Research and assessment of the rock burst hazardous of the Kola Peninsula mineral deposits by seismic-acoustic monitoring data

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Abstract. The results of geomechanical studies to assess the rock burst hazard at the deposits (Kukisvumchorr and Apatite Circus) of the Kola Peninsula are presented in the article. These results are obtained by special set of technical means, including an automated seismic acoustic rock pressure monitoring system "Prognoz-ADS" and a portable geoacoustic device "Prognoz L" developed at the Mining Institute of the Far Eastern Branch of the Russian Academy of Sciences. Based on the measurement and analysis of the parameters of seismoacoustic events, reflecting the geomechanical processes in the mined rock mass, maps of seismoacoustic activity combined with 3D mining and geological models of mines were developed. Based on the analysis of the spectral parameters of the signals, it was concluded that the use of the developed software and hardware complex is promising for predicting dynamic phenomena in the rock massif. The rock burst hazard can be assessed by the measuring complexes at these deposits; necessary safety measures can be taken for decrease of geodynamic risk.

1. Introduction
Underground development of mineral resources and mining construction in difficult mining and geological conditions and at increasing depths are associated hazard manifestations of rock pressure, both in statistical and dynamic forms. Rock pressure manifestations in hazard forms are displacement and collapse of areas of the massif, sudden outbursts of rock and gas, rock shots, rock and tectonic bursts leading to catastrophic consequences. A distinctive feature of the dynamic manifestations of rock pressure, especially rock and rock-tectonic bursts, is their suddenness and great destructive force. They cause great material and social damage to mining enterprises, lead to long stops in the mining process. It is caused by large-scale restoration work on large areas of the mine field. In terms of scale of negative consequences, powerful rock bursts can be attributed to man-made disasters [1-7].

There are a number of burst hazard ore deposits in Russia. JSC "Apatite" develops a number of deposits of apatite-nepheline ores, characterized by difficult geomechanical and rockburst hazardous conditions (figure 1). The object of research was two deposits: Kukisvumchorrsk ("United Kirovsk" mine) and Apatite circus (Rasvumchorrsk mine). Growth of depth of mining operations leads to an increase in the number and intensity of hazard phenomena. The high intensity of mining at these mines led to the formation of a vast zone of technogenic disturbance of the geo-environment, which was one of the reasons for the activation of geodynamic processes in the rock mass containing the mined deposits.
In recent years, manifestations of technogenic seismicity have been observed at the Khibiny deposits, recorded in underground mine workings and on the surface.

![Figure 1. Longitudinal section of the exploited Khibiny deposits.](image)

2. Mining and geological conditions for the development of the Khibiny deposits

Khibiny apatite-nepheline deposits are unique deposits of phosphate raw materials in terms of reserves and quality, located in the Murmansk region on the Kola Peninsula, Russian Federation. Khibiny deposits are central type of alkaline mass. Their area is over 1300 km². Spatially and genetically, they are related to ijolite-urtite rocks that form an arc in the plan and lie among nepheline syenite. Ore deposits form tabular and lenticular bodies with 80 m average thickness. The main types of ores are apatite urtites and ijolite, sphene-apatite, apatite-nepheline. The apatite content is 10-80 %, nepheline is 20-65 %. Main ore minerals are apatite, nepheline; secondary are alkaline pyroxenes, feldspar, sphene, titanomagnetite, etc [8-10].

3. Methods and technical means of rock burst hazard control

Reliable and operational information about the geomechanical state of the rock mass is an important for forecasting and preventing hazard manifestations of rock pressure. This information can be obtained using geophysical methods and measuring instruments. The most developed and included in the regulatory documents are microseismic, geoacoustic, ultrasonic, electrometric and the method of registration of electromagnetic radiation. Microseismic (seismoacoustic) and geoacoustic methods are widely used. It is possible to carry out both local and regional control of the state of the rock mass by the seismoacoustic and geoacoustic methods. Scale of the assessment (local or regional) depends on the applied technical means. These methods are based on the experimentally observed and theoretically studied phenomenon of acoustic emission (AE). Acoustic emission and electromagnetic radiation accompany the process of mechanical loading and destruction of rocks [11].

One of the main tasks of geomechanical monitoring at rockburst hazardous mines is local hazard assessment (forecast of the probability of dynamic events near the mine). The seismoacoustic multi-channel automated rock pressure monitoring system “Prognoz-ADS” developed at the Mining Institute of the Far Eastern branch of Russian Academy of Sciences and the local device “Prognoz-L” are used on these deposits for local hazard assessment (figure 2).

Assessment of the geomechanical state of a rock mass based on seismoacoustic monitoring data using the automated rock pressure monitoring system (ARPMS) "Prognoz-ADS" is one of the most promising directions for forecast and prevention sudden destruction of rock structures. They are effective for forecast and prevention of rock and rock-tectonic bursts (man-made earthquakes) and sudden destruction of pillars and mine workings [12–16]. ARPMS Prognoz-ADS is designed for continuous recording of seismoacoustic emission pulses in 0.5...12 kHz frequency range in a rock mass. Prognoz-ADS determines parameters of seismoacoustic emission (energy, coordinates, spectral and other characteristics of acoustic events) and presenting monitoring results in the form of catalogs, maps, graphs using modern 3D visualization software [17–20].
Figure 2. Technical means for assessing the burst hazard: a - underground modules of the automated seismoacoustic system for monitoring rock pressure "Prognoz-ADS"; b – portable device "Prognoz-L".

Portable devices are designed for local express-assessment of the geomechanical state of the edge parts of the rock mass and the boundary sections of underground mine workings. These devices allow not only recording a large number of AE parameters, but also processing and detailed analysis of the information received, which significantly increases the reliability of predicting dangerous dynamic manifestations [21-23].

Based on the results of long-term geomechanical studies using the seismoacoustic method, analysis and generalization of a representative amount of experimental data obtained in a number of rockburst-hazardous deposits, a comprehensive burst hazard indicator \( K_{BH} \) was substantiated. Burst hazard indicator takes into account the changes in the geomechanical state of the geomedium during the preparation of hazard geodynamic phenomena. The \( K_{BH} \) indicator is defined as the ratio of the normalized (for the previous 5 days) values of the total energy and the number of acoustic emission events in the acoustic active zone to the product of the normalized values of the distance, time between subsequent events and the migration rate of the center of the acoustic activity zone. A processing technique of experimental data is used to identify potential foci of large dynamic manifestations of rock pressure. This technique is based on the methods of cluster analysis and the theory of random graphs. A technique based on statistical analysis of experimental data using the Sturgess distribution rule is used to identify the critical values of the complex indicator \( K_{BH} \). Critical values of \( K_{BH} \) correspond to the transitional stage of the geomechanical state of the rock massif. Sturgess distribution rule is based on the selection of groups in distribution series subject to the normal law [24-25].

4. The results of the research of rock burst hazard according to seismoacoustic monitoring data

The Prognoz-ADS system was installed at the Kukisvumchorr deposit in 2015; at the end of 2019 it was installed at the Apatite Circus deposit. Currently, at the Kukisvumchorrsk deposit (Kirovsk mine), 13 piezoelectric sensors are installed in the control zone; 10 sensors are located at the 170 m horizon. Another 3 sensors are located on 236 m horizon. At the Apatite Circus field (Rasvumchorrsk mine), 16 piezoelectric sensors were installed in the control zone at three horizons (470 m, 450 m, 425 m).

Interesting seismoacoustic activity data were obtained during monitoring of the section of the massif of the Kukisvumchorr deposit of the Kirov mine in the area of 7/10 block. Along with the beginning of the block development, several acoustic active zones (AAZ) began to form. One of the largest active acoustic zones is located at the +236 m horizon. The most representative data on the nature of changes in the acoustic activity of the rock mass in block 7/10, reflecting the preparation of a major geodynamic event, were obtained in January 2016. The formation of an acoustically active zone was observed in the pillar at the horizon of +236 m. It resulted in a dynamic manifestation of rock pressure in the 27th January, 2016. 2497 acoustic events with a total energy of 159.7*10^3 J were registered during this dynamic manifestation of rock pressure. The period of activity of the acoustically active zone was 14 hours (figure 3).
The assessment of rock burst hazard has not yet been carried out at the Apatite Circus deposit (Rasvumchorrsk mine). At the moment there are pilot tests here and a database of seismoacoustic events is being formed. With a sharp increase in seismoacoustic activity in the rock mass, rock burst hazard factors are revealed. Mining operations are corrected by rock pressure control measures in the area of the identified acoustically active zones. The measures are “relaxation” of mined area, drilling of relief wells, shaking blasting.

Figure 3. Map of seismic-acoustic activity in the rock mass before the push on 01/27/2016 at the Kirovsk mine.

Based on the data of long-term mine observations, it was established that the main indicators of the preparation of a rock burst include:

- an increase in the number of SAE events by 2 or more times ($N_{AE}$);
- reduction of the root mean square distance ($R_{MR}$) from the source to the center of the forming focus;
- increase in total energy ($E_{AE}$) by more than 80%;
- reduction in the time interval between the SAE events ($t_{ST}$);
- decrease in the migration rate ($v_{OZ}$) of the epicenter of the focal zone down to 8 m/day.

On this basis, a comprehensive rock burst hazard ($K_{BH}$) indicator was developed, which is defined as the ratio of the normalized (to the data for the previous 5 days) values of the total energy and the number of AE events in the active focal zone to the product of the normalized values of the distance, time between subsequent events and the rate of migration of the center of the zone acoustic activity:

$$K_{BH} = \frac{E_{AE} N_{AE}}{R_{MR} t_{ST} v_{OZ}}$$

(1)

where $E_{AE}$ – summary energy of SAE-events in the focal zone (connected events), J; $N_{AE}$ – number of SAE-events in the focal zone; $R_{MR}$ – distance between subsequent SAE-events, m; $t_{ST}$ – time between the subsequent AE-events, s; $v_{OZ}$ – speed of migration of the center of a focal zone, m/days.

An increase in the number of events in several parts of the massif, a decrease in the migration rate of acoustically active zones and a change in a number of other parameters of the seismic-acoustic events have been observed for 24-27 January 2016. The values of the rock burst hazard indicator ($K_{BH}$) increased 2 days before the manifestation. $K_{BH}$ exceeded 300 immediately before the rock burst (figure 4).
Figure 4. Graphs of changes in acoustic activity parameters during the preparation of a geodynamic phenomenon in block 7/10 of the United Kirovsk mine.

“Hazard” category is given on the basis of the quantitative values of an $K_{BH}$ indicator. The indicator is calculated by methods of the discrete analysis and mathematical statistics with the application of interval algorithms of a pattern recognition. For the uranium Antej deposit the critical value of the burst hazard indicator was 5.11 ($K_{BH} > 5.11$). The reliability of forecasts of dynamic manifestations for the last 5 years was rather high and was 84.4%.

At the end of 2019, the Prognoz-ADS seismoacoustic system was also installed at the Apatite Circus deposit. Apatite Circus is developed by the Rasvumchorsk mine. According to the seismic acoustic control, 22364 events has been registered at the Rasvumchorsk mine by the Prognoz-ADS system for 1.02.2020-1.02.2021. A preliminary assessment of the geo-mechanical state of the massif was carried out on the basis of filtering criteria for technological interference developed for the Kirovsk mine database. Based on the filtration results, 15713 events (70%) were classified as technological noise (drilling, explosions, etc.).

In total, 6651 acoustic emission events were registered at the Rasvumchorsk mine for 1.02.2020-1.02.2021. Analysis of the diagram of the number and total energy of acoustic emission events reflects their fairly uniform monthly distribution (figure 5). On average, from 300 to 700 acoustic events were recorded per month.
Figure 5. Diagram of the distribution of the amount and energy of AE events registered at the Rasvumchorr mine for the period from February 2020 to the end of January 2021.

Acoustic activity was observed at the 425m horizon in the first half of February, April and May 2020 after blasting operations carried out at the intersection of the Southern bottom gate and the ventilation assembly (figure 6). In total, 4 acoustically active zones were recorded here with a total of 309 AE events. The distribution of acoustic activity at the 450 m horizon is shown in figure 6. 2269 AE events has been registered here for 12 months of the “Prognoz-ADS” system operation. High acoustic activity was observed in the area of some mine workings. The lowest acoustic activity was observed at the 470 m horizon; 723 AE events were recorded during the research period. The overwhelming majority of recorded AE events are located at the intersection or in close proximity to fault structures.

Figure 6. Map of the acoustic activity of the Rasvumchorr mine 1.02.2020 – 1.02.2021, horizon 425 cross-section.
A push was registered by the "Prognoz-ADS" system on 10.06.2020 at 14:44 at the Rasvumchorr mine. The epicenter coordinates are X = 1126.94 m, Y = 153.61 m, Z = 305.70 m. The event energy is 6761 J. No precursors or aftershocks were recorded. This is explained by the remoteness of the monitoring network from the epicenter. The push coordinate is located at 189 m distance of the nearest sensor.

5. Conclusions
1. A measuring complex consisting of an automated seismoacoustic rock pressure monitoring system "Prognoz-ADS" and portable geoacoustic devices "Prognoz L" has been used to control rock burst hazard at Kukisvumchorr and Apatite Circus deposits since 2015.
2. Based on the monitoring results, maps of seismoacoustic activity are designed, combined with 3D mining and geological models of mines. The data are verified with local measurements of the measuring complex.
3. Based on the results of complex geomechanical monitoring and long-term research, it has been established that an important feature of the behavior of a rock burst-hazard massif is the formation of active zones (potential foci of geodynamic phenomena). The process of clustering of sources of microdestruction occurs inside active zones. We have developed an original technique for identification and analysis of emerging foci. This technique is based on the theory of random graphs using the established connectivity component. The state of the massif within potentially rockburst-hazardous areas is assessed using the complex indicator \( K_{BH} \), which includes a number of the most significant prognostic signs. The "Hazard" category is established by quantitative values of the indicator \( K_{BH} \). \( K_{BH} \) is determined by methods of discrete analysis and mathematical statistics using interval pattern recognition algorithms.
4. With the help of this measuring complex, it becomes possible to assess the rock burst hazard at Kukisvumchorr and Apatite Circus deposits and to determine of centers of the preparation of hazard geodynamic events at an early stage their formation. It allows taking the necessary safety measures in advance to prevent hazard geodynamic events.

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