SUSTAINABLE EXTRACTION AND PROCESSING OF RAW MATERIALS, 2024

GEOTECHNICAL ANALYSIS OF THE STRUCTURAL INTEGRITY AND BENCH FACE ANGLE OF THE ELLATZITE OPEN-PIT MINE, BULGARIA

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ABSTRACT. The paper presents a geotechnical investigation of the structural integrity of the Ellatzite open-pit mine and considers the achieved bench face angle, while looking at the final geometry shaping of the bench face. The study shows that the influence of the lithology, rock mass structure, mining technology and water saturation of the bench faces is of crucial importance for achieving a long-term sustainability of the mine benches. Therefore, some efforts need to be made to optimise the technological processes in the mine, as well as to drain precipitated and groundwater away from the slopes, by maintaining an effective and appropriate drainage and dewatering system.

Key words: open pit mine, geotechnical investigation

Introduction

The Ellatzite open-pit mine is operated by Ellatzite-Med AD, part of the Geotechmin Group. Its main activity is the extraction of porphyry copper gold-bearing ores from the Ellatzite deposit, located in the Etropolska Stara Planina, above the town of Etropole, about 100 km east of the city of Sofia (Figure 1).



Fig. 1. Location of Ellatzite open-pit mine (Google Maps 2020)

The stability and geometry of the benches is controlled by the rock mass geology and structures, factors related to the design of benches, and the applied mining technology. In this paper, the focus will be mainly on the geotechnical evaluation of the bench face angles achieved as a function of the geometry and stability of the benches.

The influence of the various factors is specific to different sectors of the open-pit mine. This needs to be accounted in slope condition assessments. The steepest angles of single and paired benches, which ensure safe excavation and working of rock mass, are achieved by preserving the strength and structural integrity of the benches, minimizing technological fractures in the rock mass, and achieving the designed bench face geometry.

The reduction of strength in the rock slope is caused by the blasting operations, through vibrations and impact of the expanding gases. Excessive disturbance of the integrity of the rock mass leads to reduced slope resistance of the benches and collapses, which are common in open-pit mines (Hoek, 2007).

Too much damage on the wall can be described as the impact of blast activities gone beyond the intended blast area or crack distribution in the rock body outside the deflecting presplitting plane. In the scope of the blast field there is an expectancy of about 80 % reduction of the rock strength (Peterson, 2001). This reduction in strength can extend beyond the blast field area along geological contacts, tectonic faults, and cracks (Krolikowski, 2015). By reducing the shear strength of the cracks, movement and displacement along them is favoured, leading to possibility of slip planes and wedge-shaped slides formation in the rock mass (Krolikowski, 2015).

The presence of groundwater and increased pore pressure within in the rock mass in blasting operations area increases the effect of blasting activities, which leads to additional deformation in bench slopes.

The open-pit mine area is mainly built up by three types of rocks:

- Paleozoic metamorphic complex (phyllites, schists and hornfelses);
- Paleozoic granodiorites and their accompanying vein phase of dyke rocks;
- Upper Cretaceous granodiorites, diorites and quartz-monzodiorite porphyries, injected between the above two groups.

Paleozoic metamorphic complex: The rocks building up the complex (hornfelses, schists and phyllites) occupy the middle and high levels in the southern, eastern and southwestern parts of the open-pit mine (Figure 2).

- **Hornfelses (HFS)** are emplaced along a weak and brittle, reactivated intrusive contact above the Carboniferous granodiorites of the Vezhen pluton. The high west and midsoutheast levels of the open-pit mine are structurally exposed below monzodiorite porphyries (MDP) with a southwest-dipping boundary that is interpreted as intrusive one.
- **Schists (SCH) –** Moving away from the contact, described above, the intensity of contact alteration gradually decreases and hornfelses change into schists. The HFS - SCH boundary extends along different tectonic structures, and in some places it is tentatively interpreted, as a transitional interval between hornfelses and shists. The transitional facies is added within the hornfelses section.

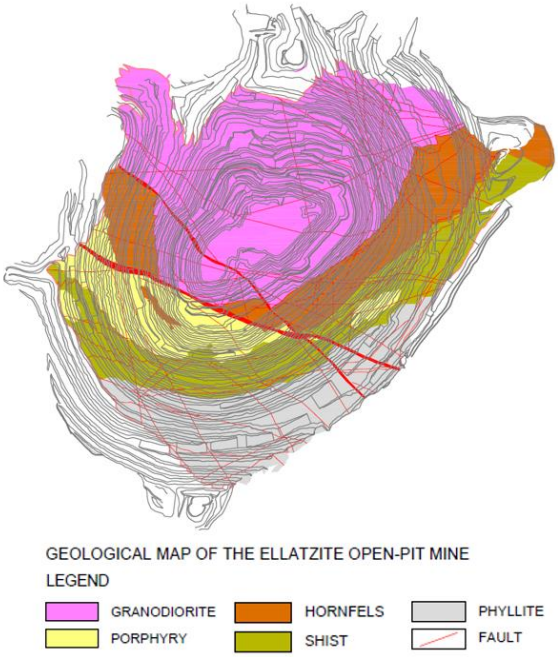


Fig. 2. Geological map of the Ellatzite open-pit mine as of March 2024, based on the geological block model, maintained by the specialists at the Ellatzite open-pit mine

The lower structural levels of the SCH section are exposed at higher levels of the eastern side of the open-pit, and are located high in the current terrain, where they enter the weathering zone close to the natural topography. In this zone, the shale is moderately weathered, with weathering oxidation crusts along almost all fractures and tectonic faults. Nevertheless, weathering affects the volume of the rock mass to a small extent.

- **Phyllites (PHY)** make up the uppermost parts of the greenschist metasedimentary rocks of the Paleozoic metamorphic basement, which remained unaffected by the contact changes associated with the Vezhen pluton intrusion. The extreme eastern parts of the section are located directly under the natural terrain and, in the weathered rock mass. These parts are characterised by oxidised limonite crusts.

Vezhen pluton: The rock varieties that make up the pluton (Carboniferous granodiorites (GRD), mafic bodies and dykes, and Paleozoic granodiorite porphyries) occupy the central (deep) and northern parts of the open-pit. Dyke bodies are rare and represent a highly subordinate part of the volume of the Vezhen pluton. The contact of the GRD with hornfelses is igneous, partially reactivated by a “Pre-contact" tectonic fault (Figure 2).

The Upper Cretaceous igneous rocks are represented by dyke porphyry bodies (Figure 2).

- **Monzodiorite porphyry (MDP)** bodies have been identified among the shales of the metamorphic frame of the Vezhen pluton at higher levels of the eastern sector. They contain plagioclase porphyries, although the phenocrysts are very clayey. In addition to the severe weathering, the porphyries are also affected by sericite alteration.
- One of the larger dykes of granodiorite porphyries (GDP) crosses the rocks of the Vezhen pluton in the middle northeastern parts of the open-pit. It has the characteristic appearance of these rocks – small to medium-sized porphyritic crystals of AMP, PLA and QTZ with a groundmass of xenomorphic fine-grained pink-reddish KFS. The imposed alterations are of minor intensity, suggesting the presence of weak potassium-silicate (POT) alteration.
- The large monzodiorite body is exposed in the southern and southwestern parts of the mine, which in composition does not differ from the classic MDP.

Materials and methods

The geotechnical assessment of the bench slopes analyses the degree of structural integrity preservation of the bench face and the achievement of the designed geometry of the benches. The geotechnical mapping and the characterisation of the resulting deformations is carried out by the Geotechnical Department of the Ellatzite open-pit mine, using the established methods of Cebrian (2017), MarshallMohr (2005), Rock-mass ratings system (RMR – Bieniawski (1989) and ISRM (1981), modified in 6/98), Mining Rock-mass ratings system (MRMR – Laubscher (1990)) and Q-slope (Bar & Barton, 2018), etc. The documentation and analysis of the data from the mapping activities is also based on the methodology applied in studies (2016 - 2023) by the research teams of SU "St. Kliment Ohridski" (Georgiev et al., 2023).

In the detailed study of bench slopes, the acquisition of the following information is of primary importance:

- lithological, structural and textural features of rocks and nature of the imposed hydrothermal alteration;
- relationships between different lithological bodies and detailed characterisation of first- and second-order tectonic faults;
- detailed characterisation of all other brittle structures, including detailed study of fractures’ groups, meeting the requirements of the Bieniawski (BRMR) and Laubscher (MRMR) classification schemes;
- observations and measurements of plastic deformation structures in benches with metamorphic rocks;
- assessment of rock mass water saturation;
- summarising kinematic analysis of the potential possibilities for emergence of new gravitational deformations and clarification of mechanisms of their formation (Georgiev et al., 2023);
- spatial analysis of the achieved bench face angles and clarification of the reasons for the formation of reduced bench face angles;
- assessment of the impact of technological processes on bench slopes (Nachev et al., 2020);
- identifying measures and activities to achieve long-term stability and limiting deformations in benches.

Results and discussion

A kinematic analysis of the potential kinematic stability of benches was prepared in the form of structural stereodiagrams with the software product Dips, version 7 of the company Rocscience. They depict the prepared stereodiagram with a constructed critical field for a specific type of deformation based on the number of violations in the corresponding interval; the type of kinematic analysis performed; the slope parameters used

to construct the diagram (slope angle, side of the slope sinking and friction angle), the percentage probability for manifestation of this type of deformations; additional parameters of a density diagram and of the stereographic projection itself. A combination of all tectonic faults, major fractures with movement traces along them, and groups of fractures by intervals and sectors were used to produce the diagrams. Abbreviations of the major, minor and some of the very small faults are indicated in the legend, accompanying stereo-diagrams. Maps of the potential risk of deformations are prepared after the analyses (Georgiev et al., 2023).

A general kinematic analysis is performed according to 3 criteria: orientation of benches, litho-tectonic domain and designed position of geotechnical ramps. The analysis was carried out by processing and interpreting the data obtained during mapping activities within the open-pit mine. Maps of the potential kinematic risk allow to get a general idea of the distribution and relative magnitude of the risk of occurrence of various gravitational deformation processes (Figure 4 and Figure 6).

Planar sliding failure – This process has a varying potential risk of occurrence throughout almost the entire open pit. No lithological preference is observed for planar sliding, but a predominantly uneven distribution is found. The highest concentrations of risk structures suitable for the manifestation of this deformation are observed both among igneous rocks (GRD and MDP) in the middle western and southern levels, and in metamorphites (HFS and SCH) from the middle southern and high eastern levels (Figures 3 and 4).

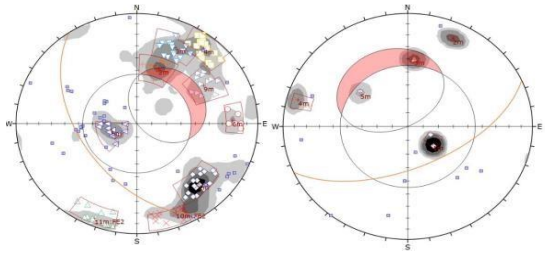


Fig. 3. Upper-hemisphere stereographic simulations of a potential planar sliding failure (Georgiev et al., 2023)

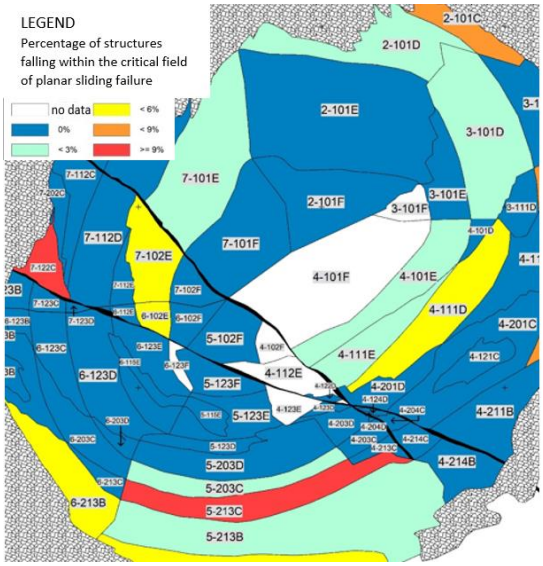


Fig. 4. Map of the potential probability of the occurrence of planar sliding failure by kinematic sectors (Georgiev et al., 2023)

Wedge sliding failure – uneven distribution and weak expression of lithological factor is found, except for the majority of sectors in which shale is exposed with low and rarely moderate probability of occurrence. It is noteworthy that most sectors with moderate to increased risk from 4 % to 22 % are those bordering the first-order faults Ellatzi-1 and Ellatzi-2 (Figures 5 and 6).

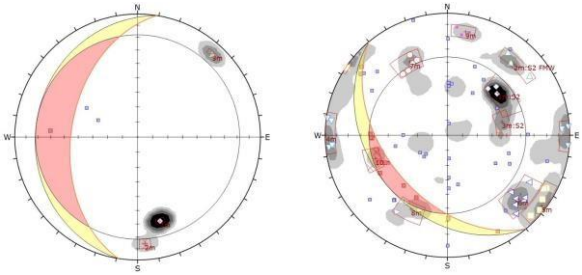


Fig. 5. Stereographic simulations in the upper hemisphere of the potential risk of wedge sliding failure (Georgiev et al., 2023)

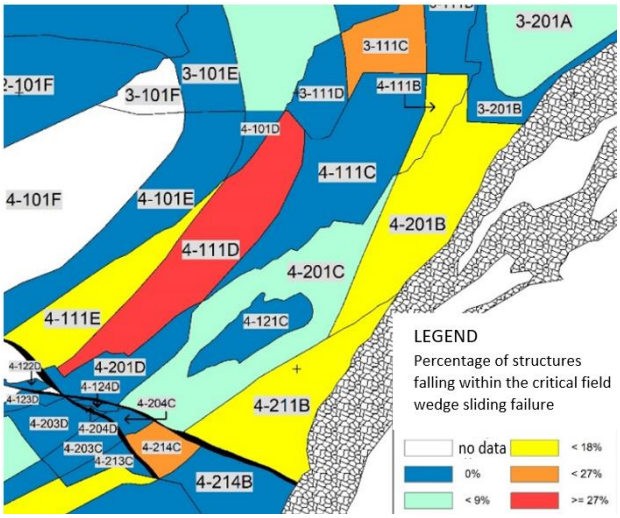


Fig. 6. Map of the potential risk of occurrence of wedge sliding failure by kinematic sectors (Georgiev et al., 2023)

Block toppling failure – This is the process most likely to occur in the open pit. It has a large variation in the potential risk of appearance in almost every single sector. This can be explained by the well-developed network of brittle structures (more common and well developed in the block-fractured rocks (mainly igneous GRD, MDP and less often HFS) of different ranks within the open pit. The most clearly delineated part of the open pit for this is the northeastern one, where we have the highest density and probability of structures suitable for the occurrence of block toppling. One of the most critical sectors in the open-pit is situated there, too. In the south-southeast parts, two critical zones are also outlined within shales. There, the main role is played by the combinations of major tectonic structures like Ellatzi fault, Submeridional fault, and Equatorial fault, as well as crossing surfaces (mostly groups of fractures) steeply dipping to the north or south (Figure 7).

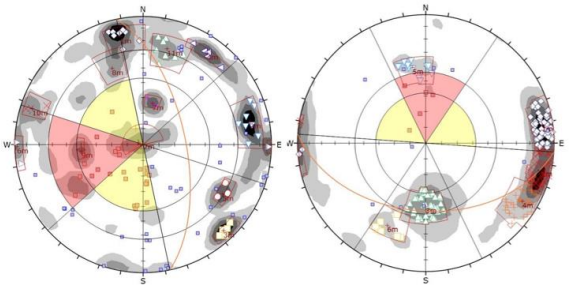


Fig. 7. Upper hemisphere stereographic simulations of the potential risk of block toppling (Georgiev et al., 2023)

Flexural toppling failure – This process is characteristic of rocks with a well defined layered - foliated texture. This is clearly delineated in the frame around almost all metamorphites (except HFS) from high eastern, through intermediate and high southern, to high south-western levels. Rocks present within these zones are contact schist and phyllites, where a well defined maximum of flexural toppling risk is observed. This is due to the metamorphic S2 foliation and structures developed along it, steeply dipping opposite to the slope dip side of the relevant section. A sector falling between the main tectonic faults – Ellatzi-1 and Ellatzi-2 is outlined as having higher potential risk of occurrence of flexural toppling (Figure 8).

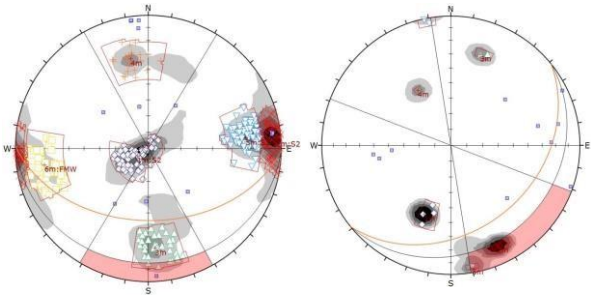


Fig. 8. Upper hemisphere stereographic simulation of the potential risk of flexural toppling (Georgiev et al. 2023)

From the analysis of the kinematic sectors, it can be seen that in all sectors of the open-pit there is a danger of appearance of different types of gravitational deformations. They are mainly related to brittle structures present into igneous rocks. Fractures play a major role among these structures. In the weakly altered and unaltered metamorphites along contact zones, these structures are combined with discontinuities along foliation S2 planes, which acquire a leading role for the high kinematic risk in the rock mass.

Spatial analysis of the achieved bench face angles (BFA) was prepared on a plan view of the open-pit with designed toe and crest edges of benches, together with the achieved bench face angles, in the form of value intervals. The analysis was performed in the areas where the final designed push back for respective levels was reached. Bench face angles were not analysed along inclined road and work areas due to their temporary nature (Figure 9).

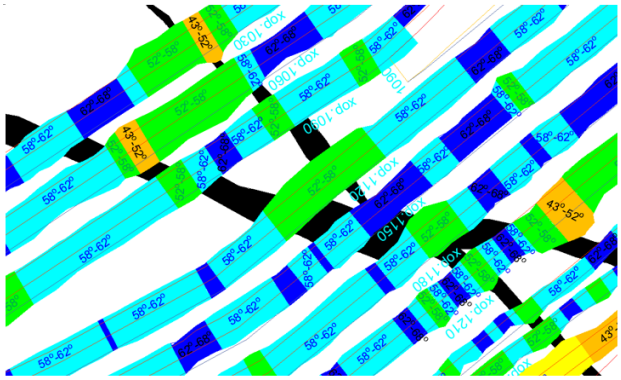


Fig. 9. Map of the intervals of the achieved bench face angles and designed toe and crest edges. Ellatzi-1 and Ellatzi-2 tectonic faults are shown in black. Their intersection is present here

For the generalized interval analysis, the achieved bench face angles were combined into three intervals for the 30 m paired benches - under 58˚ (cyan or light blue colour), from 58˚ to 62˚ (dark blue colour), and above 62˚ (green colour). The designed bench face angle of the paired benches is 65˚ and it falls into the last green interval (Figure 10).

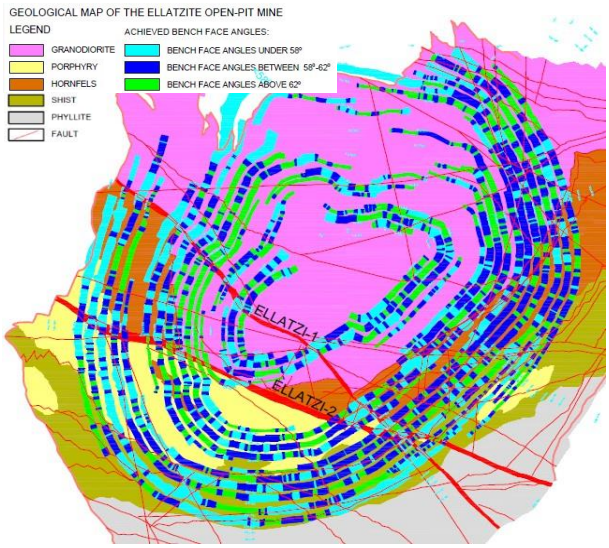


Fig. 10. Interval map of achieved bench face angles, lithology and main tectonic structures

Similar to the generalized kinematic analysis, no dependence on the lithological composition of the rocks was observed in the spatial analysis of the achieved bench face angles. The achievement of the designed angles is concentrated in the low and middle levels of the western and southern part of the open-pit, due to the favourable location of tectonic faults and fractures relatively to the orientation of the crest and toe edges of the benches (Figure 11).

At higher levels on the western open pit, which are built up of hornfelses and porphyrites, the bench face angle is below 58˚, which is due to the presence of fractures in the mass, rock weathering and infiltrated groundwater from the nearby embankment.

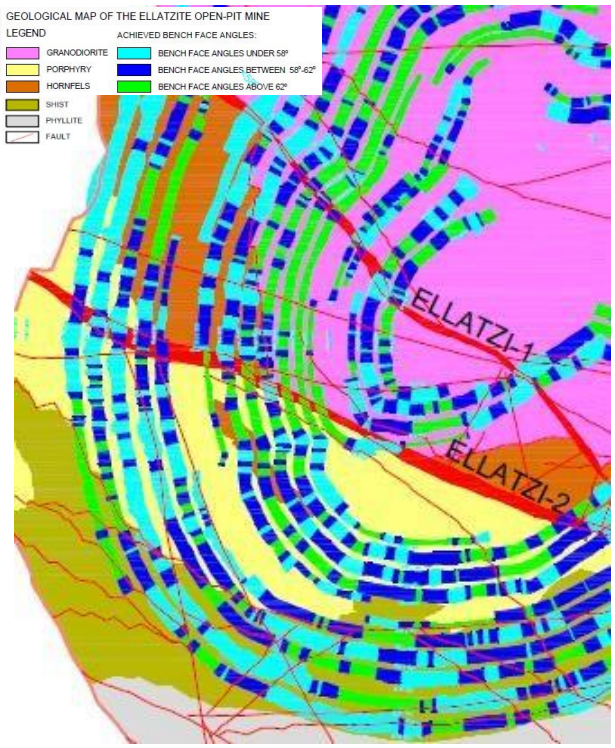


Fig. 11. The western and southern part of the open pit achieved design bench face angle of 65˚, in green.

Decreased bench face angles are observed in the fractured tectonic zones formed by the intersection of two or more tectonic faults, or in the zones intensively fractured and having small-sized blocks (Figure 12).

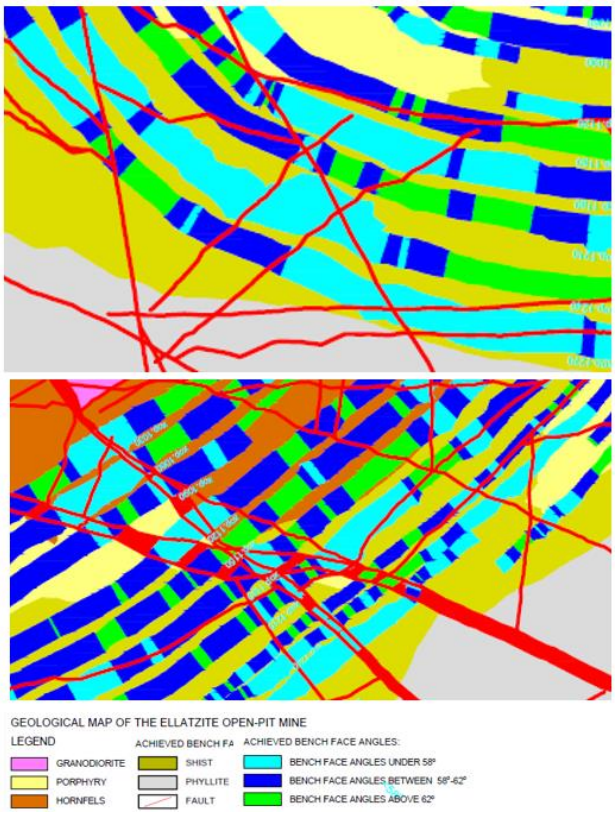


Fig. 12. Tectonic zones with reduced values of the bench face angle (below 58˚) in cyan.

The hydrogeological features of the mapped sectors, such as humidity and water inflow with different flow rates, are directly influenced by seasonal rains, their location and orientation relatively to the bench slope where seeps are present, as well as the elevation of the studied level.

In deeper levels of the open pit mine, different humidity and water flow zones are observed. Single cases of drainage structures with weakly trickling water inflow have also been noted. In the north-eastern and eastern parts of the open pit, in its middle levels, numerous wet areas are observed on benches in both granodiorites and metamorphic rocks. Consequently, four horizontal drainage drillholes were driven in this area at level 1060, in July and August, 2023. These holes drain the rock mass with an average total flow rate of 2÷4 l/s.

The generalized results of the geotechnical analysis of the bench slopes after performing controlled blasting are illustrated with 12 examples of different geometries of the resulting bench slope. The difference in geometry between the designed and the resulting bench slope, after excavating the blasted material is due to a combination between the strength characteristics of rocks, the fracturing of the rock mass and the applied blasting technology (Nachev et al., 2020).

The manner in which the blasting is carried out, and especially the final blasting of the bench, in which its final configuration and bench face angle is formed, can be critical in ensuring the ultimate stability of the overall mine slope. The correct application of the controlled blasting technique allows to minimise the blast-seismic impact on the slopes and the precise contouring of the crest and toe edges of the bench. With its help, the optimisation of the bench face angles is achieved and the maximum width of the final berm is ensured (Nachev et al. 2020).

Conclusion

Tectonic faults have a destructive effect on the intersected rock mass, and the rocks located in the hanging wall are significantly more disturbed. That leads to the formation of small surfaces with excessive destruction along the entire surface of the slope in the hanging wall of the fault.

A characteristic feature of the monzodiorite porphyrites is the development of wedge sliding in cases where the pyramid's apex of the wedge, is pointed to the bench face. Wedge sliding failures of various sizes are also often formed in hornfelses. Sometimes they cover the surface of the slope from crest edge to toe edge. Wedge sliding collapses are not that often among granodiorites.

It is noteworthy to say that in areas which have undergone more intense contact alteration, near igneous rocks, large wedge sliding and planar sliding failures are formed. This is due to the loss of plastic properties of these metamorphic rocks and sustained fracture groups formation.

The use of pre-split blasting reduces the damage behind the bench slope, controlling the zone-specific geology, location and loading of the inner and outer buffer rows. In some cases of hard rock masses, it is necessary to use a stabilizing row of boreholes to improve the weaning of the material at the top of the slope. When there are deviations from the designed bench face in the toe and lower part of the bench, the improvement can be achieved by changing the buffer row of boreholes.

The drilling of horizontal drainage drill-holes, despite the low hydraulic conductivity of the rock mass and the long period to achieve permanent dewatering and depressurization, improves the slope stability in the area of their drilling.

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