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A thermo-elastoplastic model for soft rocks considering structure

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ABSTRACT

In the fields of nuclear waste geological deposit, geothermy and deep mining, the effects of temperature on the mechanical behaviors of soft rocks cannot be neglected. Experimental data in the literature also showed that the structure of soft rocks cannot be ignored. Based on the superloading yield surface and the concept of temperature-deduced equivalent stress, a thermo-elastoplastic model for soft rocks is proposed considering the structure. Compared to the superloading yield surface, only one parameter is added, i.e. the linear thermal expansion coefficient. The predicted results and the comparisons with experimental data in the literature show that the proposed model is capable of simultaneously describing heat increase and heat decrease of soft rocks. A stronger initial structure leads to a greater strength of the soft rocks. Heat increase and heat decrease can be converted between each other due to the change of the initial structure of soft rocks. Furthermore, regardless of the heat increase or heat decrease, a larger linear thermal expansion coefficient or a greater temperature always leads to a much rapider degradation of the structure. The degradation trend will be more obvious for the coupled greater values of linear thermal expansion coefficient and temperature. Lastly, compared to heat decrease, the structure will degrade more easily in the case of heat increase.

1. Introduction

In the fields of nuclear waste geological deposit, geothermy, and deep mining, the effects of temperature on the mechanical behaviors of soft rocks have attracted extensive attention [1]. The experimental data in the literature showed that these effects are complex. On the one hand, the undrained uniaxial compression tests conducted by Fujinuma et al. [2]) and Okada [3,4] showed that a temperature increase would decrease the strengths of siltstone, sandstone, and mudstone. On the other hand, the mechanical tests conducted by He [5] showed that the strengths of deep soft rocks increase with increasing temperature. Similar results were obtained by Noble [6] as well. These two different phenomena are referred to as heat decrease and heat increase by Zhang et al. [7]. Based on the subloading yield surface, Zhang et al. [7] proposed a simple thermo-elastoplastic model by introducing a concept of temperature-deduced equivalent stress. This model satisfies thermodynamic principles and can properly describe the general mechanical and thermal behavior of some typical geomaterials.

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However, the subloading yield surface was proposed for overconsolidated remolded soils and is not suitable for structured geomaterials [8,9].

Soft rocks are usually identified as a kind of soil with a large overconsolidated ratio [10,11]. However, soft rocks can also form structures during the sedimentation process. Xin et al. [12] found that the cementation structure of the red clay rock of Upper Pleistocene were flocculent which was then proven to be a structure through repeated shear tests. Zhang et al. [13] found that, when subjected to stress and cyclical drying/wetting, localized structural collapse of soft siltstones appeared. This type of collapse of structure would then influence the hydraulic conductivity [14]. In geologic terms, this kind of structure of soft rocks is called the random fabric structure formed in the sedimentation process, sometimes also referred to as bounding. The other kind occurs when, under the same loading, the void ratio can be maintained at a higher level than that of a non-structured soft rock because of the extra strength from the structure or bonding [15]. Through SEM and X-ray CT performed on soft carbonate rocks in Southern Italy, Ciantia et al. [16] also found that there are two distinct kinds of bonding within soft rock: temporary bonding and persistent bonding. The classification of the structure contributes to the understanding of the mechanical behavior of soft rocks. The form of the structure may be complex, so that the classification method needs to be improved in the future. To summarize, these experimental data show that the structure of soft rocks cannot be ignored and should be taken account into the mechanical model.

However, only a few models have taken the structure of soft rocks into account. Many models considering the structure are usually proposed for natural soils, but their applications to structured soft rocks are questionable [17–24]. Based on the disturbed state theory, Liu et al. [25] proposed a one-dimensional compression model for structured geomaterials, including soft rocks. This model cannot describe some complicated stress states such as triaxial compression and hollow torsional shear with drained and undrained conditions. Leroueil and Vaughan [26] investigated the effects of the structure on the strength, yield curve and compression curve of silty mudstone through drained and undrained isotropic compression tests. Based on the modified cam-clay model, several models were then proposed for structured soft rocks [27,28,15]. While these models could describe complicated stress states, the factors for the degradation of the structure were not fully analyzed.

The structure of soft rocks will be degraded by mechanical conditions during tests [29–32]. Temperature also will affect the structure of soft rocks. Wang et al. [33] found that the structure of montmorillonitic soft rocks would be nearly completely damaged at 100 °C. However, few models can describe this thermal effect on the structure of soft rocks. It is known that the concept of superloading yield surface proposed by Asaoka et al. [29] can describe structured soils properly. This concept was then adopted by Zhu et al. [15] to investigate the structure of soft rocks, which was validated using drained triaxial compression tests and triaxial creep tests. Therefore, even though this concept was initially proposed for soils, it is reasonable to adopt it in this work for the analysis of the structure effects of soft rocks. Combining the concepts of superloading yield surface and temperature-deduced equivalent stress, the effects of temperature on the degradation of the structure of soft rocks can be then analyzed.

Based on the superloading yield surface and the concept of temperature-deduced equivalent stress, a thermo-elastoplastic model considering structure for soft rocks is first proposed in this paper. Numerical simulations are then conducted to analyze the heat increase and the heat decrease of soft rocks. The proposed model is then validated by comparing the results predicted by the model with the experimental data in the literature. Finally, the effects of temperature and of the linear thermal expansion coefficient on the degradation of the structure of soft rocks are analyzed.

2. A thermo-elastoplastic model for soft rocks

When the mean stress is maintained at a constant value, the temperature increase from a reference temperature θ_0 to θ will generate a thermoelastic volumetric strain increment $\Delta\varepsilon_{\mathrm{v}}^{\mathrm{e}\theta}$. The reference temperature θ_0 is assumed to be 15 °C, representing the average global temperature. The thermoelastic volumetric strain increment is a linear function of the temperature change θ_0–θ, and can be expressed as

$$\Delta\varepsilon_{\mathrm{v}}^{\mathrm{e}\theta} = 3\alpha_{\mathrm{t}}(\theta - \theta_0) \tag{1}$$

where α_{t} is the linear thermal expansion coefficient and takes a negative value because a compressive volumetric strain is assumed as positive in geomechanics. Zhang et al. [7] suggested that the volumetric strain increment due to the temperature increment was equivalent to the volumetric strain increment caused by a certain unloading mean stress increment referred to as the equivalent stress increment

$$\begin{cases} \Delta\varepsilon_{\mathrm{v}}^{\mathrm{e}\theta} = \dfrac{\kappa}{1+e_0} \ln \dfrac{\sigma_{\mathrm{m}} + \Delta\widetilde{\sigma}_{\mathrm{m}}}{\sigma_{\mathrm{m}}} \\ \Delta\widetilde{\sigma}_{\mathrm{m}} = \sigma_{\mathrm{m}} \exp\left[\dfrac{3\alpha_{\mathrm{t}}(\theta-\theta_0)(1+e_0)}{\kappa}\right] - \sigma_{\mathrm{m}} \\ \widetilde{\sigma}_{\mathrm{m}} = \sigma_{\mathrm{m}} + \Delta\widetilde{\sigma}_{\mathrm{m}} = \sigma_{\mathrm{m}} \exp\left[\dfrac{3\alpha_{\mathrm{t}}(\theta-\theta_0)(1+e_0)}{\kappa}\right] \end{cases} \tag{2}$$

where σ_{m} is mean stress, i.e. $\sigma_{\mathrm{m}} = p = \sigma_{ii}/3$, $\Delta\widetilde{\sigma}_{\mathrm{m}}$ is the equivalent stress increment, $\widetilde{\sigma}_{\mathrm{m}}$ is the equivalent stress, κ is the swelling index and e_0 is the void ratio in the reference state when the reference stress is assumed to be a standard

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