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Higher rank aerological risks in coal mines

S.V. Balovtsev

National University of Science and Technology MISIS, Moscow, Russian Federation

balovcev@yandex.ru

Abstract

The steady trend of complication of mining and geological factors in underground coal mining and at the same time the processes of mining intensification cause growth of dynamic manifestations of natural factors of mining, such as sudden coal and gas outbursts, rock bursts, rock collapses, leading to gas and dust explosions and fires. This requires developing the models of different phenomena manifestation risks, which enable improving the process safety of a mining enterprise. In this study, based on the methodology of aerological risk assessment in coal mines, a structural analysis of aerological risks was carried out. The criteria of hazard of mining-geological and mine engineering factors and vulnerability of schemes and methods of ventilation, ventilation facilities, and main fans were developed. A hierarchical structure of aerological risks of higher ranks was developed. The presented risk structure allows determining the area of superposition of hazards of coal mining and vulnerability of ventilation systems for each mine and its individual facilities, as well as quantifying these areas in the form of aerological risks. The ranges of aerological risk values of higher ranks for super-category mines and mines hazardous by sudden coal and gas outbursts for different ventilation modes were established. The presented methodology enables forecasting and reducing aerological risks in course of designing, operation, liquidation, and conservation of coal mines.

Keywords

coal mine, aerological safety methodology, hierarchical risk structure, aerological risk ranks, methane, coal dust, hazard criteria, vulnerability of ventilation systems

For citation

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ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ В МИНЕРАЛЬНО-СЫРЬЕВОМ КОМПЛЕКСЕ И ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Аэрологические риски высших рангов в угольных шахтах

С.В. Баловцев

Университет науки и технологий МИСИС, г. Москва, Российская Федерация

balovcev@yandex.ru

Аннотация

Устойчивая тенденция перехода к осложнению горно-геологических факторов при подземной добыче угля и одновременно при этом процессы повышения интенсификации горных работ вызывают рост динамических проявлений природных факторов горного производства, таких как внезапные выбросы угля и газа, горные удары, обрушения пород, приводящие к взрывам газа и пыли, пожарам. Это приводит к необходимости разрабатывать модели рисков проявления разных явлений, что позволяет повысить технологическую безопасность горного предприятия. В представленном исследовании на основе методологии оценки аэрологических рисков в угольных шахтах проведен структурный анализ аэрологических рисков. Сформированы критерии опасности горно-геологических и горнотехнических факторов и уязвимости схем и способов вентиляции, а также вентиляционных сооружений и вентиляторов главного проветривания. Разработана иерархическая структура аэрологических рисков высших рангов. Представленная структура рисков позволяет для каждой шахты и отдельных ее объектов определить область пересечения опасных факторов угледобычи и уязвимости систем вентиляции, а также количественно оценить эти области в виде аэрологических рисков. Установлены диапазоны значений аэрологического риска высших рангов для сверхкатегорийных шахт и шахт, опасных по внезапным выбросам угля и газа, для разных вентиляционных режимов. Представленная методология позволяет осуществлять прогнозирование и снижение аэрологических рисков при проектировании, эксплуатации, ликвидации и консервации угольных шахт.

Ключевые слова

угольная шахта, методология обеспечения аэрологической безопасности, иерархическая структура рисков, ранги аэрологических рисков, метан, угольная пыль, критерии опасности, уязвимость схем вентиляции

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Introduction

The problem of ensuring aerological safety of coal mines has a complex, systemic nature. The solution of the problem requires the effectiveness of implementation of an interrelated set of technical, technological, engineering, and information systems, production activities, and skilled personnel, aimed at reducing not only the level of aerological risk, but also other types of risk, such as geotechnical, geomechanical, hydrogeological, organizational, and technical [1–3].

The main hazards in coal mines are dust and gas, they lead to the most severe types of accidents, gas and dust explosions and fires [4, 5]. In recent years in the Russian Federation and abroad, an intensive search for new, more effective means and methods of explosion protection of mine workings, meeting modern requirements and technical capabilities is carried out [6–8].

As a result of these studies, the following areas have been studied in greater depth with the use of numerical modeling:

– methane distribution in areas of intensive mining in coal mines [9–11];

– properties of multicomponent explosive gas-air mixtures in a mine atmosphere [12];

– processes of coal dust deposition in mine workings [13, 14].

In the current conditions of high loads on the mining faces, an intensive in-situ degassing of mines is carried out to ensure the safety of high-productive faces, as exemplified by the Mine named after S.M. Kirov (Leninsk-Kuznetsky) [15]. In [16, 17] successful solutions for degassing of mine working fields and reduction of dust formation in longwall faces are presented.

In the conditions of development of high-gas-bearing coal seams, hazardous by the dust factor, it is impossible to ensure aerological safety without applying degassing and technologies of dedusting of coal seams [18, 19]. However, ventilation is still the primary method for gas and dust hazard control in coal mines. At a sudden stop of the main fan in fiery mines, if turning on the standby fan is impossible, all work in the mine areas must be stopped, electrical equipment should be de-energized, all personnel should be relocated to the air shaft in 30 minutes, and at faults, which require a long time to fix, the personnel should be delivered to the surface. Therefore, for effective selection of air-supply schemes in coal mines, the issues of evaluation and analysis of aerodynamic parameters of air streams require continuous research [20–22]. It is necessary to calculate the stability of air streams in mine workings based on quantitative parameters, ventilation directions, and the factor of thermal drop of ventilation pressure [23]. Aspects of aerological safety, based on quantitative assessments of accident risks, find their application in the implementation of the projects of digital transformation and intellectualization of mining systems [24, 25]. This, in turn, determines the promising directions of coal mines technological structure development [26, 27], allows developing evolutionary models of the safety system of coal mines based on multifactor modeling, including with the use of intelligent algorithms and methods [28, 29].

Methodology for aerological risk assessment

In order to successfully solve many design and production issues related to ensuring aerological safety of coal mines at the proper level, it is necessary to analyze and process huge flows of structured information, which are interconnected hierarchically and represent a kind of information architecture of aerological safety. For this architecture, hazard criteria for the system as a whole and the vulnerability of its elements should be prescribed, in accordance with which engineering solutions to prevent the impact of hazardous mining and geological and mine engineering factors of coal mining should be developed. The ultimate goal of building an aerological safety architecture is to quantify aerological safety and identify ways to improve it.

One of the quantitative characteristics of aerological safety are aerological risks, which express a probabilistic measure of the hazard of accidents due to unsatisfactory composition of the mine atmosphere, occurring in ventilation schemes of a certain vulnerability. As a result of this research, hazard and vulnerability criteria were formed in the structure of aerological risks, covering the entire aerological safety architecture. This made it possible to combine all the studies conducted and quantify both the aerological safety of the mine as a whole and its individual components.

The hierarchical structure of aerological risks was created from particulars to generals according to "the bottom-up approach" from the individual facilities of the mine to the mine as a whole. For this purpose, the entire mine was divided into three areas based on the level of operation of its facilities. First, the concept of aerological risks was developed for working areas and development workings, which took the lower position in the ranking system and were defined as rank III risks. Aerological risks of failures capable to lead to accidents within mine wings took the middle position in the ranking structure and were defined as rank II risks. Aerological risks of failures capable to lead to accidents of the entire mine scale took the top position in the ranking structure and were defined as rank I risks.

Aerological risks of rank III were investigated in earlier works of the author, and based on these studies findings, the following was developed:

– the hierarchical structure of risks of this rank;

– the hazard criteria of factors and vulnerability of ventilation schemes at the level of areas and development workings;

– the methods of aerological risk assessment for working areas and development workings;

– the methodology for calculating the predicted values of risk when using measures to manage gas release through degassing of high-gas-bearing coal seams, hazardous in terms of dust explosions;

as well as:

– quantitative comparison of gas hazard risks of mine workings with different ventilation schemes was obtained; the influence of mine workings aerodynamic ageing on the risks of area and permanent mine openings with different methods of their protection was assessed;

– values of rank III aerological risks were calculated for a number of mines in the Kuznetsk Basin.

Since the structure of rank III risks has already been given in previous publications of the author, it is necessary to focus in more detail on the structure of risks of ranks II and I.

Hazard and vulnerability indicators in the structure of risk ranking I and II

The basic scheme of the structures of all ranks is the same, almost the same set of mining hazards is used, but the areas of impact of these factors at each level are different. This makes it necessary to establish different types and levels of ventilation vulnerability and, correspondingly, different levels of negative consequences of ventilation failures. The main hazard indicators in the structure of aerological risks of all ranks are gas and dust hazards as well as rock temperature. Assessment of the explosiveness of coal mines includes an assessment of the explosive properties of multicomponent gas-dust-air mixtures containing heavy hydrocarbons in the mine atmosphere. For rank II risks, the most hazardous layer of a mine wing is selected, while for rank I risks, the most hazardous seam of the mine is selected.

Aerological risk of rank I $R_{\alpha m}$ is calculated by the formula

$$R_{\alpha m} = \lambda_m v_m, \quad (1)$$

where λ_m is accident hazard factor for a mine; v_m is mine ventilation vulnerability factor;

$$\lambda_m = (\delta_{dm} q_{dm} + \delta_{gm} q_{gm})\lambda_0, \quad (2)$$

where δ_{dm} is factor of significance of the dust factor for a mine; q_{dm} is value of the mine hazard indicator code based on specific dust emission; δ_{gm} is factor of significance of the gas factor for a mine; q_{gm} is value of the mine hazard indicator code based on relative gas content; λ_0 is normalizing multiplier;

$$v_m = (\varphi_{vs}\alpha_{vs} + \varphi_{vm}\alpha_{vm} + \varphi_{mf}\alpha_{mf})v_0, \quad (3)$$

where φ_{vs} is vulnerability significance factor of the mine ventilation scheme; α_{vs} is vulnerability code value of the mine ventilation scheme; φ_{vm} is vulnerability significance factor of the mine ventilation method; α_{vm} is vulnerability code value of the mine ventilation method; φ_{mf} is vulnerability significance factor of the main mine fans; α_{mf} is vulnerability code value of the main mine fans; v_0 is normalizing multiplier.

By decomposing the values of the indicators in formula (3), we obtain:

$$\varphi_{vs} = (\varphi_{spd}\alpha_{spd} + \varphi_{di}\alpha_{di} + \varphi_{vsi}\alpha_{vsi})v_1, \quad (4)$$

where φ_{spd} is factor of significance of the influence of the mine ventilating pressure drop value on the vulnerability of the mine ventilation scheme; α_{spd} is vulnerability code value of the mine ventilation scheme depending on the value of the mine ventilating pressure drop; φ_{di} is significance of the degree of influence of direction of fresh air and return air on air leaks; α_{di} is vulnerability code value of the mine ventilation scheme depending on the degree of influence of direction of fresh air and return air on air leaks; φ_{vsi} is significance of the influence of ventilation stability on the vulnerability of the scheme; α_{vsi} is vulnerability code value of the mine ventilation scheme depending on the mine ventilation stability; v_1 is normalizing multiplier;

$$\varphi_{vm} = \varphi_{vmgh}\alpha_{vmgh}v_2, \quad (5)$$

where φ_{vmgh} is factor of significance of the degree of influence of the ventilation method on the workings gas hazard at a sudden stop of the main fan; α_{vmgh} is value of the vulnerability code of the degree of influence of the ventilation method on the workings gas hazard at a sudden stop of the main fan; v_2 is normalizing multiplier;

$$\varphi_{mf} = (\varphi_{mfs}\alpha_{mfs} + \varphi_{mfp}\alpha_{mfp} + \varphi_{mfl}\alpha_{mfl})v_3, \quad (6)$$

where φ_{mfs} is factor of significance of the degree of influence of the stability of the joint operation of the main fans; α_{mfs} is value of the code of the degree of influence of the stability of the joint operation of the main fans; φ_{mfp} is factor of significance of the degree of the mine provision with air; α_{mfp} is value of the code of significance of the degree of the mine provision with air; φ_{mfl} is factor of significance of the magnitude of the external air leakage; α_{mfl} is value of the code of significance of the magnitude of the external air leakage; v_3 is normalizing multiplier.

The presented indicators of hazard and vulnerability in the structure of the risks of rank I are hierarchically linked in the functional system shown in Fig. 1.

The vulnerability of ventilation at the rank I risk level includes: the vulnerability of mine ventilation schemes and methods and the vulnerability of main fans. The vulnerability of mine ventilation schemes is determined by: the magnitude of the mine ventilating pressure drop, the degree of influence of the fresh air and return air movement directions on air leakage; the stability of mine ventilation. The vulnerability of ventilation methods at the level of rank I risks includes: the degree of influence of the method of ventilation on the workings gas hazard in the case of stopping the main fans.

The vulnerability of main fans is determined by: the stability of joint operation of main fans, the degree of the mine provision with air, the magnitude of external air leakage.

The vulnerability of ventilation at the rank II risk level includes: the vulnerability of schemes and methods of ventilation of mine wings and the vulnerability of ventilation facilities. In turn, the vulnerability of ventilation schemes of mine wings is determined by: the magnitude of the ventilating pressure drop in haulage and ventilation main drifts, which depends on the type of drift (field, seam), method of protection (pillar-pillar, pillar-mined-out space, mined-out space-mined-out space); the degree of influence of the direction of fresh air and return air motion on air leakage; stability of ventilation of a mine wing; the value of thermal drop of ventilation pressure in inclined workings.

The vulnerability of ventilation methods at the level of rank II risks includes: the degree of influence of the method of ventilation on the workings gas hazard in the case of stopping the main fans. The vulnerability of ventilation facilities is determined by the degree of their effect on the stability of ventilation.

Aerological risk of rank II is calculated by the following formula:

$$R_{\alpha mw} = \lambda_{mw}v_{mw}, \quad (7)$$

where λ_{mw} is the accident hazard factor for a mine wing; v_{mw} is the vulnerability factor of a mine wing ventilation;

$$\lambda_{mw} = (\delta_{dmw}q_{dmw} + \delta_{gmw}q_{gmw})\lambda_{0mw}, \quad (8)$$

where δ_{dmw} is factor of significance of the dust factor for a mine wing; q_{dmw} is the value of the mine seam hazard indicator code based on specific dust release for a mine wing; δ_{gmw} is factor of significance of the gas factor for a mine wing; q_{gmw} is the value of the mine seam hazard indicator code based on relative gas content for a mine wing; λ_{0mw} is normalizing multiplier;

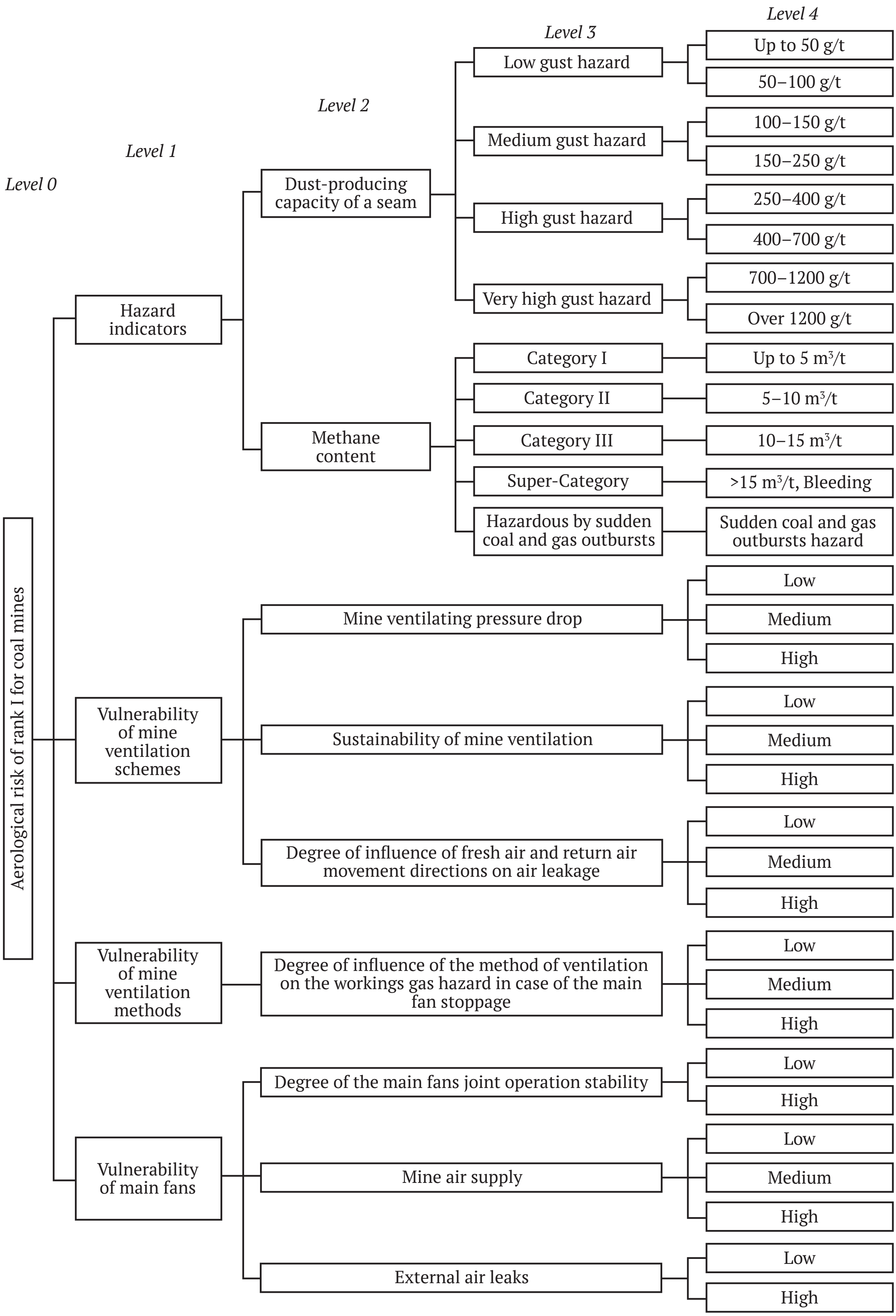

Fig. 1. Hierarchical structure of rank I aerological risks

$$v_{mw} = (\varphi_{wvs}\alpha_{wvs} + \varphi_{wvm}\alpha_{wvm} + \varphi_{mwvf}\alpha_{mwvf})v_{1k}, \quad (9)$$

where φ_{wvs} is vulnerability significance factor of a mine wing ventilation scheme; α_{wvs} is vulnerability code value of a mine wing ventilation scheme; φ_{wvm} is vulnerability significance factor of a mine wing ventilation method; α_{wvm} is vulnerability code value of a mine wing ventilation method; φ_{mwvf} кis vulnerability significance factor of a mine wing ventilation facilities; α_{mwvf} is vulnerability code value of a mine wing ventilation facilities; v_{1k} is normalizing multiplier.

By decomposing the values of the indicators in formula (9), we obtain:

$$\varphi_{wvs} = (\varphi_{pds}\alpha_{pds} + \varphi_{mwvc}\alpha_{mwvc} + \\ + \varphi_{mwvs}\alpha_{mwvs} + \varphi_{ivptd}\alpha_{ivptd})v_{2k}, \quad (10)$$

where φ_{pds} is significance factor of the effect of the magnitude of ventilating pressure drop in haulage and ventilation main drifts; α_{pds} is vulnerability code value of the mine wing ventilation scheme depending on the magnitude of ventilating pressure drop in haulage and ventilation main drifts; φ_{mwdv} is significance factor of the degree of influence of the direction of fresh air and return air movement on air leaks; α_{mwdv} is vulnerability code value of a mine's wing ventilation scheme depending on the degree of influence of the direction of fresh air and return air movement on air leaks; φ_{mwvs} is significance factor of the influence of ventilation stability on the vulnerability of the ventilation scheme of a mine wing; α_{mwvs} is significance code value of the vulnerability of the ventilation scheme of the mine wing, depending on the stability of ventilation; φ_{ivptd} is significance factor of the magnitude of thermal drop of ventilation pressure in inclined mine workings; α_{ivptd} is significance code value of the magnitude of thermal drop of ventilation pressure in inclined mine workings; v_{2k} is normalizing multiplier;

$$\varphi_{vmw} = \varphi_{vmwgh}\alpha_{vmwgh}v_{3k}, \quad (11)$$

where φ_{vmwgh} is factor of significance of the degree of influence of a mine's wing ventilation method on the workings gas hazard at a sudden stop of the main fan; α_{vmwgh} is value of the vulnerability code of the degree of influence of a mine's wing ventilation method on the workings gas hazard at a sudden stop of the main fan; v_{3k} is normalizing multiplier;

$$\varphi_{vfs} = \varphi_{vfs}\alpha_{vfs}v_{4k}, \quad (12)$$

where φ_{vfs} is factor of significance of the degree of influence of ventilation facilities on the stability of ventilation; α_{vfs} is the value of the code of the degree of influence of ventilation facilities on the stability of ventilation; v_{4k} is normalizing multiplier.

The presented indicators of hazard and vulnerability in the structure of rank II risks are hierarchically represented in the form of a functional diagram in Fig. 2.

Thus, the presented methodology of aerological safety architecture design, including aerological risk assessments, enables quantifying the effectiveness of various methods of mine ventilation improvement.

Research Findings

A well-known approach of obtaining normalizing factors characterizing the share of vulnerability (aerological risk) of schemes and methods of mine (mine wing) ventilation as compared with the most adverse situation (taken as a unit) was taken as a basis for quantitative assessment of hazard, vulnerability, aerological risk. For a mine it comprises a central duplex ventilation scheme, blow-in method of ventilation, exacerbated by unfavorable conditions: the scheme with low degree of stability (tilting of the ventilation stream occurs at normal operation of the mine — the 3rd category of stability), a great mine ventilating pressure drop, a large degree of influence of the direction of fresh air and return air movement on air leakage, a large degree of influence of the ventilation method on gas hazard (content) in workings when the main fans stop, low mine provision with air, high external air leaks, etc.

Table 1 shows ranges of values of aerological risk of rank I for super-category mines and mines hazardous by sudden coal and gas outbursts for different ventilation modes The first figure of the range of the risk values reflects the most favorable conditions: the least dust emission, no diagonals in the ventilation network, direct-flow scheme of air movement, low mine ventilating pressure drop, stable joint work of main fans, the availability of air supply reserve in a mine, low external leaks, etc.

Analysis of the calculated data shows that while the risks for different ventilation schemes and methods increase from the best to the worst conditions in 2.1 times (0.152/0.078), the value of the risk depends on the values of ventilation parameters to much greater extent and the risk increases in 6.8 times (0.535/0.078) from the best to the worst conditions. A similar dependence was identified for rank II risks (Table 2).

It should be noted that the methodology makes it possible to highlight the most significant components (ventilation indicators) from the risk structure and develop engineering measures to reduce aerological risks and increase the efficiency of aerological safety.

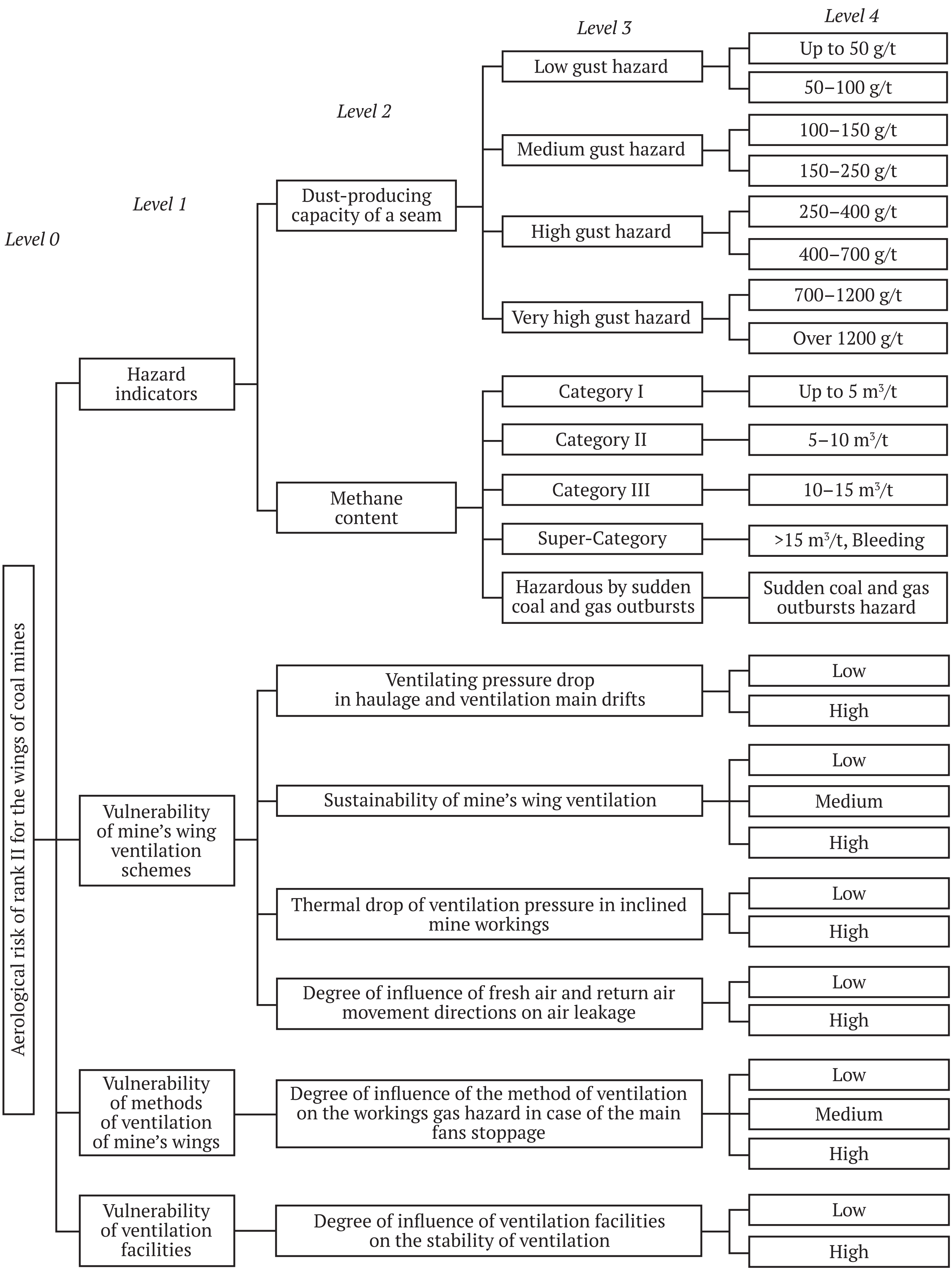

Fig. 2. Hierarchical structure of rank II aerological risks

Table 1

Rank I aerological risk values for super-category mines and mines hazardous by sudden coal and gas outbursts

Ventilation scheme and method	Rank I aerological risk values		
	Sustainability category 1	Sustainability category 2	Sustainability category 3
Flank scheme, suction method	0.078–0.535 / 0.093–0.611	0.101–0.575 / 0.121–0.657	0.203–0.733 / 0.242–0.838
Flank scheme, combined method	0.083–0.545 / 0.098–0.623	0.105–0.595 / 0.125–0.68	0.224–0.756 / 0.267–0.864
Flank scheme, blow-in method	0.087–0.556 / 0.104–0.635	0.108–0.615 / 0.129–0.703	0.245–0.78 / 0.292–0.891
Combined scheme, suction method	0.088–0.571 / 0.105–0.653	0.109–0.647 / 0.129–0.739	0.237–0.786 / 0.282–0.898
Combined scheme, combined method	0.1–0.599 / 0.119–0.685	0.133–0.685 / 0.159–0.783	0.262–0.808 / 0.313–0.923
Combined scheme, blow-in method	0.111–0.627 / 0.133–0.717	0.159–0.724 / 0.189–0.827	0.288–0.83 / 0.344–0.948
Central duplex scheme, suction method	0.105–0.614 / 0.126–0.702	0.179–0.715 / 0.213–0.817	0.3–0.832 / 0.357–0.951
Central duplex scheme, combined method	0.129–0.635 / 0.154–0.726	0.198–0.74 / 0.236–0.846	0.312 – 0.853 / 0.372 – 0.975
Central duplex scheme, blow-in method	0.152–0.656 / 0.182–0.75	0.217–0.766 / 0.259–0.875	0.325 – 0.875 / 0.388 – 1.000

Note: The numerator shows risk values for super-category mines, and the denominator shows risk values for mines hazardous by sudden coal and gas outbursts.

Table 2

Rank II aerological risk values for super-category mines and mines hazardous by sudden coal and gas outbursts

Ventilation scheme and method	Rank II aerological risk values		
	Sustainability category 1	Sustainability category 2	Sustainability category 3
Flank scheme, suction method	0.078–0.429 / 0.093–0.49	0.127–0.543 / 0.151–0.621	0.244–0.659 / 0.291–0.753
Flank scheme, combined method	0.088–0.48 / 0.105–0.548	0.141–0.589 / 0.168–0.673	0.258–0.707 / 0.308–0.808
Flank scheme, blow-in method	0.098–0.531 / 0.117–0.607	0.155–0.635 / 0.185–0.725	0.273–0.755 / 0.326–0.863
Central duplex scheme, suction method	0.093–0.514 / 0.111–0.587	0.146–0.607 / 0.174–0.694	0.252–0.719 / 0.301–0.821
Central duplex scheme, combined method	0.108–0.586 / 0.128–0.670	0.167–0.678 / 0.199–0.775	0.278–0.797 / 0.332–0.911
Central duplex scheme, blow-in method	0.122–0.658 / 0.145–0.752	0.188–0.749 / 0.224–0.856	0.304–0.875 / 0.362–1.000

Note: The numerator shows risk values for super-category mines, and the denominator shows risk values for mines hazardous by sudden coal and gas outbursts.

Conclusion

The steady trend of complication of mining and geological factors of coal mining associated with increasing the mining depth and the temperature of rocks, as well as the simultaneous intensification of mining operations with the use of up-to-date high-performance equipment cause growth of dynamic manifestations of natural factors of mining, such as sudden coal and gas outbursts, rock bursts, rock collapses, leading to gas and dust explosions and fires. This imposes additional requirements on the formation and functioning of the architecture of coal mine aerological safety, namely, the need for integrity of risk assessment for both a mine and its facilities, and hence flexibility, responsiveness, and interconnectedness of the organizational-technical and technological solutions for reducing the level of aerological risks.

Such requirements of aerological safety are met by a hierarchical structure of aerological risks at coal mines, which allows determining, for each mine and its individual facilities, the area of superposition of hazards of coal mining and vulnerability of schemes and methods of ventilation and ventilation facilities and quantifying these areas in the form of aerological risks. The presented methodology enables forecasting and reducing aerological risks in course of designing, operation, liquidation and conservation of coal mines.

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Information about the author

Sergey V. Balovtsev – Cand. Sci. (Eng.), Associate Professor, National University of Science and Technology MISiS, Moscow, Russian Federation; ORCID 0000-0002-0961-6050, Scopus ID 56780405300; e-mail balovcev@yandex.ru

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