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Monitoring of aerological risks of accidents in coal mines

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Abstract
The assessment and management of aerological risks in coal mine accidents are based on the development of a data analytics system that hosts design values for various parameters and subsystems related to coal mines, as well as the real-time monitoring of operational parameters through various sensors and devices. This study presents the methodology for monitoring aerological risks. It utilizes mining, geological, and geotechnical conditions for seam extraction, along with statistical data concerning elements of coal mine ventilation and gas drainage systems, to assess aerological risks at individual coal mine functionality levels and individual risk factors. Eight coal mines have been ranked according to their aerological risk level. For rank I, the minimum aerological risk is 0.0769, while the maximum is 0.5698. Rank II is associated with category II mines. Aerological risk for this rank is the lowest and ranges from 0,1135 to 0,3873. In the case of rank III, the minimum aerological risk is 0.057, with a maximum of 0.595. This ranking of coal mines by aerological risk level allows to identify potentially unsafe mines in terms of aerology, and enables us to determine aerological risk mitigation measures (technical, technological, and organizational) for each mine to enhance aerological safety.

Keywords
coal mine, data analytics system, aerological system, aerological risk monitoring, vulnerability of ventilation schemes and types

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ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ В МИНЕРАЛЬНО-СЫРЬЕВОМ КОМПЛЕКСЕ И ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Мониторинг аэрологических рисков аварий на угольных шахтах

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Аннотация
Оценка и управление аэрологическими рисками аварий в угольных шахтах основываются на создании информационно-аналитической системы данных, включающей в себя проектные значения показателей разных уровней и подсистем угольных шахт, эксплуатационные значения показателей, отслеживаемых системой мониторинга в реальном времени с использованием различных датчиков и устройств. В настоящем исследовании представлена методология мониторинга аэрологических рисков. На основании горно-геологических и горнотехнических условий отработки пластов, статистических данных по элементам вентиляционных и дегазационных систем угольных шахт приведены результаты оценки аэрологических рисков по отдельным уровням функциональной структуры угольных шахт, а также по отдельным факторам риска. По уровням аэрологических рисков выполнено ранжирование восьми угольных шахт. Установлено, что минимальное значение аэрологического риска I ранга составляет 0,0769, максимальное – 0,5698. Наименьшие значения аэрологического риска II ранга (0,1135–0,3873) относятся к шахтам II категории. Минимальное значение аэрологического риска III ранга составляет

0,057, максимальное – 0,595. Ранжирование угольных шахт по уровням аэрологических рисков позволяет выявить шахты с низким уровнем аэрологической безопасности и для каждой шахты определить направления технических, технологических и организационно-технических мероприятий по повышению аэрологической безопасности.

Ключевые слова

угольная шахта, информационно-аналитическая система, аэрологическая безопасность, мониторинг аэрологических рисков, уязвимость схем и способов вентиляции

Для цитирования

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Introduction

The trend towards intensified mining and increased underground coal mining in increasingly complex geological, geotechnical, and mining conditions requires a focused and systematic approach to HSE (Health, Safety, and Environment) issues, with aerological safety being a major concern.

Failures in the aerological safety system may result from an unfavourable combination of various factors. These factors include fluctuating gas emissions from the seam under development, worked-out space, unsteady gas dynamic processes [1, 2], fluctuations in air discharge, unplanned change in the resistance of workings, and failing ventilation systems [3, 4], fluctuations in mining, geotechnical, and geological conditions, as well as changing physical and technical properties of the formation (such as gas content, gas permeability, gas recovery factor, formation porosity and permeability, and dust generation capacity), geological disturbances, and more [5, 6]. When investigating the regularity of aerological safety system failures, some of the above-mentioned parameters are often treated as continuous random variables, rather than discrete ones, which can take any value within a given range, and are not known in advance.

Unsteady dynamic processes (involving gas-dust-heat emissions) in mines are the primary causes of the loss of operability in aerological safety management systems. Changes in mining, geological, and geotechnical conditions during the development of coal seams can lead to risk of explosions, ignitions of dust-gas mixtures, fires, rock bumps, spontaneous coal ignition, and other types of accidents [7, 8].

The properties and conditions of coal seams and host rocks determine the sources and locations of gas emissions, dust formation, sudden outbursts of coal, rocks, and gas, spontaneous coal ignition, and rock bumps [9, 10]. Therefore, a thorough study of the processes in coal formations is necessary to select an appropriate technical solution for the aerological safety management system. The effectiveness of such technical solutions directly depends on the reliability of and prompt access to data that characterize many technological processes [11, 12]. Knowledge of process patterns helps assess the importance and weighting factors of safety system mitigation measures. For example, gas drainage (early preventive, preliminary, in-seam) is crucial when mining coal seams with high gas concentration that are prone to dust explosions. [13, 14]. The order in which seams are mined in the formation is also important, followed by the selection of ventilation schemes, ventilation with gas-suction units, and more [15, 16].

As coal seams are mined deeper, roof-to-floor convergence intensifies, leading to aerodynamic aging of workings that impacts the performance of the aerological safety system [17, 18].

The management of gas emissions plays an important role in aerological safety and involves a series of measures to redistribute or alter gas emission flows. The purpose of gas emission management is to enhance the ventilation of mine workings, improve the ventilation of working areas, preparatory workings, and the mine as a whole.

Key measures in gas emission management include changing ventilation schemes, modifying the aerodynamic resistance of mine workings using ventilation facilities and devices, selecting the appropriate order for mining seams in the formation and mining systems; implementing special ventilation for mined-out space, using gas-suction units, degassing mine workings and seams, gas-draining mine workings and holes, and more.

To study the interaction between gas and coal and the mechanism of spontaneous ignition in the mined-out space, numerical simulation of gas explosion risks can be applied [19, 20].

Methodology for monitoring aerological risks

The assessment of aerological safety system performance can be achieved through the evaluation of aerological risks at various levels and subsystems within coal mines. This includes risks categorized as I, II, and III-rank risks, risks of high gas concentration, risks of reusing mine workings, risks linked to the impact of heavy hydrocarbons (HCs), as well as composite and expected estimated risk factors (Table 1). Accident-related aerological risk monitoring at coal mines can be effectively carried out using predictive analytics based on available data.

Predictive analytics uses collected, processed, and structured data to create scenarios for the further development of events of interest. Consequently, the primary challenge in this regard pertains to data retrieval, processing, scenario development, and the interpretation of obtained results to make informed management decisions related to aerological safety.

Data collection can be quite complex and relies on personnel involvement, and manual work, which is still not highly reliable and carries a high risk of errors. [21, 22]. To improve the reliability of the obtained solutions, ensemble methods, comparing basic individual solutions, are applied [23, 24].

There are four types of data analytics:

1. Descriptive analytics, which involves collecting data over the monitoring of the object (target). The gathered data are analyzed to address the question, "What has happened?" In the context of coal mines, descriptive analytics may be employed to collect the data pertaining to accidents in coal mines, including their causes, extent of damage, mining, geological, and geotechnical conditions at the time of the accident, and accident investigation data, etc. [25, 26].

2. Diagnostic analytics involves diagnosing the causes of the event under study using statistical analysis. All collected data can be categorized into separate groups and subgroups, with an analysis of data correlation. Significant factors influencing the outcome of the event are identified. Diagnostic analytics can group statistical data based on seam properties, coal grades, mining depth, methane

Table 1

Operational parameters of aerological risks

Rank of aerological risk	Operational parameters of aerological risks	Notes
I	Rank I aerological risk $R_{a\,m}$	Depends on specific dust emission, relative gas content, mine ventilation scheme and method, vulnerability of main ventilators
II	Rank II aerological risk $R_{a\,mw}$	Depends on specific dust emission, relative gas content, scheme and method of mine wing ventilation, vulnerability of ventilation structures
II	Rank III aerological risk R_a	Depends on specific dust emission, relative gas content, vulnerability of working area
	Aerological risk of accidents *R hHCwa* in working areas induced by heavy HCs impact	Depends on heavy HCs content in residual coal gases (grades D, G, DG, GZh, Zh, KZh, K, KS, OS), methane concentration in coal seams, specific dust emission, mining depth and technological vulnerability of working area
	Estimated composite aerological risk Q_{es}	Depends on specific dust emission, relative gas content, vulnerability of working area; accounts for seam ignitibility and susceptibility to rock bump, application of gas drainage, gas sucking units and gas draining drive
	Risk of high gas concentration in the working area R_{hgca}	Takes into account average statistical data of failure rates in mine workings and the working area ventilation scheme
	Risk of high gas concentration in the reused working area R_{hgca}, day^{-1}	Takes into account average statistical data of failure rates in mine workings, the working area ventilation scheme, and workings reuse
	Aerological risk of accidents in preparatory workings induced by heavy HCs impact R_a	Depends on specific dust emission, relative gas content, vulnerability of preparatory workings
	Aerological risk of accidents *R hHCwa* in preparatory workings induced by heavy HCs impact	Depends on heavy HCs content in residual coal gases (grades D, G, DG, GZh, Zh, KZh, K, KS, OS), methane concentration in coal seams, specific dust emission, mining depth, and technological vulnerability of preparatory workings
	Estimated aerological risk of accidents in preparatory workings Q_{es}	Depends on specific dust emission, relative gas content, vulnerability of preparatory workings; accounts for seam ignitibility and susceptibility to rock bump, gas draining

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concentrations in seams, dust hazard factor, load on the mine face, absolute methane-bearing capacity of mines, the rate of face advance, ventilation schemes and types in mines and working areas, parameters of the main and local fans, and more.

3. Predictive analytics predicts the further development of events based on pre-processed data obtained through descriptive and diagnostic analytics. For example, predictive analytics can analyze the aging of mine workings, allowing for the properly scheduling of preventive maintenance in the workings, thereby reducing aerological risks in mine ventilation systems [4, 27].

4. This type of analytics enables the understanding and justification of steps to be taken to prevent undesirable events. One can call it prescriptive analytic. In the context of the aerological safety system, these steps encompass technical solutions aimed at managing coal seam properties and condition (such as pre-moistening, advance, preliminary, in-seam gas drainage, and emergency shut-down system parameters, etc.), as well as technical and technological measures.

Therefore, in order to assess the performance of the aerological risk management system, a comprehensive statistical dataset is required, relating to ventilation system components (main fans, gas-sucking units, local site fans, vent doors, and airlocks, crossings, main downcast and air shafts, longwalls, gas-intake pipelines, ACS, etc.), as well as mining and geotechnical conditions (longwall productivity, seam thickness, rock strength, workings protection technology, mining depth, mining system, etc.) (Table 2).

Results and discussion

Table 3 presents the computed results for aerological risk of all three ranks (I – for the entire mine, II – for the mine wing, III – for working areas and preparatory workings). The additional risks estimates were made for the working areas, including the risk of high gas concentrations in the areas due to their ventilation scheme, the risk of high gas concentrations of the working reuse, as well as the risk of accidents induced by heavy HCs (based on coal grades). An expected composite aeroligical risk was also calculated for the working areas, assuming gas drainage is applied. These estimations were made for the case of maximum mining depth. It's important to note that the expected risk considered seam ignitability and susceptibility to rock bursts. For mines No. 2 and 8, gas drainage efficiency was 0.95 and 0.9, respectively, while the average gas drainage efficiency of 0.6 was used for the rest of the mines.

For the preparatory workings, estimates were made for the accident risk caused by heavy HCs and the aerological risk, assuming gas drainage measures are implemented.

In the study of eight analyzed mines, three mines are categorized as methane hazard category II, while five mines are super-category. The analysis of the data presented in Table 3 reveals the following findings: for I rank aerological risk, the minimum risk is 0.0769, and the maximum is 0.5698, representing a 7.4-fold difference between the two extremes. The minimum risk is observed in category II mines (No. 3, 4, 5), indicating low risk, with the threshold for safe operations set at a maximum of 0.15.

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Among the super-category mines, the risks vary significantly. Two mines (No. 1 and 6) exhibit moderate risk (reduced operational safety with a risk range of 0.15–0.3), two mines (No. 7 and 8) show high risk (poor operational safety level with a risk higher than 0.3 but lower than 0.5, and one mine (No. 2) faces an emergency-level risk, which could potentially lead to an accident, with a risk exceeding 0.5.

The analyzed geological, geotechnical, and mining factors (as detailed in Table 2) revel that rank I risks are less affected by the scheme and method of mine ventilation, air supply availability in mines, external and internal air leakage, but more affected by the absolute methane content in mines and main fans pressure. For Mine No. 8, these values are particularly high, with an absolute methane content of 239 m^3/min and a main fan pressure of 820 daPa. Notably, this mine has the largest number of ventilation facilities compared to others (190).

The estimated rank II aerological risk shows a range of conditions, from the best (low depression of haulage and ventilation drifts, ventilation stability in the mine wing, low impact of thermal depression in inclined workings, low impact of ventilation method on gas concentration in the workings at the main fan emergency shut-down, low impact of ventilation facilities on ventilation stability) to the worst. In the worst conditions, the factors listed in brackets above have a more significant impact on the vulnerability of ventilation schemes, methods, and facilities in mine's wings.

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Table 2

Aerological risk factors

Aerological risk factor	Coal mine No							
	1	2	3	4	5	6	7	8
Gas hazard category	Super-category	Super-category	CategoryII	CategoryII	Category II	Super-category	Super-category	Super-category
Seam susceptibility or rock burst	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Seam ignitibility	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dust hazard	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Coal grade	G	G, GZh	D, DG	D	D, DG	D, DG	D, DG	G
Methane content in coal seams, m^3/t	10–15	13–15 17–20	4–6 4–9		0–5	0–5 0-6	10–15	14–20
Mining depth, m	130–480	420–660	400	400	240–290	540	350–440	540
Mine ventilation pressure, daPa	292	820	290	220	295	265	306	320
Mine ventilation stability	Category II	Category II	Category II	Category II	Category II	Category II	Category II	Category II
Mine ventilation scheme	Combined	Radical	Combined	Radical	Combined	Combined	Combined	Combined
Mine ventilation method	Blowing	Combined	Combined	Combined	Blowing	Blowing	Blowing	Combined
Stability of combined operation of main fans	Low vulnarable	Highly vulnerable	Low vulnarable	Low vulnarable	Low vulnarable	Low vulnarable	Highly vulnerable	Highly vulnerable
Mine air availability	1.33	1.47	1.2	1.17	1.27	1.13	1.05	1.46
External air leakage (estimated), %	13.14	13.45	14	14	10	10		12.9
External air leakage (actual), %	16.69	8.43	11	9.8	5	6	5.77	12.9
Stability of mine wing ventilation	Category II	Category II	Category II	Category II	Category II	Category II	Category II	Category II
Scheme of mine wing ventilation	Central-dual	Radical	Central-dual	Radical	Central-dual	Central-dual	Central-dual	Central-dual
Method of mine wing ventilation	Blowing	Blowing	Blowing	Blowing	Blowing	Blowing	Blowing	Blowing
Impact of ventilation structures on ventilation stability	Low vulnerable	Highly vulnerable	Low vulnerable	Low vulnerable	Low vulnerable	Low vulnerable	Low vulnerable	Low vulnerable
Per face output t/day	6300	13500	13300	10900	7500	13400	20900	6600
Absolute methane content in mine, m^3/min	109	239	28.34	32	17	16.6	181	108
Face performance rate, m/day	7	7 9.5	9 9.5	5	7.2	5.2	8.3	5.73
Face length, m	230	365 365	300 300	350	300	410	400	300
Extraction panel length, m	1960	2100 2550	2850 2800	2850	2500	2300	3000	2100
Gas drainage	No	Yes	Yes	Yes	No	No	Yes	Yes
Number of stopes	1	2	2	1	1	1	1	1

Table 3

Estimated aerolological risks

Aerological risk parameter	Coal mine No							
	1	2	3	4	5	6	7	8
Rank I aerological risk $R_{a\,m}$	0.2074	0.5698	0.0974	0.0769	0.1159	0.2134	0.3831	0.3532
Rank II aerological risk $R_{a\,wm}$	0.2457–0.6931	0.2125–0.6166	0.1373–0.3873	0.1135–0.3322	0.1373–0.3873	0.2457 0.6931	0.2457 0.6931	0.2457 0.6931
Rank III aerological risk R_a	0.425	0.272; 0.272	0.3325; 0.3325	0.057	0.3325	0.595	0.595	0.255
Aerological risk of accidents *R hHCwa* in working areas induced by heavy HCs impact	0.5464–0.9255	0.5551–0.94; 0.5813–0.9846	0.3026–0.6548	0.2858–0.7317	0.2385–0.5297	0.2628–0.5547	0.5372–0.9256	0.5551–0.94
Estimated composite aerological risk Q_{es}	0.4675	0.2346; 0.2346	0.3358; 0.3358	0.0576	0.3857	0.6902	0.6009	0.2231
Risk of high gas concentration in the working area R_{hgca}	0.189	0.065 0.065	0.189 0.189	0.097	0.189	0.189	0.189	0.097
Risk of high gas concentration in the reused working area R_{hgca} day^{-1}	0.2403	0.1244 0.1244	0.2403 0.2403	0.155	0.2403	0.2403	0.2403	0.1244
Aerological risk of accidents in preparatory workings R_a	0.17–0.85	0.17–0.85	0.095–0.475	0.095–0.475	0.095–0.475	0.17–0.85	0.17–0.85	0.17–0.85
Aerological risk of accidents *RhHC pw* in preparatory workings induced by heavy HCs impact	0.0696–0.9846	0,0696–0.9846	0.0454–0.8185	0.0454–0.9692	0.0432–0.7996	0.0476–0.8373	0.0675–0.9692	0.0696–0.9846
Estimated aerological risk in preparatory workings Q_{es}	0.187–0.935	0.1466–0.7331	0.096–0.4798	0.096–0.4798	0.1102–0.551	0.1972–0.986	0.1717–0.8585	0.1488–0.7438

The lowest rank II aerological risk corresponds to category II mines and is 1.78 times lower for both the best and the worst conditions.

The minimum rank III aerological risk is 0.057, and the maximum is 0.595, which is 10.4 times higher than the minimum. The minimum risk refers to the category II mine No. 4 and is classified as a low risk.

Two mines (No. 2 and 8) have estimated moderate risk, two mines (No. 1 and 5) exhibit high risk, and two mines (No. 6 and 7) have an emergency-level risk, potentially leading to accidents due to a U-ventilation in the working areas with partial dilution of harmful agents at the emission sources. The ventilation scheme in mines No. 6 and 7 is quite intricate because of a diagonal connection, which can lead to air flow-back under specific conditions.

Aerological risks of accidents in working areas, induced by heavy HCs in coal residual gases, are more likely when mining coal seams of grades D, G, DG, GZh, Zh, KZh, K, KS, or OS, particularly with a high load on the mining face at a high mining face advance rate. The highest heavy HCs-related risk of accidents was observed in mine No. 2, which is developing a GZh gradeseam [28].

The expected composite aerological risk takes into account additional hazards, such as coal seam susceptibility to rock bumps and spontaneous ignition, as well as gas release management measures like degassing, gas-draining workings, and gas-suction units. Depending on the mining, geotechnical, and geological conditions, the value of the expected composite risk may increase or decrease. Generally, the expected risk has slightly increased for all mines, except for mines No. 2 and 8, which develop formations not prone to spontaneous ignition.

Histograms for five types of risks in the analyzed mines (Fig. 1) were plotted based on the data provided by Table 3. These histograms demonstrate that three of the mines (No. 3, 4, 5) exhibit low aerological risks, falling within the normal safety range, even though the risks in their working areas slightly exceed this range. There is a return-flow ventilation scheme with diagonal connections there, but due to the low absolute gas content (from 17 to 28.4 m3/t), these risks are not very dangerous. In general, all the three mines are characterized by low aerological risks.

The data from Table 3 was used to generate histograms representing five types of risks for the examined mines (Fig. 1). Analysis of the data reveals that three of these mines (No. 3, No. 4, No. 5) exhibit low aerological risks that fall within the acceptable safety range. Slight elevation of risks is observed in their working areas, attributed to their use of

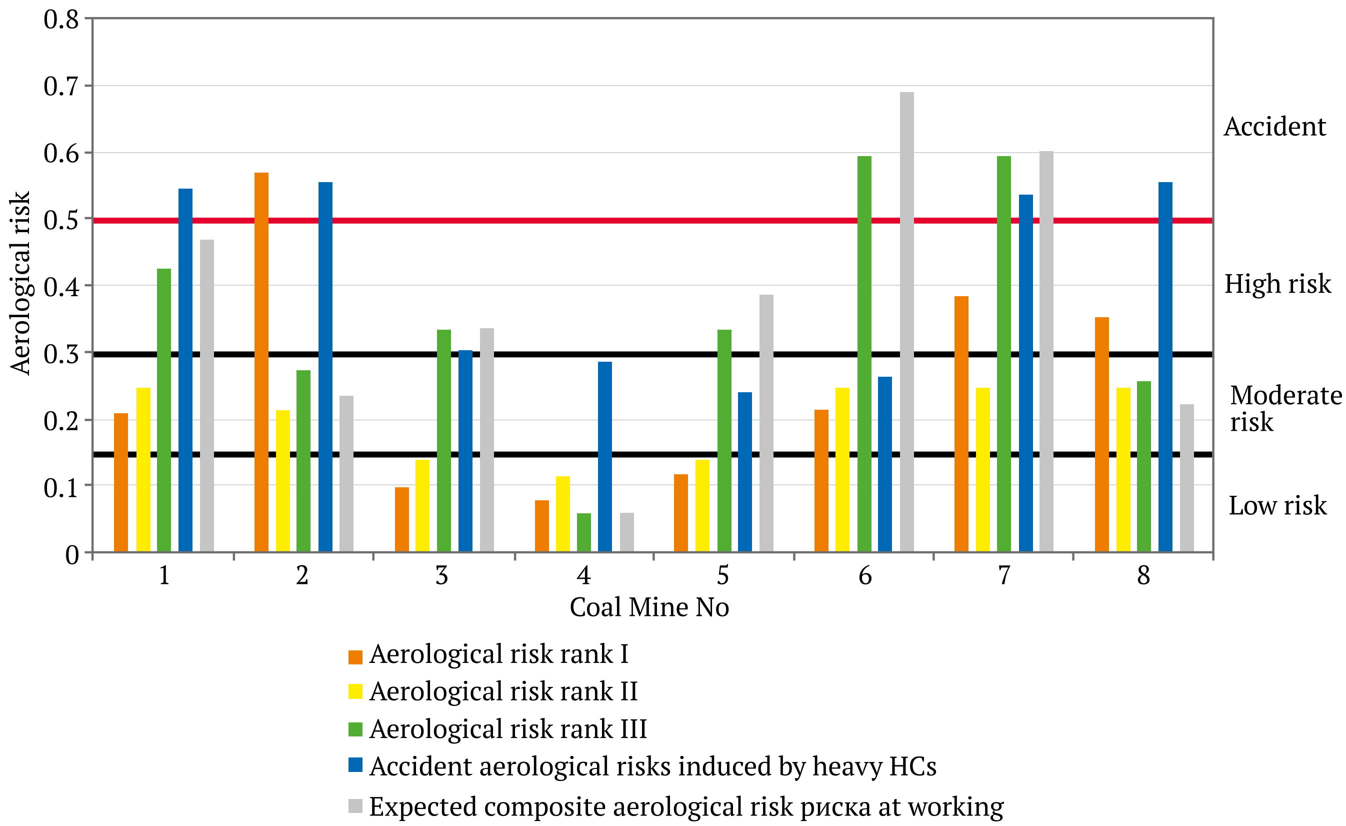

Fig. 1. Comparative assessment of aerological risks in coal mines

return-flow ventilation schemes with diagonal connections. However, the absolute gas content in these areas is low (ranging from 17 to 28.4 m^3/t), making these risks relatively insignificant. In summary, these three mines can be classified as having low aerological risks.

The analysis of the remaining five mines, which are categorized as super-category mines, revealed high risks. These risks primarily result from the development of seams containing heavy HCs in residual coal gasses, which are prone to spontaneous ignition and rock bursts. These risks are exacerbated by vulnerable ventilation schemes that fail to ensure complete dilution of harmful agents at their emission sources (mines No. 6, 7). For mine No. 2, while the risks in working areas are low, the risks of the highest rank are of emergency level for the mine as a whole, indicating an urgent need for technical solutions in the mine ventilation scheme. The lowest aerological risks, of moderate degree, are characteristic of mines No. 8 and 1, signifying a reduced safety level and the necessity for ongoing monitoring of geological, geotechnical, and mining parameters that are crucial for the mine's aerological safety system.

Conclusion

The data analytics system for coalmines plays a pivotal role in assessing aerological risks and aerological safety system. The system's database should contain both the design values of various parameters of coalmine subsystems and the real-time operational values monitored by various sensors and devices [29, 30]. Aerological safety can be achieved through an analytical tool that assesses aerological risk for individual levels of the coal mine's functional structure and individual risk factors. These factors include the risks associated with high gas concentration at the working site and in reused workings, as well as the risk of heavy HCs impact, among others.

The final stage of aerological risk assessment involves computing expected values, considering technical and technological measures to eliminate or mitigate the identified negative factors, as well as accounting for hazards like rock bursts and spontaneous coal ignition. Ranking coal mines by their aerological risk levels enables the identification of mines with poor aerological safety and the development of organizational and technological measures to improve aerological safety.

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