Hydrogeological Investigations in Sangan Iron Mine, Iran, to Control Groundwater Problems: Mathematical Modelling and Field Study

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Abstract
Designing an appropriate dewatering system at the early stages of mine planning is important in managing and controlling groundwater inflow into big open pit mines. To better design a dewatering system, it is necessary to investigate the hydrodynamic parameters of the aquifer involved with the mining operation. Such investigations are also important for the prediction of post-mining pit lake formation and mine drainage quality control. A series of pumping tests was carried out at Sangan iron mine, Mashhad, Iran, in order to determine the transmissivity and storativity of the confined aquifer. The pumping data were first evaluated with analytical Theis and Cooper-Jacob equations. An axi-symmetric finite element software, SEEP/W, was used to simulate transient, radial flow to a fully penetrating well in the confined aquifer. The groundwater recovery pattern was also considered in the numerical model. Analytical solutions and field data were used for the evaluation of the numerical model predictions. The results show a close agreement between three methods. The error of modelling is less than 3 percent. This model predicts realistic results that can be used by mine operators and environmental engineers to control water problem in large open pit mines.

Key words: Groundwater, numerical modeling, dewatering, Sangan iron mine, confined aquifer, inflow, recovery

Introduction
The exploitation of minerals and its associated activities have direct and indirect influences on many environmental elements (Keqiang et al. 2006). During mining, groundwater inflow and the impacts of groundwater drainage, such as regional lowering of the water table, overlapping cones of depression, subsidence, and water quality deterioration are environmental problems that endanger mining production and human life. Effective prevention of water inflow, timely determination of the mechanism of water bursts, and reasonable design of drainage plans are the most urgent mining challenges. Open-pit operations carried out below the water table can create a number of water-related problems (Azrag et al. 1998). Water inflow from the surrounding strata towards the mining excavation will require installation of dewatering facilities to keep the mine workings dry. In order to design an effective dewatering system for a surface mine, estimation of water inflow into the pit is essential (Singh et al. 1985; Doulati Ardejani et al. 2003; Aryafar et al. 2007).
Operation of a dewatering program in a surface mine causes considerable hydrological stress on the regional groundwater flow system around the mine due to the creation of an extensive and prolonged cone of depression. When the mining operation is closes and the pumping operation has ceased, the surrounding water will continue to flow towards the mine until it reaches to its pre-mining equilibrium condition (Doulati et al. 2007). Prediction of water inflow is a necessary aspect of assessing the long-term hydrological impact and provides useful information for environmental studies (Naugle and Atkinson 1993). To establish a dewatering system, it is necessary to investigate the hydrogeological characteristics of the aquifer involved with the mining operation. Such investigations are also important for the prediction of post-mining pit lake formation and mine drainage quality control. In the present research, pumping data obtained from a fully penetrating well in a confined aquifer at Sangan iron mine, located 280 km southeast of Mashhad, Khorasan Province, Iran, were used.

Methods

A two-dimensional groundwater flow model called SEEP/W (Geo-Slope International Ltd. 2007) was slightly modified to simulate dewatering and recovery in a fully penetrating well in a confined aquifer at Sangan Iron Mine. The results obtained from such simulations provide valuable information for modelling of the dewatering program and post-mining recovery process associated with Sangan open pit mine. This software solves the governing equation for the two-dimensional groundwater flow by considering both saturated and unsaturated flow conditions in the following form (Freeze and Cherry 1979):

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

where K_x and K_y are the hydraulic conductivities in the x and y directions respectively, Q is the boundary flux, h is the hydraulic head, t is time. This model can simulate heterogeneous hydraulic properties such as hydraulic conductivity and storage coefficient in an isotropic and heterogeneous flow system (Doulati and Singh 2004).

Results and discussion

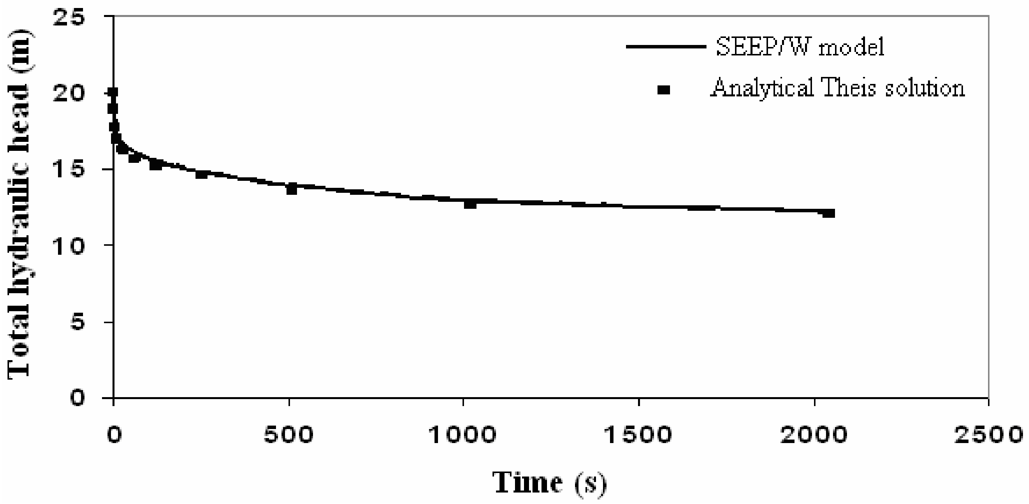
Model calibration

In calibrating the numerical model, a dewatering test in a hypothetical confined aquifer was used. The total hydraulic head predicted by the SEEP/W model was compared to the head calculated using the Theis analytical solution. The aquifer has three layers, the hydraulic conductivities of which, from bottom to top, were 0.0007, 0.0006 and 0.0008 m/s respectively. The aquifer has an average storage coefficient of 0.0001. The initial potentiometric elevation in the aquifer was 20 m. The thickness of each layer was 4 m. The pumping rate was $0.1\, m^3/s$. The well radius was 0.2 m.

To solve the problem numerically, a finite element mesh consisting of 62 nodes, 30 elements and 3 layers each 4 m thick was constructed. An axisymmetric analysis was used for the simulation. To consider the transient dewatering process 10 time steps (2, 6, 14, 30, 62, 126, 254, 510, 1024, 2046 s) were used.

No–flow boundary conditions were assigned to the top and bottom boundaries of the model to describe impermeable layers in the aquifer. A fixed head boundary value equal to 20 m was specified at the right-hand side of the grid (outer boundary). A flux boundary value equal to 0.00663 m/s was considered at the left side, next to the well simulating the pumping rate. Figure 1 compares total hydraulic head predicted by the SEEP/W model with that obtained by the Theis equation, showing an error less than 1%.

Figure 1 *Comparison of total hydraulic head predicted by SEEP/W model (line) and calculated by the Theis method (dots) at the well axis*

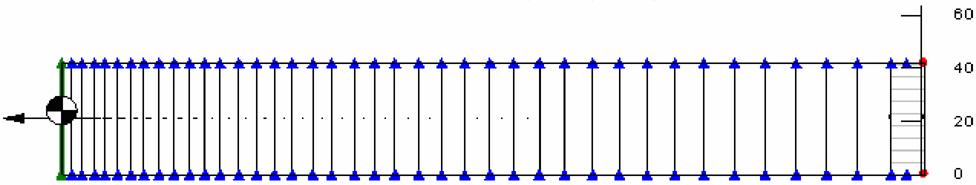


Model prediction

After calibration, the numerical model was run to simulate both dewatering test and recovery processes of a fully penetrating well in the confined aquifer associated with the Sangan iron mine. The initial potentiometric surface (from sea level), hydraulic conductivity, storativity, well radius, thickness of aquifer, transmissivity of the aquifer and pumping rate were 1024.75 m, 0.000093 m/s, 0.000278, 0.3048 m, 43 m, 343.95 m^2/day and 3120 m^3/day respectively. These parameters were applied in the simulation.

For numerical modelling of the dewatering test, a finite element grid was constructed with 40 elements and 82 Nodes in a single layer of 43 m thick (Figure 2). An axisymmetric simulation was considered for this problem. The number of time steps was 32.

Figure 2 *Finite element grid of the problem*



The following initial and boundary conditions were applied to the model:

- Initial condition: steady state modelling was first performed to establish an initial condition. The head at the two ends of the aquifer was set as 1024.75 m.

To perform a transient analysis, different types of boundary conditions were considered:

- A flux boundary at the left side of the model next to the dewatering well
- No-flow boundary conditions at the upper and lower boundaries of the aquifer in order to simulate a confined aquifer, and
- A head boundary value equal to 1024.75 m at the outer boundary of the model (right side)

The results obtained using Theis analytical solution and those predicted by the SEEP/W model were compared to the field data. A close agreement was obtained between the three methods (Table 1).

Table 1 *Comparison of field, numerical and analytical drawdown at the axis of well No. 2w of Sangan iron mine*

Method	Drawdown (m)	Relative error (%)
Field data	4.83	-
SEEP/W model	4.90	1.44
Theis solution	4.94	2.27

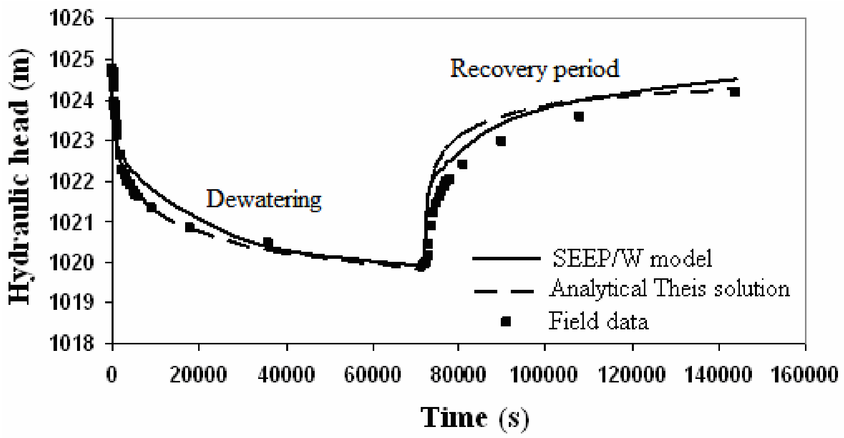
A finite element analysis was also performed to consider the transient well recovery period. 20 time steps were used for this process. The final estimation of the groundwater level calculated during the well dewatering modelling was used as an initial condition for the simulation of the recovery process. No–flow boundary conditions were specified at the upper and bottom boundaries of the model. A fixed-head boundary value equal to 1024.75 m was specified at the right-hand side of the grid. Table 2 shows the residual drawdown calculated by different methods and the relative error.

Table 2 *Comparison of field, numerical and analytical residual drawdown at the axis of well No. 2w of Sangan iron mine*

Method	Residual drawdown (m)	Relative error (%)
Field data	5.24	-
SEEP/W model	5.1	2.67
Theis solution	5.44	3.81

Comparison of the drawdowns and residual drawdowns predicted by the SEEP/W model, calculated by the Theis analytical solution, and observed in field data related to well No. 2w of the Sangan iron mine are shown in Figure 3.

Figure 3 *Comparison of drawdowns and residual drawdowns predicted by SEEP/W model, calculated by Theis solution, and field data related to well No. 2w, Sangan iron mine, at the well axis*



Conclusion

To design an appropriate dewatering system, it is necessary to investigate the hydrodynamic parameters of the aquifer involved in the mining operation. In this research, an axisymmetric finite element model called SEEP/W was used to simulate transient, radial flow to a fully penetrating well in a confined aquifer at Sangan iron mine. The ground water recovery pattern was also considered in the numerical model. Comparison of the results obtained using different methods show a good agreement. The results of inflow and recovery simulations can provide significant information for designing mine dewatering system and water pollution prevention schemes.

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