Advancements in hydromechanical simulation: Embracing complexity for enhanced mine safety and prediction

T. Chung[a], S. Dehkhoda[b], A. Flatten[c] and V. Levkovitch[c]

[a]*Beck Engineering, Sydney, Australia*

[b]*Beck Engineering, Brisbane, Australia*

[c]*Beck Engineering, Berlin, Germany*

ABSTRACT

The significance of hydrogeological simulations in mine-scale modelling cannot be overstated. Accurate hydrogeological models are pivotal for ensuring mine safety, predicting environmental impacts, and planning for potential mine closures. These simulations provide insights into groundwater behaviours and fluid-rock interactions, which are critical for informed decision-making in mining operations. Recognizing the limitations of traditional hydro simulations, which often rely on assumptions like steady-state and fully saturated flow, we have pioneered a cutting-edge hydro framework. This approach offers a more realistic representation of subsurface water dynamics. The traditional methodologies, although foundational, can sometimes oversimplify complex hydrogeological phenomena, potentially leading to inaccurate predictions.

Our innovative framework, built on the open-source parallel finite element framework MOOSE, encapsulates real physics, emphasizing unsaturated flow dynamics and accounting for geological inconsistencies such as faults. It is equipped with realistic boundary conditions, including drainage, rainfall, and the nuanced interaction between flexible flux and pore water pressure. By adopting an element-based approach to material properties, the model ensures that parameters like permeability, porosity, and saturation parameters are not generalised but tied to specific geological domains up to elements. Furthermore, the fully transient nature of our simulation allows for time-dependent observations, providing an evolving perspective of the mine's hydrogeological landscape. Notably, the framework's ability to simulate pit reflooding sets it apart, addressing a crucial aspect of mine safety and environmental conservation. These unique features of our novel framework not only elevate the accuracy and depth of mine scale hydromechanical simulations but also underscore the need for continuous innovation in the realm of hydrogeological modelling.

1 INTRODUCTION

The significance of hydrogeological simulations in mining operations is well-documented, serving as a cornerstone for ensuring mine safety, environmental management, and strategic planning for mine closures. The foundational work by Wolkersdorfer (2008) and Younger (2004) has laid the groundwork for understanding the critical interplay between groundwater dynamics and mining activities, emphasizing the necessity of accurate hydrogeological models for informed decision-making in mining operations.

The limitations of traditional hydro simulations, which often rely on simplified assumptions, have been a focal point of recent research efforts to develop more accurate and comprehensive models. The seminal works by Bear and Verruijt (1987) and Anderson and Woessner (1992) have been instrumental in highlighting the challenges and limitations of conventional hydrogeological modelling techniques, paving the way for developing more advanced and realistic simulation frameworks.

One such pioneering approach is to develop a cutting-edge hydrogeological framework built upon the open-source parallel finite element framework MOOSE (Lindsay et al., 2022). This innovative framework represents a significant leap forward in hydro simulations, offering a more comprehensive and realistic representation of subsurface water dynamics by emphasizing unsaturated flow and accounting for geological inconsistencies such as faults. Adopting realistic boundary conditions, including drainage, rainfall, and the nuanced interaction between flexible flux and pore water pressure, further enhances the model's capability to accurately simulate complex hydrogeological phenomena.

Moreover, the MOOSE framework and its PorousFlow module (Wilkins et al., 2020; Wilkins et al., 2021) have been specifically designed to address the challenges associated with modelling multiphysics problems in porous media, including those relevant to mining hydrogeology. By multiphysics, we refer to the simultaneous simulation of interacting physical phenomena within a single model, such as fluid flow, heat transfer, and mechanical deformation. This approach captures complex interactions in natural systems. For example, Nguyen and Selvadurai (1998) demonstrated the need to integrate mechanical and hydraulic processes to simulate the behaviour of rock joints under stress accurately.

By introducing an element-based approach to material properties, this framework ensures that critical parameters such as permeability, porosity, and saturation parameters are not generalized but are instead closely tied to specific geological elements. The fully transient nature of the simulation allows for time-dependent observations, offering an evolving perspective of the mine's hydrogeological landscape and enabling the simulation of crucial processes such as pit reflooding, which is essential for mine safety and environmental conservation.

The advent of advanced hydro simulation frameworks marks a pivotal moment in the field of hydrogeological modelling. It underscores the importance of continuous innovation and adopting more sophisticated and realistic modelling approaches to enhance the accuracy and depth of mine-scale simulations. The ongoing development and refinement of such frameworks are vital for advancing our understanding of subsurface hydrology in the context of mining operations and for fostering more sustainable and informed decision-making processes.

This study will investigate a case study that exemplifies the application of realistic hydrogeological modelling in a complex subsurface environment featuring caves and rivers. By incorporating these natural geological formations, we aim to illustrate the intricate dynamics of groundwater flow and its interaction with the surrounding rock matrix. The focus will be on examining how accurately modelled hydrogeological phenomena, when coupled with mechanical simulations, can predict the behaviour of subsurface structures under various stress conditions. This case study will demonstrate the capabilities of our advanced hydro simulation frameworks, which is adapted from MOOSE and its PorousFlow module, and highlight the significant impact of hydrogeological results on the outcomes of mechanically coupled simulation results.

2 METHODOLOGY

Hydromechanically coupled discontinuum Finite Element method with LR4 constitutive framework (Levkovitch and Reusch, 2010) for mechanical behaviour of the material is used for analyses. LR4 has significant computational capacity, enabling the incorporation of complex DFNs and structural models, and non-linear hydromechanical coupling. This means that the hydraulic conductivity and the Biot coefficient can be expressed as functions of the modelled plastic strain tensor for rock mass and discontinuities across all relevant length scales. Other model features essential for high similitude with this environment were:

- The models are regional in scale and use higher-order elements.
- A large strain, strain-softening dilatant material model with a modified 3D Hoek-Brown yield criterion for the rock mass and Mohr-coulomb for dumps, soils and narrow rock mass defects is used (Levkovitch and Reusch, 2010).
- Regional faults and mine scale structural models are built explicitly. All discrete regional structures were active as discrete flow paths for the hydro-mechanical modelling process. Foliation was simulated by defining anisotropic properties for the rock mass domains.
- The DFN and foliation orientations vary on a node-by-node (sub-element) basis according to a 3d joint set block model.

1.1 Simulation of hydraulic flow

In modelling the transport of fluids through the rock mass, the fundamental flow equations are based on the conservation of mass in conjunction with Darcy's law, extended to account for time-dependent processes. The following partial differential equation presents the governing equation for fluid flow within a porous rock mass (Wilkins et al., 2020; Wilkins et al., 2021):

$$\frac{d(\rho_w\, s\, \varphi)}{dt} + \mathrm{div}\left(\rho_w \frac{\boldsymbol{k}k_{rw}}{\mu_w} \cdot (\nabla P_w - \rho_w g)\right) = q \qquad (1)$$

Here φ represents the porosity of the medium, which is the fraction of the total volume available for fluid flow. The t is time, capturing the transient nature of the process. ρ_w is the water density (kg/m^3), which is a measure of the mass per unit volume of the fluid. s is the fluid saturation. $\boldsymbol{k}$ is permeability-tensor of the medium (m^2), which characterizes the medium's ability to transmit fluids. k_{rw} is the relative permeability of the medium, which reflects the ease of flow through the medium as a function of saturation. μ_w is the dynamic viscosity of the fluid (Ns/m^2), which describes its resistance to flow. The ∇P_w is the pressure gradient (Pa/m), and g is the acceleration due to gravity (m/s^2). q is the source term (kg/m^2s^2).

For the boundary conditions at the excavated surfaces (tunnels, shafts and pits), a piecewise linear relationship is employed to model the flux of fluid into or out of the system:

$$s = f(t, x) \times g(P - P\mathrm{e}) \qquad (2)$$

Where the unit of the flux sink (s) is in (kg/m^2s^2). $f(t, x)$ is the basic sink function and $g(P - P_e)$ being a piecewise linear function of the pressure difference where P_e a reference value.

The spatial discretization of the domain involves using different types of finite elements. Four-node tetrahedral elements (C3D4) are used for most of the geometry to accommodate complex shapes with fine detail. For areas with faults and discontinuities, six-node wedge elements (C3D6) are utilized alongside Multiple Point Constraints (MPC) to effectively model the interaction and mechanical behavior across these irregular features. This combination accurately represents the media's heterogeneity and anisotropy, ensuring that the mechanical response of faults and discontinuities to fluid flow is appropriately captured in the simulation.

In the simulation of fluid flow through a porous rock mass, the Corey equation is utilized to define the relative permeability which characterises the ease with which a fluid moves through a partially saturated rock. This empirical relationship, established by Corey in 1954, links the relative permeability to the effective saturation of the porous medium:

$$k_r = S_{eff}^n \qquad (3)$$

Where S_{eff} is the effective saturation, representing the ratio of the volume of fluid to the volume of void space available to the fluid, excluding any immobile fluid bound to the solid matrix. The exponent n is an empirical parameter that varies with the rock type and the wetting characteristics of the fluid within the rock.

Capillary pressure is based on the 'van Genuchten' equation (Genuchten, 1980). The equation describes the relationship between the capillary pressure and the degree of saturation in unsaturated soils or rocks and is given by:

$$S_{eff} = \begin{cases} \left(1 + (-\alpha P)^{\frac{1}{1-m}}\right)^{-m}, & P < 0 \\ 1 & P \geq 0 \end{cases} \quad (4)$$

Where α is an empirical parameter related to the inverse of the air entry suction or the capillary rise. P is the pore pressure, which is the negative of the capillary pressure. m is another empirical parameter related to the pore-size distribution.

2.2 Close non-linear coupling framework

A close 2-way coupling has been implemented for the rock mass and all rock mass defects, including the fault and ductile fractures (Figure 2). This coupling framework operates on the principle that mechanical damage due to the evolution of plastic deformation will increase hydraulic conductivity. In other words, local hydraulic conductivity is assumed to be a function of rock mass damage. Figure 1 illustrates the REV scale effects of rock mass plastic strain and the assumed relation for rock mass damage and hydraulic conductivity as functional dependence of the equivalent plastic strain (ε_p).

Here, the exponential relation proposed by Rutqvist et al (2009), motivated by the work from Mahyari and Selvadurai (1998) and Shirazi and Selvadurai (2005) is used:

$$k_w(\varepsilon_p) = k_{w_o} exp\{A_H \varepsilon_p\} \leq k_{w_{max}} \quad (5)$$

Where A_H is a material-dependent fitting coefficient and k_{w_o} is the initial (undamaged) conductivity. The increase in conductivity is capped with an upper limit maximum conductivity $k_{w_{max}}$, which is roughly three to four orders of magnitudes larger than the initial conductivity, ie $k(\varepsilon_p) \leq k_{w_{max}}$.

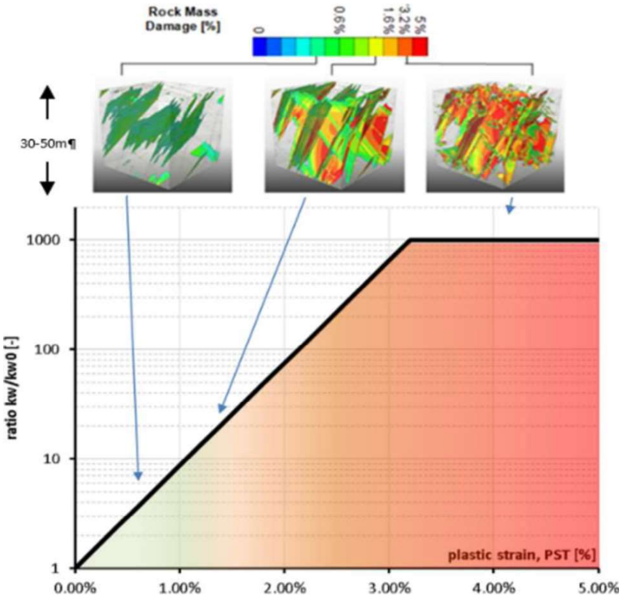

Figure 1 Relationship of plastic strain in the model and hydraulic conductivity.

For any degraded material, the parameter A_H is determined using:

$$A_H = \ln(k_{w_{max}} / k_{w_o})/1.71 \quad (6)$$

This relation has been described further in Flatten and Beck (2015) and verified via simulations related to field and laboratory observations in Flatten et al. (2016).

The computed pore water pressures (p_w) from hydrosimulation are then considered in the mechanical constitutive equations via Terzaghi's effective stress concept (Terzaghi, 1936):

$$\boldsymbol{\sigma}_{eff} = \boldsymbol{\sigma} + \alpha_B p_w \quad (7)$$

Where $\boldsymbol{\sigma}_{eff}$ is effective stress, $\boldsymbol{\sigma}$ is total stress, and α_B is Biot's coefficient. This means that the ingress of surface water into damaged and dilated zones is directly simulated, allowing for the calibration of relevant variables based on the interaction between hydraulic and mechanical processes.

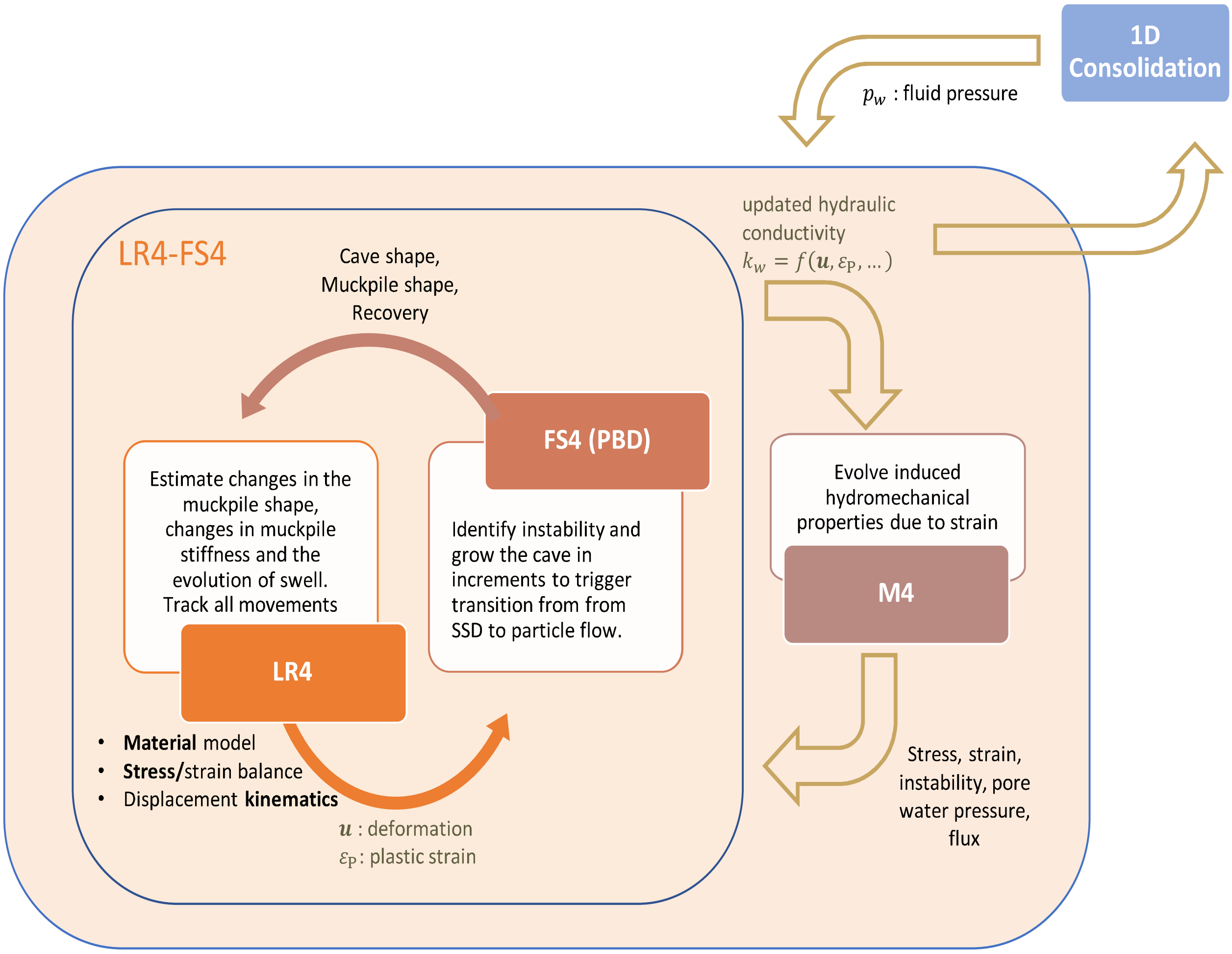

Figure 2 BE hydro coupling framework for stress-strain-cave flow modelling using LR4-FS4.

3 CASE STUDY

This section details an example case study in which mining-induced hydraulic drawdown and associated surface subsidence are simulated using the described numerical framework. The case study is a hybrid caving and stopping mine located in an area with low mountains, numerous large lakes and ponds, and a continental climate.

Several key pieces of data are essential for developing an accurate hydro-mechanically coupled model. These include the pre-mining phreatic surface, initial hydraulic conductivity values for various rock materials, data on surface water recharge, and records of groundwater monitoring and seepage mapping. The model can also integrate local surface drainage provided by creeks and rivers.

The hydro simulation has the following setup and assumptions:

- Permeability and porosity are modelled to vary with depth and damage state. A predefined relationship with depth and initial hydraulic conductivity values is implemented for all lithologies.
- The model's far-field boundary conditions are established at 5 meters below the topography surface on all four walls using a piecewise linear sink function. This function allows the simulation of a natural gradient and flow direction by controlling the flow at the boundary.
- Surface recharge, attributed to rainfall and snowmelt, is applied uniformly across the topography surface using a flow source boundary condition that varies with material properties, as illustrated in Figure 3 - green areas.

- Rivers and creeks with permanent water reserves were mapped, and pore water pressure was forced. These areas were always treated as fully saturated (Figure 3 - blue).
- Mining excavations, such as tunnels and shafts, are considered fully drained, with a piecewise linear sink boundary condition (drain only) applied at the surfaces of these open excavations to simulate the removal of water.
- In contrast, filled stopes (backfill) have the drain boundary condition removed, preventing water flow through these areas, thus becoming saturated and allowing pore water pressure to accumulate.

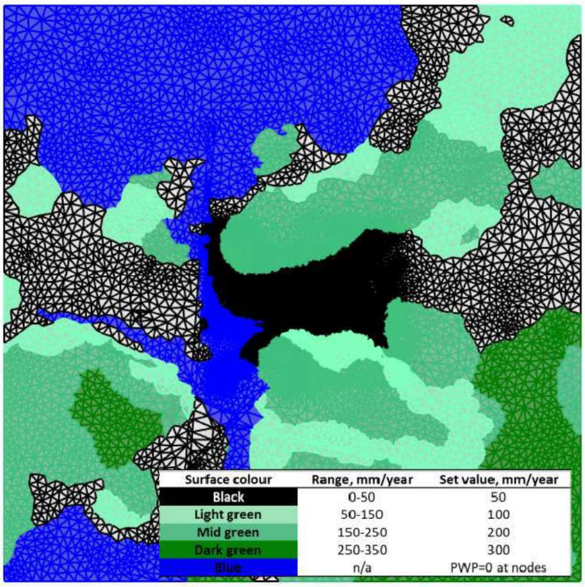

Figure 3 Implemented variable surface recharge. Blue areas indicate rivers and lakes where the pore water pressure (PWP) is set to zero at nodes. Green areas represent surface recharge attributed to rainfall and snowmelt, with specific recharge rates.

This model setup encapsulates the complex interplay between geological features and hydrological processes, providing a detailed framework for understanding the impacts of mining activities on subsurface water dynamics.

4 RESULTS

The evolution of groundwater drawdown due to mining activities is illustrated in Figure 4. The model indicates that from a certain point in time, the rate of groundwater drawdown increased markedly. This change is linked to enhanced conductivity from the rapid increase in mining-induced damage. This phenomenon is corroborated by increased water ingress into the mine, as indicated by the escalated pumping rates required for water management.

Figure 4 also illustrates the evolution of pore pressure as a direct consequence of mining activities. As can be seen, the model can capture the influence of geological features like faults and cavities on pore pressure distribution throughout the mining lifecycle. As mining progresses, pore pressure across different strata changes, demonstrating the model's precision in predicting subsurface water behaviour in response to anthropogenic and geological changes.

The gradient of the hydraulic head at the soil/bedrock interface demonstrates the model's ability to capture the impact of geological discontinuities on head distribution (Figure 5). The colour gradients tracing the hydraulic head conform to the network of faults, reflecting the model's acute sensitivity to these critical subsurface features. These results confirm that the role of the structures, either as conduits or barriers to fluid flow, is well represented in the model. This outcome is attributed to the precision of the coupling framework in capturing the interaction between rock mass, underground water, and geological structures. These capabilities are indispensable for understanding the hydro-mechanical behaviour of the subsurface environment, particularly in areas with complex geology where faults play a dominant role in fluid dynamics.

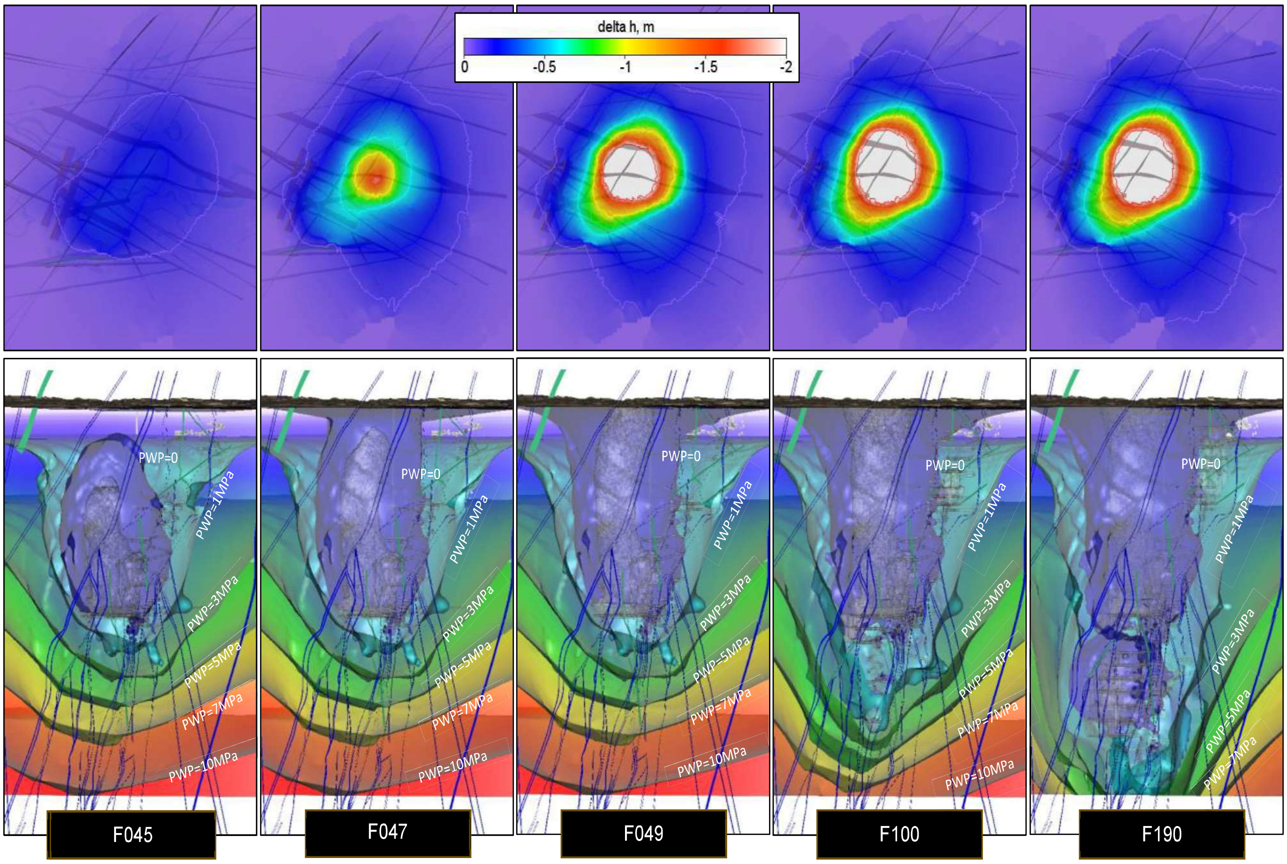

Figure 4 Evolution of hydraulic head at surface and pore pressure with underground mining.

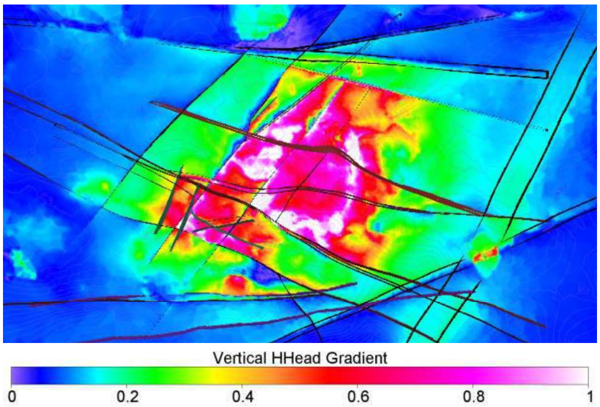

Figure 5 Vertical gradient of hydraulic head on the bedrock interface.

5 CONCLUSIONS

In conclusion, the hydrogeological models explored in this study demonstrate a significant advancement in simulating and predicting the complex interactions between groundwater dynamics and mining operations. The robust framework of these models, underpinned by advanced computational tools and informed by comprehensive datasets, allows for the intricate representation of subsurface hydrological processes. Notably, integrating realistic parameters such as depth-dependent permeability and porosity, coupled with incorporating geological features like faults and caves, provides a nuanced understanding of fluid flow mechanisms.

The model's predictive capabilities are particularly evident in their alignment with observational data, such as the notable correlation between hydraulic head distributions and fault structures. These correlations affirm the models' sensitivity to geological variances and their potential impact on mine safety and environmental management strategies.

By capturing the essence of hydro-mechanical behaviour in response to mining activities, this study's models serve as an invaluable asset in the planning and executing mining projects. They highlight the importance of continuous refinement and validation against real-world data, ensuring that predictive models are effectively utilised for sustainable and environmentally responsible mining operations. The resulting insights offer a clearer perspective on the proactive measures needed to mitigate environmental impacts and uphold structural integrity.

REFERENCES

Anderson, M. P. & Woessner, W. W. (1992). Applied groundwater modeling: Simulation of flow and advective transport. Academic Press.

Bear, J. & Verruijt, A. (1987). Modeling groundwater flow and pollution.

Corey, A. T. (1954). The interrelation between gas and oil relative permeabilities. Producers Monthly.

Flatten, A. & Beck, D. A. (2015). Applications of hydro-mechanically coupled 3D mine and reservoir scale, discontinuous, strain-softening dilatant models with damage. American Rock Mechanics Association, ARMA. 49th US Rock Mechanics and Geomechanics Symposium, San Francisco, USA.

Flatten, A., Reusch, F. & Beck, D. A. (2016). The application of hydro-mechanical mine-scale modelling for large block caving operations. 7th International Conference & Exhibition on Mass Mining – MassMin 2016, Sydney, Australia.

Genuchten, M. Th. van (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44(5), 892-898.

Lindsay, A. D., Slaughter, A. E., Permann, C. J., Peterson, J. W., Miller, J. M., Andrš, D., Gaston, D. R., Kong, F., Martineau, R. C. & Tonks, M. R. (2022). 2.0 - MOOSE: Enabling massively parallel multiphysics simulation. SoftwareX, 20, 101202. https://doi.org/10.1016/j.softx.2022.101202.

Mahyari, A. T. & Selvadurai, A. P. S. (1998). Enhanced consolidation in brittle geomaterials susceptible to damage. Mechanics of Cohesive-frictional Materials. Wiley.

Nguyen, T. S. & Selvadurai, A. P. S. (1998). A model for coupled mechanical and hydraulic behaviour of a rock joint. *International Journal for Numerical and Analytical Methods in Geomechanics*, 22(1), 29-41. https://doi.org/10.1002/(SICI)1096-9853(199801)22:1<29::AID-NAG907>3.0.CO;2-N

Rutqvist, J., Birkholzer, J. T., Cappa, F. & Tsang, C.-F. (2009). Modeling of damage, permeability changes and pressure responses during excavation of the TSX tunnel in granitic rock at URL, Canada. *Environmental Geology*, 57, 1263-1274.

Selvadurai, A. P. S. & Shirazi, A. (2005). An elliptical disc anchor in a damage-susceptible poroelastic medium. *International Journal for Numerical Methods in Engineering*, 62(8), 1063-1088. https://doi.org/10.1002/nme.1354

Shirazi, A. & Selvadurai, A. P. S. (2005). Lateral loading of a rigid rock socket embedded in a damage-susceptible poroelastic solid. *International Journal of Geomechanics*.

Terzaghi, K. (1936). The shear resistance of saturated soils and the angle between the planes of shear. Proceedings of the 1st International Conference on Soil Mechanics and Foundation Engineering, 1, 54-56.

Wilkins, A., Green, C. P. & Ennis-King, J. (2020). PorousFlow: A multiphysics simulation code for coupled problems in porous media. *Journal of Open Source Software*, 5(55), 2176. https://doi.org/10.21105/joss.02176.

Wilkins, A., Green, C. P. & Ennis-King, J. (2021). An open-source multiphysics simulation code for coupled problems in porous media. *Computers & Geosciences*, 154,104820. https://doi.org/10.1016/j.cageo.2021.104820.

Wolkersdorfer, C. (2008). Water management at abandoned flooded underground mines: Fundamentals, tracer tests, modelling, water treatment. Springer.

Younger, P. L. (2004). Environmental impacts of coal mining and associated wastes: A geochemical perspective. Geological Society, London, Special Publications, 236(1), 169-209.