Geodynamic risk magnitude as an objective indicator of rockburst prevention effectiveness (in terms of apatite mines in Khibin)

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Abstract. The results of the statistical retrospective analysis of the officially recorded geodynamic events in mines of Apatit Company within the Khibiny Massif are presented. The risks and aftereffects of geodynamic events have been calculated. Under discussion are the results of three calculation variants taking into account the scale of human impact on rock mass. The analysis shows that the main damage due to geodynamic events is different-degree destruction of mine workings while the remaining aftereffects account for less than ten percent. That is, the geodynamic risk in apatite mines can be identified as technological.

1. Introduction
Among the numerous problems in the mining industry, the most acute issue is still induced seismicity—rock bursts and induced earthquakes governing geodynamic risks. This problem remains of concern in Russia, Australia, South Africa, Canada, USA, South America and in many other countries. Irrespective of ownership, the most widely used standard risk factor is individual risk characterizing number of fatal accidents (or severe injury accidents) and including probability of negative event. Different values of maximum permissible level (MPL) of individual risk in different countries show that mortality risk higher than $10^{-4}$ per year is inapplicable (too high) as MPL. Expert estimates based on generalization of implemented research findings, including avowed safety, state that MPL of individual risk in Russia should be within $10^{-6}$–$10^{-5}$ per year [1, 2].

Risk ratings and indexes customary in geodynamic safety are mostly qualitative. This is explained by the complex physical nature of initiation and instance of dynamic events, huge number of interfering factors and difficulty of mathematical formalization for determining quantitative parameters of danger level. Geodynamic risk, depending on probability of hazardous event, hazardous situation or hazardous process, is ranked as low, medium and high (ore negligible, admissible and inadmissible).

All that is positively applicable in estimation of geodynamic risk at rockburst-hazardous mineral deposits in Khibiny [3].

2. Object of research
Khibiny is an alkaline intrusive of central type, the natural events are seldom and have magnitudes not higher than 1–2 on a scale from 1 to 12 by Medvedev–Sponheuer–Karnik (MSK-64). Shallow induced earthquakes with magnitudes 2–4 (MSK-64) and low-energy geodynamic events recorded in the Khibiny mines are explained by effects (both natural and technical) on the actual large-scale mining.
Out of natural effects, mines are heavily affected by variation in water content of rock mass, which is seasonal (except for the cases when mines expose aquifer strata, which is independent of seasons). Temperature changes, lunar and solar cycles, gas emanation, etc. have weaker influence on mining performance. Influence of natural factors on geodynamic events depends on structural features of rock mass—the impact is stronger near faulted and oxidized zones and lower in weakly damaged zones of hard rock mass.

Technology factors also have different effect on geodynamic behavior of rock mass. Geodynamic risks differ by the scale of their aftereffects. In a greater degree, the influence of technology factors is conditioned by the scale of mining operations: in the course of apatite–nepheline mining in Khibiny, nearly 4.5 Bt of rock mass are extracted, displaced and stored partly. This is added by the influence of change in the mining technology (for example, transition from block caving to sublevel caving). In a lesser degree, the technology impact is connected with the adjustment of separate process designs (e.g. transition to another type of explosives, etc.).

A geodynamic event may end in no failure in mines but is unambiguously indicative of a hazard. It is clear that aftereffect of a geodynamic event is governed the power of the event and its source coordinates [4]. After a remote event, tremors are possible in underground excavations, and the sound and strength of the tremor depends on the energy of the geodynamic event; after a near by geodynamic event, a rock burst is possible in a mine. The risk assessment should account for influence exerted by different factors.

The expert risk estimate (in the first approximation) uses standard methods of the statistical analysis in order to find trends of change in parameters; thereupon, a decision is made on expediency of detailed elaboration and multifactor analysis.

3. Calculation procedure
For the geodynamic risk assessment in apatite mines, based on the statistical post-even analysis of records, probability of geodynamic events and degree of their aftereffects were calculated using the available data base on geodynamic events recorded in mines by the Commission on Rockbursts of Apatit Company over the period from 1981 to 2015. The assessment was implemented for seven spans of 35, 30, 25, 20, 15, 10 and 5 years with regard to the change in the geotechnical situation by the ends of these periods.

Within the whole time period mention, round 70 geodynamic events were recorded, with different-degree destruction in mines and, sometimes, equipment damage and injuries. Geodynamic events without aftereffects were also recorded.

For the geodynamic risk assessment, 54 events were picked up in the data base as their records contained all information on all parameters involved in the analysis.

The probability of a geodynamic event and its aftereffects (if any) were calculated using the formulas presented below in this section.

The geodynamic event probability \( P_{\text{total}} = N_{\text{total}}/T_{\text{total}} \), where \( N_{\text{total}} \)—number of recorded events; \( T_{\text{total}} \)—period of time within which these events were recorded.

It is possible to calculate a general probability (all events irrespective of class), or a probability per a class (for rock bursts only, or for induced earthquakes only). This paper presents data calculated based on all recorded events of different classes in the specified time spans.

The excavation failure probability \( P_{\text{exc}} = (N_{\text{exc}}/L_{\text{exc}})/L_{\text{tas}} \), where \( N_{\text{exc}} \)—number of recorded events resulted in failure of underground excavations; \( L_{\text{exc}} \)—failure zone length; \( L_{\text{tas}} \)—total length of excavations.

These calculations used information from logs of specific rock bursts recorded by the rockburst prediction and prevention services of mines. On the whole, these formulas can involve prehistory data (length of damages during spalling, extensive formation of loose rocks in walls and roofs in mines). In this case, the information is taken from field books of the rockburst prediction and prevention services of mines.
The equipment damage probability \( P_{be} = \frac{N_{be}}{(T \cdot N_e)} \), where \( N_{be} \)—number of recorded events; \( T \)—time; \( N_e \)—number of machines in excavations.

Unfortunately, not every process damage is recorded (mainly, the most severe cases). For example, when a dynamic event damages equipment but the machine leaves the place in self-propelled mode, this case remains beyond records (here, social and economic factors come forward). In this respect, this parameter is calculated very approximately (at different times, the value can increase by 10 to 30%).

The injury probability \( P_{bm} = \frac{N_{bm}}{(T \cdot N_m)} \), where \( N_{bm} \)—number of recorded events; \( T \)—recording period of time; \( N_m \)—number of personnel in excavations.

This parameter depends on the recording process quality, too. Only permanent injuries and fatal cases are entered on rockburst logs. Thus, the calculated values of this parameter do not show the truth picture and impair the statistical estimation results.

The no-aftereffect probability \( P_w = \frac{N_w}{T} \), where \( N_w \)—number of recorded events; \( T \)—recording period of time. The data on this parameter are seldom recorded as are identified as tremors. As a rule, it is economically unreasonable to interrupt production processes in case when no damages are revealed. Thus, these statistical calculation results also can be insufficiently representative.

The calculation procedure assumed some constraints. For instance, the probabilities of geodynamic events and aftereffects were calculated for 1 year for the excavation damage probabilities—for 1 m³ of excavation for year. It was also taken into account that within 86 years-long mining at apatite–nepheline deposits in Khibiny since 1929 till 2015 by Apatit Company, tunnel driving reached 600 km log (7000 m per year on average). The analysis used data on geodynamic events recorded in all mines of Apatit Company, in one mine and on a single level.

4. Results and discussion

We present the calculated results with respect to the mining scale for there variants: 1—for all mines of Apatit Company; 2—for Kirov Mine (KM) of Apatit and 3—for a level in KM.

Variant 1 for all mines: the calculations of the event probability and risk level took into account that: for 35 years tunnel drivage totaled 245000 running meters out of which in 20% of this length (average 1400 m/yr) damage was recorded, and 20000 machines and 4000 people were there within a year.

Table 1 gives the values of the calculated probabilities for geodynamic events of a certain class for different spans of times and their aftereffect probabilities for the period from 1981 to 1985 (5 years) and from 1981 to 1990 (10 years) and so on. The time span was selected in order to trace the change in the values of the calculated parameters as mining front was advanced.

It is clear from Table 1 that the calculated probabilities have values within \( 10^{-9}–10^{-7} \), i.e. they are very low and their risk depends on the whole period of observations and on the spans of its constituents.

Variant 2 for Kirov Mine: the calculation conditions were 164000 running meters of tunnel drivage (7000 m per year on average) out of which 20% (average 1400 m) were damaged and accommodated 5000 machines and 1000 miners within a year. The calculated results are compiled in Table 2.

It follows from Table 2 that, similarly to Variant 1, the calculated probabilities and risk levels are very small and are within \( 10^{-10}–10^{-8} \). As against Variant 1, the range expanded towards lower values, and the values of some parameters decrease by an order of magnitude.

Variant 3 for a level in a mine: the calculations assumed that drivage made 1000 running meters on the level over the period from 1981 till 2015, and 600 machines and 250 miners were yearly present in the excavations on this level.

In Variant 3 the calculated values are within \( 10^{-9}–10^{-7} \) per year. As compared with the data obtained in the first two variants, the third variant values of probabilities and risks lie in a narrower range — \( 10^{-9}–10^{-8} \) per year. The no-aftereffect probability in this variant is higher by an order of magnitude. Nonetheless, the values of the other parameters remain at the level of negligible risk.
Table 1. General probability of negative geodynamic events and their aftereffects in Apatit Co. mines between 1981 and 2015.

| Time span $T_{	ext{total}}$ years | Number of events $N_{\text{total}}$ | Geodynamic event probability $P_{\text{total}}$ | Risk of event $N_{w}$ per $1 \text{ m}^3$ of excavation per year | Excavation damage probability $P_{wa}$ | Equipment damage probability $P_{wb}$ | Risk of event $N_{w}$ per year | Injury rate $N_{\text{inj}}$ men | Risk of event $P_{\text{inj}}$ per year | No-aftereffect event $N_{n}$ | Risk of event $P_{n}$ per year |
|----------------------------------|-------------------------------------|---------------------------------------------|-------------------------------------------------|-----------------------------------|-----------------------------------|--------------------------|-----------------------------|-----------------------------|-----------------|-----------------------------|
| 35                               | 54                                  | 2.0E-08                                     | 51                                              | 2.0E-07                          | 4.0E-09                          | 4                        | 2.0E-08                     | 4                          | 3.0E-04         |                |
| 30                               | 49                                  | 2.0E-08                                     | 43                                              | 2.0E-07                          | 3.0E-09                          | 3                        | 2.0E-08                     | 3                          | 3.0E-04         |                |
| 25                               | 41                                  | 3.0E-08                                     | 37                                              | 2.0E-07                          | 1.0E-09                          | 3                        | 2.0E-08                     | 2                          | 2.0E-04         |                |
| 20                               | 34                                  | 3.0E-08                                     | 31                                              | 2.0E-07                          | 3.0E-09                          | 3                        | 4.0E-08                     | 2                          | 3.0E-04         |                |
| 15                               | 30                                  | 5.0E-08                                     | 30                                              | 3.0E-07                          | 5.0E-09                          | 3                        | 7.0E-08                     | 1                          | 2.0E-04         |                |
| 10                               | 23                                  | 9.0E-08                                     | 20                                              | 3.0E-07                          | 9.0E-09                          | 0                        | 0                           | 0                          | 0               |                |
| 5                                | 12                                  | 2.0E-07                                     | 12                                              | 3.0E-07                          | 0                               | 0                        | 0                           | 0                          | 0               |                |

The comparison of the values obtained in all three variant shows that, on the whole, the level of risk of a geodynamic events and its aftereffects is low in apatite mines and lies within the range of negligible individual risk values—$10^{-11}$–$10^{-7}$ per year. This means that, depending on the data analysis scale (for the whole mine, or for a level in a mine), the values of individual risk change but the risk level is yet low.

Table 2. General probability of negative geodynamic events and their aftereffects in Kirov Mine of Apatit Co. between 1981 and 2015.

| Time span $T_{\text{total}}$ years | Number of events $N_{\text{total}}$ | Geodynamic event probability $P_{\text{total}}$ | Risk of event $N_{w}$ per $1 \text{ m}^3$ of excavation per year | Excavation damage probability $P_{wa}$ | Equipment damage probability $P_{wb}$ | Risk of event $N_{w}$ per year | Injury rate $N_{\text{inj}}$ men | Risk of event $P_{\text{inj}}$ per year | No-aftereffect event $N_{n}$ | Risk of event $P_{n}$ per year |
|----------------------------------|-------------------------------------|---------------------------------------------|-------------------------------------------------|-----------------------------------|-----------------------------------|--------------------------|-----------------------------|-----------------------------|-----------------|-----------------------------|
| 35                               | 21                                  | 7.0E-09                                     | 18                                              | 2.0E-09                          | 3.0E-09                          | 2                        | 2.0E-08                     | 3                          | 6.0E-08         | 2                          | 2.0E-04         |
| 30                               | 16                                  | 7.0E-09                                     | 16                                              | 2.0E-09                          | 4.0E-09                          | 3                        | 2.0E-08                     | 3                          | 8.0E-08         | 2                          | 2.0E-04         |
| 25                               | 13                                  | 8.0E-09                                     | 13                                              | 3.0E-09                          | 2.0E-09                          | 3                        | 2.0E-08                     | 3                          | 1.0E-07         | 1                          | 1.0E-04         |
| 20                               | 11                                  | 1.0E-08                                     | 11                                              | 4.0E-09                          | 2.0E-09                          | 3                        | 4.0E-08                     | 0                          | 0               | 0                          | 1.0E-04         |
| 15                               | 6                                   | 1.0E-08                                     | 6                                               | 3.0E-09                          | 2.0E-09                          | 0                        | 0                           | 0                          | 0               | 0                          |                |
| 10                               | 2                                   | 8.0E-09                                     | 2                                               | 3.0E-09                          | 1.0E-09                          | 0                        | 0                           | 0                          | 0               | 0                          |                |
| 5                                | 1                                   | 2.0E-08                                     | 1                                               | 5.0E-09                          | 1.0E-09                          | 0                        | 0                           | 0                          | 0               | 0                          |                |
5. Conclusion
The data reported in this paper show that the main impact of geodynamic events consists of the various degree damage caused to underground excavations while the other aftereffects total less than 10 percent. This means that the geodynamic risk can be identified as technological.

Thus, geodynamic risks are common in mining in high-stress hard rock mass. The calculations of separate risks over certain time period, based on the available statistics for the conditions of mine-technical systems in apatite mines show that the individual risk level under geodynamic event and its aftereffects is very low and lies within $10^{-11}$–$10^{-8}$ per year, i.e. inside the range of negligible quantities, which is an evidence of high efficiency of rockburst countermeasures. It has been found that the highest damage is caused to mine workings, i.e. to the technology process. For this reason, the issues of the geodynamic risk control should be the top-priority goal alongside with their prediction and estimation.

References
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