GEOMECHANICAL ANALYSIS FOR EXCAVATION OF AN UNDERWORKED ORE PLACER

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Introduction. Defining the working methods and excavation sequences for disseminated ores is an important aspect of geomechanical studies of the Talnakh mines. It is a unique mining and engineering situation because disseminated ores typically occur over previously mined rich ore bodies. As an illustration, we describe a real situation in the Komsomol'skii mine field (all dimensions are given as approximate estimates). At a depth of 600 m a low-angle 30 m thick rich ore placer has been worked. The worked-out space has been gobbed with a solidifying filler (Fig. 1a); the space size is 0.4 × 1.0 km.

As a result, a 50-m bed of disseminated ores has been underworked immediately over the filler mass. In the near future these ores will be mined. The initial cutting will be done at the center of the underworked region (hatched area in Fig. 1b). Two main methods of working are discussed. The first method is the system with complete filling of the worked-out space, common in the excavation of rich ore placers in the Talnakh fields. Given the high cost of the solidifying filler mixes and the relatively low value of disseminated ores, an alternative combination technique is also considered; it includes the following components.

In the first stage, primary strips are worked with filling. Ore pillars between them are then worked in the second stage by excavation blocks with collapse of ore and surrounding rocks and a certain lag behind the primary front (Fig. 2). This version is more cost-effective but, in developing it, one must prepare predictions of the stability of the main elements of the working system. This paper discusses methods and results of solution of this problem.

Substantiation of a Finite-Element Model. One necessary step in solving this problem is the construction of a geomechanical model which should be used to predict the behavior of a rock mass during the course of mining of a deposit. We adopt a finite-element model. The comparison of solutions of two- and three-dimensional problems of the formation of an elastic half-space with a prismatic cavity indicates that a two-dimensional model is acceptable for predicting the condition of the bed near the center of the ore field (Fig. 3). Calculations on two grids, with one grid presenting a detailed actual geometry and structure of the bed (Fig. 4a), have confirmed that, for acceptable general estimates, a simple grid with mean mechanical rock constants averaged for the bed is suitable [1]. In fact, detailed analysis of the geometry of inhomogeneities and variations of rock properties is hardly possible: first, because of the high cost of calculations, and second, because of the lack of detailed data. A diagram for calculation region (simple grid) is presented in Fig. 4b. A disseminated ore bed with thickness $h_d = 45$ m and a span S_d is excavated after the rich ore body of span S_f and thickness $h_f = 30$ m has been worked out and filled.

Rich Ore Excavation. In the first step we modeled the situation to be expected at the beginning of the working of disseminated ore ($S_d = 0$). We took into account the nonlinear relationship between the pressure in the filler and the convergence of the roof and floor of the worked-out space because of incomplete filling Δ (Fig. 5). Note that Δ is an effective parameter which reflected combined action of actual technological incomplete filling (cavities at the "filler−rock") and the compaction of solidifying filler by compression. The solution was found by successive approximations [2]. In the first step, we computed the convergence of the roof and the floor of the worked-out space, compared the result with Δ, and took the positive difference valuated by the thickness of the rich ore body as the first approximation for the vertical deformations of the filler bed. The reaction of the filler bed was estimated from elastic relations in absence of horizontal strains. In the second and subsequent steps we solved the problem for a weightless region where surface forces are applied at the contour of the worked-out space which are statistically equivalent to the reaction of the filler mass; initial deformations and resistances were then adjusted. From three to five iterations sufficed for estimating with acceptable error the stress distribution in the rock mass, ore mass, and filler mass. The main model parameters, including the effective elastic modulus of the mass ($E_d = 33$ GPa) and

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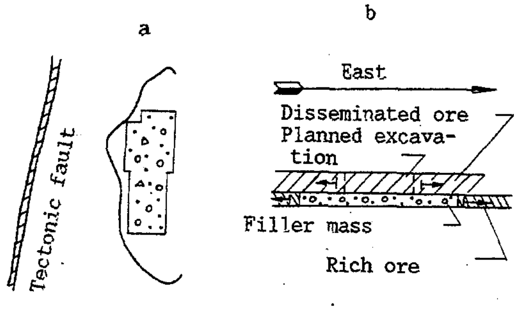

Fig. 1. Plan (a) and transverse cross-section (b) of a mine.

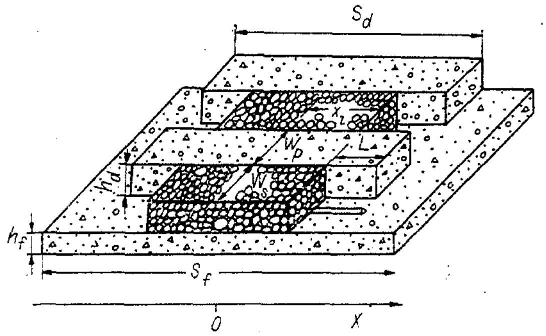

Fig. 2. Excavation layout for disseminated ore by combination method.

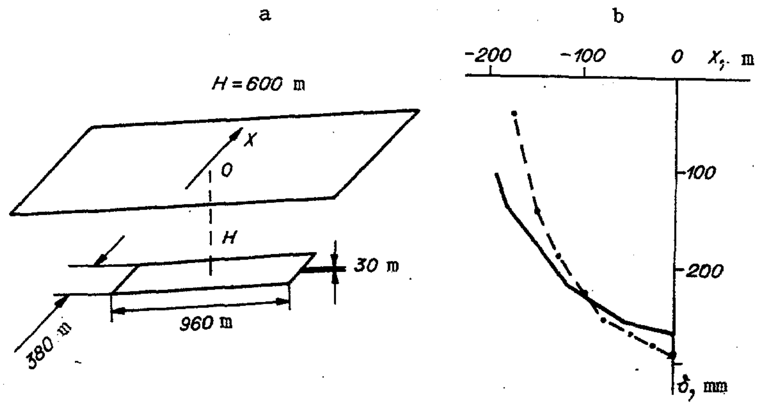

Fig. 3. Calculated region of three-dimensional problem (a) and roof and floor convergence in central cross-section of a cavity (b): solid curve – two-dimensional; dashed curve – three-dimensional.

the filling shortage ($\Delta = 210$ mm) were estimated proceeding from the maximum convergence of calculated and experimental data on displacements of underworked bed and pressures on the filler mass.

The deformation properties of the filler mass ($E_f = 2.5$ GPa, $\nu_f = 0.3$) were determined experimentally in situ. Figure 6a plots experimental (dot-dash) data (from the Institute of Mining, Geomechanics, and Surveying) and calculated (solid) vertical displacements of the underworked bed. Figure 6b shows calculated pressures in the filler mass for various worked-out space spans. Note that the experimental estimate of the additional load in the central part of the filler mass obtained earlier with a bore hole dilatometer at an actual span of approximately 300 m is 5-6 MPa, which is consistent with calculated data.

We discuss in some detail the results of an independent series of measurements performed by the method with hydraulic rupture of holes [3].

Experimental Evaluation of the Stress Field. The variation of the ratio of initial horizontal stress to vertical stress in a wide range (0, 2...3, 0) does not affect significantly either the additional displacement caused by the working of a long horizontal placer nor the pressure in the filler mass. Therefore, there is some arbitrariness in the choice of initial horizontal stresses; to eliminate this arbitrariness, additional experimental data are needed.

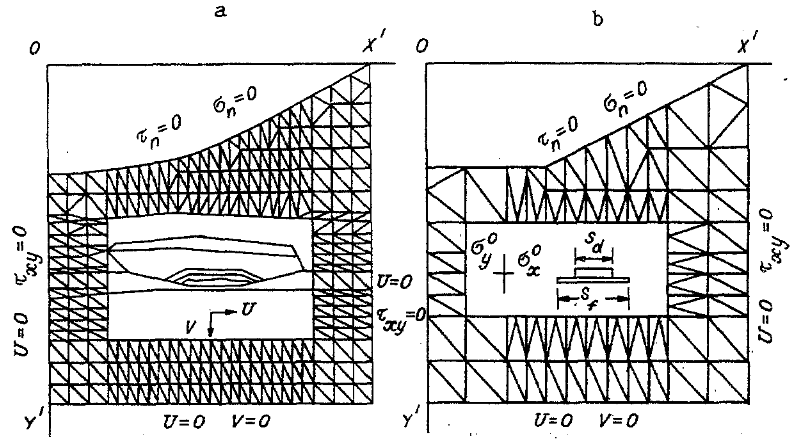

Fig. 4. Detailed (a) and simple (b) grids for solution of two-dimensional problems.

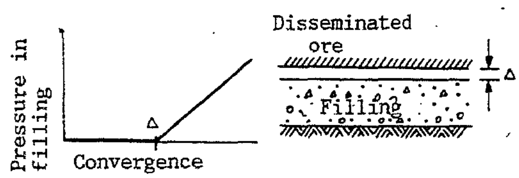

Fig. 5. Support pressure of filler mass as a function of roof and floor convergence.

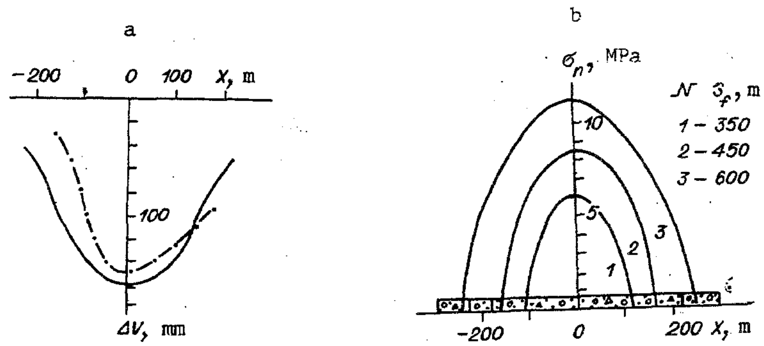

Fig. 6. Vertical displacements of underworked bed (a) and pressure in filling (b).

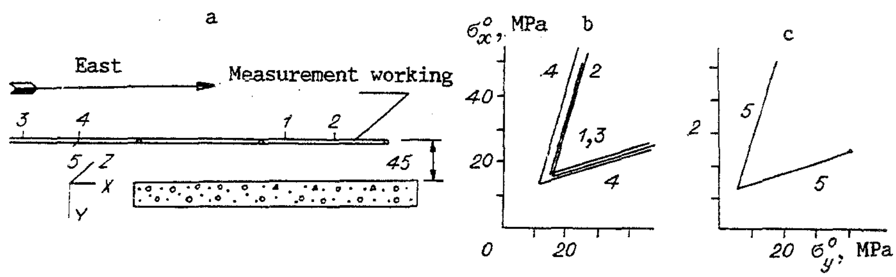

Fig. 7. Vertical cross-section of the central portion of an ore body with location of measurement holes (a) and permissible values of initial stress component (b, c).

Figure 7a is a diagram of the section of the central portion of worked ore body with locations of measurement holes in a single working. A series of hydraulic rupture experiments were performed in vertical holes (1-4) and a horizontal hole (5). The most stable parameter in all experiments was the reopening pressure. The average values for each hole outside the zone affected by a single working are given in Table 1. In interpreting these values in terms of initial stresses we made substantial use of the above-mentioned fact that the components of additional stresses around an elongate narrow cavity outside

TABLE 1

Hole	σ_x	σ_y	σ_z	τ_{xy}	$\overline{P}_g$
	MPa				
1	$\sigma_x^0 - 6,0$	$\sigma_y^0 - 12,0$	$\sigma_z^0 - 5,5$	1,0	20,0
2	$\sigma_x^0 - 5,5$	$\sigma_y^0 - 13,5$	$\sigma_z^0 - 5,5$	1,5	22,0
3	$\sigma_x^0 + 1,5$	$\sigma_y^0 + 4,0$	$\sigma_z^0 + 2,0$	0,0	35,0
4,5	$\sigma_x^0 + 1,0$	$\sigma_y^0 + 8,0$	$\sigma_z^0 + 3,0$	0,0	28,5

the zone affected by side exposures are affected little by the components of the initial stresses acting in the plane XZ (see Fig. 7). We assume that initial horizontal principal stresses σ_x^0, σ_z^0 are oriented in the south-north and west-east directions. After the working of the rich ore body, the stress components at each point acquire an increment:

$$\sigma_x = \sigma_x^0 + \Delta\sigma_x; \ \sigma_y = \sigma_y^0 + \Delta\sigma_y, \ \sigma_z = \sigma_z^0 + \Delta\sigma_z, \ \tau = \Delta\tau_{xy}.$$

The additional stresses $\Delta\sigma_x$, $\Delta\sigma_y$, $\Delta\sigma_z$, $\Delta\tau_{xy}$ at locations of measurement holes can be estimated from the model with an arbitrary ratio of initial horizontal stresses equal, for example, to unity. The respective numeric values are given in Table 1.

In the vertical holes, the crack opening pressure is linked with acting stresses by the following relations:

$$Pr = 3\sigma_x - \sigma_z \ \text{at} \ \ \sigma_x \leqslant \sigma_z, \ Pr = 3\sigma_z - \sigma_x \ \text{at} \ \ \sigma_z \leqslant \sigma_x.$$

Setting Pr values from the experiment and the values of $\Delta\sigma_x$, $\Delta\sigma_y$ from calculations, we can construct in the cavity (σ_x^0, σ_z^0) the region of permissible stress values. We note a good convergence of the results (see Fig. 7b) considering that holes 1-4 were situated in different locations relative to the worked-out space (hole 4, deviated 27° from the vertical). This region, constructed from experimental and analytic data, allows us to estimate possible values of σ_x^0 and σ_z^0 of the initial stress field. Figure 7c shows the region of permissible stresses σ_x^0 and σ_y^0 that correspond to calculated and experimental data for horizontal hole 5. Estimating the vertical component by the weight of the overlaying rock bed $\sigma_y^0 = \rho gH = 16$ MPa and making use of the data from Figs. 7b,c, we obtain three alternative distributions of initial stresses MPa:

Variant	σ_x^0	σ_y^0	σ_z^0	σ_x^0/σ_y^0	σ_z^0/σ_y^0
1	16	16	16	1,0	1,0
2	42	16	24	2,6	1,5
3	42	16	93	2,6	5,8

Additional approximate analysis indicates that the first alternative is closest to the actual conditions. For each alternative we calculated, according to the model, the stressed state components of three sections of the bed where measurements in holes 1-3 were performed. The results were substituted as initial stresses in the solution of the problem of the distribution of stresses around an elongate cylindric working. Theoretical distributions of the parameter Pr in the roof of the workings were then compared with the experimental data in the working-affected zone. As a result, we found that the best match is obtained with hydrostatic initial stress field.

Excavation of Disseminated Ores. The technological arrangement for the combination method of excavation of disseminated ores is illustrated by Fig. 2. The stope front moves from the central part of the worked-out space. W_p is the width of the primary strips worked with filling; W_s is the width of the secondary strips worked with collapse with a lag L. Excavation of secondary strips is performed by a set of workings arranged in front of the stope in ore pillars. Of most interest for estimating the mine stability are stress estimates at the phase of secondary strips. We must also evaluate the state of workings in case of possible placement in the underlying filler mass.

By computer simulation, we estimated the convergence of the roof and the floor in case of complete excavation of underworked disseminated ores ($S_d = S_f$). Additional convergences $\delta_{fe}(X)$ for various spans S_d are illustrated by Fig. 8a. In case of partial excavation of disseminated ores by the combination technique, the additional convergence of the roof and the floor was estimated by means of an elementary linear approximation:

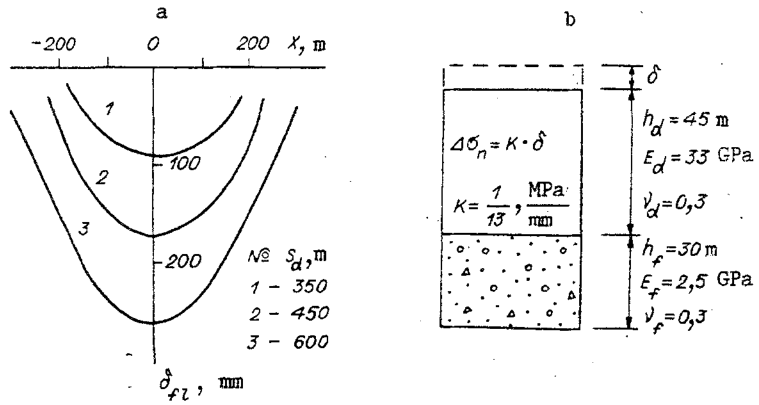

Fig. 8. Additional convergence as a function of span length during complete excavation of disseminated ore (a) and the "ore pillar–underlying filler mass" system (b).

N	1	2	3	4	5	6
W_s/W_p	2	$\frac{1}{2}$	2	$\frac{1}{2}$	2	$\frac{1}{2}$
S_f, m	350		450		600	

N	1	2	3	4	5	6	7	8	9
L, m	0	50	100	0	50	100	0	50	100
S_f, m	350			450			600		

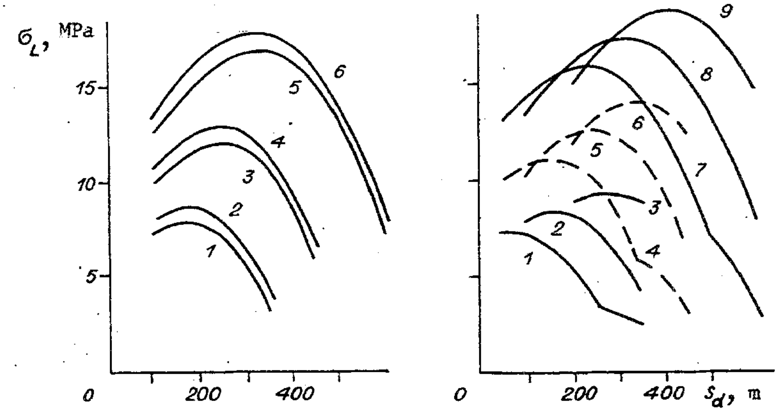

Fig. 9. Vertical stresses at phase of secondary strips as a function of span for various geometric parameter values.

$$\delta_{pe}(X) = \frac{S_d W_p + 2X_L W_s}{S_f (W_p + W_s)} \delta_{fe}(X),$$

where $2X_L = S_d - 2L$ is the distance between faces of secondary strips (see Fig. 2). The vertical stresses at the face of the secondary strips in this case are

$$\sigma_L = K\delta_{pe}(X_L) + \sigma_n(X_L).$$

Here $\sigma_n(X_L)$ are vertical stresses in the floor of the ore body before the beginning of the excavation of disseminated ores (see Fig. 6b). K is coefficient which expresses the rigidity of the system "ore pillar–underlying filler mass" (Fig. 8b): $K = (h_j/E_f + h_d/E_d)^{-1}$. The behavior of σ_n as a function of S_d for various spans of the underworking S_f, ratios of sizes of primary and secondary strips W_p/W_s, and lags L is illustrated by plots in Fig. 9. We see that the pressure is determined mainly by the underworking span S_f. Vertical stresses are several times as high as the strength of the solidifying filler (1-5) MPa, which means that for large spans of underworking it is inadmissible to place workings in the filler mass ahead of the stope front of secondary strips.

CONCLUSIONS

1. Approximate analysis suggests the following sequence for working of disseminated ores by combination technique in terms of mine stability ahead of the stope in secondary strips. The preferred arrangement involves early central cutting of the disseminated ore mass with undeveloped underworking spans S_f. The spacings between the faces of primary and secondary strips should be as small as possible. The worst working conditions are to be expected in case of divergence of faces ($2X_L$) to 0.3-0.6 S_f.

2. An experimental/analytic evaluation of acting stresses suggest that in the Komsomol'skii mine field the initial conditions are close to the hydrostatic state.

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