A rational approach to the management of underground mining in complex hydrogeological and geomechanical conditions based on a risk assessment

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Abstract. The problems that arise during the combined development of vertical and subvertical ore bodies under complex hydrogeological and geomechanical conditions are considered, and their influence on the safety of mining operations is analyzed. In the course of the research, using the example of kimberlite deposits in Yakutia, new mechanisms were identified and spatial patterns were established for the development of processes of deformation, displacement and destruction of ore and rock masses during preparatory excavations and treatment works near surface and underground water bodies, including high-pressure ones. The mechanisms of complex accounting of the structural state of the massif, preliminary technogenic impact, the effect of complicating mining and geological and hydrogeological factors in substantiating the parameters of hazardous zones and barrier pillars are proposed. Risk assessment method based on hazard identification, a qualitative and quantitative analysis of the likelihood of an emergency considering the severity of the consequences when conducting mining in hazardous areas is presented. The application of the method in combination with the timely adjustment of technological processes provides a rational integrated use of geo-resources in the framework of sustainable development of mining system. The experience of training young personnel for scientific research institutes is described. Starting with university education and ending with their participation in real design work.

1. Introduction – the scope of the research

Currently, the approach to the design and development of deposits is reduced mainly to the generally accepted consideration of mining conditions and the selection of development systems and technologies on this basis, considering also the economic efficiency of mining [1]. So, in most cases, vertical and subvertical ore bodies with access to the earth's surface are developed by a combined mining method. The conditions of occurrence of such ore bodies are determined by mining operations at great depths, where the most acute problems are development of deposits under conditions of high rock pressure, gas and hydrodynamic phenomena [2].

Mining is associated with a high level of risk, usually higher than in most other industries. For a long time, it was believed that this was due to the inability to change the development conditions, but modern achievements in mining provide ample opportunities and tools for managing the state of the rock mass and working conditions in them, however, the problem of reducing the accident rate at the
mining enterprise remains relevant. The incomplete study and high heterogeneity of factors, together with the constantly changing environment of the working environment, necessitate a change in approaches to the design and operation of mining systems.

2. Features of the development of kimberlite deposits in Yakutia

Russia is the world leader in the extraction of rough diamonds, the bulk of which is mined in kimberlite deposits in the north of the country, in the continuous distribution of permafrost rocks with a thickness of more than 200 m. The deposits are tube-shaped subvertical bodies extending to a depth of several kilometres. At the largest fields, combined geotechnology with phased mining is used, initially the upper part of the field is mined with a quarry, with a depth of 380-750 m. The time gap between the end of open and the beginning of underground mining can reach several years. Underground mining of deposits with high and medium ore values is carried out by development systems with the laying of the worked-out space, which determines the need to leave a protective ore pillar under the bottom of the quarry [3]. Ore mining is carried out using combines.

The development conditions are characterized by a complex hydrogeological and geomechanical situation due to the non-standard structure of the massif, the presence of powerful high-pressure aquifers, sharp filtering anisotropy of water-bearing rocks, the occurrence of soluble formations in the sole of the complex, the presence of secant cracks, the deterioration of the strength properties of rock and semi-rock rocks under the influence of water, and the presence of tectonic violations. As a result of many years of experience in the development of kimberlite deposits in Yakutia, a hazard analysis was carried out, which showed that they can be ranked for geomechanical, hydrogeomechanical, gas-dynamic depending on natural and technogenic factors and are subject to risk assessment of the possibility of emergency situations and the development of measures to reduce the risk of accidents.

3. Risk assessment of accidents during work in hazardous areas

In order to identify the dangers of the impact of damaging factors on miners, the state of mining, equipment and the selection of optimal technological solutions, the technical means used, it becomes necessary to conduct an accident risk assessment. In the classic version, these goals are partially achieved due to compliance with the requirements stipulated by regulatory documents, however, in this case, the individual specificity of the development conditions may not be considered. Also, the implementation of the goals falls on the shoulders of the employees of the enterprise, however, to develop effective solutions in difficult conditions, expert qualifications of the employee are required.

The development of a deterministic approach based on risk assessment allows you to create an objective situation at the mining enterprise and provide compensation measures for a timely response if necessary, which in turn increases the likelihood of an uninterrupted and stable functioning of the mining system [4-8].

Based on the study of world experience [9-15] and research conducted at IPKON RAS, an assessment of the risk of accidents during mining in hazardous areas for the conditions of kimberlite deposits in Yakutia was carried out.

Risk assessment is proposed to be carried out on the basis of a qualitative and quantitative analysis of the risk of the accident, determining the level of risk and comparing it with acceptable values, including the selection of measures aimed at achieving an acceptable level of risk (Figure 1).

Risk assessment is carried out when designing and exceeding safety criteria during the construction and operation of mines based on hazard identification and a qualitative and quantitative analysis of the likelihood of an emergency taking into account the severity of the consequences according to the formula (1):

\[ R = P \times SC \]

where: \( R \) is the risk; \( P \) is the probability of an accident; \( SC \) - the severity of the consequences.

Accident risk analysis includes:

- hazard identification during the operation of a hazardous production facility;
- identification of the main accident scenarios;
- a qualitative assessment of the severity of the consequences of the implementation of the scenarios;
• high-quality and low-quality accident risk assessment.

Hazard identification is a qualitative method of hazard analysis of technological processes, the purpose of which is to identify the main hazards, negative factors and events that could disrupt the safe operation of the facility and harm the activities and the entire technological system of a hazardous industrial facility as a whole. Hazards are identified on the basis of the analysis of geological and mining and technical conditions of development, mining technology (Table 1).

Figure 1. Flowchart of risk assessment methodology.
A qualitative assessment of the risk of an accident is made on the basis of determining the probabilities of the initial events of the accident and the stages of implementation and the likelihood of an accident (Table 2). After assigning a qualitative assessment of probability, an assessment of the severity of the consequences takes place (Table 3). Based on the data obtained, the degree of risk is determined using the matrix (Table 4).

### Table 1. Types of accident hazards.

| Factors               | Hazards                                                                 |
|-----------------------|------------------------------------------------------------------------|
| Geomechanical         | • destruction, blockages, collapse of mine workings;                   |
|                       | • rock movement;                                                       |
|                       | • dynamic phenomena, rock bursts, destruction of the lining of mine workings. |
| Hydrogeomechanical    | • flooding of trunks and mine workings;                                |
|                       | • formation of dips, breakthrough of water in mine workings.           |
| Gas dynamic           | • sudden release, breakthrough of toxic and combustible gases into the workings; |
|                       | • accumulation of toxic gases exceeding the maximum permissible concentrations |

### Table 2. Event probability.

| Level designation | Level description | Object characteristics | Numerical assessment of probability 1 / year |
|-------------------|-------------------|------------------------|--------------------------------------------|
| A                 | Very high         | The event is expected to be highly likely | > 10^3                                    |
| B                 | High              | The event occurs repeatedly at similar facilities | 10^4 ÷ 10^3                               |
| C                 | Middle            | Event may happen        | 10^5 ÷ 10^4                               |
| D                 | Low               | Event may occur, but not expected | 10^6 ÷ 10^5                               |
| E                 | Extremely unlikely| Event may occur in exceptional circumstances. | < 10^6                                    |

### Table 3. The severity of the consequences of the accident.

| Level designation | Level description | Impact on people | Impact on the enterprise | Impact on the environment | Economic damage [mln.rub] |
|-------------------|-------------------|------------------|--------------------------|---------------------------|-------------------------|
| 5                 | Catastrophic      | Numerous accidents | Violation of the technological cycle. Reconstruction required | Extreme environmental damage | > 150.0                 |
| 4                 | High              | Disability, single accidents | Loss of prepared reserves. Damage or loss of stock | Significant environmental effect | 30.0 ÷ 150.0            |
| 3                 | Middle            | Significant injuries or damage to health | Damage to equipment and / or infrastructure requiring repair | Moderate environmental damage | 15.0 ÷ 30.0             |
| 2                 | Low               | Minor injuries    | Accidents do not affect the process | Local environmental damage | 1.5 ÷ 15.0              |
| 1                 | Minor             | Minor damage to health | Local repairs | Minimal environmental damage | < 1.5                  |
Table 4. Risk assessment matrix.

| Risk matrix | Effects | Qualitative | Quantitative |
|-------------|---------|-------------|--------------|
| Risk probability | 1 | 2 | 3 | 4 | 5 |
| A | Very High - The event is ongoing with a high degree of certainty. | >40% | medium | high | high | very high | very high |
| B | High - An event often occurs with a high degree of certainty | 20 ÷ 40% | low | medium | high | high | very high |
| C | Medium - An event can occur. It happened earlier | 10 ÷ 20% | low | low | medium | high | very high |
| D | Low - An unlikely event. May occur at a certain point | 1 ÷ 10% | very low | low | medium | high | very high |
| E | Very low - Reasonable confidence that the event will not happen. May occur in exceptional circumstances | < 1% | very low | low | medium | medium | high |

Depending on the level of risk obtained, a decision is made on the need to adjust it. Risk management is to reduce the likelihood of accidents and reduce the severity of its consequences by developing response measures in accordance with the level of risk (Table 5).

Table 5. Risk Response.

| Risk level | Response measures | Activities | Note |
|------------|-------------------|------------|------|
| Very high (emergency state) | Immediate stoppage of work in this area, withdrawal of people | Determination of the boundaries of the danger zone and the prohibition of finding people. Conducting additional research and developing operational measures to reduce risk to an acceptable level. | Resumption of work as agreed with the territorial regulatory body |
| High (pre-emergency condition) | Suspension of work on this site, withdrawal of people and equipment | Determination of the boundaries of the danger zone. Analysis of the situation and development of operational measures to reduce risk to an acceptable level. | Resumption of work by decision of the technical manager of the operating organization based on monitoring the situation |
| Medium (state of limited working capacity) | Commission decision on the need to suspend work | Conducting a situation analysis and developing long-term measures to reduce risk to an acceptable level | Monitoring the implementation of activities |
| Low and very low (operational state) | Allowable risk should be controlled, but does not require additional measures to reduce it. | No measures are required. | - |

According to the above methodology, the analysis of the adopted design decisions of the sizes of hazardous water breakthroughs into the mine workings of the zones at the “Internatsionalnaya” kimberlite pipe deposit was analysed, as a result of which a high level of risk of water breakthrough into the mine with catastrophic consequences was assigned. The reduction in the probability of the event was achieved due to the improvement of the reliability of the initial data in the calculation method and the refinement of the calculation model with the involvement of additional influencing factors.
4. Establishment of hazardous area parameters from water bodies

One of the priority ways to prevent the occurrence of possible incidents and accidents in the regulatory documentation provides for the use of passive protection with an effective distance (including physical barriers) from the harmful effects of the damaging factors of possible accidents at the design stage of hazardous industrial facilities. In mining, these areas are called hazardous areas. A hazardous area is understood as a developed subsurface area within which additional mining safety measures are required during mining operations, usually accompanied by separate projects [2].

Previously, the basis of the methodological approach used to determine the size of the barrier pillars between open and underground mining in the kimberlite deposits of Yakutia was based on determining the conditions for the appearance and development of subvertical water-supply cracks in the pillar, which were calculated on the basis of the theory of rock displacement.

The provisions of the theory satisfactorily describe the processes of displacement, deformation, and crack formation in massifs of sedimentary rocks, when underworking passes are equal to or greater than the depth of mining operations, at depths of up to 500-700 m. are not performed, respectively, the results of calculations made in accordance with the provisions of the regulatory documents in force at the enterprise do not provide the necessary reliability of the calculations, thereby overestimating the probability of a negative event when calculating the risk.

Previous studies [3] carried out at IPKON RAS under the conditions of mining indigenous kimberlite deposits in Yakutia, including based on the results of actual observations, made it possible to establish that the process of deformation and subsidence of undermined kimberlite massifs is discrete, rather than smooth, due to the block structure of the massif.

Depending on the physicomechanical and structural properties of the rocks, the parameters of the ore body, the depth of the mining operations and the development technology used, the formation of the zone of water-supply cracks can develop according to various schemes.

When the power of the pillar is less than the height of the arch of rock caving above the worked-out space, the formation of the zone of water-conducting cracks occurs due to the deflection of the pillar with the formation of through secant cracks and can be determined by the method of maximum subsidence of the layer.

When the power of the pillar is greater than the height of the arch of the collapse of rocks, the formation of water-conducting cracks develops within the arch of the collapse. Outside the boundaries of the collapse arch, there are no tensile stresses in the rocks and, accordingly, there are no conditions for the development of water-conducting cracks [16].

For the correct determination of the parameters of the ore pillar under the conserved quarry, it is necessary to use a calculation method that considers the geological structure of the pipe, the stress-strain state of the ore and rock mass, the qualitative characteristic of the rock mass of the pillar, and the potential impact of subsequent mining operations.

Given the above calculation methodology has been adjusted. The establishment of the parameters of the danger zone from the water body is based on the mechanisms of development of geomechanical processes, but it is selected after assessing the state of the massif.

To determine the characteristics of the massif, it is proposed to use the MRMR indicator, which determines the tendency of the massif to collapse in specific mining and geological conditions and the geological strength index (GSI) in mathematical modelling. To date, in world practice, the rating classification of D. Lobshire (MRMR) is the most multifunctional and practical. Correct application of the system gives good results and is widely used in design in Austria, South Africa, the United States, India and Europe. However, as shown by practical experience, each calculation should be performed for a specific part of the rock mass. Averaging a large range of ratings will inevitably lead to a false quantitative indicator.

The adjusted design scheme is based on the mechanism of collapse development, in which the destruction of rocks occurs under the influence of its own weight due to weak ties of structural blocks to each other. Such a mechanism is characteristic of disturbed arrays with low resistance to tensile stresses and most fully takes into account the structural state of the array.
As a result of the analysis, it became possible to develop effective compensation measures aimed at reducing the development of self-collapse processes in the lower part of the pillar and preventing the development of dome formation processes, which made it possible to provide an acceptable level of risk for the time of working out the under-quarry part of the kimberlite pipe.

5. Conclusions
In conditions of continuous variability of the field’s operating conditions and under-exploration, a necessary condition for safe mining is manoeuvrability in a changing situation. The work carried out clearly demonstrates that the application of the risk-based approach allows us to take effective measures to manage the conditions of mining operations and to increase their level of safety.

Preliminary ranking of areas by risk, that is, the likelihood of a particular negative event occurring at the mining enterprise, will ensure a high level of safety at all stages of field development, and it will also stimulate the development of automation and robotics in mining. The application of the proposed approach is fully consistent with the modern concept of sustainable development of civil engineering works [17] and subsoil development [18].

It should be noted that in Russia, as in some other countries with a high level of mining education and science, the practice of phasing in young people to engage in serious scientific research at the stage of university education is successfully used [19,20]. And subsequently their work in serious design institutes.

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