Experimental research data on stress state of salt rock mass around an underground excavation

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Abstract. The paper presents the experimental stress state data obtained in surrounding salt rock mass around an excavation in Mir Mine, ALROSA. The deformation characteristics and the values of stresses in the adjacent rock mass are determined. Using the method of drilling a pair of parallel holes in a stressed area, the authors construct linear relationship for the radial displacements of the stress measurement hole boundaries under the short-term loading of the perturbing hole. The resultant elasticity moduli of rocks are comparable with the laboratory core test data. Pre-estimates of actual stresses point at the presence of a plasticity zone in the vicinity of the underground excavation. The stress state behavior at a distance from the excavation boundary disagrees with the Dinnik–Geim hypothesis.

Mir Mine, ALROSA, extracts ore reserves under the closed open pit mine bottom by top-down cut-and-fill with cemented backfill. The underground excavations are protected from flooding by brines from high-pressure Metegero-Ichersky aquifer exposed by open pit mining using the method of 'dry' deactivation of the open pit mine with the safety pillar left under the open pit bottom [1].

To control the safety crown pillar (20 m thick), Yakutniproalmaz together with the Institute Mining developed and implemented the integrated geomechanical monitoring project in Mirny Mine in 2014. The geomechanical behavior in rock mass under the pit bottom is monitored [2], and development of geomechanical processes is predicted by mathematical modeling given available information on stress state and mechanical properties of intact rock mass [3].

Enclosing rock mass under the open pit mine bottom at the depth of extraction blocks 1 and 2 (550–750 m) below the surface is composed of salt rocks (halite) and thin carbonate interbeds [4]. By laboratory core tests, elasticity modulus of halite within Charskaya suit is 14.6–19.6 GPa, limit strength of halite at the supposed measurement depth (750 m) is 24.7 MPa [5]. At the average bulk overburden rock weight of 2.61 t/m^3 [5], the vertical stress in intact rock mass is $-\gamma H = 19.6$ MPa.

Tectonically, Mir pipe is governed by interaction of north-west, meridional and north-east subvertical faults, and the extension of the faults in some areas of the ore body is reflective of activation of the fault-and-block structure at post-ore stages [4]. Modern regional stress field has not been assessed whereas these parameters as mechanical properties of rocks are required as the boundary conditions in numerical modeling. Assessment of state and properties of rocks is a complex and laborious problem, both theoretically and practically, and requires target-oriented and long-term operation. In this connection, it is planed to carry out experimental research of stress state by stages. The first stage is the approximated estimation of the intact tock mass stresses from the viewpoint of

applicability of hypotheses on stress distribution (by Dinnik and Game). Stress state of intact rock mass should be estimated beyond the influence zone of open pit and underground mining.

Aiming to estimate applicability of stress measurement in parallel drill holes [6] in salt rock mass, the experimental test series the automated measurement equipment designed at the Institute of Mining [7]. The authors think it is inexpedient to assess stresses outside the salt rock mass enclosing blocks 1 and 2 because of thin carbonate interbeds where stresses behave specifically. The test location was selected adjacent rock mass of a conveyor crossway at the level –410 m (750 m below the surface), beyond the influence zone of either open pit or underground mining.

Figure 1 depicts arrangement of the holes and orientation of the measurement direction of strainmeter (Figure 1).

The Institute of Mining has developed the method of stress measurement in parallel drill holes [6]. In this method, a measurement hole is first drilled and strainmeter is placed in it. After the strain meter readings become stable, initial stress state in rocks around the measurement hole is excited by means of drilling a parallel disturbing hole. The stresses are estimated by radial displacements caused by the parallel drilling of a disturbing hole, and deformation properties of rocks in the measurement area are determined by the change in the radial displacements under the further loading of the disturbing hole. The validity of the elastic model of rock mass behavior in stress calculation is determined by the data on rock mass response to loading of the walls of the disturbing hole.
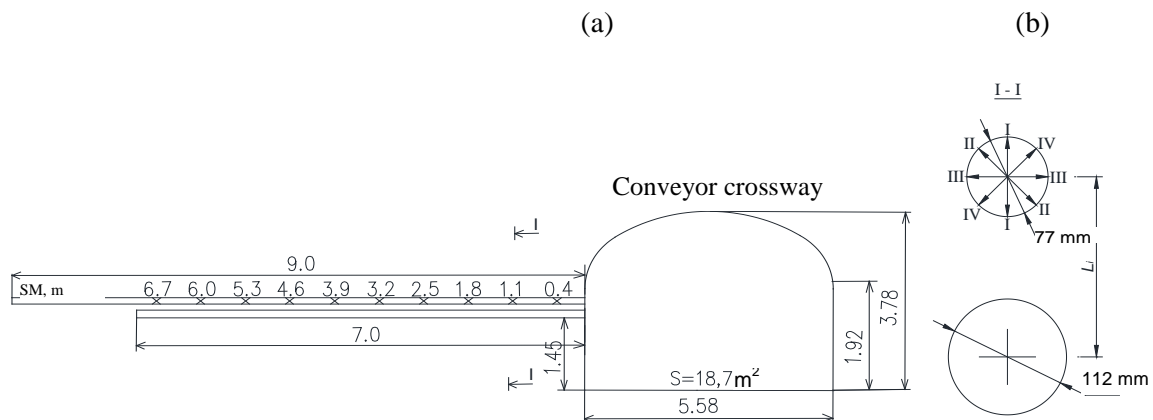

Figure 1. (a) Arrangement of measurement and disturbing holes; (b) orientation of measurement directions of strainmeter in vertical plane.

Drilling used diamond drill bits with the diameters 77 and 112 mm. Visual inspection of the walls in the measurement hole before the tests by a downhole video camera showed no defects along the whole depth of the hole (9 m).

Figure 2 shows the curves of the radial displacement in the walls of the measurement hole under disturbing hole drilling at the installation of the strainmeter (SM) 1.1 and 2.5 m away from the crossway wall. The measurement was carried when the bottom of the disturbing hole with the diameter of 120 mm was 30 mm higher and than 30–35 m lower the installation place of SM.

The analysis of the obtained results shows that:

—at the depth of 1.1 m (Figure 2a) deformation of the measurement hole walls starts when the disturbing hole bottom is 20 cm higher SM place and stops when the bottom is 30 cm lower it (the measurement accuracy 1 μm);

—after the termination of the disturbance drilling, there is a stable linear trend in all measurement directions of SM at the depth of 2.5 m (Figure 2b), which is strengthens with distance from the crossway wall.

Starting from the depth of 2.5 m and below, reading of the strainmeter show no stabilization even after the termination of drilling. The total radial displacement is composed of instantaneous elastic

displacement due to the disturbing hole drilling and displacements due to irreversible deformation of salt (creep).
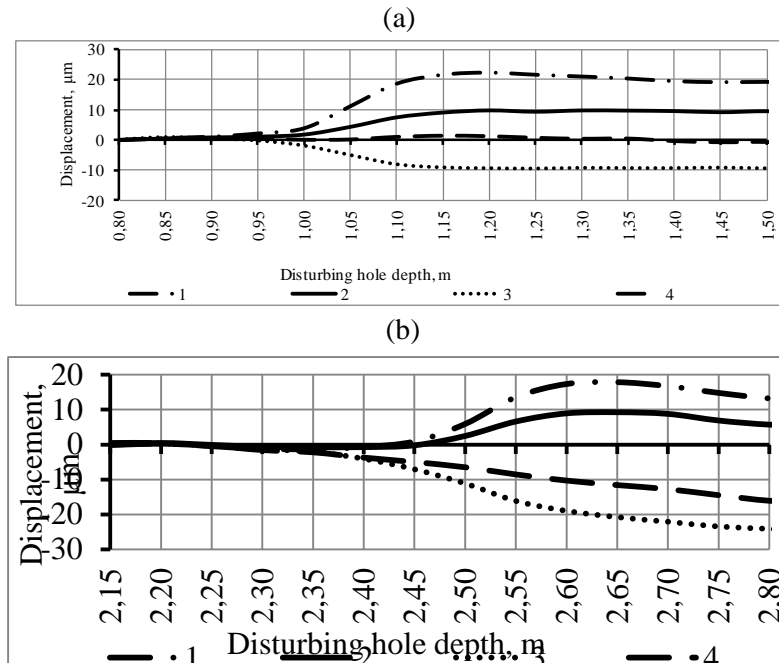

Figure 2. Displacements in measurement hole walls under disturbance drilling along the directions of SM beams at (a) 1.1 m and (b) 2.5 m.

The calculations in the parallel hole drilling method is based on the elastic model; for this reason, an approach was proposed to processing of data obtained farther than 2.5 m from the crossway wall. In each measurement direction of SM beams, the overall recorded displacements are subtracted by the displacements determined from the displacement trends after the drilling termination within the time corresponding to the time of the disturbance drilling behind the zone of SM installation (3 min). The resultant difference is assumed the elastic displacements induced by the disturbance drilling and used in the calculations of the quasi-principal stresses.

For the assessment of stresses by the radial displacements of the measurement hole walls under the disturbing hole drilling, the modulus of elastic deformation of salt, $\sigma_{\ae} = 4(1 - \nu^2)$, is determined by means of step-by-step loading of the disturbing hole after the termination of drilling. It is also becomes possible to validate applicability of the elastic model of the rock mass behavior.

Figure 3 illustrates the results of loading by the data of SM at 1.1 and 6.7 m. The analysis of the deformation in all 4 directions of SM beams points at the linear relation between pressure and displacement (elasticity of rocks) under short-term load and at insignificant residual displacements under unloading, not higher than the measurement error. The difference in the displacements in SM beams 2 and 4 at the depth of 6.7 m is reflective of deviation of the holes from coaxiality. Mutual position of the holes along the depth was checked by tacheometry. With regard to the obtained data, $\sigma_{\ae}$ was assessed (Table 1).

The values of the elasticity modulus agree by depths. At the same time, these values of the elasticity modulus ($E_e = 14.6–20.0$ GPa) are comparable with the core test results (14.6–19.6 GPa).

Table 2 and Figure 4 present the values and orientations of the quasi-principal stresses in the vertical plane at different distances from the crossway wall.

The analysis of the obtained results shows the unloaded (plastic zone) 3 m away from the crossway wall; the values of stresses in this zones do not exceed the vertical stresses due to

overburden rock weight ($\gamma H \approx 20\text{МПа}$). At the distance of 3 m from the crossway walls, the horizontal stresses exceed γH by 1.5–2 times.
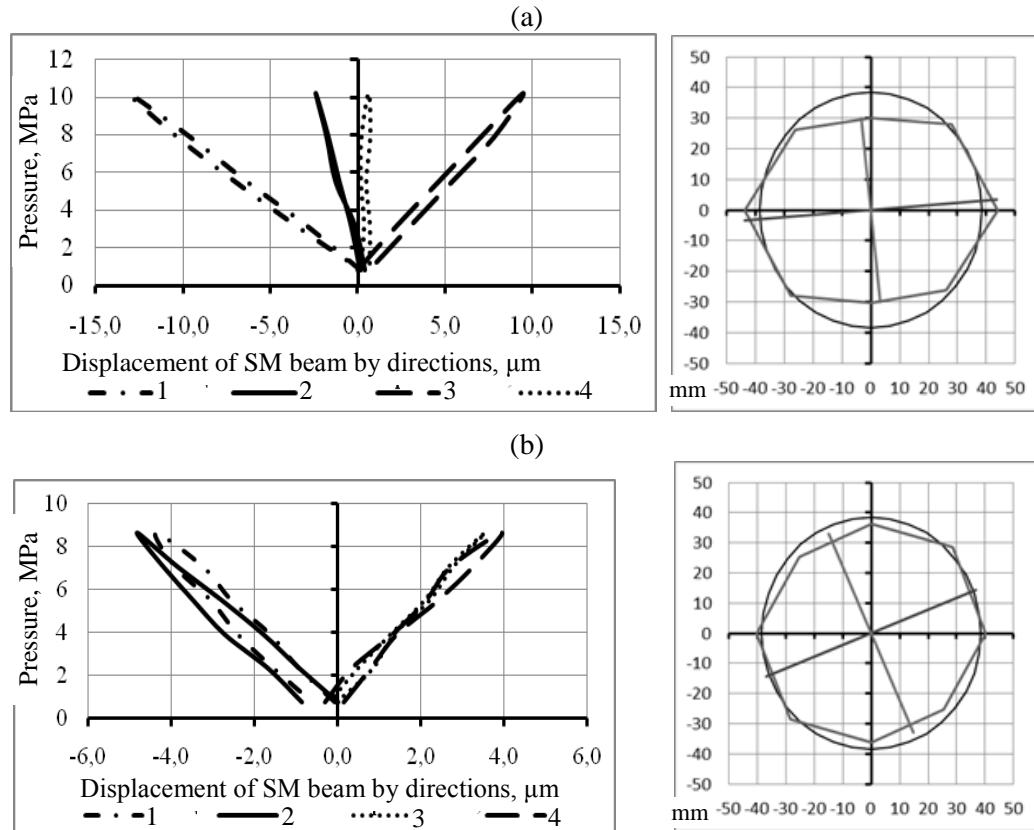
(a)

(b)

Figure 3. Radial displacements of SM beams under step-by-step loading and unloading of disturbing hole walls and orientation of principal axes of deformation in the measurement hole under the peak load at the depth of (a) 1.1 and (b) 7.6 m.

Table 1. Deformation properties of halite rock mass in the stress measurement area.
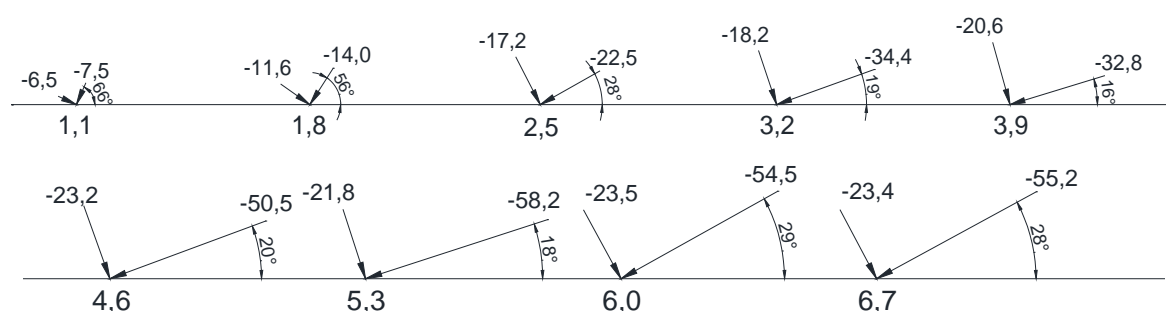
Distance to crossway wall, m	Pressure, MPa	Unloading branch		Unloading branch	
		$\sigma_{\text{æ}}$, GPa	E_d**, GPa	$\sigma_{\text{æ}}$, GPa	E_e **, GPa
0.4	8.6	4.0 (3.7÷4.4)	14.6	4.0 (3.6÷4.4)	14.6
1.1	10.2	4.6 (4.2÷5.1)	16.7	4.7 (4.3÷5.3)	17.1
1.8	10.2	4.9 (4.5÷5.3)	17.8	5.1 (4.5÷5.8)	18.6
2.5	10.2	5.3 (4.8÷5.8)	19.3	5.3 (4.7÷5.9)	19.3
3.2	10.2	5.3 (4.9÷5.8)	19.3	5.2 (4.6÷6.0)	18.9
3.9	10.2	5.3 (4.8÷5.9)	19.3	5.5 (4.8÷6.3)	20.0
4.6	10.2	5.5 (5.1÷6.0)	20.0	5.3 (4.9÷5.7)	19.3
5.3	10.2	5.2 (4.7÷5.7)	18.9	5.1 (4.8÷5.4)	18.6
6.0	10.2	5.2 (4.8÷5.6)	18.9	5.3 (4.9÷5.7)	19.3
6.7	10.2	5.1 (4.8÷5.5)	18.6	5.4 (5.2÷5.7)	19.7

* Confidence interval 90%; ** E_d —deformation modulus; E_e —elasticity modulus; $E = 3.64\sigma_{\text{æ}}$ at $\nu = 0.3$

Table 2. Values of stresses in vertical plane.

SM, m	Stresses, MPa			Quasi-principal stresses, MPa		Orientation of σ_2, deg**
	σ_v	σ_h	τ_{sh}	σ_1	σ_2	
1.10	–7.3 (0.5)	–6.8 (1.6)	0.4 (0.3)	–6.5	–7.5	66
1.80	–12.9 (1.1)	–12.7 (3.4)	1.2 (0.5)	–11.6	–14.0	56
2.50	–17.7 (0.5)	–22.0 (1.6)	1.5 (0.2)	–17.2	–22.5	28
3.20	–19.0 (1.0)	–34.2 (3.3)	1.8 (0.5)	–18.8	–34.4	19
3.90	–20.7 (1.2)	–32.8 (3.9)	0.3 (0.6)	–20.6	–32.8	16
4.60	–23.3 (2.9)	–50.3 (10.0)	1.9 (1.4)	–23.2	–50.5	20
5.30	–21.8 (1.4)	–58.2 (5.0)	0.5 (0.7)	–21.8	–58.2	18
6.00	–24.5 (1.2)	–53.5 (4.4)	5.3 (0.6)	–23.6	–54.5	29
6.70	–23.6 (2.2)	–54.9 (8.5)	3.1 (1.0)	–23.4	–55.2	28

σ_v, σ_h, τ_{sh}—vertical, horizontal and shearing stresses; *standard deviation; **positive value of the angle is assumed from the horizon counterclockwise.

Figure 4. Orientations and values of the quasi-principal stresses (MPa) in the vertical plane.

The accuracy and reliability of the stress measurement using the method of parallel hole drilling at deeper levels in rocks can be improved by changing geometry of the experiment (first of all, spacing of the holes), which reduces deformation in rock around the measurement hole and, as a consequence, abates development of rheological processes.

Conclusion

The method of stress measurement by parallel hole drilling ensures reliable assessment of stresses in salt rock mass, which do not exceed the uniaxial compression strength of rocks. Stabilization of readings of strainmeter before and after disturbance drilling is the evidence of absence of inelastic deformation of the measurement hole walls.

The preliminary estimation of the values of the quasi-principal stresses shows the presence of a plasticity zone in rock mass around a tunnel. Beyond this zone, the subhorizontal stresses exceed the vertical stress due to overlying rock weight by 1.5–2.9 times.

The linear dependence of the radial displacements at different distances from the measurement hole walls under step-by-step loading of the disturbing wall, nearly without residual deformation under

unloading, points at the elastic behavior of salt rocks under the short-term relief, and the values of the elastic modulus are compared with the laboratory test data.

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