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A critical state based thermo-elasto-plastic constitutive model for structured clays

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ABSTRACT

In this paper, a critical state based thermo-elasto-plastic constitutive model is developed for destructured, naturally structured and artificially structured saturated clays. The model is an extension of the previously developed thermo-mechanical model by the authors for saturated clays, considering the effects of structure on the mechanical behaviors of the soil. It is based on change in the position of normal consolidation line (NCL) in a compression plane ($e - \ln p'$) due to the soil's structure and variation of temperature. The present model is able to simulate the mechanical behavior of structured saturated clays in a triaxial plane at elevated temperatures lower than the boiling point of water. An attempt has been made to use the lowest possible number of parameters compared with that of Cam–Clay model and to ensure that these new parameters have clear physical interpretations. The sufficiency of the model was verified by the test results on artificially and naturally structured soils using thermal triaxial tests.

1. Introduction

Due to the rapid industrial development in recent decades, evaluation of the effect of thermal gradients on the mechanical behavior of soils has been a challenging issue. Disposal of radioactive nuclear wastes, temperature increase around high voltage cables, geothermal energy storage, geothermal structures, oil extraction and the use of heating for an increase in soil permeability around drainage systems and a decrease of soil texture disturbance on permeability are examples to define the necessity of studying the soil behavior at elevated temperatures.

Variations of temperature affect the physical and mechanical properties of soil microscopically and macroscopically. These changes also affect properties such as volume, shear strength, soil stability and pore water pressure. In this circumstance, ability to predict the engineering behavior of soils is of critical importance; in this regard, development of a constitutive model that is able to predict soil response to temperature change is needed.

Over the past decades, a number of studies on the temperature-dependent clay behavior under increased temperature have been conducted. These observations proved that temperature changes both the physical and mechanical characteristics of soil. For this purpose, various thermo-mechanical models have been developed which are able to represent the main characteristics of clays under thermal gradients (Hueckel and Borsetto, 1990; Robinet et al., 1996; Thomas et al., 1996; Cui et al., 2000; Hamidi and Khazaei, 2010; Yao and Zhou, 2013; Xiong et al., 2014, 2017; Bellia et al., 2015; Hamidi et al., 2015; Tourchi and Hamidi, 2015; Hong et al., 2016; Kurz et al., 2016; Hamidi and Tourchi, 2017).

For normally consolidated clays, the contraction of volume change due to thermal loading is irreversible; however, these changes are of reversible dilation for overconsolidated clays (Baldi et al., 1988; Cui et al., 2000; Abuel-Naga et al., 2007). A number of studies show increase of drained and undrained shear strengths of the soil by elevated temperature (Kuntiwattanakul et al., 1995; Graham et al., 2001; Cekerevac and Laloui, 2004; Abuel-Naga et al., 2007). Other researchers showed strength reduction by an increase of temperature (Houston et al., 1985; Hueckel and Baldi, 1990). Also, some researchers witnessed independence of soil strength to the thermal situation (Burghignoli et al., 1992).

Hueckel and Borsetto (1990) studied the plastic behaviors of clays under isothermal condition. They found that the elastic yield surface is temperature-dependent and the dependency appears as a decrease in yield stress by an increase in temperature. Robinet et al. (1996) used modified Cam–Clay model and developed a

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thermo-elasto-plastic model for saturated clays with two separate yield mechanisms. The new feature of the model in comparison to previous ones was the introduction of permanent thermal strains using two yield surfaces for the prediction of both thermal and mechanical softening behavior. Thomas et al. (1996) developed a thermo-hydro-mechanical model for unsaturated soils based on thermo-elasto-plasticity, and considered deformation-temperature coupling and energy balance in which moisture and heat storage were included.

Cui et al. (2000) suggested a thermal Cam Clay based model that was able to predict the thermoplastic strains at different preconsolidation ratios. They defined temperature effects on clays as an inverse relation between preconsolidation pressure and temperature.

Abuel-Naga et al. (2009) proposed a thermo-mechanical model for saturated clays under triaxial test conditions based on the model proposed by Masad et al. (1998). The first part was an isotropic thermo-elasto-plastic model with the ability to simulate thermally induced volume change for normally and overconsolidated saturated clays. The second part extends the parameters of the first part for prediction of strains under deviatoric stress condition.

Hamidi and Khazaei (2010) developed a thermo-elasto-plastic model based on modified Cam Clay concept. It was capable of predicting the mechanical behavior of saturated clays at temperatures above the ambient one under triaxial stress state condition. The main idea originated from the difference between normal consolidation line (NCL) of the soil in ambient and higher temperatures. Yao and Zhou (2013) presented a non-isothermal constitutive model with constant hardening based on a previous model developed by Yao et al. (2009) using unconfined hardening to simulate the thermo-elasto-plastic behavior of normally and overconsolidated clays. Hamidi et al. (2015) modified the original model (i.e. Hamidi and Khazaei, 2010) based on critical state theory, using a different equation for the yield surface and a temperature-dependent flow rule to improve the simulation results for saturated clays.

Xiong et al. (2014) developed a thermo-elasto-viscoplastic model for soft rocks with the ability to analyze thermo-hydro-mechanical (THM) coupling of heating tests, considering the effect of intermediate stress on the initial model of Zhang and Zhang (2009). Using the modified model, they developed a program called SOFT to simulate THM behavior of geological materials and concluded that the thermal volume change response is greatly dependent on overconsolidation ratio (OCR).

Hong et al. (2016) presented a thermo-mechanical model based on the model of Cui et al. (2000) using two yield surfaces, i.e. the current thermo-mechanical yield surface and the other one inside it which was formed based on thermal effects on yield stress. The model was able to predict the behavior of saturated clays at the non-isothermal condition. Bellia et al. (2015) proposed a thermo-mechanical model for unsaturated clays based on the effective stress concept and bounding surface plasticity, and they used suction and temperature to predict the behavior of unsaturated soils. Wang et al. (2016) also developed a non-isothermal model for soft, saturated clays based on modified Cam–Clay model which was capable of defining the thermal effects on the undrained shear strength. Tourchi and Hamidi (2015) and Hamidi and Tourchi (2017) proposed an isothermal model for unsaturated clays based on the modification of their previous model (i.e. Hamidi et al., 2015), considering Bishop's stress and suction as independent stress parameters and modifying the hardening rule and yield criterion to take into account the role of suction.

Kurz et al. (2016) proposed a semi-empirical thermo-elasto-viscoplastic model for clay considering creep behavior in compression and shear using a creep rate coefficient that varied with plasticity index and temperature but not with stress level and overconsolidation ratio.

Xiong et al. (2017) presented a unified thermo-elasto-viscoplastic model for soft rocks in the critical state framework. Two evolution equations were introduced for the shear strength and overconsolidation to take into account the influences of the confining stress and time-dependent behaviors, respectively. The model was able to describe the fundamental mechanical behavior of soft rock, such as strain softening and hardening, time-, temperature- and confinement-dependency in addition to the intermediate principal stress.

The influence of soil structure on the mechanical properties of soil has long been recognized. Here, the term "structured soil" is used to represent the arrangement and bonding of the soil constitutions. Removal of soil structure is referred to as "destructuring" and this is usually a progressive process. Generally, soils have natural structures due to the chemical, thermal, mechanical or environmental interactions and these types of soils behave differently in comparison to the reconstituted soils of similar materials (Burland, 1990; Leroueil and Vaughan, 1990; Cuccovillo and Coop, 1999). While the structure can arise from many causes, its effects follow a simple general pattern that involves stiff behavior followed by yield behavior. This yield behavior can be described in a similar way to that occurring due to overconsolidation, although it is a separate phenomenon (Leroueil and Vaughan, 1990).

Clays in their application as a buffer layer in nuclear waste disposal around high voltage cables or geothermal energy storage structures are permanently exposed to high temperatures which in combination with the surcharge pressures can result in the structured clay. Due to the differences in the mechanical behavior of non-structured clay and structured clay, the thermo-mechanical behaviors should also be different from each other. The effects of structure on the thermal characteristics of clays have not been considered in previously developed constitutive models and it seems necessary to elaborate it in a general framework for simulation of the thermo-mechanical behavior of structured clays.

Liu and Carter (2002) and Horpibulsuk et al. (2006, 2009) proposed a modified structured Cam–Clay (SCC) model that was formulated based on variations of NCL in compression plane. Also, Suebsuk et al. (2010) improved the model for naturally structured, artificially structured and destructured clays, which was considered as the modified structured Cam–Clay (MSCC) model. Yang et al. (2014) presented a model to describe the compression behavior of structured clays at large surcharge pressures using a differential function of NCL considering the effects of particle crushing. Horpibulsuk and Liu (2015) imposed cementation effects on strength and deformation of cohesive soils MSCC by defining a new mean effective stress parameter for cohesive/cemented soils. Xiao et al. (2017) developed a model to predict the behaviors of cemented clays considering the effects of cemented bonds by defining a cohesion parameter in flow rule of Cam–Clay model.

In this paper, the thermo-mechanical constitutive model presented by Hamidi et al. (2015) is revisited by a combination of thermal and structural effects on the void ratio of saturated clay and NCL. The model is able to predict the behavior of saturated structured clay in temperatures ranging from ambient one up to the boiling point of water. It is applicable to isothermal boundary value problems for naturally or artificially structured clays based on the modified Cam–Clay model and critical state soil mechanics concepts.

2. Basic concepts of the proposed model

In this section, the thermo-mechanical model proposed by Hamidi et al. (2015) for saturated clays is modified in consideration