Assessment of Groundwater Rebound in Backfilled Open Cut Mines using the Finite Element Method

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ABSTRACT

Simulation of the post-mining groundwater rebound within the backfill of an open cut coal mine is important consideration for developing mine rehabilitation strategies. This analysis enables prediction of the maximum water rise within the backfill mass and consequential settlement of the backfill which may enable control measures for the prevention of pollution potential of mine water to be devised. A two-dimensional finite element model has been developed for predicting the groundwater rebound process using the numerical finite element software called SEEP/W. This computer model operates on the PC under Microsoft Windows 95, 98, Me, NT, 2000, and XP operating systems (Geo-slope International Ltd., 2002). The model has the ability to simulate groundwater flow in partially saturated porous media incorporating hydraulic conductivities and water content as a function of pore-water pressure. The results of the simulation of groundwater rebound are presented and compared with those obtained using an existing analytical solution as well as with field data monitored at a shallow backfilled site in the East Midlands Coalfield, Nottingham, United Kingdom. The model provides important information regarding groundwater rebound problems, the cause of groundwater pollution and backfill settlement. These results can be used by mine-operators and environmental groups to develop the mine rehabilitation and environmental management plan for a mine.

Keywords: Coal mining, ground water rebound, finite element method

1. INTRODUCTION

Open cut coal mining makes a considerable contribution to the Australian mining industry and the national economy. The management of groundwater plays an important

role in the overall success of the mining operation and prevention of groundwater pollution even after dewatering has ceased and the mine has been abandoned. Water has an important role in creating pollution problems in the post mining regimes and influencing the surrounding environment. The purpose of this study is an assessment of groundwater rebound in a surface mine site and to assess the pollution potential of groundwater in the backfill mass within the surface mining void.

2. OUTLINE OF PROBLEM

During the life of a surface mine excavating below the level of the natural groundwater table, water inflow takes place from the surrounding strata towards the mining excavation. Thus the site dewatering facilities are necessary in order to keep the mine workings dry. Consequently, performance of a dewatering program in surface open cut mines causes a 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 planned to close and the pumping operations have ceased, the surrounding water will continue to flow towards the mine until it reaches the original water table level in pre-mining conditions. This process is normally defined as 'water table rebound'. The mine water pollution potential creates an adverse effect, which may be caused by the water rebound process when the groundwater covers the backfill containing oxidized pyrite and oxidation products. The generation of water pollution potential may start during the mining operation, and it will be continued after the abandonment of the mine if no attempt is made to prevent it. Settlement of the backfill is an important factor contributing to groundwater rebound process. It has been observed that the backfill in a restored open cut mine undergoes three-dimensional movements. The stability of a backfill mass has a great importance in making a decision for its further use, either for agricultural use or structural development purposes (Reed and Singh, 1986). Research into backfill settlements made by Norton (1983), and Reed (1986) suggested that once the water table has reached a static equilibrium level, then there is no further appreciable settlement.

Hence, prediction of post-mining water table levels within the mine backfill is important for

- applying special handling techniques for neutralizing purposes,
- predicting the maximum water rise, and
- estimating backfill settlement for building purposes.

In addition, it has now become obligatory in Australia, in particular in NSW to prepare a Mine Rehabilitation and Environmental Management Plan (MREMP) during the design stage of an open cut mining operation.

Simulation of the post-mining filling of pit lakes has been carried out by many modellers including Naugle and Atkinson (1993), Vandersluis et al. (1995) and Shevenell (2000). These models are not directly related to the rebound problems in open cut mines. Many research workers have carried out studies in relation to groundwater rebound problems in open cut coalmines (Henton, 1981; Norton, 1983; Reed, 1986; and Reed & Singh, 1986).

Davis and Zabolotney (1996) developed a groundwater flow model for simulating the post-mining recharge rate from precipitation at a surface coalmine. In this paper a numerical model incorporating saturated/unsaturated and confined/unconfined flow conditions is described which simulates post-mining groundwater rebound within the backfill of an open cut mine.

3. METHODOLOGY

In order to develop an understanding of the post-mining groundwater rebound in a backfill site, a two-dimensional groundwater flow model using the *SEEP/W* code was modified. The code solves the governing equation for the two-dimensional groundwater flow taking into consideration both saturated and unsaturated conditions in the following form:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial y}\right)-C_w \frac{\partial}{\partial t}(H)+Q=0 \qquad (1)$$

where,
H = hydraulic head;
K_x and K_y = components of the hydraulic conductivities in x and y directions;
Q = recharge or discharge rate per unit volume;
t = time; and
C_w = slope of the moisture characteristic curve.

The model can take into account both saturated and unsaturated flow. The ability of the model to assume unsaturated flow condition allows it to solve a wider range of problems than some other codes and obtain realistic simulation of groundwater rebound process. One of the most important features and capabilities of the present model using the SEEP/W code is definition of the hydraulic conductivity and volumetric water content as a function of pore-water pressure in saturated-unsaturated flow systems. The model can simulate heterogeneous hydraulic properties such as hydraulic conductivity and storage coefficient in an isotropic and heterogeneous flow system. Therefore, a conductivity function which defines the relationship between hydraulic conductivity and pore-water pressure can be defined for each material. This feature of the model is very important in simulation of groundwater rebound in backfilled open cut mines where hydraulic characteristics of the fill materials are different from those of the un-mined aquifer and unexcavated rocks.

3.1 Analytical Equation for the Rise of the Groundwater Level

The rise of the water level may be approximately calculated using the following equation (Mittel and Singh, 1993):

$$h_{(t)} = h_0\, e^{-\alpha t} \qquad (2)$$

where,

$h_{(t)}$ = water level rise at time *t (m)*;

$h_{(0)}$ = initial water level (*m*);

α = hydro-geological characteristics of the basin (%); and

t = time interval for the water level to rise from $h_{(0)}$ to $h_{(t)}$.

The main objective of using analytical Eq. 2 was to further evaluate and assess the model simulation results and to find the appropriate ranges for α, applicable to backfilled open cut coalmines. If this is achieved, this analytical equation with modified α describing the hydro-geological characteristics of the site can produce a reasonable preliminary estimate of the groundwater rebound process within the backfill. It was found that α predominantly ranges from about 0.9 to 3.5 at a backfill site.

4. CASE STUDY

The ground water rebound problem at a backfilled site 'A' in the East Midlands area, United Kingdom is presented below.

4.1 General Consideration

In this problem, results from the numerical finite element model are verified with the monitored field data. For verification purpose, the observation made by Reed (1986) on a shallow backfilled site, called "truck & shovel site 'A'" in the East Midlands area in the UK were used. The site was relatively small in size with 0.9 hectares, 6 coal seams, with an overburden to coal ratio of 10:1. The mining operations extended down-dip from the coal outcrop to maximum depth of 31 metres, the average depth of excavation on the site was 17 metres. The mining operation was carried out over a period of 2 years by truck and shovel methods. The average rate of coal production was 1000 tonnes per week. The mining void was backfilled by dump trucks tipping over the edge of the loose wall. Scrapers were employed to regrade the overburden levels and to replace soils.

4.2 Site Topography, Geology and Backfill Characteristics

The pre-mining land surface was essentially flat, lying at a level of 46 to 47 metres above ordinance datum (A.O.D). The site was bounded on the eastern and southern sides by railway lines. Figure 1 presents the layout of the site with respect to site boundaries, areas of excavation and position of monitoring instruments and Figure 2 illustrates the pre-mining geological section along A-A' (after Reed, 1986).

Overburden and inter-burden strata consisted of mainly mudstone rocks together with occasional bands of silty or sandy material. Alluvial deposits covered the entire area of the site to a depth of approximately 3 to 4 metres, which increased to 9 metres in the North-Western part where a buried river channel lay. These deposits mainly contained 0 to 2 metres of sands and gravels overlain by clay layers. During the life of the mining

operation 2,200 litres per minute were dewatered from the void using the sump pumping techniques. The backfill is identified as having an uniform composition over the area of the site. The backfill was mainly mudstone (70 per cent), containing 12 per cent alluvial deposits. The rest of the spoil consisted of sandstones, siltstones and seat earths.

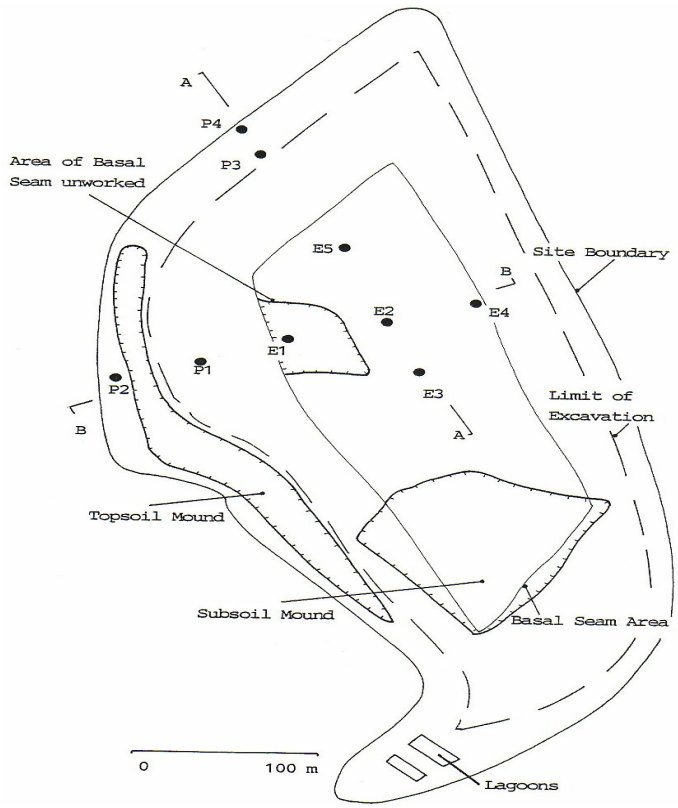


Fig. 1- Site characteristics and instrumentation stations (Reed, 1986)

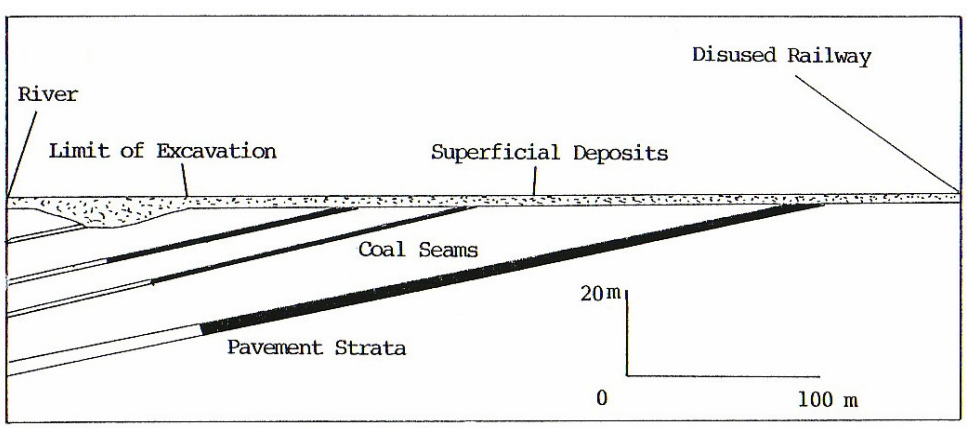


Fig. 2 - Illustration of pre-mining geological profile A-A' (after Reed, 1986)

4.3 Instrumentation Pattern

The instrumentation was commenced as soon as the overburden was restored to its final level, prior to the replacement of the soils in order to minimize the time gap between installation of the instruments and the cessation of dewatering. The instrumentation scheme includes five magnetic extensometers/piezometers (E1, E2 to E5) in two profiles across the mine, and four piezometers (P1, P2, P3, P4) in the unmined strata, two at one end of each profile (Fig. 1). The piezometers were installed to monitor water levels in the solid strata and the rate of the water rebound process. Furthermore, the magnetic extensometers/piezometers were installed in the backfilled site in order to monitor groundwater rebound through the backfill as well as measuring settlement within the backfill. All bore holes were then backfilled on installation with a weak bentonite grout. Table 1 outlines the initial surface levels and depths of each instrument and gives the individual magnet positions.

Table 1- Instrumentation details (after Reed, 1986)

Extensometer	Fill depth (m)	Surface level (m A.O.D)	Magnet positions (Depth metres)					
E1	20.56	45.48	20.5	17.5	13.8	8.70	3.80	1.90
E2	23.90	44.98	23.3	22.7	18.5	13.4	7.80	2.70
E3	22.70	45.67	21.9	17.8	15.3	11.7	7.50	2.80
E4	21.40	45.04	20.4	16.9	13.0	10.3	6.40	2.50
E5	25.40	45.40	24.7	19.4	15.7	10.8	6.00	2.20
Piezometers	Depth							
P1	33.60	45.51						
P2	33.60	47.22						
P3	33.60	48.94						
P4	33.20	48.27						

Figures 3 and 4 illustrate cross-sections of the backfill site along the profiles A-A' and B-B'. Instrumentation scheme was also shown in the figures. Drilling of the boreholes and installation of instruments were completed within three weeks.

4.4 Evaluation of Field Monitored Groundwater Rebound

Groundwater levels were monitored (Reed, 1986) at a depth of 11 m below the restored surface, recovering to flood the surface of backfilled site within 120 days. As the groundwater rebound is a continuous process and observations commenced 48 days after the cessation of dewatering therefore, there were 48 lost days. In that time period prior to monitoring, groundwater levels in the site had measured from 24 m below the restored surface to 15 m, a recovery of 9 m. During the first 48 days of monitoring, groundwater levels rose by a further 9 m, and in the second similar period by 5 m. Therefore, within 144 days from the termination of dewatering, the groundwater recovered 23 m. Water levels initially showed the expected trends of a draw-down curve lowering towards the final void area. The highest initial groundwater level was monitored on instrumentation

at point E3, the one farthest from the final void. Water levels in instruments E1 and E2 were observed to be the same whilst in E4 the water levels were slightly lower. Insignificant rebound was monitored on instrument E3 for the first 15 days. Water levels in all instrumentation points then rose uniformly from day 15 to 50. Between days 50 to 70, an abnormal rainfall was reported which flooded areas of the restored surface, particularly around instruments E2 and E4. 110 days after the commencement of monitoring groundwater levels in the fill of E3 stood above the restored levels of E2. Finally by day 120, the surface became flooded.

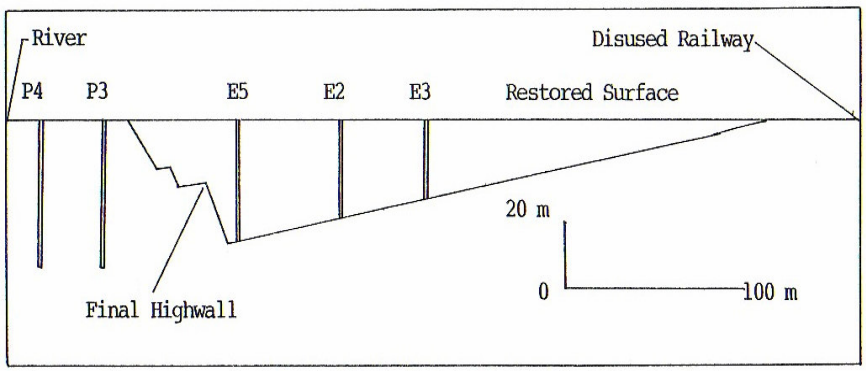


Fig. 3 - Instrumentation scheme along section A-A'(Reed , 1986)

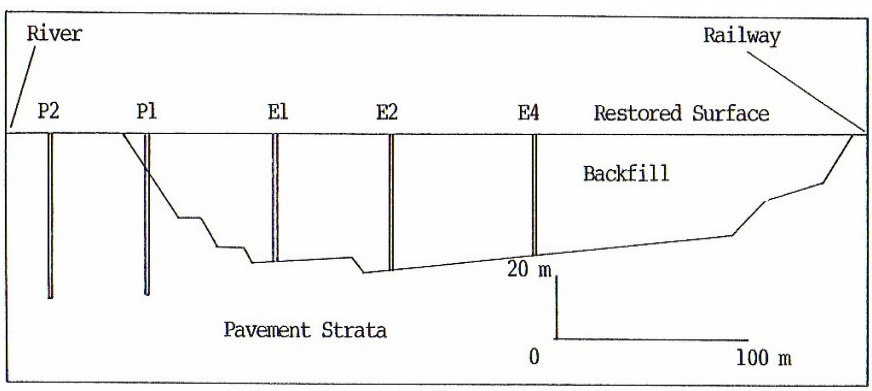


Fig. 4 - Instrumentation scheme along Section B-B' (Reed, 1986)

5. FINITE ELEMENT ANALYSIS AND RESULTS

5.1 Modelling Performance and Prediction (Profile A-A')

A finite element grid consisting of 4903 nodes and 4557 elements was constructed (Fig. 5). The problem domain was divided into rectangular elements, while triangular elements were used near the boundaries of backfill and unmined strata. A finer mesh was constructed at boundaries where a rapid change of hydraulic conductivities is seen.

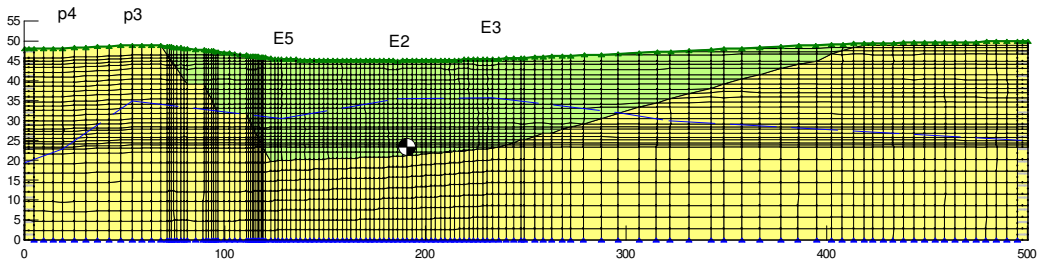


Fig. 5 - Finite element mesh along Section A-A'

The following boundary conditions were assigned in the model:

- A no-flow boundary condition at the lower boundary of the aquifer
- An infinite boundary condition at two ends of the model
- A recharge boundary condition at upper boundary in order to take into consideration net rate of precipitation

The initial water table was established from water levels recorded in the instrumentation points (Fig. 6). These water levels should be used as an initial condition for the transient simulations of the post-mining rebound.

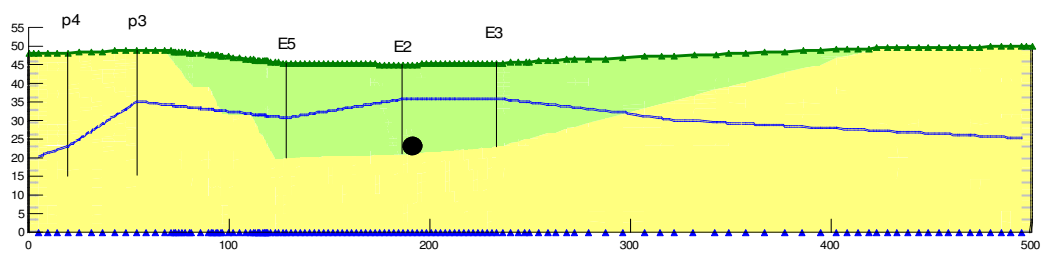


Fig. 6 - Water table before groundwater recovery, the position of instruments was also illustrated

The saturated hydraulic conductivities of 9 x 10^{-5} m/s and 6.4 x 10^{-6} m/s were assigned to the backfill and unmined aquifer respectively. A saturated water content of 0.35 was assumed in this model based on measured values (Rogowski and Weinrich, 1981). An average precipitation of 3 x 10^{-8} m/s was maintained for the model. However, because of the abnormal precipitation rate between days 50 to 70, this value needed to be increased to 5 x 10^{-8} m/s.

After specification of all initial and boundary conditions, the transient simulation was made and groundwater was then allowed to rebound. The simulation was carried out in three distinct phases:

1) Groundwater was allowed to rebound until day 50. The model for this part of the simulation was called *SITEA_S_A_A*.

2) Between days 50 to 70, because of an abnormal rainfall, the recharge value was changed to 5 x 10^{-8} m/s and the model was then run using SITEA_S_A_A as an initial condition and finally it was named SITEA_S_A_A_1.
3) The transient simulation was eventually completed with reducing recharge value to 2.7 x 10^{-8} m/s. The model for this phase of the simulation was known SITEA_S_A_A_2.

Figure 7 shows the groundwater rebound patterns within 120 days after the cessation of dewatering. It illustrates a rapid rate of groundwater recovery in the backfill because the hydraulic conductivities of spoil are much greater than those of the unexcavated aquifer. Modelling predictions verified the field observations that the surface of the backfill was flooded after 120 days from cessation of pumping.

Comparisons were made over each time period between the simulated groundwater levels and actual water levels measured at the site as well as groundwater rebound predictions using the analytical Eq. 2 (Fig. 7).

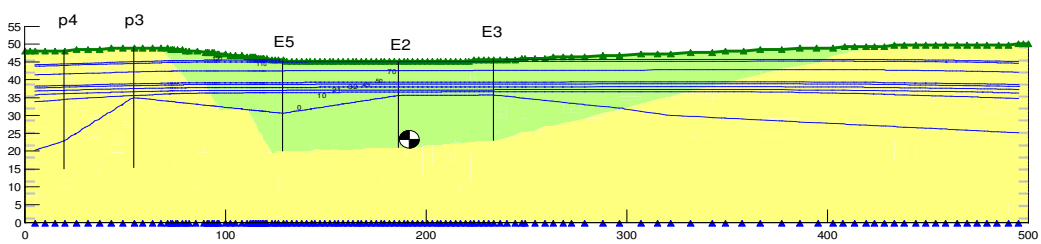


Fig. 7 - Water recovery patterns after 10, 21, 32, 43, 50, 70, 110 and 120 days ceasing of pumping

Figure 8 indicates that for the period 50 to 110 days both analytical equation and the model slightly underestimated the groundwater levels. For the period 0-50 days, a close agreement was achieved between three methods in instrumentation point E2 at the backfill area. Although model simulated groundwater levels in observation point E3 at the backfilled site were in agreement with the analytical solution for the period 0-50 days, but slight overestimation appeared. Similarly, the model slightly over-predicted water levels at point E5 over the backfilled area and at P4 above the unexcavated aquifer for the period 0-50 days. At instrumentation point P3 located in solid strata, the model slightly underestimated the rebound process.

5.2 Modelling Performance and Prediction Along Profile B-B'

To evaluate the groundwater rebound process within the backfill site, the simulation was also carried out along the section B-B'.

A finite element model consisting of 3466 grid points and 3311 elements was constructed. The model was mainly divided into rectangular elements. Triangular elements were also used for those parts of the flow system representing the boundaries of the backfill and unmined strata. The proposed model is a rectangular shape 700 m length and 50 m width. Figure 9 shows a finite element mesh of the problem.

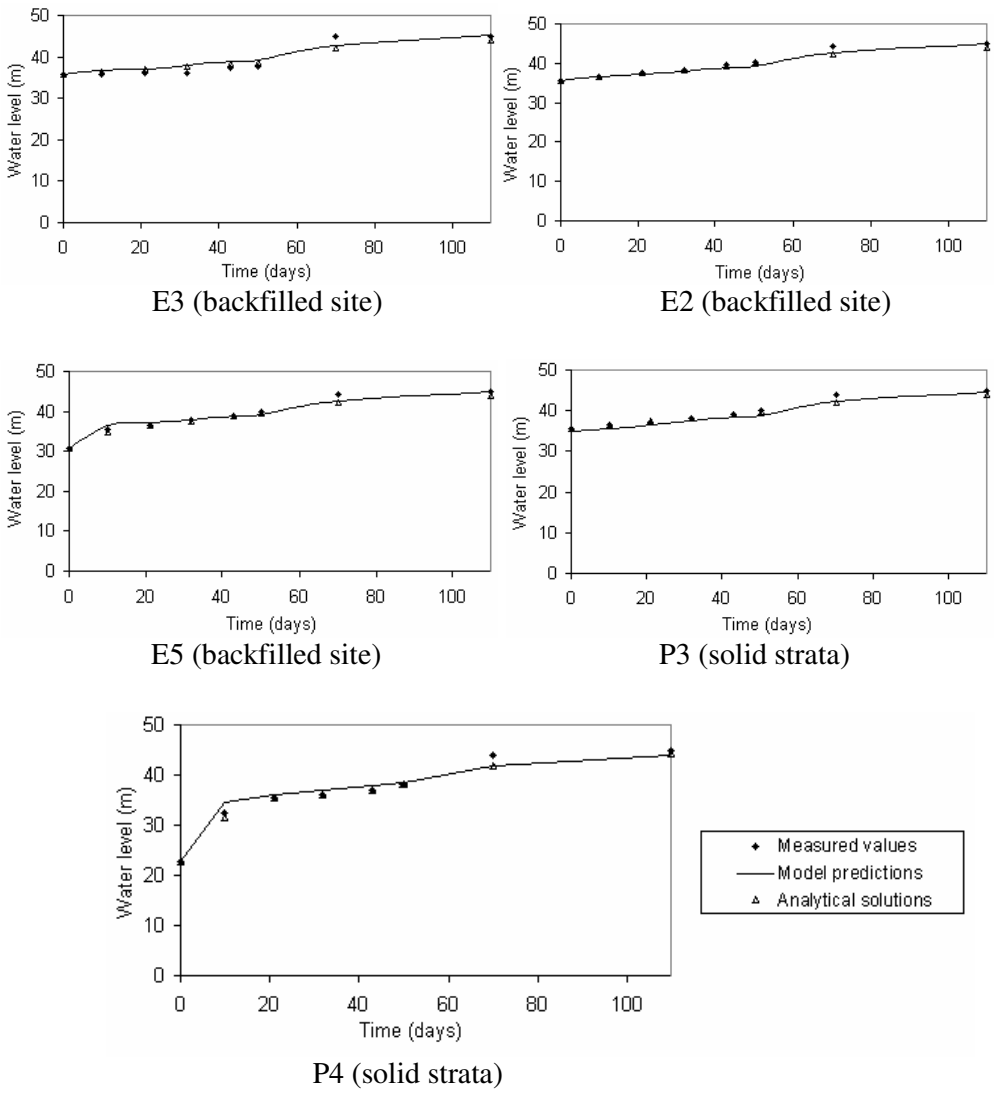


Fig. 8 - Comparison of measured values, analytical solutions and model predictions for groundwater rebound process at instrumentation stations, Section A-A'

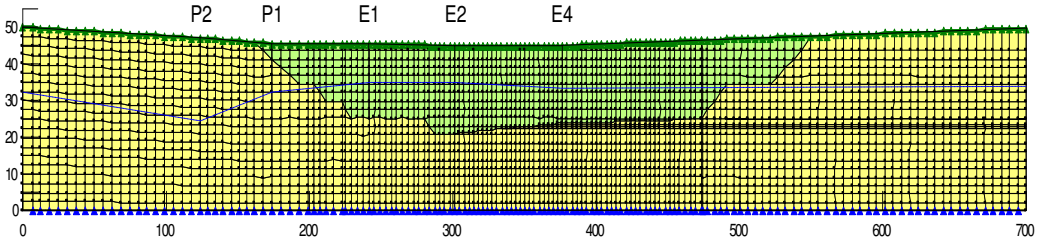


Fig. 9 - Finite element mesh along Section B-B'

A no-flow boundary condition was maintained at the lower boundary of the model. An average precipitation of 3 x 10^{-8} m/s was assigned at the upper boundary of the model. No change was made on this value over the period of 0-50 days while this value changed to 5 x 10^{-8} m/s within the time period of 50-70 days to take into account the abnormal rainfall that took place during this period. The value of 3 x 10^{-8} m/s was again maintained over the period of 70-84 days. After that it was, however, reduced to 1 x 10^{-8} m/s for better representation of the real system. Considerable attempt was made to adjust the initial water table at backfill and unmined strata using field data monitored at instrumentation points (Fig. 10).

This level represents the lowest groundwater table was maintained by the use of dewatering operation in order to prevent its effects on mining works. As previously mentioned this initial water level was used as an initial condition for the transient groundwater rebound simulation.

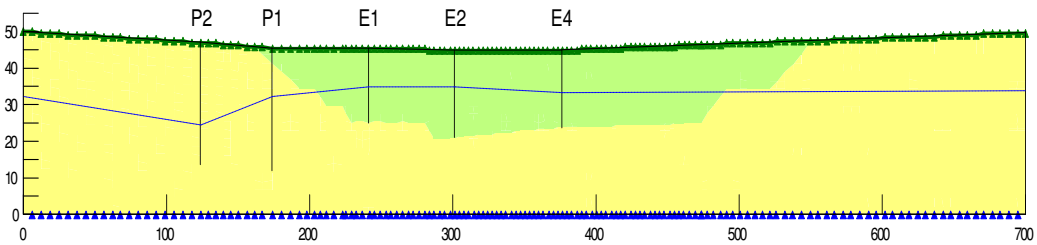


Fig. 10 - Water table before rebound process and the position of instrumentation stations

As it is illustrated, the saturated hydraulic conductivities were 9 x 10^{-5} m/s and 8.5 x 10^{-5} m/s for the backfill and the solid strata respectively. However, slight modification was made on the hydraulic conductivity function of the backfill in order to take into consideration the settlement that took place in the backfill as the groundwater level rose within it. Therefore the saturated hydraulic conductivity of the backfill was changed from 9 x 10^{-5} m/s to 1 x 10^{-5} m/s in the final stage of the rebound process.

Figure 11 shows the hydraulic conductivities as a function of pore-water pressure assigned for the backfill and unmined strata.

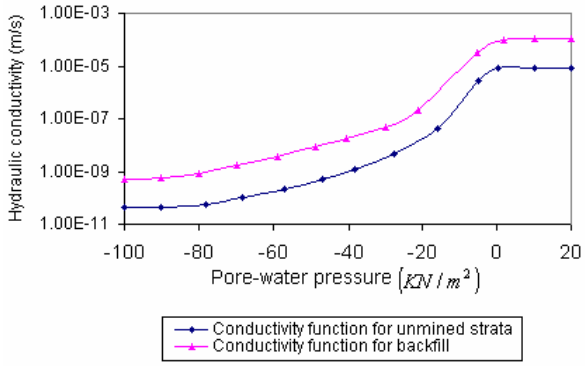


Fig. 11- Modified conductivity function assigned in aquifer and backfill

The transient simulation of post-mining rebound was then carried out in four phases as given below:

The first phase takes into account groundwater recovery over a period 0-50 days. The model for this part of the simulation was named *SITEA_S_B_B*. The second, third and the fourth phases simulate groundwater rebound over time periods of 50-70, 70-84, and 84-120 days respectively. The models for these three distinct phases were named *SITEA_S_B_B_1, SITEA_S_B_B_2,* and *SITEA_S_B_B_3* respectively. It should be noted that the simulated values made in each phase used as an initial boundary condition for the next phase simulation. Figure 12 illustrates the simulated water levels at different time steps. The groundwater levels measured at the site were compared with those predicted by the use of a finite element model and those calculated using the analytical Eq. 2 (Fig. 12).

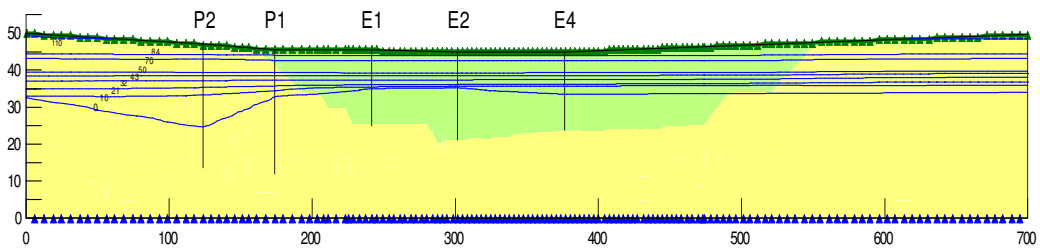


Fig. 12 - Water recovery patterns after 10, 21, 32, 43, 50, 70, 84 and 110 days ceasing of pumping

Figure 13 shows that both analytical and numerical methods predicted approximately similar water levels at instrumentation points E1, E2, and E4 and close agreement was achieved with the measured values.

However, both the analytical and the numerical methods underestimated the water levels over the period 50-70 days. After this time period, the model-simulated the water levels were similar to those monitored at the site while the analytical equation slightly underestimated the water levels. At point E1, the model slightly underestimated the water levels in comparison to analytical prediction and field monitored water levels. A close agreement was achieved between the analytical predictions of the water levels and the measured values at point P1 but the model overestimated the water levels at this point. On the other hand, at point P2 over unmined strata, a close agreement was achieved between the simulated values and field-measured values and the analytical equation slightly underestimated the water levels.

6. SENSITIVITY ANALYSIS

A sensitivity analysis was carried out to assess which parameters most affected the simulation results. A time period of 0-50 days after ceasing dewatering operations was selected for the performance of the analysis. It was found that although modelling results can be highly affected by the hydraulic conductivities and storage coefficients, rainfall

values appeared to be the most sensitive characteristic (Figure 14). Based on the sensitivity analysis, annual precipitation of 2×10^{-8} - 3×10^{-8} m/s was selected for the simulation. This range is most identical with the average annual rainfall (600-800 mm/yr) quoted by National Coal Board (NCB, (1982) for this area.

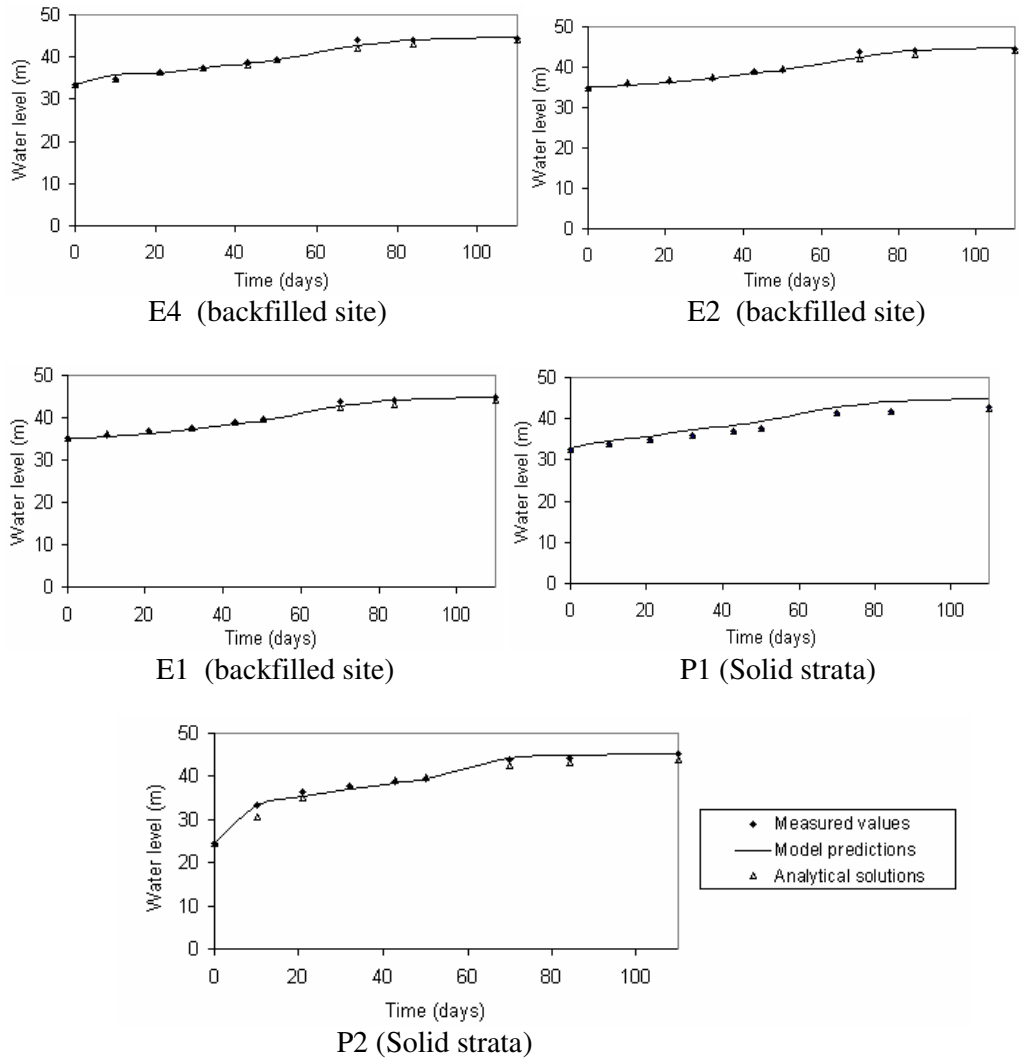


Fig. 13- Comparison of measured values, analytical solutions and model predictions for groundwater rebound process at instrumentation stations, Section B-B'

7. ERROR ANALYSIS

Table 2 illustrates the maximum percent error for prediction of the groundwater rebound by the model at different instrumentation points using the following equation (quoted in Hughson and Codell, 2001). For error calculation, the results of present numerical simulation were compared with field-monitored data.

$$E_i = \left(\left| \frac{\Delta x_i}{x_i} \right| \times 100\% \right) \tag{3}$$

The maximum percent error in each instrumentation point is reduced to:

$$E_{\max} = \max\left(E_i\right) \tag{4}$$

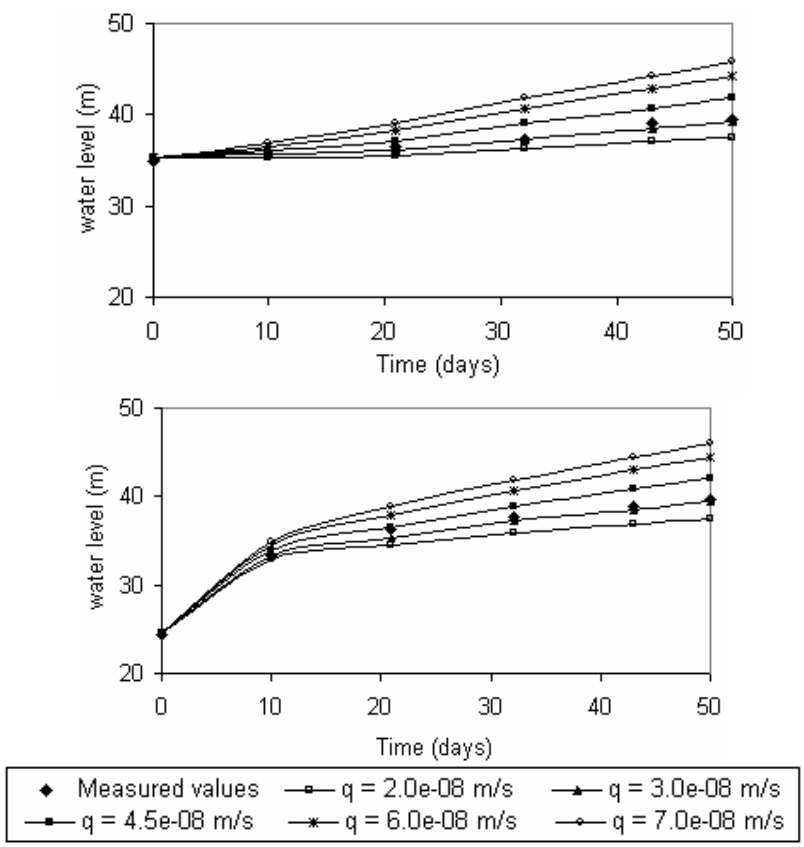
where,

E_i = percent error (%);

$E_{\max}$ = maximum percent error (%);

Δx_i = difference between measured water level and predicted water level (*m*); and

x_i = measured water level (*m*).



E2 (backfill site) P2 (Solid strata)

Fig. 14 - Sensitivity analysis for rainfall values

Table 2 - Calculated error related to measured values

Instrumentation Point	E_1	E_2	E_3	E_4	E_5	P_1	P_2	P_3	P_4
Maximum Error (%)	3.09	3.68	4.92	3.10	3.67	5.33	2.80	4.03	6.61

8. CONCLUSIONS

A finite element model for simulating post-mining groundwater rebound within the backfill of an open cut mine in a partially saturated medium has been presented. The results of the groundwater rebound simulations were compared with those calculated using an analytical equation and with monitored field data observed at a shallow backfilled site in the UK. The transient groundwater rebound simulations showed that the groundwater rebound process is very rapid at the early stages after termination of dewatering operation, where a significant proportion of the fill settlement can be monitored at these times. Comparison of the results obtained with the three methods for simulation of post-mining groundwater rebound yields values for the hydro-geological characteristics coefficient in the range of 0.9 to 3.5. These values can produce a reasonable preliminary estimate of the groundwater rebound within the backfill of an open cut mine. The results obtained from the simulation of the post-mining groundwater rebound can be used by environmental groups and mine operators for the following purposes:

- Designing efficient techniques to prevent mine drainage pollution
- Providing useful information related to the settlement of backfill mass, which it is particularly important for further use and development of abandoned mine land.

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