The stress distribution around the mining excavations under different tectonic loads

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Abstract. The article studies the features of stress distribution around the mining excavations under different tectonic loads on the case study of the Zhdanovskoe copper-nickel ore deposit, Murmansk region, Russia. The deposit is located in the Arctic zone on the Russia-Norway state boundary and is excavated by the Severny underground mine using simultaneously the sublevel caving and the open stoping methods. The combination of these mining methods in the same area affects the geomechanical conditions; moreover, the highest level of stresses is identified between the opposing excavation fronts. The deepening of mining increases the geodynamic risks caused by the stress state in the rock mass. In this regard, the study of the Zhdanovskoe deposit rock mass stress state and its transformation due to the mining progress is urgent. To address the issues a numerical geomechanical 3D model was created. To specify the correct boundary conditions, the results of the in-situ measurements were compared to visual observation results. To achieve the most accurate result, the direction and ratio of the tectonic loads were varied and the results were analyzed. The authors have analysed the modelling results in the form of the stresses and deformations distribution in the area around the excavations under different directions of tectonic loads. Based on this analysis, the authors have substantiated a relevant variant of direction of tectonic forces relatively the ore body strike. The results have been applied to forecast the changes in perspective stress-strain state during the mining progress.

1. Introduction
The Zhdanovskoe deposit is located on the eastern flank of the Pechenga ore field, which is located in the northeastern part of the Kola Peninsula, Russia (figure 1). The location of the Zhdanovskoe deposit is shown in figure 1. The deposit was explored in the early 20th century, and its commercial development bedding plane began in the 1960s [1]. The deposit includes several ore bodies: Tsentralnoe, Zapadnoe, Yugo-Zapadnoe-1 Yugo-Zapadnoe-2, Vostochnoe and Yugo-Vostochnoe ore bodies (Eremenko 2010) (figure 2). All the ore bodies are bedded plane shaped with the average dip angle is about 50°. The Tsentralnoe ore body is the largest in terms of reserves. Initially, the Zhdanovskoe deposit was exploited by open-pit mining, but in 2010, the transition to underground mining started [2]. The Zhdanovskoe deposit is currently fully mined by the Severny underground mine of the Kola MMC.

In 2021, the mining depth in different areas of the Zhdanovskoe deposit ranged from 500 to 600 meters. It is well known that the increase of the depth of mining leads to deterioration of mining and engineering conditions, increasing probable occurrence of dynamic rock pressure. Two main mining methods are sublevel caving and an open stoping. A combination of these methods worsens the geomechanical conditions due to the occurrence of stress concentration areas in the inter-chamber and
inter-level pillars and in the rock mass between the opposing stoping fronts. The above features negatively affect the stability of the stopes and pillars and induce conditions for dynamic failure of the rock mass. In this regard, there appeared a need to create a numerical finite-element geomechanical model of the deposit, which could be useful in predicting the change of the rock mass stress-strain state as the mining progresses.

Figure 1. The Pechenga ore field. Location of the Zhdanovskoe deposit.

Figure 2. The main ore bodies comprising the Zhdanovskoe deposit. 1-1 – horizontal cross-section, 2-2 – vertical cross section

2. Study methods

Numerical modeling of the stress-strain state using the finite element method allows taking into account a set of geomechanical factors when planning the mining operations, their individual levels and sections. The Hoek elastic stress-strain relation for isotropic material was applied to calculations.

The geomechanical model included strength and strain characteristics of the rocks and ores comprising the deposit, data from in-situ stress measurements using the doorstopper method, and data describing the configuration and location of model objects, such as ore bodies, open pits, and the day surface. The strength and strain characteristics of general types of rocks are shown in table 1. The
Young’s modulus and the Poisson’s ratio values were assigned as elastic characteristics of the rock mass to the model.

The geomechanical model includes the boundary conditions, which largely determines the adequacy of the results and their compliance with the actual stress state of the rock mass. Based on the results of stress measurements by the doorstopper method, the stress field of the Zhdanovskoe deposit was interpreted to be of gravity-tectonic type [3]. The maximum stress component $\sigma_{\text{max}}$ is subhorizontal, of tectonic origin and has an azimuth varying within a fairly wide range [4]. The minimum component $\sigma_{\text{min}}$ is also tectonic, is orthogonal to the maximum, lies on a subhorizontal plane and is oriented normal to the strike of the ore bodies. The intermediate component $\sigma_{\text{med}}$ is vertical gravitational, and is and close to the lithostatic stress. The main stress components $\sigma_{\text{max}}, \sigma_{\text{med}}$ and $\sigma_{\text{min}}$ are set as loads, more specifically, nodal forces, on the model faces as the boundary conditions.

### Table 1. Strength and strain characteristics of the rock types

| Type of rock  | Compressive strength, ($\sigma_c$) [MPa] | Tensile strength, ($\sigma_t$) [MPa] | Young’s modulus [GPa] | Poisson’s ratio | Fragility coefficient, ($\sigma_c/\sigma_t$) |
|---------------|------------------------------------------|-------------------------------------|-----------------------|----------------|------------------------------------------|
| Tuffaceous rocks | 140                                      | 12.7                                | 82.9                  | 0.24           | 11.0                                     |
| Solid ore     | 186                                      | 12.8                                | 84.2                  | 0.26           | 14.5                                     |
| Gabbro        | 99                                       | 18.0                                | 64.7                  | 0.28           | 5.5                                      |
| Diabase       | 76                                       | 15.3                                | 66.6                  | 0.27           | 5.0                                      |
| Peridotite    | 94                                       | 14.0                                | 82.8                  | 0.28           | 6.7                                      |

Simultaneously with the creation of the numerical geomechanical model, a database of visual observations at the underground workings of the Zhdanovskoe deposit was prepared. The systematization and analysis of these data have allowed determining that the rock mass failure under the rock pressure, in the vast majority of cases, takes place in the drift workings (figure 3). It is well known that the concentration zone of failure is perpendicular to the maximum stress component direction. As a result, it can be assumed that the maximum stress acts normal to the strike of the ore body.

![Figure 3. Typical form of rock mass failure in the drift workings of the Zhdanovskoe deposit](image-url)
3. Results
The in-situ measurements of stresses by the doorstopper method have resulted in obtaining a rather wide range of tectonic stress directions. The poor correlation of tectonic stress directions with the data of visual observation of failure near the contour of workings has lead to development of two variants of numerical geomechanical models. The first variant took into account the tectonic loads obtained by in-situ measurements of stresses; the second one provided changes in the directions of their action in accordance with the visual observations.

3.1. Orientation of the maximum stress component along the strike of the ore bodies
As indicated in section 2, according to the results of in-situ stress measurements, $\sigma_{\text{max}}$ is subhorizontal and its direction varies within a significant range. In this regard, we decided to select the general direction $\sigma_{\text{max}}$ along the strike of the ore bodies as shown in figure 4. Based on this decision, the first version of the numerical geomechanical model [5] was created in Sigma GT software [6] in 2019.

![Figure 4](image-url)

**Figure 4.** Scheme of orientation of the principal stress vectors when creating the first version of the model.

As a result of numerical modeling of the stress-strain state of the Zhdanovskoe deposit, we obtained stress distributions at different mining stages [5]. The study considers the Tsentralnoe ore body, the largest ore body of the Zhdanovskoe deposit. In the horizontal section, the $\sigma_{\text{max}}$ vector is directed along the strike of the ore body as shown in figure 5. The modeling has found out that the vector of maximum compressive stress is oriented irregularly around the stoping spaces, in the vertical section normal to the strike of the Tsentralnoe ore body (figure 6). We assumed that under the influence of the stoping space, the vector $\sigma_{\text{max}}$ will change its direction, but the results of the stress-strain state modeling have allowed a conclusion that the direction of maximum compression does not quite correlate with the direction determined by visual observation by characteristic destruction of the adjacent to contour zones of mining workings (figure 3).

Despite the good correlation of the absolute values of the calculated stress field with the level recorded during visual observation, the direction of the calculated $\sigma_{\text{max}}$ values in the mining area did not give the expected reorientation across the strike of the ore body. Thus, we can assume that the maximum compression should act perpendicular to the axes of the drifts, respectively across the strike of the ore body. Therefore, it was decided to adjust the boundary conditions. The given nodal forces were inverted.
3.2 Orientation of the maximum stress component across the strike of the ore bodies

To obtain a result, consistent with the visual observation data, the directions of the maximum and minimum stress field components were inverted at the stage of setting the boundary conditions (figure 7).

As a result of modeling, we found out that the resulting stress vector is oriented as an envelope around the stoping spaces formed by mining operations, in the vertical section across the strike of the Tsentralnoe ore body (figure 8). In the horizontal section, the direction of the resulting stress vector is oriented across the strike of the ore body (figure 9), which agrees well with the results of the visual observations of the mining workings.
4. Conclusions

The paper considers the changes in the stress-strain state of the Zhdanovskoe deposit rock massif under variation of tectonic loads. Stress calculations were carried out using a FEM numerical simulation through the Sigma GT software. Based on the results of in-situ stress measurements by means of the doorstopper method, laboratory physical and mechanical tests of rock samples, as well as visual observations of mine workings, we created two numerical geomechanical models, which described two variants of the location of principal stress vectors.

The variation of tectonic stress directions was based on the contradiction between the results of in-situ stress measurements through the doorstopper method and visual observations of the failed zones of mine workings. In the first variant, the maximum compressive component ($\sigma_{\text{max}}$) was directed along the strike of ore bodies, while in the second variant - across the strike. The tectonic loads were changed at the stage of setting the boundary conditions.

As a result of the stress-strain stress modeling, it was found out that there was no significant reorientation of the stress vectors around the stoping spaces formed by the mining operations. Thus, in the second case, with orientation ($\sigma_{\text{max}}$) normal to the strike of ore bodies, the obtained directions of stress vectors correlate well with the direction of stresses inferred from visual observations of mine workings and more correctly describe the field of stresses acting in the Zhdanovskoe deposit rock massif.

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