Using *MINEDW* to simulate pore pressure as input for *FLAC^{3D}* and *3DEC*

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ABSTRACT: It has become common practice to create a three-dimensional (3-D) geomechanical model for the analysis of rock stability. One of the key inputs for a geomechanical model is the 3-D pore-pressure distribution. For complicated geologic settings under excavation, such as open pit walls and underground mine workings, pore pressures generally do not follow hydrostatic distributions with depth; therefore, a 3-D groundwater flow model is required to simulate pore-pressure distributions. *MINEDW* is a groundwater flow model code that was specifically developed to simulate the complicated hydrogeologic conditions related to mining. It is capable of simulating the excavation of open pits and underground workings, and the changing hydraulic conductivity of the displaced rocks surrounding the excavated area. This paper describes the features of *MINEDW* and how *MINEDW* can export 3-D pore-pressure distributions to be readily useable in *FLAC^{3D}* and *3DEC* models.

1 INTRODUCTION

Pore-pressure distributions of a slope depend upon many factors. For the highwall of an open pit, the distribution of pore pressures below the bench are affected by factors such as the operational periods of dewatering and depressurization, the length of time since the benches have been excavated, and the vertical and horizontal hydraulic conductivities (K) of the geologic units. These concepts are further illustrated in Figures 1 through 3. Figure 1 shows simulated pore-pressure distributions along a cross section of a 3-D model for two time periods. The geologic units consist of relatively low-permeability geologic units with K values ranging from 1.0×10^{-3} m/day in the GDF unit to 1.0×10^{-5} m/day in the ZCM/ZCI units. The pore pressure in the less permeable zone (ZCM/ZCI) of the highwall deviates significantly from the hydrostatic distribution. As shown in Figure 2, under hydrostatic conditions, the pressure increases linearly with increasing depth below the phreatic surface. As shown in Figure 3, under non-hydrostatic conditions there may be a strong deviation from the hydrostatic distribution. Figures 1 & 3 also show the localized depressurization due to the installation of a draining hole in 2010.

The depressurization of a highwall can occur through natural seepage, dewatering, and draining. The extent of depressurization, ΔP, of a geologic material at a given location is a function of the relationship

$$\Delta P \propto \frac{K_i t}{S_s x_i^2} \tag{1}$$

where K_i = hydraulic conductivity in the three directions x, y, and z; x_i = distances from the dewatering/draining point; S_s = specific (or elastic) storage; and t = time.

Equation 1 further shows that more effective depressurization of the low K sediments will require, however, a combination of some or all of the following:

1. lateral drainage to the highwall via intercalated, more permeable units (e.g. sandstone stringers),
2. discharge from depressurizing boreholes, and
3. ‘underdrains’ in underlying permeable geologic units.

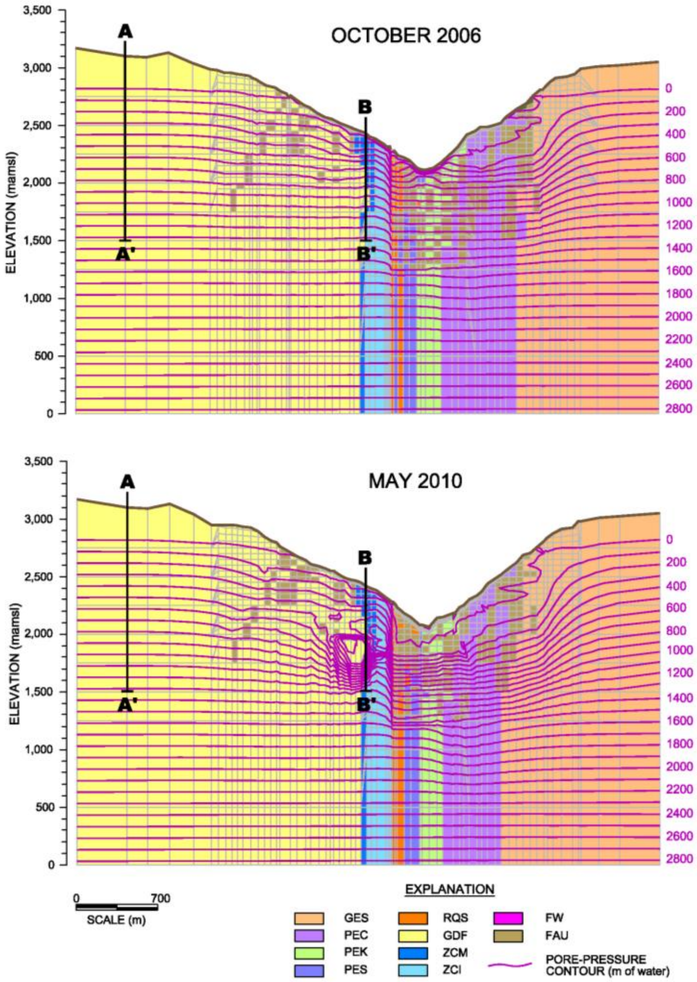


Figure 1. Simulated cross-sectional pore-pressure distributions in Oct 2006 and May 2010.

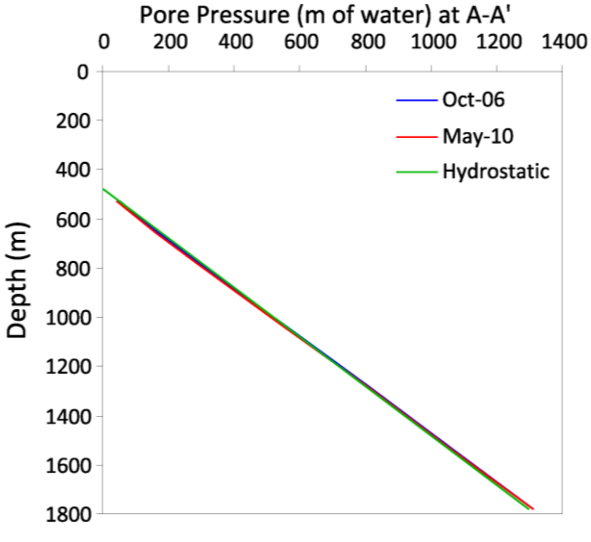


Figure 2. Simulated pore pressures outside of pit area.

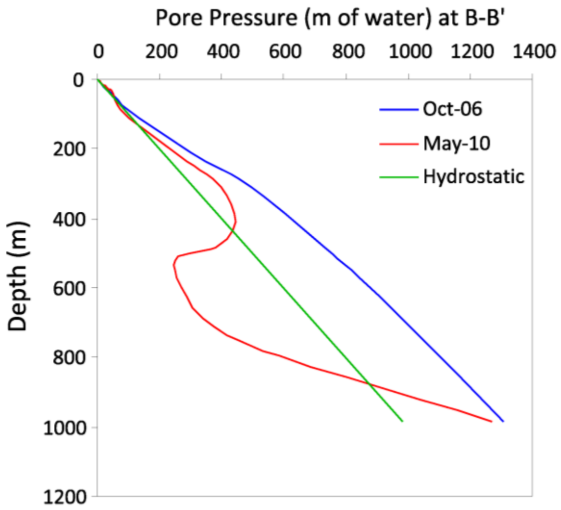


Figure 3. Simulated pore pressures in a less permeable zone.

The functional relationship in Equation 1 indicates that, when K is very low, to achieve a reasonable amount of depressurization, a very long period of time or very close spacing between dewatering points (e.g., a well) is required. Equation 1 also suggests that, for the low K material beneath the pit bench, the pore-pressure reduction due to natural seepage to the highwall would be very small after the excavation.

To assess whether the desirable pore-pressure reduction through natural seepage, or the combination of natural seepage and dewatering and depressurizing, can be achieved within a reasonable amount of time, a groundwater flow model which incorporates the relationship of Equation 1 in a very robust, fully 3-D way, should be developed. The groundwater flow model should (1) simulate the groundwater flow conditions before the pit excavation, (2) use pre-mining conditions as the initial flow conditions to simulate the pit excavation sequences and to estimate the pore-pressure distributions over the course of the pit excavation, and (3) provide 3-D pore-pressure distributions that can readily be used for geomechanical models for stability analysis.

2 MODELING APPROACHES FOR SIMULATING HIGHWALL PORE PRESSURE

Simulations of pore-pressure distributions of the highwall require either 2-D sectional or 3-D groundwater flow models (Read & Stacey 2009). While they have some advantages in terms of the ease of construction, 2-D sectional flow models have the following limitations:

1. 2-D sectional (or slice) flow models cannot simulate the 3-D flow conditions that occur at open pit mines that are generally conical. The 3-D flow field tends to converge at the open pit; thus, there are three directions of flow that cannot be incorporated in a 2-D analysis.
2. 2-D sectional flow models have limited predictive capabilities in cases where flow occurs perpendicular to the analysis plane due to, for example, an important recharge source, or highly transmissive structures, or dewatering.
3. 2-D sectional flow models are often difficult to calibrate. A good model calibration should compare both seepage rates and measured groundwater heads over time. 2-D sectional flow models often try to match measured groundwater heads but not the seepage rates for a certain point in time.
4. 2-D sectional flow models may not be cost effective because for each section one model is needed for a given time and a given pit configuration. 3-D models can incorporate the entire pit configuration and may be more cost effective and accurate.

Following are corresponding advantages when using 3-D models:

1. 3-D flow models adequately simulate the effects of hydraulic stresses such as dewatering and drainage in 3-D extent. The same advantage applies for flow perpendicular to the plane of a 2-D model.

2 A 3-D flow model is often cost effective because only one model is required and only one transient model simulation is run over the life of the mine. Given the enhanced computational power of current computers, a 3-D groundwater flow analysis can be performed in a relatively short amount of time. In addition, 3-D flow models (regional and mine scale) with appropriate refinement near the pit can be used to provide input to slope geomechanical models, and can also avoid problems that can occur with transferring boundary conditions from regional flow models to mine-scale flow models to 2-D sectional models.

The *MINEDW* code (Azrag et al. 1998) is a finite-element groundwater flow model code that was developed by Itasca Denver, Inc. The code has been used on numerous mining hydrogeologic projects throughout the world and is publically available (Itasca Denver 2012). Predictions made by *MINEDW* models have been verified by field data collected at several large mines with more than five years of operation. *MINEDW* was specifically developed to overcome the limitations of common groundwater flow model codes in simulating the following issues related to mining:

1 simulating continuous excavations of open pits and underground workings;
2 effectively simulating temporal changes in hydraulic properties of the disturbed rocks due to excavation or caving;
3 predicting the configuration of the phreatic surface and height of the seepage face of highwalls for slope-stability analysis;
4 exporting 3-D pore-pressure distributions for the model domain and grid space required by 3-D geomechanical models; and
5 predicting inflow to underground mines, particularly from discrete geologic structures and under non-Darcian flow conditions.

2.1 *Features of MINEDW*

In comparison to conventional groundwater flow model codes, *MINEDW* efficiently simulates the key components related to the prediction of 3-D pore-pressure distributions of excavated slope.

2.1.1 *Excavation*

MINEDW is efficient in simulating excavation in its capability of incorporating the excavation schedule for the life of excavation in one transient model run. In addition, *MINEDW* collapses the vertical finite-element grids as the excavation proceeds to deeper portions of the mine. 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 seepage points of the slope.

2.1.2 *Water levels during pit refilling*

MINEDW simulates the water levels of the pit during the refilling stage based on the volume of the open pit. It accurately predicts the temporal change of the phreatic surface as the water level in the pit increases. This feature allows for the prediction of changes in pore-pressure distributions over time for the slopes of a pit or reservoir where fluctuations in water levels occur.

2.1.3 *Zone of relaxation*

The stress releases to the rock and disturbance to the rock due to excavation cause rock beneath the pit benches to be more permeable than the in situ rock. The disturbed rock is referred to as the zone of relaxation (ZOR). The thickness of the ZOR could be as thick as several hundred meters. *MINEDW* is able to simulate the development of the ZOR according to the mining schedule by increasing the K value of the ZOR along the depth.

2.1.4 *Transition from open pit to block caving*

The displacement of rock above the drawzone will enhance the permeability of the displaced rock and change the groundwater flow conditions and pore-pressure distributions. *MINEDW* is capable of simulating the propagation of the displaced rock with enhanced K values based on the configuration of the displaced rock predicted from the geomechanical models.

2.1.5 *Exporting the 3-D pore pressures from MINEDW to FLAC^{3D} and 3DEC models*

The domain and grid spacing of the geomechanical models are generally different from a groundwater flow model. In general, the model extent of a geomechanical model is smaller than a groundwater flow model; however, the grid spacing of the geomechanical model is finer than the grid size of the groundwater flow model; therefore, it is necessary to interpolate 3-D pore pressures generated from the groundwater model to the specified mesh of the geomechanical model. *MINEDW* is capable of interpolating 3-D pore-pressure distributions and providing pore pressures in a data format readily usable for *FLAC^{3D}* (Itasca 2012) and *3DEC* models (Itasca 2007).

2.1.6 *Capability to simulate non-Darcian flow*

MINEDW is capable of simulating non-Darcian flow that may occur near high-capacity wells or water transmissive structures (Atkinson et al. 2010). The non-Darcian flow condition can affect both the flow rate and phreatic surface.

3 CASE STUDY

3.1 *Description of model*

A 3-D groundwater flow model was constructed using *MINEDW* to simulate the groundwater conditions at the Chuquicamata mine located in Chile (Liu et al. 2012). The model domain and hydrogeologic study area is shown in Figure 4. The primary purpose of the flow model was to predict pore-pressure distributions as input to the on-going geomechanical model for slope-stability analysis. The model simulated the main features of this large open pit mine:

1 Time varying pit topography: The surface of the pit wall and floor were simulated as zero pore-pressure boundaries that act as groundwater drainage points. Therefore, simulations of continuously changing topography are critical in predicting changes in pore pressure over time. For lower-permeability materials, simulating the time varying topography is particularly important in understanding the temporal changes in pore pressure because the dissipation of pore pressure is slow and deviates from the hydrostatic pore-pressure distribution.

2 Development of ZOR: A 150 m thick ZOR was simulated according to the excavation schedule and simulated with three higher-permeability zones with K values gradually decreasing from most permeable at the surface of the pit floor to a K value reflective of in situ rock at the bottom of the ZOR.

3 Dewatering and drainage system: The extensive dewatering and drainage systems as shown in Figure 5 were simulated in the model according to their implementation schedules. The complicated configuration of the dewatering and drainage system can be simulated with the flexible finite-element grid in *MINEDW*.

The 3-D groundwater flow model simulated the mining excavation from 1990 to the end of mine life in 2020. The model simulated various geologic units as shown in Figure 6.

As shown in Figure 6, different geologic units (shown in different colors in Figs. 6 & 7) were simulated in the model, with the K values ranging from 10^{-6} m/day (ZCI unit) to approximately 2×10^{-2} m/day (FAU). The FAU unit is a discretely, localized permeable feature that exists over the mining areas, as shown in Figures 7 & 8. The effect of these permeable features on the groundwater flow conditions can only be reasonably simulated in a 3-D model.

The 150 m thick ZOR was observed at the site. Figure 7b shows the spatial extent of the ZOR simulated in the model by assigning the K along the depth of the ZOR as follows, based on the combination of field data and transient model calibration:

1 From 0 to 50 m depth below the surface, the K value is assigned to be approximately 50 times the K value of the in situ rock.

2 From 50 to 100 m depth below the surface, the K value is assigned to be approximately 10 times the K value of the in situ rock.

3 From 100 to 150 m depth below the surface, the K value is assigned to be 1.5 times the K value of the in situ rock.

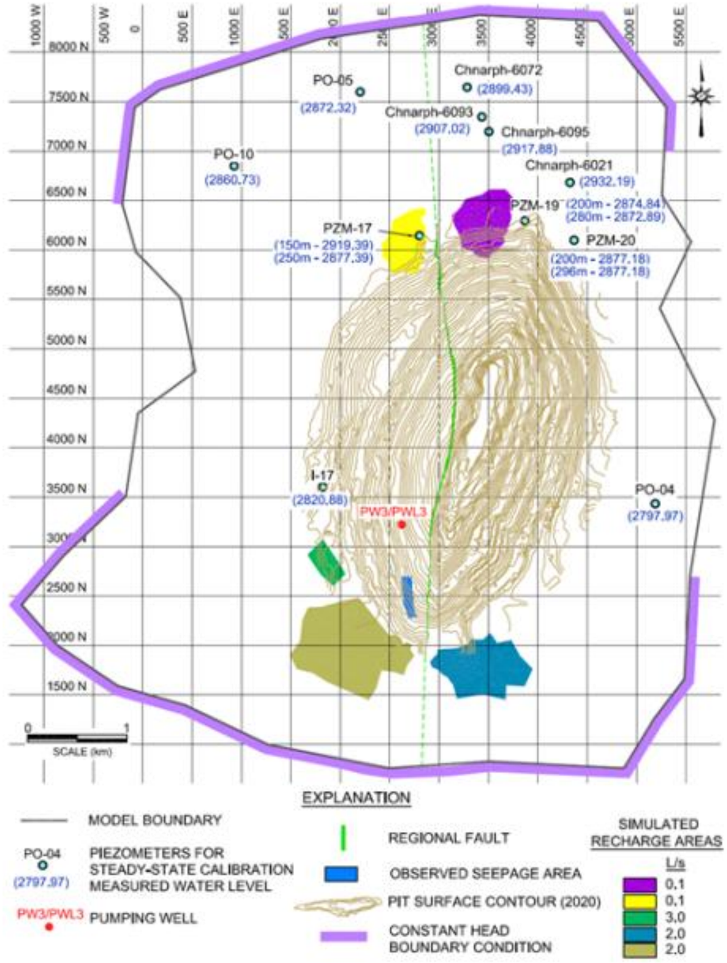


Figure 4. Hydrogeologic study area.

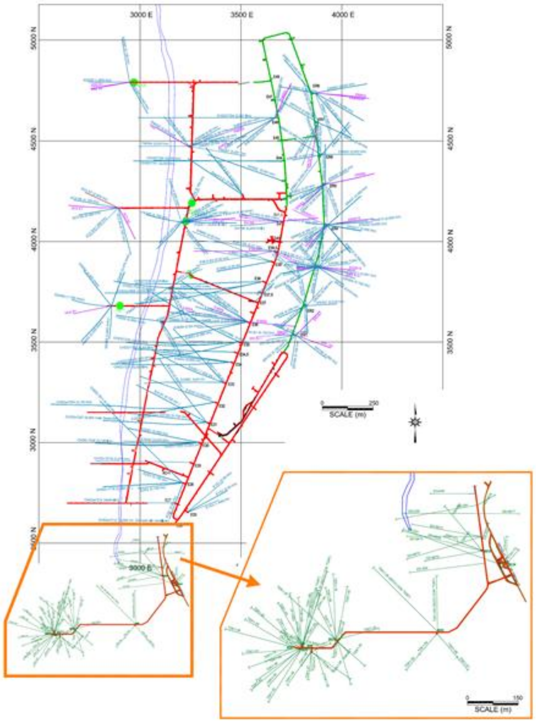


Figure 5. Simulated drain system.

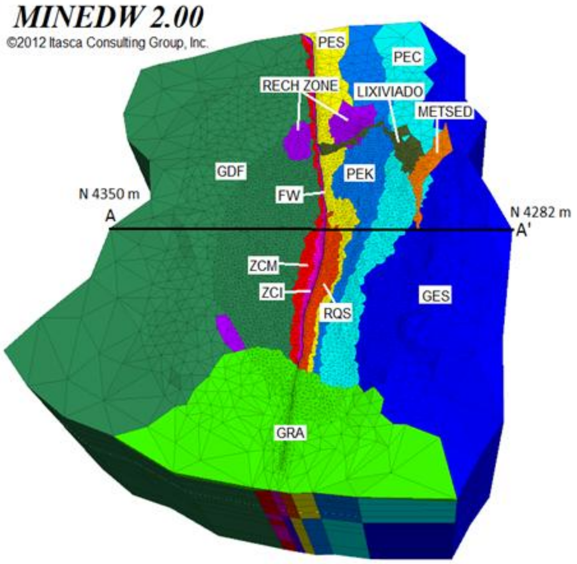
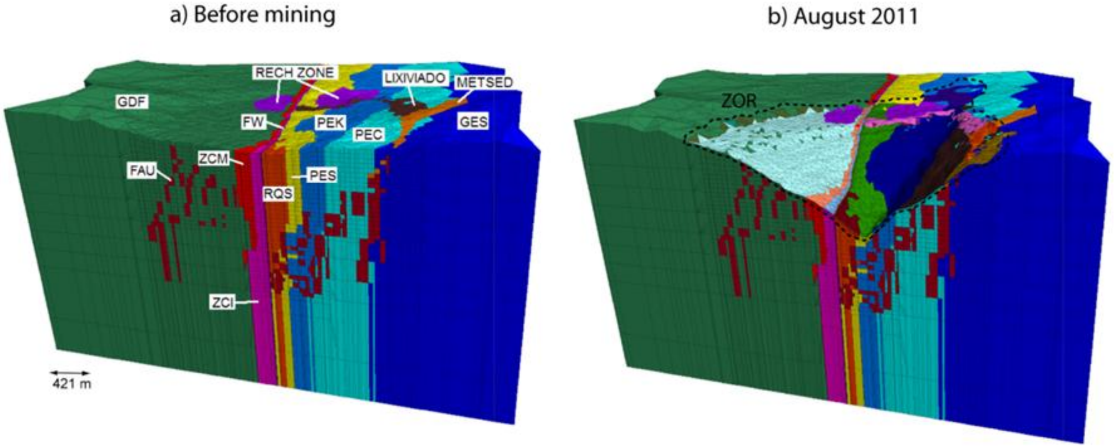


Figure 6. A plan view of the model and simulated geologic units.


a) Before mining

b) August 2011

Figure 7. Cross section A-A’ of Figure 6 before mining, and, as of August 2011.

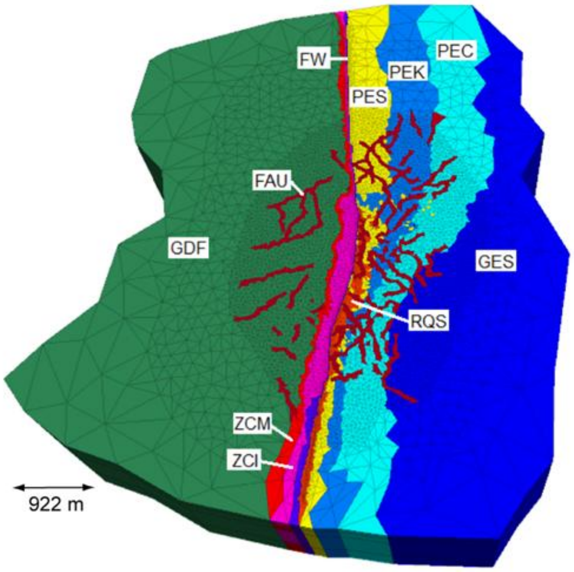


Figure 8. Simulated geologic units at 2200 mamsl before mining (3000 m below ground surface).

3.2 *Model simulations of pore pressure*

The 3-D groundwater flow model was calibrated as follows:

1. A steady-state calibration was conducted using water levels measured in 12 piezometers.
2. The transient calibration was conducted to achieve a reasonable agreement between the measured piezometric levels from December 1996 to August 2011 with the simulated water levels. A total of 50 single-point monitoring wells and multi-level piezometers with 104 monitoring points were used for the transient calibration.
3. The transient model calibration was also conducted to match the simulated inflow rates to selected draining systems and the seepage rate of a selected area.

The calibrated 3-D flow model was used to simulate pore-pressure distributions from 1990 to 2020. The simulation incorporates the monthly pit bench excavation based on the pit plan. The pore-pressure distributions were provided to both regional and local *3DEC* models for the various mining stages.

For each mining stage, a total of approximately 10,000,000 and 3,000,000 records of pore-pressure values are required for regional and local geomechanical models, respectively. The large number of records for pore-pressure data points required by both regional and local *3DEC* models suggests that it is computationally impractical to construct a regional groundwater flow model to simulate pore pressures for the life of a mine using the same grid spacing used in a geomechanical model; therefore, it is important that the groundwater flow code is capable of interpolating simulated pore pressures to generate input for 3-D geomechanical models.

In this case study, the mesh of the groundwater flow model is coarser than that of the *3DEC* geomechanical model. Pore pressures were communicated between *MINEDW* and *3DEC* by:

1. the geomechanical code providing either volumes of rock mass in 3-D with the grid size or 2-D sections with the grid size,
2. *MINEDW* interpolating the simulated groundwater pore pressures for the geomechanical model meshes, and
3. *MINEDW* exporting the pore pressures in a data format specified by the geomechanical model.

The advantage of using *MINEDW* over the groundwater facilities of *FLAC*^{3D} in simulating pore pressures is the computational speed in simulating regional groundwater flow conditions. *MINEDW* simulates the unsaturated flow regime with the similar approach as the saturated flow regime but with different hydraulic properties and by using the approximation approach. This approximation is proved to be adequate in simulating the position of the phreatic surface (Sandia 1998) yet only needing a fraction of the computational time that is required for the simulation of 3-D unsaturated flow using *FLAC*^{3D}. In this case study, the simulation of the groundwater flow conditions from 1970 to 2020 using *MINEDW* required approximately 16 hours of computer run-time using a single desktop computer.

4 RESULTS AND DISCUSSION

This paper provides an overview of key components that should be simulated in the groundwater flow model to generate 3-D pore-pressure distributions as input for *FLAC*^{3D} or *3DEC* models. This paper also describes the main features of Itasca's *MINEDW* code for simulating groundwater flow conditions related to open pit excavation. As demonstrated in the case study, a 3-D groundwater flow model is essential in predicting pore-pressure distributions for the highwalls with complicated geologic settings and dewatering systems. Also demonstrated in the case study is that, in order to provide input for geomechanical models, the interpolation of predicted pore pressures from a regional groundwater flow model is generally required.

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