Geomechanical substantiation of the Oleniy Ruchey deposit underground mining in a protective pillar of the Niorkpakhk open pit

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Abstract. The location of significant volumes of the lower level reserves close to an open pit which produces the adjacent Niorkpakhk deposit considerably complicates underground mining of the Oleniy Ruchey rockburst-hazardous deposit. The progress of underground excavations into the under-pit space is permitted if the undermined rock thickness and open pit walls remain stable. 3D numerical studies of stress-strain state have indicated particularities in deformation such as increase in undermined thickness stability under high tectonic stresses. The parameters of safe mining of temporary inactive reserves were scientifically substantiated. The boundaries of maximal development of underground mining were determined. The stability of overlying rocks and open pit walls is maintained by forming an advance of overlying sublevels relative underlying ones under 45° angle and providing the monitoring for the undermined rock mass. The mining method in a protective pillar the authors propose allows increasing reserves of the first mining stage by 76.9% and avoiding decrease in production volumes when mining operations terminate.

1. Introduction
The Oleniy Ruchey apatite-nepheline deposit is located at the Khibiny rock massif, north-western Russia. Nowadays the deposit is being mined by both the open pit and the underground mine. Acting tectonic stresses typical for all the Khibiny deposits [1] and rock proneness to brittle fracture determine the geomechanical state of the deposit's rock mass. One of the factors restraining underground mining progress is a close location of underground reserves to the adjacent Niorkpakhk open pit. Due to this fact, the considerable part of the Oleniy Ruchey reserves is conserved in a protective pillar (figure 1).

The current instructions [2] use a simplified approach to determine parameters and construction of protective pillars. This approach ignores secondary compression of the rock mass typical for the deposits under study. “Management Instructions of overlying rocks caving” [3] also disregards a factor of high tectonic stresses in the part of construction of protective pillars. The boundaries of the protective pillars are determined by planes under an angle of 75° (or 70° in oxidized zones). The production of underground reserves of the Khibiny apatite deposits with ore and host rock caving mining methods has shown the difficulty to achieve total caving of undermined rocks in analogous conditions. For example, the Apatitov Tsirk deposit’s ore body thickness is several-fold larger and initial excavation depth is smaller by 100 and more meters. The total caving of undermined rocks took place there while constructing a stoping excavation of 1 km length.
The earlier studies [4] have shown a principal possibility of underground mining in a protective pillar. The studies in our paper are aimed at determination of secure parameters for underground mining when correcting boundaries of a protective pillar.

2. Geological and geomechanical characteristics of a deposit
The Oleniy Ruchey deposit is located at the eastern part of the Khibiny apatite arc and has a complicated multilevel structure consisting of alternating tabular apatite-nepheline ore, trachytoid urtite, ijolite, melteigite, massive urtite, juvite, and nepheline syenite. The deposits are separate tabular ore bodies which are located in two ore levels: upper (thickness of 200 m) and lower (thickness of 50-330 m) and separated by thick (200-300 m) barren rocks.

Host rocks, including majority of ores, are brittle and strong. Table 1 gives principal physical and strength rock properties.

| Rock parameter                  | Host rocks | Apatite-nepheline rocks |
|---------------------------------|------------|-------------------------|
| Compressive strength, $\sigma_{\text{uccs}}$, MPa | 80-340     | 60-120                  |
| variation limits                |            |                         |
| average value                   | 210        | 95                      |
| Tensile strength, $\sigma_t$, MPa | 8-37       | 5-8                     |
| variation limits                |            |                         |
| average value                   | 19         | 5                       |
| Brittleness index, $\sigma_{\text{uccs}} / \sigma_t$ | 11         | 19                      |
| P-wave velocity, km/s           | 4.6        | 4.0                     |
| average value                   |            |                         |
| Young's modulus, E, GPa         | 13-90      | 15-60                   |
| variation limits                |            |                         |
| average value                   | 55         | 3.8                     |

During some last years, specialists from the Mining Institute carried out in-situ studies of the deposit’s stress field parameters. The doorstopper method has established that the maximum
component vector of compressive stresses has the azimuth of 71-90° and an inclination to horizon not more than 30°. The measurement data refer the Oleniy Ruchey deposit stress state to gravity-tectonic type.

Table 2. The stress measurement results, the Oleniy Ruchey deposit.

| Depth (level), m | Maximum principal stress, MPa | Middle principal stress, MPa | Minimum principal stress, MPa |
|-----------------|-----------------------------|-----------------------------|-----------------------------|
| 340 (+240)      | 26                          | 20                          | 8                           |
| 400 (+240)      | 31                          | 23                          | 9                           |
| 600 (+40)       | 43                          | 32                          | 11                          |

High stress values in the rock mass and rock proneness to brittle fracture allow referring the deposit to rockburst-hazardous, which is fixed in instructive documents [5].

At this stage of the research, geotechnical core logging and outcrop mapping in underground openings were not performed. And there wasn’t any information about the rock mass quality. That is why we have to use a homogeneous isotropic model.

3. Study methods

We determined the safe parameters for underground mining in correction of the boundaries of a protective pillar. For this, we estimated the rock mass stress-strain state for different options. The calculations were performed with 3D finite element method in Sigma GT software [6]. The software was designed in the Mining Institute KSC RAS and is successfully applied at the Russia’s mining enterprises [7].

The boundary conditions were based on in-situ stress measurement data from the underground mine (table 2) and on a previously developed model of the Oleniy Ruchey and Niorkpakkh deposits [5]. When designing the model, we considered a complicated relief, ore body parameters, rock properties (table 1), marks of underground levels and sublevels. figure 2 shows a three-dimensional view of the model, where the gray elements are waste rock, and the green elements are modeled ore bodies. figure 3 shows the vertical cross section of the upper part of the model.
Reduced mesh elements are used in an area of mining operations, where the size of every element is 10m×10m×5m. The model is oriented in accordance with the mine coordinate grid and contains 1 640 000 elements; its dimensions in plan are 2420m x 2050m; the bottom is -1000m.

The maximal stress distribution analysis permits determining the most rockburst-hazardous rock mass parts at different production stages. We assumed that in the rock mass areas where the maximum stresses exceeded the half compressive strength of the rocks, dynamic failures like a rockburst can occur [6].

The minimal stress data are determinative when defining the undermined rock mass caving parameters. Analyzing minimal stresses, we supposed possible development of ruptures in the zones of tensile stresses $\sigma_{\text{min}}$. Based on ruptures we can estimate the parameters of disturbed zones in the undermined rock mass. The analysis of their values and distribution in undermined rock mass allow estimating the underground mining impact on a protective pillar of the Niorkpakkh open pit.

4. Results
We have performed a multivariate modelling of the rock mass stress-strain state and specified the ore bodies’ parameters and consequent stoping extraction up to P6+40 m cut. We also varied the parameters of advance of overlying mining to underlying operations within protective angles of 45, 60 and 75°. The increase in the angle of progressing mining front allows additional augmentation of reserves to be mined. We considered current boundaries of the Niorkpakkh deposit mining site and specified parameters of the Oleniy Ruchey ore bodies. figure 4 shows a scheme of modelling options on the mining progress towards the Niorkpakkh open pit.

![Figure 4](image)

Figure 4. A scheme of modelling options on mining progress (vertical cross-section along the ore bodies).

We analyzed the distribution of $\sigma_{\text{max}}$ and variation of parameters of advances of overlying sublevels to underlying sublevels with general angles of 45°, 60° and 75°.

The maximum stresses distribution is shown on figures 5 and 6 for mining front angles of 45° and 60°, correspondently. The dotted area shows the underground mining zone. Since the ore body is inclined to the cross-section plane, only a part of the stope (excavated ore body) is in the section.

The analysis has shown that the increase in the angle leads to increase of compressive stress concentration area next to the upper mining front progressing toward the Niorkpakkh open pit. This can change the geodynamic mode of a rock mass next to the mining site and has total negative impact on the mine excavations close to the mining front.
The distribution of minimum stresses is shown on figures 7 and 8 for mining front angles of 45° and 60°, correspondently.

Stress distribution analysis in undermined rock mass has shown considerably slow development of tensile stress zones in the roof of the outcrops formed. This relates to the compression caused by tectonic stresses in the rock mass.

At the beginning of stoping operations in the protective pillar, a tensile stress zone is formed on centre of the outcrop formed. Under the following progress of mining operations and achievement of under-open pit space, the maximal stresses still do not cover the mining site. The stress-strain state parameters next to the open pit wall do not change; a zone of tensile stresses $\sigma_{\text{min}}$ is kept in the near-surface part of the open pit wall where acting compressive stresses are minimal.

Minimal stresses distribution considerably changes under different advance parameters. The increase in the angle from 45° up to 60° results in extension of the tensile stress zone, where ruptures can be formed and develop. The upper boundary of this zone elevates by 100 and more meters into the undermined rock mass and reaches $\approx +250$ m elevation point. The further change of the advance angle...
up to 75° increases the tension zone both in plan and along elevation points; the upper boundary is +300 m. On the surface we can observe separate tensile stress zones. It should be noted that the undermined rock mass was considered as a homogeneous, without disturbances. It means that for the advance angles more 60°, the presence of natural fissures oriented in the direction of \( \sigma_{\text{max}} \) can augment the dimensions of a potential failure zone and its outcrop on surface. Therefore, it is a good practice to progress mining operations with advance of overlying levels to underlying ones, approximately equal to the sublevel’s height.

At the same time, under the proposed 45° angle of advance, the conditions are formed for a partial failure of hanging wall and filling of the stoping space in the volume appropriate to create a rock pad. This is a required condition for protecting the underground mine working zones from the dynamic impact of rock failure.

Having performed the model specification, we considered the calculation options with the selected 45°angle of advance and sequenced development of mining stoping operations with a 40 m interval to estimate a potential of additional augmentation of reserves. Let’s consider a variant with mining progress up to cut P7 (figures 9-10). As is seen, in this case the stress-strain state of undermined rocks considerably changes. In the lower part of the Niorkpakhk mining site, cuts P7÷P9, the level of compressive stresses increases. At that, a zone of probable failure in the roof of stoping space covers a part of the mining site in the cuts P10÷P11.

In our study we are going to substantiate a probable progress of mining operations towards the Niorkpakhk open pit without disturbing the protective pillar’s rocks. For this reason, cut P8 should be considered as a boundary of the excavation progress, such as with the development of mining operations to it, there are no significant changes in the stress-strain state of the protective pillar’s rocks.

When deciding to change the boundaries of the protective pillar, it is necessary to envisage a set of measures to monitor the undermined rock mass conditions, which will allow assessing the occurring changes and ensuring the safety of surface facilities and within the Niorkpakhk mining site when conducting mining operations in cuts P8÷P11. The set of measures should include:

- specification of rock stress state parameters with in-situ methods (the doorstopper method, core disking methods, etc);
- monitoring of geomechanical conditions of the rock mass at different scale levels, which provides for solutions of tasks on an integrated assessment of the rock mass based on geophysical control methods;

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**Figure 9.** Distribution of minimum stresses along M+400 m with development of mining operations up to cut P7, 45°angle of mining front.  

**Figure 10.** Distribution of minimum stresses along M+400 m with development of mining operations up to cut P7, 45°angle of mining front.
- mathematical modelling of stress-strain state and stability of undermined rocks, considering specified parameters of the stress field, geological structure of the rock mass and actual and planned stoping operations.

As a result, the stress-strain state of the undermined rock mass is forecasted, and its stability is determined. If necessary, the underground mining technology is corrected.

5. Conclusions

The analysis of multivariate calculations of the stress-strain state and development of critical tensile strain zones in the roof of created outcrops and close to the surface have shown that the undermined rock mass of the protective pillar stays stable, when the Oleniy Ruchey reserves are extracted in marks of +180÷-100m maximum up to cut P8 and overlying levels advance the underlying ones at 45° angle. At that, the monitoring system of the underground rock mass should be provided. Also, the tensile stress zones are forecasted in the centre of the outcrop's roof without significant increase of tensile stress zones close to the surface and in the protective pillar rocks, including vicinities of the Niorkpakhk open pit benches.

In future it is necessary to carry out additional geological and geotechnical studies aimed at specifying the ore body and host rock parameters, the rock mass structure and quality. The received data should be entered into the geological and geomechanical model of the deposit, which will increase the stress-strain state calculations reliability at the project decision stage. The set of measures to control the undermined rock mass conditions should be realized, which will allow assessing the occurring changes and providing the surface facility safety and within the Niorkpakhk mining site.

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