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INTEGRATED APPROACH TO SLOPE STABILITY ESTIMATION IN DEEP OPEN PIT MINES

Rock mass adjacent to the Zhelezny open pit wall is composed of various rocks with different mechanical properties. The set of factors affecting the pit slope stability consists of natural and technological components. The study presents the results of the recent comprehensive studies into visual, experimental and analytical assessment of slope stability of the Zhelezny open pit wall and its structural elements.

The stress state was studied by the stress relaxation method in the form of end measurements. The results of the long-term investigation allowed zoning of the pit wall rock mass at the ultimate pit limits in terms of stresses and revealed higher stability of the open pit wall at the deeper levels as against the absolute elevation of ± 0 m and above.

The studies of mining-induced disturbance by a set of instrumental methods confirm slope stability in the north and at the deep levels of the pit wall.

In order to determine elastic characteristics of adjacent rock mass, the specialists performed 6 cycles of periodic observations by the seismic tomography method, which, together with visual observations and zoning by the level of the effective stresses, confirmed the unfavorable geomechanical condition in the east of the Zhelezny open pit wall.

The geomechanical state of the Zhelezny pit wall rock mass was analytically assessed using SVSlope software. The assessment proved critical state of some areas in the pit wall rock mass. To maintain stable final pit slopes, it seems reasonable to minimize the impact of adverse factors as well as to perform geomechanical monitoring of slope stability using a set of methods.

This approach can be applied at other mineral object developed by the open geotechnology under complicated geotechnical and geological conditions.

Key words: *open pit wall, stress–strain state of rock mass, structural geology, relaxation method, seismic method, stability factor, monitoring.*

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Introduction

As the domestic and international experience of deep open pit mining shows, the critical demand for a production cycle to function continually is safety immediately governed by slope stability of pit walls [1, 2]. Regarding the Zhelezny open pit mine of Kovdor Mining and Processing Plant developing the Kovdor baddeleyite–apatite–magnetite deposit, the local geotechnical situation is distinguished for the considerable size of the open pit and its depth exceeding 500 m [3].

The Zhelezny pit wall rock mass is composed of different-type hard rocks having various mechanical properties. Large structural discontinuities detected in the rock mass affect stability of the pit wall [4]. The set of factors that influence stability of benches and the pit wall as a whole consists of natural and technological components. The major natural influences include:

- physical properties of pit wall rocks and their time variation under natural conditions;
- structural discontinuity and damage of pit wall rock mass;
- hydrogeological mode;
- stress state of rock mass.

Stability of elements in open pit mining is greatly influenced by technological factors, namely, by drilling and blasting at ultimate pit limits and by sizes of induced fracturing zone.

The listed natural and technological factors are the determinants in the stability assessment of the open geotechnology elements, especially in deep open pit mining, and should be subjected to monitoring using various techniques. The aim of this article is to describe the results of the recent integrated research into visual, experimental and analytical estimation of slope stability in the Zhelezny open pit mine.

In the earlier estimates of slope stability in the open geotechnology, stress state was assumed to be of gravity type, governed only by overlying rock weight. The latest research findings by the Mining Institute of the Kola Science Center, RAS, and by other institutions show for pit walls composed predominantly by strong and hard rocks, at the stage of ultimate pit limits, the stress state of the adjacent rock mass depends both on the rock weight and tectonic stress which is several times higher than gravitational stress [5–7]. In this regard, determination of stress state parameters and their inclusion in the slope stability estimate of pit walls is of specific significance.

Investigation results

Before 2013 stress state monitoring for estimating slope stability embraced the whole area limits of the Zhelezny open pit on the levels above elevation ±0 m. The studies used the method of stress relaxation in the variant of end measurements [8]; efficient application of the method is described in [9]. Generalization of large bulk

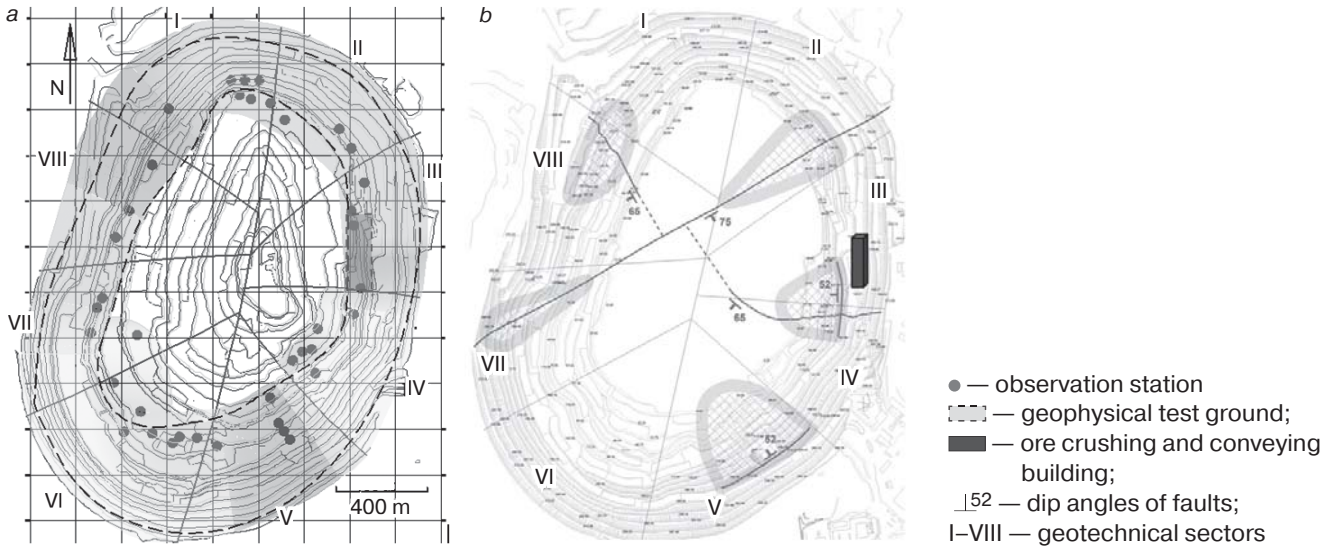


Fig. 1. Rock mass zoning around the Zhelezny open pit mine:
(*a*) by level of effective stresses; (*b*) by location of major faults (*1*) and strain zones (*2*) (based on the data of the Slope Stability Monitoring Service within the Geology Department at Kovdor Mining and Processing Plant)

of research data allowed zoning of the open pit mine field by the effective stress level in the pit wall above the absolute elevation ±0 m (**Fig. 1a,** the domain delineated by the dash contour lines), i.e. down to the depth of 300 m below the the initial terrain surface. Regarding the effective stresses in the pit wall rock mass, Fig. 1a shows stable zones (*A, A′*), less stable zones (*B, B′, B″*) and unstable zones (*C, C″, C‴*) [10]. The stable zones are understood as the zones of moderate compressive stress (σ_{eff} = = 0.1÷0.4σ_c) without any tension.

Later on, with mining below the absolute elevation ±0 m, stress state is investigated in the course of the pit wall formation at deeper levels. The deep stress state studies in geotechnical sectors (GTS) I and II in the northern pit wall show the positive effect of the horizontal tectonic stresses σ_{eff} on the slope stability. The effective stress in the pit wall rock mass has the maximum value of σ_{max} 22 MPa and minimum value of σ_{min} 8 MPa (**Fig. 1**a), which is somewhat higher than the measured stresses at the positive elevations (σ_{max} = 20 MPa, σ_{min} = 6 MPa).

Stability of the west and south pit walls within V–VIII GTS at deeper levels (below ±0 m) is uncertain and needs extra investigation. Single tests of effective stresses in the south and west of the pit walls reveal the absence of the tensile stresses σ_{min} and the high-repeatable compressive stresses σ_{max} as against the higher levels exposed to tension (σ_{min} = –1÷7 MPa). The trend of the increasing σ_{max} with depth is also observed in the east of the pit walls (III and IV GTS) below the level of elevation ±0 m. Here, the values of the effective stresses are higher than at the elevations above ±0 m. The average stresses σ_{max} and σ_{min} make 24 and 15 MPa, respectively, while at the positive elevations in the east pit wall, the average values of σ_{max} and σ_{min} are, respectively, 14 and 7 MPa. There are no high-rank discontinuities undercutting the pit walls below elevation ±0 m, which fosters rock mass stability in these sectors.

The resultant parameters of the effective stress state conform with the influence exerted by faults on the geomechanical behavior of rock mass and with the previously revealed extent of strain zones at the Zhelezny open pit mine (**Fig. 1b**). At the same time, as evident in Fig. 1b, on the east and south–east slopes of the pit, at the boundary of III and IV GTS, stability is lower within the areas of the faults that undercut the open pit mine.

Considering the planned expansion of the open pit horizontally and vertically, continuous geomechanical monitoring and analysis of the effective stress distribution is the first-order condition for elaboration of the open pit mining safety measures.

Relative stability of the pit walls in the north and at the deeper levels is on the whole proved by the integrated downhole local surveys aimed to assess sizes of anthropogenic damage area. That parameter was determined in 2000 to 2018 in the pit wall sections having different structural constants when at the ultimate limits. The studies were carried out in the sections of moderate and environmentally sound blasting at the stage of the final pit limit formation [11].

Thus, the damage zone in the pit wall rock mass can extend to 3 m along the most pit boundary and is reflective of the drilling and blasting quality, considering physical and mechanical properties of rocks and geomechanical behavior of various pit wall sections in the period of the studies. The natural factors (e.g. the undercutting jointing zones) shown in the map in **Fig. 1b** impair stability of some sections of the pit wall.

Discontinuities (closed-spaced joints, local faults) undercutting the east pit slope are the subject of integrated research for some recent years already. For example, jointly with the Geological Institute of the Kola Science Center, RAS, the mid-term prediction of deformation area expansion owing to growth of induced cracks toward the benches immediately under the ore crushing

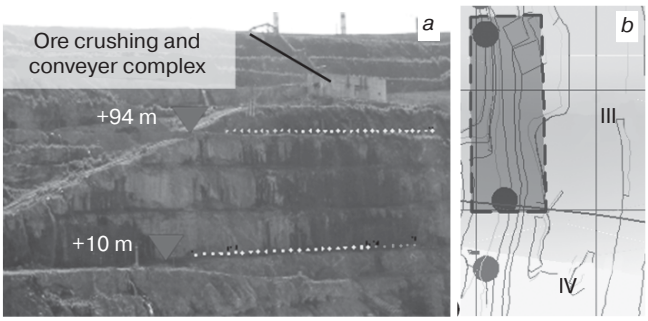
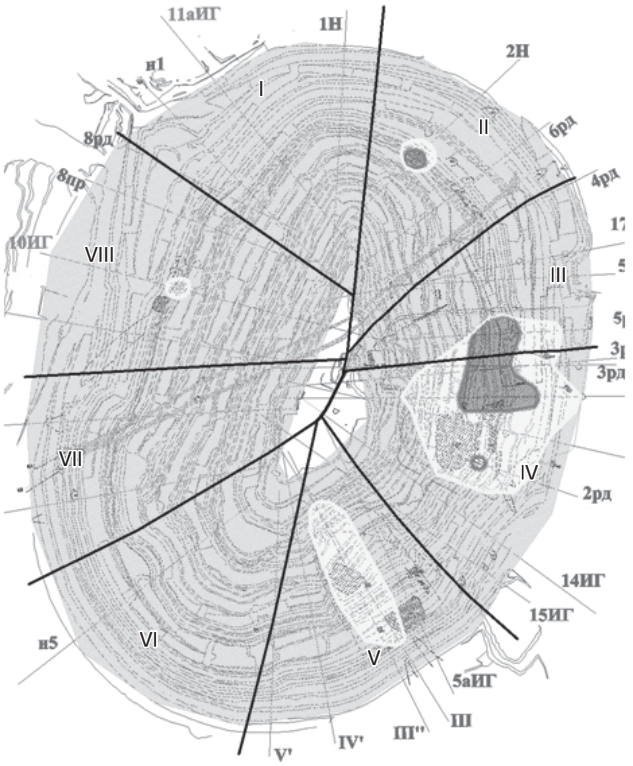


Fig. 2. Geophysical test ground in the east of the Zhelezny open pit wall:
(*a*) composite photograph of test rock mass area;
(*b*) superimposition of mining layout and geophysical test ground site; ▒ — location of geophysical test ground;
III and IV—geotechnical sectors

and conveying building (OCCB) within the actual elevation interval +70...–20 m has been performed [12]. The visual observation data are confirmed by the results of the seismic tomography monitoring implemented on the geophysical test ground in the actual elevation interval +94...+10 m beneath OCCB in 2014 to 2016 (**Fig. 2a**) [10]. Elastic characteristics of the pit wall rock mass were obtained in six measurement cycles in different seasons in order to include the effects of water content governed by groundwater level, first, and weathering, second. The analysis of P- and S-wave velocities in the test sections revealed an increase in the values of Poisson's ratio, which was reflective of weakened structural bonds and increased jointing in the rock mass. Superimposition of the geophysical test ground layout and the zoning plan of the Zhelezny open pit points at the adverse geomechanical condition of this area in terms of the level of the effective stresses (Figs. 1a and 2b).

Alongside with full-scale studies, the geomechanical evaluation of the Zhelezny pit wall rock mass was carried out using SVSlope software tool, and the mine field zoning chart by the slope stability factor was developed as a result (**Fig. 3**). The mentioned software is widely applied both in Russia and abroad [13]. The slope stability estimate involved such factors as: cohesion, internal friction angle, structural weakening coefficient, weakened surfaces, and groundwater level. In each calculation model, potential weakened surfaces, if any, were found both automatically and manually. Using the cross-sections mapped on the open pit mine layout, different stability zones were distinguished in the pit walls by the method of interpolation (Fig. 3). The analytical data agree in principle and qualitatively with location of the major faults and earlier revealed strain zones in the Zhelezny pit wall rock mass (refer to Fig. 1b).



Stable zone ($K_{SS} \geq 1/3$);
Limiting stability zone ($1 \leq K_{SS} < 1.3$);
Instability zone ($K_{SS} < 1$); I—VII—Geotechnical sectors

Fig. 3. Rock mass zoning by slope stability factor K_{SS} of the pit wall rock mass as a whole

Conclusions

The integrated slope stability estimation has confirmed reduced stability of the east pit slope, especially, in the zone underlying OCCB, as compared with the other pit wall areas.

The full-scale geophysical studies and theoretical analysis reveal the limiting-state areas in the Zhelezny pit wall rock mass; these areas are to be subjected to through geomechanical monitoring and dedicated safety measures in the course of mining operations.

The expedient actions recommended for the slope stability at the ultimate Zhelezny open pit limits include minimization of influence exerted by natural and induced factors on the pit slope, as well as the geomehanical monitoring of the pit wall stability using a set of techniques [13, 14]. This approach is applicable in case of other open pit mines producing ore in difficult geological and geotechnical conditions, for example, the apatite–nepheline deposits of the Khibiny Massif, etc. [15–19].

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