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Modeling of pressure on retaining structures for underground fill mass

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ABSTRACT

To retain fresh cemented paste backfill (CPB) (a large fill mass made of man-made fine soils that undergo cementation) in a stope (underground mining excavations), a retaining structure or wall (called a barricade) must be constructed at the base of the stope. Due to the coupled thermo-hydro-mechanical-chemical (THMC) processes that occur in CPB, changes in the total horizontal stress and pore water pressure (PWP) take place with backfilling operations that are flexible, which directly affects the stability of the barricade. Hence, an investigation of the changes and distribution of barricade pressure is crucial for the assessment of the stability of CPB and the barricade. In this paper, an integrated multiphysics model composed of a fully coupled THMC model, a fully coupled multiphysics model that analyzes the consolidation process in CPB and an elastoplastic model that analyzes changes in the interface behavior during the interaction of rock mass/backfill is adopted. The predictive ability of the model is validated by the good agreement between the simulation results and in-situ measurements from a series of field monitoring programs. Then, the validated multiphysics model is used to numerically investigate the changes and spatial distribution of barricade pressure under various conditions (including elapsed time, barricade location and shape, initial temperature, and drainage conditions). The obtained results can provide practical insight into the factors that affect the geotechnical stability of barricade structures.

1. Introduction

Cemented paste backfill (CPB) is an engineered mixture of dewatered full stream tailings (man-made granular soils), hydraulic binder and water (Ghirian and Fall, 2016). The application of CPB can improve ground stability, enhance ore recovery and reduce ground surface subsidence (Belem and Benzaazoua, 2004; Cui and Fall, 2015b; Li and Yang, 2015; Haiqiang et al., 2016; Suazo et al., 2016). Moreover, due to the rapid increase in strength compared to the use of rock fill and hydraulic fill (Yilmaz et al., 2004; Veenstra, 2013), the integration of CPB into mining operations can significantly reduce the mining cycles and thus increase productivity. In addition, tailings are utilized as a key component for CPB preparation, and then transported into underground mined-out voids (called stopes). Thus, CPB technology can be considered as an effective alternative to surface tailings storage, and reduce the risk of the environmental pollution (e.g., acid mine drainage) associated with surface tailings disposal. Therefore, CPB technology has been increasingly and widely utilized in underground mining operations around the world (Benzaazoua et al., 2006; Fall et al., 2015).

After preparation, the fresh CPB paste is transported through pipelines or gravity and poured into a stope. To keep the fresh CPB in a stope, a retaining structure called a barricade (also called bulkhead or fill fence) must be constructed in the crosscut (Helinski et al., 2010a). The failure of the barricade may result in catastrophic consequences (e.g., personnel injury and/or fatalities, drift flooding, equipment damage and related financial ramifications) (Li et al., 2009; Nasir and Fall, 2009). Thus, barricade stability is considered to be a crucial design criterion of a CPB structure.

To analyze the stability of barricade structures will require determining the barricade pressure. After placement of fresh CPB into a stope, the barricade pressure is controlled by the complex multiphysics processes that occur in the CPB, including thermal, hydraulic, mechanical and chemical (THMC) processes (Cui and Fall, 2015c; Doherty, 2015). The backfilling operation is flexible, and can take place in stages or different sequences, and thus the pressure exerted onto the stope base and barricade structure increases with increases in the fill height. Therefore, mechanical processes can directly contribute to barricade pressure. Moreover, water consumption caused by binder hydration (i.e., the chemical process) and the water drainage through the barricade (i.e., the hydraulic process) can also contribute to the changes of barricade pressure. In addition, the thermal process has significant impacts on the rate of binder hydration (Haiqiang et al., 2016; Walske et al., 2016) and thus the dissipation of the pore-water pressure (PWP)

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induced by binder hydration, which means that the thermal process must be considered during the assessment of barricade pressure. Therefore, an understanding of the multiphysics processes in CPB and modeling of these processes are crucial for reliably assessing and predicting the barricade pressure. Furthermore, the consolidation process in CPB can result in relative displacement between the rock walls and backfill (El Mkadmi et al., 2013; Cui and Fall, 2016c). As a result, interface resistance (including interface adhesion and shear stress) will develop, which results in the transfer of stress from the CPB mass to the rock walls (i.e. the arching effect) (Fahey et al., 2009; Li and Aubertin, 2009; Cui and Fall, 2017), and thus reduces the barricade pressure. Therefore, the coupled THMC processes, consolidation behavior and the backfill/rock mass interface interaction must be taken into consideration in the evaluation and prediction of stress on bulkheads in practice.

To provide more in-depth insight into the changes in the barricade pressure, several field monitoring programs of backfilled stopes have been discussed in the literature (e.g., Belem et al., 2004; Yumlu, 2008; Thompson et al., 2012; Doherty et al., 2015). Some of the factors that affect pressure are identified based on the field measurements. For example, Yumlu (2008) found that filling sequences that are carried out in stages can significantly enhance the dissipation of excess PWP compared to the use of a strategy that involves continuous filling. Aside from the backfilling strategy, CPB recipe, stope geometry, filling rate and drainage conditions are also identified as significant factors that affect the barricade pressure (Thompson et al., 2009; Doherty et al., 2015). Moreover, the field measurements conducted by Belem et al. (2004) demonstrated that the barricade pressure initially increases with fill height. However, with increased fill height, the barricade pressure gradually approaches its maximum value. A similar trend of change in the barricade pressure was observed in the field monitoring program conducted by Helinski et al. (2010a). These in-situ investigations have made a tremendous contribution to the understanding of the characteristics of change in barricade pressure during and after filling operations, which provide in-depth insight into the mechanisms that control barricade pressure and the related influential factors.

With an improved understanding of the changes in barricade pressure in stopes, several analytical models have been subsequently developed to quantitatively assess the pressure that acts on barricades. For example, Belem et al. (2004) and Li et al. (2009) respectively derived an analytical model from Marston's cohesionless model (Marston, 1930) based on limit equilibrium analysis of CPB stopes. The closed-form analytical solution provides a simple method to assess the pressure exerted onto barricades. However, the applicability of the analytical models is limited because of their assumptions (e.g., constant material properties, and uniform distribution of horizontal stress at a given height). Therefore, several partially and fully coupled multiphysics models have been developed to reliably predict the changes in the pressure in stopes. For instance, Helinski et al. (2007) developed a hydro-mechanical-chemical (HMC) model to predict the volume changes and PWP in CPB. Wu et al. (2014) developed a thermo-hydro-chemical (THC) model to predict the PWP and temperature changes with the progression of binder hydration. A fully coupled THMC model for CPB material was developed by Cui and Fall (2015b) to simulate time-dependent changes of the material properties of CPB under various multiphysics loading conditions. Then, this fully coupled THMC model was used to derive a multiphysics model that analyzes the consolidation process in CPB (Cui and Fall, 2016c) and then further incorporated into an evolutive elastoplastic model that analyzes changes in the behavior of the rock mass/backfill interface (Cui and Fall, 2017) and simulates the arching effect in CPB. However, a more accurate assessment of barricade pressure in stopes at the field scale can be carried out with the integration of these models into one model. Therefore, in this paper, a fully coupled THMC model (Cui and Fall, 2015b), coupled multiphysics model (Cui and Fall, 2016c) and elastoplastic model (Cui and Fall, 2017) are combined to numerically investigate the changes in barricade pressure under different backfilling conditions.

2. Mathematical models

To characterize the interaction of the multiphysics processes and their influence on the pressure acting on the barricade, a fully coupled THMC model proposed by Cui and Fall (2015b), multiphysics model that analyzes the consolidation process in CPB derived by Cui and Fall (2016c) and elastoplastic model that analyzes changes in the interface behavior during the interaction of rock mass/backfill developed by Cui and Fall (2017) are adopted in the present study. Details on all of these models including the model assumptions, and derivation and determination of the model coefficients are presented in Cui and Fall (2015b, 2016c, 2017). A brief description of the three models is provided in the following sections, respectively. Moreover, it should be noted that in practice, the barricade pressure refers to the total horizontal stress rather than the PWP acting on the barricade structure (Yumlu, 2008; Li et al., 2009). Hence, this convention is also adopted in this paper.

2.1. Coupled THMC model

To assess the coupled multiphysics process, the fully coupled THMC model proposed by Cui and Fall (2015b) is adopted in this study. In this THMC model, the transport of conserved quantities, such as mass, energy and momentum in a CPB structure is described by four equilibrium equations: (i) water mass, (ii) air mass, (iii) momentum (mechanical equilibrium), and (iv) energy conservation equations:

$$nS\frac{\partial\rho_w}{\partial t}+n\rho_w\frac{\partial S}{\partial t}+S\rho_w\left[\frac{\partial\varepsilon_v}{\partial t}+\frac{(1-n)}{\rho_s}\frac{\partial\rho_s}{\partial t}\right]-nS\dot{m}_{hydr}\left(\frac{\rho_w}{\rho_s}S-1\right)=-\nabla\cdot(nS\rho_w\mathbf{v}^{rw}) \quad (1)$$

$$n(1-S)\frac{\partial\rho_a}{\partial t}-n\rho_a\frac{\partial S}{\partial t}+(1-S)\rho_a\left[\frac{(1-n)}{\rho_s}\frac{\partial\rho_s}{\partial t}+\frac{\partial\varepsilon_v}{\partial t}-\frac{nS}{\rho_s}\dot{m}_{hydr}\right]=-\nabla\cdot n(1-S)\rho_a\mathbf{v}^{ra} \quad (2)$$

$$\nabla\cdot\left(\frac{\partial\boldsymbol{\sigma}}{\partial t}\right)+\frac{\partial[(1-n)\rho_s+nS\rho_w+n(1-S)\rho_a]}{\partial t}\mathbf{g}=0 \quad (3)$$

$$[(1-n)\rho_s C_s+nS\rho_w C_w+n(1-S)\rho_a C_a]\frac{\partial T}{\partial t}+Q_{ad}+Q_{cd}=Q_{hydr} \quad (4)$$

where n denotes the porosity; S refers to the degree of saturation; ρ_i is the density (i = air, water and solid); t represents the elapsed time; ε_v stands for the volumetric strain; $\dot{m}_{hydr}$ refers to the time rate of changes in the pore-water mass per unit volume due to binder hydration; $\mathbf{v}_s$ and $\mathbf{v}^{ri}$ respectively represent the phase velocity with respect to the current configuration (Eulerian quantity), and the corresponding relative apparent velocity of the fluids in the porous medium; σ is a total stress tensor; $\mathbf{g}$ refers to the acceleration of gravity; C_i denotes the specific heat capacity (i = solid, water and air); Q_{ad} and Q_{cd} stand for the heat transfer via advection and conduction, respectively; and Q_{hydr} is the heat generated through exothermic binder hydration.

The developed THMC model was implemented into COMSOL Multiphysics (a finite element code, (Comsol, 2015)). Specifically, conservation equations contain three terms including time rate of conserved quantities (i.e., temperature, displacement and pore water pressure), convective terms (i.e., transfer of matters, energy and momentum), and source or sink terms. For the fluid mass equilibrium equations (Eqs. (1) and (2)), the time derivative terms can be converted into storage term to interpret contributions of compressibility of fluid and matrix, and the moisture capacity to changes of fluid mass. The fluid compressibility can be specified directly in COMSOL, and the moisture capacity can be obtained by the water retention curve of CPB. Moreover, the matrix compressibility (the third term on the left-hand side of Eqs. (1) and (2)) has been expressed by the rate of change of volumetric strain which can be derived from mass equilibrium equation of solid phase. Then, the matrix compressibility terms can be