



Improved subloading thermo-viscoplastic model for soil under strictly isotropic conditions

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HIGHLIGHTS

- Thermo-viscoplastic subloading soil model with a mobile centre of homothety.
- Describes influence of non-isothermal conditions on the stress-strain-time behaviour of soils.
- Restricted to isotropic stress and strain conditions.
- Model able to accurately reproduce the experimental results of heating and cooling tests on clay.

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ABSTRACT

This paper presents a thermo-viscoplastic subloading soil model with a mobile centre of homothety. The model is formulated to describe the influence of non-isothermal conditions on the stress-strain-time behaviour of soils and is restricted to isotropic stress and strain conditions. Numerical simulations of three isotropic drained heating tests, two of which followed by a cooling stage, at constant isotropic effective stress for different overconsolidation ratios were performed. The model was able to accurately reproduce the experimental results, including the cooling behaviour, mainly due to the introduction of a direct influence of temperature on the mobile centre of homothety hardening law and also rate dependency.

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1. Introduction

The effect of the stress, strain and temperature histories on the thermo-mechanical behaviour of clays has been the focus of laboratory and constitutive model research. Drained tests under constant mean effective stress presented by Cekerevac and Laloui¹ and Laloui and Cekerevac² in Kaolin clay samples showed a remarkable influence of the stress history on the thermally induced volumetric strains. Similar tests performed by Hueckel and Baldi³ on other soils also confirm this finding. This type of test was first performed by Campanella and Mitchell⁴ only on normally consolidated clays. Consideration of this behaviour is important as it determines the stresses and strains induced by changes in the soil temperature field due to radioactive waste disposal or the exploitation of geothermal systems among others. In order to reproduce this thermo-mechanical behaviour, adequate constitutive relations are required and it is in this context that the present paper has been developed.

Cekerevac⁵ has presented a comprehensive and detailed experimental study regarding the thermo-mechanical behaviour of

Kaolin clay. Some of the results were used in the present study. One of the main results obtained and highlighted by Cekerevac and Laloui¹ was the significant values of dilatant volumetric strains at the start of isotropic drained heating for the most overconsolidated soil conditions. These values are significantly larger than the volumetric strains due to the thermal expansion of the constituent minerals of the Kaolin clay's solid phase. The experimental studies evidence the irreversibility of soil behaviour under thermal actions. In a very concise way, under normally consolidated conditions at constant mean effective stress, irreversible compaction volumetric strains are observed under heating. As OCR increases the contractive strains turn to expansive ones. If, as appears to be the case, due to the incongruence with the known values of the coefficients of volumetric thermal expansion of the minerals composing the soil, the large observed expansive strains are in part irreversible then arises the need to introduce a model with inelastic strains inside the yield surface. Inelastic strains also appear to occur during cooling.

The constitutive modelling of different aspects of thermo-mechanical behaviour has been attempted with different soil models using diverse phenomenological approaches. In Ref. 6, a relatively simple thermo-elastoplastic model was presented that,

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despite including some important thermal features, revealed significant shortcomings in describing the thermal response of over-consolidated soils. The model was not able to reproduce the large values of dilatant volumetric strains measured at the start of heating in constant mean effective stress tests. The computed values were limited by what was assumed to be a realistic value for the elastic (reversible) thermal expansion. This limitation is shared by classic thermo-elastoplastic models unless a difficult to explain stress or OCR dependent coefficient of thermal expansion of the solid skeleton that does not apply to its constituent minerals is assumed.⁷

Rate dependency is one of the most relevant features of soil behaviour. Thus, the possibility that rate-dependent behaviour may influence the observed thermo-mechanical response is used in this paper to overcome the apparent limitations of the thermo-elastoplastic models. Several thermo-viscoplastic models for soils have been proposed such as those of Modaressi and Laloui⁷, Xiong et al.⁸, Kurz et al.⁹, Raude et al.¹⁰, Zhang and Cheng¹¹, Zhang and Kurimoto¹² and Qiao and Ding¹³. From these models, only Zhang and Cheng¹¹ and Zhang and Kurimoto¹² tried to reproduce the laboratory tests described in Ref. 5.

Recently, Maranhã et al.¹⁴ proposed a purely viscoplastic subloading model that has the capability of simulating the main aspects of rate-dependent soil behaviour. The model has a mobile centre of homothety, enabling the occurrence of viscoplastic strains inside the yield surface and avoiding the abrupt change in stiffness of the traditional overstress viscoplastic models, i.e. the elastoplastic soil hardening models (such as Cam Clay) extended into the rate-dependent range using the formulation proposed by Perzyna¹⁵. The model showed the ability to reproduce the main observed aspects of rate-dependent behaviour under complex loading paths. An extension of this model, restricted to one-dimensional isotropic stress and strain conditions to non-isothermal conditions was presented by Maranhã et al.¹⁶ with the aim of reproducing the thermo-mechanical response during heating including rate-dependent behaviour (the model of Xiong et al.⁸ is a subloading thermoplastic model with creep and does not use the concept of overstress). The model was able to reproduce very accurately three drained heating only tests at constant isotropic effective stress and different overconsolidation ratios with the same set of constants. The significant expansion of the overconsolidated clay was reproduced as mainly inelastic strains. This was only possible due to the use of the non-verifiable hypothesis that the viscous strains due to isotropic stress unloading that takes place in overconsolidated soils where still occurring at the start of thermal loading (heating) in order to be able to induce the large expansive inelastic volumetric strains observed. Here the original model is improved to be able to reproduce tests with heating followed by cooling with distinct OCR values. For that purpose, several alternative model versions assuming different hypotheses were formulated and their relative performance determined by means of an evolutionary algorithm.¹⁷

A criticism frequently levelled at advanced models for soils is the large number of constants and the need to define a simple procedure to determine each of them separately. With the use of global optimisation algorithms, such as evolutionary algorithms, the determination of the material model constants can be an almost automatic procedure. The number of constants becomes much less relevant, as the main restriction to their precise determination (besides computing power) is the availability of adequate experimental data, which, in any case, would be needed. Also, the constants' values are found all at once and the definition of procedures to determine each constant separately is not needed. This is an advantage, not a drawback as, in general, it is not possible to isolate the effect of each constant because they interact between them nonlinearly. As several independent runs are made, the statistical variation of the parameter values can also give important information on whether there is sufficient experimental data to determine those constants.

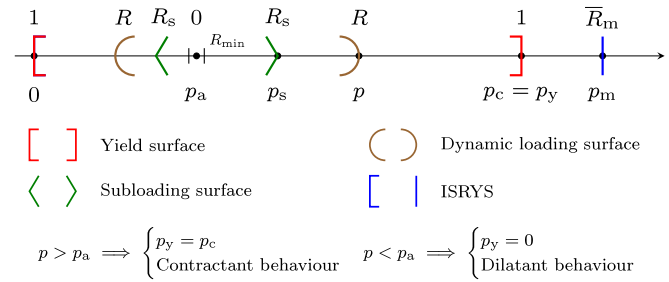


Fig. 1. Schematic representation, in the isotropic stress space, the different homothetic surfaces which define the thermal-viscoplastic subloading model, with a mobile centre of homothety, p_a .

2. Thermo-viscoplastic subloading soil model

In this section, the mathematical formulation of a thermo-viscoplastic subloading soil model is presented. The constitutive model is formulated to represent the non-isothermal behaviour of soils under strictly isotropic stress and strain conditions. The stress and strain spaces are one-dimensional but they are defined in the Euclidean three-dimensional physical space. This model is an extension to the non-isothermal behaviour of the viscoplastic subloading soil model presented by Maranha et al.,¹⁴ restricted to isotropic stress and strain conditions. Therefore, the capability of reproducing relevant soil behaviour's characteristics, under isotropic stress and strain conditions, such as elastic to viscoplastic smooth transition, loading reversals, rate-dependency as well as the occurrence of viscoplastic strains inside the yield surface is preserved. In this and in the following sections, stresses are assumed effective, strains small and compression positive.

Fig. 1 schematically represents, in the isotropic effective stress space, the different homothetic surfaces which define the thermoviscoplastic subloading model, with a mobile centre of homothety, p_a . In one-dimensional isotropic effective stress space, the surfaces are represented by two points.

Considering that p_y , given by

$$p_y = p_a + \frac{1}{R} (p - p_a) \quad (1)$$

and

$$p_y = p_a + \frac{1}{R_s} (p_s - p_a) , \quad (2)$$

is the homothetic image of the current stress point p on the yield surface relative to p_a and p_s the image of the same current stress point p on the subloading surface. R and R_s are the homothetic ratios of the dynamic loading and subloading surfaces relative to the yield surface, respectively. The stress state is always on the dynamic loading surface. Additionally, it is assumed that $p_m = \bar{R}_m p_y$ is the homothetic image of p_y on the Infinite Strain Rate Yield Surface (ISRYS), with the centre of homothety at the origin of the stress space, where $\bar{R}_m$ is the respective homothety ratio relative to the yield surface. The ISRYS defines a limit to the evolution of the stress for very high volumetric strain-rates.

Non-zero volumetric viscoplastic strain rate, $\dot{\varepsilon}_v^{\text{vp}}$, occurs when p is outside the subloading surface, even if it is also inside the yield surface. The ISRRYS defines a limit to the evolution of p . Therefore, when $p \rightarrow p_m$, $\dot{\varepsilon}_v^{\text{vp}} \rightarrow \infty$.

2.1. Subloading, dynamic loading and yield surfaces

f , $\hat{f}$ and $\bar{f}$ designate the yield, dynamic loading and subloading functions, respectively. The subloading and dynamic loading surfaces are determined from the yield surface in the stress space p

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