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Application of artificial neural network coupled with genetic algorithm and simulated annealing to solve groundwater inflow problem to an advancing open pit mine

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SUMMARY

In this study, hybrid models are designed to predict groundwater inflow to an advancing open pit mine and the hydraulic head (HH) in observation wells at different distances from the centre of the pit during its advance. Hybrid methods coupling artificial neural network (ANN) with genetic algorithm (GA) methods (ANN–GA), and simulated annealing (SA) methods (ANN–SA), were utilised. Ratios of depth of pit penetration in aquifer to aquifer thickness, pit bottom radius to its top radius, inverse of pit advance time and the HH in the observation wells to the distance of observation wells from the centre of the pit were used as inputs to the networks. To achieve the objective two hybrid models consisting of ANN–GA and ANN–SA with 4-5-3-1 arrangement were designed. In addition, by switching the last argument of the input layer with the argument of the output layer of two earlier models, two new models were developed to predict the HH in the observation wells for the period of the mining process. The accuracy and reliability of models are verified by field data, results of a numerical finite element model using SEEP/W, outputs of simple ANNs and some well-known analytical solutions. Predicted results obtained by the hybrid methods are closer to the field data compared to the outputs of analytical and simple ANN models. Results show that despite the use of fewer and simpler parameters by the hybrid models, the ANN–GA and to some extent the ANN–SA have the ability to compete with the numerical models.

1. Introduction

Groundwater is a natural resource, which can have negative effects on mining operation (Brawner, 1986). In mines where excavation is carried out below the water table, water flows from the surrounding strata towards the mining works. In particular, in the case of a confined aquifer, as the overburden materials and the mineral deposit are extracted during the mining operation, the impervious bed(s) may break and water under high-pressure may flow into the mining excavation (Bahrami et al., 2014). Investigations have revealed that the resulting unexpected inflows in large quantities may impede production, delay the project and may cause many safety and environmental problems (Singh and Atkins, 1985a, b). Undesirable effects of this may include:

- loss of access to all or part of the mine working area,
- greater use of explosives,
- increased explosive failures resulting from wet blast holes, or the need to use special explosives,
- increased wear to equipment and tyres,
- inefficient loading and hauling,
- unsafe working conditions (Morton and Van Mekerk, 1993).

Furthermore, groundwater inflow can have a harmful effect on pit slope stability. Hence, it is necessary to design an effective dewatering system to defeat these problems and simulation of groundwater inflow will greatly assist in this design work.

Further problems can follow because dewatering can place considerable hydrological stress on the regional groundwater system by creating an extensive and prolonged cone of depression, regional groundwater table lowering, overlapping cones of depression, land subsidence, and water quality deterioration, problems which can endanger mine productivity and even human life (Keqiang et al., 2006). All of these problems are related to changes in

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hydraulic head (Morton and Van Mekerk, 1993) so modelling the hydraulic head during pit advance can provide valuable information for designing an appropriate dewatering scheme.

Many analytical solutions have been used to estimate groundwater inflow into mining excavations (e.g. Hofedank and Engineers, 1979; Lewis, 1999; Marinelli and Niccoli, 2000; McWhorter, 1981; Singh and Atkins, 1985a, b; Singh et al., 1985; Singh and Reed, 1987; Singh and Atkins, 1984; Vandersluis et al., 1995) but analytical models are based on some assumptions and specific boundary conditions that limit their applicability in different mining situations. For example, most analytical solutions do not directly account for inflow through the pit bottom (Hanna et al., 1994) and they cannot simulate hydraulic head and saturated/unsaturated flow conditions in a confined aquifer (Doulati Ardejani et al., 2003a). Hence, analytical solutions are not appropriate for all hydrogeological situations.

Numerical models are routinely used for simulation of the groundwater flow in a complex aquifer system, the finite element method incorporating the Galerkin approach (Gray and Pinder, 1974) being recognised as a strong and powerful numerical technique for this purpose (Rabbani and Warner, 1994). Several numerical models have been developed to predict the groundwater inflow to open pit mines and to predict the hydraulic head in observation wells at different distances from the centre of the pit (e.g. Aryafar et al., 2009; Bahrami et al., 2014; Crowe et al., 2004; Doulati Ardejani et al., 2003a; Hernández et al., 2012; Singh et al., 2012).

Bahrami et al. (2014) presented a two-dimensional (2D) numerical finite element model using SEEP/W (Geo-slope International Limited, 2012) software to predict the groundwater inflow to an open pit mine, and modelled the hydraulic head in observation wells at different distances from the centre of the pit, for the period of the mining process. The accuracy and reliability of this model results were verified by field data and the results obtained by analytical solutions.

Doulati Ardejani et al. (2003a) presented a 2D numerical finite element model using SEEP/W software to predict groundwater inflow to surface mining excavations and to calculate the height of the seepage face in and around the pits. They simulated saturated/unsaturated flow conditions, taking into account the hydraulic conductivities and the water content as a function of pore water pressure. The simulation results were compared to those from analytical solutions and other existing numerical codes developed for pit inflow prediction but the application of the model in a real mine was not evaluated.

Crowe et al. (2004) developed a numerical model to simulate groundwater–wetland interactions and contaminant transport. The model calculates transient hydraulic head and a transient free surface in a 2D, heterogeneous domain, with variable and transient boundary conditions. It includes infiltration, evapotranspiration and surface water flow together with the water and contaminant fluxes across the aquifer–wetland interface.

Hernández et al. (2012) developed a physically-based numerical model that includes new approaches for a finite element solution to the steady-transient problems of the joint surface-groundwater flows of a particular region using a Geographic Information Systems to store, characterise, manage and take decisions on all the simulated conditions.

Aryafar et al. (2009) applied SEEP/W software as a simulation tool to predict groundwater inflow from an infinite confined aquifer into the Sangan open pit mine. The inflow simulation was first evaluated and verified by comparing the output from the model with results obtained from Theis, Cooper–Jacob and Jacob–Lohman analytical solutions. The model was then used to predict groundwater inflow into the Sangan open pit mine during its advance. It was found that the analytical Jacob–Lohman solution and the numerical model present an approximately similar trend of inflow rate as a function of time. Although the model describes well the inflow problem related to a confined aquifer, a comparison between the predicted inflow and the real inflow was not presented.

Singh et al. (2012) investigated the hydrogeological problems relating to the Thar lignite field in Sindh, Pakistan. They described the proposed mine dewatering system to facilitate depressurising of the rock mass surrounding the mining excavations. A SEEP/W finite element model was used to predict groundwater inflow to the surface mining excavation during its advance. A sensitivity analysis was carried out to evaluate various factors affecting groundwater inflow. It was concluded that the model is very sensitive to permeability of the aquifer.

Numerical methods have been also used by the other researchers to simulate mine water problems (e.g. Azrag et al., 1998; Davis and Zabolotney, 1996; Dong et al., 2012; Naugle and Atkinson, 1993; Rogowski and Weinrich, 1981).

Although numerical methods have been widely used for groundwater flow modelling and mine water related problems, these models require many parameters including hydraulic conductivity of the aquifer, transmissivity, pre-dewatering initial hydraulic head, rainfall data, saturated thickness of the aquifer, specific storage, porosity and other specific initial and boundary conditions. Determining all of these highly nonlinear characteristics is very difficult and requires a lot of time and cost. In addition, the number of factors required for developing a model can increase the uncertainty of its final results by accumulation of the miscalculations in the factors.

Approximation models such as artificial neural networks (ANNs) provide a powerful and reliable alternative with fewer required inputs to predict the nonlinear behaviour of groundwater inflow to open pit mines and changes in hydraulic head in the vicinity of the mine during pit advance. An ANN is an empirical modelling tool that is based on the behaviour of biological neural structures (Doulati Ardejani et al., 2013; Yao et al., 2005) and the use of such networks is rapidly increasing, especially in process modelling, simulation and predictions (Banerjee et al., 2011; Doulati Ardejani et al., 2013; Khalil et al., 2011; Sadeghiamirshahidi and Doulati Ardejani, 2013; Yoon et al., 2011).

Doulati Ardejani et al. (2013) presented a neural network model to predict the groundwater rebound process after cessation of dewatering at a restored open cut coal site in the East Midlands area of the UK. Time (days after dewatering), water table levels in the aquifer and the backfilled site, hydraulic conductivity of the aquifer and backfilled site, and precipitation were used as inputs. The output of the network was the water table height (residual drawdown). A feed-forward artificial neural network incorporating batch gradient descent with a momentum-learning algorithm and 6-1-6-1 arrangement was used to achieve this goal.

Banerjee et al. (2011) developed an artificial neural network (ANN) to estimate groundwater salinity in island aquifers. A feed-forward ANN model with quick propagation as training algorithm has been used to forecast the salinity under varied pumping rates.

Yoon et al. (2011) presented two nonlinear time-series models for predicting groundwater level (GWL) fluctuations using artificial neural networks (ANNs) and support vector machines (SVMs). The models were applied to GWL prediction of two wells at a coastal aquifer in Korea.

Three models have been developed by Khalil et al. (2011), for the estimation of water quality mean values at ungauged sites. The first model is based on ANNs, the second model is based on ensemble ANN (EANN) and the third one is based on canonical correlation analysis (CCA) and EANN.

Sadeghiamirshahidi and Doulati Ardejani (2013) presented a feed-forward multi-layer ANN with back-propagation learning