.C.; methodology, M.G.; formal analysis, M.C.; investigation, M.G.; resources, M.G.; data curation, M.G.; writing—original draft preparation, M.G.; writing—review and editing, M.C.; visualization, A.S.; supervision, M.C. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

Conflicts of Interest: The authors declare no conflicts of interest.

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