Influence of different geological structures on stress–strain state of hard rock mass

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Abstract. The results of numerical simulation of stress–strain state in a hard rock mass area with the complex geological structures are presented. The variants of the stress value change are considered depending on the boundary conditions and physical properties of the model blocks. Furthermore, the possibility of in-situ stress formation under the influence of energy coming from the deeper Earth's layers is demonstrated in terms of the Khibiny Massif.

1. Introduction

Currently there exists a hypothesis that rock mass take energy from large faults, and horizontal components of the resultant stress fields are much higher that the vertical components [1–4]. The major horizontal stresses are oriented in perpendicular to the fault edges in this case. Rock mass structurally arranged as hierarchies of blocks are mostly composed of hardest rocks capable to accumulate huge energy until the critical threshold and failure as a consequence. The maximum stresses are observed in intrusions as the most illustrious representatives of hard rock masses [3]. It is typical for intrusions to contain predominantly vertical or subvertical structural discontinuities of various rank and genesis. These discontinuities, having different physical properties than enclosing rock mass, can change stress concentrations at the boundaries. The change in the stress concentration can be governed by the shape of a discontinuity, or by the properties of constituent blocks, or by the value of energy coming from the deepest levels of the Earth. This paper discusses modeling of two discontinuities in enclosing rock mass (both monolithic and composed of blocks having different physical properties) at the preset intake energy value with a view to checking the above mentioned hypothesis in terms of the Khibiny Massif.

2. Object of the research

The Khibiny Massif in the north–east of the Baltic Shield is one of the world's largest central-type, complex multi-phase intrusions with an area of 1327 km^2 (36×45 km). The Massif elevates to 900–1000 m over the surrounding valley. The Hercynian age is round 290 million years. The Massif features a variety of tectonic structures at different hierarchical scales, connected in time with the conical and radial faulting. There are two stages in the tectonics of the Khibiny Massif. The first stage coincides with the time of the conical faulting. This is the period of formation of apatite–nepheline deposits, and it predetermines basic tectonic elements of individual deposits. The second stage is the period of the regional and radial fault that cut the Khibiny Massif into an ore body and separate blocks, respectively. As a consequence, the initially single ore body was split and dislocated relative to its original position. Structurally, the zones of radial faults are very thick (from 100–150 m to 2–3 km), have steep dip angels, and are characterized by considerable deformation of rock mass and by multiple-stage formation [5].

Iolite–urtite rock mass makes a thick conical intrusion arc. The internal structure of the arc is nonuniform. Jointing of apatite–nepheline rock masses is represented by four sets of joints: gently dipping and diagonal joints of set 1 (more than 60%) and steeply dipping joints of sets 2–4 (totally less than 40%). General jointing decreases with depth. Steepness of set 1 joints grows. There area large-block and small-block joints, the large-block joints stretch from hundreds meters to a few kilometers, and their width ranges from 1 to 200 mm. The small-block joints are not longer than 10 m and have the width of fractions of millimeter. Some joints (both large- and small-block) have the fill of hydrothermal minerals.

3. Results and discussion

The analysis of influence of geological structures and physical properties on stress state of hard rock mass was carried out using the finite element method. For the conditions of the Khibiny Massif, three models of two geological structures were constructed: fault F1 and dyke D1. The other blocks were composed of enclosing rocks. The physical properties of rock blocks were chosen based on the test data [6] and from the handbook [7]; the distributed force from below was determined by modeling natural stress field with selection of values to match the in situ measurement results.

The first model is shown in Figure 1 (profile). The boundary conditions are: Figure 1b (variant one)—bottom and side boundaries are fixed, rock mass experiences only gravity, lateral earth pressure is created owing to fixation of the side boundaries; Figure 1b (variant two)—lateral sides are fixed, rock mass is subjected to gravity and distributed load of 750 MPa from below. The enclosing rock blocks have: bulk weight $w = 3.3$ g/cm^3, elasticity modulus $E = 80.0$ GPa, Poisson's ratio $v = 0.20$. The fault blocks (F1): $w = 1.5$ g/cm^3, $E = 5.0$ GPa, $v = 0.46$; the dyke blocks (DД1) composed of monchikite: $w = 5.0$ g/cm^3, $E = 120.0$ GPa, $v = 0.10$. The modeling yields the distribution of the major principal stress σ_1. In variant one (Figure 1b), in the enclosing rocks, σ_1 gradually grows with depth from 10 to 80 MPa. For the dyke, it is found that the stress gradually grows with depth from 30 to 110 MPa, and the increased compressive stresses to 150 MPa are observed at the dyke and fault intersection (elevation 3800 m). At the lower portion of the dyke (elevation 500 m and below), a zone of increased stresses forms. For the fault, σ_1 vary from 1 to 45 MPa and no relation with the depth is observed. On the whole, at the depth of 1000 m (elevation 4000 m), where mining operations are carried out, the principal stress σ_1 have the average value of 30 MPa. In variant two (Figure 1c), under the load applied from below, the principal stress also grows with depth though its value is much higher, from 30 to 770 MPa.
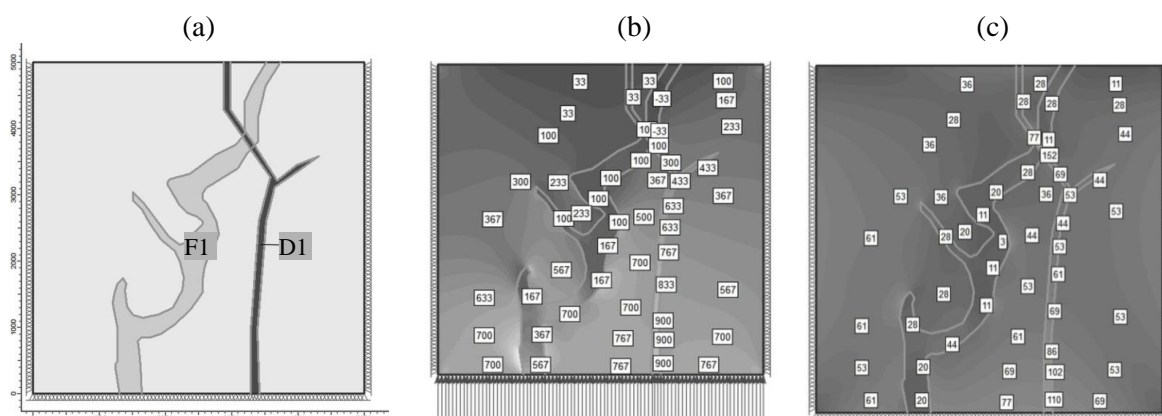

Figure 1. The first model (a) schematic fault F1 and dyke D1; (b) distribution of σ_1 (MPa) in the domain with the fixed boundaries; (c) distribution of σ_1 (MPa) under the load applied from below.

The stress state in the block in-between the fault and dyke is higher than in the external blocks. In the dyke, the stress σ_1 varies from 30 MPa at the top to 900 MPa at the bottom below elevation of 1000 m. At the dyke and fault intersection, σ_1 is 100 MPa, i.e. 50 MPa smaller then in variant one. In the fault at the top of the rock mass (above the elevation 4000 m), there are tensile stresses of −30 MPa; at the bottom (below the elevation of 1000 m), there are compressive stresses of 700 MPa. On the whole, σ_1 increases with depth in the fault zone, thought there are areas (folds and pockets), where σ_1 can either grow or decrease considerably.

Summing up, in the variants within the first model, it is typical that the major principal stress σ_1 increases with depth in the blocks of enclosing rock mass and in monchikite dyke. The stress state in the fault depends on the fault geometry and on the physical properties of enclosing rock mass. The highest values of the stress σ_1 are observed in the dyke which is a strong stress raisor. The least stresses are found in the fault zones. At the top of the model (down to the elevation of 4000 m), the average stress value is 30 MPa.

The second model is depicted in Figure 2. Similarly to the first model, there are two geological structures, i.e. the fault and the dyke. These structures are divided into blocks with different physical properties. For the fault blocks F1: $w = 1.5$ g/cm^3, $E = 5.0$ GPa, $v = 0.46$; F2: $w = 1.8$ g/cm^3, $E = 8.0$ GPa, $v = 0.44$; F3: $w = 2.0$ g/cm^3, $E = 10.0$ GPa, $v = 0.41$; F4: $w = 2.2$ g/cm^3, $E = 12.0$ GPa, $v = 0.39$; F5: $w = 2.4$ g/cm^3, $E = 16.0$ GPa, $v = 0.35$; F6: $w = 2.6$ g/cm^3, $E = 20.0$ GPa, $v = 0.32$. For the dyke blocks D1: $w = 5.0$ g/cm^3, $E = 120.0$ GPa, $v = 0.10$; D2: $w = 4.7$ g/cm^3, $E = 115.0$ GPa, $v = 0.12$; D3: $w = 4.4$ g/cm^3, $E = 110.0$ GPa, $v = 0.15$. The other blocks are composed of enclosing rocks having $w = 3.3$ g/cm^3, $E = 80.0$ GPa, $v = 0.20$. The boundary conditions are set as in the first model: variant one—the side and bottom boundaries are fixed, and the model is only subjected to gravity (Figure 2b); variant two—the side boundaries are fixed, the model undergoes gravity and the load of 750 MPa applied from below (Figure 2c).
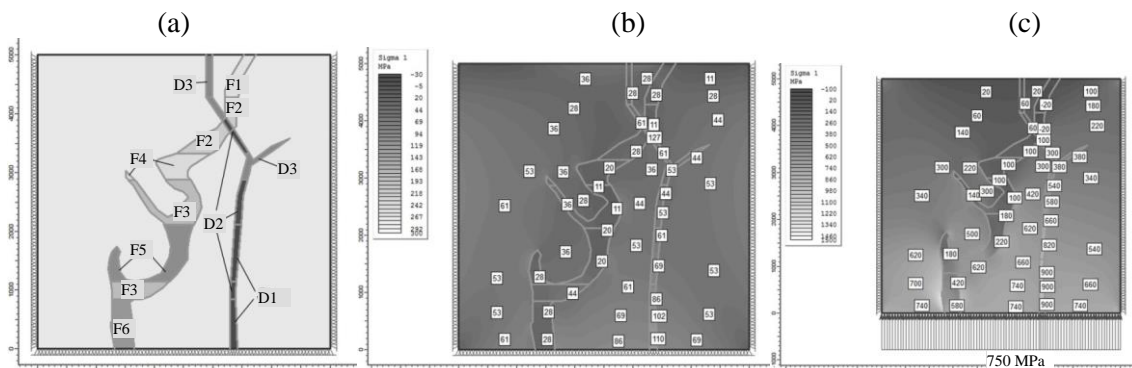

Figure 2. The second model: (a) F1–F6 are the blocks with different properties in the fault; D1–D3 are the blocks with different properties in the dyke; (b) distribution of σ_1 (MPa) in the domain with the fixed boundaries; (c) distribution of σ_1 (MPa) under the load applied from below.

In the second model, in variant one in Figure 2b, the distribution of the major principal stress σ_1 conforms with the distribution in variant one of the first model. Accordingly, the difference in the physical properties of rocks composing the fault and the dyke has caused no significant variation in the stress state of rocks. The comparison of variants two in the first and second model shows that in the latter case (Figure 2c), the stresses σ_1 in the enclosing rock blocks decrease by 20 MPa on average (the stresses change from 20 to 740 MPa with depth). The enclosing rock mass between the fault and the dyke undergoes lower stresses than in the first model. In the dyke, the values of σ_1 double (from 30 to 60 MPa) at the top (elevation 4000 m) and decrease by 50 MPa in the interval from 2000 to 4000 m. In the blocks composing the fault, at the top (above the elevation of 4000 m), tensile stresses are observed as in the first model. On the whole, the stress σ_1 in the fault zone increases by 20 MPa on

average. Thus, in the considered variants of the second model, the behavior of the principal stresses σ_1 in many ways conforms with the stress behavior in the first model. At the same time, in the second model variant one, the difference in the properties of the dyke and fault rocks results in no change in the model rock mass state while in variant two with the load applied from below, the influence of the properties grows.

The third model is shown in Figure 3. There are two geological structures split into blocks with different physical properties totally coincident with the block properties in the second models. The enclosing rock blocks have the other properties: B1—w = 3.3 g/cm^3, E = 80.0 GPa, v = 0.20; B2—w = 2.9 g/cm^3, E = 60.0 GPa, v = 0.23; B3—w = 2.6 g/cm^3, E = 40.0 GPa, v = 0.26. The boundary conditions are the same as in the first and second models: variant one—the side and bottom boundaries are fixed, and the model is only subjected to gravity (Figure 3b); variant two—the side boundaries are fixed, the model undergoes gravity and the load of 750 MPa applied from below (Figure 3c).

In variant one of the third model, the values of the principal stress σ_1 in the enclosing rock mass gradually increase from 10 to 80 MPa with depth as in the first and second models. On the other hand, in the third model, at the elevations from 1000 to 4000 m, in all blocks composed of the enclosing rocks, it is observed as the stresses lower by 10 MPa on average. In the dyke, to the elevation of 2000 m, the stresses conform with the stresses in the first and second models on the whole but are higher by 30–40 MPa in the interval between the elevations of 500 and 2000 m. The stresses in the fault are the same as in the previous models. Regarding variant two of the third model the principal stress σ_1 in the outside enclosing rock mass blocks remains the same as in the second model and lowers by 80 MPa in the blocks in-between the fault and the dyke. In the dyke blocks, in the interval from 1000 t0 3500 m, the stresses jump by 200 Moa as compared with σ_1 in the second model. In the fault the stresses are higher by 40 MPa than in the second model.

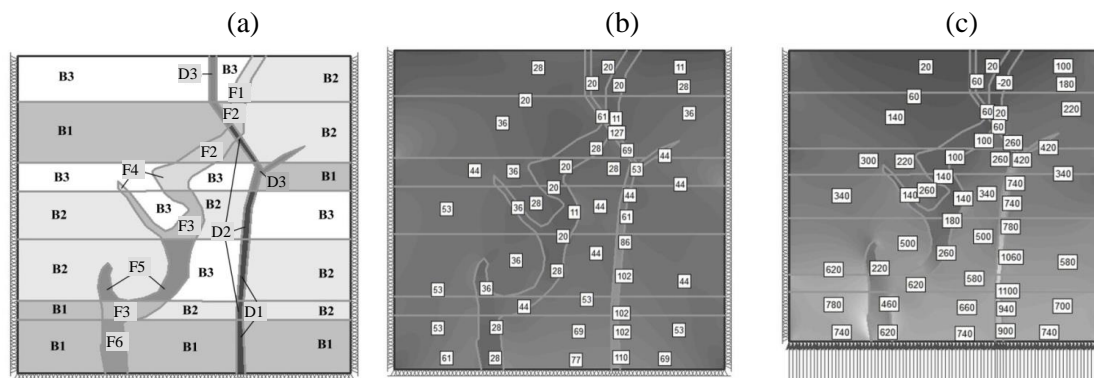(a)   (b)   (c)

Figure 3. The third model: (a) F1–F6 are the blocks with different properties in the fault; D1–D3 are the blocks with different properties in the monchikite dyke; B1–B3 are the blocks of enclosing rock mass with different properties; (b) distribution of σ_1 (MPa) in the domain with the fixed boundaries; (c) distribution of σ_1 (MPa) under the load applied from below.

In this manner, in variant one of the third model, the behavior of the principal stress σ_1 to a higher degree corresponds to the second model. In the enclosing rock blocks with the decreased properties, the stresses are lower; in the dyke blocks adjoining the enclosing rock blocks, the stresses are higher. When the load is applied from below, the difference in the physical properties results in essentially different stress state in the model rock mass.

4. Conclusion
The numerical modeling of the rock mass stress state in terms of the Khibiny Massif conditions shows that the presence of such geological structures as faults and dykes can influence the stress behavior.

The dykes act as the stress raisors, and the faults generate stress field considerably governed by the geometry of the faults and by the properties of rocks the faults are composed of.

Furthermore, it has been found that in the geological medium structured as a hierarchy of blocks subjected to the action of gravity only, the difference in the physical properties of rocks has no essential influence on the stress state. In case when the energy enters the rock mass from the deeper levels of the crust, the difference in the properties of rock blocks can result in the excessive horizontal stresses generated in the dykes and in the fold/pockets of the faults, as well as at their boundaries. Mining operations in such zones are exposed to the highest hazard of dynamic events due to rock pressure.

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