TRANSIENT, THREE-DIMENSIONAL, HYDROGEOLOGICAL NUMERICAL MODEL OF ELLATZITE OPEN PIT MINE

Nikola Toshkov, Ivan Vasilev, Lyubomir Svilenov

Mining Complex, "Ellatzite-Med" AD, 2180 Etropole; n.toshkov@ellatzite-med.com; i.vasilev@ellatzite-med.com; l.svilenov@ellatzite-med.com

ABSTRACT. The nature of the groundwater behaviour in active open pit mines is transient due to the constant mining and installation of active dewatering/depressurisation systems. Prediction of the groundwater flow in such a conditions is mainly important in two aspects - assessment of the pit inflow in order to design dewatering/depressurisation systems for normal operation and investigation of the slope stability in order to design the optimum geometry. In Ellatzite Open Pit Mine a three-dimensional, hydrogeological numerical model is developed that has the ability to do transient calculation not only with reference to the dewatering systems but also to the change in the pit geometry, hydraulic parameters, recharge zones and climate changes.

Keywords: numerical modelling, mine dewatering

ТРИМЕРЕН, ХИДРОГЕОЛОЖКИ ЧИСЛЕН МОДЕЛ НА РУДНИК ЕЛАЦИТЕ В РЕЖИМ НА НЕСТАБИЛИЗИРАНА ФИЛТРАЦИЯ

Никола Тошков, Иван Василев, Любомир Свиленов

Рудодобивен комплекс, „Елаците-Мед“ АД, 2180 Етрополе

РЕЗЮМЕ. Поведението на подземните води в активни открити рудници е променливо или в състояние на постоянна нестабилизирана филтрация, поради минните дейности и инсталирането на различни отводнителни системи. Прогнозирането му в такива условия е важно в два аспекта – оценка на водопритока към рудника за проектиране на отводнителни системи с цел нормална експлоатация и изследване на устойчивостта за проектиране на оптималната геометрия. В рудник „Елаците“ е разработен тримерен хидрогеоложки числен модел, с възможност да извършва изчисления в режим на нестабилизирана филтрация по отношение не само на отводнителните системи, но и по промяната в рудничната геометрия, хидрогеоложките параметри, зоните на подхранване, и климатичните условия.

Ключови думи: числено моделиране, минно отводняване

Introduction

Groundwater dewatering and control under operation of large open pits is a complex and challenging process that requires design and construction of drainage tunnels, pumping wells, sub horizontal boreholes, ditches, sumps, pumping stations and pipelines. The main purposes of these systems are to sustain the normal operation work of people and machines, increase stability and design optimal pit geometry (Read and Beale 2014). In order to achieve that we need to determine the climatic, hydrological, geological, hydrogeological and mine exploitation settings.

If we assume that climate conditions and geological settings are known during the lifetime of a pit, the rest have transient character because of the active mining activities. They constantly change the surrounding topography and create new watersheds in different scale. Due to the large mass being excavated, the rock near the pit slope is under relaxation. This causes the processes of swelling and joint opening, which are changing the hydraulic properties of the rock mass (Liu 2013; Ugorets 2015). Moreover, the installation of new drainage systems alters the groundwater flow and its boundary conditions.

The Ellatzite open pit mine is located about 1.5 km north of the main ridge of the Balkan mountain in the region of Etropole and consists of a single large excavation. At present, the highest bench is at 1510 m.a.s.l. while the lowest at 865 m.a.s.l. The shape of the pit in plan is elliptical with the longest and shortest axes being 2100 and 1500 m, respectively (Figure 1). The mining activities are carried out with the help of a third drainage tunnel under the pit bottom and slope toes. The tunnel has four adits and it is connected to the bottom of the pit through vertical boreholes. While the tunnel transmits the surface water and part of the groundwater flow, several horizontal drainage boreholes depressurise the slope.

Those dynamic and complex specifics of large open pit mines impose the use of a numerical three dimensional hydrogeological model that is able to do transient calculations. Such a model was accomplished in 2019 together with the specialists from the mine and consultancy company Itasca with the software MineDW that is specially adapted for mines (Liu 2013; Ugorets 2015). The geological and structural models of the pit, the drainage tunnels and dewatering boreholes, all the historical surfaces of the pit are implemented in the model. Discharge data from surface and groundwater flows, in-situ filtration tests and data from monitoring systems are also used.

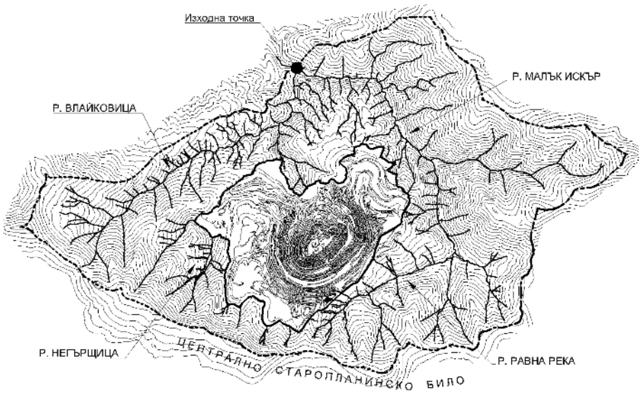

Fig. 1. Ellatzite open pit mine and its surrounding areas. Mining activities' extent, hydrogeological model boundaries and river streams are shown with thicker lines. The point of the model drainage is indicated in the northern part

Hydrogeological conditions and conceptual model

The surface and base runoff in the hydrogeological model is drained by the Maluk Iskar River and its main tributaries, the rivers Ravna and Negarshtitza. The former surrounds the pit area from southeast while the latter is partially covered by the west waste dumps of the mine. The Vlaicovitza River is the main tributary of the Negarshtitza River and the Dascalski Polqni ridge is their watershed divide (Fig. 1). The river is located in the most western part of the model area. The south boundary of the model is the main ridge of the Balkan mountain. A section of Maluk Iskar after the Negarstitza River flows in it as a drainage point of the model. The watershed area of this section is 31 km^2 and it is used as an external boundary of the model.

The terrain around the area of mining activities is natural and it is characterised by steep slopes and various forestation type. The lowest elevation in the model is 760 m.a.s.l. at the drainage point, while the highest is 1822 m.a.s.l. and it is located at Korduna peak. In the area with mining activities the terrain is considerably changed. The waste dumps are constructed with horizontal levels that are filed up to the projected extent, whereby slopes with heights of 10m to 50m, rarely 100 m are formed. The surface water which could enter the piles is caught and diverted with surface and underground drainage systems and it is later released in natural streams. The polluted water that discharge from them is also caught, but this time it is diverted to the purification plant at elevation 840 m.a.s.l. and the floatation plant (Hristov et al. 2014, 2016).

The region of the mine is characterised by mountainous climatic conditions of the continental climatic zone (Belda et al. 2014; Hristov et al. 2014), which means that the temperature fluctuations are considerable in the range of 25-30° C. In January, the average monthly temperature is below 0° C, while during the summer the temperature is above 20° C. For the last ten years, the average annual precipitation, measured by a meteorological station located at elevation 1103 m.a.s.l. in the centre of the hydrogeological model, is 1110.5 l/m^2. For the groundwater budget (1) the precipitation (P) is the only recharge for the model, since there are no other water bodies to recharge the system (Hristov et al. 2016). After estimating the evaporation (E) and the surface run off (Qs) the quantity of the rain that enters the groundwater system (Qu) is calculated. The values are used for recharge of the hydrogeological model and it is different for the pit and waste dump areas.

$$Q_u = P - Q_S - E \tag{1}$$

The evaporation (E) is calculated using the analytical formula of Turk (2), which is widely used for various conditions and takes into account the values of the temperature (t). The applied formula estimates that the annual average evaporation is from 35% to 48% depending on the year (Hristov et al., 2016).

$$E = \frac{P}{\sqrt{0.9+\frac{P^2}{L^2}}} \tag{2}$$

where:

$$L = 300 + 25t + 0.05t^3 \tag{3}$$

Estimating the surface run off and groundwater discharge is a challenging task, if there is not enough detailed data of the daily river stage at the discharge point. However, it is empirically assessed that the groundwater recharge (Qu) as a part of the precipitation is about 23% to 42% depending on the year (Hristov et al., 2016). The percentage is higher for the area of the waste dump and it can reach up to full infiltration of the precipitation (100%).

Six lithological units comprise the hydrogeological model – granodiorites, hornfelses, monzodiorite porphyries, schists, phyllites and sandstones. In most of them the groundwater movement is due to the fracture system. Major faults have considerable influence over the formation of the groundwater flow, acting as an aquiclude or transmitting the water depending on the flow direction. This effect in the model is achieved by grouping the elements of the mesh in fault zones (like the faults on Fig. 4a) and applying their hydraulic conductivity parameters. In such a manner the model can reproduce the observed (by monitoring systems) vertical pore pressure gradient.

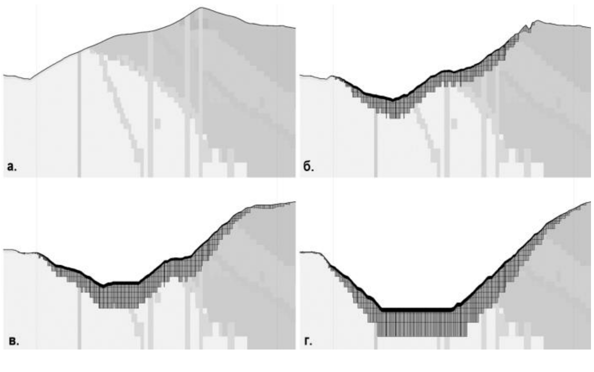

Fig. 2. ZOR extent in the section oriented north-south across the middle of the mine – before the start of the mine (a), at the beginning of year 2005 (b), 2015 (c) and 2031 (g). The two ZOR are with black and grey (covered with the mesh) with 1/10 and 1/3 from the excavation thickness. Different geological units are also illustrated with dim colours (without calculation mesh)

The conductivity change of the rock mass close to the pit surface caused by active mining is modelled with zones called Zones of Relaxation (ZOR). There are two in the model divided by a vertical extent and are dependent on the pit excavation (fig.

2). They are simulated as elements with increased hydraulic conductivity. The first zone has ten times higher hydraulic conductivity compared to the unchanged rock mass and encompasses elements with depth of 1/10 the thickness of excavation mass above. The second zone reaches a depth of up to 1/3 of the excavation thickness and has three times higher hydraulic conductivity. The extent of the ZOR and their hydraulic conductivities are based on Itasca experience (Xiang and Sterrett 2019).

The constitutive law that calculates the groundwater flow budget in each element is the Darsy's law for transient flow in three dimensions (4).

$$S_s \frac{\partial h}{\partial t} = k.\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2}\right) + w \qquad (4)$$

where:
S_s – *specific storage, [m^{-1}];*
k – *hydraulic conductivity, [m/s];*
h – *head, [m];*
x, y, z – *directions in the model;*
w – *recharge from precipitation, [m/s];*
t – *time, [s].*

All external boundary conditions of the model, rivers, pit excavation, drainage galleries and horizontal drain boreholes are represented with their particular boundary condition. The flow rate is calculated in the nodes of the elements of the external boundary conditions by analytical solution for a semi-infinite aquifer. This allows to reduce the size of the model and decrease the influence of the external boundary condition on the calculation ("MineDW, User's Manual" 2018). On a pre-defined river stream route the nodes of the elements are made as drainage nodes and the groundwater that recharge them is taken out. If the head of the groundwater system (H) becomes higher than the surface topography elevation (Hs) of the river nodes the model discharges groundwater that does not infiltrate back. The nodes of the pit excavation are also drain nodes, whose elevation varies with time (the elevation is reduced for excavations). The drainage galleries are drainage nodes that are activated at the time of completion. The flow rate of the rivers, the pit excavation and the galleries nodes are calculated by formulas (5) and (6) and the pit can be assessed by lithological units.

$$Q_{seepage} = CL * (H_s - H), \qquad (5)$$
when $H > H_s$,
otherwise $Q_{seepage} = 0$

$$CL = \frac{K * D_2 * D_3}{D_1} \qquad (6)$$

where:
$Q_{seepage}$ – *drainage nodes flow rate, [m^3/d];*
H *u* H_s – *nodes calculated head and elevation, [m];*
CL – *leakage factor, [m^2/d];*
K – *hydraulic conductivity, [m/d];*
D_1, D_2 *u* D_3 – *dimension of an element, [m].*

The excavation is simulated by changing the elevation of the pit nodes between the known pit geometries over time (Fig. 3).

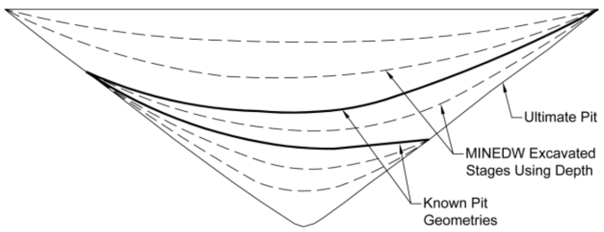

Fig. 3. Reduction of the node elevations in the pit vicinity, by interpolation between the know geometries ("MineDW, User's Manual" 2018)

Input data

The initial heads that are required at the beginning of the transient simulation are obtained by steady state calculation (with time $\partial t = 0$ (4)). After finding the pre-mining groundwater condition for the year 1978, the model starts to reduce the pit nodes elevations and to add drainage nodes for the galleries on a monthly base. The model recharge is also changed for the same time period. Moreover, the annual recharge over the waste dump area is 41% from the precipitation, while in the rest of the model it is 34%. The end of the simulation is the year 2031.

The hydraulic conductivity for all six lithological units is listed in Table 1. Higher hydraulic conductivity values are used for phyllites, schists and granodiorite units at the surface of the model to simulate the effect of rock mass weathering. The hydraulic conductivity of all faults is the same - 1.0 e^{-5} m/d. All units hydraulic conductivity is isotropic (kx = ky = kz).

Overall twelve underground mining structures are implemented in the model. Eight of them are exploration galleries constructed between elevation 1160 and 1285, between 1960 and 1968 before the start of the mining activities. Three out of the four other structures are made on elevations 1030, 950, 840 m.a.s.l to dewater the pit. The last is at elevation 1050 and it has an ecological purpose. Apart from the underground structures, eighteen sub-horizontal boreholes also acting as drainage nodes are implemented in the model.

Table 1. *Filtration parameters of the lithological units*

Lithological Unit	Hydraulic conductivity, m/d ($k_x = k_y = k_z$)	Specific storage, m^{-1}
Granodiorites (weathered)	$2.0e^{-1}$	$5.0e^{-6}$
Granodiorites	$2.0e^{-3}$	$5.0e^{-6}$
Porphyries	$3.0e^{-3}$	$5.0e^{-6}$
Hornfels	$2.0e^{-3}$	$5.0e^{-6}$
Schists (weathered)	$2.0e^{-1}$	$5.0e^{-6}$
Schists	$1.0e^{-2}$	$5.0e^{-6}$
Phyllites (weathered)	$1.0e^{-3}$	$5.0e^{-6}$
Phyllites	$1.0e^{-5}$	$5.0e^{-6}$
Sandstones	$3.0e^{-2}$	$5.0e^{-6}$

To calibrate the transient simulation data, thirty-five vibrating wire sensors (recording pore-water pressure) and twenty eight piezometers (recording water level) are used. Records of the flow rates of galleries, river streams and sub-horizontal boreholes are also used. Mapped locations and measured flow rates of seepages in the pit are compared with those calculated from the model.

Hydrogeological model and calibration

The simulated steady state head and the boreholes measured from the exploration are shown on Fig. 4. In both cases, northeast from the main fault zone (Ellatzi 1) a convex water level is formed, while southwest from it the shape is concave. The flow rate at the model drainage point (Fig. 1) is 270 l/s, while the measured flow rate of the base flow in the same point in years 2014 and 2015 is in the range of 200 to 400 l/s. Right before the inflow of the Ravna River in Maluk Iskar the measured flow rates of the base flow are around 34 l/s, while the simulated are 32 l/s.

The simulated by the transient simulation and the measured groundwater pressures are in accordance. The comparison between the measured and the simulated water levels for some monitoring boreholes is illustrated on Fig. 5. The calculated flow rates for the drainage gallery at elevation 840 are from 38 l/s to 77.5 l/s, while the measured ones for the same period are 38 l/s to 128 l/s. The measured flow rate for the drainage gallery at elevation 950 is from 22 to 95 l/s, while the simulated one is from 66 to 128 l/s. For five sub-horizontal boreholes located on two benches in the pit the calculated flow rates are in the range of the same magnitude as the measured.

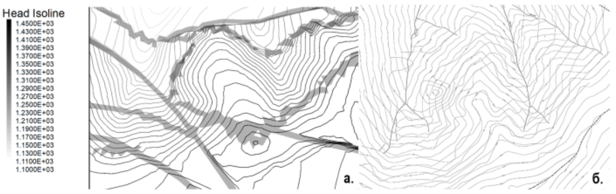

Fig. 4. Simulated (a) and measured (b) water levels before the mining activities being used for calibration and initial head of the transient simulation. In grey in (a) the major fault zones with elements of the calculation mesh are represented. Isolines of the groundwater head on the same plot are visualised between 20 m, from 1100 m to 1450 m. The measured head in (b) is visualised between 25 m, from 1175 m to 1425 m

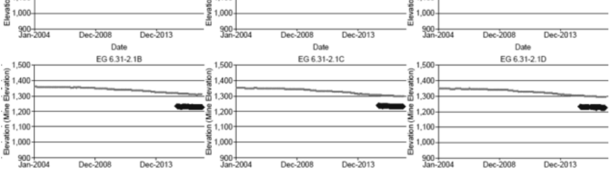

Fig. 5. Simulated (continuous lines) and measured (black symbols) by vibrating wire sensor pore pressure (illustrated as head)

The model recharge is 0.28% higher than the water quantity of the model discharge from the drain point. This shows that the model drainage point is discharging the whole model and negligible water quantity is recharged to the model from the external boundaries. The simulated groundwater budget for December 2017 is as follows: flow rate of the model drainage point 270 l/s (99.76%); groundwater recharge to the rivers 178 l/s (66%); flow rate to the drainage galleries 34 l/s (13%); inflow to the pit 23 l/s (23%); discharge from groundwater storage 33 l/s (12%) (Xiang and Sterrett 2019). The measured seepages flow rate during the dry season in 48% of the pit benches in 2015 is 10 l/s, while during the wet season in 57% of the benches the flow rate is 72 l/s (Hristov et al. 2016)

Fig. 6 clearly shows how the drainage tunnel at elevation 840 and the fault zones change the groundwater dynamics. Along with the reduced pore pressures in the lower part of the pit and under the bottom of the mine above the drainage gallery 840, in the upper sectors of the pit slope, behind the tectonic zones (playing the role of aquicludes), conditions for groundwater accumulation are formed that cause additional pore-pressures. This is prominent for the southern mine sector (Fig. 6, profile line A-A'), which in its upper parts consists mainly of weak geological units (phyllites and schists) with low filtration properties. This fact has an additional negative impact on the stability of the slope. In this regard, a conceptual drainage system has been developed.

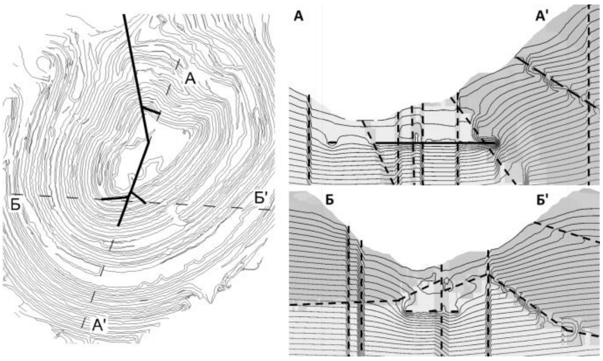

Fig. 6. Longitudinal (A-A') and transverse (B-B') section along the drainage gallery at elevation 840, with pore-pressure distribution in depth for year 2015. The isolines are between 250 kPa, starting from 0 kPa, the gallery location is illustrated with a continuous black line, while the major fault zones are marked with dashed line

Conceptual drainage system

The developed conceptual drainage system (Fig. 7) consists entirely of sub-horizontal boreholes, simulated on pit benches with elevation from 1200 to 1400 m, and the time of their activation in the model (from 2020 to 2022) is consistent with the project development of mining activities. For the purposes of the initial simulation, the boreholes were modelled with a length of 220 to 250 m and an average horizontal distance of 40 m between them on each bench. After stabilisation of the groundwater levels in the area, the calculated total flow rate of the system gradually decreases to about 12 l/s after year 2022.

Similar simulations are to be performed with modelling of future underground drainage galleries, as well as a combined drainage system, including galleries, sub-horizontal and/or inclined drilling, sumps and ditches.

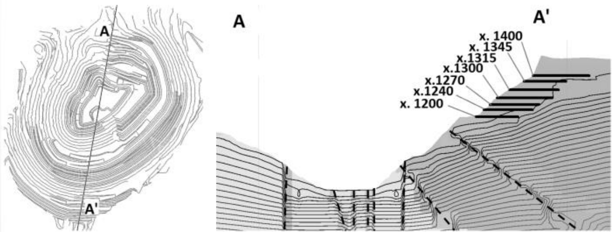

Fig. 7.Conceptual drainage system in phyllites and schists with horizontal drainage boreholes from elevation 1200 to 1400 m. The left plot shows a plan of the Ellatsite mine at the end of 2022 with the position of the section shown in the right diagram. The section shows the horizontal drainage boreholes and the isolines of the pore pressure distribution in depth, with difference of 250 kPa, starting from 0 kPa

Conclusions

The following more important conclusions can be summarised from the performed transient three-dimensional hydrogeological numerical simulation:

- The used software product MineDW is able to take into account the change of the hydrogeological conditions in the dynamically changing environment, such as the open pit mines;
- The constructed three-dimensional model is able to reliably simulate both the spatial and quantitative distribution of groundwater, and can be successfully used for the design of various drainage systems, depending on the operational needs of the mine;
- It is necessary to continuously upgrade and calibrate the model through the newly gathered meteorological, hydrological, structural-geological and hydrogeological information, for the acquisition of which it is necessary to expand the monitoring system of the mine by building new observation points;
- To more accurately dimension and design the future drainage systems of the mine, it is necessary to perform pilot in-situ experimental-filtration investigation, through which to validate the design parameters of the sub-horizontal boreholes.

References

Belda, M, E Holtanová, T Halenka, and J Kalvová. 2014. *Climate Classification Revisited: From Köppen to Trewartha.* Climate Research 59 (1): 1–13.

Liu, H. 2013. *Using MINEDW to Simulate Pore Pressure as Input for FLAC3D and 3DEC*. 9.

MineDW, User's Manual. 2018. Itasca International Inc.

Read, John, and Geoff Beale. 2014. *Guidelines for Evaluating Water in Pit Slope Stability*. Boca Raton, Florida: CRC Press.

Ugorets, Vl. 2015. *Benefits of MINEDW Code for Mine Dewatering Projects in Complex Hydrogeological Settings,* 10.

Xiang, Jianwei, and Robert Sterrett. 2019. *Three-Dimensional Groundwater Flow Model and Conceptual Dewatering Programme at Ellatzite Med Mine, Bulgaria.* 4003. Denver, Colorado, USA.

Hristov, V., Benderev, A., Kolev, S., et al. 2016. *Hydrogeological site investigations carried out in Ellatzite open pit mine and surrounding areas during years 2014 and 2015*, Sofia, GI BAS "Strashimir Dimitrov"

Hristov, V., Benderev, A., Shanov, S., et.al. 2014. *Hydrogeological site investigations carried out in Ellatzite open pit mine and surrounding areas during years 2013* Sofia, GI BAS "Strashimir Dimitrov".