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Research Paper

Multiphysics modeling of arching effects in fill mass

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ABSTRACT

A numerical modeling study is conducted to assess and gain a better understanding of the arching effects of field cemented tailings backfill (CTB). An integrated multiphysics model is developed that can illustrate and capture the changes in the material properties of CTB, consolidation behavior of CTB mass, and the shear behavior at the CTB/Rockwall interface. The predictive capability of the model has been successfully verified with comparisons of the predicted results with monitoring data taken from a series of field studies. The model is then used to simulate a series of applications that are relevant to CTB in practice.

1. Introduction

Soil arching, a phenomenon commonly encountered in geotechnical engineering, was described by Terzaghi [1] as “one of the most universal phenomena encountered in soils both in the field and in the laboratory”. He defined the arching effect as the transfer of pressure from a yielding mass of soil onto the adjoining stationary parts [1]. Soil arching, which involves load transfer and stress redistribution, should be and has been taken into account in the analysis of many geotechnical issues [2], such as earth pressure on retaining walls [e.g., [3,4]], vertical stress and support requirements above tunnels and other underground situations [e.g., [2,5]], and mine tailings backfilling [e.g., [6,7]].

Assessing the arching effects of mine cemented tailings fill or backfill (CTB) is a complex task due mainly to the changing properties of the CTB medium and the complex coupled thermal (T; e.g., temperature, heat transfer), hydraulic (H; e.g., pore water pressure (PWP), suction, fluid flow), mechanical (M; e.g., stress, deformation, strength) and chemical (C; e.g.; binder chemical reaction) processes that occur in CTB and their effect on its geotechnical behavior [8,9]. CTB is essentially made of tailings (human-made soils; that is, materials that remain after minerals of value are removed), binder (e.g., Portland cement, blast furnace slag, fly ash), and water. After preparation and placement, the hardening CTB must satisfy certain requirements of mechanical stability to ensure a safe working environment for underground mining personnel. To assess the in-situ mechanical performance of CTB under static loading condition, the uniaxial compressive strength (UCS) of hardened CTB is often adopted in practice [8]. Based on previous studies on CTB [10,11], it has been found that the curing stress (mechanical factor), temperature (thermal factor), suction associated with moisture content (hydraulic factor) and binder type and chemistry (chemical factor) (i.e., the coupled THMC processes) largely govern the UCS development. Moreover, to prevent the CTB from flowing into the active mining zone, retaining structures (called barricades or bulkheads) are commonly constructed in the drawpoints (access points at the base of the stopes). It is critical that the horizontal pressure or stress developed by the CTB is not greater than the resistance of the retaining structure because its failure can have drastic work safety consequences and significant financial ramifications [8,12]. Therefore, an understanding of the stress development and distribution in CTB structures is critically important for the optimal geotechnical design of CTB structures and barricades.

Field investigations [e.g., [13,14]] have previously confirmed that the vertical stress in the CTB is significantly less than the overburden stress due to the arching effect, which primarily results from the consolidation process of the CTB, and the improvement of CTB/rockmass interface properties with binder hydration. The consolidation of the CTB results in the development of settlement and effective (horizontal) stresses, thus enabling shear stresses to develop at the CTB-rock interface [6]. As a result, the stress in the CTB will be redistributed and the vertical stress

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Nomenclature

b_i	fitting constant (i = 1–10) of hardening/softening parameter
c_B	CTB cohesion
c_{intf}	interface adhesion
c_{n1}, c_{n2}	fitting parameters of interface normal stiffness
c_{s1}, c_{s2}, c_{s3}	fitting parameters of interface shear stiffness
c_1, c_2	fitting parameters of CTB cohesion
C_b	apparent binder density with respect to the total volume of CTB mixture
C_i	specific heat capacity (i refers to air, water and solid)
C_{intf}	material parameters of D-P criterion
C_k	material constants of saturated hydraulic conductivity
C_m	binder content
d_1, d_2, d_3, d_4, d_5	fitting parameters of water retention curve
D_k	material constants of saturated hydraulic conductivity
e	void ratio of CTB
e_0	initial void ratio of CTB
E	elastic modulus
E_a	apparent activation energy
E_T	elastic modulus of tailings
E_{u_p}	ultimate stiffness of dense cement paste
$f_{,}f_2, f_3, f_4$	fitting parameters of CTB stiffness
F_δ, F_c	fitting parameters of interface friction angle and adhesion
g	gravitational acceleration
$h_{filling}$	filling height
H_c	total heat released by cement hydration
$R_{n-w/hc}$	mass ratio of the chemically combined water and hydrated cement
R_1, R_2	fitting constants of residual water content
S	saturation degree
S_e	effective saturation degree
t	elapsed time
t_e	equivalent age of binder hydration
T, T_r	current and reference temperature of CTB
$\mathbf{v}^{rw}$, $\mathbf{v}^{ra}$	Darcy's velocity of pore water and pore air
v_w, v_n, v_{ab-w}, v_c, $v_{tailings}$	specific volume of the capillary water, chemically combined water, physically absorbed water, cement and tailings
v_1, v_2	volume fraction of tailings and ultimate cement paste with respect to the total volume of solid phase
w/c	water to cement ratio
w_ψ	inverse of one GPa
w_1, w_2	fitting constants of interface dilation angle
x_i	weight ratio of compounds in cement in terms of total cement content (i refers to cement compounds)
X_i	weight proportion of binder components to total binder weight (i refers to cement, fly ash and blast furnace slag)
α_{Biot}	Biot's effective stress coefficient
α_{intf}	material parameters of D-P criterion
α_{Ts}	coefficient of thermal expansion of CTB solid phase

α_{WRC}	material parameters of water retention curve
β	hydration shape parameter
δ_{ij}	Kronecker's delta
I_1	first stress invariant
J_2	second deviatoric stress invariant
k	intrinsic permeability of CTB
k_{eff}	effective thermal conductivity
k_{rw}, k_{ra}	relative permeability of pore water and pore air
k_{sat}, k_{dry}	thermal conductivity of the porous media in saturated and completely dry condition
$k_{tailings}$, k_w, k_a	thermal conductivity of tailings, water and air
K_b	bulk modulus of CTB matrix
K^e	interface stiffness matrix
K_s	bulk modulus of tailings
K_s^e, K_n^e, K_t^e	shear, normal and tensile interface stiffness
K_{sat}	saturated hydraulic conductivity of CTB
K_ψ	material parameter of interface dilation angle
m_{hc0}	initial cement mass
m_{WRC}	material parameters of water retention curve
n_1, n_2	fitting parameters of interface friction angle
n_3, n_4	fitting parameters of interface adhesion
P_a, P_w	pore-air and pore-water pressure
$\overline{P}$	average pore pressure
Q_{CTB}	plastic potential function of CTB
Q_{intf}	interface plastic potential function
R	ideal gas constant
R_{intf1}, R_{intf2}, R_{intf3}, R_{intf4}	material constants of hardening/softening parameter
R_L	roughness index of the rock wall
δ_{intf}	interface friction angle
Δ	total relative displacement
Δ_e, Δ_p	elastic and plastic part of relative displacement
Δ_κ	cumulative plastic displacement
ε_v	volumetric strain
ϕ	porosity
ϕ_B	internal friction angle of CTB
ϕ_r	internal friction angle of surrounding rock
λ	non-negative plastic multiplier
μ_a, μ_w	dynamic viscosity of pore air and pore water
v	Poisson's ratio
θ, θ_s, θ_r	volumetric, saturated and residual water contents
ρ_{CTB}	backfilling density
ρ_i	density (i refers to air, water and solid)
$\boldsymbol{\sigma}$	total stress tensor
$\boldsymbol{\sigma}'$	effective stress
$\boldsymbol{\sigma}'_n$	effective normal stress acting on the interface
τ	time parameter of binder hydration
ξ	binder hydration degree
ξ_u	ultimate hydration degree
ψ_{intf}	interface dilation angle

gradually becomes less than the self-weight stress (i.e., the arching effect takes place). Therefore, it is evident that to investigate and evaluate arching and the stress distribution in CTB, it is necessary to understand and assess the changes in the interface shear stress and the consolidation of CTB during and after filling. This development of the interface shear stress and consolidation behavior is strongly influenced by the THMC processes (Fig. 1) in CTB [15]. It is well known that the consolidation and interface shear behavior of CTB are not only affected by mechanical loads, but also by thermal, hydraulic and chemical (binder hydration) processes or their various combinations. Reproducing these THMC processes and assessing the arching effect in a laboratory on a CTB structure that measures several dozens of meters or in the field are technically difficult and extremely costly. Consequently, it is clear that a proper assessment and understanding of the arching effect of CTB and the resulting stress redistribution require integrated multiphysics models that can illustrate and capture the changes in the material properties of CTB (thus, a THMC model), consolidation behavior of the evolutive CTB mass, and the shear behavior at the interface between the CTB with changes in its properties and the rock wall. However, to date, no studies have addressed these issues and there is no model that can describe the aforementioned