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## Estimate of rock mass stability in surface–borehole mining of high-grade iron ore

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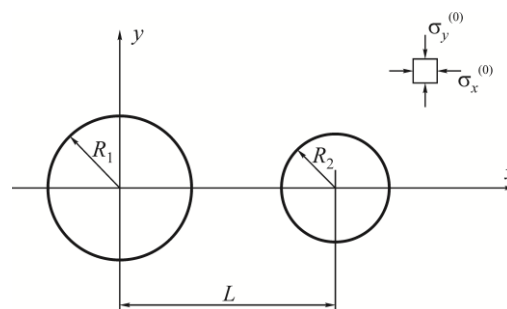
**Abstract.** Under consideration is the estimate of rock mass stability around underground openings generated as a result of hydraulic borehole mining of iron ore. The authors use analytical solutions of two plane elasticity problems on stress state of infinite media with the zone of weakening in the form of one or two circular holes, given initial stresses are set in the study domains.

Hydraulic mining by boreholes is a promising method to develop difficult-to-access hard minerals. The main process flows involved in hydraulic mining is drilling, washing-out of minerals by water jets and lift of pulp slurry on the surface [1]. The evident advantages of this technology are low capital costs, applicability in complicated ground conditions, high-rate automation of the mining process and weak environmental impact.

The wide use of the hydraulic mining technology is mainly impeded by such factors as low actual productivity of holes as against the design capacity and risk of ground subsidence, especially in mining at shallow depths. As a consequence, hydraulic mining method is currently at the stage of trial, with low production outputs [2].

The most amplitudinous example of application of the hydraulic borehole mining method is iron ore production in the Shamrai site of Bolshe-Troitsk deposit in the Belgorod Region. Over the period from 2006 to 2013, eight boreholes produced round two thousand tons of ore, which resulted in generation of cylindrical cavities filled with pressure water at a depth of 500–700 m.

Upon completion of mining, a question arose on expediency of backfilling of the mined-out voids in order to prevent the ground surface from considerable subsidence and damage of water-tight strata. With this end in view, it was decided to assess stability of surrounding rock mass around excavations.



**Figure 1.** Schematic of an elastic problem on stability of cylindrical voids in iron ore–rock mass. Explanation is in the text.

The set problem had two stages: assessment of stability of walls in two cylindrical voids generated by the neighbor production boreholes and estimation of strength of a thick limestone bed overlying a layer of loose iron ore.

The first stage task used the known solution of plane elasticity on stress state of an infinite linearly deformable medium with two circular zones of weakening that modeled mined-out voids (Figure 1).

The stability assessment used the approach put forward in [3] and based on construction of conditional zones of inelastic strains, i.e. zones where the Mohr–Coulomb strength criterion holds true

$$(\sigma_{\theta}^2 - \sigma_r^2) + 4\tau_{r\theta}^2 > (\sigma_{\theta} + \sigma_r - 2C \operatorname{ctg} \varphi)^2 \sin^2 \varphi,$$

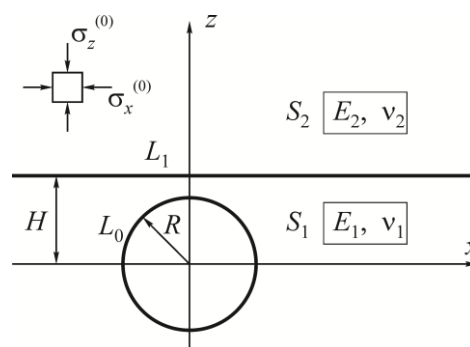
where  $\sigma_r$ ,  $\sigma_{\theta}$ ,  $\tau_{r\theta}$  are the estimated stresses of rocks surrounding the voids (tension stresses are assumed positive);  $C$  is the cohesion, MPa;  $\varphi$  is the internal friction angle.

The operations on assessment of rock mass stress state and delineation of conditional zones of inelastic strains involved the input data: radii of the cylindrical voids (determined based on the ore production output under assumption that the voids were cylinders with the constant radii)  $R_1 = 6.0$  m and  $R_2 = 7.0$  m; spacing of the voids  $L = 45$  m; strength characteristics of rocks (in the weakest bed, considering the structural weakening coefficient)  $C = 1.6$  MPa,  $\varphi = 30^\circ$ ; initial stresses in the horizontal plane  $\sigma_x^{(0)} = \sigma_y^{(0)} = -14.3$  MPa.

The calculations have shown that the mutual effect of the voids is insignificant, and the maximum size of the inelastic strain zone is not more than 2.2 m. Based on the classification of stability of excavations depending on the size of the conditional inelastic strain zones [3], a conclusion has been drawn that iron ore mass is insufficiently stable near the test voids and collapse is quite probable.

The second stage calculation used another approach to rock mass stability assessment. Under analysis was the stress state of a thick limestone bed overlying the iron ore bed where hydraulic mining was carried out. It was assumed that even in case of instability of the boreholes, the limestone bed would be sufficiently strong to eliminate probable subsidence.

The estimate of the limestone stability assumed that the iron ore bed contained a spherical void that touched limestone at the top of the bed. To find the influence of the void on the stress state of the limestone layer, a plane elasticity problem illustrated in Figure 2 was considered.



**Figure 2.** Schematic of an elastic problem on stress state of contiguous media with a circular zone of weakening in one of the media. Explanation is in the text.

In this case, a semi-infinite medium  $S_1$  with an elasticity modulus  $E_1$  and Poisson's ratio  $\nu_1$ , weakened by a hole with a radius  $R$ , models the iron ore bed, and the medium  $S_2$  with  $E_2$  and  $\nu_2$  models the bed of limestone. In the media  $S_1$  and  $S_2$ , the field of initial stresses is uniform and nonequicomponent. At the horizontal interface of  $S_1$  and  $S_2$ , the conditions of continuity of the stress and displacement vectors are fulfilled, and the hole boundary is free of external forces.

It follows from the above formulation of the problem that the spherical cavity is replaced by the horizontal cylindrical hole, and the calculated stresses in limestone appear somewhat overestimated as

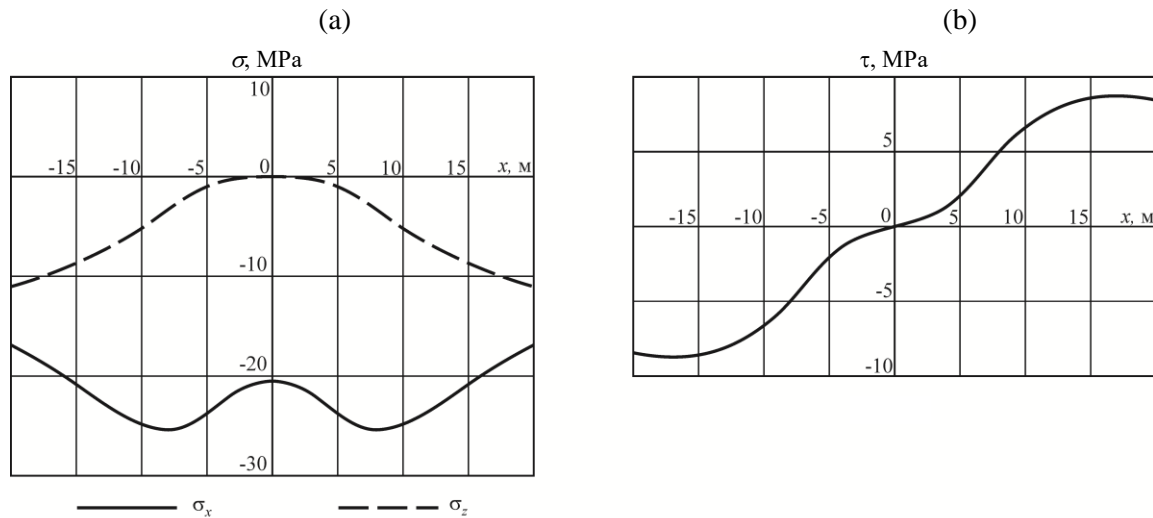
a consequence. This assumption is applicable in actual calculations for the resultant error is included in the safety margin of mine excavations.

The problem was solved using the theory of functions of complex variable, Kolosov–Muskhelishvili integrated potentials [4], analytical extensions of these potentials, being regular in the lower semi-plane outside the hole, across the contact line, to the upper semi-plane [5], properties of integrals of the Cauchy type and complex series.

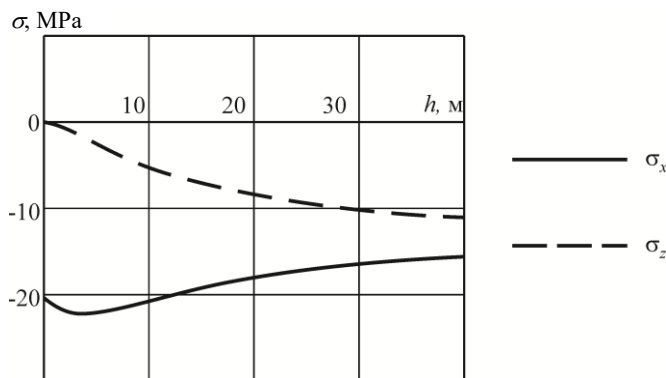
The assessment of stresses in limestone and the delineation of conditional zones of inelastic strains included the input data:  $E_1 = 1400$  MPa,  $\nu_1 = 0.33$ ,  $E_2 = 59000$  MPa,  $\nu_2 = 0.30$ ,  $C = 4.4$  MPa,  $\varphi = 40^\circ$ . The void radius determined based on the output of iron ore produced by the hole of the maximum capacity was  $R = 23$  m.

The initial stress field due to the dead weight of rocks was assumed uniform and equicomponent (hydrostatic). The estimated initial stresses  $\sigma_x^{(0)} = \sigma_z^{(0)} = 13.1$  MPa. The distance from the hole center to the interface was assumed approximately equal to the hole radius,  $H \approx R$ .

The stress distribution in limestone at the interface is depicted in Figure 3. Figure 4 illustrates variation in normal stresses across the thickness of the limestone bed. The vertical coordinate  $h$  is counted from the iron ore and limestone interface.



**Figure 3.** Distribution of (a) normal and (b) shear stresses at the interface of the two beds.



**Figure 4.** Variation in the normal stresses height-wise the limestone bed.

After the analyses of the resultant stress distribution in the limestone bed, the conditional zone of inelastic strains is localized at the limestone and hole contact and has a shape close to a circle, with a width of 12.2 m and a height of 1.6 m.

Since the maximal vertical size of potential damage zone is much less than the limestone bed thickness (approx 60 m), it is possible to conclude that the limestone bed in the vicinity of the production holes possesses sufficient stability and prevents from the ground surface subsidence and from disintegration of water-tight stata.

It is noteworthy that analytical calculations are currently applicable in solving of geomechanical problems of the types discussed in this paper only with considerable simplifications which reduce reliability of the obtained results.

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