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Thermo-hydro-mechanical-air coupling finite element method and its application to multi-phase problems

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ABSTRACT

In this paper, a finite element method (FEM)-based multi-phase problem based on a newly proposed thermal elastoplastic constitutive model for saturated/unsaturated geomaterial is discussed. A program of FEM named as SOFT, adopting unified field equations for thermo-hydro-mechanical-air (THMA) behavior of geomaterial and using finite element-finite difference (FE-FD) scheme for soil–water–air three-phase coupling problem, is used in the numerical simulation. As an application of the newly proposed numerical method, two engineering problems, one for slope failure in unsaturated model ground and another for in situ heating test related to deep geological repository of high-level radioactive waste (HLRW), are simulated. The model tests on slope failure in unsaturated Shirasu ground, carried out by Kitamura et al. (2007), is simulated in the framework of soil–water–air three-phase coupling under the condition of constant temperature. While the in situ heating test reported by Munoz (2006) is simulated in the same framework under the conditions of variable temperature but constant air pressure.

1. Introduction

Multi-phase issue has attracted more attention recently because of its wide involvement in geotechnical engineering problems, not only in instant failure problem like slope failure, but also in long-term stability problem like deep geological repository of high-level radioactive waste (HLRW). Numerous researches, both in laboratory/field tests and numerical simulation/prediction, have been conducted in this field ceaselessly. Yet it is still far away from the state with which we can satisfy. The key problem is that, in most cases, people have to simplify a real geotechnical problem with some assumptions and to pick up one or several factors they think the most important and take them as their concerns while other factors are neglected. For instance, constitutive model is always divided into two parts, one for saturated material and another for unsaturated. Thermal and viscoplastic effects are the other questions needed to be addressed. What we want to emphasize here is that, the physical states, such as the saturation (S_r) or the temperature (T) are only the states of a geomaterial, you cannot say that the geomaterial is a different material when the states are different. Unfortunately, in most cases, a constitutive model usually merely considers the geomaterial in a specific state; in other words, it can describe the mechanical behavior of the geomaterial in the specific state but cannot fit anymore at other states.

As is known, geomaterial is different from some other engineering materials such as steel and concrete in that it consists of more than one phase. Geomaterials are usually made of soil grain, water and air. When the voids are fully occupied with water, soil is called as saturated soil, otherwise unsaturated soil. Followed by the pioneering work (Alonso et al., 1990), in which Barcelona Basic Model (BBM), a fundamental model for unsaturated soil, was proposed using the concept of loading-collapse (LC) and suction increase (SI), a number of elastoplastic constitutive models have been developed to describe the behavior of unsaturated soil. Some of these models were proposed in the framework of net stress and suction such as Cui and Delage (1996), Chiu and Ng (2003), and Sheng et al. (2008), whereas others are in the framework of Bishop-type effective stress and suction such as Kohgo et al. (1993), Loret and Khalili (2002), and Sun et al. (2007). More recently, some constitutive models using the effective stress and the degree of saturation as independent state variables have been proposed, such as Ohno et al. (2007), Zhang and Ikariya (2011), and Zhou et al.

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(2012a,b). As pointed out by Zhang and Ikariya (2011), using the effective stress and the degree of saturation in modeling unsaturated soil is much easier and smoother to describe the behavior of soil from unsaturated state to saturated state than that using the net stress or effective stress and the suction as the independent state variables.

On the other hand, researches related to the thermal effect on geomaterials have also been done extensively due to the huge demand for assessing the safety of deep geological repository of HLRW. Until now, a number of experimental studies have been conducted to investigate the thermal effects on mechanical behaviors of the saturated geomaterials, e.g. Campanella and Mitchell (1968), Baldi et al. (1988, 1991), Cekerevac and Laloui (2004), Okada (2005), and Nishimura (2013).

At the same time, many constitutive models for saturated geomaterials considering thermal effects have been proposed, e.g. the works by Cui et al. (2000, 2009), Laloui (2001), Zhang and Zhang (2009), and Zhang et al. (2012). In comparison with the saturated geomaterials, researches related to the thermal effects on unsaturated soils were rarely reported because of the difficulty for independent measurement and control of pore air pressure (PAP), pore water pressure (PWP), mechanical loading and temperature at the same time. Yet the researches on the modeling of unsaturated geomaterials under non-isothermal condition can be found in the literature. Francois and Laloui (2008) proposed a unified thermo-mechanical model for unsaturated soils, in which the temperature and suction effects are studied within the framework of elastoplastic theorem. Dumont et al. (2011) proposed a thermo-hydro-mechanical (THM) model for unsaturated soils based on the extension of effective stress concept to unsaturated soils using a capillary stress. Uchaipichat and Khalili (2009) conducted a comprehensive non-isothermal test on compacted samples of silt with triaxial loading device.

Meanwhile, the THM behaviors of artificial and natural barriers in the deep geological repository of HLRW have also been investigated intensively, both in experiment and numerical simulation. A lot of field heating experiments have been reported in the last decades, such as the works by Gens et al. (2007, 2009), Jia et al. (2007), Akesson et al. (2009), Gens (2010), and Sawada et al. (2009). In reality, however, the heating period caused by the HLRW will last for hundreds thousands years or even longer for some radioactive substances. Therefore, sometime it is impossible to reproduce the whole process in the field tests. Numerical simulation would be a potential effective method to describe and predict the THM behaviors on the condition that the numerical method is able to fit the results of field experiments, at least in a limited period of time. For this reason, the laboratory tests on the THM behaviors of geomaterials at element level will play an important role in improving the accuracy of the numerical analyses. Many laboratory element tests of geomaterials have been conducted in order to investigate the basic thermo-mechanical behavior. It is overwhelmingly reported that the strength of geomaterial will decrease when its temperature increases, e.g. the works performed by Okada (2005, 2006) and Nishimura (2013). Volumetric change of geomaterials induced by heating was also conducted by Towhata et al. (1993), Laloui and Cekerevac (2003), and Cekerevac and Laloui (2004).

As to the numerical methods in multi-phase problems, many works can be found in the literature, e.g. the work related to soil–water two-phase coupling problem by Oka et al. (1994) and the works related to the soil–water–air three-phase coupling problem by Li et al. (2004), Borja (2005), Uzuoka et al. (2007, 2008, 2009), Uzuoka (2010), and Oka et al. (2010). In the works related to finite element-finite difference (FE-FD) scheme (Oka et al., 1994) for soil–water coupling problem, finite element method (FEM) is used for the spatial discretization of the equilibrium equation and the energy conservation equation, while the backward finite difference scheme proposed by Akai and Tamura (1978) is used for the spatial discretization of the continuity equation. In the works related to THM coupling problem by Oka et al. (2010), the THM coupling relations are based on the work conducted by Nguyen (1995).

The aim of this paper is to establish a unified numerical method to treat the multi-phase problem related to the thermo-hydro-mechanical-air (THMA) behavior of geomaterials, based on a newly proposed thermo-elastoplastic constitutive model for unsaturated/saturated soil (Xiong, 2013). A FEM program, named as SOFT that adopts unified field equations in finite deformation scheme and uses FE-FD scheme for discretizing thermo-soil–water–air coupling problem, is employed in the numerical simulation. As an application of the newly proposed numerical method, two engineering problems, one for slope failure in unsaturated model Shirasu ground (Kitamura et al., 2007) and another for in situ heating test related to deep geological repository of HLRW (Munoz, 2006), are simulated to verify the availability of the proposed numerical method.

2. Thermo-hydro-mechanical-air coupling finite deformation algorithm of field equations

In deriving the unified field equations for the THMA coupling problem in finite deformation algorithm for geomaterials, the following assumptions are adopted:

(1) The distribution of porosity, n, in space and time is very small compared with other variables.
(2) The distribution of degree of saturation, S_r, in space is very small compared with other variables.
(3) The relative acceleration of the fluid (water and air) phase to the solid phase is much smaller than that of the solid phase.
(4) Soil grain is incompressible.

In the following context, the superscripts "s", "w" and "a" represent the soil, the liquid and the air phases, respectively.

2.1. Equilibrium equation

First of all, definition of appearance density is introduced. The appearance densities of the solid phase $\bar{\rho}^s$, the liquid phase $\bar{\rho}^w$ and the air phase $\bar{\rho}^a$ are defined as

$$\left.\begin{aligned}\bar{\rho}^s &= (1-n)\rho^s\\ \bar{\rho}^w &= nS_r\rho^w\\ \bar{\rho}^a &= n(1-S_r)\rho^a\end{aligned}\right\} \tag{1}$$

where ρ^s, ρ^w and ρ^a are the densities of soil, liquid and air, respectively; n is the porosity of the soil; and S_r is the degree of saturation.

With the use of appearance densities, the density of the three-phase mixture can be expressed as

$$\rho = \bar{\rho}^s + \bar{\rho}^w + \bar{\rho}^a = (1-n)\rho^s + n[S_r\rho^w + (1-S_r)\rho^a] \tag{2}$$

Considering the mean pore pressure p^F, the relationship between total stress tensor $\boldsymbol{T}$ and effective stress tensor $\boldsymbol{T}'$ are as follows:

$$\left.\begin{aligned}\boldsymbol{T} &= \boldsymbol{T}' + p^F\boldsymbol{I}\\ \dot{\boldsymbol{T}} &= \dot{\boldsymbol{T}}' + \dot{p}^F\boldsymbol{I}\\ p^F &= S_r p^w + (1-S_r)p^a\end{aligned}\right\} \tag{3}$$

where $\boldsymbol{I}$ is the identity tensor.