Mine Water and the Environment (2003) 22: 39–44 © IMWA Springer-Verlag 2003

Technical Article

A Finite Element Model to: 2. Simulate Groundwater Rebound Problems in Backfilled Open Cut Mines

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Abstract. A two-dimensional finite element software called SEEP/W can be easily modified to simulate the groundwater rebound process within the spoil of an open cut mine taking into account saturated and unsaturated flow, hydraulic conductivity, and water content (as a function of pore-water pressure). Flexibility in the model is achieved by assigning different boundary conditions. In this paper, the results of the numerical model of the ground water rebound are presented and compared with those obtained from analytical solutions, another numerical model, and with data measured at the Horsley backfilled site in the UK. This model calculates realistic results that can be used by mine operators and environmental engineers to control the quality of mine drainage in a backfilled open cut operation.

Key words: Backfilled open cut mine, finite element method, groundwater rebound, Horsley opencast mine

Introduction

The depletion of shallower deposits and improvements in mining techniques have led to a considerable increase in economic working depths in open cut mines. Surface mining can now be carried out well below the groundwater table. However, associated water-related problems can affect the operational efficiency and economic viability of the mining operation. Abandonment, groundwater rebound due to cessation of dewatering, and associated pollution issues are also serious problems associated with open cut coal mining (Henton 1981) and sulphide ore mines. If the effects and magnitude of a water-related problem can be properly identified in advance of mining, appropriate water management strategies can be undertaken to minimize the socio-economic and environmental impacts of mine dewatering.

Dewatering of surface mines during mining operations can place considerable hydrological stress on the regional groundwater flow system. When mining is completed and the dewatering operations have ceased, the water table rebounds. The rising groundwater saturates the mine spoil, which may be contaminated with pyrite-oxidation products. Prediction of post-mining water table elevation within the mine spoil is important so that the adverse effects can be countered with an appropriate addition of alkalinity to the backfill and special re-handling techniques.

Numerical groundwater flow models can be used to predict groundwater rebound after mining (Henton 1981; Norton 1983; Naugle and Atkinson 1993; Vandersluis et al. 1995; Davis and Zabolotney 1996; Shevenell 2000).

Groundwater Model

Predicting inflow to an open cut mine during mine extensions and estimating the groundwater rebound at backfilled open cut mines are among the more complex problems encountered in mining operations. Predicting the configuration of the ground water table and the height of the seepage face in highwalls for slope stability analysis is also very important. Problems concerning groundwater flow in partially saturated porous media are relatively difficult to model for cases involving highly nonlinear ground characteristics. In particular, it is difficult to assign to the model the highly sensitive behavior of unsaturated field variables such as hydraulic conductivity, specific storage and atmospheric boundary conditions associated with the seepage face, infiltration and evaporation.

Due to the limitations of the most common groundwater flow codes in dealing with these problems, a two-dimensional finite element software called SEEP/W (Geo-slope International Ltd 2002) has been modified to predict post mining groundwater rebound within the spoil of a open cut mine.

Governing equation of groundwater rebound model

As discussed in the preceding paper, the governing equation for the two-dimensional groundwater flow incorporating both saturated and unsaturated conditions can be expressed as follows (Freeze and Cherry 1979):

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)=C_{uw}\frac{\partial h}{\partial t}-W \qquad (1)$$

where K_x and K_y are components of the hydraulic conductivity tensor in the x and y directions respectively, W is the recharge or discharge per unit volume, t is the time, C_{uw} is the slope of the water storage curve and h denotes the hydraulic head.

Groundwater Rebound Model

Final measurements of the groundwater table elevations made during the mine dewatering program were used as an initial condition for the transient simulations of the groundwater rebound after mining. For prediction of groundwater rebound within spoil, it was necessary to assign new hydraulic characteristics to those parts of the model elements that represented excavated rock as well as backfilled materials. A finite hydraulic conductivity value was assigned to the part of the model that represents excavated rocks and spoil (Naugle and Atkinson 1993). Hence, the predicted groundwater elevations were different in the spoil at the edges and the centre of the excavation. To reduce the error in the predicted water table elevations within the spoil and the pit, the permeability was modified to a value that would minimize the differences of water table levels. The hydraulic conductivity of backfilled material was assigned about two orders of magnitude greater than that of the unmined strata. The following aquifer characteristics were the main input parameters:

- Initial potentiometric heads and rainfall data
- Saturated thickness
- Hydraulic conductivity and transmissivity
- Specific yield and porosity

A flowchart (Figure 1) summarizes the groundwater rebound modelling procedure in an open cut mine.

During model calibration, sensitivity analyses were performed to consider the parameters that most affected the simulation results. Transmissivity and storage coefficient appeared to be the most sensitive of the input parameters. Davis and Zabolotney (1996) have reported the same results during the sensitivity analyses of groundwater modelling for the determination of post mining recharge rates at the Belle Ayr mine. The present model results were compared with the analytical Theis solution and a close agreement was achieved.

Model verification

Three problems are described to verify the numerical modelling of groundwater rebound after mining:

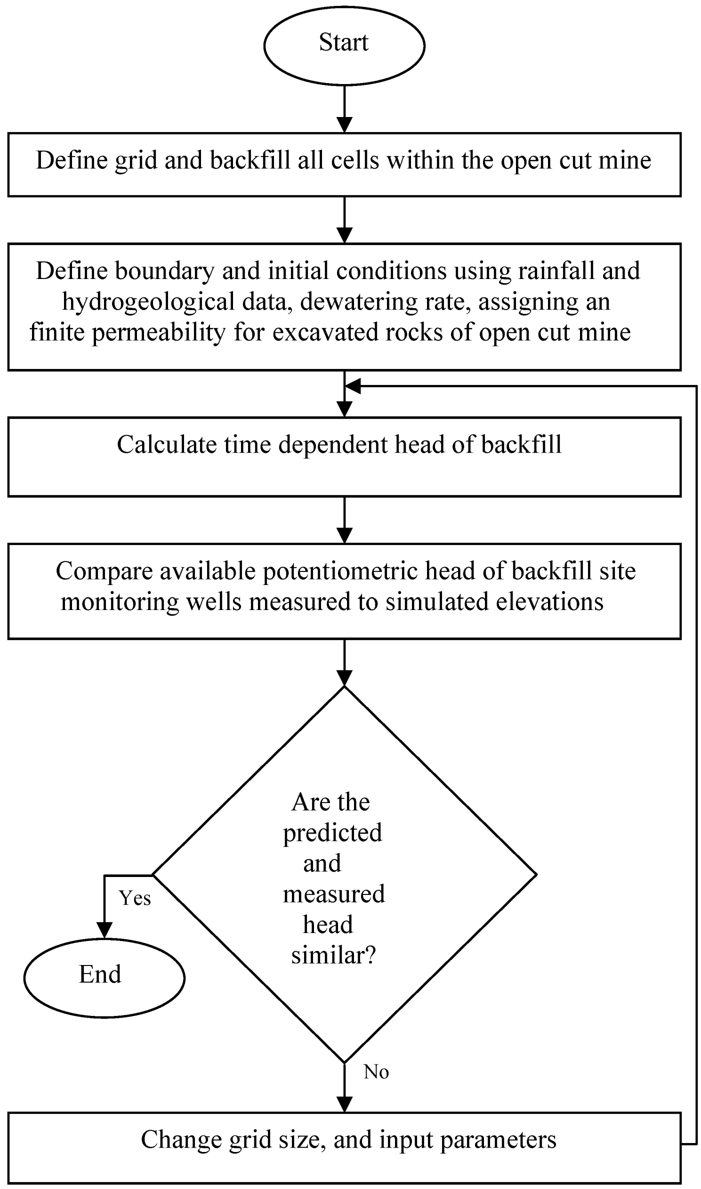


Figure 1. Flowchart of groundwater rebound

Problem 1—Dewatering simulation in a confined infinite aquifer

This first problem is modelled to compare the results of a dewatering test in a confined infinite aquifer under transient conditions using an analytical solution incorporating the Theis equation (Walton, 1970; Watson and Burnett 1993) with the numerical model. The recovery period has been taken into consideration. An axisymmetric analysis was used to simulate radial flow to a well. The total hydraulic head in the aquifer was taken as 15m. The aquifer had a hydraulic conductivity of 2.0 x 10^{-3} m/s and a storativity of 0.06. The dewatering rate was 0.12 m^3/s and the well radius was 0.15 m. The first part of the simulation was mostly taken from the SEEP/W user's manual (Geo-slope International Ltd. 2002) but it was slightly modified.

To solve the problem numerically, a finite element grid was considered with 126 nodes and 45 elements in a single layer 5 m thick. The rectangular grid consisted of eight-noded elements with an infinite element at the right end of the model. The length of the grid was 45 m. Figure 2 shows the finite element grid for the problem where 11 time steps were used for the simulation. From time steps 1-7, an increment of 10 seconds and expansion factors of 2 up to a maximum increment size of 900 seconds were used.

The increment size was changed for the remaining time steps. A steady-state simulation was performed to establish initial conditions. The head at the two ends of the aquifer was set as 15 m. This will generate a uniform total head distribution of 15 m throughout the aquifer. The model for this part of the analysis was used as the initial condition. The following boundary conditions were considered for transient simulation:

- no-flow boundary conditions at the upper and lower boundaries of the aquifer
- a head boundary at the right side of the model and
- a flux boundary at the left side next to the dewatering well.

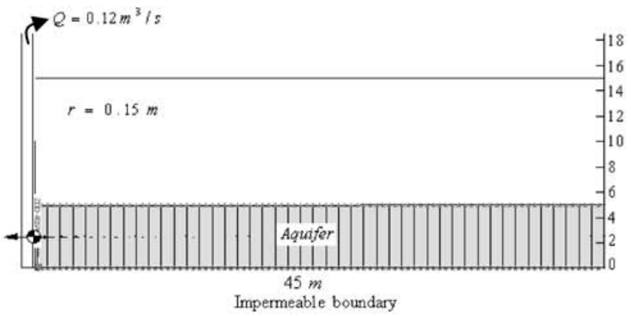


Figure 2. Finite element representation of the problem

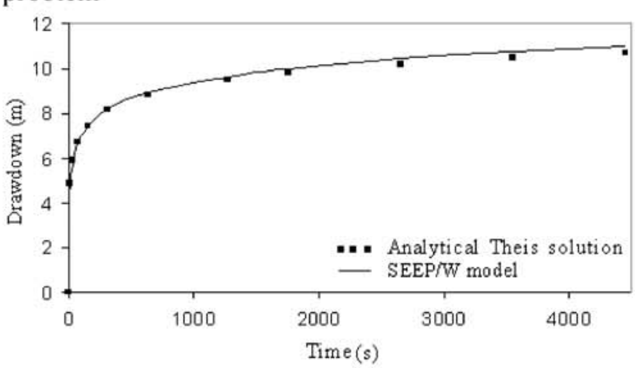


Figure 3. Comparison of drawdown predicted by numerical method and calculated values by the Theis method at the well axis

The drawdowns calculated by analytical solution were compared with those predicted by the numerical model in Figure 3, showing an error of 0.42 %.

An analytical solution was used to compute the recovery of a well after dewatering has stopped. This analytical solution was presented by Theis (Kruseman and De Ridder 1979). The equation calculating the residual drawdown during the recovery period is:

$$h = \frac{Q}{4\pi Km}\left\{\ell n\left(\frac{4Kmt}{r^2 S}\right) - \ell n\left(\frac{4Kmt_1}{r^2 S_1}\right)\right\} \quad (5)$$

where t_1 = time since pumping stopped (s); S_1 = coefficient of storage during recovery; m = thickness of the aquifer (m); S = coefficient of storage during pumping; r = radius of the pumped well (m); t = time since pumping started (s); Q = dewatering rate (m^3/s); K = permeability of the aquifer (m/s); and h = residual draw-down or rebound (m)

This equation assumes that the rate of recharge is constant and equal to the mean rate of discharge during dewatering. This means that draw-down variations resulting from slight differences in the rate of discharge do not occur during the recovery period (Kruseman and De Ridder 1979).

The Theis recovery method also assumes that conditions and assumptions of the Jacob method are satisfied. The final predictions of groundwater elevations calculated during the well dewatering simulations were used as the initial conditions for transient simulation of the recovery period. The following boundary conditions were set for transient simulation of the recovery period:

- no-flow boundary conditions for the upper and lower boundaries of the aquifer and
- head boundary conditions at the right side of the model (outer boundary).

Based on the sensitivity analysis made of the hydraulic characteristics of the aquifer, a close agreement was achieved between the analytical results and the numerical predictions of the residual drawdown for a permeability of 2.0 x 10^{-3} m/s and a storage coefficient of 0.05 (Figure 4).

Problem 2—Simulation of groundwater recovery in an idealized pit

Results from the SEEP/W finite element model were then compared to those from a numerical finite element model of groundwater recovery in an open pit after mining (Naugle and Atkinson 1993). Only the recovery period of their first example was selected for verification of the model using the SEEP/W software. In that problem, pit radius, transmissivity, and specific storage were 150 m, 120 m^2/day, and 0.001 respectively.

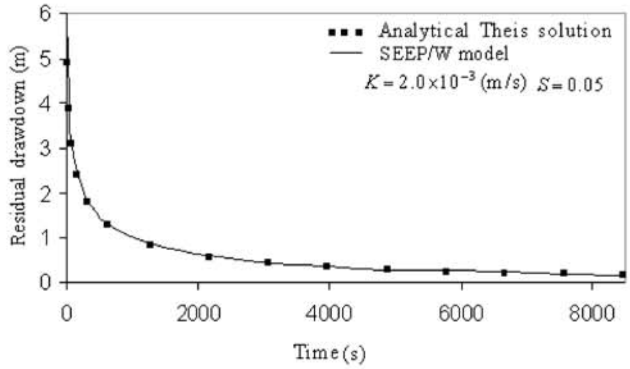


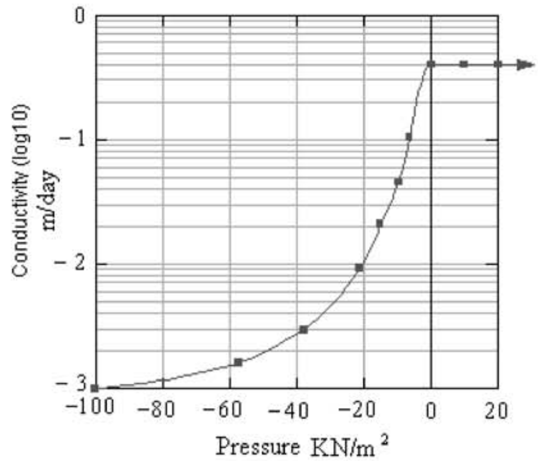
Figure 4. Comparison of analytical and numerical residual draw-down as a function of time (calculated error 3.58%)

A finite element axisymmetric grid consisting of 2501 nodes, 2400 elements, and 40 layers (each 10 m thick) was constructed. A finer grid was designed near the pit while the grid was coarse at the far end from the pit (the grid spacing increases from the pit to the outer boundary). A constant head of 300 m was maintained at the outer boundary while the head in the pit was adjusted to 50 m. A no-flow boundary condition was maintained at the lower boundary of the aquifer. A model representing the final stage of dewatering was simulated incorporating the boundary conditions. The second phase of simulation concentrated on the post-mining effects on the hydrologic system. The final estimates of groundwater elevations were used in predicting the post-mining recovery of groundwater. Figure 5 shows the modified conductivity functions assigned to the aquifer and excavated rock. A conductivity function defines the relationship between pore-water pressure and hydraulic conductivity values (Geo-slope International Ltd. 2002). Many hydraulic conductivity and volumetric water content functions for solid materials are incorporated in the SEEP/W data files. Such functions can be imported into any particular problem and then modified by moving the entire function up or down until the best matching is achieved between the imported function and given saturated hydraulic conductivity.

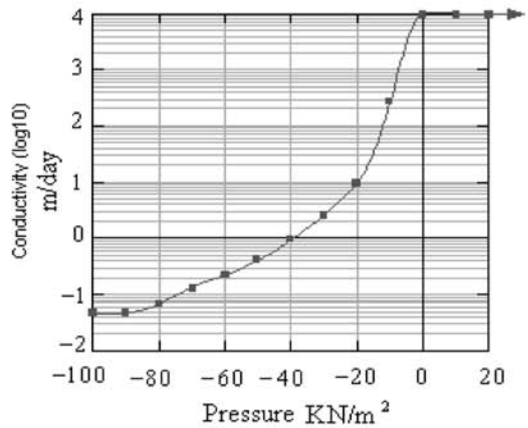
The results of the numerical simulation were then compared to the published numerical finite element model developed by Naugle and Atkinson (1993). The agreement was relatively good (Figure 6). The difference, 6.85 %, can probably be attributed to the hydraulic conductivity values assigned to the excavated rocks and the errors occurring during the digitisation of the groundwater recovery curve.

Problem 3—Modelling of groundwater rebound in an open cut mine site

The main objective of this third problem was to further evaluate the finite element model with the



(a) Aquifer conductivity



(b) Conductivity of the excavated rock

Figure 5. Modified hydraulic conductivity functions of (a) aquifer and (b) excavated rocks

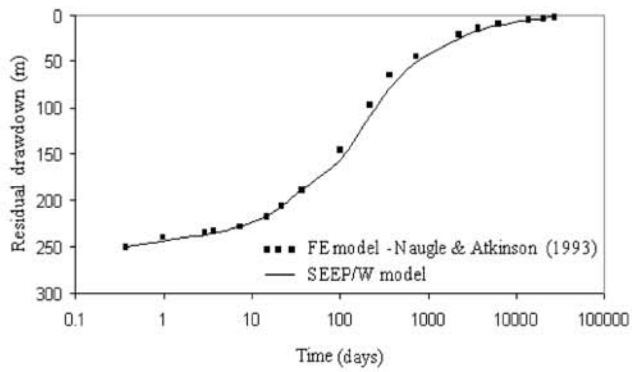


Figure 6. Comparison of the SEEP/W finite element model and finite element model developed by Naugle and Atkinson (1993) for prediction of groundwater rebound in an idealized pit.

monitored field data. For this purpose, the observations made by Norton (1983) at the Horsley backfilled site in the United Kingdom were used. The Horsley site is located about 15 km to the west of Newcastle-upon-Tyne in Northumberland, England in a complicated geological structure in the Coal

Measures strata. The mining operation was carried out between 1961 and 1970. Approximately 370,000 t of coal was extracted from the excavation with a maximum depth of 63 m. The strata were the normal Coal Measure sequence with about 30% arenaceous deposits. The site was very wet with artesian water (the piezometric elevation was high). Advance dewatering was used to prevent inflows to the mine excavation. The working head for the pump was 72 m and the pump had a working capacity of 42 L/s. The Horsley site was backfilled in 1970 and dewatering continued until 1974. The hydraulic conductivity of the spoil was assessed to be greater than 10^{-4} m/s. For the simulation, both two-dimensional and axisymmetric analyses were used. For the axisymmetric analysis, a grid consisting of 1776 nodes, 1679 elements, and 23 layers with different thickness was constructed. The grid spacing increases to the outer boundary (Figure 7). Constant heads of 48 m and 4.8 m were assigned at the backfill and at the model boundary in order to construct an initial condition. A sensitivity analysis was performed to evaluate the parameters most sensitive to the simulation results. The transmissivity and the storage coefficient appeared to be the most sensitive of the remaining parameters.

Axisymmetric model

For an axisymmetric analysis, an average precipitation of 4.65 x 10^{-8} m/s (Norton 1983) was assigned at the upper boundary of the model. Saturated hydraulic conductivities of 9.5 x 10^{-6} m/s and 4.0 x 10^{-3} m/s were assigned at the aquifer and at the backfilled site respectively. The first time step was selected at 2 months, after that time steps of 6 months were assigned. Storage coefficients of 0.0055 and 0.0065 were considered at the aquifer and at the backfilled site respectively. Figure 8 shows the predicted and measured values of residual drawdown at the backfilled site as a function of time.

Figure 8 indicates that for the period 0-500 days, the model slightly overestimates the residual drawdown, while for the period of 500 to 1000 days, it slightly underestimates the amount of rebound. The average error in calculation of the rebound by the model is estimated at 2.19%.

Two-Dimensional Model

For the two-dimensional simulation, a finite element grid consisting of 3381 nodes, 3200 elements and 20 layers was designed. A finer grid mesh was constructed around the open cut as well as the boundary between the aquifer and the spoil (Figure

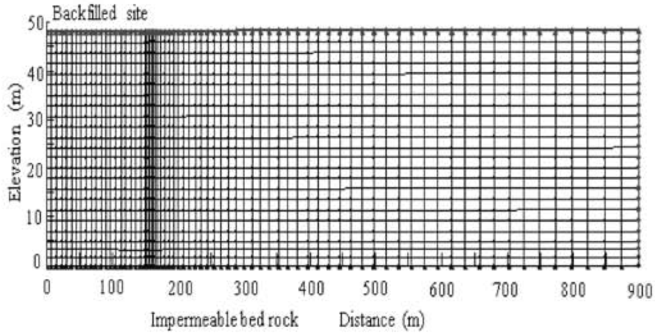


Figure 7. Finite element representation of the axisymmetric problem

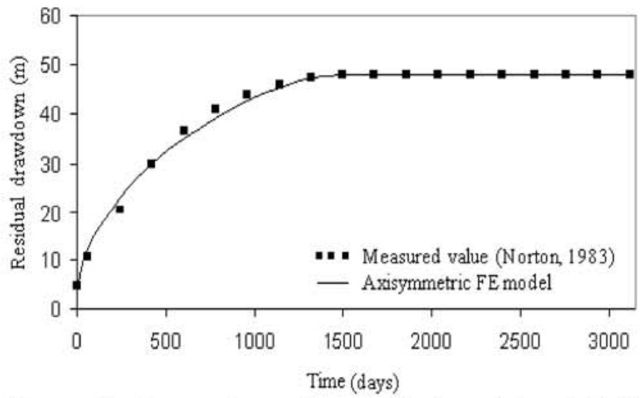


Figure 8. Comparison of numerical model and field data (from Norton, 1983) for prediction of water table rebound at Horsley backfilled site in UK.

9). In order to establish an initial condition for the model, constant heads of 48 m were assigned at the outer boundaries of the aquifer. A corresponding head of 4.8 m was assigned at the backfill site. An impermeable layer was simulated by assigning a no-flow boundary condition at the lower boundary of the model. A two-dimensional simulation was then performed using hydraulic conductivities of 10^{-6}, 10^{-4}, and 4.0 x 10^{-3} m/s, for the aquifer, backfill, and excavated rock respectively. The hydraulic conductivity of excavated rock was set at 4000 times the original hydraulic conductivity of the aquifer in order to minimize the errors occurring during the prediction of groundwater table elevations.

Anisotropy ratios of 1.25 and 1 were used as input parameters for the aquifer and spoil respectively. An average precipitation of 10^{-10} m/s, and a storage coefficient of 0.001 were assigned in the model. The comparison of the residual drawdown predicted by the two-dimensional finite element model and that observed at the Horsley site (Norton 1983) are compared in Figure 10. As Figure 10 shows, the model underestimates the rebound for a period of 500-1000 days and the average error in predicted values are within 0.82% of the measured values.

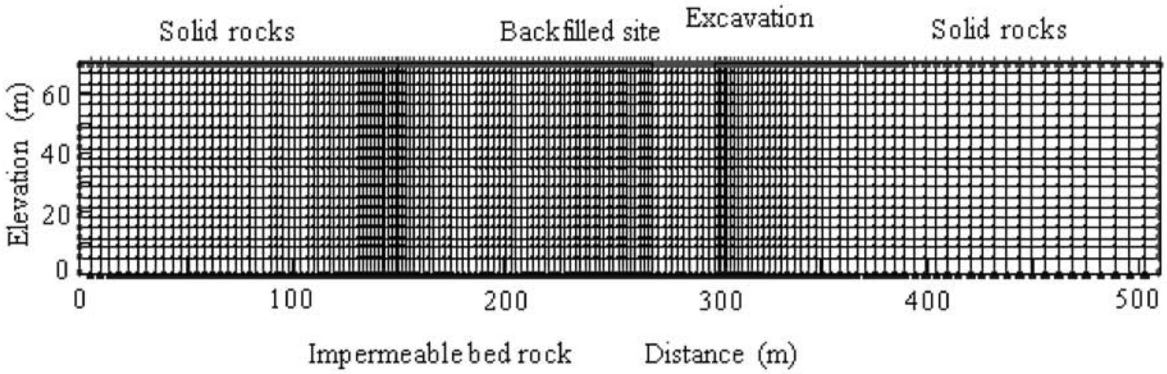


Figure 9. Finite element representation of two-dimensional problem.

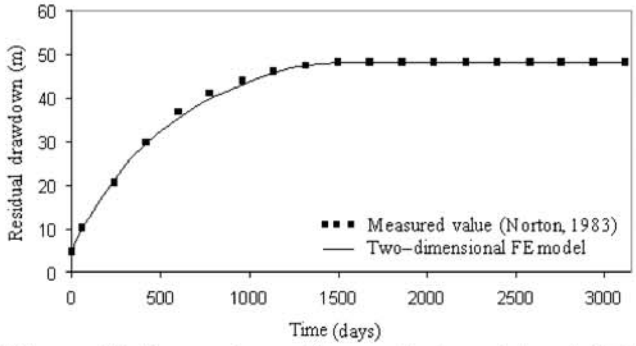


Figure 10. Comparison of numerical model and field data (Norton 1983) for prediction of water table rebound at the Horsley backfilled site in the UK

Conclusions

A numerical two-dimensional groundwater model has been presented in this paper. The model utilised a suite of the SEEP/W features and data file together with modified permeability functions to simulate groundwater rebound process within a backfilled open cut mine. The model was evaluated by comparing the output from an existing model and the results obtained from analytical solutions, as well as field monitored data. The time-dependent simulation of post-mining groundwater rebound within spoil of an open cut coal mine showed that the groundwater recovery took place very fast at the early times after cessation of dewatering operation due to the considerable difference in hydraulic heads. Using this model to predict post-mining groundwater rebound within backfilled materials can be useful in designing mine drainage pollution prevention schemes.

Acknowledgements

The financial support provided by the Ministry of Science, Research and Technology of the Iranian Government and Shahrood University is acknowledged. The assistance provided by the Faculty of Engineering, University of Wollongong is also appreciated.

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