GEOTECHNICAL ZONING OF THE ZHELEZNY MINE (JOINT STOCK COMPANY KOVDOR GOK) FOR MANAGEMENT OF SLOPES STABILIZATION

Dmitry Zhirov[1]
Victor Soharev[2]
PhD. Vadim Rybin[3]
Sergey Klimov[1]
[1] Geological Institute of the Kola Science Center RAS, **Russia**
[2] Kovdor GOK, JSC, **Russia**
[3] Mining Institute of the Kola Science Center RAS, **Russia**

ABSTRACT

The mining of deep and super-deep horizons in the mineral deposits puts forward advanced requirements to safety. The Kovdor apatite-magnetite deposit exemplifies that timely geotechnical and geomechanical zoning allows increasing accuracy and possibility of risk prediction for loss of open pit elements stability at various stages of the open pit development, and justifying activities in ensuring safety of mining via anchoring/stabilizing slopes and walls of the open pit. Thus, the company has an actual opportunity of adequate evaluation and risk management due to timely planning and implementation of relevant measures. General principles and approaches to geotechnical and engineering-geological zoning are stidued by the example of the Zhelezny open pit rocks of Kovdor GOK, JSC, in order to optimize works in anchoring/stabilizing the open pit slopes.

Keywords: geotechnical, engineering-geological, geomechanical, geodynamic, zoning, prediction, hazardous geological (geophysical) and technogenic processes, massif of rocks, mining, open pit, mine, slopes stabilization, anchoring

INTRODUCTION

For mining companies in Russia and all over the world based on large and giant mineral deposits, depletion of the easy-access near-surface deposit part in 10-30 years of exploitation is a key negative factor. In modern economic conditions, for the majority of such companies this means unprofitability or financial instability of mining that results in suspension of operations and refusal from social and economic encumbrance/liabilities. Thus, the companies face an acute dilemma of closing the production or continuing mining under the conditions of underestimated and poorly controllable economic, ecological, and hazardous geological and geophysical factors. These include reduction in volumes and content of valuable components with depth, deterioration of quality indicators and processing behavior of ores, complication of mining and geotechnical conditions of the open pit development, increase in natural and man-caused geodynamic activity of the subsoil causing negative and even catastrophic phenomena and processes. Uncertainties and poor knowledge about these factors prevent from elaborating a comprehensive scientific and process solution to this issue. This, in turn, has negative impact on risk evaluation, practicability, and efficiency of continued mining activities. The situation is often aggravated by the impossibility to execute open pit walls cutback during the deepening due to the vicinity to the boundaries of the existing capital mining infrastructure and/or urban area.

This research is devoted to methods of geotechnical and geomechanical zoning in order to optimize operations in fixation/stabilization of the open pit elements by the example of such stidues in the Zhelezny mine of Kovdor GOK, JSC [1]. The results of such studies allow solving the following tasks: planning and management of geodynamic mining safety at deep deposit horizons due to the identification and ranking of hazardous geological and geophysical processes and phenomena; development of the managerial solutions support system in ensuring the geodynamic safety during mining of solid mineral resources due to the timely planning and implementation of activities in fixing the slopes. The research in this light and degree of detail has been made for the first time.

MAIN PRINCIPLES AND METHODS TO THE GEOTECHNICAL AND GEOMECHANICAL ZONING

The zoning is a process of allocating and geometrizing (division) of areas or elements with homogeneous properties and variables in the structure of the deposit rocks. The detailed analysis of main literature references in this topic [1-12] shows significant variety of zoning types in profile, purpose, and applied methods and approaches. The geotechnical (engineering-geological) zoning with identification of main heterogeneities and lithotypes (petrotypes) in physico-mechanical, hydrogeological, geological (lithological and petrographic), and structural properties and variables [5-7, 12] is most extensively used. Depending on the purpose, it is possible to execute any separate items of the list, or various combinations thereof. The geodynamic zoning has an increased focus and serves for identification and geometrization of geodynamically active (and/or potentially active) structures, establishment of kinematics and trends of varying activity, and dynamic interaction (of units/structures) [2,4]. The geomechanical zoning is based on deformative properties of rocks, fields of modified (around borrow excavation) and initial (reconstructed) stresses, and with due regard to features and laws of variations during mining of mineral resources [3, 9-10]. Microseismic and seismic zoning results from mapping of seismic hazard based on identification of earthquake source zones and study of the seismic effect on the earth surface [11]. In the final form, it reflects possibility of emerging and possibly exceeding seismic intensity (in MSK-64 points) in the given territory for the given period of time.

Despite the variety of the listed zoning types, no practical recommendations and experience of similar studies for the sake of optimization and management of operations in fixation/stabilization of the open pit elements have been found. All Russian and international stabilization practice for slopes, banks, and weak soils in the mining engineering, hydraulic engineering, and road construction, as well as in other industries operates either with the identified specific target, for example, with a fault, weakened surface, landslide, critical construction site, etc., or with total (whole) application of a certain lining method along the whole surface of a pit, slope, bank, or in the whole volume of the fixed soils [14, 15]. Thus, issues of comprehensive zoning and ranking of targets and potential hazards with the launch of a differential approach to the stabilization of the open final pit boundaries are still not completely covered. The experience of such studies at the Zhelezny mine of Kovdor GOK, JSC, is of significant practical and scientific importance [1].

The zoning method for optimizing and managing operations in fixation/stabilization of the open pit slopes and walls is based on staged (approximation method) and topical principles that has allowed organizing studies and operations depending on the priority of the execution and subject matter as follows:

1) Zoning by types and intensity of hazardous geological and geophysical phenomena and processes, types of expected deformations and of assumed stabilization targets (structural heterogeneities and sectors of the open pit wall design).

2) Zoning by purpose and lining / stabilization targets as part of stabilization methods and tools.

3) Zoning by lining rationality for the revealed targets based on evaluating the balance between expected potential losses and resource costs of open pit design stabilization and prevention of deformations.

The proposed sequence or stage nature of zoning reflects the algorithm and order of getting answers to the posed questions: Which elements or sectors of the open pit wall design need to be fixed/stabilized? → How to fix/stabilize it? → How efficient, costly, and relevant is the solution to the issue due to the fixation/stabilization as compared to alternative ones (for example, by partial modification of the final pit boundary)? When answering to the last question, the combination of targets and related solutions mostly profitable for the company in terms of comprehensive cost evaluation of various resources, efficiency, design inertness, and mining safety, shall be filtered.

It shall be noted that each further zoning stage is based on the results of the analysis of the previous one. Applying these principles and approaches allows achieving the purpose stage by stage, in complex, with relevance, maximum efficinecy, and balanced manner in terms of economics and ensuring mining safety. The implementation in combination yields a comprehensive set of initial parameters for taking a decision about the following: − availability of potentially hazardous targets and their spatial localization and geometrization; - efficient ways of lining in accordance with the types and scale of allocated structural heterogeneities; − time and spatial indicators for the implementation of activities in fixation (stabilization) of the open pit design; − final evaluation of the lining relevance/need of specific sectors and areas as compared to the alternative solutions.

In accordance with the results of the 1st stage studies at the Zhelezny mine of Kovdor GOK, JSC, the most hazardous geological (geophysical) factors that are ranked from the least to the most significant ones in terms of negative impact on the open pit design stability were defined as follows:

− unfavourable location and occurrence of the geological boundaries;
− physical and mechanical properties and aggregate state of rocks;
− hydrogeology and hydrology;
− stress and strain state (SSS);
− structural heterogeneities, fault tectonics, and fissuring with dangerous occurrence;
− actual deformations and disturbances of the slope and wall integrity.

Each of the listed factors is characterized by various intensity and time and spatial laws of manifestation and development. Each factor was subject to discrete or gradational ranking with the mapping of boundaries/zones in the form of a corresponsing layer within hazardous geological abd structural processes and phenomena. The spatial alingment/superimposition of several (especially mostly intensive) hazardous factors in one place marks sectors for priority consideration of the need to fix these. As a result, we have gained a combination of targets subject to fixation/stabilization and differing in geotechnical conditions, depth, and intensity of the hazardous process within the open pit.

In order to move to the further stage of zoning (in terms of purpose and targets subject to fixation), levels by the depth of fixed rocks were identified (from the bank/slope surface) with allocation of 3 main types: nearest zone (up to 3-6 m from the open pit contour); middle zone (5 to 15-18 m from the contour); remote zone (20 to 100-120 m from the contour). These groups involve main types of targets subject to fixation/stabilization: surface area of intensive rock disintegration, linear rock disintegration zones with staffelite, and tectonic breakage and cataclasis; intensive wedged and combined low and medium-scale deformation zones hazardous in terms of disturbance of slope stability; planar structural elements zones, and individual large fissures, or faults hazardus in terms of deformation and collapse of whole banks, or groups of banks. Thus, in accordance with these classifications, 5 groups of targets were defined by the purpose of lining in connection with recommended and optimal fixation ways, tools, and techniques in terms of resultant effect (Table 1). The following was allowed for, and namely: spatial position and morphology of structural heterogeneities, boundary, and manifestation intensity of various hazardous geological and geophysical processes, depth of the fixed rocks, appied fixation materials and methods, volume of possible deformation, values of the expected gravity pressure and active forces in the area of hazardous surface, etc. For example, for a man-induced disturbed fissured surface bank zone, the purpose is to prevent rock inrush and fall of fragments/debris, and for a long teared-off plane dipping at an angle of 30-55º towards the borrow excavation, in the middle-remote zone, it is necessary to achieve fixation of the above (hanging) partially broken and disintegrated wall with a low-disturbed (underlaying) massif of rocks. It is obvious that for such cases, the applied calculation approaches, methods, ways, and techniques of fixation principally differ in the following: for surface broken bank part, the purpose is to prevent from shifting of individual fragments and units (mesh, anchor-mesh, or anchor-rope curtain is recommended), and for the plane, supporting the hanging rock massif due to the force of friction and tensile and shear strength to the reinforcing elements (passive anchor or preliminarily tensioned reinforcement with the hinges beyond the surface of the structural heterogeneity is recommended).

The final stage of the geotechnical and geomechanical zoning in order to optimize operations in fixing/stabilizing banks and wall sectors is represented by a comprehensive evaluation of the relevance/need of such actions based on the balance of the expected potential losses on the one hand in case of implementation of the negative scenario, and expenses for the prevention of the stability disturbance or integrity of the open pit design elements, on the other, via fixation/stabilization, or modification of the final contour in part or in whole. The purpose of this operation lies in the fact that by the direct feasibility cost calculation methods, evaluations of the open pit design elements stability with due regard to the requirements of the company's operations safety at all stages of the open pit construction and exploitation, as well as calculation of the potential opportunity costs in case of implementing a negative scenario allow defining (filtering) only key task sectors that directly affect the efficiency and safety of the company's operations. The criteria to allocate such sectors are as follows: multiple excess of losses over costs for fixation/stabilization of the open pit banks and slopes; possible catastrophic consequences with victims and destruction of the main production infrastructure and machinery; large scale of investment for recovery/neutralization of possible consequences; time factor: production shutdown, cancellation or significant review of the production/investment plan and schedules, etc.

Table 1
Compliance of recommended typical fixation/stabilization methods for the open pit design elements with the identified varieties of structural heterogeneities

No.	Group of structural heterogeneities	Recommended typical ways of fixation, stabilization, and maintenance of the open pit design stability
1.	Rock disintegration zone (area and linear weathering crust)	Reduction of the slope to the natural grade angle, execution of preventive measures in catching and draining ground waters: drainage around the erosion areas, slope plantation, reinforcement of the slope surface by pouring special substances, backing of taluses and landslides with rocks.
2.	Disturbed zone of the upper slope part	Mesh, passive anchor-mesh, and rope-mesh lining/curtains.
3.	Low and medium-scale wedged and combined type deformation zone (failure)	Active (preliminarily tensioned) anchor (roof bolting and anchor-rope lining) with the anchor beyond the surface of plane fissures for 3-5 meters.
4.	Low and medium-scale planar type deformation zone (failure) - disturbance of stability of part slope	Group anchor lining with preliminarily tensioned roof bolts (dowels) with the hinge beyond the surface inside the massif of rocks with fissures for 3-5 meters and anchors with rope or mesh lining of the slope.
5.	Elongated fault surface with even or undulating plane (or a package of planes) potentially hazardous in terms of planar collapse (failure) within a whole slope, or a set of slopes	Modification of the open pit design or group preliminarily tensioned anchor-rope (strands), roof bolting (anchor), or pile reinforcement with the hinge beyond the surface of the undisturbed massif of rocks for 5-8-10 m, additionally, options of resin-polymer injection, or grouting of the fault surface(s).

In accordance with the results of all intermediate stages and activities in zoning at the Zhelezny mine of Kovdor GOK, JSC, 7 priority targets were identified within the current mining project (Fig. 1) and classified in terms of significance and relevance of special measures into 3 groups (from most essential to least).

<u>1st Group:</u>
− fault No. 62 in the eastern (E) sector of the open pit wall, a zone of large-scale planar failures (see 1a in Fig. 1);
− fault R2 in the southeastern (SE) sector of the open pit wall, a zone of large-scale planar failures (see 1b in Fig. 1);

<u>2nd Group:</u>
− zone of intensive development of wedged and combined deformations, and intensive ingress of ground waters in sector W of the open pit wall (see 2b in Fig. 1);
− zone of increased fissuring and development of wedged deformations in the junction of the R1 fault SW flank and open pit banks (see 2c in Fig. 1);
− zone of increased fissuring and development of wedged deformations in the junction of the R1 fault NE flank and open pit banks (see 2a in Fig. 1);

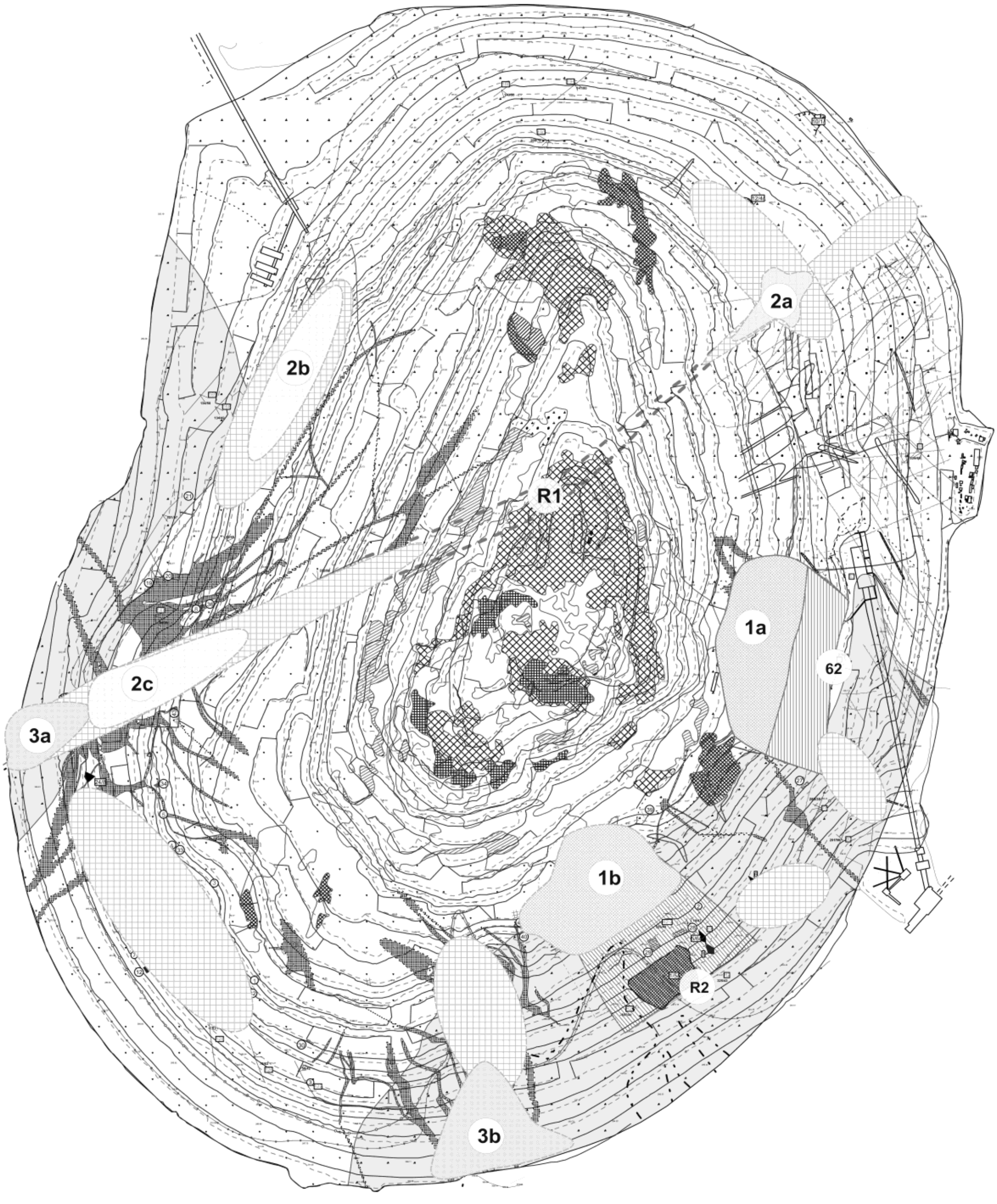

Figure 1. Geotechnical and geomechanical zoning chart for optimizing operations in fixation/stabilization of slopes and wall sectors at the Zhelezny mine of Kovdor GOK, JSC within the current mining project. The targets are explained in the text.

<u>3rd Group:</u>

− upper disintegrated part of the R1 fault SW flank (see 3a in Fig. 1);

− surface zone of the linear weathering crust disintegration in the SSE sector of the open pit wall (see 3b in Fig. 1).

For each of the group represented, there are elaborated recommendations and typical solutions in technical means and methods for fixation/stabilization of the open pit design elements.

CONCLUSION

The present geotechnical and geomechanical zoning for the sake of optimizing operations in fixation/stabilization of slopes and wall sectors results in revealing priority targets for implementing special operations and ranking these in terms of relevance, significance, and order of execution. As well, it shows impossibility of applying only one typical technical and process solution in stabilizing slopes on the total open pit scale.
The most hazardous and correspondingly most essential in terms of risks of catastrophic events are structural planar type heterogeneities in the eastern and southeastern sectors of the open pit wall (see 1a and 1b in Fig. 1). These are traced and geometrized along strike and dip in the rock mass beyond the limits of the final current project boundaries by numerous geotechnical boreholes with sampling the oriented core. Where these tend to approach structural heterogeneities, the shape of the upper banks deforms, becoming a plane dipping towards the mining space at angles of 40-45º. At deeper horizons, hazardous approach to the designed final pit boundary is noticed. As the lower banks deepen and come to the final boundaries, no counteraction may definitely result in large-scale planar collapses.

This may be exemplified by the SE open pit wall sector (see R2 and 1b in Fig. 1), where the solution for fixation was not elaborated, and necessary activities were not taken due to several reasonable factors. At present, almost all banks concerned are in the final position that prevents experts and machinery from accessing the necessary horizons. As a result, the company is facing a need to adjust the current project with partial modification of the open pit design contours in this sector.

As contrast to this, towards fault No. 62, it is still possible to start elaborating and implementing a fixation project with horizons of -10 and -40 meters. Thus, it is shown that timely geotechnical and geomechanical zoning allows increasing the accuracy of predicting risks of destabilizing the open pit design elements at various stages of the mine development, as well as timely justifying the set of measures in ensuring mining safety. This provides the company with an actual opportinuty of adequate risk evaluation and management due to the timely planning and executing corresponding measures.

The elaborated methods of zoning allow gradually evaluating and ranking the rock mass in terms of actually manifested hazardous geological (geophysical) and man-induced factors), defining structural heterogeneities potentially hazardous for the stability of slopes, sectors, and open pit wall as related to the typical optimal fixation ways, as well as evaluating and ranking the relevance/need of fixation depending on the results of the comparative analysis of potential damage and resource costs for executing activities in ensuring safety. The practical significance of the solution may be shown as follows: prevention of contingencies in eliminating the consequences of catastrophic events (few million to several billion roubles depending on the scale of the event); provision of scheduled continuous company's operation (timely earnings and profit, financial and commercial reliability and stability); preservation of the company's staff life and health.

At present, operations and studies in this topic are developing from 2D (plane + cross-sections) to comprehensive 3D modelling of the whole engineering decision taking space. This allows generating a system of supporting managerial solutions for medium and long-term planning of the company's development at the top scientific and methodolohgical, information, and process levels.

ACKNOWLEDGEMENTS

The research was supported by the Russian Scientific Fund (project nos. 14-17-00751) and Research and Development contracts with Kovdor GOK, JSC.

REFERENCES

[1] Research & Development Report, geotechnical and engineering-geological zoning of the Zhelezny mine of Kovdor GOK, JSC, for optimizing operations in stabilization of rock slopes (R&D contract No. 155-12 dd. 01 August 2012) / Zhirov, D.V., Rybin, V.V. et al., Russia, Apatity: GI KSC RAS: vol. 1, 2012, 219 p.; vol. 2, 2013, 55 p.; vol. 3, 2013, 82 p.; vol. 4, 2014, 304 p.
[2] Batugin, I.M., Petukhov, I.M. Geodynamic zoning during designing and exploiting mines. Russia, Moscow: Nedra, 1988. 166 p.
[3] Zhirov, D.V., Melikhova G.S., Rybin, V.V, Klimov, S.A. New method for comprehensive geotechnical and engineering-geological research of rock masses for the purpose of designing and exploiting deep mines. Proceedings of the Conference Deep Mines, 12-16 June 2012. Russia: Apatity-St.-Peterburg, 2012. pp. 368-382.
[4] Geodynamic mineral resources zoning. Guidelines. Leningrad: VNIMI, 1990. 129 p.
[5] Kuzkin, V.I., et al. Geotechnical, hydrogeological, and geoecological research during the exploration and exploitation of ore deposits (guidelines). Russia, Moscow: RIC VIMS, 2002. 119 p.
[6] Kuzkin, V.I., et al. Guidelines for studying geotechnical conditions of ore deposits during exploration. Russia, Moscow: RIC VIMS, 2001. 153 p.
[7] Study of hydrogeological and engineering-geological conditions in solid mineral deposits. Guidelines and requirements. Russia, Moscow: Nedra, 1986. 172 p.
[8] P 55-90. Geostructural mapping (modelling) guidelines for rock masses at the basement of hydraulic works. VNIIG. Manual to SNiP 2.02.02-85 / Gureyev, A.M., Voronkov, O.K., Russia, Leningrad, 1991. 95 p.
[9] U.S. Army Corps of Engineers. Engineering and Design Slope Stability. Engineer Manual , Manual No. 1110-2-1902, USA, 2003, 205 p.
[10] Geotechnical considerations in open pit mines. Guidline. State of Western Australia, 1999. 50 p.
[11] RSN 65-87 Engineering surveys for construction. Seismic microzoning. Technical requirements to work execution. Russia, Moscow: RSFSR Gosstroy, 1987. 11 p.
[12] Nesvetaylova, N.G., Gorelik, A.I. Guidelines in engineering-geological zoning of the terrotiry using aerial survey data when studying roads in Siberia and Far East. National Research Institute of Traffic Construction. Russia, Moscow, 1971. 18 p.
[13] Fisenko, G.L., Revazov, M.A., Galustyan, E.L. Mine slope lining and stabilization. Russia, Moscow: Nedra, 1974. 208 p.
[14] Gaziyev, E.G. Rock mass stability and stabilization methods. Russia, Moscow: Stroyizdat, 1977, 160 p.