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FIELD TESTING OF THE METHODS FOR PREVENTION AND CONTROL OF COAL AND GAS OUTBURST – A CASE STUDY IN POLAND

Coal mining tends to face increasing stress and gas conditions when it extends to deeper levels. The mining-induced high stress and gas pressure concentrations often result in gasogeodynamic phenomena such as rock bursts and coal & gas outbursts. Over the last decades, these gasogeodynamic events have been observed more often in the Upper Silesian Coal Basin, Poland. With the increasing mining depth, these hazards not only become a serious safety risk but also represent a significant challenge for coal mining. In order to eliminate future hazards and improve safety in underground coal mines, it is necessary to apply particular methods for the prevention and mitigation of possible hazards during mining operations. Inaction or incorrect use of preventive measures may lead to gasogeodynamic events, which may result in accidents and material losses, thereby affecting the mine's economic performance.

Several coal mines operated by Jastrzębska Spółka Węglowa S.A. (JSW group), such as Pniówek, Budryk and Zofiówka coal mines have been identified as the area most prone to rock bursts as well as coal and gas outburst. Generally, the longwall panels often experience a high degree of these mining hazards. Therefore, the main aim of this research is to examine and optimise the possibility of application of prevention methods in order to reduce the frequency and scale of dangerous gasogeodynamic phenomena such as coal and gas outburst. As a main part, the field testing of the selected preventive methods that were conducted in the JSW coal mines. Based on the obtained results, the possibility of application of an optimal method for the prevention and control of coal and gas outburst in the geo-mining conditions of the JSW coal mines was discussed. The research results could be an example for other coal mines in mine planning and designing in the gasogeodynamic (coal and gas outburst) hazard-prone conditions.

Keywords: Gasogeodynamic phenomena; coal and gas outbursts; rock bursts; coal mining

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1. Introduction

Change of the original state of stresses and pressure distribution of gases is the main cause of many mining hazards, including the occurrence of rock bursts, and coal & gas outbursts in the underground mines. These events are observed as a dynamic movement of crushed rocks or coal to the excavation by the energy of gases released from the rock mass as a result of the interaction of many geological and mining factors combined. The basic criterion for assessing the risk is the possibility of occurrence of the following gasogeodynamic phenomena: rock bursts, coal and gas outbursts or a sudden outflow of gases from the rock mass into the excavation.

The natural factors of hard coal deposits that affect the possibility of occurrence of the gasogeodynamic phenomena are: in situ stress, seam thickness, the degree of gas (CH_4, CO_2 or their mixture) saturation of coal seams and surrounding rocks (gas concentration), physical and mechanical properties of the coal and surrounding rocks (e.g. coal rank, grain size, porosity, compressive strength, conciseness, desorption intensity, permeability), rock mass tendency to seismic phenomena, tectonic structures and discontinuities (faults, shear bedding zones) [1-10]. In addition, technical factors such as mining method, advance rate, gas drainage measures, and distance from the coal seam to the overlying and underlying mined seams also have a significant impact on the possibility of occurrence [11-19].

Recently, the highest threat level for rock bursts and coal & gas outburst was observed in the hard coal mines of the Upper Silesian Coal Basin. The coal mines with the highest absolute methane concentration reported in 2022 included (mln m^3): Borynia-Zofiówka (JSW group) – 115.85, Brzeszcze (TAURON Wydobycie) – 94.25, Pniówek (JSW group) – 87.38, Budryk (JSW group) – 77.61, Knurów-Szczygłowice (JSW group) – 76.14, Staszic-Wujek (PGG group) – 57.24, Sośnica (PGG group) – 53.03. In 2022, 126 longwalls were mined in hard coal mines, of which 23 longwalls (18.3%) were in non-methane seams, and 103 longwalls (81.7%) were in methane seams. The actual absolute methane concentration of longwalls in the most threatened areas was as follows: 16 longwalls with a methane concentration from 20 to 40 m^3/min and 6 longwalls with a methane concentration over 40 m^3/min (TABLE 1).

TABLE 1

Summary of these longwalls with the methane concentration of over 40 m^3/min [20]

Name of coal mine	Name of coal seam	Number of longwalls	Methane concentration, m^3/min
Budryk, JSW group	405/1	1	58.91
Borynia-Zofiówka, JSW group	505/1	2	53.65/51.50
Knurów-Szczygłowice, JSW group	407/3	1	42.69
Sośnica, PGG group	414/1	1	45.92
Brzeszcze, TAURON Wydobycie	364	1	41.70

The JSW coal mines are located in highly gassy and complex geological conditions. TABLE 2 presents selected examples of events related to the outflow of methane to mining excavations and gasogeodynamic phenomena in the JSW mines.

Monitoring, assessment and preventive measures are commonly applied in order to eliminate the possible gasogeodynamic hazards and improve safety in underground coal mines. This research aims to indicate, based on the conducted field testing, the optimal method for prevention

TABLE 2

Major occurrence of gasogeodynamic events in the JSW coal mines [21]

Name of coal mine	**Name of the underground working**	**Name of coal seam**	**Type of mining hazard**	**Amount of coal and rock burst [Mg]**	**Methane concentration [m^3]**	**Date**
1 Maja	Drift S	280	Methane outburst with intensity of 200 m^3/min and pressure of 0,3 MPa	—	—	—
Zofiówka	Roadway F-5	360/3	Methane and coal outburst	15	2170	10.08.1979
Zofiówka	Roadway H-5	403/1	Methane and coal outburst	95	5000	12.06.1985
Pniówek	Incline S-5	363	Methane outflow	—	19 700	03.01.1987
Pniówek	Shaft inlet at level of 1000 m b.g.l.	404/4+ 405/1	Methane and coal outburst	325	51 448	23.08.2002
Zofiówka	Roadway D-6	409/4	Methane and coal outburst	350	10 200	22.11.2005
Zofiówka	Drift F at the level of 1080 m b.g.l.	—	Methane outflow	—	6092	1.06.2019
Zofiówka	Roadway (tailgate) D-4a	412łg+łd and 412łg	Rockburst and methane outflow	Floor rocks uplifted to 0.7 m	124 500	23.04.2022

and control of the gasogeodynamic hazards such as coal and gas outburst. Selected methods were examined in the conditions of the Pniówek and Budryk coal mines as the most prone area to the gasogeodynamic hazards. Field experiments, monitoring and interpretation of the preventive measures for prevention and control of coal and gas outbursts were conducted, including the use of large diameter boreholes and destress blasting and the use of high water injection. Based on the results of the in situ testing, the possibility of application of the selected methods for the prevention and control of such hazards in the geo-mining conditions of the JSW coal mines was discussed. Consequently, some practical recommendations were formulated.

2. A historical overview of worldwide occurrences in coal & gas outburst, including Polish mines

Gasogeodymanic phenomena such as rock bursts, and coal & gas outbursts have been reported in the worldwide underground mines for more than 150 years in at least 21 countries: China, Russia, Australia, France, Ukraine, Poland, Belgium, Japan, and Turkey [6,7,15-19,22-30]. From 1894 to 2014, 497 coal and gas outbursts occurred in the Czech Republic [22,31-33]. The most disastrous coal and gas outburst in the world occurred in the Kozlu coal mine, in the Zonguldak Coal Basin, Turkey, on March 3, 1992, at a depth of 560 m. The outburst caused a massive explosion of methane and coal dust and resulted in 263 fatalities and 77 injuries of miners [34,35]. In China, mining accidents related to coal and/or gas explosions have taken place in almost 1650 mines, among which nearly 98% of cases occurred in the mines prone to coal and gas outburst. A coal and gas outburst accident occurred in the Daping Coal Mine, Zhengzhou Mining Group, which caused 148 deaths in 2004. A coal and gas outburst accident occurred in the Xingxing coal mine, Longmei Mining Group, which caused 104 deaths in 2009. A coal and gas outburst accident took place in the Henan Yichuan National Coal Industry Co., Ltd., which caused 46 deaths in 2010. Recently, coal and gas outburst accidents still account for about 22% of the total number of accidents in Chinese underground mines [8,12,18,36-38].

In Poland, gasogeodynamic phenomena were dominant in the hard coal mines in the Lower Silesian Coal Basin in the 80s. In this coal basin, methane, carbon dioxide and a mixture of these two gases were involved in gas and rock outbursts. One of the most disastrous coal and gas outbursts occurred in the Nowa Ruda coal mine in the Lower Silesian coal basin, Poland, and resulted in 187 deaths of miners [18,39,40]. The issue of the occurrence of gasogeodynamic phenomena in the mines of the Upper Silesian Coal Basin has been observed in the 90s. In the strong methane seams, the occurrence of high-energy tremors was the cause of rock bursts involving methane. One of the first phenomena of this nature took place in the Bielszowice coal mine in Ruda Śląska on December 12, 1996. In the 303 longwall panel, in the 507 coal seam, a high-energy tremor occurred, which caused a collapse and interruption of the ventilation roadway [41]. As a result, the roadway was deformed, and a large area of seam 507 was destroyed. The airflow stopped, and methane rapidly flowed out from the rock mass, which resulted in methane concentration in the mine air to over 30%. This led to an accident, i.e. the death of 6 miners, while 2 miners, moving along the longwall roadway to the place of the collapse, died in an unbreathable atmosphere due to high concentrations of methane. In 1999, in the N-303 longwall panel, there was another collapse caused by a high-energy tremor. The consequences covered the conjunction of the longwall work with the roadway. As a result, there was also a rapid release of methane into the longwall workings. In 2002, in the Pniówek coal mine, during the excavation of the shaft inlet at the level of 1000 m, a gas and rock outburst took place after a driving operation with an explosive. This event was not accompanied by a rock mass tremor, however, the face of the excavation was located at the height of a fault with a drop of about 0.7 m [5,9]. In 2005, in the Zofiówka coal mine, in the transportation roadway, gas and rock outbursts occurred during a driving operation with a shearer, as a result of which three miners died. The cause of the outburst of coal, rocks and methane is that the roadway face was approaching the tectonic disturbance seam zone with a changed structure, high methane saturation, very low conciseness and high fissures. In this case, no rock mass tremors were registered either [5]. In 2013, in the Wujek coal mine, in the area of the 409 coal seam, during the driving of the headgate, a high-energy tremor occurred in the goaf of one of the longwalls. This tremor caused effects in two galleries in the form of an uplift of the floor up to 0.5 m and a rapid outflow of methane into these galleries, causing its increase in the mine atmosphere to the value of 24% [41]. The latest mining accident took place on April 23, 2022, in the Borynia-Zofiówka coal mine, JSW group. A tremor with an energy of 4.0×10^6 J occurred in the area of the D-4a longwall panel in the 412łg+łd and 412łg coal seam. This tremor caused a collapse of longwall working and rapid release of significant amounts of methane (approx. 124500 m^3). As a result of the event, 10 miners were suffocated. The cause of the catastrophe was a high-energy tremor combined with methane outbursts.

These above examples provide a clear warning against the threats associated with gasogeodynamic phenomena. Therefore, it is necessary to apply preventive measures to reduce the frequency and scale of the gasogeodynamic hazards. Due to different geological and mining conditions, each case should be analysed individually for a specific mining area. A field testing was conducted, aiming at evaluating the selected preventive measures in the JSW coal mines. As a result, the optimal preventive measures were recommended.

3. Methods for prevention and control of coal & gas outburst

In mining practice, it is recommended to apply preventive methods to reduce the risk of gas and rock outbursts. The idea of these methods is to locally remove or lower the high-stress concentration and gas pressures in the coal face [3,4,10,16,21,23,32,42]:

- Local de-gasifying consists of lowering the gas pressure in the zone around the roadway face. Methane drainage is carried out through in-seam boreholes drilled from the roadway face. The effectiveness of methane drainage depends on the permeability of the coal seam. This method is reported effective in the USA or Australia, where the coal seams are shallow with high permeability. The situation is the opposite in Poland, where the coal seams are low permeable, which makes the gas intake with such boreholes drilled in the roadway face small and ineffective. Therefore, this method is not used in the conditions of Polish mines.
- Destressing boreholes are performed in order to reduce the stresses in the coal seam and to remove local stress concentration in the roadway face. The diameter of the boreholes depends on local conditions, from 42 mm to 152 mm and more, as well as the length of the boreholes – they can be up to 40 m. This method is considered time-consuming and requires the use of drilling equipment to make such boreholes. In Poland, it was used only in the Lower Silesian Coal Basin mines. It is also applied in the Ostrava-Karviná coal basin, Czech Republic and in Germany.
- Destress blasting is performed only for local destressing of the rock mass without mining the seam. Such boreholes can be performed and controlled periodically and together with the cutting boreholes. This method is commonly used in Polish mines.
- Destressing-mining blasting: the layout of the boreholes for such a blasting is similar to ordinary blasting, while the explosive charge is increased in order to not only mine the seam but also to destress the coal face zone. Similarly to the destress blasting method, such blasting may provoke an outburst without the presence of the mining crew in the roadways.
- High-pressure water injection is used much less often than the destress blasting in Polish mines. They involve the requirement to perform several 6-m-boreholes through which the seam is injected with a pressure of 20 MPa in 3÷4 hours. The effectiveness of this method varies and depends on local conditions. Implementation of this method is time-consuming.

The decision on the application of a specific method is made after identifying a degree (category) of the gas and rock outburst hazard and determining the geological and mining factors that affect such a hazard. In fact, field testing was conducted in the Pniówek and Budryk coal mines to examine two commonly used methods in the conditions of Polish mines i.e. destress blasting and high-pressure water injection due to the specific factors such as the physical and chemical properties of coal, the coexistence of seismic and rock burst hazards, and the mine planning. Other mentioned methods are less effective.

4. Field experiments, monitoring and interpretation of selected methods for prevention and control of coal and gas outburst

4.1. Location of the JSW coal mines

The JSW coal mines are located in the south of Poland in the Silesian Voivodeship, 350 km southwest of the capital, Warsaw. The JSW Group is the largest producer of high-quality hard coking coal in Europe with a yearly coal production of 14 million tonnes.

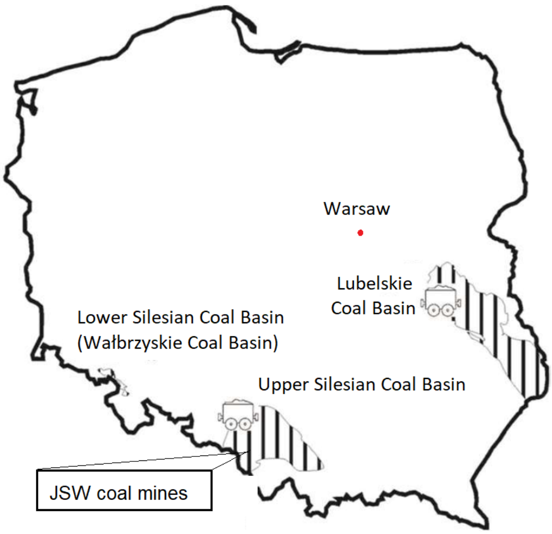

Fig. 1. Location of the JSW coal mines

The Pniówek and Bydryk coal mines are one of the heavy methane mines in the Upper Silesian Coal Basin. The emission of methane to the workings and goafs of these mines exceeds the value of 40 m^3 CH_4/min. The methane saturation of coal seam in these mines is high and ranges from 6 to 10 m^3 CH_4/Mgdaf. During mining operations, the methane hazard is at a high level. Along with the depth of exploitation, there was an increase in the risk of methane and rock outbursts, as well as the risk of rock bursts due to the seismic activity of the rock mass and changes in the gaseous properties of coal. The rock mass tremors cause the increase in the gas permeability of the coal seam, leading to the occurrence of gasogeodynamic phenomena, i.e. rock bursts or methane and rock outbursts. The coexistence of hazards, including methane and rock bursts, as well as methane and rock outbursts, creates the possibility of gas hazards in active mining excavations and on the air discharge routes to the ventilation shaft.

4.2. Brief description of geo-mining conditions of the studied sites

The studied sites are located in the 404/1 coal seam, Pniówek coal mine and the 401 coal seam, Budryk coal mine. Actual mining coal seams are located at a depth of about 880÷1000 m with an inclination of 2÷13°. The average thickness of seams is 1.5÷2.5 m. In the roof and floor rocks are mainly: claystone, shale, mudstones and sandstones with different thicknesses. Fig. 2 shows an example of the geological profile in the area of the 404/1 coal seam, Pniówek.

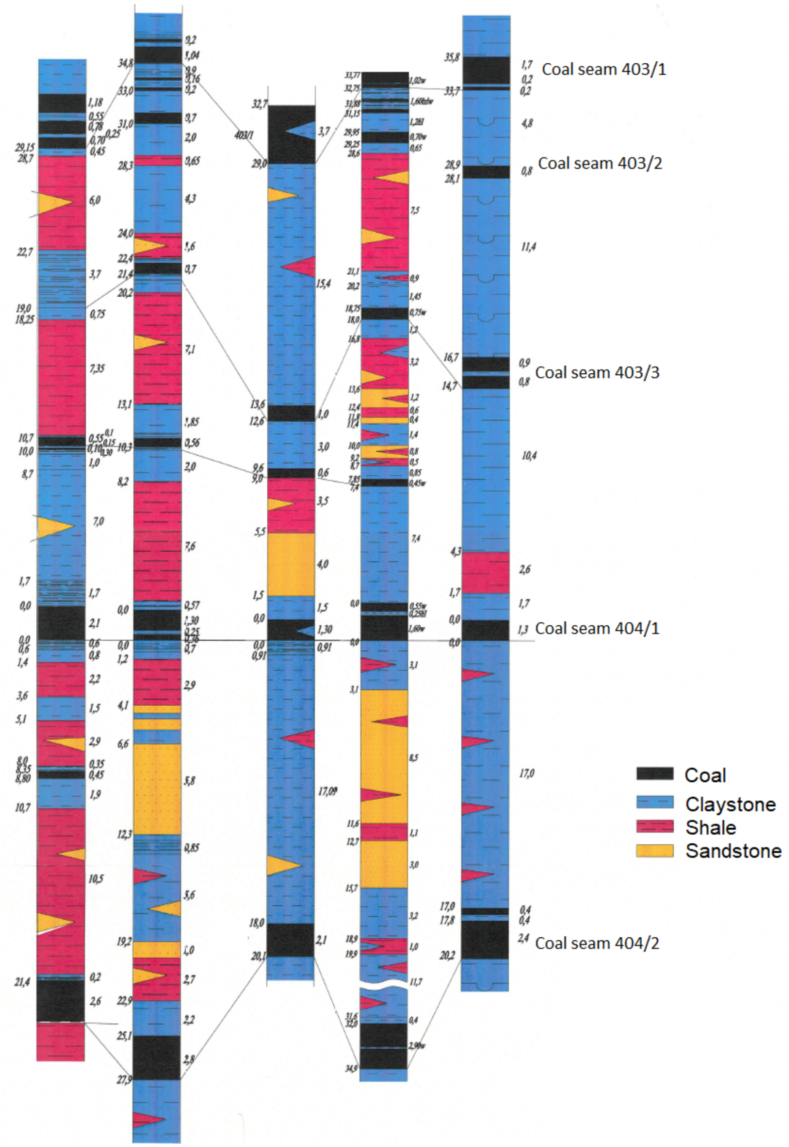

Fig. 2. A fragment of geological profile around the 404/1 coal seam, Pniówek

The compressive strength of coal and surrounding rocks are following:

- Coal 3.0÷15.2 MPa,
- Roof rocks: 32.8÷95.3 MPa,
- Floor rocks: 28.1÷114.8 MPa.

The level of risk of coal and gas outbursts is determined based on the following values: coal methane-bearing capacity in the coal seams, methane desorption intensity index, coal conciseness index, coal cuttings production per one metre of the borehole performed from the roadway face, sorption capacity, effective diffusion coefficient (TABLE 3). Based on these indexes, the risk of coal and gas outbursts in the Pniówek and Budryk coal mines is identified at the highest level (III category).

TABLE 3

An example of coal and gas outburst risk assessment for the 404/1 coal seam, Pniówek

Date of measurements	Coal and gas outburst indexes					
	Methane-bearing capacity [m^3 CH_4/Mg_{daf}]	Desorption intensity, [kPa]	Coal conciseness	Coal cuttings production [dm^3/m long of the borehole]	Effective diffusion coefficient De [cm^2/s]	Sorption capacity [cm^3/g]
09.05.2016	6.8	1.14	0.45	2.6	$0.107 \cdot 10^{-8}$	3.366
16.05.2016	3.5	0.72	0.46	2.5		
03.05.2016	2.5	0.86	0.46	2.5		
01.06.2016	6.2	1.16	0.44	2.7		
08.06.2016	5.6	1.12	0.43	2.7		

4.3. Application of selected methods for prevention and control of coal and gas outburst

4.3.1. Destress blasting applied in the 404/1 coal seam, Pniówek coal mine

Destress blasting was carried out in the roadways in the 404/1 coal seam based on the blasting record. The performance of the destress blasting and the calculation of the volume of released methane after blasting were reported. The developed blasting record assumed the borehole length of 6-9 m and the amount of explosives from 12 to 17.5 kg. The layout of the blasting boreholes is shown in Fig. 3.

TABLE 4 presents the results of the destress blasting conducted in 2 roadways in the 404/1 coal seam. It can be noted that methane-bearing capacity releases are varied from each other after the destress blasting. Blasting no. 1, 6 and 7 were characterised by a low intensity of methane outflow from the roadway face, where the maximum value of methane released from the coal face after destress blasting was max. 0.10 m^3 CH_4 from each tonne (Mg) of coal before the roadway face advance. The blasting no. 2, 3, 4, 5, 8 and 9 were more effective in terms of methane-bearing capacity release, i.e. the maximum value of methane-bearing capacity released from coal seam ranged from 0.45 to 1.16 m^3 CH_4 from each tonne of coal. In the case of the blasting no. 3 and 8, the max. methane concentration was 75.43 and 85.33 m^3 CH_4/min, respectively. It should be noted that in the period of breaks in the progress of excavation, the open coal face causes degasification of the seam, i.e. methane from the destressed zone migrates into the excavation,

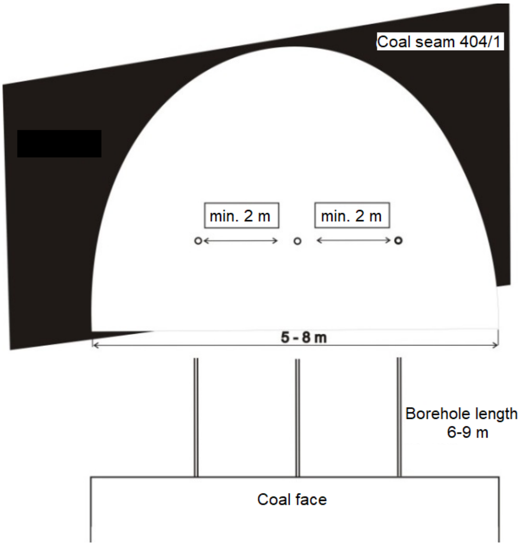

Fig. 3. Layout of boreholes for destress blasting

lowering the methane-bearing capacity in the coal seam. This technical factor affects the degasification ratio of coal and thus, the safety of mining operations. Moreover, the high heterogeneity and significant difference in methane saturation of coal seam along the designed roadway also impact the amount of methane released as a result of destress blasting.

TABLE 5 and Figs 4 and 5 show the results of methane-bearing capacity tests carried out after the destress blasting in the roadway with boreholes of 6 m, 7.5 m and 8 m long. Coal samples were collected from boreholes performed from the roadway face, using the direct drill cuttings method, every 2 m, the length of the borehole from the roadway face. In addition, methane-

TABLE 4

Destress blasting in 2 roadways in the 404/1 coal seam

Amount of explosive material		**Number of boreholes**	**Borehole length**	**Methane-bearing capacity after destress blasting**	**Volume of destressed coal after blasting**	**Amount of destressed coal**	**Amount of methane-bearing capacity released from 1 Mg coal after destress blasting**
—	kg	—	m	m^3 CH_4/min	m^3	Mg	m^3 CH_4/Mg
1	12.0	3	6,0	0,0	45.0	58.50	0.00
2	12.0	3	6,0	26.63	45.0	58.50	0.45
3	15.0	3	7.5/8.0	75.43	60.0	78.00	0,97
4	17.0	3	8.0	57.99	60.0	78.00	0.74
5	17.5	3	9.0	42.90	67.5	87.80	0.49
6	15,0	3	7,5	1.41	56.25	73.13	0.02
7	12.0	3	6,0	5.66	45.0	58.50	0.10
8	14.5	3	7.5	85.33	56.26	73.13	1.16
9	12.0	3	6.0	33.71	45.0	58.50	0.58

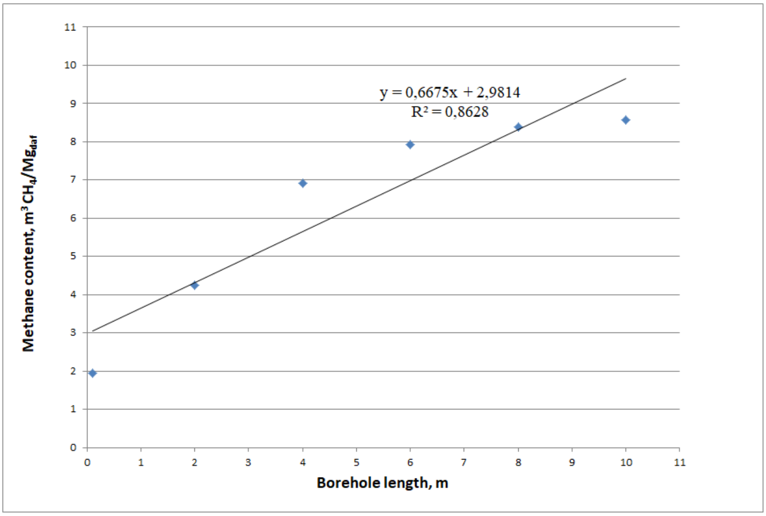

Fig. 4. Methane-bearing capacity in the roadway face of the 404/1 coal seam after destress blasting conducted in the 10-m-borehole

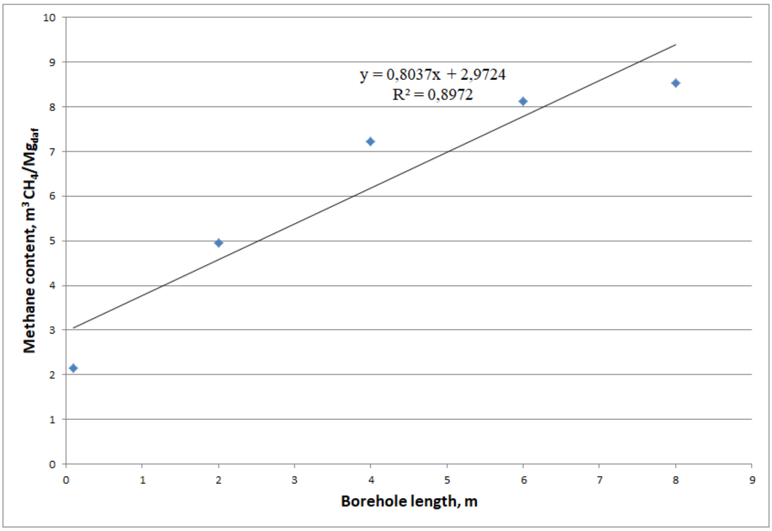

Fig. 5. Methane-bearing capacity in the roadway face of the 404/1 coal seam after destress blasting conducted in the 8-m-borehole

bearing capacity tests were carried out using the coal bit samples method (coal was collected at a distance of 0.1 m from the roadway face). For the coal samples collected from the boreholes methane-bearing, capacity was determined in the laboratory.

The results of the tests showed that the methane-bearing capacity increased along with the length of boreholes. It should be noted that the increase in coal methane-bearing capacity stabilizes at a distance of more than 6 m from the coal face. Coal failure and its degasifying in the coal face were observed greater in the shorter distances to the coal face.

TABLE 5

Results of the methane-bearing capacity tests in the borehole after blasting

Distance from coal face	**Methane-bearing capacity measured in the roadway face of the 404/1 coal seam after destress blasting conducted in the 10-m- borehole**	**Methane-bearing capacity measured in the roadway face of the 404/1 coal seam after destress blasting conducted in the 8-m- borehole**
m	$m^3\ CH_4/Mg_{daf}$	
0.1	1.946	2.150
2,0	4.250	4.960
4,0	6.910	7.230
6,0	7.925	8.134
8,0	8.388	8.542
10.0	8.560	

Based on the results of the laboratory methane-bearing capacity tests and the field methane-bearing capacity tests carried out in the tested boreholes after destress blasting, calculations of the degasification ratio of coal were determined using the following formula:

$$\eta_i = \left(1 - \frac{M_i}{M_0}\right) \cdot 100 \tag{1}$$

where:

M_0 – methane-bearing capacity measured during roadway excavation, $m^3\ CH_4/Mg_{daf}$,

M_i – methane-bearing capacity measured in tested borehole after destress blasting, $m^3\ CH_4/Mg_{daf}$,

i – the distance from the coal face, where the coal sample is collected, m.

Coal degasification ratio in the 404/1 coal seam after destress blasting is presented in TABLES 6 and 7. The results of the calculations confirmed the degasification ratio of coal in seam 404/1 with the increasing distance from the coal face.

TABLE 6

Degasification ratio of coal in the tested 10-m-borehole

Distance from the roadway face	**Methane-bearing capacity measured in the 404/1 coal seam**		**Degasification ratio of coal**
	Before destress blasting	**After destress blasting**	
m	$m^3\ CH_4/Mg_{daf}$	$m^3\ CH_4/Mg_{daf}$	%
0.1	8.93	1.946	78.0
2.0		4.250	52.0
4.0		6.910	23.0
6.0		7.925	11.0
8.0		8.388	6.0
10.0		8.560	4.0

TABLE 7

Degasification ratio of coal in the tested 8-m-borehole

Distance from the roadway face	Methane-bearing capacity measured in the 404/1 coal seam		Degasification ratio of coal
	Before destress blasting	After destress blasting	
m	m^3 CH_4/Mg_{daf}	m^3 CH_4/Mg_{daf}	%
0,1	8.93	2.150	76.0
2.0		4.960	45.0
4.0		7.230	19.0
6.0		8.134	9.0
8.0		8.542	5.0

Based on the results of the destress blasting tests, the following observations can be drawn:

- Intensive release of methane was observed after destress blasting, contributing to partial degasifying of the coal seams in the roadway face and consequently reducing the level of the risk of rock bursts and coal and gas outbursts.
- Reducing the gas potential in the roadway face is considered an effective prevention method limiting the occurrence of gasogeodynamic phenomena.
- The coal methane-bearing capacity tests after destress blasting indicated the length of drilling boreholes in the coal face up to 6 m.
- Reducing the stress and methane concentration in the coal face using explosive blasting eliminates the possibility of the occurrence of the gasogeodynamic phenomenon, thus improving the safety of mining crews.

4.3.2. High-pressure water injection applied in the 401 coal seam, Budryk coal mine

The average methane emission rate at previously mined longwall panel in the 401 coal seam was 110 m^3 CH_4/min, with the maximum recorded value being 134 m^3 CH_4/min. Therefore, longwalls in the 401 coal seam were classified as one of the gassiest longwall panels exploited in Polish hard coal mines. Two high-pressure water injection tests were performed in a roadway of the 401 coal seam, and the effect of water injection on gas release efficiency was analysed. The water injection experiments were conducted in a roadway using the high-pressure pump T-100 with a minimum operating pressure of 10 MPa. The only difference between the two water injection experiments was the length of the boreholes. In the first test, the length of the injec-

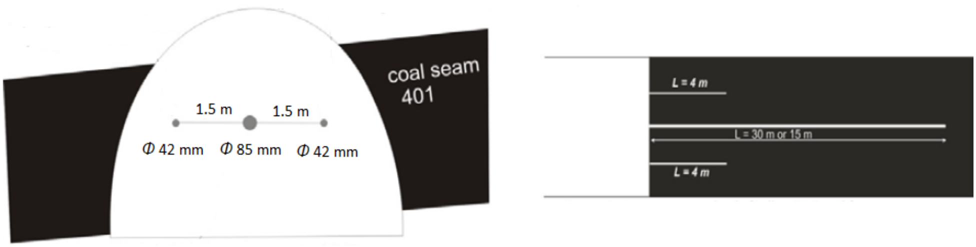

Fig. 6. Drilling layout for water injection tests in the roadway coal face in the 401 coal seam

tion borehole was 30 m, and in the second one, it was 15 m. Fig. 6 presents the water injection tests layout, including one borehole with a diameter of 85 mm (centre) and one borehole with a diameter of 42 mm (left-hand side), drilled at a distance of about 1.5 m from each other into the 401 coal seam to determine its methane-bearing capacity. After injecting the water into the central borehole with a diameter of 85 mm, another borehole with a diameter of 42 mm (right-hand side) was drilled. This borehole was also used to collect coal samples to determine the 401 coal seam methane-bearing capacity.

An automatic methane detector was installed in the studied roadway about 50 meters from the coal face, and data was recorded at the control centre on the surface. In addition, air samples were taken at 30 m distance from the roadway face before, during and after water injection and analysed by chromatography. The increase of methane concentration during the water injection tests into boreholes varied between 0.1 to 0.2%. The total volume of additional methane released into the roadway during 3.5 hours of water injection was calculated as 52.25 m^3.

The methane-bearing capacity of seam 401 before and after water injection at 30 m length was determined from coal samples taken from the side boreholes (with a diameter of 42 mm) shown in Fig. 6. It was found that water injection in the seam reduced the methane-bearing capacity by around 20% at 4 m depth.

The second water injection test was performed with the water injection borehole 15 m long. The results have shown that water injection was more effective in reducing methane-bearing capacity at shorter distances to the coal face, which should guide the design of this practice in coal mines.

The following considerations were pointed out:

- Water injection into the coal bed resulted in increased methane release from the coal face and decreased the methane-bearing capacity of the coal in the roadway face,
- The methane-bearing capacity of coal at 4 m long was reduced by approx. 20%,
- The methane volume released during the injection period of 3.5 h was 52.5 m^3 CH_4,
- Water injection into a 30-m-borehole did not reduce the methane-bearing capacity of the coal seam at greater length,
- Water injection into a 15-m-borehole was more effective in reducing methane-bearing capacity at shorter distances to the coal face. Therefore, the water injection boreholes should not be drilled too deep into the coal seam.

During the field testing of high-pressure water injection, some technical issues were observed:

- preparation of equipment for the use of this technology is labour-consuming, disrupting the mining operation, with low effectiveness,
- the presence of high water pressures caused the leaks in the watering system in seam 401,
- the direct presence of the mining crew in the testing area poses a high safety risk in case of a failure of the high-pressure equipment (up to 20 MPa).

5. Conclusions

The field testing of the selected preventive measures for the prevention and control of coal and gas outbursts, including destress blasting and high-pressure water injection, was carried out in the JSW coal mines. Description of each field experiment and results interpretation were presented and discussed in detail. Based on the results analysis of the conducted field experiments, the following conclusions can be formulated:

- the most effective method for preventing and controlling the threat of gasogeodynamic phenomena is the method of disintegration of the seam and the roadway surroundings, based on destressing and degasifying coal face by destress blasting. Moreover, destress blasting may provoke the occurrence of a gasogeodynamic phenomenon in the excavation without any risk to the mining crew. For this reason, this method is considered safe and optimal for use in the gasogeodynamic hazard-prone conditions of the JSW mines
  – application of high-pressure water injection is characterised by low effectiveness with time and labour-consuming. In addition, it also poses a risk to the mining crew due to possible failure of high-pressure equipment during its application. When compared to the destress blasting method, it was found that the water injection method was not as effective in reducing gas outburst risks.
  – despite the research objectives achieved, further search for effective prevention methods aimed at limiting the impact of gasogeodynamic hazards should be fully justified. Because it is difficult to predict the high-energy seismic events (tremors) that may directly lead to discharge/outflow or/an outburst of significant amounts of methane and other gases into the excavations, as observed by the circumstances of the above-mentioned accident in 2022 in the Borynia-Zofiówka coal mine.
  – extensive field microseismic monitoring (real-time) should be carried out at the mine sites. The outcomes can be effectively used for the preventive measures against coal and gas outbursts. Numerical modelling is considered a helpful tool for solving the geoengineering issues when it couples with the laboratory or field data. Therefore, it is suggested that numerical modelling methods (e.g. the coupled geomechanical and gas flow model, the fracture mechanics-based gas outburst model, and the microseismicity model) should be developed and validated in future research based on the obtained monitoring results.
  – the research results are expected to provide a reference for other mines in Poland, assisting the mine authority in taking proper and sufficient preventive measures to avoid gasogeodynamic accidents.

Declaration of competing interest

The author declares that there are no personal or institutional conflicts of interest associated with this publication, and there is no financial support that could influence its results.

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Data availability

Data will be made available on request.

Reference

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