Simulation of stress distribution around cylindrical mined out spaces

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ABSTRACT: Numerical simulation is performed for the changes of stress field at consecutive extraction of a diamond ore deposit. The features of stress distribution around openings are examined. Failure zones of rock mass are determined with using of Coulomb-Mohr criterion. The results of calculations were compared with the experimental data of observations *in situ.* Geomechanical recommendations are proposed for placing of technological workings.

1 INTRODUCTION

Open-pit mining method is used for excavation of ore at Siberian diamond deposits. The maximum depths of open-pits are reached. Last years the deep mining is applied. The features of stress distribution around openings are examined at experimental industrial block of the "International" kimberlite pipe, which is mined at the depth of 700 - 800 m. Cut-and-fill mining in slices about 3.5-5 m in height and about 5 m in width is applied in various variants of room and pillar mining with a combine. As a result some cylindrical mined out spaces with a diameter 60 m and a height 10-70 m were filled with the solidifying fillings. Under these conditions a number of geomechanical problems arises. The main of them is the possible rock fall into workings. The experience of application of geomechanical investigations in practice is discussed. Numerical simulation is performed for the changes of stresses in ore mass and in country rock at consecutive extraction of the diamond deposit. Character of failure in rock mass is researched. Strength of rock has a wide rage of values. The difference in mechanical properties sets a limit of accuracy of analysis. The finite element method was applied for forecasting the stress state of rock mass near the mined out spaces during development of mining works.

2 FINITE ELEMENT MODEL

The results of experimental investigations showed the initial principal horizontal stresses are approximately equal to 0.7-0.8 of vertical pressure been due to a weight of overlying rock thickness at this depth (Baryshnikov et al. 2003). Therefore the numerical solutions of axisymmetrical problems were used. The initial stress state of rock mass is following

$$\sigma_z^0 = \gamma z,\ \sigma_r^0 = \sigma_\Theta^0 = \lambda\gamma z,\ \tau_{rz}^0 = 0,$$

where z is a distance from the surface of the earth, γ is specific gravity of rock (27 KN/m^3), λ - ratio of initial horizontal stress to vertical one at the depth H (800 m).The problems were solved in terms additional displacements (Boltengagen 1999) under the following boundary conditions on the external boundary (the surface of the cylinder with a diameter 4 km and a height 2 km): the upper horizontal boundary is free from stresses, additional displacements are equal to zero on the lower horizontal boundary, additional horizontal displacements and tangential stresses are equal to zero on the vertical boundary. Elastic modulus of rock was taken equal to 10 GPa, Poison's ratio of rock ν is equal to 0.25. The height of mined-out spaces (cylinders with the diameters 60 m) are quoted on the corresponding illustrations of problems. Elastic modulus of artificial fillings is one-tenth or one-hundredth of elastic modulus of rock. Reaction of filling massif, been due to displacements of contour of mined-out space with the height about 100 m, is not in excess of 1-2 MPa. Stresses of rock are approximately equal to 20 MPa on the depth. Mine-fill creates small pressure, which prevents the rock fall into workings. The filling massif did not come into account in the modeling. In the case of axisymmetric problems with elements in form of ring with triangular cross section the element contribute to stiffness matrix is defined as

$$k_{ps}^e = \frac{\pi\bar{r}}{2|\Delta|}\mu\begin{vmatrix} b_p b_s + c_p c_s + \alpha(b_p d_s + d_p b_s) + \beta c_p c_s & \alpha(b_p + d_p)c_s + \beta c_p b_s \\ \alpha c_p(b_s + d_s) + \beta b_p c_s & c_p c_s + \beta b_p b_s \end{vmatrix}$$

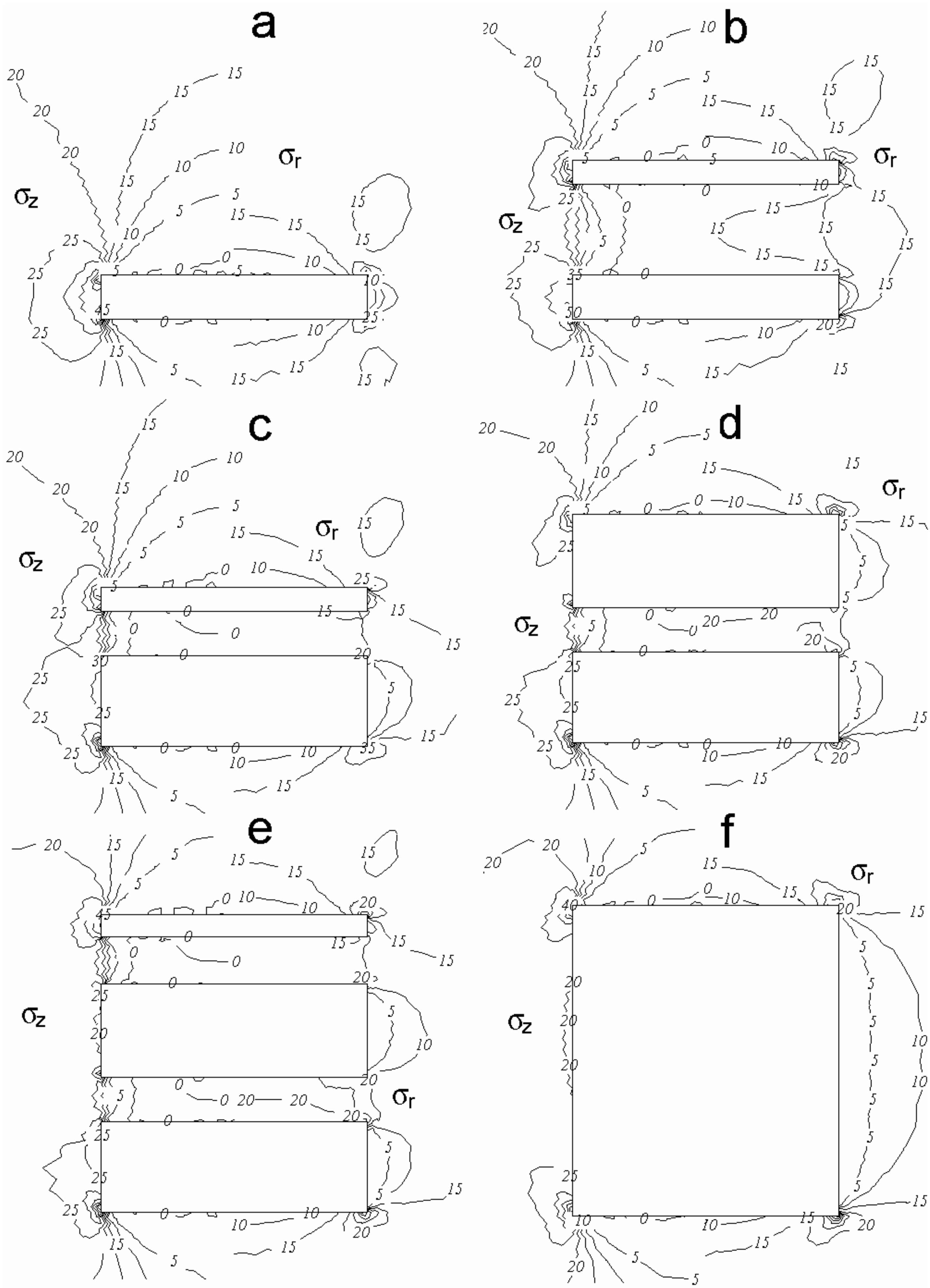

Figure 1. Vertical (left) and horizontal radial (right) components of stresses (MPa) in rock around mined- out spaces at consecutive extraction of ore in experimental industrial block of “International” Mine at the depth of 800 m (λ=0.8).

where parameters are determined as follows

$$\alpha = \frac{\nu}{1-\nu}, \ \beta = \frac{1-2\nu}{2(1-\nu)}, \ \mu = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$$

(E is Young's modulus of rock) (Boltengagen 2001). Matrix k^e_{ps} characterizes the dependence of the displacements (u_r, v_θ) of neighbouring nodes with numbers p and s. The geometrical parameters b, c, d are defined with coordinates of nodes of the element (Zienkievicz 1975)

$$b_p = z_s - z_q, \ b_s = z_q - z_p, \ c_p = r_q - r_s, \ c_s = r_p - r_q,$$

$$d_p = \frac{r_q z_s - r_s z_q}{\bar{r}} + b_p + \frac{c_p \bar{z}}{\bar{r}}, \ d_s = \frac{r_p z_q - r_q z_p}{\bar{r}} + b_s + \frac{c_s \bar{z}}{\bar{r}}$$

($\bar{r}, \bar{z}$ are coordinates of the center of triangular cross section of the element with nodes p,q,s). The absolute value

$$\Delta = 1/2\,[(r_q - r_s)(z_p - z_s) - (z_q - z_s)(r_p - r_s)]$$

is equal to the area of the triangle. The components of nodal forces

$$R^e_p = sign(\Delta)\pi\bar{r}(b_p\sigma^0_r + d_p\sigma^0_\Theta + c_p\tau^0_{rz})$$

$$Z^e_p = sign(\Delta)\pi\bar{r}(c_p\sigma^0_z + b_p\tau^0_{rz})$$

take into account the initial stresses σ^0_{ij} in the element (Boltengagen 2002). The nodal forces are not equal to zero on the internal boundaries of the domain. A system of linear equations for nodal displacements was solved with the successive over-relaxation method (Hageman & Young 1986).

3 RESULTS OF CALCULATIONS

The ore body in limits of the experimental industrial block was divided into three sub-levels about 30 m in height (lower, middle and upper sub-levels). Each sub-level was mined with horizontal layers about 5 m in height from the bottom to the top. Figure 1 illustrates stress distributions around mined-out spaces in experimental block at various stages of extraction of ore: a – first 10 meters of lower sub-level were mined; b – 5 meters of middle sub-level were mined in addition; c – 20 meters of lower sub-level were mined; d – 20 meters of middle and lower sub-levels were mined; e – 5 meters of upper sub-level were mined in addition; f – lower and middle sub-levels were mined and a mined-out space about 70 m in height was created. At the depth 800 m the initial vertical and horizontal stresses are equal to 21 and 17 MPa accordingly. The main peculiarities of stress state of rock are the increase of vertical stresses at vertical boundaries of mined-out spaces and the unloading of rock at roof and floor. Mined-out spaces in sub-levels are divided with the ore ceilings. Vertical stresses of rock in the center of ceiling are approximately equal to zero, and the concentration of horizontal stresses rises from 1.1 to 1.4 under decreasing of its height from 25 m to 5 m.

The calculated safety factor

$$f = \frac{2C\cos\varphi + (\sigma_{max} + \sigma_{min})\sin\varphi}{\sigma_{max} - \sigma_{min}}$$

was used for analysis of rock massif's failure, where σ_{max} and σ_{min} are the largest and smallest principal stresses, found from the elastic solution. C and φ are the parameters of the rectilinear envelope of the limiting Mohr circles (cohesion and angle of internal friction) (Boltengagen et al. 1997). The safety factor becomes equal to 1, when the Mohr circle is tangent to the envelope. The following term has been accepted in the paper. The failure zone is the area, where the safety factor is less than 1 for the supercritical stress state. The figure 2 illustrates a calculated failure zone of undermined ore rock massif and a real fracture of technogenic, which was discovered with practical visual observations of the state of workings (C is equal to 3.2 MPa and φ is equal to 30^0). The computer modeling let to determine the form and the sizes of rock failure zones and to estimate a position of fracture in undermined ore rock massif. The figure 3 illustrates failure zones of country rock (C is equal to 5 MPa, φ is equal to 30^0 and the height of the mined-out space is approximately equal to 140 m). The technological workings are necessary for filling mined-out space with the solidifying fillings. In the case, when the technological workings are on the distance 5 m from the boundary of the pipe (the left side of the fig.3), the failure zones are larger than in the case of distance 10 m (the right side of the fig.3). The carried out geomechanical analysis let to recommend the distance 10 m between the technological workings and the contour of the ore body.

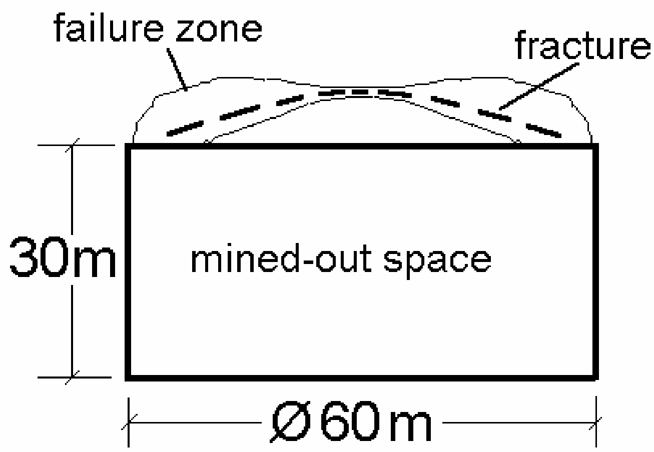

Figure 2. Failure zone above the mined-out space

4 CONCLUSION

The axisymmetric elastic model can not describe all peculiarities in deformation of rock massif near cylindrical mined-out spaces, but it allows to estimate

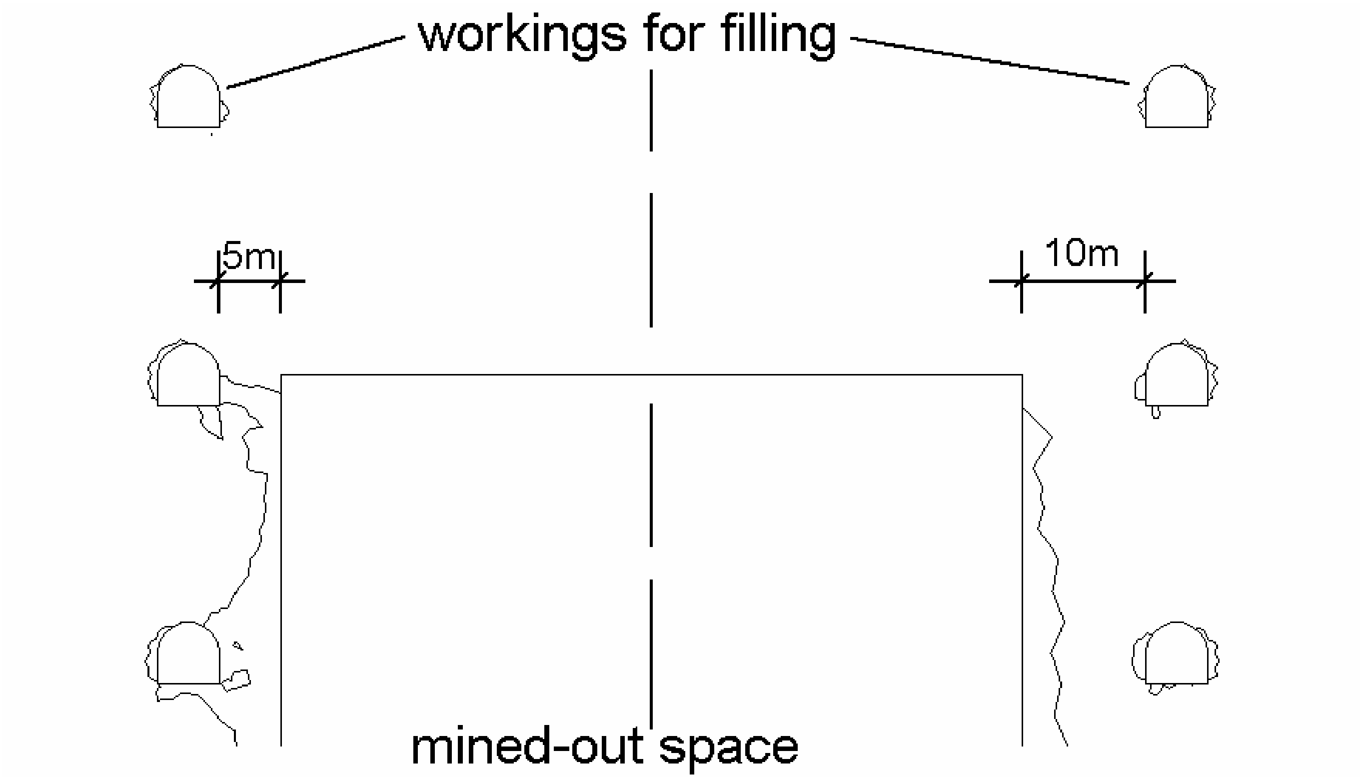

Figure 3. Failure zones of country rock.

sizes and limits of failure zones around workings. The proposed approach may be used for geomechanical analysis of state of rock mass near cylindrical mined-out spaces, which have been created during extraction of diamond ore deposits.

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