Using MODFLOW with TMR to Model Hydrologic Effects and Recovery in the Shallow Aquifer System Above Longwall Coal Mining.

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Abstract

We are applying MODFLOW using Telescopic Mesh Refinement (TMR) to simulate hydrologic responses in the shallow aquifer system overlying longwall mining. The shallow system is separated from the deeper, heavily fractured zone by a confining zone and does not drain to the mine. Nevertheless, it presents special modeling problems due to rapid spatial and temporal changes in heads and hydraulic properties. TMR, in which a finer local model is embedded in a regional model, is a possible approach. For model development, we use a previous Illinois case study for which abundant data are available. In this preliminary study, we examine approaches to model boundaries, subsidence-induced changes in permeability and progression of the subsidence zone (in discrete stages), and head drops due to new fracture porosity (as sinks).

Key words: longwall; mine hydrology; modeling; TMR; subsidence; aquifer recovery

Introduction

This paper describes the early stages of a study into modeling the hydrologic response of the shallow overburden over longwall mining. We can apply standard MODFLOW approaches to the shallow groundwater system – here, the top 60-70 m of the overburden above a longwall mine that is 220 m deep – because it is separated from the deep fractured zone and direct drainage to the mine by a confining zone that is normally present in the mid-overburden over longwall panels. Nevertheless, because of subsidence-induced fracturing the shallow system undergoes substantial hydrologic impacts, including steep hydraulic gradients and rapidly changing boundary conditions and hydraulic properties around the mine subsidence zone, which itself is moving. These problems require detailed model discretization across spatially difficult areas and thus should be suited to Telescopic Mesh Refinement, an established technique in which the boundary conditions for a finely discretized, local/site model are defined from a coarser regional flow model in which the local model is nested. We are currently using Groundwater Vistas® (Environmental Simulations Inc.) a widely used MODFLOW interface. We focus on procedures for application and are not making code changes.

Hydrologic Effects of Longwall Mining

Longwall mining extracts large rectangular panels of coal, typically 200-400 m wide and several km long, causing rapid subsidence of the overlying strata and ground surface, and producing a subsidence trough over the advancing panel. Fracturing and bed separations increase fracture porosity and permeability of the overburden strata. In the heavily fractured strata immediately above the mine, extensive dewatering and drainage to the mine occur. However, intermediate levels in the overburden typically retain low-permeability aquitard (confining) characteristics that isolate shallower aquifers from draining to the mine. Hydrologic responses above the aquitard zone result from subsidence-induced *in situ* changes in hydraulic properties and typically include large drops in potentiometric water levels in bedrock aquifers, often followed by recovery, and changes in hydraulic gradients, groundwater discharge, and well yields (see Booth, 2002, for overview and references).

Head drops in the shallow bedrock are caused by several mechanisms other than mine drainage:

(1) Increased fracture porosity due to opening of joints and separation of bedding planes. Water drains rapidly into the new void space, producing a deep potentiometric low across the subsidence area.
(2) Water levels in the surrounding area decline as water drains toward the potentiometric low. This "drawdown" spreads ahead of mining at a rate and to a distance dependent on aquifer transmissivity; it controls the hydrologic "radius of influence" of longwall mining.
(3) Increased fracture permeability within subsided strata reduces hydraulic gradients and lowers water levels upgradient.

(4) In areas with significant topographic relief, drainage of high-level aquifers through fractured aquitards to lower aquifers causes significant, often permanent head drops.

After the initial subsidence phase, rapid partial recovery of water levels may occur during settlement and compression. In the longer term, recovery results from flow of water into the transient potentiometric depression, and depends on site-specific factors such as sources of recharge, transmissive aquifers, and continued drainage losses.

Modeling the effects of longwall mining

The complexity of longwall hydrology has deterred the application of typical groundwater modeling tools. It is thus difficult for engineers and hydrogeologists in companies or regulatory agencies to make site-specific hydrologic predictions or characterizations for specific mine permits and cases. Integrated models coupling strata deformation, changes in hydraulic properties, and groundwater flow (including variably saturated flow) throughout the overburden have been developed at a research level (e.g. Kim et al., 1997). However, the working engineer or hydrologist is more likely to look for familiar, available groundwater flow models such as commercially available interfaces for the USGS finite-difference model MODFLOW (McDonald and Harbaugh, 1988, and later developments). Such models cannot be applied to the mine and the intensely fractured, variably saturated region immediately above it, but they can be applied to the shallower system – of most interest for groundwater resources and stream interactions – that is above the intermediate confining zone. Nevertheless, several problems must be resolved, particularly the changing hydraulic properties, advancing subsiding zone, and steep hydraulic gradients and sharp spatial changes over the panels.

Finely discretized grids are needed to simulate such local areas of special complexity and rapid changes. However, using a fine grid over the entire model domain is computationally inefficient, and using variable spacing (finer in the area of interest) in a single MODFLOW-type finite-difference model is often inefficient and may generate errors (Mehl et al., 2006). Neither approach is suited to longwall subsidence configurations. We examine TMR, a well-established approach in which a coarse-grid “regional” model (RM) is used to define the ambient system and head and flux conditions on the boundary of a finer “local” model (LM) embedded within it, as a feasible approach. Although not to our knowledge previously used with longwall mining, TMR has been applied to other hydrogeological problems since the 1980’s (e.g. Ward et al., 1987). Procedures for using TMR with MODFLOW are discussed by Leake and Claar (1999) and for applying boundary conditions by Leake et al. (2003). Hunt and Steuer (2000) used TMR with Groundwater Vistas to connect a regional model (400-m spacing) to a site-scale model (100-m spacing), using the RM to assign constant-head boundary conditions for the refined model.

Mehl et al. (2006) distinguish between traditional TMR without interactive feedback, and recent methods that involve numerical coupling of the local and coarse grids, either directly or iteratively. In this preliminary study, we are applying traditional approaches in which LM boundaries are defined non-interactively from the RM. Our focus is how to apply the MODFLOW-TMR approach to the special problems generated by longwall mining.

Case study

For model development and calibration, we are using a well-documented case study (Rend Lake Mine, Jefferson County, Illinois, USA) conducted by Northern Illinois University (NIU) and Illinois State Geological Survey (ISGS) in 1988-1995 through active mining and five years’ recovery (Mehnert et al., 1994; Booth et al., 1997, 1998). The study focused on the last two panels of a four-panel section. Data monitored included ground subsidence, strata deformation, water levels in piezometers on-site and private wells across the mining area, and hydraulic properties from slug, pump, and packer tests.

The mine extracted the Pennsylvanian Herrin Coal (3 m thick) at depths of around 220 m, producing ground subsidence of about 2 m in a gently rolling landscape with only about 15 m of local relief.

About 90% of subsidence occurred within 3 months of mining. Overburden strata are shales and siltstones with clays, sandstones, and thin coals and limestones. A bedrock aquifer, the Mount Carmel Sandstone, comprises two sandstone benches locally separated by a shale-siltstone and totaling about 23 m in thickness, the top being 21-23 m BGS (below ground surface). The main sandstone bench is part of an apparent paleochannel (Mehnert et al., 1994), the edge of which is about 1.5 km west and

2.5 km north of the site. The sandstone is overlain by 15-18 m shale and 3-10 m surficial cover of glacial deposits.

The sandstone is moderately permeable. Natural hydraulic conductivities around 10^{-6} m/s increased during subsidence by one order of magnitude in the central subsidence trough and two orders in the residual tension zone along its edges. Initial water levels (already affected by mining) in the sandstone were about 20 m BGS (confined condition) and fell to a low of 42 m BGS during maximum tension in 1989 (unconfined). They recovered to about 10 m BGS by the end of monitoring in 1995.

Conceptual model development and current status

Lateral extent and spatial boundaries

The models represent the upper 60-70 m of the 220-m overburden system. Layers include the sandstone, immediately underlying shale-limestone units, and overlying shale and glacial drift. The regional model (RM) has an area over 20 km^2 and natural boundaries at the edge of the sandstone paleochannel to the west and north and a fault zone (in the bedrock) and large man-made lake to the east. The four longwall panels (each 200 m wide) and their barrier pillars and subsidence zones occupy only about 2.8 km^2. However, the effective radius of transmitted hydrologic influence is estimated at about 600 m, giving a total local model (LM) area of about 6.6 km^2. We intend to eventually apply automated interactive linkage between the RM and LM, but in this preliminary study we are applying traditional interaction and addressing model interaction and mine progression as discrete simulation stages.

Transient considerations and stress steps

Initial conditions and perimeter boundary conditions for the LM will be set from the steady-state, unmined solution of the RM. Within the LM, the following special problems must be addressed:

(1) Subsidence zones move as the panel advances.
(2) Elevations of ground and strata units change during subsidence.
(3) Bedrock permeability increases 1-2 orders of magnitude during the tensional phase.
(4) Bedrock fracture porosity increases rapidly during tension. Porosity itself is not a direct parameter in MODFLOW, but is contained in the storage coefficient (about an order of magnitude increase). However, the immediate physical mechanism is rapid opening of new void space into which water from the aquifer drains. This is not represented in the changing storage coefficient, but can be simulated by appropriate well sinks that are switched on during active tensional subsidence.
(5) Post-subsidence compression causes a slight back-reduction in permeability and porosity.
(6) Long-term recovery comprises a transient simulation with stable hydraulic properties and no well sinks.

Of the above, only well sinks and long-term recovery can be directly represented in the existing MODFLOW stress-step transient structure. There is no procedure for including transient changes in elevations or hydraulic properties, nor for progression of the subsiding zone through space. We will approach these changes by discrete runs of separately defined local models, the output from one being input to the next. From model to model, the zone of active subsidence will move discretely in space through successive runs. This zone is about 0.5 km^2 in area, covering the distance from observed first strain response to completion of major subsidence after about 3 months.

Current status

Adequate data for most aspects of the study, including subsidence, detailed site information, hydraulic properties, and potentiometric calibration values, are available from the 1988-1995 study or have been obtained from ISGS well records. Currently, we are in the early stages of the study. We have collected site data, are discretizing input to the models using GIS, and developing the model structures. The most straightforward modeling task and obvious first stage is the long-term recovery, which only requires stable properties with existing model structures. By the time of the conference we hope to have preliminary simulations and clarification of the conceptual issues discussed above. However, this is a work in progress and we welcome any input from colleagues.

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