Simulation and Numerical Modelling of Ground Water Rebound after Opencast Mine Closure and its Relationship with Backfill Settlement in a Shallow Aquifer

F. Doulati Ardejani[*]
&
R.N. Singh[**]

** Faculty of Mining, Petroleum and Geophysics,*
Shahrood University of Technology, Shahrood, Iran
Email: fdoulati@shahroodut.ac.ir

*** Nottingham Centre for Geomechanics,*
School of Civil Engineering,
University of Nottingham, UK

ABSTARCT

The ground water rebound process that occurs in a shallow aquifer was simulated using a two-dimensional finite element model to qualitatively predict the rate at which soil settlement would take place. This model considers saturated and unsaturated flow, hydraulic conductivity, and water content as a function of pore-water pressure. Ground water rebound was very fast immediately after opencast mine closure and cessation of dewatering; a significant part of the backfill settlement occurs at this time. This paper presents an easy method for deriving the relationship between post-mining ground water rebound and backfill settlement associated with backfilled opencast mines that can be used by mine operators and environmental engineers in deciding future agricultural use and structural developments.

Keywords: Ground water rebound; Backfilled opencast mine; SEEP/W model, Backfill settlement.

1 INTRODUCTION

Planning for the re-utilisation of mining areas in many countries, in particular the UK, dictates the controlled restoration of sites on completion of mining to enable regeneration of the land as soon as possible after backfilling has been completed. Backfill is typically non-homogeneous materials composed of mudstone, siltstone, and sandstone, depending on the overburden that covered the coal (Hassani et al. 1979). Suitably restored sites can be used for a wide range of developments, including highways, airports, recreation centres, tourism applications, housing, and industrial developments.

Dewatering prevents water inflow into mines during the life of the mining operations. When mining is completed and pumping activities cease, the natural ground water regime re-establishes to its pre-mining equilibrium position. This process, which is called ground water rebound, affects backfill settlement, which has two components: short-term settlement, which occurs quickly, and short-term creep, which is less rapid but often varies significantly across a site (Egretli and Singh 1988; Goodwin et al. 2003).

Investigations into ground water recovery and associated backfill settlement have been discussed widely (Egretli and Singh 1988; Goodwin et al. 2003; Henton 1981; Norton 1983; Reed 1986; Reed and Singh 1986). According to Henton (1981), pollution problems occur when a coal mine has been abandoned and the ground water is allowed to rebound to its equilibrium level. Field observation and monitoring of ground water rebound problems and backfill settlement at the Horsley backfilled site, located about 15 km to the west of Newcastle-upon-Tyne in Northumberland, UK, and a shallow backfilled site at Nottingham, UK have been reported (Norton 1983; Reed 1986). These studies revealed that the recovery of ground water after mining had ceased, was the main factor controlling the rate of opencast backfill settlement; and that the backfill in a restored mine void undergoes three-dimensional movements. Norton (1983) and Reed (1986) also showed that during the course of ground water recovery, the rate of spoil settlement slows dramatically as the water table reaches a static equilibrium level. Reed and Singh (1986) showed that the stability of a backfill mass is important in deciding its potential use for agriculture and structural developments.

Hills and Denby (1996) presented a model to predict post-restoration movements of backfills, but most of the mathematical models for the simulation of post-mining ground water recovery have been limited to modelling the rates at which pit lakes filled (Naugle and Atkinson 1993; Shevenell 2000; Vandersluis et al. 1995). A numerical model was developed by Davis and Zabolotney (1996) to calculate the post-mining recharge rate at a coal surface mine, but similarly does not take into account backfill mass settlement. Doulati Ardejani et al. (2003a) presented a two-dimensional finite element model to simulate ground water rebound associated with open cut mines, and showed that ground water rebound and the associated pollution problems were not directly related to the settlement of the areas affected by mining and dewatering. Although the numerical model presented by Doulati Ardejani and Singh (2004) for assessment of ground water rebound after open cut mine closure considered aspects of both long-term pollution and backfill settlement, it does not fully describe the relationship between ground water rebound and associated backfill settlement. Moreover, their model assumes that the opencast mine was fully restored by backfill mass immediately after cessation of dewatering. The numerical model presented by Doulati Ardejani et al. (2006) for simulation of post-mining ground water rebound and mine land settlement is not related to what occurs in a backfilled opencast mine.

We used SEEP/W commercial software (Geo-Slope International Ltd. 2006) to derive a logical and realistic relationship between post-mining ground water rebound and associated backfill settlement in an opencast mine sites. This two-dimensional finite element numerical model should facilitate environmental management planning during the design stage of surface mining and thereby improve mine rehabilitation and future use of restored opencast mines.

2 THE MODEL

For a two-dimensional case, SEEP/W solves the following partial differential equation governing ground water flow incorporating both saturated and unsaturated conditions (Freeze and Cherry 1979):

$$\frac{\partial}{\partial x}\left[K_u(\psi)\frac{\partial \psi}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_u(\psi)\frac{\partial \psi}{\partial y}\right]+Q=C(\psi)\frac{\partial \psi}{\partial t} \tag{1}$$

where $K_u(\psi)$ = hydraulic conductivity (m/s); ψ = matrix potential (m); x, y = Cartesian coordinates (m); t = time(s); $C(\psi)$ = slope of the moisture characteristic curve (1/m); and Q = boundary flux (1/s).

Analytical equations, previous numerical models and field data were used to verify the model (Doulati Ardejani et al. 2003a, b; Doulati Ardejani and Singh 2004; Doulati Ardejani et al. 2006).

3 NUMERICAL SIMULATION AND RESULTS

The model was run to perform numerical simulations using the following example of ground water rebound problem in an idealized opencast mine in a shallow unconfined aquifer and under transient flow conditions. The excavation had a maximum length of 1000 m and a width of 50 m. The backfill zone had a maximum length of 350 m, as shown in Fig. 1.

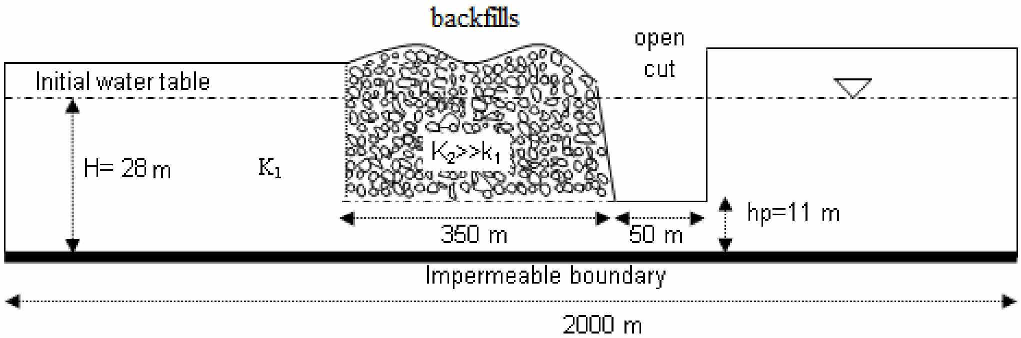
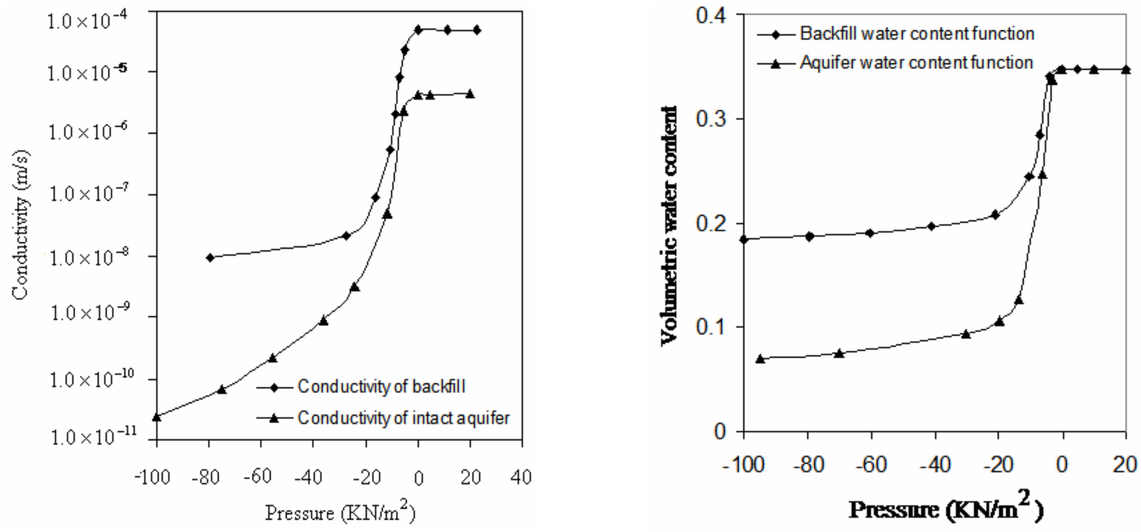


Fig. 1 - Schematic diagram showing backfilled materials of an idealised opencast mine in a shallow unconfined aquifer

The pre-mining water table elevation was 28 m. The water table elevation in the open cut (h_P) was 11 m. Saturated hydraulic conductivities of 0.39 m/day (4.5x10^{-6} m/s) and 4.32 m/day (5x10^{-5} m/s) were assigned at the intact aquifer (K_1) and at the backfill (K_2) respectively. The porosities of the aquifer and the spoil were 0.38 and 0.39 respectively. Figure 2 shows the modified conductivity functions (Fig. 2a) and volumetric water content functions (Fig. 2b) considered for the intact aquifer and backfill materials. Many hydraulic conductivity and volumetric water content functions for a few types of solid materials are incorporated in the SEEP/W data file called FN_METRE_SEP (in metric units) and FN_FEET.SEP (in terms of English units). 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.

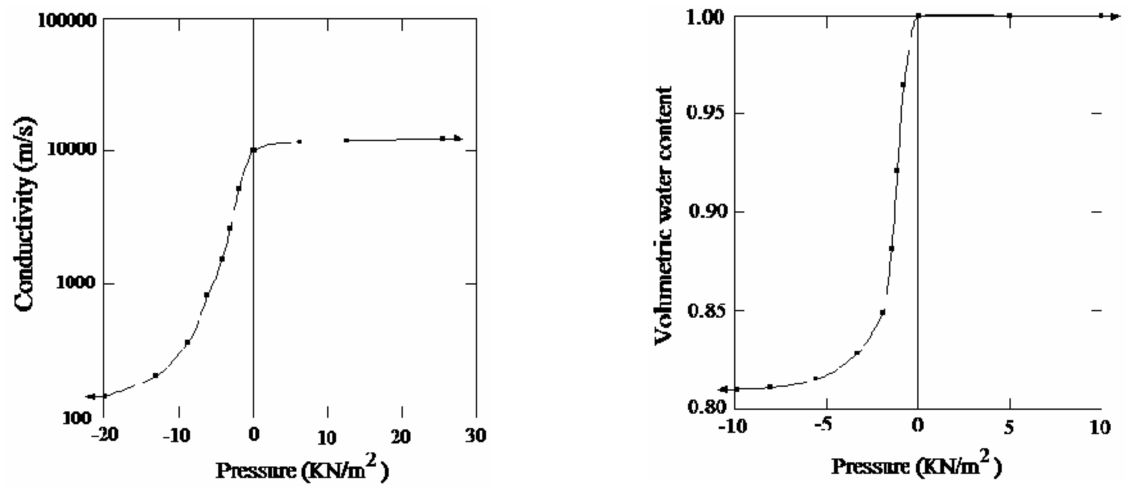
Figure 3 shows the modified hydraulic conductivity (Fig. 3a) and water content (Fig. 3b) functions of open cut used for simulation.



(b)

(a)

Fig. 2 - Modified hydraulic conductivity functions (a) and volumetric water content functions (b) considered for intact aquifer and backfilled materials



(a) - conductivity of excavated rocks

(b) - water content function of excavated rocks

Fig. 3 - Modified hydraulic conductivity (a) and water content (b) functions of open cut

For numerical modelling of the problem, a two-dimensional finite element mesh was constructed with 609 elements, 689 nodes, and 10 layers of 3.5m thickness (Fig. 4). A steady state simulation was first carried out to establish an initial condition for the transient simulation of the ground water recovery process. The head at the outer boundaries of the model was set as 28 m. A constant head of 11 m was considered at the open cut bottom.

Figure 5 shows the position of the water table before the transient simulation.

To achieve a transient simulation, 120 time steps were considered. The elapsed times were selected as 30, 120, 250, 500, 750, 1250, 2000, …, 58500 days. The number of iterations was 1500. A no-flow boundary condition was maintained at the lower boundary of the aquifer describing an impermeable layer. A fixed head equal to 28 m was set to the outer boundaries of the model, representing the pre-mining water table elevation. The results of ground water elevations obtained in steady state analysis were used to predict the post-mining rebound of ground water.

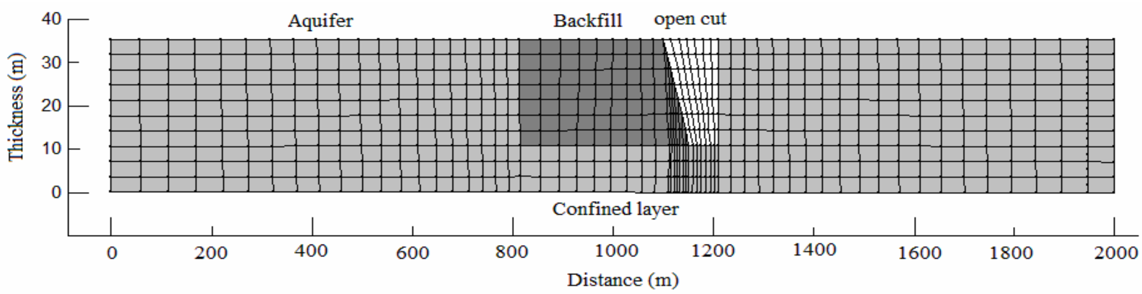


Fig. 4 - Finite element model for a backfilled opencast mine in a shallow unconfined aquifer

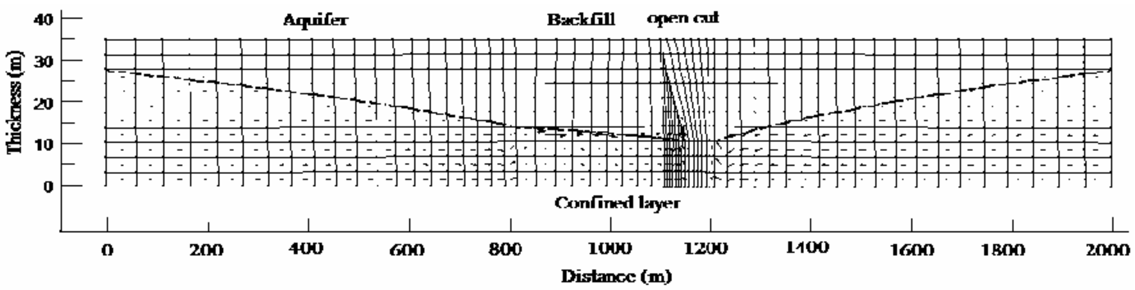


Fig. 5 - The results of a steady state simulation for establishing initial head pattern

Figure 6 shows the distribution of predicted hydraulic heads during the mine rebound period. It is evident from Fig. 6 that during the earlier stages of the simulation, the rebound process takes place more rapidly. The rate of rebound decreases as time progresses. As Fig. 6 shows, ground water recovery process differs in the unexcavated materials, in the mine cut and in the spoil. This is due to the fact that the hydraulic properties of the aquifer, the spoil and the mine excavation are different.

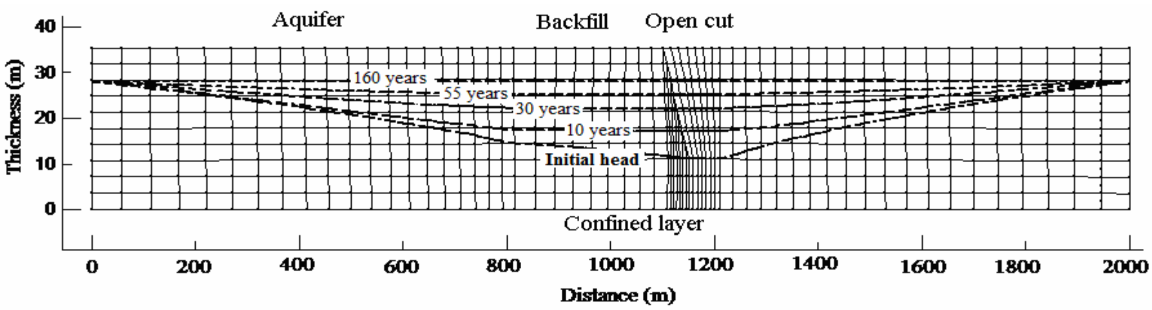
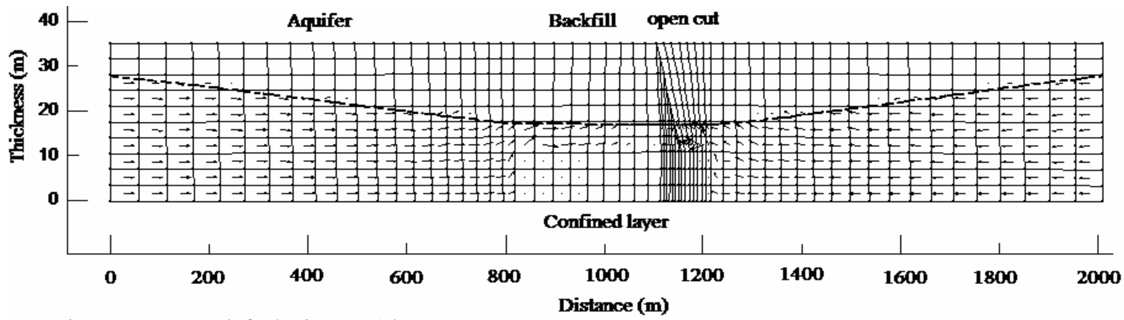
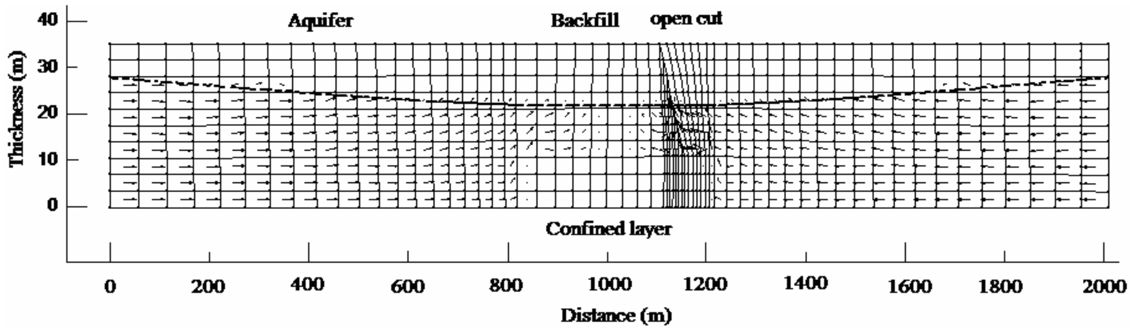


Fig. 6 - Transient modelling results for ground water rebound patterns and the areas around the opencast mine influenced by mining and subsequent settlement

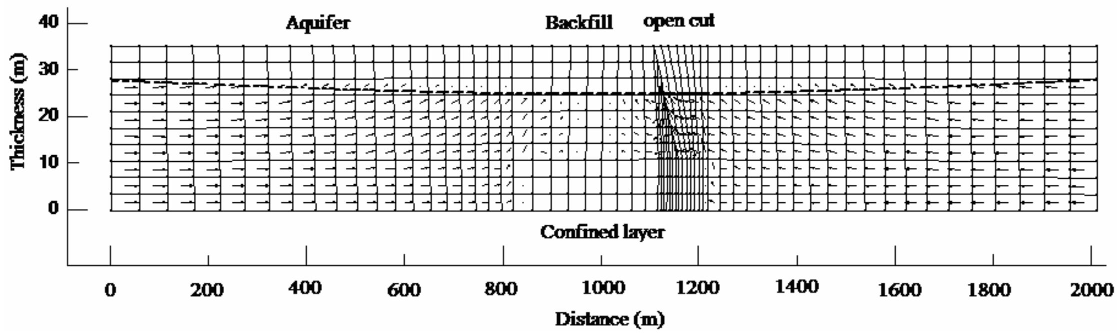
Figure 7 shows the stages of pit rebound predicted at various elapsed times. The water table returns to its initial level as it was prior to the commencement of the mining operation reaching a state of equilibrium. This figure presents valuable information for assessing the backfill settlement in opencast mine sites. Moreover, the results of opencast mine rebound simulation can provide a basis for designing a mine water pollution remediation plan.



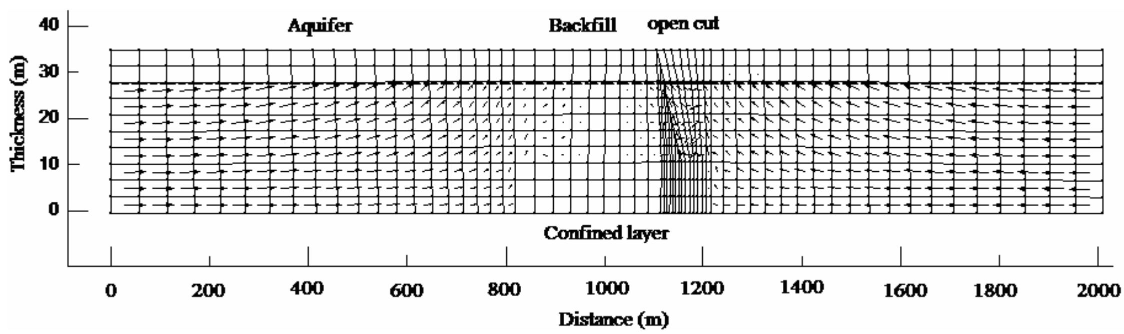
Simulation time: 3650 days (10 years)



Simulation time: 10950 days (30 years)



Simulation time: 20075 days (55 years)



Simulation time: 58400 days (160 years)

Fig. 7 **-** Simulation results for ground water rebound process as a function of time in a backfilled opencast mine in a shallow unconfined aquifer

Figure 7 also shows a flat water table in the backfill due to the high permeability of this material and during rebound as water drains towards the open void, the head is lower in the backfill than in the surrounding aquifer.

Figure 8 shows the predicted residual drawdown at the right wall of the open cut versus time. It is evident that about 83% of the ground water rebound process was completed within 13,500 days ($\approx$37 years), during which time the rate of backfill settlement was high. After this time period, ground water rebound gradually continued. It is expected that the rate of backfill settlement is very low for times greater than 20,000 days ($\approx$55 years). Agricultural use and structural developments should be avoided during time periods with a high rate of backfill settlement.

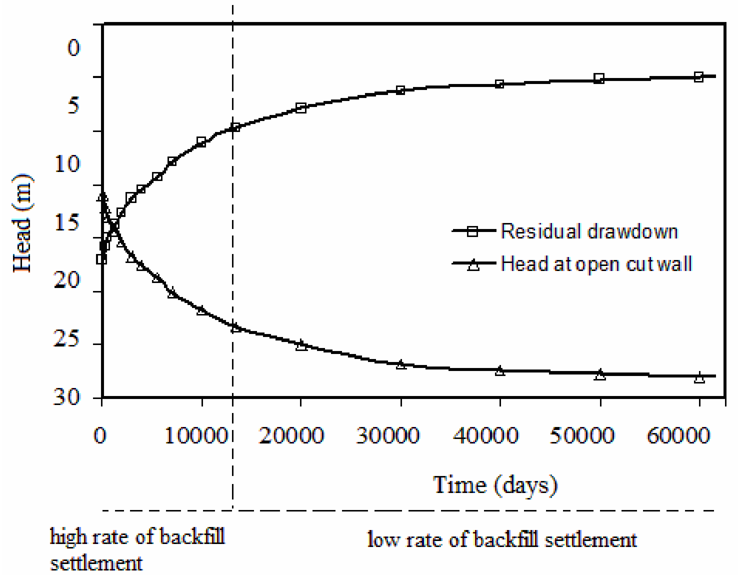


Fig. 8 - Residual drawdown as a function of time predicted at right wall of open cut, for a opencast mine in a shallow unconfined aquifer

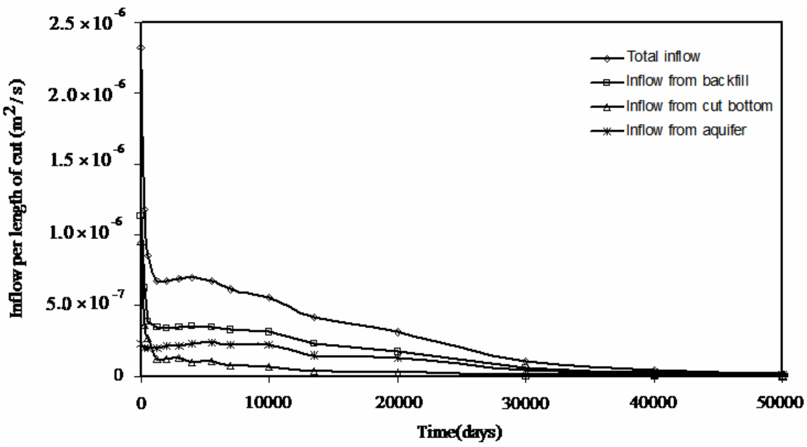


Fig. 9 - Quantity of ground water inflow per length of open cut predicted at various times

Figure 9 illustrates how the quantity of ground water inflow into an open cut of an opencast mine differs across a mine site. The amount of inflow occurring through the backfill is greater than inflows that take place from the cut bottom and through the unmined aquifer. Figure 9 shows that the inflow decreased rapidly within the first 500 days of the ground water rebound process, and that it continued to gradually decrease as simulation time progresses.

4 CONCLUSIONS

This paper presents a two-dimensional numerical finite element model to simulate ground water problems associated with backfilled opencast mines. The model used a suite of the SEEP/W libraries together with modified permeability and volumetric water content functions to simulate ground water rebound within a backfilled opencast mine. The model takes into account both saturated and unsaturated flow conditions. Ground water rebound is very fast soon (0-13,500 days) after cessation of dewatering, and that most of the backfill settlement is expected to occur at these times. Long-term creep settlement, which is less rapid, may occur during the remaining time period of the rebound process. These results from the modelling of the post-mining ground water rebound process give valuable information about settlement of backfill materials in coal opencast mines and suggest that land development should be postponed to the time period when backfill settlement is less significant.

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