A method for calculating loads on roof support in mines

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Abstract. The author proposes an approach to the stress–strain analysis of mine support with regard to all displacements of the stope boundary until it makes contact with the support using the stiffness matrix of intact rock mass. Modeling of the void formation and of the joint deformation of the support and adjacent rock mass uses iterative procedures from the methods of initial stresses and initial strains. The support load algorithm and software package are developed.

1. Introduction
Complication of deep-level mining conditions under stresses comparable with the ultimate strength of rocks imposes higher standards on mine support to ensure the required life of mine openings [1, 2]. Mechanical characteristics of mine support with regard to the support installation technology are selected from the design model of the stress–strain behavior of the support and adjacent rock mass [3].

Most support designs commonly assume that a mine opening with installed support deforms under the weight of overlying rocks and under the forces at the boundaries of the mine opening, which agree with the initial stress state of rock mass (Figure 1). Such design disregards free deformation of the mine opening boundary before the support installation. As a result, the stresses and strains in support and in adjacent rock mass are greatly overestimated as compared with the actual in situ values.

![Figure 1. Conventional-design stress–strain analysis of mine support and adjacent rock mass: $\sigma_x$ , $\sigma_y$ , $\tau_{xy}$ —normal and shear stresses; $\gamma$ —bulk density of rocks; $\lambda$—lateral earth pressure coefficient; $V$—vertical displacement.](image-url)
Figure 2 also illustrates the need to take into account free deformation of mine opening boundary in the support design by depicting elastic displacements of the circular opening boundary in the vicinity of the face [3]. The radial displacements of the opening boundary reach 30% of the total elastic displacement already at the line of the face.

![Figure 2. Relative radial displacement of the boundary of a circular mine opening versus distance to the face under elastic deformation of rocks in terms of the opening radius fractions.](image)

Seldom support designs take into account support installation technology. In this case, the stress–strain analysis is performed for free deformation of the mine opening boundary and then joint deformation of the opening boundary and support is modeled [4, 5]. The main difficulty of this approach is the need to measure forces at the boundary of a mine opening before it comes into contact with support. For another thing, joint mine support–adjacent rock deformation under residual forces at the boundary of the mine opening is yet an unsolved problem. Thus, the methods of the stress–strain analysis of mine support generally incompletely account for the features of mechanical interaction between mine support and surround rock mass. Accordingly, it is of the current concern to develop design methods capable to consider in detail the force–deformation relationship of mine support and adjacent rock mass.

2. Stress-strain behavior analysis

The Institute of Mining has developed the method for the stress–strain behavior analysis of backfill and rock mass, and it is proposed to use this method to determine stresses in mine support as it interacts with mine opening boundary. Here we use the finite element method and construct the stiffness matrix for intact roc mass without mine excavations. This stiffness matrix is unchanged in the course of mining [6]. Modeling of mined-out voids with backfill or with support having different physical and mechanical properties uses the iterative procedure from the method of initial stresses, with changing only right-hand side of linear equations in the system to be solved [7]:

\[
[K]\{\delta\} = \{F\} + \{F\}_{\sigma^i} \quad \{F\}_{\sigma^i} = \int_{V} [B]^T \Delta\sigma^i \, dv.
\]

Here, \([K]\) is the stiffness matrix; \([B]\) is the matrix of coupling of strains at the finite elements with displacements of mesh points; \(\{F\}\) is the vector of external forces at the mesh points; \(\{F\}_{\sigma^i}\) is the vector of the forces caused by the initial stresses \(\sigma^i\) at the mesh points.

The stresses required for the calculation of the vector of the initial forces at the mesh points are given by:

\[
\Delta\sigma^i_x = \sigma^1_x - \sigma^2_x = (\lambda^1 - \lambda^2) e + 2(G^1 - G^2)e_x,
\]

\[
\Delta\sigma^i_y = \sigma^1_y - \sigma^2_y = (\lambda^1 - \lambda^2) e + 2(G^1 - G^2)e_y.
\]
\[
\Delta \sigma^i_j = \sigma^1_j - \sigma^2_j = (\lambda^1 - \lambda^2) e + 2(G^1 - G^2) e_z,
\]
\[
\Delta \tau^i_{xy} = \tau^1_{xy} - \tau^2_{xy} = (G^1 - G^2) \gamma^y_{xy},
\]
\[
\Delta \tau^i_{xz} = \tau^1_{xz} - \tau^2_{xz} = (G^1 - G^2) \gamma^y_{xz},
\]
\[
\Delta \tau^i_{yz} = \tau^1_{yz} - \tau^2_{yz} = (G^1 - G^2) \gamma^y_{yz},
\]
where \( e_x, e_y, e_z, \gamma_{xy}, \gamma_{xz}, \gamma_{yz} \) are the strain tensor components; \( e \) is the volumetric strain; \( \lambda^1, \lambda^2 \), \( G^1, G^2 \) are the Lamé constants of the intact rock mass and the material of mine support.

The stress–strain relation obtained using the above formulas:
\[
\Delta \sigma_j = \frac{1}{\sqrt{2}} \sqrt{(\Delta \sigma_j - \Delta \sigma_j)^2 + (\Delta \sigma_j - \Delta \sigma_j)^2 + (\Delta \sigma_j - \Delta \sigma_j)^2 + 6(\Delta \tau_{xy}^2 + \Delta \tau_{xz}^2 + \Delta \tau_{yz}^2)} = 3(G^1 - G^2)e_j
\]
is a special case of the ‘single curve’ in the theory of small elastoplastic strains (Figure 3a).

At the same time, the iterative procedure of the method of initial stresses has a limited application range in the mine support stress analysis as it is only implemented when Young’s modulus of the support is smaller or insignificantly differs from Young’s modulus of rock mass. When young’s modulus of the support exceeds Young’s modulus of adjacent rocks, the iterative procedure of the method of initial stresses diverges. It is suggested to overcome these constraints using the iterative procedure from the method of initial strains (Figure 3b).

![Figure 3. Computational schemes of (a) initial stresses and (b) initial strains in problems of mine support deformation: 1—stress–strain curves for intact rock mass; 2—stress–strain curve for mine support; \( \Delta \sigma_j, \Delta e_j \) —mysties of stresses and strains for calculation of vector of initial forces at mesh points; \( E_{\text{rock}}, E_{\text{sup}}, G_{\text{rock}}, G_{\text{sup}} \) —Young’s and shear moduli of intact rock mass and support, respectively.](image)

It follows from Figure 3 that joint application of the iterative procedures from the methods of initial stresses and initial strains enables computations at any ratios of Young’s moduli of rock mass and support. The components of the vector of the initial forces at mesh points, agreeable with the method of initial strains, are found from the formula:
\[
\{F\}_{\{e^n\}} = \int[B]^T[D]\{\Delta e^n\}dv.
\]

These formulas are included in the software for the stress–strain analysis of mine support and surrounding rock mass with regard to their interaction features at any mechanical characteristics of rocks and support. By way of illustration, Figure 4 presents calculations at Young’s modulus of support 10 times as much as Young’s modulus of adjacent rocks. Natural stress state of intact rock
mass is assumed to obey the Dinnik hypothesis. Enclosing rock mass has Young’s modulus of 25000 MPa and Poisson’s ratio \( \nu = 0.25 \).

![Figure 4](image)

**Figure 4.** Patterns of vertical stresses in mine support and adjacent rock mass, MPa: displacements of mine opening boundary down to its contact with mine support make (a) 10% and (b) 60% of total displacements of walls in unsupported void.

The support comes into operation after some displacement of unsupported boundary of mine opening, which results in qualitative re-distribution of stresses in the abutment pressure zones: two concentration domains of vertical stresses appear (Figure 4b).

### 3. Conclusions

The method proposed by the author for the stress–strain analysis of mine support and adjacent rock mass takes into account displacement of the boundary of mine void before the support is installed and comes into operation. The computation algorithm is implementable even when the support and rock mass have considerably different mechanical parameters.

In an arched mine opening under the action of gravitational initial stresses, the highest compression is initiated at the junction of the support and the floor of the mine void. The compressive stress concentration is preserved in these zones as displacements of the unsupported boundary of the mine opening grow.

Joint deformation of the support and adjacent rocks after partial free deformation of the mine opening boundary before the support installation initiates two concentration zones of vertical stresses. The first zone appears after deformation of rocks around the unsupported void. The second zone is generated by joint deformation of the support and rock mass.

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