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Extended Abstract

An Elasto-Thermo-Viscoplastic Constitutive Model for Predicting the Behavior of Buried Underground Infrastructures in Structured Clays

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Abstract
In numerous geotechnical applications, structured clay layers are often exposed to prolonged loading conditions and temperature variations. A comprehensive review of the technical literature indicates that most existing constitutive models tend to address the effects of structural characteristics, creep deformations, and temperature variations either independently or, in some cases, by considering only two of these factors in combination. However, there remains a significant gap in models that integrate all three phenomena simultaneously. This study aims to bridge this gap by proposing a novel constitutive model that incorporates the combined effects of structure, creep, and temperature on the thermo-mechanical behavior of structured clays. The development of this model begins with a detailed evaluation of the individual impacts of each phenomenon within the $e - lnp'$ consolidation plane. These individual contributions are then systematically integrated into a unified model formulation. While previous studies, such as the work by Hamidi (2020), employed a similar methodology based on the critical state soil model to analyze the combined effects of temperature, time, and structure on isotropic compression behavior, the present research extends this approach by focusing on the influence of these three factors on the shear behavior of structured clays. In this study, an effort has been made to ensure that the new parameters have obvious physical or mechanical interpretations and to use the least additional parameters compared to the Modified Cam-Clay (MCC) model. This advancement provides a more comprehensive understanding of the complex interactions governing the mechanical response of structured clays under varying environmental and loading conditions.

1. Introduction

The Modified Cam Clay (MCC) family of constitutive models has been widely employed to describe the behavior of remolded clay. These models demonstrate good agreement with laboratory test results. However, studies have shown that natural clays possess a structure that results in behavior distinct from that of remolded clays [1-5]. Natural clays generally exhibit compression curves that, due to their structure, lie above those of their remolded counterparts in the stress-void ratio space, leading to errors in predicting their behavior.

The consolidation behavior of structured clays has been investigated by various researchers. Alongside studies evaluating the effect of structure, some researchers have explored the combined influence of temperature and structure. Sultan et al. [6] proposed a new formulation based on the MCC model, describing changes in the shape, size, and orientation of the yield surface in response to stress history. Their model, with eight parameters, successfully captured the anisotropic behavior of natural clays under thermomechanical loading in both compression and shear.

Despite significant efforts to refine the Liu and Carter [2] model for structured clays, the large number of required parameters limits its practical application. A review of prior research indicates that some studies have experimentally or theoretically assessed the combined effects of

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one or two factors—temperature, structure, or creep. Kurz et al. [7], building on the constitutive model proposed by Kelln et al. [8] for simulating creep, developed a model to describe the combined effects of creep and temperature on clay behavior. Fathalikhani [9] further refined the Kurz et al. [7] model to enhance its applicability across a wide range of strain rates and temperatures. A limited number of studies have also investigated the combined influence of all three factors—structure, creep, and temperature. Hamidi [10] examined the combined effects of strain rate, temperature, and structure on the isotropic compression behavior of clays.

Given that many nuclear waste disposal projects and thermal piles are situated in natural, structured clay layers and are subjected to prolonged thermomechanical loading, this study reviews the existing literature and proposes a new constitutive model to account for the combined effects of structure, strain rate, and temperature on clay behavior under both compression and shear. The proposed model builds upon the foundational framework developed by Hamidi [10].

2. Basic assumptions of the model

The proposed model, inspired by Hamidi (2020), examines the combined effects of creep, temperature, and structure on the compression and shear behavior of clay. Initially, changes in each factor are assessed individually in the compression plane ($e - lnp'$), followed by their integration into the model. Similar to Hamidi's approach, which analyzed temperature, strain rate, and structure on isotropic compression, this research extends the focus to shear behavior.

The key assumptions include: temperature shifts the NCL downward, clay structure raises the void ratio and shifts the NCL upward, CSL slope remains unaffected by temperature, and NCL slope decreases with temperature, converging to CSL at maximum soil temperature. Structured soils exhibit higher mean effective stress than reconstituted ones, and time-dependent behavior reduces the void ratio at constant stress.

The study investigates the individual impact of temperature, time, and structure on clay behavior.

3. Results

3.1. Flow rule

Fig. 5 illustrates a thermo-elasto-viscoplastic process in structured clay. Studies show temperature changes can increase, decrease, or maintain the ratio $d\varepsilon_v^p / d\varepsilon_s^p$ at a given stress ratio [11]. Soil structure influences the flow rule, increasing this ratio compared to intact soil at a given yield stress [12, 13]. The parameter c, derived from experimental calibration, represents the material's creep effect in the flow rule.

$$\psi = \frac{d\varepsilon_v^p}{d\varepsilon_s^p} = \frac{(1 - \delta\Delta e_i)[M_T^2(\beta - 1) - \eta^2]}{2\theta\eta c} \quad (1)$$

3.2. Yield surface

Assuming energy conservation during yielding, the following equation determines the yield surface:

$$f = \frac{P'_{cT}}{P'} - \left(\frac{\left((-2c\theta - \delta\Delta e_i + 1)\eta^2 + (\delta\Delta e_i - 1)(\beta - 1)M_T^2\right)}{(\delta\Delta e_i - 1)(\beta - 1)M_T^2}\right)^{\frac{c\theta}{2c\theta + \delta\Delta e_i - 1}} = 0 \quad (2)$$

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