ADOPTED APPROACHES AND PRACTICES DURING THE STRUCTURAL-GEOLOGICAL INVESTIGATION OF THE ROCK MASS IN ELLATSITE OPEN PIT MINE, FOR THE PURPOSE OF NUMERICAL MODELLING AND MINE DESIGN

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ABSTRACT. The rapid development of software products and the improved computational power of the computer technologies over the last two decades allowed spatial georeferencing of the geological information and the ability of more complex three-dimensional geological and structural modelling of the rock mass. The article contains the applied approaches during the geological mapping, the data processing and interpretation for the deposit's geological model construction and update. Briefly discussed is the applicability of the results to the activities, related to the mining process.

Keywords: geological mapping, geological wireframing

ВЪЗПРИЕТИ ПОДХОДИ И ПРАКТИКИ В ХОДА НА СТРУКТУРНО-ГЕОЛОЖКОТО ИЗУЧАВАНЕ НА СКАЛНИЯ МАСИВ В РУДНИК „ЕЛАЦИТЕ" ЗА ЦЕЛИТЕ НА ЧИСЛЕНОТО МОДЕЛИРАНЕ И МИННО ПРОЕКТИРАНЕ

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РЕЗЮМЕ. Бурното развитие на софтуерните продукти и повишената изчислителна мощност на компютърните технологии през последните две десетилетия позволи пространствено привързване на геоложката информация и възможността за по-детайлно триизмерно моделиране на геоложките тела и разломните нарушения в скалния масив. Статията съдържа възприетите подходи при теренното събиране на данни за прекъснатостите в масива, необходимата обработка и интерпретация на тази информация при изграждането и актуализацията на структурния модел на находището. Засегната накратко е приложимостта на резултатите при дейностите, свързани с миннодобивния процес.

Ключови думи: геоложко картиране, геоложко моделиране

Introduction

The management of Ellatzite-Med AD commenced a campaign in 2013, aiming to develop a geomechanical and hydrogeological numerical models of the rock mass of Ellatzite mine. Another project for updating the existing model of the deposit, which had been built in the *Datamine* software suite, began in 2015. The update was performed by the newly implemented *HxGN MinePlan 3D* software for mine planning and design. Firstly, the available geological information was analyzed and a spatial tectonic faults model (structural model) together with a spatial lithological model have been developed as a base for these two projects.

The modelling of tectonic faults and geological boundaries within the deposit and its vicinity, and the discussion on them herein do not aim to solve any problems keen to the regional geology. A guiding line was as precisely as possible to define the tectonic faults surfaces, by accounting the available field and drill-hole data, while minimally judge over their location – predominantly in the model's peripheral regions. This article mainly aims to describe the preliminary activities and adopted approaches for processing and analyzing the existing geological data, which has been used for developing of the geomechanical, hydrogeological and block models of the deposit.

Geology

The Ellatzite deposit is the northernmost one of the Upper Cretaceous copper-porphyry systems, part of the Panagyurishte Ore Region. The deposits in this region are arranged in an en-echelon array. They are located in the western parts of Central Sredna Gora and Central Balkan Mountains. Some regional summary tectonic works on the Upper Cretaceous magmatic arc development in the Sredna Gora region, interpret the deposits as a result of an oblique subduction at the front side of Rhodope Massif. Deep seated strike slip faults are considered as a main cause for structural placement of the deposits (Von Quadt et al., 2001).

Rock varieties present at Ellatzite deposit could be divided in two main groups: *Paleozoic metamorphic and intrusive igneous rocks* and *Upper Cretaceous intrusive to subvolcanic and sedimentary rocks*. The first group consists of low-grade metamorphic varieties from the Vezhen pluton collar – phyllites, contact-altered schists and hornfelses, and the granodiorites of Vezhen pluton. The second group consists of quartz-monzodiorite porphyries, granodiorite porphyries and Turonian sandstones. The latter are outcropped at the southernmost parts of the deposit, close to the mountain ridge.

Input data types, their processing and outcomes

Detailed sketches of rock slope outcrops, M 1:500

An approach for detailed data collection from the newly outcropped slopes has been adopted at Ellatzite mine. This is achieved by detailed sketches of the slopes in M 1:500 (Figure 1)

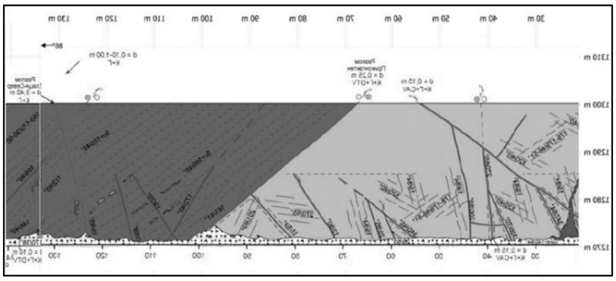

Fig.1. Part of a large sketch of a rock slope outcrop, M 1:500

The field structural and geological data collection has been established during the last 17 years. Firstly, paint marks are placed at every 5 m along a slope being mapped and marks' coordinates are recorded. Then all geological and structural features are spatially related to the paint marks. This detailed geological and structural mapping has been completed year by year by a team of geologists from NIS at Sofia University "St. Kliment Ohridski", under the supervision of prof. Zhivko Ivanov (2003-2015) and assoc. prof. Neven Georgiev (2015-2020). The field study results are presented in a sequence of applied science reports. The authors of this article participated in the field works from 2007 to 2012.

Field works especially accented on:

- the lithology and spatial interrelation between different geological bodies (incl. the degree of alteration underwent by rocks – hydrothermal, weathering, etc.);
- the texture of different segments along the rock slope – features of tectonic faults and shear zones, jointing, etc.;
- detailed study of brittle structures – separation of all joint sets in a particular segment of the slope, their spatial orientation and elements (length, frequency, joint profile morphology, joint surface alteration, fill, and degree of openness);

The brittle structures description (Ivanov et al. 2008) defines three different types, depending on their scale and role for rock mass rupturing: faults (F), master joints (GF) and joints (P).

Faults (F) are large discontinuities, accompanied by tectonic brecciation, cataclasation, fault gouge, while their thickness exceeds 2-3 cm. The boundaries between lithologic bodies are frequently delineated by such faults.

Master joints (GF) are large discontinuity planes, along which there is no visible displacement. Their traces could be often followed in 1-2 benches. Sometimes they are kinematically connected (splay structures) to the main faults. In other cases, they are parts of a well-defined joint set, having similar features and orientation. Master joints are accompanied by thin frictional zones of grinding, up to 1-2 cm in thickness.

Joints (P) are the smallest discontinuities. They tend to form separate sets with similar orientation and morphology. Several (from 2 to 4-5) joint sets are reported in different mapped slopes, independently of their host rocks and having different spatial and morphological parameters.

Metamorphic rocks, affected by regional green-schist metamorphism, are mapped in rock slopes. They show three foliation generations – S_{0-1}, S_2 and S_3. Georgiev at al (2017) interpret them as a results of at least three different deformational events.

All field measurements through the yearly campaigns are accompanied by their coordinates. They are summarized in a tabulated spreadsheets. The spatial orientation of faults, master joints and foliation surfaces are coupled to the coordinates along the metric scale of the outcrops, at the slope heel. Joint sets are centered to the middle point coordinates of each studied rock slope segment. Each mapped discontinuity is accompanied by attributive columns for: coordinates (X, Y, Z), dip, dip direction, host rocks, type of the structure (F, GF, P, S), kinematics, thickness (openness), trace length along the slope, fill, litho-tectonic domain, open pit sector, metric location along the bench, and year of measurement.

The so catalogued structures allow their comparatively fast integration into different software applications and implementation of statistical, stereographic, and kinematic analyses. Spatial analysis is also possible by applying different sub-data sets and criteria. The most used software application for such spatial analysis at Ellatzite-Med AD is *Move*. It allows criteria searches – after different attributive data, location, or relative position to some other geometric objects. Examples for such objects are: a 3D surface of the open pit (real or designed), a directional line or a cross-sectional plane for stability analyses. The current volume of data consists of: 3320 fault measurements (Figure. 2a), 6060 master joints (Figure 2b), 7040 joint sets measurements (Figure 2c), and 5360 foliation surfaces (Figure 2d). It is important to note, that the number of fault measurements does not represent 3320 different fault structures. There are tens of measurements for each structure, which are collected at different bench levels, and different sequential push-ups (3 to 4 in number) of the mine.

The possibility to render different structural types with their spatial orientation is useful and has its own advantages. On the other hand, the simultaneous viewing of thousands of spatial measurements often is misleading and not very informative. This prompted the authors to develop a methodology for coupling of raster images of field sketches. The information contained therein helps to figure out the interrelationship between different discontinuities and their subordination (Figures 3 and 4).

For this purpose, again in the *Move* application, the metric paint marks along the mapped slope, with their coordinates, are imported in a 3D mode (Figure 3) and a continuous polyline is constructed. In the ideal case, it coincides with the slope heel line. The polyline is used for a cross section generation, which follows the polyline. The metric scale is projected over the generated cross section. In a 2D mode of operation, the raster image of the complete sketch or a part of it is imported and properly scaled.

Fig.2a.

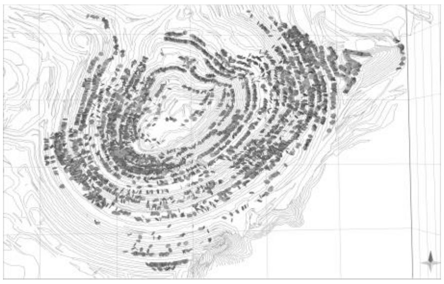

Fig.2b.

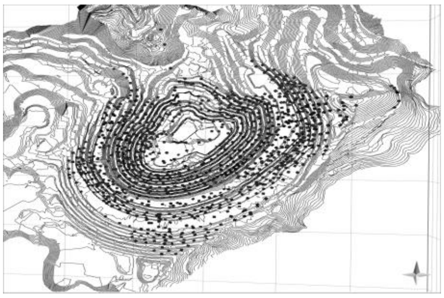

Fig.2c.

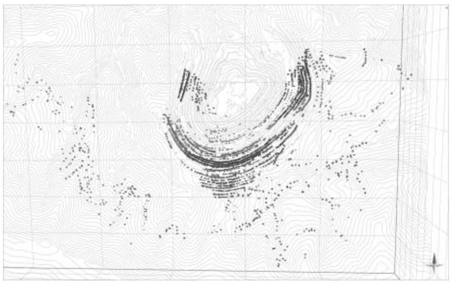

Fig.2d.

Fig.2. Location and distribution of structural measurements of faults (2a), master joints (2b), joint sets (2c) and foliation surfaces (2d)

Drill-hole data

The undertaken lithologic and structural modelling demanded an upgrade and supplementing with the existing drill-hole data. It has been summarized and complemented by data for all underground exploration and drainage galleries. The latter were modelled as a sub-horizontal drill lines. Different terms used through the years of study, by different teams, have been standardized and unified – different descriptive terms for rock varieties, especially for metamorphic ones. As a result, the outcropped within the open pit rocks have been divided into six main varieties: hornfelses, schists, phyllites, granodiorites, quartz-monzodiorites, and granodiorite porphyries. These varieties possess clear differences in their physical and mechanical properties, structural anisotropy, and location along the deposit stratification.

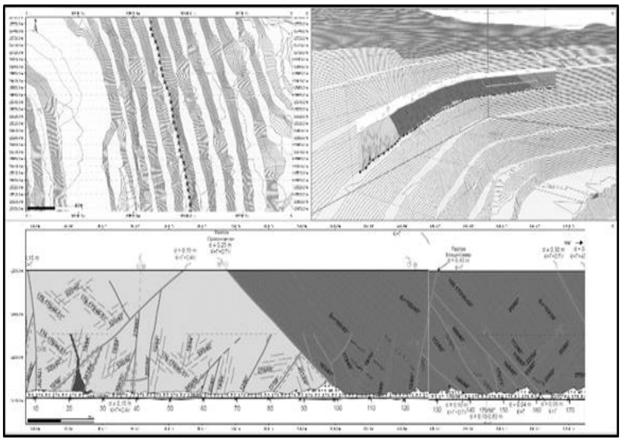

Fig.3. Spatial coupling of a large sketch. Top left – metric scale points along the bench in a plan view. Bottom – scaled raster image of the sketch, placed along the constructed cross section. Top right – 3D view of the sketch, viewed to SE.

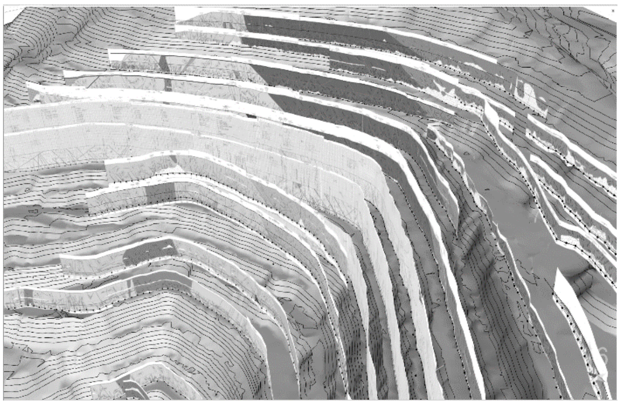

Fig.4. General view of the spatially coupled scaled sketches of rock slopes, from the eastern sector of the open pit, viewed to NE.

The lack of data or the scarcity of oriented drill cores did not help much to define the spatial orientation of penetrated by drilling faults. Therefore the intersections were imported in the models only as points in space, accompanied by attributive data for the apparent fault zone thickness along the drill-hole, fill features and the angle between the drill-hole axis and the fault planes. The adopted approach is also appropriate if we take into account the difficulties to collect oriented drill cores out of the tectonically altered and disintegrated sections of the drill cores. Our experience from recent drilling campaigns show some 80-90% oriented core out of the whole drilled length, while the presence of faults discontinuities in the drill-hole prevents the successful core orientation or only allows low reliability in it.

Geophysical prospecting

Applied geophysical exploration has been performed in the higher peripheral levels of the southern and eastern sectors of the open pit, from 2013 to 2015, which aimed to fill up some lack of knowledge there. This included electric resistivity and polarization profiling, together with vertical electric sounding (Yaneva et al., 2015). The results were accomplished and interpreted by a team from Geology of Earthquakes Department, Geological Institute, Bulgarian Academy of Sciences, under the supervision by assoc. prof. Marlena Yaneva, PhD and prof. Stefan Shanov, PhD.

The interpreted geophysical profiles (Figure 5a) were placed in their corresponding location by using the same methodology, described above. The results of this exploration were also analyzed and interpreted by the team in 24 horizontal plan views, vertically separated by 15 m, from levels 1510 to 1165 m. The raster images were georeferenced and digitized. The interpreted fault and geological boundary trace lines on each of the plan views were used for constructing of triangulated surfaces (Figure 5b).

The results were used for modelling of boundary surfaces, part of the lithological model, as well as of fault surfaces in the structural model, at the particular sector of the open pit.

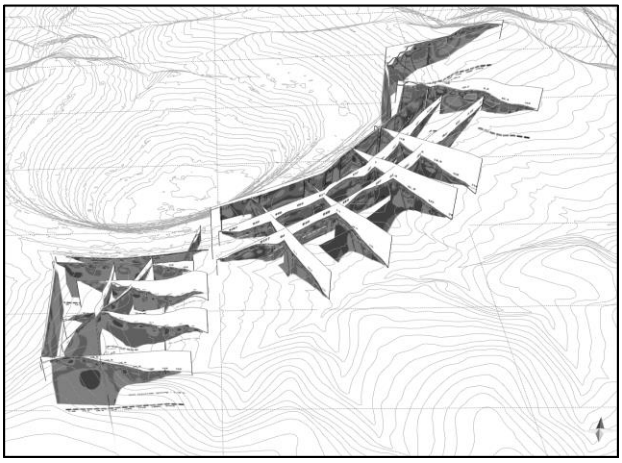

Fig.5a.

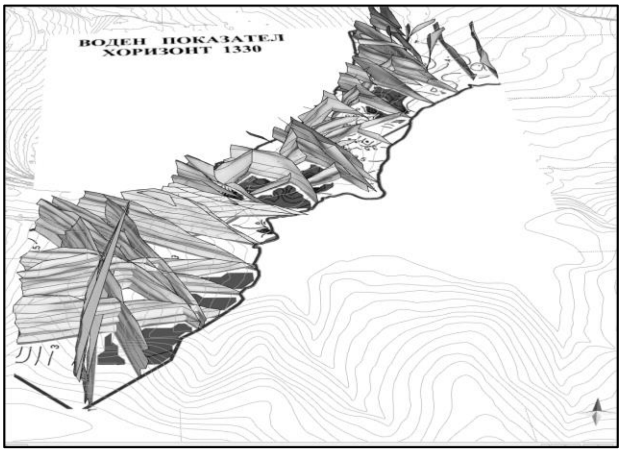

Fig.5b.

Fig.5. Location of processed geophysical profiles (5a) and the corresponding plan views, with their constructed 3D surfaces, viewed to the North.

Archived maps, cross-sections and plan views of the detailed exploration of the deposit

Raster images of the available maps, not in vectorized format, were georeferenced and digitized. Later, vectorized objects, bearing geological information, were spatially placed by their projecting over preliminary prepared 3D surfaces, representing the open pit geometry (Figure 6a). The existing digital, 2D maps were spatially oriented.

The scanned geological cross sections and plan views of the detailed exploration of the deposit (Hadzhiiski, 1968), were placed along vertical and horizontal cross sections, generated in *Move* (Figure 6b), with their corresponding orientation and level.

These geological data were used as auxiliary to the drill-hole information, mainly for modelling the rock mass, which had been mined out, up to the natural landscape.

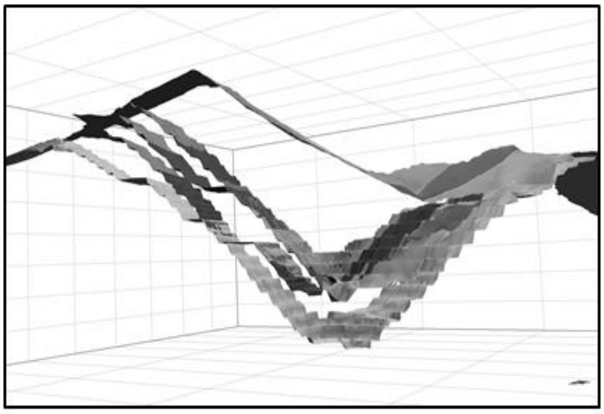

Fig.6a.

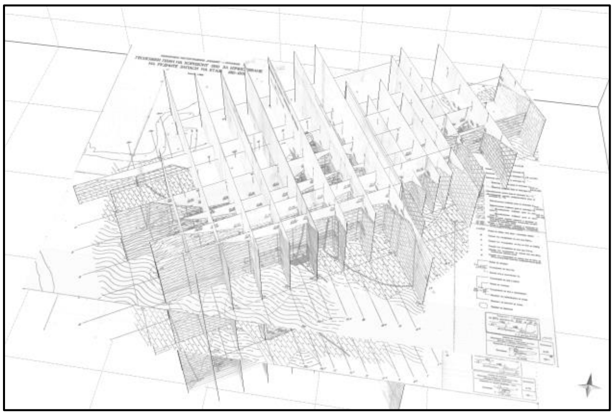

Fig.6b.

Fig.6. A part of the digitized and spatially oriented archived map data (6a) and a set of vertical and horizontal cross sections from the detailed exploration of the deposit (6b)

Lithological and structural modeling

The summarized geological information was interpreted along 58 2D profiles, SE-NW oriented. They were separated at 50 m in the central parts of the deposit and at 100 and 200 m in the periphery. The geological boundaries and first order faults were interpreted in a solid, 4930 x 4770 x 1400 m in size, for the necessities of the geomechanical and hydrogeological models of the deposit. The rock mass has been divided into four main tectonic blocks (Figure 7a), which are separated by two first order fault structures – Elatsi-1 and Elatsi-2. These structures show larger vertical and horizontal displacements. The two faults, according to their kinematics, are classified as dextral strike-slip faults, bearing a superimposed normal faulting displacement (Georgiev et al., 2017).

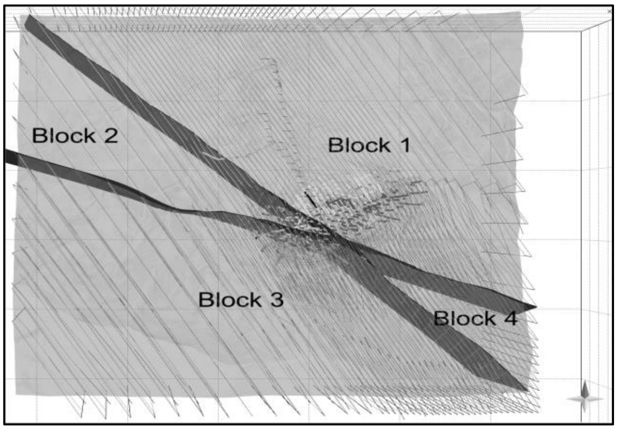

Fig.7a.

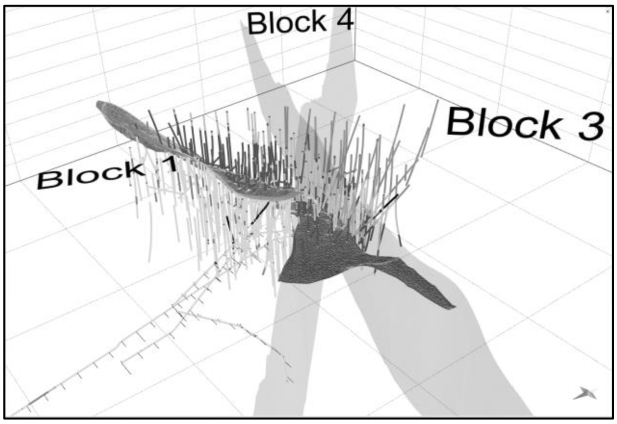

Fig.7b.

Fig.7. Location of the interpreted profile lines in a plan view, with four tectonic blocks denoted (7a). Three-dimensional view of the boundary surfaces modelled between granodiorites and hornfelses, tectonic blocks 1 and 2, viewed to SE (7b).

The geological boundaries are mostly tectonically reactivated magmatic contact surfaces. They are drawn as polylines, for each tectonic block. The resulting polylines are used for constructing triangulated boundary surfaces, separating different rock varieties, at each tectonic block (Figure 7b). The so constructed surfaces are edited in 3D working space, by several iterations of geometric files, between *Move* and *HxGN MinePlan3D* applications. The editing consists of simplification or addition of more nodes on surfaces, as well their coupling to lithologic boundaries, detected by drilling or surface mapping. The surfaces are extended along their strike and dip toward the open pit peripheral areas, so that the surfaces to pass through the whole solid, in which they are in. That is to allow easy work with Boolean operators. All surfaces have been checked for possible gaps, overlaps or intersecting facets.

As a result from the whole modelling, the six main rock varieties (Figure 8) are divided into 23 litho-tectonic domains. This detailed classification gives the opportunity for more thorough statistical (geostatistical) analysis, for different types of studies and structural measurements, which fall in different domains. It also provides flexibility when different properties and parameters are set for the geomechanical, hydrogeological and block modelling. This is also helpful for finding of optimal conceptual boundaries of the deposit, as they are constructed within the *HxGN Mine Plan Economic Planner* module, for long-term mine planning.

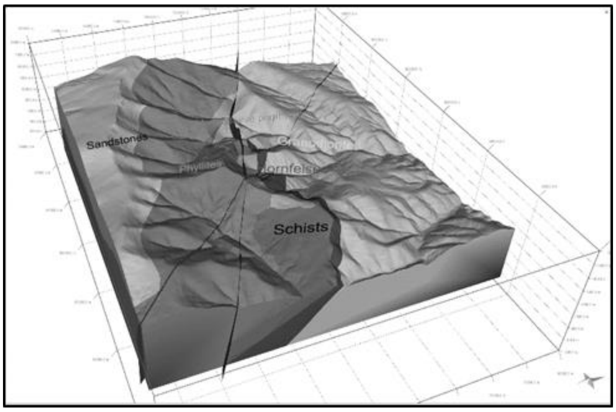

Fig.8. Three-dimensional view of the spatial lithologic model of the deposit. Left to right: sandstones, phyllites, schists, quartz-monzodiorite porphyries, hornfelses, and granodiorites, viewed to NW.

Part of the fault surfaces were modelled during interpretation of geological data along 2D cross sections. The remaining ones were constructed in a 3D working mode at *Move* and *HxGN MinePlan3D* applications. All drill-hole and mapped data were used for construction of triangulated surfaces. Spatially referenced large- and middle-scale archived geological maps, together with corresponding cross sections in M 1:5000, 1:10000 и 1:25000, were very useful for the peripheral areas around the open pit. The interpretation of interrelations between different fault surfaces is based on scaled field sketches of rock slopes, archived mapping campaigns, and the field experience of the authors, working within the open pit.

The current structural model of the deposit consists of 70 3D fault surfaces (Figure 9). They are ranked according to their size: first-order (21), second-order (34), and third-order (15). The first-order faults cross-cut the whole open pit or are present in one of the sectors, but also play a role of a lithologic boundary. Second-order faults pass through the entire single wall of the open pit, in a particular sector. Third-order faults are present across several benches (inter-ramp scale). Excluding two of the first-order faults, all others are modelled as singular surfaces. Ellatzi-1 and Ellatsi-2 faults are modelled as having certain thickness, varying between 4-5 and 10-12 m. These two main structures are modelled by a couple of subparallel fault wall surfaces, representing their brittle boundaries. The geometric files for the lithologic and structural models are annually updated with the newly collected drilling and mapped data.

Conclusions

The summarized geological information considered in this article is a good foundation for all activities, necessary for the geomechanical, hydrogeological and block modelling of the deposit. Results obtained from the accumulated data base, together with the 3D geological model, are used on a daily base for planning and design of drilling and blasting works. They are used as input data for: geotechnical plan views, which reflect the rock mass zoning according to its blastability; preparation of text and graphic files, containing geological bedrock information and constructing 2D cross sections for stability analyses; preparation of entire or local model designs for stability purposes.

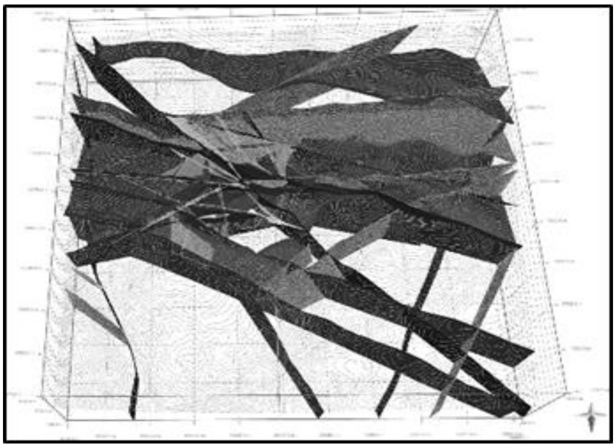

Fig.9. Three-dimensional view of the modelled surfaces, part of the structural model of the deposit, viewed to the South.

These results are also used for preparation of the geological base, which is integrated into the radar system software, used for real time slope stability monitoring. Another application goes for design of exploration and drainage drilling. The detailed classification of the rock domains allows the assessment of different rock slope geometries, within those domains. The models described in this article are used for strategic mine planning and design, while searching for economically feasible deposit boundaries. The importance of the described here modelling requires a critical thinking over the spatial models, a permanent pursue for their upgrade with good quality data and improving their reliability.

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