# Benefits of *MINEDW* Code for Mine Dewatering Projects in Complex Hydrogeological Settings

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ABSTRACT: Numerical modeling of mine-dewatering projects requires specialized features that are not present in mass-use groundwater-flow codes such as *MODFLOW* and *FEFLOW*. Many features critical to modeling groundwater flow in mine settings can be found in Itasca's *MINEDW* finite-element groundwater flow code. The critical features include the ability to remove elements/nodes to simulate excavation of a pit; pinch-out capability to simulate in greater detail underground mines or specific areas of hydrogeological interests; simulation of non-Darcian flow and the transition to Darcian flow as heads and hydraulic gradients decrease; calculation of seepage faces in highwalls; and changes in hydraulic parameters in time to simulate block cave mining, longwall coal operation, or relaxation around a deep, open pit. Other features of *MINEDW* that enhance or simplify the modeling of mine dewatering projects include the use of specified-flux or specified-head boundary conditions, which when coupled with the fault-linking routine can simulate pumping from multiple levels in a well, variable-flux boundary conditions along external model boundaries, simulation of multiple faults without adding discretization with a fault-link subroutine, the use of a collapsing or rigid grid, pit-lake infilling simulations for both passive and active scenarios, and effective coupling of large, regional groundwater models with detailed window models.

## 1 HISTORY OF *MINEDW* DEVELOPMENT

The original version of the finite–element code *MINEDW* (version 1.0) was developed in 1992 by Tim J. Durbin (HCI, 1993) in purpose to the limitations of the current modeling software at that time, which included:

- Inadequate discretization (especially to simulate geologic features)
- Poor representation of pits and underground excavations
- Inability to properly handle non-linear flow at discharge points
- Poor representation of seepage faces in the pit

The core of the *MINEDW* code is based on algorithms of thefinite-element code *FEMFLOW3D* developed for the United States Geological Survey *(*Durbin and Berenbrock, 1985; afull description is given in Durbin and Bond, 1998).

The original version of the *MINEDW* code was modified between 1993 and 2005 by Elfadil A. Azrag, to handle more diverse hydrogeological features for mining applications, and graphical visualization of model inputs and outputs. These modifications were made based on groundwater modeling of "world class" mine dewatering projects in Nevada, Canada, Indonesia, Chile, South Africa, and Botswana. The incorporation of new, and modification of existing, features was completed on an "as needed" basis to enhance groundwater model predictability. It should be noted that the *MINEDW* code (version 1.0) is based on numerous ideas conceived by Lee C. Atkinson and the groundwater hydrologists team (author was a member) who worked for HCI and HCItasca between 1992 and 2007.

Itasca Denver (Houmao Liu, Jianwei Xiang, et al.) developed *MINEDW* version 2.0 in 2012 and this version has been commercially available since April 2012. This version has significantly enhanced the three-dimensional graphic presentation based on the same framework as that implemented in the widely used geotechnical codes *FLAC3D* and *3DEC*, but some significant groundwater modeling features (e.g., collapsing grid to simulate the water table, simulation of permeable faults a by fault-link subroutine, interaction between regional model with more detailed window models, simulation of non-Darcian flow in the faults, removal of elements during mining, and subdividing of elements on seepage faces to better simulate pore pressures) developed in earlier versions of *MINEDW* have been deactivated and no longer exist for users in the commercially available version 2.0 of this code. These features need to be reconsidered for incorporation into version 3.0 so that the full capability of the code can be utilized.

It should be noted that the author is familiar with both versions of *MINEDW* (1.0 and 2.0) and the description of its key features and benefits for use in large scale mine-dewatering project described below are based on the author's more than 10 years of *MINEDW* modeling experience. This includes more than 10 projects to assess dewatering requirements for open pits, underground mines, and block-cave operations within complex hydrogeological conditions (Azrag et al. 1998; Ugorets et al. 1999; Hanna et al. 1999; and MacDonald and Ugorets, 2003).

## 2 KEY *MINEDW* FEATURES AND BENEFITS FOR MODELING MINE DEWATERING PROJECTS

### 2.1 *Generation of Optimized Model Grid for Mine Dewatering Applications*

<u>*Finite-Element Capability*</u>

As a finite-element code, *MINEDW* uses its capability of applying variable-sized elements to generate very detailed grids that match the configuration of mine developments. Figure 1 shows a plan-view of a model grid developed to simulate groundwater inflow to an underground mine with an element size around the mine workings equal to 5 meters.

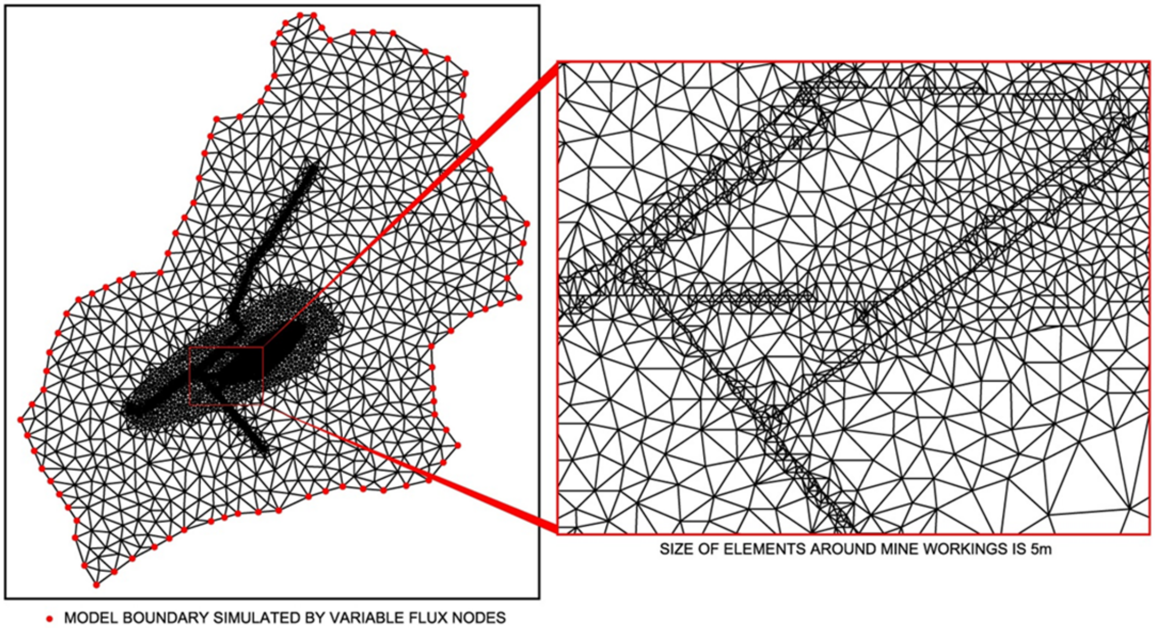


Figure 1. Model grid of detailed underground workings in plan-view using *MINEDW* finite-element capability.

<u>*Pinch-out capability*</u>

In order to maintain reasonable computational efficiency, *MINEDW* implements the concept of "layer pinch-out" allowing the user to (i) significantly reduce the total number of elements and nodes and (ii) create a "window" model within a large scale regional model. Figure 2 shows an example of the layer pinch-out configuration of a model in cross-section. In mine area, 26 model layers were used to simulate the underground workings. Immediately outside the mine area, the number of layers is 14. In the regional area, the number of model layers is six. By implementing the layer pinch-out approach, more vertical model layers can be assigned to the mine area, but these are gradually pinched out towards the boundaries of the model and common hydraulic parameters are 'smeared' through the pinched layers.

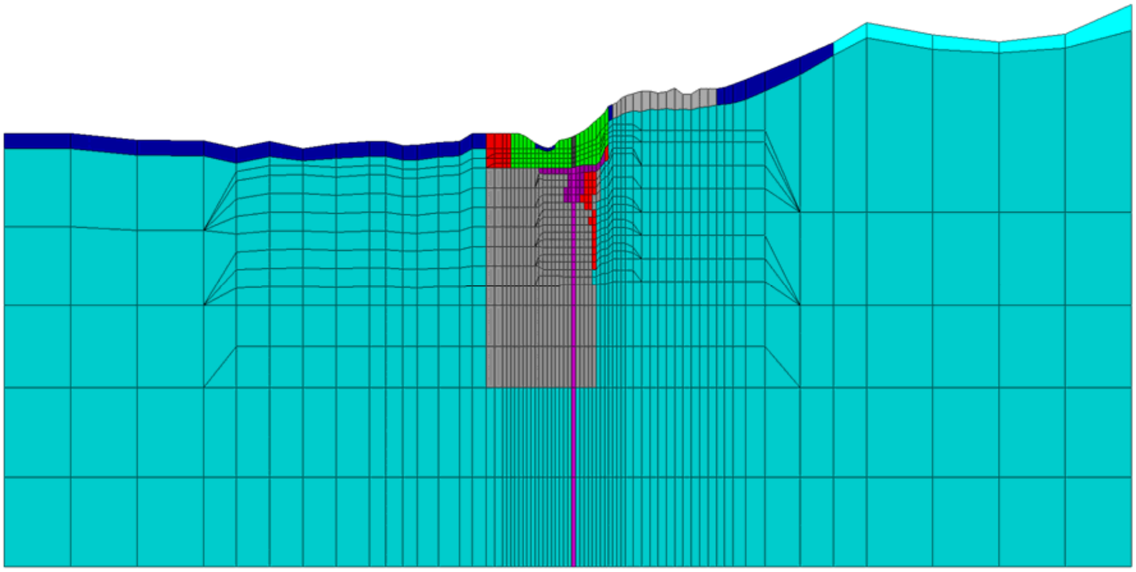


Figure 2. Modeled grid of underground mine in cross section using *MINEDW* pinch-out capability.

*<u>Window Model Capability</u>*

*MINEDW* implements coupling of a regional model and window models by extracting time-variable head values from selected locations in the regional model and then assigning them to boundary nodes at complementary locations in the window model.

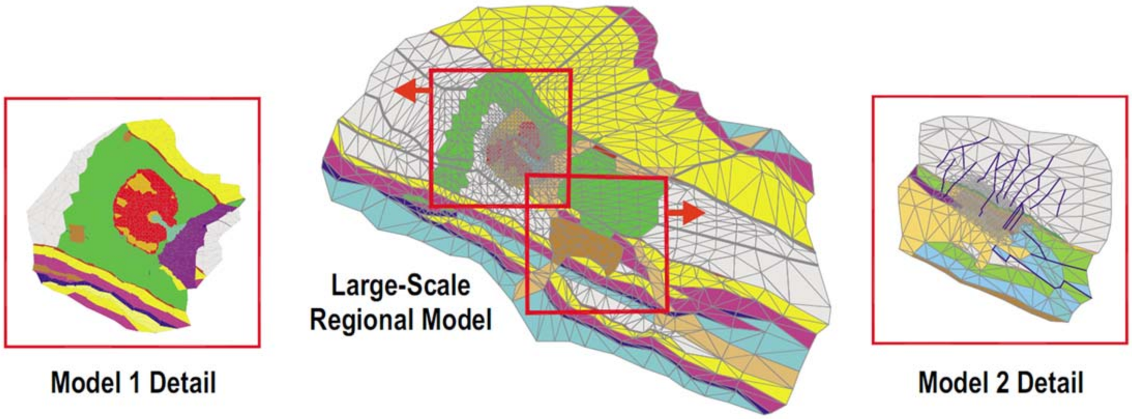


Figure 3. Modeled Regional Groundwater System with Detailed Mine Scale Window Models Using *MINEDW* Telescoping Capability.

Figure 3 shows a plan-view example of two detailed "window" models developed by the author to assess dewatering requirements for (i) an open pit and two block cave operations (Window Model 1) and (ii) multilevel vertical block cave operations (Window Model 2) within a large regional groundwater model used for environmental impact evaluation. In this example, the hydraulic heads at the nodes in the regional model that correspond to the boundary nodes of the window models were extracted at each time step. These extracted heads were then assigned as time-variable, specified-head boundary conditions for the window models used to predict large scale and long term dewatering requirements.

### *Variable Flux Boundary Capability*

Variable-flux boundary nodes used in *MINEDW* allow simulation of boundary fluxes that would result if the modeled groundwater flow domain is extended outward a great distance from the actual boundary of the model domain. This is accomplished by attaching the analytical solution for a semi-infinite linear aquifer (Carslaw and Jaeger 1959) to the boundary of the modeled flow domain. To ensure that the variable-flux boundary conditions are implemented properly, the actual boundary of the model domain should be far enough from the hydraulic stress so no part of the model layer is dewatered below the bottom of the layer. An example of simulation of the model boundary by variable flux nodes is shown in Figure 1 which allowed optimization of the model domain for assessment of dewatering requirements for an underground mine. The Author's experience indicates that use of variable flux nodes allows more precise simulation of additional groundwater flow from outside the model domain compared to General Head Boundaries (commonly used in the *MODFLOW* and *FEFLOW* codes) which potentially greatly over simplify conditions beyond model boundaries. This is because inflow/outflow to variable-flux nodes depends on groundwater storage parameters, while general head boundary flow depends on fluxes coming from constant head boundaries assumed at some distance from the model domain.

## 2.2 *Simulation of Open Pit*

*MINEDW* (version 1.0) allows simulation of an open pit excavation by two methods:

- Removal of elements and corresponding inactivation of nodes, or
- Collapsing of the grid inside the pit area

In the first method of simulation (described in Atkinson, Durbin, and Azrag, 1992), the input file identifies the elements representing the excavation that are to be removed in a specified time step. The code automatically removes any nodes that no longer are associated with any remaining elements. To represent the potential occurrence of a seepage face on the highwalls of the pit, the input file identifies the remaining nodes that define the surface of the excavation and specifies these as seepage face nodes. In order to adequately represent the seepage face, a relatively fine grid discretization is usually needed on the seepage face. To accomplish this, *MINEDW* automatically inserts additional elements and nodes on the surface of the excavation in each time step. As the excavation progresses, additional elements and nodes from the previous mining stage are removed and a new set of additional elements and nodes are inserted on the new surfaces of the excavation.

The second method (fully described in Itasca Denver, 2012 and incorporated in version 2.0) permits changing the elevation of the nodes at the top of the first layer within the pit area to the specified pit elevation based on mine plans. The hydraulic properties within the area of the collapsing grid are adjusted to the appropriate values representing the hydrogeologic units being excavated as the grid is collapsed to simulate mining. A minimum thickness of collapsed elements is specified by the user. By collapsing the vertical finite-element grids, the vertical discretization of the pit surface will be refined. This vertical refinement enables *MINEDW* to predict accurately the seepage rate to the excavated zone and the location of the seepage face (i.e., the outcrop of the phasing surface) on the slope.

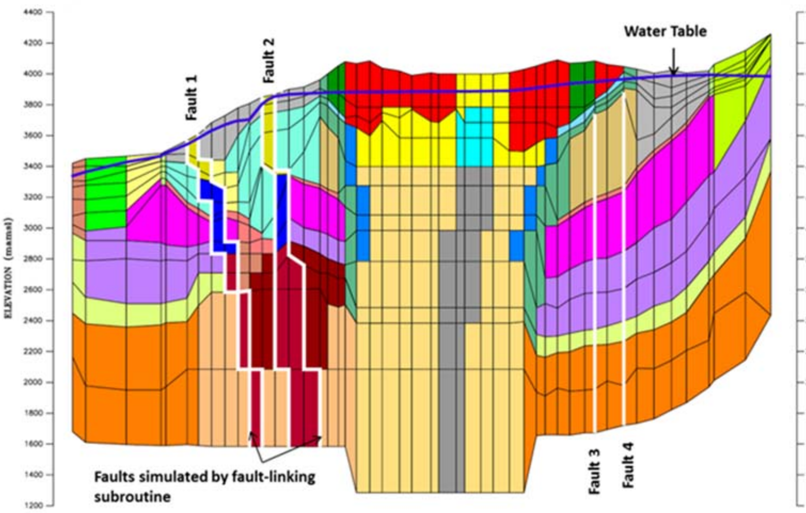
Seepage nodes used in both methods have specially-assigned parameters:

- The pressure at the node is zero (relative to atmospheric pressure) if the hydraulic gradient is outward (i.e., into pit) , or
- The flow assigned to the node is zero if the hydraulic gradient is inward (i.e., into highwall)

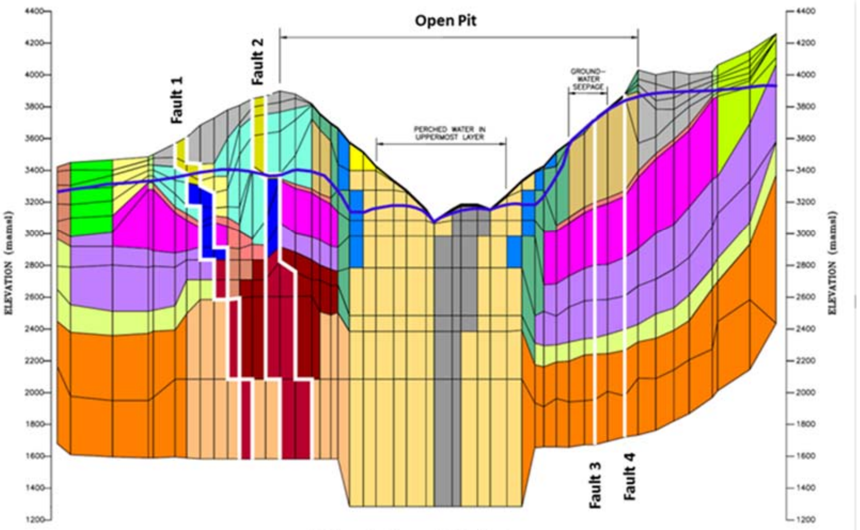
An example of open pit simulation by a collapsing grid is shown in Figure 4, where the original ground surface (Figure 4a) in time over a 20-year period was collapsed to an ultimate pit bottom elevation (shown in Figure 4b). The hydraulic properties within the area of the collapsing grid were adjusted by *MINEDW* automatically.

In the author's experience, *MINEDW* very efficiently incorporates open pit plans (yearly or even quarterly) and simulates pit excavation during life of mine in one transient model run. Pit lake infilling can be included in this run as well, in this case the ultimate pit shell is used for the pit-lake configuration.

a) Simulation of Pre-Mining Conditions



b) Simulation of Open Pit



c) Simulation of Block Cave

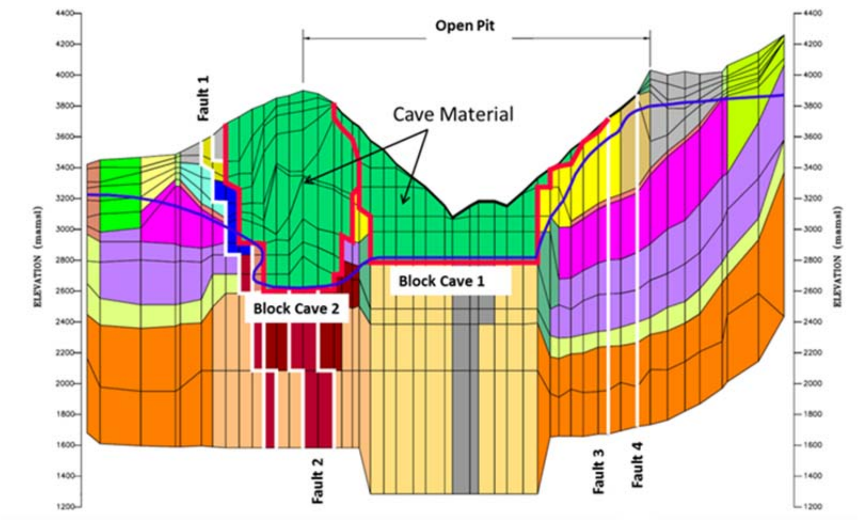


Figure 4. Simulation of open pit excavation and transition to block cave mining.

### 2.3 *Simulation of Underground Developments*

Uunderground workings and associated dewatering systems are usually simulated by drifts and drillholes. *MINEDW* allows incorporation of them using specific drain nodes with leakance factors calculated by:

$$C_L = \frac{K_m \cdot L \cdot w}{b} \tag{1}$$

where $C_L$ = leakance factor; $K_m$ = hydraulic conductivity of material; $L$ = dimension of element; $w$ = width of area; and $b$ = thickness of "membrane".

The value for $K$ is the computed average of the hydraulic conductivities (input value) of the elements around the drain node, $L$ is a function of grid discretization, and $w/b$, the so-called “connectivity factor”, is a value obtained through model calibration.

Additionally, *MINEDW* allows the user to account for local resistance to flow at relatively constrained discharge points such as drifts or drainholes by modifying the traditional drain node leakance factor $C_L$ to:

$$C'_L = \frac{C_L}{\sqrt{(\Delta h)}} \tag{2}$$

where $\Delta h$ = difference between hydraulic head and the specified drain elevation.

Incorporation of factor the $(\Delta h)^{1/2}$, which is dynamically calculated by *MINEDW*, is deduced from the Darcy-Weisbach relationship for pipe flow. The factor simulates additional resistance to flow into the drift or drainhole immediately after their installation when the gradient into them is high (i.e., $\Delta h$ is large). However, when the gradient decreases, the $(\Delta h)^{1/2}$ factor becomes smaller. Thus, the leakance factor becomes larger, resulting in less resistance to inflow.

### 2.4 *Simulation of Highly Transmissive Faults and Non-Darcian Flow*

*MINEDW* can simulate the effect of highly conductive zones such as faults without requiring the addition of discrete elements to the model grid. The so-called “fault linking” is accomplished by specifying node pairs which are coupled with a large (user specified) transmissivity. The effect is to simulate enhanced movement of groundwater between the linked nodes (vertically and horizontally) in addition to the normal calculation of flow between all nodes within the element. Examples of such highly transmissive features simulated by the*FAULT* subroutine include a fault zone, where groundwater easily can move parallel to the fault plane, or a well with a long completion interval, where groundwater easily can move from one depth zone to another through the well and gravel pack.

Groundwater flow near discharge points in fractured and faulted rock is almost always non-Darcian (Dudgeon, 1985), and the standard groundwater flow equation breaks down in describing such flow. To account for this non-Darcian flow, *MINEDW* utilizes the non-linear flow algorithm (described in Durbin, Atkinson, Azrag, 1992), which is based on the relationship:

$$K' = \frac{1}{a + bq} \tag{3}$$

where $K'$ = effective hydraulic conductivity; $a$ = linear coefficient from the Forchheimer equation; $b$ = non-linear coefficient from the Forchheimer equation; and $q$ = flux.

The values of $a$ and $b$ in the form of the ratio $b/a^2$ are input values that are varied during calibration, and the model dynamically changes the effective hydraulic conductivity near a discharge point based on the computed local fluxes. In practical application, the nonlinear ratio $b/a^2$ can be assigned a value of 0 for the matrix rock and from 1 to 100 for water-bearing structures which can be simulated by the *FAULT* subroutine of *MINEDW*.

An example of modeling transmissive faults in the vicinity of an open pit and block cave operation is shown in Figure 4. Eighteen faults were simulated by about 8,400 pairs of “linked” nodes with a transmissivity between 100 to 1,000 m$^2$/d, gradually decreased with depth to a value of 0.1 m$^2$/d. All drainholes and parts of the drifts which have intercepted significant inflows (greater than 50 gpm) were simulated in the model by drain nodes with leakance factors (Equation 2) and considered non-Darcian flow (Equation 3). They are represented by a series of more 400 drain nodes. The nonlinear ratio $b/a^2$ was assigned a value of 0 for the matrix rock (defaulting Equation 3 to Darcian flow) and 10 for water-bearing structures simulated by the *FAULT* subroutine of *MINEDW*. Results of completed modeling for this and another large scale dewatering project show that:

- Simulation of non-Darcian flow can be a significant factor in "throttling back" the inflow that could occur under totally Darcian flow
- Use of a time-variable leakance factor (depending on the change in hydraulic head) allows more realistic simulation of high water discharge by drainholes drilled into the transmissive faults

### 2.5 *Changing Hydraulic Parameters in Time*

*MINEDW* has the ability to change hydraulic parameters in time and space, simulating 3-D propagation of:

- Crackline and caved material during block cave mining
- Zone of relaxation around an excavated open pit (automated assigning of this zone is available only in version 2.0 of *MINEDW*)
- Open pit and underground void backfilling
- Deformation zone (goab) above longwall coal operations

Examples of model grids developed by the author to predict groundwater inflows to a block cave are shown in Figure 4c (multiple locations of the block caves, one of them – below an open pit) and Figure 5 (multilevel block caving) developed by author for large scale mining operations.

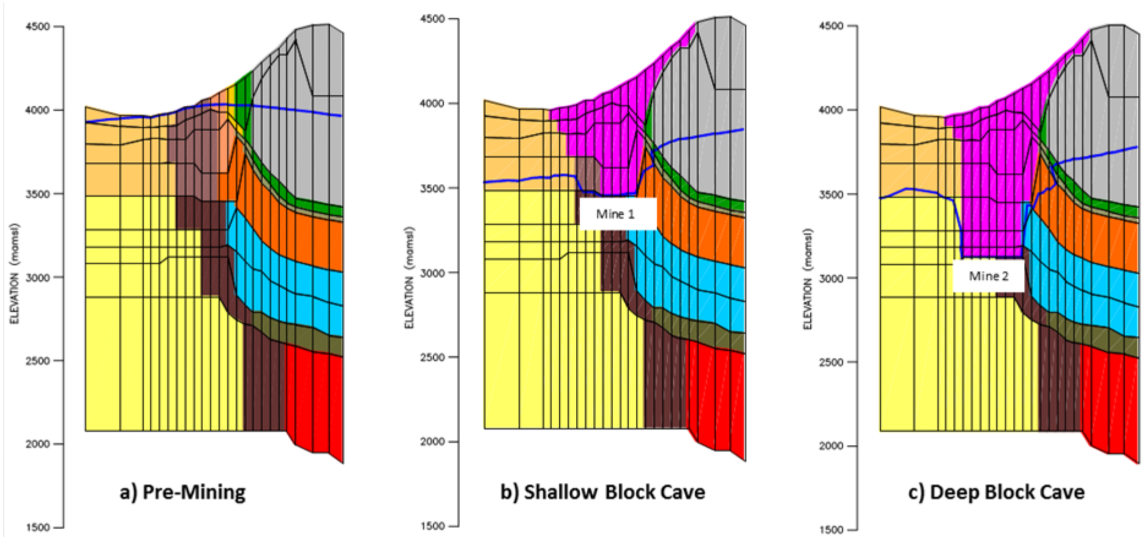


Figure 5. Simulation of multilevel block caving.

Forming of block caves was simulated by increasing (i) the hydraulic conductivity of deformed rock mass and (ii) recharge from precipitation over the area where the crackline is predicted to propagate to the ground surface in time. Hydraulic conductivity was increased gradually from an original value of 0.003 m/d to 0.1 m/d and 1 m/d within cracklines and block caves, respectively. The recharge factor (percent of precipitation) was increased from pre-mining values of 0.1- 0.85 to 0.95.

## 3 COMPARING *MINEDW* WITH MODFLOW-SURFACT AND FEFLOW

A detailed comparison of *MINEDW* with mass-used *MODFLOW-SURFACT* and *FEFLOW* groundwater-flow modeling codes completed by the author is shown in Table 1.

Table 1: Comparison of key features of *MINEDW* with *MODFLOW-SURFACT* and *FEFLOW* codes used for mine dewatering projects

| Factor/Attribute | | *MINEDW* | *MODFLOW-SURFACT* | *FEFLOW* |
|---|---|---|---|---|
| Mining and dewatering features | Open pit excavation with simulation of seepage face | Explicitly solves for height of seepage face (i.e. saturated material with P=0); simulates excavation of a pit by element removal with additional subdividing of seepage face elements1) or by collapsing of model grid in pit area with proper change in hydraulic parameters of collapsed elements; simulates pit excavation in time during one model run. | Uses seepage-face boundary but grid collapsing and changes in hydraulic parameters need to be done manually. | Seepage face boundary conditions can be scheduled with constraints. Alternatively deactivation /reactivation element feature can be use to simulate mining. |
| | Underground mine with increased resistance to groundwater flow due to non-Darcian flow | Explicitly calculates effective hydraulic conductivity based on classic Forcheimer relationship for two-regime flow; dynamically changes with time1). | Conduit Flow Process (*CFP*) package can be used with *MODFLOW 2005* only (does not work with *MODFLOW-SURFACT*). | Discrete elements can be used. Available flow laws are: Darcy, Hagen-Poiseuille, and Manning-Strickler. |
| | Dynamic changes in hydraulic conductivity due to mining (e.g. zone of relaxation adjacent to excavations, material in block cave, goab for long wall mining) | Hydraulic conductivity varies in time for individual elements or hydrogeologic zones. Automatically simulates zone of relaxation below pit by assigning thickness and hydraulic conductivity of deformation zone. | Version 4.0 of *MODFLOW-SURFACT* allows simulate time-varying material properties using *TMP1* package. | Simulates time-dependent material properties by linking the zone (the part of the model that needs to change) with a function. |
| | Pit lake infilling | Automatically generates volume/area vs. stage relationship, simulates pit lake infilling during the same run with mining, computes groundwater flows to pit from each geologic unit through time. Can simulate active pit lake infilling. | Uses *LAK2* package with separate model input. Difficult to simulate contribution of inflows from different geological units. | Not capable but an external code (*IFMLAKE*, freely available) can be used to simulate pit lake infilling. |
| | Pumping/dewatering wells | Simulates pumping wells by specified flux nodes which are replaced by drain nodes at specified freeboard elevation. Automatically links model within screen interval by high transmissivity. | *FWL4* well package simulates wells by pumping cells which are replaced by drain cells at specified freeboard elevation. Vertical hydraulic link of multiple layers within the screen cells needs to be done manually by increasing of $K_v$. | Uses Multilayer Well package with head constraints which allows specified pumping rate to be changed to a constant head. Replacement of pumping rate to a drain node required additional programming. |

| Factor/Attribute | | *MINEDW* | *MODFLOW-SURFACT* | *FEFLOW* |
|---|---|---|---|---|
| Grid discretization and geological features | Grid refinement around area of hydraulic stress (e.g., mines, pumping centers, etc.) | Accomplished by subdividing prisms only in area of interest. | Typically requires reduction of width of columns and rows throughout entire model domain2). | Accomplished by subdividing 3-D elements only in area of interest. |
| | Groundwater flow system beyond model boundaries | Uses Variable Flux Boundary nodes allowing use of analytical solution to simulate flux-drawdown relationship at boundary based on hydraulic conductivity and storage of material (analytical solution for a semi-infinite linear aquifer). | Uses General Head Boundary (*GHB*) condition which potentially greatly over simplifies condition beyond model boundaries. | Uses *GHB* condition which potentially greatly over simplifies condition beyond model boundaries. |
| | Geological layering including pinch-out of some layers | Grid refined only where needed and simply pinched-out where geologic layers disappear. | Typically requires adding several layers, columns, and rows throughout model domain2). | Mixes tetrahedrons with other type of elements (similar to pinch-out). |
| | Telescoping models (window models within regional model) | Simulates Window Model within Regional Model by outputting/inputting hydraulic heads at common nodes1). | No specific routine to address these conditions2). | Simulates Window Model within Regional Model by outputting/inputting hydraulic heads at common nodes. |
| | Transmissive faults simulated without discrete elements or cells | Uses fault link subroutine *FAULT* 1). | No specific routine to address these conditions2). | Uses discrete element capability. |
| | Hydraulic flow barriers simulated without discrete elements or cells | No specific routine to address these conditions. | Uses Hydraulic Flow Barrier package. | Uses discrete element capability. |
| | Simulation of angled faults | Not capable | Not capable | Will be available in Version 7.0 in late 2015. |
| Other | Simulation of groundwater budget within part of model domain | No specific routine to address these conditions. | Uses Zone Budget subroutine | Has sophisticated sub-domain budgeting features. |
| | Simulation of density driven flow and mass transport | Not capable but can use particle tracking with groundwater velocities calculations1). | Capable | Capable |

Note: 1 - Commercially available *MINEDW* version 2.0 does not support this option (as of June 2015)
2 - *MODFLOW-USG* unstructured grid code has been available since 2013 and introduces several capabilities similar to MINEDW including pinch-outs, telescoping models, and transmissive faults simulated by Connected Linear Network (*CLN*).

## 4 CONCLUSIONS

Analysis of Table 1 indicates that the unique features of *MINEDW* to simulate open pits, seepage faces and pore pressure distributions, zone of mass rock deformation and relaxation, nonlinear flow to underground workings through transmissive features, pit lake infilling, dewatering wells, and unbounded groundwater system give *MINEDW* an advantage over other codes for groundwater modeling of mine dewatering projects in complex hydrogeological settings. However *MINEDW* code has some deficiencies related to simulation of low permeable linear features, angled faults, components of the groundwater budget within part of model domain and cannot be used if modeling of density driven flow and 3-D mass transport is required.

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