New insights in the thermomechanical modelling of soils

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Introduction

There are many applications related to the thermo-mechanical modelling of soils, notably for high-level nuclear waste disposal, geothermal structures [1], thermal pre-treatment of clays to strengthen their resilience under cyclic loading as well as others related to seasonal and daily cyclic temperature variations. Due to the importance of such applications, the thermo-mechanical behaviour of soils is becoming one of the major issues in modern soil mechanics. This abstract addresses some new insights in the thermo-mechanical constitutive modelling of soils.

Thermal induced effects

Soil is a two-phase material including a solid part (a skeleton of grains or particles surrounded by adsorbed water, for clays) and a fluid part (free water) in voids. When a soil is heated, all of the constituents dilate. However, in normally consolidated conditions, the cohesive soil contracts when it is heated and a significant part of this deformation is irreversible upon cooling. On the contrary, the highly overconsolidated states produce mainly reversible dilation (Figure 1). Another important non-isothermal behaviour is the fact that the preconsolidation pressure p'_c (i.e. the stress yield limit which separates "elastic" pre-yield from "plastic" post-yield behaviour in isotropic or oedometric conditions) decreases with increasing temperature [2]. The analysis of the thermal effect on strength tends to show that the friction angle at critical state can either slightly increase or decrease with temperature [3].

ACMEG-T: An elasto-thermoplastic constitutive model for soils

In the presence of a temperature field, the elasto-plasticity principle (concept of a loading surface f in the stress space, which limits the region of elastic deformation), allows that the total strain rate tensor, $\dot{\varepsilon}$, be splitted into thermo-elastic, $\dot{\varepsilon}^e$, and thermo-plastic, $\dot{\varepsilon}^p$, components. The formulation is given in terms of infinitesimal increments or rates in the small deformation regime. The ACMEG-T model considers a multi-dissipative plasticity in order to develop the thermo-mechanical formulation [4]. The material plasticity is induced by two coupled mechanisms: an isotropic one which may be activated by any mechanical or thermal load and a deviatoric mechanism acting only under a deviatoric mechanical load [5]. The yield functions of the two mechanical thermo-plastic mechanisms (f_{iso} and f_{dev} representing the isotropic and deviatoric yield limits, respectively) have the following expressions (Figure 2):

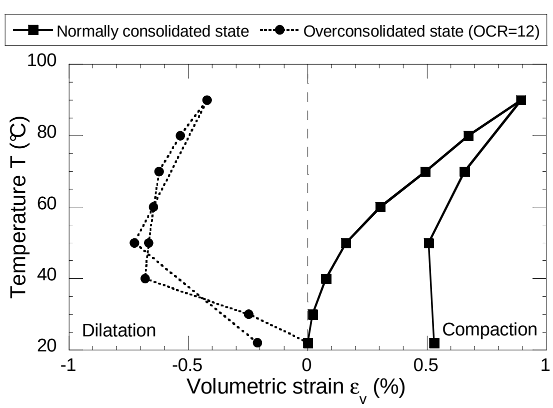

Figure 1. Typical thermal behaviour of saturated argillaceous materials during a heating-cooling cycle – Kaolin clay.

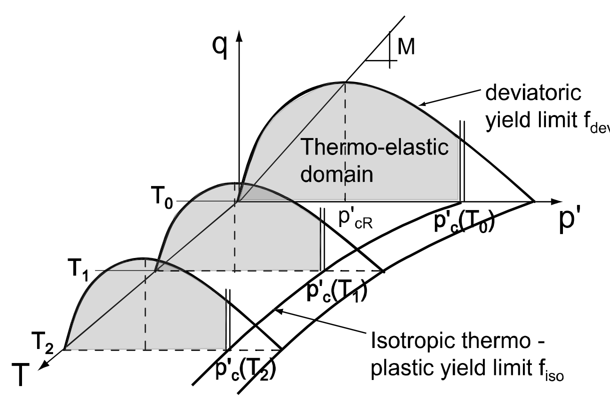

Figure 2. Yield limits for the thermo-mechanical elasto-plastic framework

$$f_{iso} = p' - p'_c \, r_{iso} = 0 \quad ; \quad f_{dev} = q - Mp'\left(1 - b\, Log\, \frac{d\, p'}{p'_c}\right) r_{dev} = 0 \qquad (1)$$

where *p'* and *q* are the mean effective and deviatoric stresses, respectively. r_{iso} and r_{dev} are the degree of mobilization of the isotropic and deviatoric mechanisms and are hyperbolic functions of the plastic volumetric strain induced by the isotropic mechanism and of the plastic deviatoric strain, respectively [6]. *M*, *d* and *b* are material parameters. p'_c is the preconsolidation pressure which depends on thermal conditions and increases during the hardening process. The flow rule of the isotropic mechanism is associated, whereas it is non-associated for the deviatoric mechanism:

$$\dot{\varepsilon}_{ii}^{p,iso} = \lambda_{iso} \frac{\partial g_{iso}}{\partial \sigma'_{ii}} = \frac{\lambda_{iso}}{3} \quad ; \quad \dot{\varepsilon}_{ij}^{p,dev} = \lambda_{dev} \frac{\partial g_{dev}}{\partial \sigma'_{ij}} = \lambda_{dev} \frac{1}{Mp'}\left[\frac{\partial q}{\partial \sigma'_{ij}} + \alpha\left(M - \frac{q}{p'}\right)\frac{1}{3}\right] \qquad (2)$$

where $\dot{\varepsilon}_{ii}^{p,iso}$ and $\dot{\varepsilon}_{ij}^{p,dev}$ are the components of plastic strain rate tensor induced by the isotropic and the deviatoric mechanisms respectively. α is a material parameter. The figure 3 illustrates typical numerical responses of the ACMEG-T model with respect to experimental results.

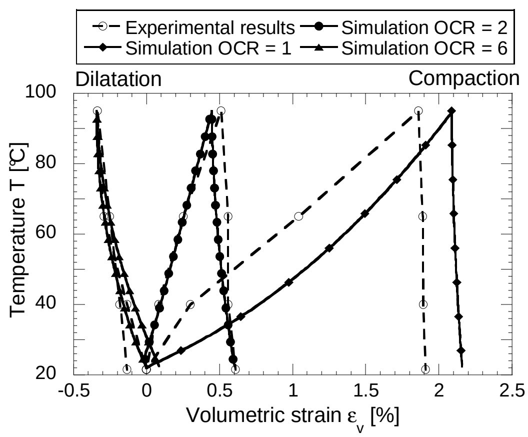

Figure 3a. Simulation of a heating-cooling cycle on Boom Clay at different isotropic stress level (p'_c=6Mpa)

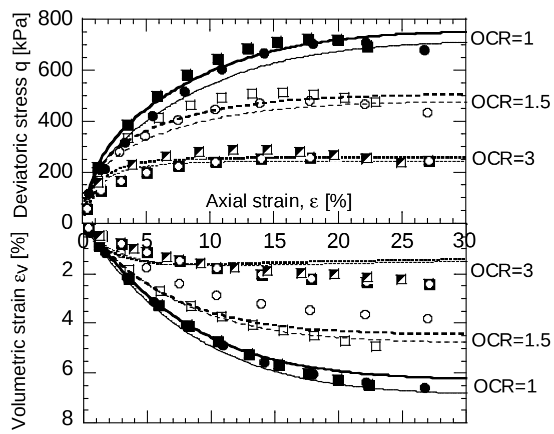

Figure 3b. Simulation of triaxial shear tests under different confining pressure (p'_c=600kPa). Circle (square) points: Experimental results at T=22°C (T=90°C) [3]. Thin (thick) lines: numerical simulations at T=22°C (T=90°C).

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