

Research Article

Study of Potential Failure Points of Ventilation Shafts

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Article Info	Abstract
Article History	This study aims to identify potential failure zones in the ventilation shaft to enhance its safety and durability. The study involved parameter measurement, software modeling, finite element analysis, and analytical calculations. The study confirmed that loose ventilation pits pose a potential operational hazard. The creation of technological regulations for their fixation, including their specifics, proved necessary to ensure safety. The analysis of inelastic deformation zones using RocData and RS3 software revealed that RocData allowed a successful transition from laboratory rock characteristics to massive rock characteristics. At the same time, RS3 provided effective numerical modeling of the stress-strain state of rocks using the finite element method.
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Keywords	The analysis results identified the areas of the ventilation shaft that are most vulnerable to failure under various loads, including wind forces, snow loads, and seismic activity. The application of a comprehensive approach, including assessment of the current condition, determination of load types, modeling and analysis of structural integrity, as well as the development of safety and strengthening measures, allowed us to formulate effective strategies for maintaining the safety of the ventilation shaft. Regular monitoring and inspection ensure the reliability and durability of the infrastructure. Based on the identified vulnerable areas, recommendations are developed to strengthen and protect the shaft structure. Proposed safety measures may include changing materials, adding reinforcements, or modifying the structure's geometry.
Rock mass	
Numerical modeling	
Stress-strain state	
Inelastic deformation zones	
Safety assurance	



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1. Introduction

In engineering practice, the key issue is ensuring the safety and durability of infrastructure structures. Ventilation shafts are crucial components of underground structures, as they play a vital role in ensuring optimal ventilation and maintaining safe conditions. These facilities not only provide fresh air to the underground premises but also remove exhaust air, smoke, vapors, and other harmful substances, thus ensuring safe working and living conditions for people underground. Investigating potential failure zones in ventilation shafts is becoming an integral part of ensuring their functionality and safety. Identifying the areas

most susceptible to failure under various stress conditions is, therefore, essential. The study is of key importance in ensuring the safety and efficient operation of underground facilities. Ventilation shafts are an integral part of the infrastructure of underground complexes, providing not only the required level of ventilation but also maintaining the stability and safety of structures. Destruction or damage to the ventilation shaft can lead to serious consequences, including potential accidents, as well as poor working conditions for personnel and environmental risks. Therefore, the research relevance is determined by the need to identify vulnerable areas of the structure, determine the factors contributing to their destruction, and develop appropriate measures to strengthen and protect them, thereby increasing the reliability and safety of underground structures in general.

The problem in this area is the lack of a systematic approach to assessing and monitoring the safety of ventilation shafts in underground structures. The lack of an integrated approach can lead to an insufficient risk assessment and underestimation of potential threats, which can create conditions that exacerbate emergencies and deteriorate working conditions and personnel safety. Kwon and Yoo (2021) conducted a study on the numerical modeling of the dynamic behavior of ventilation shafts under seismic activity. Zuo, et al. [1] presented a study on the analysis of the effect of snow loads on the structural integrity of ventilation pits. Mussin, et al. [2] focused on identifying zones of inelastic deformation around vertical workings using RocData software. Remennikov, et al. [3] considered methods for predicting the destruction of ventilation shafts under the influence of wind loads. The work of Yin [4] presents an analysis of the technological aspects of fixing loose ventilation pits. Li, et al. [5] studied the effect of temperature changes on the stress-strain state of ventilation shafts. Tang, et al. [6] analyzed methods of visual inspection of ventilation pits to identify signs of potential destruction. Jacobs, et al. [7] addressed the issue of developing software regulations to ensure the safety of ventilation shafts. Zhang, et al. [8] presented a study on the development of methods for monitoring the structural integrity of ventilation systems. Boyd, et al. [9] considered aspects of creating effective strategies for strengthening and protecting ventilation shafts based on the results of the analysis of studies of potential failure zones. The results of these studies contribute to a deeper understanding of the problem and the creation of effective strategies for strengthening and protecting ventilation systems. This improved the safety and durability of underground structures, ensuring reliable operation and reducing the risk of emergencies.

This study aims to identify potential failure zones within the ventilation shaft to enhance both its structural integrity and operational lifespan. The specific research objectives are as follows:

1. To conduct a comprehensive analysis of ventilation shafts to identify vulnerable areas subject to different types of loads and risk of failure, using modern diagnostic and monitoring methods.
2. To develop and justify a systematic approach to creating strategies for strengthening and protecting ventilation systems based on the results of the analysis of potential failure zones and risks.
3. To study and adapt modern methods and technologies for preliminary assessment of the structural integrity of ventilation shafts to improve decision-making on their safety.

2. Literature Review

The study of potential ventilation shaft failure zones is a crucial task that ensures the safety and efficiency of mining operations and other underground structures. Understanding and assessing potential failure points is essential to preventing accidents, minimizing risks, and ensuring the stable operation of infrastructure. This was investigated by Cao, et al. [10], whose results confirmed that the geological features of the field are of great importance for assessing potential ventilation shaft failure zones. Different types of rock have different strengths and resistance to various factors, such as pressure and movement, which can lead to fractures or cracks in the borehole. For instance, soft rocks are more susceptible to deformation and fracture than hard rocks, making it essential to consider the geological environment when planning and designing ventilation shafts.

Qiu, et al. [11] determined that dynamic loads, such as groundwater pressure or rock movements, can also have a significant impact on the stability and reliability of a ventilation shaft. Increased water pressure in the rock can cause water to penetrate the borehole, resulting in extensive fractures. Moreover, rock movements resulting from natural processes or mining operations can cause deformations and stresses that impact the shaft's structure. Therefore, dynamic factors must be considered when assessing risks and developing measures to protect and strengthen ventilation shafts.

The study of potential ventilation shaft failure zones involves an analysis of the geological features of the deposit, including the rock structure, the presence of cracks, folds, and other deformations that could lead to shaft failure [12, 13]. This identified areas with an increased risk of failure and took measures to strengthen or prevent them. This aspect has attracted the attention of many scientists. Among them, Ala-Aho et al. (2021) emphasize that the hydrogeological conditions of the field are essential for the stability of the ventilation shaft. The presence of groundwater or changes in groundwater levels can lead to additional pressure on the borehole walls, which increases the likelihood of fracture zones. This requires additional precautions in the design and operation of the

shafts, such as the installation of additional reinforcements or drainage systems. The presence or change in the groundwater level can lead to a significant increase in pressure on the shaft walls, potentially causing their destruction [14]. In addition, the geomechanical properties of rocks directly affect their ability to withstand external loads and maintain wellbore integrity throughout the entire service life [15, 16].

It is also necessary to account for the geometric features and design characteristics of the ventilation shaft when conducting the study. This includes the length, diameter, material, attachment, and reinforcement methods, and the presence of additional security features. Sun, et al. [17] determined that geometric features such as the length and diameter of the ventilation shaft can have a significant impact on its stability and ability to resist various impacts. For instance, longer shafts may be at greater risk of deformation due to their weight and hydrodynamic pressure, while a larger diameter may increase their resistance to mechanical stress.

Investigating potential ventilation shaft failure zones is a crucial stage in the design, construction, and operation of underground facilities. This allows us to develop effective risk prevention measures and ensure the safety and reliability of the infrastructure under variable geological and technical conditions. Xia, et al. [18] concluded that in the presence of weak rocks or cracks, the probability of cave-ins or deformations of the shaft increases significantly, which can potentially lead to accidents. In addition, the study by Askaripour, et al. [19] found that dynamic loads, such as groundwater pressure or seismic activity, also play an important role in the formation of ventilation shaft failure zones. Understanding and addressing these factors enables effective strategies for strengthening and protecting the shaft, which significantly enhances its reliability and ensures safe operation under various conditions.

3. Materials and Methods

The subject of the study was the Zhomart mine of the PLC Kazakhmys branch (Zhezkazgantsvetmet). The survey was carried out on the sides and mouths of the pits of blocks 19 and 37, as well as in ventilation pit 3. The RHINO 2007 DC drilling rig drilled ventilation shaft No. 3. The layout of the air supply shaft No. 1 P-37 was a detailed image of the location of a given shaft on an object or device. This was necessary documentation that was used to determine the exact location of the air supply shaft and ensure the required airflow in the respective system or process. The detailed description of this scheme included the coordinates of the shaft, its orientation relative to other elements of the system, and features or equipment that could affect its operation or functionality.

The geological section in the vertical shaft area provides a detailed description of the layered structure of the Earth's crust, including rock types, soil layers, and aquifers. It served as the basis for further geological research and engineering work. The 3D model of the ventilation shaft represented its geometry and components, facilitating the analysis and optimization of the design. A 3D model of the surrounding area was also created to assess the impact of the environment on the system's operation and safety. These models were used for virtual testing and risk analysis, as well as for engineering decision-making.

The shape of the shaft cross-section at the intervals of crushing red rock described its geometry in the deformation areas. This included information on the dimensions, contour, and features of the shaft under pressure. This description was used to assess the stability of the shaft and planning measures to strengthen it. The deformed areas of the borehole that were recorded represented changes or deformations in its structure, such as bends, cracks, or folds. The deformations were recorded through observation and control, which was crucial for assessing the structural integrity and making informed decisions about the repair or strengthening of the shaft. The support designed to be run down the borehole had to be tested for stability against external hydrostatic pressure using the formula for smooth round pipes:

$$P = \frac{E\delta^3}{4R_z(1-\mu^2)^2}, \quad (1)$$

where: P_{kr} – the critical pressure on the fastener, MPa; E is the elastic modulus, MPa; δ – pipe wall thickness, cm; R – specified pipe radius, cm; μ – the Poisson's ratio of steel.

In this study, theoretical calculations were carried out, and a model was created using Rocscience RS3 software. This process involved analyzing various parameters and characteristics using numerical modeling methods provided by the software. The created model was used to conduct a more detailed and accurate study of the system or process under investigation, as well as to predict its behavior in various conditions. This provided a deeper understanding of physical processes and phenomena, enabling informed decisions based on the results obtained.

Inelastic deformation zones with a specified Geological Strength Index (GSI) value were calculated to analyze areas where inelastic deformation (e.g., plastic deformation) occurs in rocks or soils. A GSI value of 20 indicates low rock or soil strength in the relevant areas. The calculations included an assessment of the mechanical properties of the materials, the geometric parameters of the areas, and the loads or environmental conditions to which they were subjected. These calculations can be used to determine the likelihood of deformation, design appropriate engineering solutions, or take measures to mitigate risks during

the construction or operation of engineering structures. Thus, in each of the above cases, similar calculations were carried out considering a specific GSI value reflecting the mechanical characteristics of rocks or soils in the respective zones.

The methodology comprised several essential stages. Comprehensive geological surveys were undertaken to obtain detailed information regarding rock types, soil layers, and aquifers within the study area. This information was crucial for constructing accurate three-dimensional geological models. Based on the collected data, detailed 3D models of the ventilation shaft and surrounding geological structures were developed using RS3 software, which facilitated the integration of various geological and geotechnical parameters. A series of simulations were conducted to evaluate the stability and deformation characteristics of the shaft under different loading conditions and environmental influences. These simulations provided valuable insights into the structural behavior of the shaft in diverse scenarios. The simulation outcomes were validated through comparison with field observations and empirical measurements. Following this validation, the design and support measures for the ventilation shaft were optimized to enhance stability and safety. This methodological approach demonstrates several advantages over previous research. The integration of advanced software tools with high-resolution geological data enabled the development of highly accurate and detailed models. This, in turn, supported more refined analyses and contributed to the formulation of robust engineering solutions for maintaining the stability of ventilation shafts in underground mining environments.

4. Results and Discussions

Investigating potential ventilation shaft failure zones is a crucial aspect of ensuring the safety and sustainability of underground structures. Ventilation shafts are crucial in the mining industry, providing air exchange in mines and mine workings while also ensuring safety and comfortable working conditions for workers. The study of potential failure zones in a ventilation shaft involves an analysis of geological, hydrogeological, and geotechnical conditions that may impact its stability and reliability. The main factors addressed in such studies include the strength of rocks, the presence of geological faults, aquifers, and the impact of hydrodynamic processes [20]. One of the research methods is numerical modeling using specialized software tools, such as RS3 and others. These programs were used to model the impact of various factors on the stability of the shaft, including hydrodynamic loads, rock stresses, and deformations. Another important aspect of the study is the engineering inspection of the shaft using modern non-destructive testing

methods, such as ground-penetrating radar, ultrasonic tomography, and others. These methods were employed to identify potential defects, cracks, or structural changes in the shaft that could lead to its destruction [21]. Based on the research results, recommendations for strengthening and safe operation of the ventilation shaft are developed. These recommendations may include the use of additional steel or concrete casing, the installation of additional support elements, and control measures to minimize the impact of geological and hydrogeological factors.

The RHINO 2007 DC drilling rig drilled ventilation shaft No. 3 (Figure 1). The shaft in question was drilled in panel 37 in the eastern part of the deposit. The shaft is designed to supply air to the shaft. The depth of the shaft is 490.72 m. The bottom of the shaft is 142.72 m. The shaft diameter is 4.5 m. The shaft was sunk in 2017. Currently, the shaft walls are not fixed.

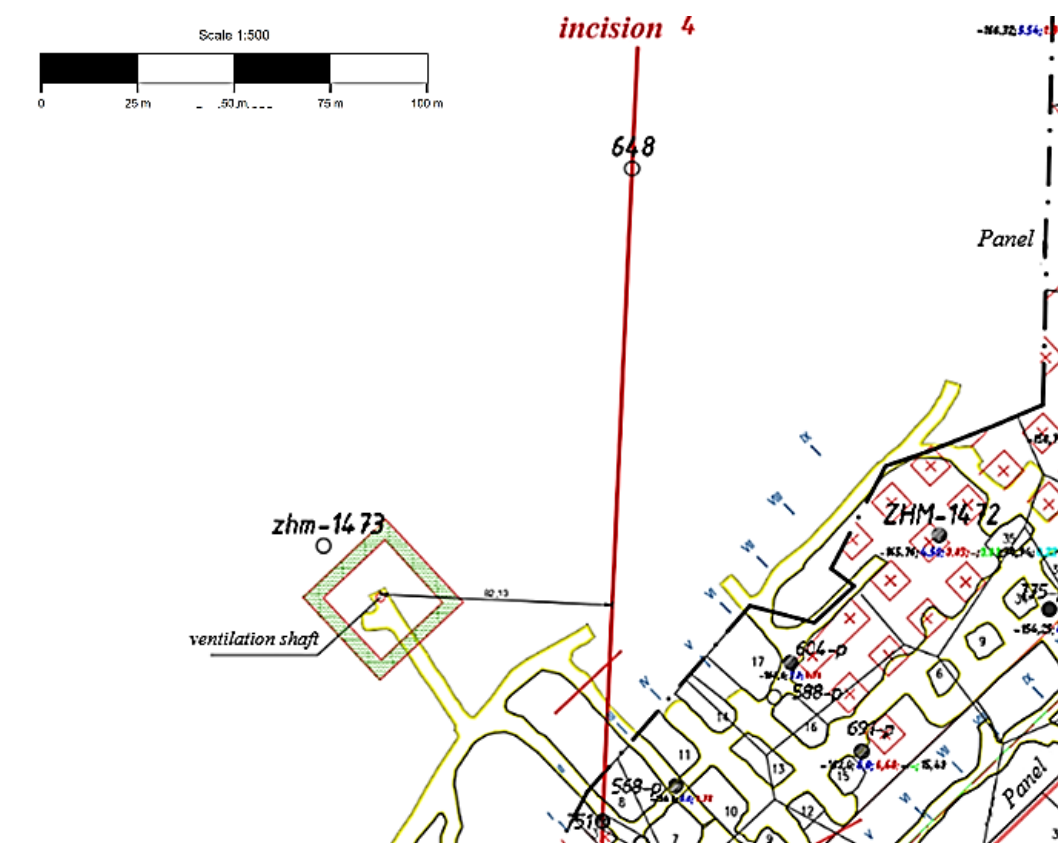


Figure 1. The layout of the air supply shaft No. 1 P-37

In general, the deposit is dominated by medium-stable rocks up to a depth of 550 m, with medium-stable, stable, and very stable rocks with rare layers of unstable rocks in the 550-860 m depth range. According to engineering and geological zoning, the flank parts of the deposit are usually unstable and cover about 30% of the area [22]. In the context of the study, the following stand out: red-colored fine-grained sandstones, grey fine-grained sandstones, and grey and greenish-grey siltstones.

Grey sandstones are the most durable, depending on their material composition and structural and textural features, the uniaxial compressive strength (σ_c) ranges from 48 to 281 MPa; tensile strength (σ_p) – from 2.3 to 12.8 MPa; for brown fine-grained sandstones, σ_c =27-163 MPa, σ_p =1.3-11.6 MPa [23]. Conglomerates from the Raimundov Formation have uniaxial compressive strength (σ_c) in the range of 84 to 141 MPa and tensile strength (σ_p) of 6 to 10.1 MPa. The lowest values of strength characteristics are observed in siltstones and mudstones, with uniaxial compression strengths (σ_c) ranging from 10 to 88 MPa and tensile strengths (σ_p) from 0.5 to 7.5 MPa. The azimuth of the shaft deviation at the actual position of 62 m is 159°58'35". The azimuth of the shaft deviation at the actual position of -143 m is 168°59'40" (Figure 2). The shaft parameters are: Cross-section – 15.9 m²; Length – 490.72 m; Sinking volume – 7802 m³; Diameter – 4.5 m.

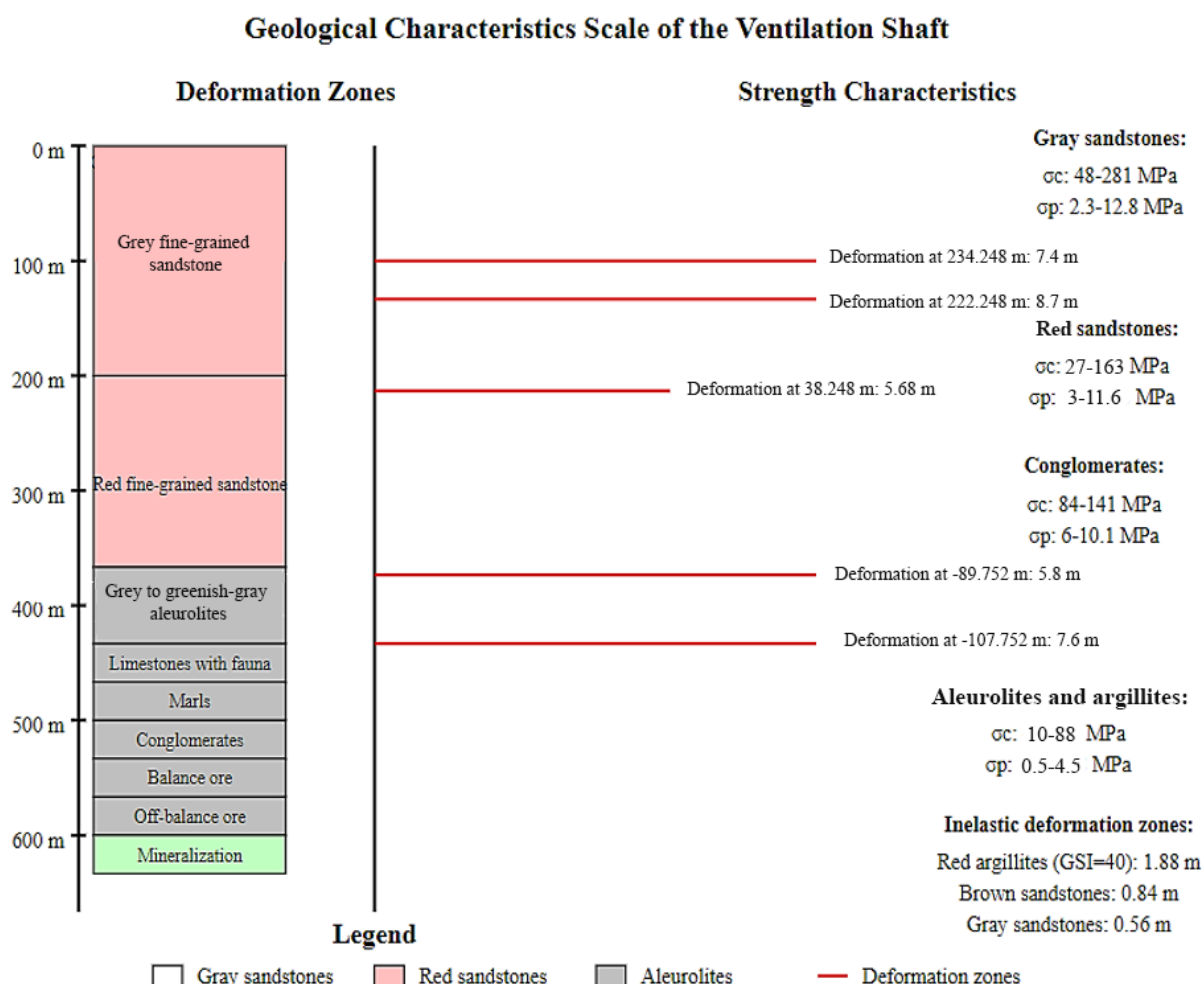


Figure 2. Geological characteristic scale of the vertical shaft

Laser scanning of the shaft contour revealed the locations, shapes, and volumes of the dumps from its walls along the entire depth, from the surface at 338 m to the face, with the collecting vent at -143 m. A fragment of the survey is shown in Figure 3.

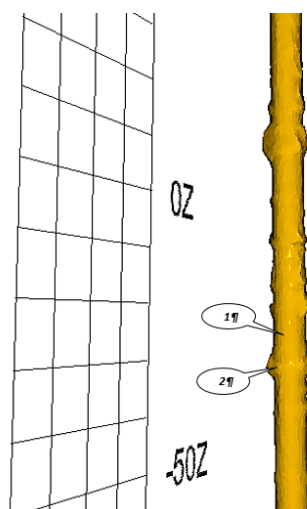


Figure 3. 3D model of the ventilation shaft (1 – outcrops; 2 – intersections with faults)

The wedge-shaped block outcrops are notable for their characteristic shape, which is elongated in the vertical direction, and their number is limited. Areas of rock crushing by horizontal stresses are represented by horizontal intervals alternating with areas of stable rock. The 3D model of the shaft was used to create horizontal sections of the contour at 2-m depth increments. Sections were found in which the contour of the shaft had become elliptical as a result of the crushing of red rock. An example of such a crushed section is shown in Figure 4.

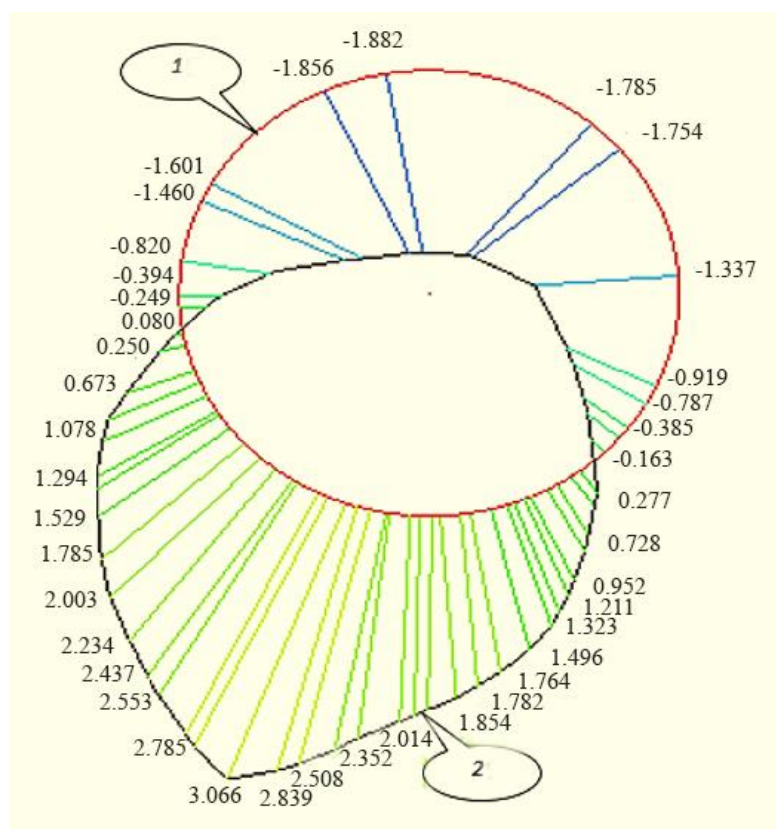


Figure 4. The shape of the shaft cross-section at the crushing intervals of red rock (1- design section of the 4.5 m diameter shaft; 2- actual results of laser scanning)

The numbers in Figure 4 represent deviations from the theoretical cross-section of the shaft. The crushing areas of the cylindrical vertical workings contour are located transverse to the direction of action in the array of maximum tectonic stresses $\sigma_1 = 1.6 \cdot \gamma H$ (i.e., along the short axis of the ellipse). The compression points of the vertical cylindrical workings contour are located along the direction of maximum tectonic stresses in the massif, where $\sigma_1 = 1.6 \cdot \gamma H$, i.e., along the short axis of the ellipse. Along the long side of the ellipse, the minimum horizontal stresses are $\sigma_3 = 0.9 \cdot \gamma H$. The values of natural horizontal stresses are based on the results of field measurements by the slot unloading method [24]. The sector of the maximum tectonic stress direction σ_1 is defined by azimuths $262^\circ \div 287^\circ$ with the most probable azimuth 275° . It is close to the East-West direction. Based on the results of structural and geomorphological analysis of the modern geodynamics of the Zhomart mine (Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences) on the eastern flank of the deposit, it was concluded that tectonic stresses act at azimuths of 285° , 287° , 291° with an average value of 288° [25].

Table 1. Recorded deformed sections of the shaft

No.	Altitude, m	Design diameter in sinking, m	Max/min distance between opposite bore walls, m	Note
1	234.248	4.65	7.4	Plot No. 1 with a deviation of the bore diameter of more than 1 m
2	212.248	4.65	8.7	
3	210.248	4.65	7.7	
4	208.248	4.65	7.75	
5	38.248	4.65	5.86	Plot No. 2 with a deviation of the bore diameter of more than 1 m
6	36.248	4.65	5.7	
7	32.248	4.65	5.3	
8	30.248	4.65	5.5	
9	4.248	4.65	5.8	Plot No. 3 with a deviation of the bore diameter of more than 1 m
10	2.248	4.65	6.6	
11	0.248	4.65	5.5	
12	-29.752	4.65	5.3	
13	-31.752	4.65	6.6	Plot No. 4 with a deviation of the bore diameter of more than 1 m
14	-32.552	4.65	6.4	
15	-89.752	4.65	5.8	
16	-91.752	4.65	6.27	
17	-105.752	4.65	5.5	Plot No. 5 with a deviation of the bore diameter of more than 1 m
18	-107.752	4.65	7.2	
19	-111.752	4.65	5.2	
20	-113.752	4.65	5.67	
21	-143.752	4.65	6.4	Plot No. 6 with a deviation of the bore diameter of more than 1 m
				Plot No. 7 with a deviation of the bore diameter of more than 1 m
				Plot No. 8 with a deviation of the bore diameter of more than 1 m

The directions of tectonic stresses based on the results of analyses of the tectonophysical (288°) and the state of the shaft (275°) confirm each other since the difference in 13° is within the limits of statistical variability. At the excavation sites, the nominal shaft diameter reaches 8.7 m (212.248 m) (Table 1).

As can be seen from Table 1, there are eight sections of the shaft with a diameter deviation of more than 1 m. The deviation of the shaft axis is noted from the mark of 230.248 m; at the mark of 30.248 m, the deviation of the axis reached half the shaft diameter (the angle of deviation of the axis from the vertical is less than 1°), at the mark of -107.752 m the deviation was more than 1.5 shaft diameters (the angle of deviation of the axis from the vertical is approximately 1°). The azimuth of the axis deviation from the vertical axis is 190° , stable, fluctuations do not exceed 5° . Due to the absence of a geotechnical model of the area under consideration, the geological section along lines 4-4 was used as the basis for the 3D massif model. The model also includes the contour of the previously scanned air supply shaft (Figure 5). The model was built on a RockIT One computer station.

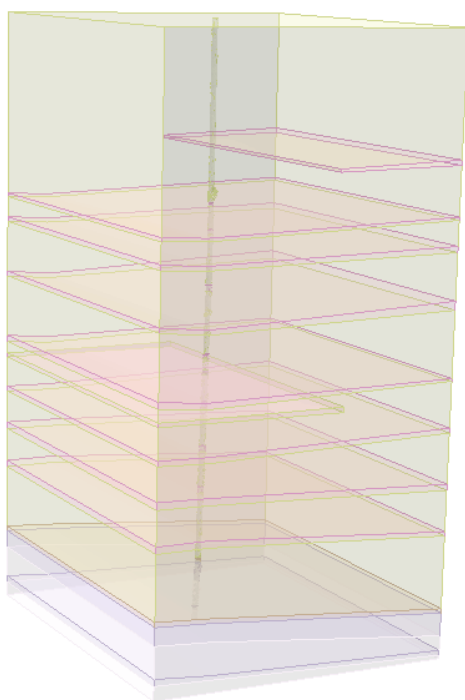


Figure 5. 3D model of the massif in the area of the ventilation shaft

Inelastic deformation zones were calculated using GSI values of 20 (Table 2), 50 (Table 3), and 70 (Table 4) [26]. Following the modeling, horizontal sections were made at +248, +148, +48, -52, and -116 m to analyze the expected fracture zones.

Table 2 shows deformation zones at the lowest GSI value, corresponding to the most unfavorable conditions. This requires a reinforced fastening system.

Table 2. Calculation of inelastic deformation zones GSI 20

GSI	248 m	148 m	48 m	-52 m	-116 m
0	1.12	0.87	0.84	0.83	0.83
2	1.2	1.15	0.97	1.01	1.09
4	1.45	1.2	1.2	1.2	1.2
6	1.76	1.6	1.39	1.25	1.44
8	2.01	1.9	1.55	1.43	1.66
10	2.19	2.07	1.68	1.55	1.8
12	2.34	2.19	1.77	1.62	1.89
14	2.44	2.27	1.85	1.7	1.97
16	2.52	2.32	1.92	1.76	2.03
18	2.59	2.37	1.97	1.81	2.07
20	2.64	2.4	2.02	1.85	2.11
22	2.69	2.42	2.05	1.88	2.16
24	2.75	2.44	2.1	1.91	2.18

Table 3 represents intermediate conditions where deformations are moderate, and the requirements for fastening are less stringent compared to GSI 20.

Table 3. Calculation of inelastic deformation zones GSI 50

GSI	248 m	148 m	48 m	-52 m	-116 m
0	1.47	1.19	1.14	0.9	0.98
1	1.71	1.26	1.2	1.24	1.2
2	2.27	1.61	1.26	1.61	1.28
3	2.65	1.93	1.57	1.88	1.79
4	2.96	2.17	1.81	2.09	2.21
5	3.1	2.39	2.02	2.26	2.49
6	3.27	2.56	2.19	2.38	2.67
7	3.36	2.7	2.34	2.48	2.79
8	3.47	2.81	2.46	2.55	2.9
9	3.52	2.89	2.56	2.61	2.96
10	3.57	2.97	2.65	2.66	3.01
11	3.61	3.03	2.72	2.7	3.06

Table 4 reflects conditions with the least deformation, corresponding to the most favorable conditions and the least stringent fastening requirements. In this study, theoretical calculations were performed, and a model was created using Rocscience RS3 software. The geomechanical data, specifically the geomechanical rock quality index (GSI), served as the basis for theoretical calculations. However, due to the lack of accurate GSI data and the impossibility of obtaining it, the study adopted conditional GSI values of 20, 50, and 70. This was used to create three different models and, accordingly, three different mounting scenarios.

The models were used to identify the most unfavorable conditions for anchoring, which addressed potential risks to the maximum extent possible. As can be seen from the tables above, the results of modeling the deformation zones at different depths with a 100-meter increment show that the GSI value has the greatest impact on the stability of the face. The study found that at GSI 20, the conditions are the most critical, requiring a reinforced fastening system. At the same time, the conditions for the GSI 70 proved to be the least demanding on the fasteners. These results highlight the importance of considering the geomechanical characteristics of the rock when designing support systems.

Table 4. Calculation of inelastic deformation zones GSI 70

GSI	248 m	148 m	48 m	-52 m	-116 m
0	1.63	1.28	1.2	1.2	1.23
1	1.91	1.74	1.74	1.79	1.64
2	2.54	2.3	2.26	2.31	2.13
3	3.02	2.68	2.61	2.62	2.53
4	3.3	2.96	2.88	2.84	2.79
5	3.53	3.16	3.07	2.97	3
6	3.67	3.3	3.2	3.08	3.15
7	3.8	3.41	3.31	3.16	3.26
8	3.92	3.51	3.38	3.22	3.35
9	3.99	3.58	3.44	3.27	3.42
10	4.05	3.63	3.48	3.3	3.48
11	4.1	3.68	3.52	3.34	3.52

To ensure the reliability and safety of mining operations, several key factors must be addressed, including the geomechanical properties of the rock, geological conditions, and potential hydrogeological risks [27, 28]. This study proposes technology and technological regulations to support these operations, which should include work to clarify the geomechanical parameters of each gap to select an effective technology and a set of measures for supporting the vertical pit. The choice of shaft sidewall fastening technology is based on the calculations performed. The design diameter of the shaft in the sinking is 4.65 m. The deviation of the actual shaft diameter from the design diameter in the areas of dumps reaches 4 m. The shafts are fastened using suspended sinking shelves in a downward direction. The shaft mount can be divided into two main parts: the shaft head and the shaft body. It is essential to secure the mouths of all workings from the surface and to secure all joints of workings regardless of rock stability [29, 30]. To sink the wellhead to a depth of up to 2 m, jackhammers are used, or drilling operations are carried out with subsequent blasting. To ensure stability, a solid crown molding is used. First, a support crown is built, after which rows of crown

elements are installed until the mouth is reached. Two or three rows of crowns are installed above the access frame so that the level of the fasteners is at least 0.3 m above the surface. It is necessary to close the wellhead with special ladders, which prevent accidental falling of objects into the pits, and to open it only for the passage of the bucket [31, 32]. Steel sectional supports can be used to secure drilled shafts [33].

The steel sectional fastener is a structure consisting of individual rings made of 16-20 mm thick sheet steel. These rings range in height from 1.5 to 3 m and are manufactured with reinforced frames made of channels. The frames are curved outwards and welded to the casing from the outside. The ovality of the casing should not exceed 10 mm, and the non-perpendicularity of the pipe end to the axis should not exceed 1.6 mm. The size of the channel profile and the installation spacing of the frames are selected based on the required load-bearing capacity, as determined in Table 6.

Table 5. Selection of steel sectional fasteners used to support mine shafts

Diameter of a mount, m	The diameter of the fastener along the outer strip, m	Length of the support section, m	Number of rings	Number of pitches of the frames	Number of frames	Bearing capacity of the fastener, MPa	
						Critical pressure	Permissible external pressure
2.3	2.34	6	4	7	8	0.904	0.632
				5	6	0.758	0.53
				3	4	0.584	0.408
2.6	2.64	6	4	7	8	0.626	0.438
				5	6	0.525	0.367
				3	4	0.405	0.283
2.85	2.89	6	4	7	8	0.475	0.332
				5	6	0.398	0.278
				3	4	0.307	0.214
3.2	3.24	3	2	3	4	0.335	0.234
				2	3	0.281	0.196
				1	2	0.216	0.151
3.5	3.54	3	2	3	4	0.257	0.179
				2	3	0.216	0.151
				1	2	0.107	0.074
4.3	4.34	3	2	3	4	0.138	0.096
				2	3	0.116	0.081
				1	2	0.089	0.062

Note: Diameter of a mount (m) – the diameter of the mine shaft; diameter of the fastener along the outer strip (m) – outer diameter of the fastening structure; length of the support section (m) - the length of each section of the fastener; number of rings - the number of rings used in the fastening structure; number of pitches of the frames - the number of frame pitches in the structure; number of frames - the total number of frames; bearing capacity of the fastener (MPa) -critical pressure and permissible external pressure,

which are important for ensuring the stability and safety of the structure.

The support designed for running into the borehole must be checked for stability against external hydrostatic pressure according to the formula for smooth round pipes, as shown in formula (1). Drilled holes may be supported in sections. The diameter of the support section should be selected based on the diameter of the drilled hole, the required diameter in the light, and the bearing capacity of the support [34, 35]. The length of each section must be determined according to the actual curvature of the shaft. This is based on the condition of the section passing through the borehole section during its descent. The length of the section is additionally checked to ensure that it does not exceed the carrying capacity of the trailed vehicles [36, 37].

It is worth noting that the successful management and prevention of potential failure zones in a ventilation shaft require a comprehensive approach and careful analysis of both geological and dynamic factors. The integration of geological data with dynamic load monitoring enables the development of more accurate models of wellbore behavior and the prediction of potential fracture zones with greater reliability [38]. This approach not only helps improve the safety and efficiency of underground facilities but also optimizes maintenance and repair costs, ensuring a longer and more sustainable operation of ventilation systems.

Alameedy, et al. [39] concluded that the geomechanical properties of the rock are also critical to the safety and reliability of the ventilation shaft. The strength, ductility, and resistance to deformation of rocks determine their ability to withstand external loads and maintain the integrity of the shaft. Assessment of these properties enables the identification of potentially hazardous areas and the implementation of appropriate measures, such as reinforcement or maintenance, to ensure the stability and safety of ventilation systems [40]. These results confirm the findings of the above study, demonstrating how hydrogeological and geomechanical factors impact the stability of the ventilation shaft in real-world conditions.

The study also includes an analysis of the dynamic loads to which the ventilation shaft is subjected during its operation. These can include hydrodynamic and geodynamic factors, such as groundwater pressure, rock movements, temperature, and pressure changes, that can affect the shaft's structure and lead to its destruction. Colas, et al. [41] studied this phenomenon, noting that hydrodynamic loads are a significant factor affecting the stability of the ventilation shaft. Changes in the groundwater level or hydrostatic pressure can cause an increase in pressure on the borehole walls, leading to deformation and potential failure of the borehole. This process is especially relevant in conditions of high humidity or when groundwater is

present in the field.

Furthermore, Bogusz, et al. [42] investigated that rock movements, seismic activity, and changes in crustal pressure can cause deformations and stresses in the wellbore structure. This can lead to cracks, dislocations, or even the destruction of the shaft, posing a serious threat to its functionality and safety. Thus, consideration and analysis of geodynamic factors are crucial for the effective design and maintenance of ventilation shafts, minimizing risks and ensuring their reliable operation under various operating conditions. These data are consistent with the thesis presented in the previous section, as they confirm the importance of considering both hydrodynamic and geodynamic factors when analyzing potential failure zones of a ventilation shaft. Both factors have a significant impact on the structure and stability of the shaft, which emphasizes the need for an integrated approach to the research and design of ventilation systems. Such data coordination confirms the validity of the approach and its relevance for ensuring the safety and efficiency of ventilation shafts in underground conditions.

It is worth noting the research of Wang, et al. [43], who demonstrated that design characteristics, such as material, fastening methods, and additional protection elements, also play a crucial role in determining the stability and durability of the ventilation shaft. For example, the use of strong materials and effective anchoring and reinforcement systems can increase its resistance to external influences and reduce the risk of failure. Comparing the data obtained during the research, it is possible to conclude that the geometric features and design characteristics of the ventilation shaft play a key role in its stability and operational safety. For example, ventilation shafts with a larger diameter and an effective support and reinforcement system can be more resistant to hydrodynamic pressure or mechanical stress, reducing the likelihood of fracture zones [44].

The analysis of the study results revealed that both geological and dynamic factors must be considered in the design and operation of the ventilation shaft. The interaction between the geological features of the field and dynamic loads creates complex conditions that affect the stability and safety of the wellbore, underscoring the importance of an integrated approach to wellbore maintenance and strengthening. Thus, the study of potential ventilation shaft failure zones plays a key role in ensuring the safety, reliability, and efficiency of mines and other underground facilities. This is a complex process that involves analyzing various factors, methods, and tools to minimize risks and ensure the stability of the ventilation shaft under different operating conditions.

5. Conclusions

Investigating potential failure zones in ventilation shafts is a complex challenge in underground mining engineering due to the critical role of geological factors. Rock type, structure, strength, and the presence of fractures significantly influence shaft stability, while dynamic loads such as groundwater pressure, seismic activity, and rock movement exacerbate potential deformation. To ensure structural safety, comprehensive protective measures, and continuous monitoring are essential.

This study analyzed geological documentation and conducted a 3D laser survey of ventilation shaft No. 1 P-37, which deviates by no more than 1° from the vertical. Numerical modeling using the finite element method and the Coulomb-Mohr criterion, performed via RS3 and RocLab software, identified inelastic deformation zones. Among the tested rocks, red mudstones or siltstones at a depth of 500 m (GSI = 40) exhibited the largest deformation zone (1.88 m), followed by brown sandstone (0.84 m) and grey sandstone (0.56 m). Based on the results, the shaft should be reinforced with a monolithic reinforced concrete structure from the mouth downward.

However, the study is limited by the scarcity of detailed geological and technical data. Furthermore, long-term impacts of groundwater fluctuations and seismic activity require further investigation. The reliability of RocData and RS3 results depends heavily on the quality of the input data, and these tools may not fully capture complex geological or dynamic conditions. Recognizing these limitations is essential for accurate interpretation and engineering decision-making.

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