The Hybrid Finite Element Mixing Cell method: a new flexible method for modelling mine water problems

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Abstract

Mine closure is often accompanied by a stop in dewatering operations. This generally induces groundwater rebound in the mined rock system with short and long term consequences that may be disastrous: soil instabilities such as landslides and subsidence reactivation, flooding, flooded basement and acid mine drainage.

Modelling tools can be very advantageous and efficient in helping understanding and managing such problems, however, classical modelling approaches have proved to be relatively unsuited to such contexts. Because of the former mining operations, the underground geological system is strongly disturbed (excavated, fractured and collapsed zones, galleries, large shafts, etc.). Using complex spatially distributed modelling approaches such as 3D finite elements usually lead to strong difficulties related to the lack of data, the complexity of geological and hydrogeological conditions (complex geometry, non Darcian fluxes…). On the other hand, using a simplified approach such as black-box models often leads to oversimplification of the reality: particularly when interactions between the mined system and its surrounding geological and hydrogeological environment are very important.

A new modelling approach is developed for simulation of the groundwater flow in such complex environments. It combines, in a single fully integrated simulator, a representation of the unmined area by a classical finite element modelling technique, together with conceptualisation of the worked areas and galleries by a group of mixing cells connected by pipes. The whole assembled groundwater flow model allows an accurate estimation and representation of (a) water infiltration (precipitations, river losses …) through the unsaturated zone reaching the exploited area (recharge of boxes) and (b) water exchanges with adjacent aquifers. The model can estimate the flow of groundwater in and around the minefield and the mean water level in the boxes. It is also capable of considering water exchanges between different mined zones, through connection pathways such as old roadways galleries and shafts.

Modelling concepts and equations are described and illustrated using basic and advances validation examples. A real case application corresponding to an abandoned coalfield in the region of Liège (Belgium) is used to illustrate the suitability and efficiency of the approach.

Introduction

Coalfield exploitation in underground mines causes significant changes in the geological and hydrogeological systems. Construction of shafts, galleries and roadways is essential to extract and transport the coal ore and dewatering operations are necessary as soon as the groundwater level is reached. These dewatering operations may lead to drawdown of groundwater levels nearby the exploitation and increased infiltration rate and seepage from the surface water network (Adams and Younger 1997). When the mine is closed, pumping operations are most often stopped causing a groundwater rebound whose short and long term consequences may cause severe damages such as soil instabilities, flooding and acid mine drainage (Younger et al. 2002). The most obvious solution to avoid these harmful consequences consists in maintaining pumping operations after mine closure. Such a solution has been considered in several cases such as in the Durham coalfield in England (Sherwood and Younger 1994) and in the Ruhr and Saarland coal mine districts (Eckart et al. 2004) but it is very expensive. Groundwater flow models have proved to be particularly useful to help decision makers in studying and managing groundwater rebound. Except for large-scale problems (Sherwood and Younger 1994), classical modelling techniques are not so suited for mine water problems because classical groundwater flow equations (based on Darcy's law) are not valid in large voids of the exploited zones. Furthermore, lack of knowledge on hydrogeological conditions and scarcity of data concerning the exploited zones and their interconnections are other reasons limiting the use of classical modelling techniques in mine problems. Consequently, specific modelling techniques are required.

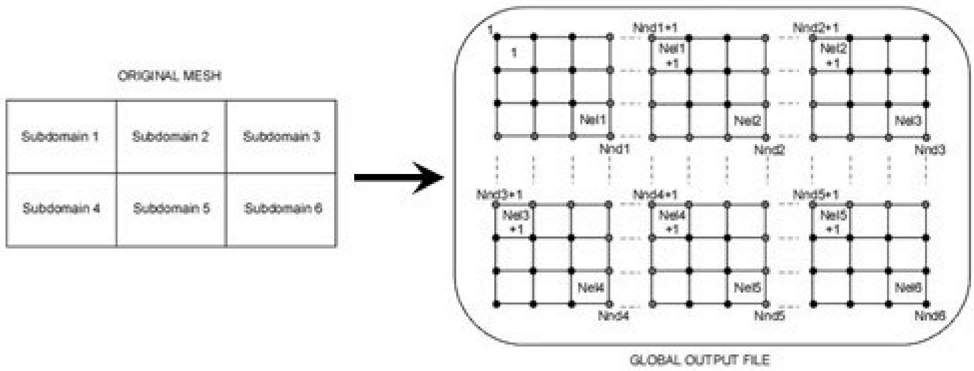
The most recent and specific techniques developed for modelling mine water problems range from box model techniques where the coalfield is conceptualised using interconnected "boxes" representing the exploited zones (Sherwood and Younger 1997) to physically-based techniques where the coalfield is conceptualised using a 3D classical modelling technique for the unexploited zones coupled with pipes representing explicitly shafts, roadways and other voids of the exploited zones (Adams and Younger 1997; Younger et al. 2002; Boyaud and Therrien 2004). Recently, Eckart et al. (2004) have also proposed a combined but decoupled dual technique where the coalfield is conceptualised using a box model approach and the overlying aquifers are modelled using classical finite elements. Simplified approaches such as box models are easy to use and most often accurate enough to model water levels in the mined zones, however, they do not allow considering explicitly the complex interactions between the mined zones and their surrounding environment. Complex 3D modelling approaches such as spatially-distributed and physically-based models require accurate data and very detailed information on the underground geometry, together with advanced parameterization of the equations, which are most often unavailable except at a very local scale.

The Hybrid Finite Element Mixing Cell (HFEMC) method proposes an elegant and advanced solution to these problems by representing, in a fully integrated and interacting way, mined zones by mixing cells that can be interconnected by pipes and unexploited zones by classical finite elements. The HFEMC method was implemented in the SUFT3D (Saturated and Unsaturated Flow and Transport in 3D) finite element code.

Concepts and equations of the HFEMC method

The fundamental principle of the HFEMC method consists in dividing the modelled zone into subdomains because they are hydrogeologically independent or they have to be modelled using different kinds of equations (Figure 1).

Figure 1 *Original mesh division into several subdomains and renumbering of dual nodes (MESHDIV)*



At the interfaces between these subdomains, internal boundary conditions are defined that allow considering and modelling the exchanged water fluxes and calculating separate groundwater budgets for each of them. Three types of internal boundary conditions can be used: (1) Dirichlet or 1st type *dynamic* boundary conditions where the coupling between subdomains implies the equality of the piezometric head along the internal boundary but this value can vary with time and remains an unknown of the problem, (2) Neumann or 2nd type boundary conditions (impervious) where the first derivative of the piezometric head is set equal to 0 on a portion of the internal boundary and (3) Fourier or 3rd type *dynamic* boundary conditions where the exchanged flux along such an internal boundary depends on the difference of piezometric heads on each side of the boundary (once more, these values can vary and remain unknowns of the problem). A specific interface (MESHDIV) has been developed to manage meshing operations such as performing the division into subdomains and the definition of internal boundary conditions.

Three mathematical and numerical formulations are available for solving the flow problem in each subdomain (Table 1). This allows using a simplified box model approach for mined compartments simultaneously with classical groundwater flow equations in porous media for unexploited zones and adjacent aquifers. The HFEMC modelling approach allows modelling direct connections between box models using first order transfer equations in order to account for by-pass flows through preferential flow structures such as shafts and roadways. These connections can be switched on and off according to user-defined rules in order to allow for rock collapses and to model water inrushes related to such events.

Table 1 *Flow equations implemented in the SUFT3D code*

Simple linear reservoir	$Q_{LR} = S_{LR} \times A_{LR} \times \frac{\partial \overline{H}_{LR}}{\partial t} = -\alpha_{LR} \times (\overline{H}_{LR} - H_{ref}) + Q$
Distributed linear reservoir	$Q_{LR,i} = S_{LR,i} \times A_{LR,i} \times \frac{\partial H_i}{\partial t} = \sum_{j=1}^{n} \alpha_{ij} \times (H_j - H_i) + Q_i$
Flow in porous media	$F \frac{\partial h}{\partial t} = \underline{\nabla} \times (\underline{\underline{K}} \times \underline{\nabla}(h + z)) + q$

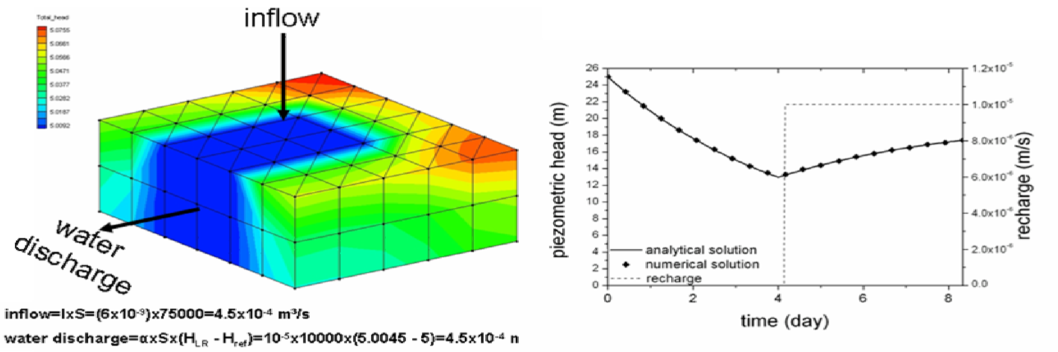
S_{LR} = specific storage of the linear reservoir (-), A_{LR} = area of the linear reservoir (L^2), $\overline{H}_{LR}$ = mean water level in the linear reservoir (L), α_{LR} = exchange coefficient of the linear reservoir (L^2T^{-1}), H_{ref} = drainage level of the linear reservoir (L), Q = source/sink term (L^3T^{-1}), F = generalised specific storage coefficient (L^{-1}), $\underline{\underline{K}}$ = hydraulic conductivity tensor (LT^{-1}), h = pressure potential (L), z = gravity potential (L), q = source/sink term by unit volume (T^{-1}).

Examples of application of the HFEMC modelling approach to mine water issues

An application of the HFEMC modelling approach to a real case study is under development. Here, a synthetic case study is presented to illustrate and validate the approach. First results obtained with the real case study are then described.

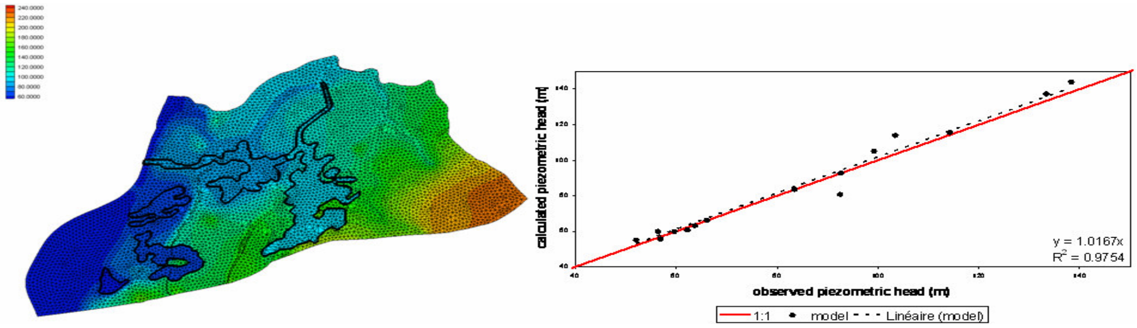
The synthetic example consists in modelling a simple parallelepiped mesh divided into two subdomains. The first corresponds to a mined zone modelled using a linear reservoir, the other represents the surrounding unexploited rock mass modelled using classical porous media. Fourier boundary conditions are prescribed at the internal (exchanged flux between subdomains) and external (water discharge from the mined system) boundaries of the linear reservoir. External lateral faces of the porous media are defined as impervious and a constant recharge (inflow) is prescribed on the upper faces of the entire mesh. Figure 2 (a) shows the resulting piezometric heads, constant in the mined zone and variable in the surrounding porous media which is drained by the mined structure. The piezometry calculated using the HFEMC modelling approach has been compared with the solution obtained by considering for the mined area an equivalent porous media of very high hydraulic conductivity instead of the linear reservoir. The two calculated piezometries are very similar, however, using a linear reservoir approach is accurate enough with the advantages of limiting the number of unknowns and preventing from numerical instabilities due to high contrasts in permeability. Another synthetic example performed on a simple parallelepiped mesh allows validating numerical solutions of the simple linear reservoir equation in transient regime (no recharge period followed by a constant recharge period). Figure 2 (b) shows the comparison between analytical and numerical solutions. Analytical and numerical solutions prove to be identical.

Figure 2 *Synthetic examples performed (a) to check the working of internal boundary conditions and (b) to validate numerical solution of the linear reservoir equation in transient regime*



A real case application is under development for the abandoned coalfield of Cheratte (Liège, Belgium). Historical data has indicated that the mined zones, galleries and roadways can be represented by five interconnected compartments interacting with adjacent and overlying geological formations modelled as classical porous media. Until now, a steady-state model has been calibrated based on mean piezometry (Figure 3) and water discharge rate measurements performed in the area. The next step will consist in calibrating the transient model before simulating possible scenarios.

Figure 3 *Application of the HFEMC method to a real case in an abandoned coalfield in Cheratte (Liège, Belgium): calibrated steady-state model*



Conclusions

A new modelling approach, called HFEMC, has been developed and validated for the simulation of groundwater flows in complex underground mined systems by the combination, in a fully integrated way, of interconnected mixing cells used to represent the mined volumes, together with classical finite elements used to represent the surrounding unexploited geological zones. The HFEMC method constitutes a useful managing tool for mine water problems since it allows estimating water infiltration through the unsaturated zone (precipitations, river losses …) and taking into account interaction between exploited zones themselves and between exploited zones and adjacent aquifers.

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