International Journal of Rock Mechanics & Mining Sciences 93 (2017) 1–12

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

A unified thermo-elasto-viscoplastic model for soft rock

Yong-lin Xiong[a], Guan-lin Ye[b,*], He-hua Zhu[c], Sheng Zhang[d], Feng Zhang[e]

[a] Faculty of Architectural, Civil Engineering and Environment, Ningbo University, Fenghua Road 818, Ningbo 315211, China
[b] Department of Civil Engineering and State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[c] Department of Geotechnical Engineering, Tongji University, Siping Road 1239, Shanghai 200092, China
[d] Department of Civil Engineering, Central South University, Shaoshan South Road 22, Changsha 410075, China
[e] Department of Civil Engineering, Nagoya Institute of Technology, Showa-ku, Gokiso-cho, Nagoya 466-8555, Japan

ARTICLE INFO

Keywords:
Thermo-elasto-viscoplastic
Soft rock
Shear strength
Confining stress dependency
Temperature

ABSTRACT

A unified advanced thermo-elasto-viscoplastic constitutive model for soft rock is proposed in the critical state framework. The model is able to describe the fundamental mechanical behavior of soft rock such as elastoplastic, strain hardening and softening, time dependency, confining stress dependency, intermediate principal stress dependency and temperature dependency with one set of parameters. The thermal-induced equivalent stress tensor $\tilde{\sigma}_{ij}$ and the transform stress tensor t_{ij} are adopted to consider the influence of temperature and intermediate principal stress. Two evolution equations for the shear strength and the overconsolidation are newly introduced to take into consideration the influences of the confining stress and time dependent behavior, respectively. The capability of the model is carefully validated through a series of element tests of different soft rocks. The material parameters involved in the model have clear physical meanings and can be easily determined by the triaxial compression tests and creep tests.

1. Introduction

As is well known, soft rock often gives rise to geotechnical engineering problems. For instance, progressive failure of soft rock slope[1,2], long-term stability of tunnels in strong weathered soft rock ground[3,4] are directly linked to the mechanical behavior of soft rock under general stress condition. The establishment of a rational constitutive model of soft rock, which can describe properly the mechanical behavior of soft rock, has a great significance for predicting the deformation of soft rock. Physically, soft rock has an unconfined compressive strength of 1 ~ 30 MPa and its strength lies between that of soil and hard rock. In the past decades, many experimental researches have been carried out to investigate the mechanical behavior of soft rock[5–12]. In general, the mechanical behavior of soft rock is elastoplastic, strain-hardening and strain-softening, and depends on strain rate, time, confining stress, intermediate principal stress and temperature.

Until now, many constitutive models have been proposed to describe the above-mentioned mechanical behavior of soft rock in the framework of continuum mechanics. Based on endochronic theory[13], Oka and Adachi[14] proposed an elastoplastic model for soft rock that can not only describe the strain hardening-softening of soft rock, but also exhibits less mesh size dependency in finite element analysis compared to the other models available at that time. By adopting a transform stress tensor called as t_{ij}[15] and Matsuoka-Nakai failure criteria[17], Zhang et al.[18] proposed an elasto-viscoplastic model for soft rocks to consider the influence of the intermediate principal stress that may greatly affect the strength and stress-dilatancy relation of soft rock under different loading paths.

In the framework of critical state soil mechanics, Nova[19] firstly proposed a constitutive model for soft anisotropic rocks. Subsequently, many constitutive models were established based on the Cam-Clay model[20–24]. For instance, Amorosi et al.[21] dealt with a critical state-based constitutive model for soft rocks, which was successfully applied to the analysis of the response of a pyroclastic rock during in situ plate load tests. Regarding soft rock as a heavily overconsolidated soil, Zhang et al.[21] proposed a modified elasto-viscoplastic model for soft rock, which can not only describe the strain hardening-softening, the strain rate dependency and the time dependency, but also the intermediate principal stress dependency, in which the t_{ij} stress tensor and the subloading concept[25] were adopted. The evolution of the state variable ρ related to overconsolidation ratio, proposed by Nakai and Hinokio[26], was redefined to consider the time dependency in the model. The model, however, has to take different value for the shear stress ratio R_f under different confining stresses, in other words, the model could not consider the confining stress dependency.

* Corresponding author.
E-mail address: ygl@sjtu.edu.cn (G.-l. Ye).

http://dx.doi.org/10.1016/j.ijrmms.2017.01.006
Received 9 December 2015; Received in revised form 6 January 2017; Accepted 9 January 2017

In addition, the thermal effect of soft rock is also a very important factor for geotechnical engineering and geophysical science. Various experimental researches[27–33] showed that in most cases, the shear strength and the creep failure time of soft rocks show a decreasing trend as temperature increases. At the same time, some constitutive models were proposed to describe the influence of temperature on the deformation and the strength of soft rock[34–37]. For instance, Gao et al.[34] proposed a thermo-viscoplastic model of rock by using thermal expansion coefficient, viscosity attenuation coefficient and damage variable, which can consider the influence of temperature on elasticity, viscosity and damage. Zhang & Zhang[35] proposed a thermo-elasto-viscoplastic model for soft sedimentary rock in the framework of critical state soil mechanics. Xiong et al.[36] modified the model proposed by Zhang & Zhang[35] using t_{ij} transformed stress to consider the influence of the intermediate principal stress.

At present, however, there is still no constitutive model that can take into consideration all the above mentioned aspects of mechanical behavior of soft rock in a unified way with one set of parameters. In this paper, regarding the soft rock as a heavily consolidated soil, a unified thermo-elasto-viscoplastic constitutive model is proposed in the framework of critical state soil mechanics, which has the following features: (1) the equivalent stress[36] is adopted to consider the influence of temperature; (2) an evolution equation for the mobilized shear strength under different confining stress is applied to consider the influence of confining stress; (3) an evolution equation for the void ratio difference related to overconsolidation is used to consider the strain hardening-softening and the time dependency based on the subloading concept; (4) the transform stress tensor t_{ij} is used to consider the influence of intermediate principal stress. Moreover, the performance of the proposed model is carefully investigated through comparison with the test results on different types of soft rocks, such as triaxial compression tests, triaxial creep tests and plane strain tests under different temperatures.

2. Thermo-elasto-viscoplastic stress-strain relationship for soft rock

Matsuoka and Nakai proposed a spatially mobilized plane[17] (SMP), in which the shear-to-normal stress ratio is maximized between two principal stresses in three-principal-stress space. Based on the SMP, Nakai and Hinokio[26] proposed a simple elastoplastic model using the stress tensor t_{ij} to take into consideration the intermediate principal stress on the deformation and strength of soil. A brief derivation of the transformed stress tensor t_{ij} is given in Appendix A. Due to the fact that SMP criterion can predict the failure of soft rocks more precisely than the extended Mises criterion, as reported by Ye et al.[7], the t_{ij} stress tensor is used instead of the normal stress tensor in the derivation of the newly proposed constitutive model for soft rock.

2.1. Thermo-elasto-viscoplastic strain rate

The total strain rate can be written as,

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{p} = \dot{\varepsilon}_{ij}^{e\sigma} + \dot{\varepsilon}_{ij}^{eT} + \dot{\varepsilon}_{ij}^{p} \tag{1}$$

where $\dot{\varepsilon}_{ij}^{e\sigma}$ is the elastic strain rate induced by the stress rate and $\dot{\varepsilon}_{ij}^{eT}$ is the elastic strain rate induced by temperature change. The plastic strain rate $\dot{\varepsilon}_{ij}^{p}$ in Eq. (1) can be calculated by Eq. (17), the thermo-elastic strain $\dot{\varepsilon}_{ij}^{eT}$ can be easy to obtain using Eq. (5), and the strain rate $\dot{\varepsilon}_{ij}^{e\sigma}$ induced by real stress change is given by Hook's law,

$$\dot{\varepsilon}_{kl}^{e\sigma} = E_{ijkl}^{-1}\dot{\sigma}_{ij} \tag{2}$$

$$E_{ijkl} = \Gamma\,\delta_{ij}\delta_{kl} + G\,(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) \tag{3}$$

where,

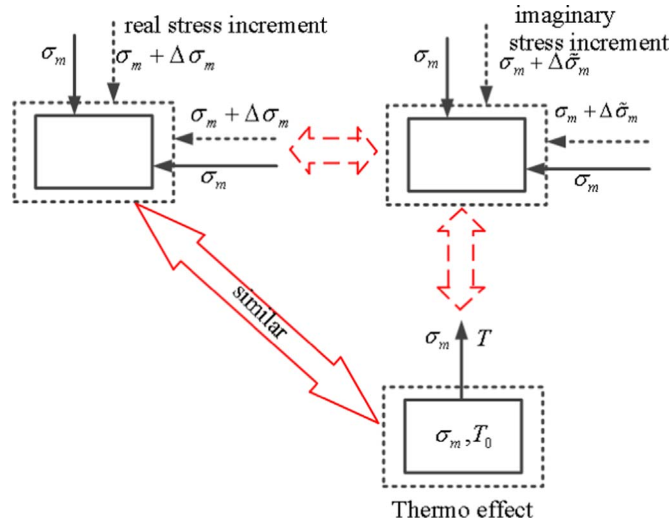

Fig. 1. Similarity of volumetric strain caused by real stress and equivalent stress due to change of temperature.

$$\Gamma = \frac{\nu E}{(1+\nu)(1-2\nu)},\quad G = \frac{E}{2(1+\nu)} \tag{4}$$

E is Young's modulus, and υ is Poisson's ratio.

2.2. Thermo-induced equivalent stress

It is well known that a change in temperature not only produce elastic volumetric strain, but also cause plastic volumetric strain in a soft rock sample. This effect is similar to the way in which a real stress acts on a soft rock sample. Accordingly, it is assumed in this study that the thermo-elastic volumetric strain is induced by an imaginary stress increment $\Delta\tilde{\sigma}_m$, namely, the equivalent stress increment. The similarity of elastic volumetric strains caused by the real incremental mean stress and the incremental equivalent stress due to a change in temperature is shown in Fig. 1.

Considering the limitation of the variation range for temperature and the fact that temperature T should be greater than or equal to 0 °C, a linear relationship between the change in temperature (T-T_0) and the thermo-elastic volumetric strain increment is assumed as:

$$\Delta\varepsilon_v^{eT} = 3\alpha_T(T - T_0) \tag{5}$$

where α_T is a linear thermal expansion coefficient, and takes a negative value because a compressive volumetric strain is assumed to be positive in geomechanics, T is the actual temperature, and T_0 is a reference temperature and is usually taken as 15 °C, an average global temperature of the earth.

Based on Hooke's law, it is straightforward to give the expression of equivalent stress:

$$\tilde{t}_N = t_N + \Delta\tilde{t}_N = t_N + 3K\alpha_T(T - T_0) \tag{6}$$

where K is the bulk modulus of the soft rock, t_N is the actual real mean stress, which is the same as p in ordinary stress space.

2.3. Yield function

The yield function of the proposed model is the same as the model proposed by Xiong et al.[36] and its expression is given as:

$$f = \ln\frac{t_N}{t_{N0}} + \zeta(X) - \ln\frac{t_{N1}}{t_{N0}} = 0 \tag{7}$$

where