Finite-Element Modelling Approach to Study Flow Processes During Groundwater Rebound in Abandoned Underground Hard Coal Mines

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Abstract

Groundwater rebound is one of the key challenges for the renaturation of underground mines. Numerical models can support the computation of rebound curves and the identification of long-term groundwater levels after steady-state conditions are reached. The present finite-element model case was to test the combination of different flow types and parameter configurations inside mine workings in order to optimally represent the flow patterns in cavity volumes and fractured rock masses. The approach may be an alternative to common pond-and-pipe models, particularly, if estimated cavity volumes of mine workings are uncertain or if groundwater levels in the surroundings are precarious.

Keywords: Groundwater Rebound, Finite-element Modelling, Flooding, Underground Mine, Hard Coal

Introduction

After the abandonment of underground hard coal mines, groundwater rebound constitutes a challenge for post-mining management of collieries. While mine water is constantly removed during active mine operation, water inflows from overlying aquifers and regional groundwater flow steadily flood mine workings once pumping is stopped. Targeting an environmentally compatible renaturation of collieries the prediction of rebound curves and steady-state groundwater levels in the surroundings of the mine are essential information.

In practice, pond-and-pipe models are typically employed to calculate the internal groundwater rebound. They use a finite-volume approach to balance the entire void space (including mine workings, mined coal seams, cavities and pore space) and the inflow of groundwater. Such models define flow functions at known water transfer points between two hydraulically disconnected volumes (Kortas and Younger 2007; Kessler *et al.* 2020). This is advantageous regarding the fragmented data basis, as mining reveals the geology and rock constitution only point-by-point relative to the entire aquifer volume mining has an effect on. On the other hand, groundwater heads in the contiguous rock matrix are not calculated and thus, cannot resolve the potentiometric rebound in the surroundings of the mine.

Fully-meshed finite-element models discretize the entire modeling space including rock matrix, geological structures and, if needed, single cavities and mine workings. That means that the model domain needs to be parameterized in its entire extent. The approach is thus costly in computation time and data requirements. The advantages are the depiction of physically-based flow and transport processes and spatially differentiated rebound curves that can be computed for any point within the modelling space (Kessler *et al.* 2020).

Model outline

The former hard-coal mining site Westfalen in Germany was selected for modelling groundwater rebound using a finite-element approach. The colliery has hydraulically an “island position” and is thus isolated from other mining sites or any neighbouring mine water management systems (Rüterkamp *et al.* 2000). It can be considered a closed system and is as such suitable for the present modeling approach. The colliery was finally closed in the year 2000 and since then infiltrating water is expected to flood the mine. Due to backfilling of the shafts, the ongoing groundwater rebound is neither measured nor documented. As a result, a classical model calibration along measured groundwater heads is impossible. The baseline of the model is a detailed representation of the "empty" mine workings embedded in large-scale model space. The mine workings constitute the bulk of the floodable cavity volume in the mine. Unlike pond-and-pipe models both free flow in the cavities and porous medium flow are combined. The hydraulic parameterization is iteratively adjusted and analysed on its sensitivity regarding the modeled rebound curve.

Despite the backfilling of the winding shafts, the focus of the model is laid on the design of a discretized model that is able to reproduce the water level rise inside the mine. Backfilled shafts are yet considered as preferential flow paths with hydraulic conductivities higher than the adjacent rock matrix (Rüterkamp *et al.* 2000). At the same time, the model should be able to show the consequences on groundwater potentials in the contiguous rock matrix. Such an approach requires knowledge about the geometry and the hydraulic circumstances of the mine workings, a profound database of material properties and fracture characteristics in the collapsed overburden, and an quantitative idea of water inflows from extraneous and geogenic sources. Most of that information is available or can be estimated for the Westfalen site.

Location and hydrogeology

The Westfalen mine is located near the city of Ahlen in North Rhine-Westphalia at the Eastern edge of the Ruhr coal mining area. The mined coal seams are part of a 650 m thick stratigraphic sequence of the Upper Carboniferous period (Angrick 1999). It consists of alternating strata of sandstones, silt- and mudstones and interposed coal seams (Rüterkamp *et al.* 2000). The thickness of the overburden varies between 730 m in the Southwest and 1060 m in the Northeast (Angrick 1999). It consists of massive Upper Cretaceous sediments forming two major aquifers. The lower aquifer is fractured and consists of 165-185 m of carbon-rich marlstones of the Cenoman and Turon stage (Rüterkamp *et al.* 2000). Overlying is a hydraulic barrier, the "Emscher Mergel", which is built of clayey marlstones with a thickness of 475-525 m. Above follows an upper aquifer which is, in the lower Campanian marlstones fractured, and covered by some quaternary sediments that form a porous aquifer (Rüterkamp *et al.* 2000). Regarding the groundwater rebound primarily water from the lower confined aquifer is expected to infiltrate into the mine workings, besides some deep groundwater that flows through the mining area.

The carboniferous layers are subject to NE-SW striking folding and NW-SE trending normal faults dividing the mining district into a set of horst and graben structures (Hahne and Schmidt 1982; Grabert 1998). From a hydrogeological point of view, the fault structures are relevant as they transfer water from the lower aquifer into the mine workings below. Secondary fracture networks evolve above the mined seams due to mining activities and collapse of the overburden. The movement and disruption of rock masses increases the fracture void space and the hydraulic conductivity (Bahls 1963). They are less important for water inflow into the mine, but in reverse may facilitate the intrusion of mine water into the overburden (Rüterkamp *et al.* 2000). These mining induced fractures are time-dependent as subsidence and the high overburden pressure slowly close the fractures and void spaces.

Methods

Model setup

The numerical flow model is setup and run with the finite-element code FEFLOW (Diersch 2014). The modelling area of the Westfalen site covers an area of 500 km² with the colliery situated in the centre of the area. The boundaries of the model are constant-head limited and set in a far enough distance from the mine to allow large depression cones without influencing the regional groundwater flow too much. Due to hydraulic barrier of the "Emscher Mergel", no meteoric inflow or groundwater recharge is defined. Instead, the entire model is considered confined aquifers with varying hydraulic potentials.

The core of the model is the representation of the mine working itself including shafts, adits, banks and longwalls. All of those mining cavities are depicted at the appropriate scale and located correctly within the three-dimensional modelling space. The colliery has seven shafts and four main levels between 850 and 1200 m below the surface. The model is discretized with a structured meshing algorithm, facilitating a layered mesh design at all depths. Each mining level is represented as one separate modelling layer (Figure 1). Around the mine workings the mesh is refined to match the dimension of the cavities. Main adits and winding shafts are represented as one-dimensional discrete structures inside the model space that are not discretized separately. They are understood as embedded cylindrical objects that facilitate pipe flow and that are computed with the Hagen-Poiseuille equation (Sutera and Skalak 1993). Similarly, tectonic faults are treated as two-dimensional, subvertical planes with a Darcy flow type.

The rock matrix honours the hydrogeological units as well as the mining induced heterogeneities in the overburden of the min workings. According to Ma *et al.* (2016) a collapsed overburden of mined seams can be classified into three zones, the cavity, fissure and bending zone. Following this scheme, the matrix is divided into a set of model subspaces (undisturbed rock matrix, broken rock matrix, fissure zone and cavity zone).

Water inflows from the overlying Turon aquifer are considered with infiltration wells inside the discrete adits. In total 8 water inflow points are defined at the two lowest mining levels summing up to 5.3 m^3 per minute. Further boundary conditions such as leakage coefficients between the lower and the deeper aquifer or between matrix and the discrete structures are not defined. The transfer rates are unknown and vertical water transfer is accounted for at the inflow points.

Parameterization

The layered model structure allows to define hydraulic conductivities and specific storage values for all geological units in the overburden separately (Table 1). The same is done for the model subspaces in the hanging wall of the mine workings. Worked areas like gobs, longwalls and collapsed hanging walls, for example, are handled as highly conductive matrix bodies relating to the level of resolution and disorder (see cavity or fissure zone in Table 1). Most of the used parameter values are taken from the literature (e.g. Bahls 1963; Baltes *et al.* 1998; Denneborg and Müller 2017; König *et al.* 2017). Adits

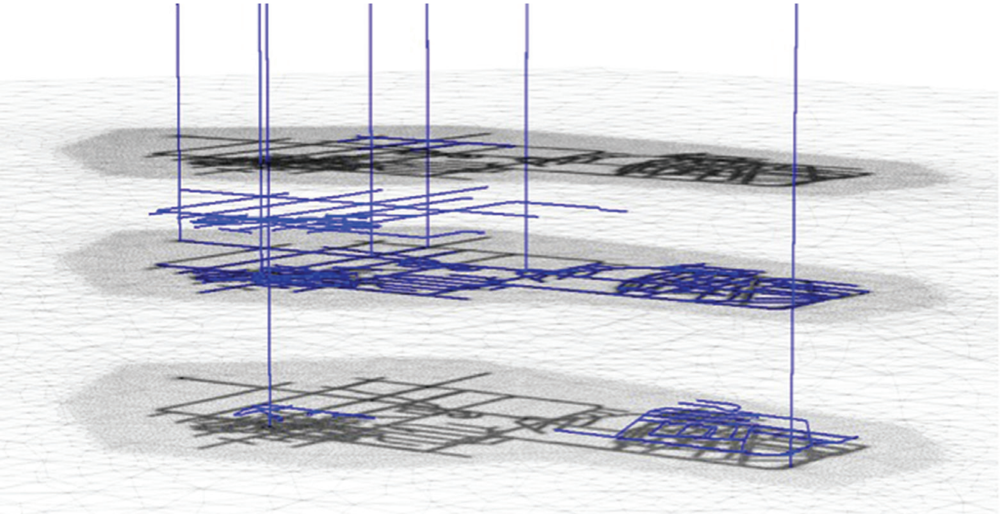

Figure 1 *Discretization of the mining layers including the winding shafts and main adits implemented as one-dimensional discrete features.*

***Table 1** Hydraulic parameterization of geological units and model subspaces within the mine workings (values adapted from e.g. Baltes* et al. *(1998); Denneborg and Müller (2017); König* et al. *(2017).*

	Hydraulic cond. horiz. [m/s]	Hydraulic cond. vert. [m/s]	Hydraulic aperture [m]	Specific storage [1/m]	Diameter / Thickness [m]
			overburden		
Campan (upper aquifer)	1e-07	3e-07	0.001	1e-04	
"Emscher Mergel" (hydraulic barrier	1e-10	1e-10	< 0.0001	1e-05	
Turon (lower aquifer)	2e-07	5e-07	0.001-0.003	1e-04	
"Essener Grünsand" (hydraulic barrier)	3e-08	5e-08	< 0.0001	1e-05	
			mining unit (carbonic deep aquifer)		
undisturbed rock matrix	8e-09	5e-09	< 0.0001	1e-07	
broken rock matrix	4e-08	1e-08	0.002	1e-06	9-24
fissure zone	4e-06	1e-05	0.005-0.05	5e-04	3-6
cavity zone	1e-02	1e-02	0.01-0.2	1e-04	1-2
			mine workings		
mine adits			0.002	0.95	5.5
mine shafts			0.002	0.95	4.0
			geological structures		
tectonic faults	1e-04	1e-04	0.001	1e-04	3.0

and shafts are defined as of tube geometry, specific storage and hydraulic aperture within the cavity volume. They determine how the structures internally facilitate water flow.

Groundwater rebound calculation

In order to model groundwater rebound, the entire colliery needs to be in a drained condition in the initial state. To achieve this, a constant-head boundary condition is set at the bottom of the deepest winding shafts. Once steady-state conditions are reached, the boundary conditions were removed and the model was converted into a transient model. Based on the steady inflow on the two lowest mining levels the model calculates the potentiometric heads inside the cavity volumes and in the adjacent rock matrix.

Unlike pond-and-pipe models for sites with an active mine water management, the present model cannot be calibrated with measured rebound curves, as the shafts of the Westfalen colliery became backfilled when the mine was closed. Instead, parameter variations are used to analyse the sensitivity of how the implementation of mining cavities or collapsed hanging walls affect the groundwater rebound. Starting point is a reference model that calculates a complete rebound in a time frame of 30 years.

Results and Discussion

The finite-element approach models the groundwater rebound as a combination of pipe and matrix flow. Mining adits and shafts are represented as one-dimensional discrete structures that are parameterized separately. Alternatively, mine workings can be discretized, too, but it is important to note that complete drainage of specific parts within the saturated zone is not feasible with internal boundary conditions.

The specific storage of cavity volumes needs to be set nearly 1, where values between 1e-04 to 1e-06 are commonly used for the rock matrix. An sensitive parameter for the cavity volumes is the hydraulic aperture inside the structures. Low values cause high storage captures inside the mine workings and keep the hydraulic gradient at a low level. Inflow water rapidly moves inside the adits and the water level increases almost simultaneously. In reverse, large apertures reduce the storage capacity and extend the

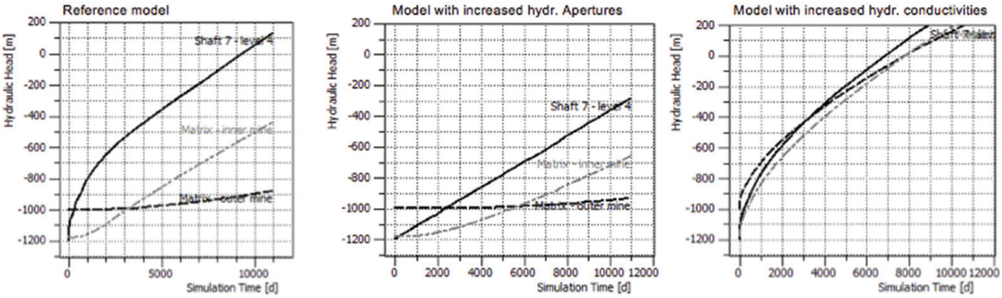

Figure 2 Groundwater rebound curves for: a) the bottom of the shaft No.7 (black solid line), b) in the unworked rock matrix within the mining area on the third mining level (grey dashed line), and c) in the rock matrix outside the mining area on mining level 4 (black dashed line). The left graph shows the reference case, the middle graph increased hydraulic apertures and the graph on the right illustrates the rebound with increased hydraulic conductivities.

flooding period. It also requires a remarkably higher computation effort. The effect of this parameter is shown in Figure 2. The left picture shows the reference model and the graph in the middle illustrates the rebound if large hydraulic apertures are used. The initial stage of the rebound in the shaft and inside the mined area is much slower and shows a linear increase.

The second important aspect of finite-element models is the parameterization of the gobs and the collapsed overburden. A vertical division of model subspaces was applied using hydraulic conductivities that decline with vertical distance from the mining level. The caving zone near the worked seams with void spaces of several decimetres in diameter have conductivities several orders of magnitude higher compared to the broken or fractured rock 20-50 m above. The fractured or disordered overburden may not be important for the downward movement of groundwater from upper aquifers. It is rather relevant for the upward infiltration during the flooding of the mine workings. The effect of an increased hydraulic conductivity of the rock matrix (two orders of magnitude) is shown in the left picture of Figure 2. The potentiometric rebound in the shaft and in the rock matrix is almost simultaneous, but also much faster compared to the reference case.

Finite-element have proven to be a good alternative for rebound modelling if the geometry and location of the main cavities are known and hydraulic properties of the adjacent rock matrix and the collapsed overburden can be estimated. The primary limitation of the approach is the numerical effort, as fine meshes as well as discrete structures require, depending on the parameterization, a lot more computational power as pond-and-pipe models would do.

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