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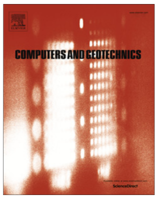

Research Paper

A coupled thermal-hydraulic-mechanical application for subway tunnel

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ABSTRACT

Subway tunnels and their surrounding geotechnical media are taken as an entirety, namely, tunnel-geomaterial system (TGS), and the stability and durability of the subway tunnels are subjected to the responses of the TGS to the thermal (T), hydraulic (H) and mechanical (M) loadings and their coupled effects. Modeling of the coupled THM processes that occur in the TGS are important for reliably assessing and predicting the performance of subway tunnels. Therefore, a numerical model of coupling the THM processes in the TGS is developed incorporating the equilibrium, motion, constitutive and compatibility equations. The proposed model considers full coupling between the thermal (temperature variation), hydraulic (water seepage), mechanical (subsidence) processes and changes in the material properties, such as stress-strain relation, viscosity, thermal conductivity, and hydraulic conductivity. The developed model is validated through comparisons of field tests, laboratory experiments and numerical simulations. Favorable agreement between the modeling results and the compared data verifies the capability of the developed model to well describe the THM behavior of subway tunnels in the TGS and their evolutions.

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1. Introduction

In recent years, subway tunnels are extensively and increasingly constructed in numerous cities in China, in order to relieve the ground traffic congestion. Safeties of the underground railway trains and people in them should be carefully ensured. This requires the subway tunnels to have favorable construction quality, and thus to perform good stability and durability. These performances, which are important engineering indicators for evaluating the subway tunnels, are also functions of the thermal (T), hydraulic (H) and mechanical (M) properties. The thermal, hydraulic and mechanical properties interact with each other (as explained in Section 2), exerting coupled THM effects on the subway tunnels.

Subway tunnels and their surrounding geotechnical media constitute a tunnel-geomaterial system (TGS). The analysis of the subway tunnels cannot be done without the consideration of the whole system (i.e., TGS). Since the subway tunnels are always constructed in shallow earth, the TGS is subjected to the temperature variations induced by local climate conditions (e.g., tropical or cold areas) as well as seasonal changes (e.g., summer or winter). These thermal loadings (or sources of heat) will cause mechanical deformation in the TGS through thermal expansion. In addition, the TGS is also affected by external (e.g., rainfall) and/or internal (e.g., developed underground water) hydraulic factors, which can contribute to the evolution of pore water pressure within the TGS and thus, results in the variation of the effective stress as well as plastic zone redistribution in the TGS. Furthermore, although in shallow earth the tectonic stress (or horizontal stress) exerts insignificant effect on the TGS, it still experience mechanical deformation under gravity (vertical stress). This mechanical load can definitely induce ground surface subsidence in the TGS after the excavation of the subway tunnels. Consequently base on the above discussions, it can be concluded that the performance of the subway tunnels (in the TGS) are controlled by complex coupled multi-physics (THM) processes. A good understanding of the complex and varying coupled THM processes can contribute to the design of stable and durable subway tunnels, and modeling of the coupled THM processes that occur in the TGS provides a theoretical solution for reliably assessing and predicting the performance of subway tunnels.

Recently, multi-physics coupled modeling has become a research focus in the field of geotechnical engineering, and numerous studies have been conducted to understand the multi-physics coupled processes accompanying with such kinds of engineering applications, or describe the response of geo-media to the multi-physics coupled processes. Correspondingly, numerical models

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have been developed and progressed to a high level, including complex geometries and complicated coupled processes. These developments have been reviewed and reported previously, such as radioactive waste disposal in deep geological repositories (DGRs) (e.g., [4,11,19,20,28], geothermal energy utilization (e.g., [1,3,7,22,26,27], and underground space excavation (e.g., [10]. However, researches with respect to the multi-physics coupled analysis in tunneling (especially subway tunneling) applications have been rarely reported. The reason for this may be that engineers and/or researchers mainly focus their studies on the tunneling engineering practice and consequence, but seldom get involved in theoretical studies, especially multi-field coupling analysis. With the increase in the research interest of multi-physics coupling and the development of corresponding numerical programs, a few studies have started to address and understand the multi-physics processes that occur in the TGS and their effects on the tunnel performance. For instance, researchers have carried out coupled HM (e.g., [12,8,16,13] and TM (e.g., [15,29] analyses on tunnels (including subway tunnels). Furthermore, Rutqvist et al. [24] have modeled the coupled THM behavior of bentonite-backfilled repository tunnels. Nevertheless, to date, no studies have been conducted on presenting a coupled THM model for a subway tunnel or describing the response of a subway tunnel to coupled THM effects. Subway tunnels are different from other kinds of tunnels, such as deep underground tunnels (for mining or disposing nuclear waste) and highway tunnels in terms of geological conditions and tunneling methods (e.g., cut and cover method or shield driven method for subway tunneling, mining method for deep underground tunneling). Therefore, the developed coupling models for other types of tunnels cannot be applied to subway tunnels directly. An effective prediction and evaluation of the performances of subway tunnels are necessary and requires the coupling of all the THM processes as well as the consideration of the whole TGS. This encourages the authors to propose a numerical model to analyze and predict the behaviors of subway tunnels within the TGS under coupled THM loadings.

The outline of this paper is as follows: first, a mathematical (THM) model is developed by coupling the equilibrium, motion, constitutive and compatibility equations for the thermal, hydraulic and mechanical processes (Section 2); secondly, the developed model is validated against a field study, a laboratory study and a numerical study, respectively (Section 3); finally, the concluding remarks are noted and presented (Section 4).

2. Governing equations for the THM model

FLAC 3D [6], a three-dimensional finite difference program based on an explicit Lagrangian calculation scheme, is employed currently to carry out the numerical studies. When using FLAC 3D to analyze the response of geomaterials to the coupled hydraulic-mechanical effect, the geomaterials are ideally treated as equivalent continuum. The Darcy law is used to describe the fluid flow. The coupling between the mechanical and hydraulic calculations due to deformation can be implemented by the Biot coefficient. It is well known that temperature variation can lead to heat-induced expansion and contraction stress in the geomaterials. Hence, the mechanical and thermal processes can be coupled with each other through the thermal expansion coefficient. The governing equations for the coupled thermal-hydraulic-mechanical calculations are presented as follows.

It should be noted that, the Einstein notation is used in the following equations: the symbol a_i denotes component i of the vector $\{a\}$ in a Cartesian system of reference axes; A_{ij} is component (i, j) of tensor $[A]$. Also, $f_{,i}$ is used to represent the partial derivative of f with respect to x_i.

2.1. Equations of equilibrium

For small deformations, the fluid mass balance equation can be expressed in the following form [6]:

$$-q_{i,i} + q_v = \frac{\partial \zeta}{\partial t} \tag{1}$$

where $q_{i,i}$ is the fluid velocity, q_v is the volumetric fluid source intensity, and ζ is the variation of fluid content or variation of fluid volume per unit volume of the porous materials (the geomaterials are porous media) due to diffusive fluid mass transport.

The thermal energy balance is expressed as follows [6]:

$$-q^T_{i,i} + q^T_v = \frac{\partial \zeta^T}{\partial t} \tag{2}$$

where q^T_i is the heat flux vector, ζ^T is the heat stored per unit volume of the porous materials, and q^T_v is the volumetric heat source intensity.

The balance of momentum leads to the following expression [6]:

$$\sigma_{ij,j} + \rho_{\mathrm{eq}} g_i = \rho_{\mathrm{eq}} \frac{du_i}{dt} \tag{3}$$

where σ_{ij} is the stress vector, g_i is the gravity vector, u_i is the fluid velocity vector, and ρ_{eq} is the equivalent bulk density, which can be written as:

$$\rho_{\mathrm{eq}} = (1-n)\rho_s + ns\rho_f \tag{4}$$

where ρ_s and ρ_f are the solid matrix density and fluid density, respectively; n is the porosity of the geomaterials; and s is the fluid saturation. It should be noted that in this study, the influence of capillary pressure is neglected (the fluid pressure is equal to air pressure when saturation is less than one), and the air pressure is zero in the unsaturated zone.

2.2. Equations of motion

Darcy's law is used to describe the fluid transport within the solid matrix, which is considered as homogeneous. This law is given in the following form [6,17]:

$$q_i = -k_{ij}(p_{,j} - \rho_f \mathbf{g}_j) \tag{5}$$

where k is the hydraulic conductivity tensor, p is the fluid pressure, $\mathbf{g} = (0,\ g)^{\mathrm{T}}$ for 2D problem and $\mathbf{g} = (0,\ 0,\ g)^{\mathrm{T}}$ for 3D problem, respectively.

2.3. Constitutive equations

For the TGS, the heat transfer within it due to thermal conduction (induced by temperature gradient) is considered, neglecting thermal convection and radiation since this part of heat is insignificant [18]:

$$q^T_i = -k^T_{ij} T_{,j} \tag{6}$$

where q^T_i is the heat flux vector, T is the temperature, and k^T is the thermal conductivity tensor.

Changes in the variation of fluid content are related to changes in pore water pressure, saturation degree, mechanical volumetric strains, and temperature [6]:

$$\frac{\partial \zeta}{\partial t}\frac{1}{s} = \frac{1}{M}\frac{\partial p}{\partial t} + \frac{n}{s}\frac{\partial s}{\partial t} + \alpha\frac{\partial \varepsilon}{\partial t} - \beta\frac{\partial T}{\partial t} \tag{7}$$

where M is Biot modulus, α is Biot coefficient, ε is the strain, and β is the undrained thermal coefficient, which takes into account the fluid and grain thermal expansions.

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