PREDICTION OF GROUNDWATER INFLOW AND HEIGHT OF THE SEEPAGE FACE IN A DEEP OPEN PIT MINE USING NUMERICAL FINITE ELEMENT MODEL AND ANALYTICAL SOLUTIONS

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Abstract
Whenever a mine is operated below the water table, water inflow occurs from the surrounding layers towards the mining excavation. In order to design an effective drainage scheme for a open pit mine, prediction of water inflow into the pit is essential. This paper presents a finite element model using SEEP/W software for prediction of groundwater inflow into a deep open pit. This model is capable to consider the saturated/unsaturated flow, confined/unconfined aquifer, and can determine the height of the seepage face at pit walls. The results of the numerical model are compared to those from analytical solutions.

Introduction
The depletion of shallower deposits has led to a considerable increase in the economic working depth of open pit mining. As a consequence, many surface mining operations are now being carried out below the ground water table. Excavation of a large open-pit mine below the water table can create a number of water-related problems that affect the operational efficiency and economic viability of the mining operation (Doulati Ardejani et al., 2003a). The unexpected water flows in large scale may reduce the production, delay the time of execution and danger the total mine safety (Hanna et al., 1994). When a pit penetrates in an aquifer, the significant amounts of groundwater flow occur to a pit. Therefore, the large volumes of water must be pumped to provide a dry mining condition (Doulati Ardejani et al., 2003b). Figure 1 shows the water inflow components into a pit.

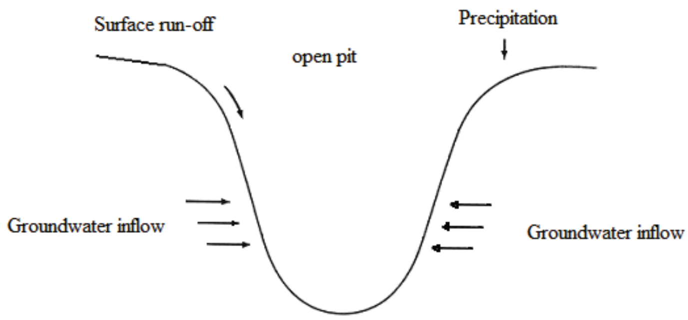

Figure 1. Inflow components into an open pit.

Recognition of groundwater regime in around of an open pit and hydraulic properties of layers in the mine vicinity is important to control water inflows to mine. To design an effective dewatering system for an open pit mine, the modelling of water related problems and prediction of water inflow into a pit is necessary.
The results of such simulations would be used to develop an appropriate water management strategy in order to minimise the operational problems below the water surface and long-term environmental problems, in the feasibility stage of mine design.
In mining operations carrying out below the water table, mine operators are potentially faced with two important water-related problems. These are the amount and pressure of groundwater that could flow into an open pit and the effect of pore water pressure on the stability of an open pit high wall (Azrag et al., 1998). Many analytical solutions for prediction of water inflow into mine excavations can be found in the literature (Hanna et al., 1994; Shevenell, 2000; Singh and Atkins, 1985a, b; Marinelli and Niccoli, 2000); these models often were developed based on some very specific assumptions and boundary conditions that restrict their applicability in many mining situations. The prediction of the amount of water inflow into a pit is very important for development of a mine dewatering program. Moreover, taking into account that the analytical solutions are not as versatile as numerical methods, which can deal with complex mining situations, so, it is necessary to develop a numerical model that includes all aquifer conditions (Doulati Ardejani et al., 2003b). Numerical models have not the limitations of

analytical solutions and they are suitable for the simulation of all aquifer conditions. Furthermore, numerical models can provide a more realistic representation of the interaction between groundwater systems and mine excavations.
In this paper, a numerical finite element model using SEEP/W software (Geo-Slope International Ltd, 2006) is presented, that is capable to predict the water inflow and estimate the height of the seepage face in a deep pit. SEEP/W model is able to analyse different flow conditions such as saturated/unsaturated flow, confined/unconfined aquifer in a two-dimensional situation.

Methodology

1. Governing equation of inflow model

The governing partial differential equation for a two dimensional saturated/unsaturated flow condition can be obtained by coupling the Darcy's law and continuity equation (Freeze and Cherry, 1979) as given below:

$$\frac{\partial}{\partial x}(K_X \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) = C\frac{\partial}{\partial t}(h) + Q \quad (1)$$

where, K_x and K_y are the hydraulic conductivities in the X and Y directions respectively, Q is the recharge or discharge per unit volume, H is the hydraulic head and t is the time.
The hydraulic head is correlated to the volumetric water content (θ) using the following equation:

$$\frac{\partial \theta}{\partial t} = C\frac{\partial h}{\partial t} \quad (2)$$

where C is the slope of the water storage curve.

2. Solution method

To solve Equation1 using finite element method, the SEEP/W model utilises the Galerkin approach to determine an approximate solution. Further details on the Galerkin formulation can be found in Pickens and Lennox (1976), Pinder and Frind (1972) and Pinder (1973).

Results and Discussion

1. Model design

Figure 2 shows a finite element model for a partially penetrated pit in an unconfined aquifer. This model consists of 1424 nodes, 1321 elements and 20 layers each 50 m thick. The saturated permeability of unconfined aquifer is $1\times10^{-6} m/s$ and the thickness of saturated zone of the aquifer is 800 m.
A two-dimensional simulation was performed under steady state flow condition and with 500 iterations. The following boundary conditions were assigned in the model:

- No-flow boundary condition in bottom boundary of the model;
- Fixed head boundary condition equal to 800 m at the outer boundary (left and right sides of the model);
- Fixed head boundary condition equal to 250 m at pit bottom.
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As it is evident in Figure 3, the hydraulic conductivity is given as a function of pore water pressure in order to simulate the saturated and unsaturated conditions in an unconfined aquifer.

2. Prediction of groundwater inflow and height of the seepage face in a deep open pit

Figure 4 shows the SEEP/W results for prediction of groundwater inflow into a deep open pit mine. The velocity vectors, iso-potential lines, flow paths and water table are illustrated. The model calculated the amount of groundwater inflow and height of the seepage face around the pit wall equal to 2.17 m^3/s and 77 m respectively.

3. Model verification

In order to verify the finite element modelling of groundwater inflow to a deep open pit mine, two analytical equations were used.
The first analytical equation was presented by Vandersluis et al. (1995). This equation is used in arid and semi-arid areas where precipitation is generally limited and water inflow to a pit in an unconfined aquifer is normally controlled by horizontal groundwater inflow.

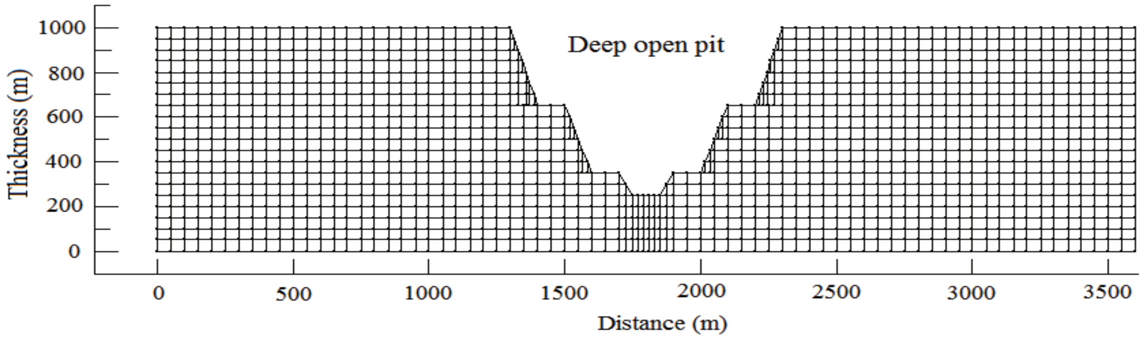

Figure 2. Finite element mesh for a deep open pit in an unconfined aquifer.

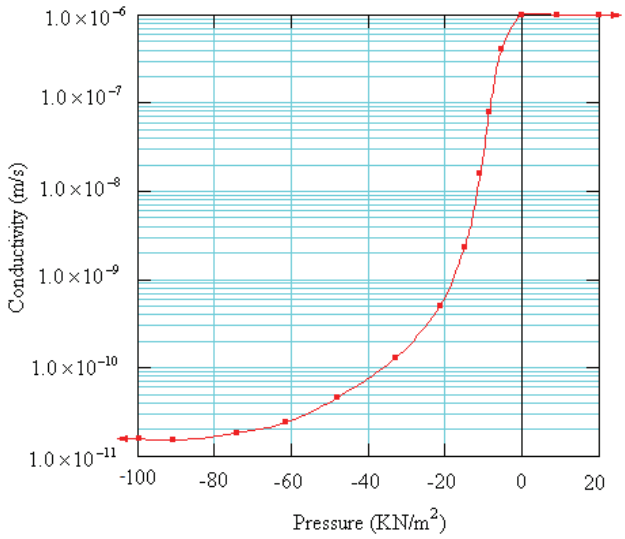

Figure 3. Hydraulic conductivity as a function of pore water pressure.

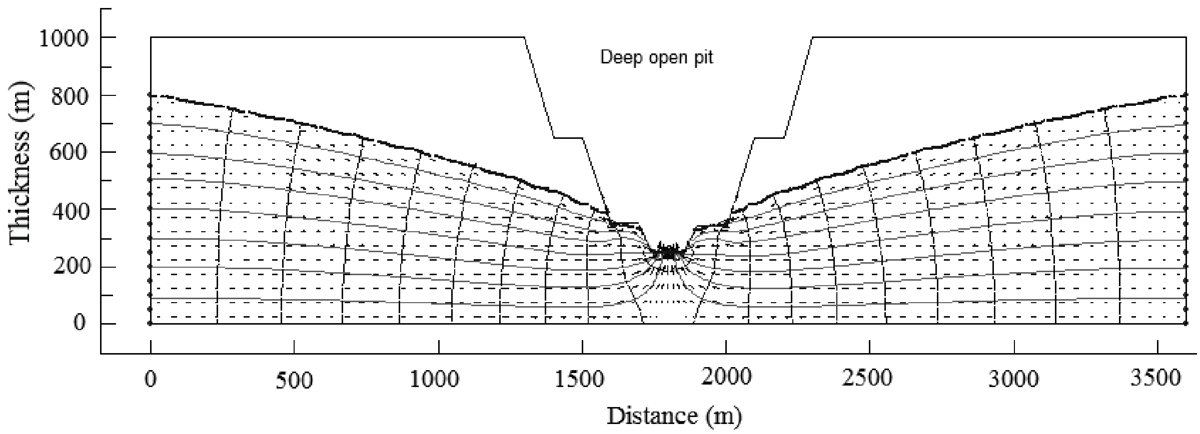

Figure 4. The results of two-dimensional modelling for a deep open pit mine in an unconfined aquifer.

Analytical Equation presented by Vandersluis et al. (1995):

$$Q = \frac{1.366 \times K(2H - \Delta h)\Delta h}{\log(R + r_0) - \log r_0} \tag{3}$$

The second analytical equation quoted in Krusseman and De Ridder (1979) and Singh et al. (1985) is based on well hydraulics and can be used for estimation of steady state inflow rate to an open pit mine. This equation was derived from Thiem-Dupuit equation and can be applied for unconfined aquifer.
Analytical Equation presented by Krusseman and De Ridder (1979) and Singh et al. (1985):

$$Q = \frac{\pi K(H^2 - h^2)}{\ln(\frac{R}{r_p})} \qquad (4)$$

The radius of influence R is reduced to:

$$R = 5755(HK)^{0.5} \qquad (5)$$

In above equations:
Q = groundwater inflow (m^3/day);
K = permeability of the unconfined aquifer (m/day);
H = potentiometeric surface or initial water table elevation (m);
R = radius of influence (m);
r_0 = reduced radius of the open pit by level (m);
h = potentiometric surface elevation at a specific point (m);
r_p = radius of the pit at the desired level (m);
Δh = drawdown at the desired level (m).
Taking into account R = 1750 (m); r_0 = 50 (m); $K = 4.3\times10^{-6}$ (m/s); H = 800 (m); h = 250 (m); Δh = 550 (m); r_p = 50(m) and $T = 2365\times10^{-6}$ (m^2/s); the amount of Q was calculated using analytical Equations 3 and 4. A comparison of the inflow rate predicted by the SEEP/W model and calculated by the analytical Equations 3 and 4 are presented in Table 1. As it is evident from Table 1, the calculated errors in related to the analytical Equation 4 is less than 1 %.

Table 1. Comparison of results of the SEEP/W model and analytical solutions.

model	Q (m^3/s)	Height of the seepage face (m)	Error (%)
SEEP/W	2.17	77	0. 91
Analytical equation (3)	2.18	-------	0.46
Analytical equation (4)	2.19	-------	-------

Conclusions
Presence of water in open pit mines causes a many environmental, operational and safety problems. This paper presents a finite element model by the use of SEEP/W software for prediction of groundwater inflow and height of the seepage face in a deep open pit. The inflow predicted by the SEEP/W model was evaluated and verified by comparing with results obtained from two analytical solutions. It was found that the finite element model could successfully predict the height of the seepage face around a deep open pit walls excavated in an unconfined aquifer. The results of inflow estimation can provide significant information for designing an effective dewatering system.

Acknowledgements
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