The Hydrogeological Factor in Open Pit Design

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Abstract

The hydrogeological factor directly affects the design of open pit mines through its impact on the stability of the pit slopes and operating costs. The present paper suggests an analysis of groundwater effect and a technique for groundwater flow prediction in the pit region. The technique incorporates the use of a numerical approach based on the boundary integral equation method and the finite element method. A case study is provided for a real open pit mine in Bulgaria and relevant conclusions are drawn.

Introduction

Contemporary design of open pit mines is characterized by the trend for increasing the number of variables used in describing the influence of different factors on the mining production process. Among the substantial factors of influence such as geological, technological, technical and economic ones, the hydrogeological factor is important in open pit design.

The influence of the hydrogeological factor on the pit region very often leads to negative consequences. There are many cases of slope failures due to the action of groundwater that have unfavorably affected the economy of mining companies [*Ngah et al., 1984; Collins, J L, 1994; Tulp, 1995; Orr et al., 1996*]. This can be explained by the state of contemporary methodology of pit design that puts a strong emphasis on the achievement of an economically based solution of the technological problems of mining and processing. The scientific based solution of the problem of groundwater influence is treated as a problem of second rate importance. The character of mining activity also explains the decision making process which is based on a restricted quantity of information that is very expensive to gather. That is why the approach of revealing the hydrogeological picture of a given open pit mine during the process of its exploitation is widely accepted in world mining practice.

The efforts of many researchers are dedicated to the problem of predicting the behavior of the pit hydro-geological system [*Ngah et al., 1984; Kilmartin, 1989; Sperling et al., 1989; Hanna et al., 1994; Gabeva, 1995; Simic et al., 1996*]. Substantial success has been achieved in its solution and this is due especially to the application of numerical methods like the finite difference method, the finite element method and the boundary element method, which are powerful tools for accurate modeling.

The present paper includes an analysis of the importance of the hydrogeological factor in open pit mine design. An original approach is suggested for modeling the groundwater flow, which is based on the use of a hybrid method between the finite element method and the boundary integral equation method.

Outline of the Problem

Hydrogeological Aspect

Open pit design and planning of mining operations is done for given geological and hydrogeological conditions. In the presence of surface and ground waters within the pit region, dewatering is compulsory. It is achieved by surface and underground dewatering works such as drainage galleries, vertical shafts and vertical dewatering wells as well as a net of monitoring piezometer wells.

The effective draining and dewatering of an open pit mine with the above-mentioned dewatering work means a lowering of the ground water level in the rock masses in such a way that the phreatic surface formed within the ultimate pit limits does not affect the stability of the working and final pit slopes negatively.

The management of the hydro-geological factor in the design and exploitation of open pit mines requires the creation of a model for predicting the groundwater flow. The development of such a model represents an essential part of the pit design and aims to ensure a normal and safe exploitation of the open pit mine during its life.

The development of the model is preceded by work on the definition of the hydro-stratigraphic units of the deposit, the type of the groundwater flow, the active thickness and zone of the distribution of the confined and unconfined aquifers, the groundwater feed, the movement and draining in the rock masses, and the filtration properties of the geological medium. These procedures provide the necessary information about the behaviour of the hydro-geological system.

There are some requirements of the model for predicting the groundwater flow. One of them is the satisfaction of the principle of parsimony, i.e. the model must be simple and must describe the behaviour of the system adequately [*Anderson et al., 1992*]. It also has to take into account the link between the fault population and the filtration properties of the medium, the constantly changing geometry of the open pit mine during the development of the mining operations at depth, the influence of the existing surface water sources, groundwater feeding from rainfalls and the work of the drainage and dewatering works.

Generally the model for predicting the behaviour of the hydro-geological system within the pit region can be presented as a mathematical expression of the law of the groundwater flow in a given geological environment having defined filtration properties and fixed boundary conditions which take into account the specific features of the pit region in space and time.

Technological Aspect

From a mining-technological point of view, surface and ground waters have a negative influence on the normal process of mining activity. This influence decreases the effectiveness of mining production in the whole chain of separate technological processes of mining and processing.

Groundwater has a predetermining influence on the geomechanical status of the pit walls. It is known that the presence of such waters leads to decreasing the shear strength of the rock and soil masses, the appearance of tensile joints on the pit terrain and the decrease of the slope stability [*Hoek, 1983*].

The consequences due to the groundwater influence have their own economic dimension. Normal production processes such as blasting, excavation, loading, haulage, waste stripping, etc. are more expensive [*Kennedy, 1990*]. The effects of the hydrogeological factor on the stability of the pit walls, however, are bigger because they have not only an economic content but also a social and ecological content. This is the main factor that causes the pit designer to accept a pessimistic position in the determination of the geomechanical pit outlines and to decrease the slope angles of the pit walls. On the other hand, the acceptance of such a compromise leads to a substantial increase of the waste quantity within the final pit limits and consequently the operating cost.

In contrast to the negative economic consequences, groundwater can sometimes have a positive economic influence if it is used as industrial water.

Economic Aspect

The solution of the problem of managing groundwater influence on the production process deals with the management of capital and operating costs. The operating costs for dewatering open pit mines are fixed costs because they are independent of the level of production [*Gentry et al., 1984*]. For open pit mines having a high degree of saturation, these costs are a significant part of the company's operating costs. This affects the economy of the mining production unfavorably and the only way of reaching a positive economic result is to increase the production throughput of the mineral resource mined within the project production capacity of the pit and processing plant. In other words, the costs of dewatering considerably affect the economic mechanism of mining production.

Case study

Object of Investigation

The object of the present investigation is the 'Kremikovtsi' iron ore open pit mine in Bulgaria. The current exploitation of the ore deposit is characterized by a complex hydrogeological situation due to the presence of a large quantity of groundwater in the rock masses. The dewatering of the open pit mine is being done through a dewatering shaft and a system of vertical dewatering wells. The shaft is located in the north part of the pit in close proximity to the upper final contour of the mine. The dewatering wells are located on the periphery of the upper contour of the pit as well as on the bottom which has already reached its project depth [*Report, 1961*].

The pit region investigated is characterised by a variety of slope failure occurrences provoked by the impact of the surface and ground waters. This fact predetermines the importance of the problem of the stability of the slopes of the north pit wall.

The present investigation covers a representative region from the whole dewatering system of the 'Kremikovtsi' open pit mine located in the vicinity to the dewatering shaft. This region is served only by dewatering and monitoring wells (Figure 1).

The groundwater flow at the pit exploitation is due mainly to the static and dynamic resources of three aquifers. The first aquifer is bound to the material of Pliocene. The second aquifer covers the iron ore body and Middle-Triassic masses (T_2). Its borders coincide with the borders of the ore body. The tectonic clays and materials of Silurian and Tithonian represent the lower impermeable boundary of this aquifer. The materials of Pliocene lay transgressively over the rock masses, which form the second aquifer. Its recharging is made partly at the expense of the atmosphere waters that infiltrate through a restricted area (0.35 sq. km) of the opening at the surface Middle-Triassic limestones as well as from the first aquifer. The groundwater of the second aquifer is a fresh hydrocarbonate-magnesium-calcium water. The average assessment of the hydraulic conductivity of the second aquifer is 27.0 m/d. The third aquifer includes karstic limestones of Oxfordian and Kimeridgian, limestones and quartzites of Doger and Lias (Middle – J_2 and Lower Jurassic – J_1) as well as dolomites and clay limestones of the Middle Triassic. The aquitards are presented by hard sandstones of Lower Triassic (T_1).

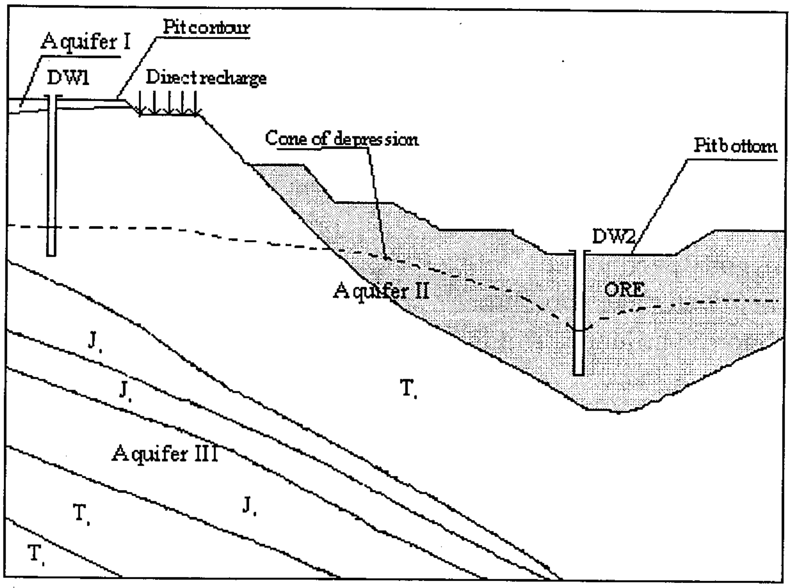

Figure 1: Hydrogeological Cross-section Through North-East Part of the "Kremikovsi"

The large quantity of groundwater and its high pressure makes the second aquifer difficult for exploitation and dangerous for underground mining engineering purposes. The existing hydraulic link of the three aquifers determines the necessity of their mutual dewatering which has to be in front of the mining operations. The recharging of the second aquifer is due to the infiltration of rainfall and outflow of the 'Kremikovtsi' river (through the alluvial masses) to the east of the ore deposit. There is a contact between the second aquifer and Pliocene sands.

The removal of the negative impact of the surface and ground waters on the open pit mine is achieved with a dewatering system which takes into account the accepted mining system for leading the mining operations.

The problem, which has to be solved in this case study, can be formulated in the following way: prediction of the lowering of the groundwater level in the active second aquifer in the north part of the 'Kremikovtsi' open pit mine due to the action of the local dewatering system, and investigation of the dewatering influence on the safety of the pit slopes. So formulated, the problem can be divided into two parts:

- prediction of the lowering of the groundwater level due to the action of the pit dewatering system;
- assessment of the stability of the pit slopes for natural and technologically dried states of the rock masses.

Technique for Groundwater Flow Prediction

The solution of the first part of the problem described above is made with a hybrid method of the boundary integral equation method and the finite element method [*Gabeva, 1992; 1995*]. The governing equation of the filtration process is the partial differential equation of Poisson, which describes in this case a 2-D steady state flow [*Liu, 1979; Lafe et al., 1981; Liggett, 1983;*]. This equation allows the prediction of the groundwater head in an isotropic geological environment due to the action of dewatering works (the so-called sources in the present formulation). The equation can be presented by the following way:

Equation 1:

$$T\nabla^2 H(x)+f(x)=0\,, \qquad x\in A$$

where: T is the aquifer transmissivity; ∇^2 is Laplace's operator; H(x) is the groundwater head; f(x) is the source function; A is the filtration domain; x is a point with (x_1,x_2) co-ordinates in the domain A, (Figure 2A).

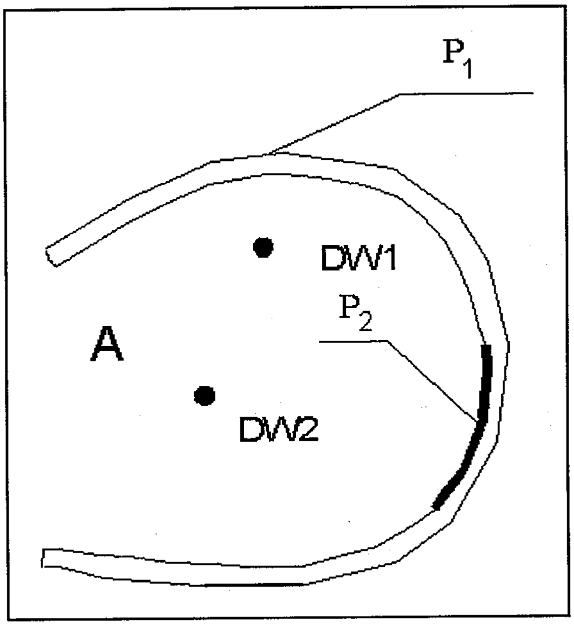

Figure 2A: Shematization of the Hydrogeological Conditions

The solution of equation (1) is achieved by fixing the corresponding boundary conditions, which characterise the filtration domain. The following boundary conditions are used:

Equation 2: $H(x)=\overline{H}(x),\quad x\in P_1$

Equation 3: $\partial H(x)/\partial n=-q_b,\quad x\in P_2$

where: $\overline{H}(x)$ is a given value of H(x) along the boundary P_1; P_1 is a portion of the boundary P; $\partial H(x)/\partial n$ is the normal deviate of the potential; P_2 is a portion of the boundary P ($P=P_1+P_2$).

Equation 2 represents Dirichlet's condition while equation 3 is Neumann's condition.

The external boundary problem is solved in a numerical way. The head function is predicted in the region restricted by the upper final contour of the open pit mine. The hydro-geological boundary (P) is located out of that contour. The schematization of this problem for the conditions of the 'Kremikovtsi' open pit mine is given in Figure 2A where the boundary P_1 is characterized by a constant water level and P_2 is characterized by a constant feeding of the aquifer. The water discharge sources are the wells DW1 and DW2 and the last one is located on the pit bottom.

Figure 2(B) illustrates the boundary integral equation and finite element grid for a 2-D model of the region investigated. The boundary P of domain A is given with 53 linear segments connecting the nodes from 1 to 53 in accordance with the requirements of the boundary integral equation method. The domain, where the function is searched for, is presented with a linear triangular grid connecting 50 nodes in 72 triangular cells and 113 points prediction. The assessments of the groundwater sources discharge are given in Table 1. The infiltration of the surface water is taken into account in all nodes of the model using an assessment of 0.000163 l/s.

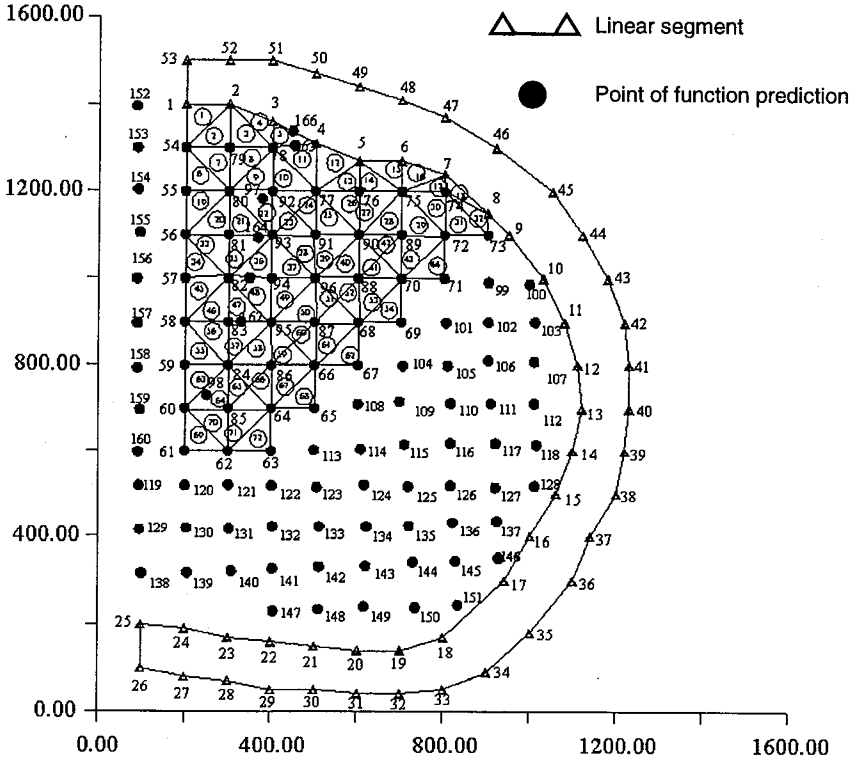

Figure 2B: Boundary Integral Elements and Finite Element Grid of the Investigated Region

The filtration medium within the outlines of the pit region is characterized with a transmissivity (T) of 520 m^2/d.

Computer Implementation

The computer code BIEMH is used for solving the above-formulated numerical model. The code is written in FORTRAN 77 and is built on a module principle. [*Gabeva, 1993*]

Example Solution

Four variants for predicting the groundwater levels are solved with the use of input data for the hydro-geological parameters that are given in Table 1.

Variant No	Coefficient Hydraulic conductivity m/d	Discharge dewatering well DW1 L/s	Discharge dewatering well DW2 L/s
I	16,8	0	0
II	16,8	22,68	19,80
III	16,8	35,00	28,00
IV	16,8	50,00	40,00

Table 1: Input Data of the Model

For example, the results obtained from the solution of the variant III are interpreted graphically in Figure 3A which represents a map with isohypses of the pit region. A 3-D presentation of this solution is demonstrated in Figure3B. These figures give a clear notion about the location of the cones of depression of the groundwater level which are modelled while taking into account the operating characteristics of the dewatering wells.

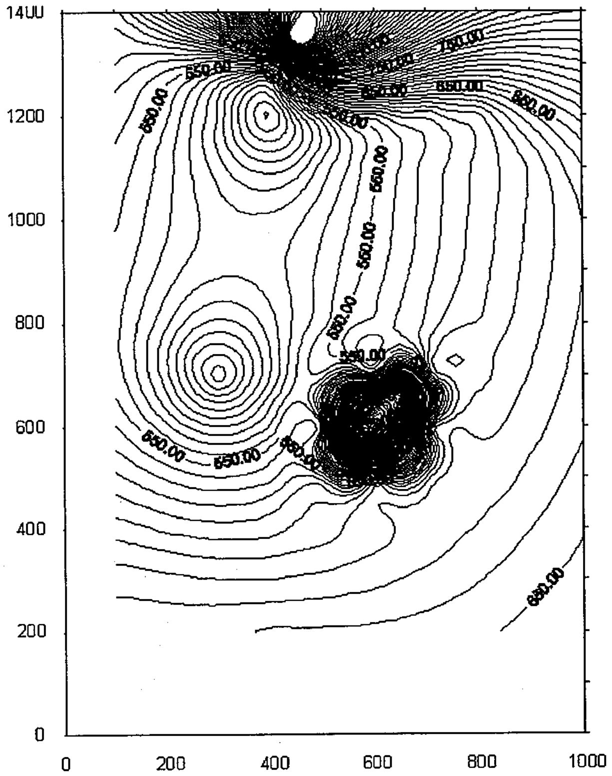

Figure 3A: Hydroisohyps Map

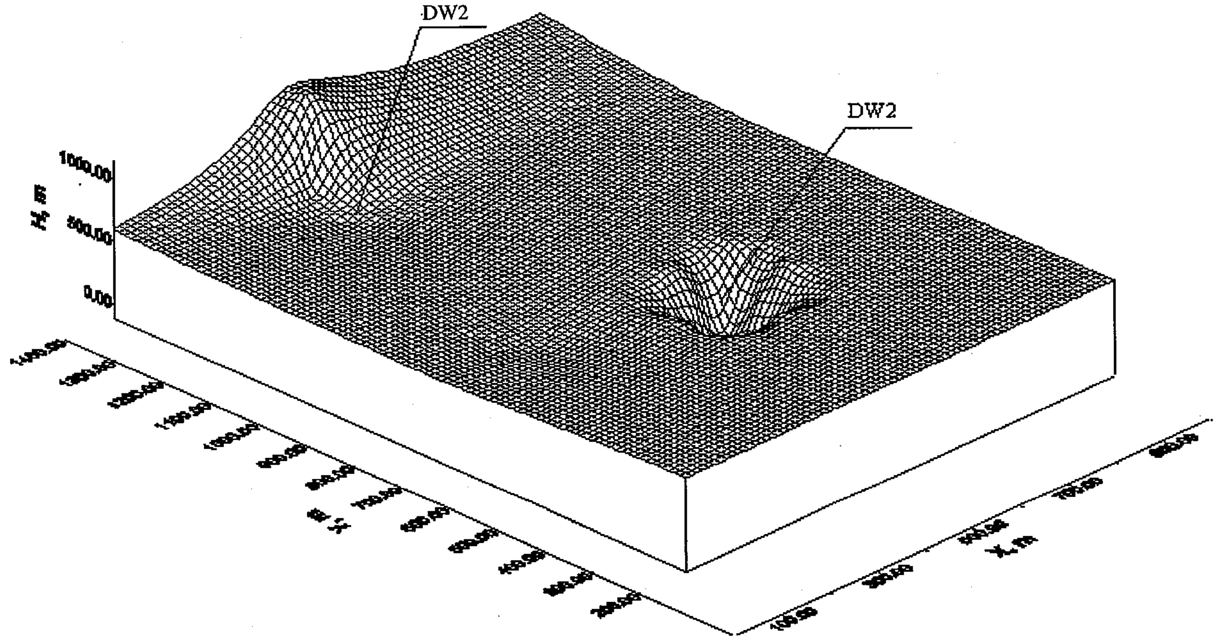

Figure 3B: 3-D Visualization of the Solution - Variant III

The predicted groundwater levels of the variants I, II and III are drawn in a cross-section passing through the two dewatering wells in Figure 4. This figure shows the slopes of the working and final wall of the pit, which are the objects of the present geomechanical investigation.

The angle of the working slope is 22 degrees and the one of the final pit wall is 30 degrees. The assessment of the stability of the two slopes is made with the computer code PROBSAR which realizes the modified variant of Sarma's method [*Halatchev et al., 1998*].

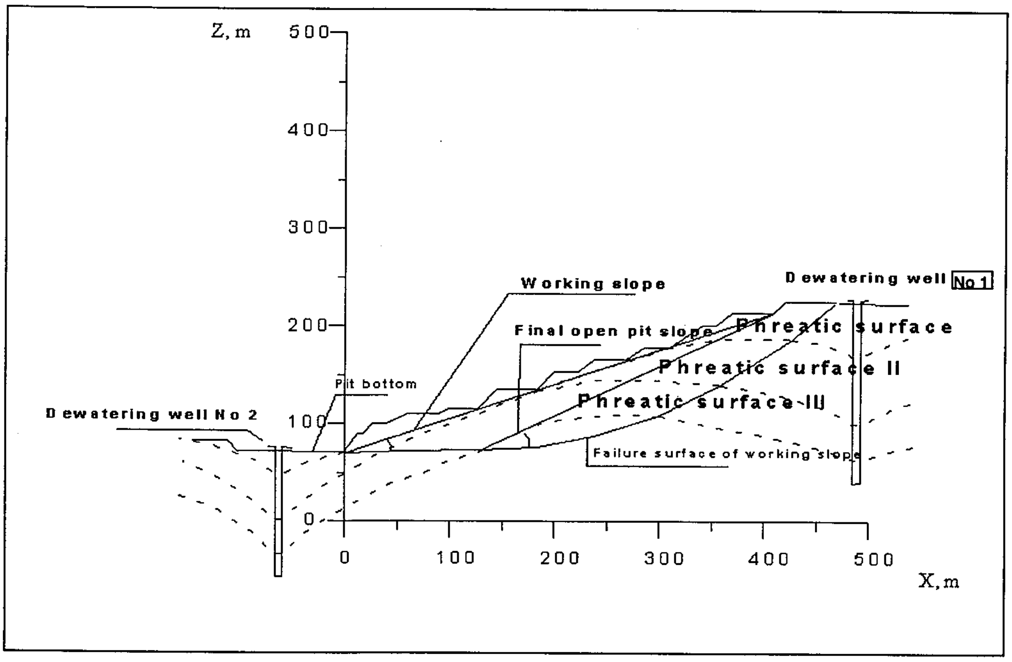

Figure 4: Scheme of the Investigated Slopes

The results obtained for the factor of safety of the slopes with regard to the variants of the groundwater prediction are graphically interpreted in Figure 5.

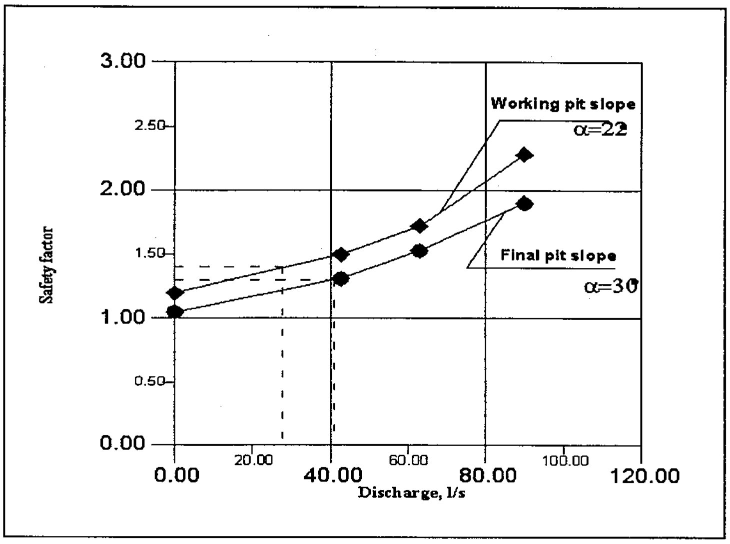

Figure 5: Safety Factor vs. Discharge

Its analysis allows the conclusion that the stability of the working slope is warranted for all variants of the groundwater lowering. The factor of safety of this slope varies within the range of 1.20 to 2.32 which corresponds to the estimates of the common pumping from 0 l/s to 90 l/s. In order to guarantee the working slope stability, for which the standard stability reserve is 40% due to not taking into account some subjective factors at the assessment of the stability, the dewatering system must pump a minimum quantity of 27.61 l/s. The factor of safety of the slope of the final pit wall varies within the range of 1.05 to 1.90 for the corresponding variants of groundwater pumping. For this slope, which will be formed after the completion of the mining operations on the working slope, the standard stability reserve is 30% and it determines the common minimum discharge of 41.15 l/s in the figure.

Generally, from the analysis of the results presented, we can conclude that without dewatering of the 'Kremikovtsi' open pit mine it is impossible, first – to provide normal working conditions for doing mining operations, and second – to guarantee the slope stability. If dewatering is not applied then the only alternative to guarantee the slope stability is to design them with smaller slope angles, which will reflect negatively on the economy of the mining company.

Conclusions

1. The hydrogeological conditions are a natural reality and pit design taking them into account must be based on a well-based scientific approach. In the context of the pit design, the hydrogeological factor has an economic, social and ecological dimension.
2. The numerical approach suggested for modelling the groundwater level is characterised by a wide range of a practical application as it allows the incorporation of the variety of specific hydrogeological conditions and their interaction with different dewatering equipment.
3. The results obtained from the example case study confirm the importance of the hydrogeological factor in the exploitation of open pit mines and are a proof of the effectiveness of the applied research approach.

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