On one approach in underground mining modeling

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Abstract. At solving of geomechanics problems it is necessary to study the features of rock mass and assess the degree of their disequilibrium. It is necessary to predict the mechanical behavior of the massif during mining excavation. Mathematical modeling of rock continua with taking into account the nonequilibrium and non-stationary processes of deformation and fracturing is a vital problem. The stress state of the rock mass is usually a compression state. Since rocks resist stretching much worse than compression, tensile stresses (when they appear) are usually very important, and therefore, when analyzing the results of solutions, special attention is paid to stretch zones. At mining operating in rock continua, a discontinuity and rupture of natural stress-strain state occur. Results of the investigation of geomechanical processes in the vicinity of underground mining are considered in this issue. There made an analysis of the solution to the problem of stresses distribution in the vicinity of horizontal excavation covered in elastic-plastic, homogeneous, and isotropic rock continua.

1. Introduction

Intensive development of transport communications and mining leads to the widespread use of engineering geology methods for solving problems of geomechanics. The problems of engineering geology cannot be a priori formulated precisely because of unknown boundary conditions, geological history, etc.

As a rule, rock masses are initially in a tense state. In this case, heterogeneity, ruptures, cracks can be crucial in determining the strength of the structure being constructed. Also, the linear theory of elasticity cannot be applicable in the calculations of such structures.

For calculation of stress-strain state in rock continua effective numerical methods as finite difference method, boundary element method, and finite element method can be applied. The implementation of the latter was considered here.

Well known rock excavation modeling by Crouch S.L. and Starfield A.M [1]. In that work, the boundary element method (BEM) was used [2-4]. However, in this paper by using the same approach was applied finite element method. Nonlinear calculations based on the finite element method (FEM) are more studied and therefore this approach was chosen here to solve and investigate the attached problem. The method for determining of stress-strain state of design where nonlinear properties of the material are taken into account proposed in this issue. So approach leads to a qualitative assessment of stresses around the mine. The two-dimensional formulation and the case of plane deformation are accepted and considered here. So the approach was used early by the boundary element method in case of the study by using plasticity models [4]. Rock mechanics problems investigated deep and comprehensive. Features of rocks are fracturing and fissuring arising due to loading [5]. Elasticity and plasticity in geomechanics problems were investigated too [6, 7]. Investigations regarding new
constitutive models, analytical solutions, numerical approaches, crack propagation, instability problems due to excavation, etc. have a place to be [8-16]. However, our approach based in FEM was applied for the case study. Using BEM in more cases gives good results. But FEM was more preferable for us here.

2. Methods

Tunnels’ strength depends from many factors like soil properties, soil-structure interaction models, foundations impact, etc. Different models and approaches are applied [17-23] in this area. But mining problems associated with underground workings, so it is necessary to postulate the initial stress state of the rock mass. The initial stress state is disturbed after the mining excavation formation. The total stresses $\sigma_{ij}$ at any point in the rock mass can be presented as the sum of the initial stresses $(\sigma_{ij})_0$ and changes in stresses $\sigma'_{ij}$ at this point due to mine workings behavior [1].

$$\sigma_{ij} = (\sigma_{ij})_0 + \sigma'_{ij}$$

(1)

Changes in stresses are called additional stresses.

First, assume that the stress state around the mine workings is not changed from the initial state if the forces are applied to the border that is equivalent to those that existed before the mine was developed.

The finite stress state corresponds to a force-free boundary $\sigma_{ij} = 0$, to which additional efforts $\sigma'_{ij} = -(\sigma_{ij})_0$ correspond. Imagine that the finite state is reached as a result of the gradual force decrease at the boundary, as shown in (see Figure 1). If the initial forces are divided into $K$ steps of magnitude, then the additional forces for the $k$-th step of load reducing are

$$\sigma'_{ij} = -k\Delta (\sigma_{ij})_0 = \frac{k \cdot (\sigma_{ij})_0}{K}$$

(2)

and complete forces are:

$$\sigma_{ij} = (\sigma_{ij})_0 + \sigma'_{ij} = -(\sigma_{ij})_0 \left(1 - \frac{k}{K}\right)$$

(3)

Figure 1. The modeling scheme of mine workings in rock continua
Therefore, the last step \( k = K \) gives, as it should be \( \sigma'_{ij} = -(\sigma_{ij})_0, \ \sigma_{ij} = 0 \)

For plasticity we will use the next assumption:

\[
(\sigma_{ij})_0 \{d\varepsilon\} = \{d\varepsilon_e\} + \{d\varepsilon_p\}
\]

Constrains between stresses and elastic strains under the limitation of Hooke's law.

\[
\sigma_{ij} = (\sigma_{ij})_0 \quad \quad \sigma'_{ij} = -k\Delta(\sigma_{ij})_0
\]

Relations between \( \{d\varepsilon_p\} \) and stresses we assume as Prandtl-Reiss incremental plasticity correlations.

\[
\{d\varepsilon\} = \lambda \left[ \frac{\partial Q}{\partial \sigma} \right]
\]

here \( Q \) is plastic potential and \( Q = F(\sigma, k) = 0 \) is yield surface.

We will use the Mohr-Coulomb yield criterion

\[
F = \frac{\sigma_1 - \sigma_3}{2} + \frac{\sigma_1 + \sigma_3}{2} \sin \phi - c \cdot \cos \phi = 0
\]

here stress components and angle of internal friction. Follow [1] we accept the stiffness matrix for the finite element approach and coefficient \( H' = \frac{d\sigma}{d\varepsilon_p} \).

![Figure 2. Initial stresses and boundary condition](image)

To implement this algorithm, a finite element model (FEM) was used; at each step, the increments of additional stresses were chosen so that one finite element passed into the plastic zone. Below (see Figure 3) the initial data and zones of the formation of plastic zones in the problem of a plane strain state are presented for two test problems. The first problem was solved at a zero hardening modulus.
$H' = 0$, and the second at $H' = 1\, \text{MPa}$. As can be seen from the figures, in the first case, a wider plasticity zone is observed. The occurrence of plastic zones in the corners of the design scheme is due to the presence of boundary conditions.

$$
E = 3\, \text{GPa}; \\
\gamma = 1.94\, \text{KPa} / \text{m}; \\
c = 981\, \text{Pa}; \\
\phi = 30^\circ; H' = 0
$$

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E = 3\, \text{GPa}; \\
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$$

3. Results
Below was defined the stress-strain state at the stages of excavation and construction of the KAMCHIK road tunnel according to limit states

Determine the amount of rock pressure on the temporary support lining of the mine workings based on the following preconditions: the upper terrace has been completed, a temporary concrete arch has been erected (two types of temporary fastening structures are taken into account), the lower terrace has been developed under the cover of a temporary concrete arch. Engineering and geological conditions of tunnel route are provided by an authorized organization(scheme № 1495-6-51) and physical and mechanical characteristics of rocks, presented below, are based on the data of “engineering-geological conditions of the construction site of A-373, Tashkent-Osh road. The sections of rock mass with a coefficient of strength $f_{cr} = 1$ and $f_{cr} \geq 2$ are taken into consideration.

Temporary support lining is taken in the form of concreted steel arches from I-beams № 27 and from the concrete arch of B25 grade of 0.7 m thick.

To study the stress-strain state (SSS) of structures, various options (design schemes) are accepted in an elastic and nonlinear statement. Numerical modeling and problem investigation are conducted using the FEM with a given algorithm. In calculations, we proceed from the fact that two tunnels are constructed sequentially or simultaneously and then we consider the pattern of stress distribution around the tunnels.

The boundary conditions are: in the upper part of the stress region - $\sigma_x = 0, \sigma_y = 0$, along the lateral and lower sides of the displacement, $U = 0, V = 0$

To reduce the effect of kinematic boundary conditions on stresses in the plane, the tunnels are located at a sufficient distance from the lateral boundaries.
Option 1. The upper terrace for one tunnel with and without fastenings is passed; Figure 4 shows the design scheme for this task. The dimensions of the finite element region are taken from the geological structure of the tunnel section. To identify the stress concentration zone, the finite grid around the mine was divided by a dense mesh.

Elastic solutions to calculate this option with and without account for temporary fastenings (concrete and partially metal ones) did not differ much. Indeed, stress concentration occurs around the tunnel and shear stresses have their maximum values exactly in this area. After mounting the temporary fastenings, the plastic zones in the arch (vault) part did not appear, but in the lower chute part, they increased. In these calculations, the height of the disturbed zone above the arch was 2.5 m, and under the chute part – 3 m. As a result of the plastic calculation, the stresses around the tunnel decreased by 15-18% compared with elastic ones.

Option 2. The lower terrace of one tunnel with fastening was passed. But as mentioned above, the transition from the elastic to the plastic zone is carried out elementwise (gradually) and here the pattern of plasticity flow around the tunnel can be observed. The inelastic zone did not remain behind the arched part, but several elements passed into the plastic zone along the lateral part. In the chute part, the depth of disturbed zones of rock mass was about 3 m.

Option 3. The upper terrace of two tunnels was passed simultaneously (see Ошибка! Источник ссылки не найден.). Disturbed zones formed above the arched part of the tunnel and under the feet, the plastic zones increased by about 20% compared with solutions for one tunnel. The construction of two types of temporary supports dramatically increased the plastic zones in the lower part of tunnels, and disturbed soil layers did not appear above the arch. The length of the disturbed zone from the arch foot downward is 5 m.

Option 4. The upper and lower terraces of two tunnels were passed simultaneously. To assess the effect of elasto-plastic zones between tunnels, the problem of simultaneous construction at full tunnel excavation without temporary fastenings was preliminary solved considering elastic-plastic design.

The results of this calculation are shown in Fig. 5, where it is seen that the plastic zones increased by 2 times especially in the direction of tunnels. This shows how necessary it is to strengthen the walls of the tunnels when the mine cross-section is large. Taking into account non-linear properties show us much different pattern for stresses and as a consequence path for developing of strengthening measures.
4. Discussions
Below recommendations for the temporary fastening of tunnel walls are presented for discussion. Based on the studies to determine the disturbed zones around the tunnel workings, the following depths of plastic layers from the surface of the workings were finally determined: no plastic zones appeared above the arch part; the maximum depth near the wall is 2 m; in the chute part it is 1.5-2 m. The most dangerous in this case from the point of view of strength are the side surfaces of the mine. Therefore, based on the experience of design and construction practices in rocky soils, we recommend the use of various measures to strengthen the walls of the workings. In our opinion, the use of anchor supports allows strengthening the rock cohesion, increases their strength and stability, and does not allow the walls to collapse. The length of the anchors is taken as 2-2.5 m. The anchor pitch can be taken 50 cm, the thickness of the plates installed on the wall is 10-15 cm. The wall stability can be provided with other types of temporary supports, such as the boards supported by anchors and channel bar grips.

5. Conclusions
The calculations made it possible to more accurately determine the zones of plastic fracture on the side surfaces of the tunnel workings. Therefore, the proposed methods for nonlinear calculation of underground workings are necessary when designing anchor fastenings.

References
[1] Crouch S L Starfield A M 1983 Boundary elements methods in solid mechanics *George Allen & Unwin* (London)
[2] Ganesh M 1996) A general convergence theory for nonlinear equations with application to integro–differential equations *Applied Numerical Mathematics* 22 pp 435-449
[3] Sladek V Sladek J 1999 Displacements gradients in BEM formulation for small strain plasticity. *Engineering Analysis with Boundary Elements* 23 pp 471-477
[4] Crouch S L Starfield A M Rizzo F J 1983 Boundary Element Methods in Solid Mechanics *J Appl Mech* 50(3) pp 704-705
[5] Scarpato D J 2011 Rock Fractures in Geological Processes *Cambridge University Press* (New York)
[6] Davis R O Selvadurai A P S 1996 Elasticity and Geomechanics *Cambridge university press* (New York)
[7] Davis R O Selvadurai A P S 2005 Plasticity and Geomechanics *Cambridge university press* (New York)

[8] Bobet A 2000 The initiation of secondary cracks in compression *Eng Fract Mech* 66(2) pp 187-219

[9] Bobet A 2009 Elastic solution for deep tunnels. Application to excavation damage zone and rockbolt support *Rock Mech Rock Eng* 42(2) pp 147-174

[10] Bobet A 2010 Numerical methods in geomechanics *Arab J Sci Eng* 35(1B) pp 27-48

[11] Jing L Hudson J A 2002 Numerical Methods in Rock Mechanics *International Journal of Rock Mechanics and Mining Sciences* 39 pp 409–427

[12] Puzrin M 2012 Constitutive Modelling in Geomechanics: *Introduction Springer* (Berlin)

[13] Selvadurai P S 2007 The Analytical Method in Geomechanics *Appl Mech Rev* 60 pp 87-106

[14] Kaiser P K Kim B-H 2008 Rock Mechanics Challenges in Underground Construction and Mining *In Proceedings of the First Southern Hemisphere International Rock Mechanics Symposium* https://papers.acc.uwa.edu.au/p/808_83_Kaiser/

[15] Martin C D Kaiser P K Christiansson R 2003 Stress, instability and design of underground excavations *Int J Rock Mech Min Sci* 40(7-8) pp 1027-1047

[16] Jiang M Yu H-S 2006 Application of Discrete Element Method to Geomechanics *Springer-Verlag* (Berlin)

[17] Adilov F Yuldoshev B Abirov R Miralimov M 2019 Numerical Approach for Estimation of Stress Strain State of Deep Tunnels *In E3S Web of Conferences* 97 (Tashkent) https://doi.org/10.1051/e3sconf/20199704064.

[18] Abirov R A 2004 Nonlinear effects in geomechanics *In Proceeding of Conference Development in plasticity and fracture* (Cracow Poland) p 13

[19] Mirsaidov M M 2019 An account of the foundation in assessment of earth structure dynamics *In E3S Web of Conferences* 97 (Tashkent) https://doi.org/10.1051/e3sconf/20199704015

[20] Mirsaidov M M Sultanov T Z 2014 Assessment of stress-strain state of earth dams with allowance for non-linear strain of material and large strain *Magazine of Civil Engineering* 49(5) pp 73-82

[21] Mirsaidov M M Sultanov T Z Sadullaev A 2013 Determination of the stress-strain state of earth dams with account of elastic-plastic and moist properties of soil and large strain *Magazine of Civil Engineering* 40(5) pp 59-68

[22] Usarov M Mamatiyev G Yarashov J Toshmatov E 2020 Non-stationary oscillations of a box-like structure of a building *Journal of Physics: Conference Series* https://doi.org/10.1088/1742-6596/1425/1/012003

[23] Usarov M Mamatiyev G Toshmatov E Yarashov J 2020 Forced vibrations of a box-like structure of a multi-storey building under dynamic effect *Journal of Physics: Conference Series* https://doi.org/10.1088/1742-6596/1425/1/012004