Soils and Foundations 2015;55(6):1364–1371

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Soils and Foundations

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Modifications to an elasto-visco-plastic constitutive model for prediction of creep deformation of rock samples

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Received 30 October 2013; received in revised form 7 June 2015; accepted 25 July 2015
Available online 21 November 2015

Abstract

Time-dependent features of rocks and rock masses, particularly soft rocks, may emerge in most tunnels, mines and underground constructions under different deviatoric stress levels. To account for the creep deformation of rocks associated with the wide range of stress levels, modifications are made to a visco-plastic model which was initially developed for large stresses in squeezing conditions. Firstly, the concept of plastic hardening behavior is adopted for both instantaneous and visco-plastic deformations of rocks to estimate the induced plastic deformation even at relatively low deviatoric stress levels. Secondly, the visco-plastic dashpot element is described as a function of the stress level to determine the secondary stage of creep during the unloading and reloading phases which are crucial in tunneling and underground.

The governing equations of the proposed model are implemented in numerical finite difference code (FLAC), using its built-in FISH language for constitutive models and then applied to a series of laboratory creep tests presented in the literature. The presented discussion compares the numerical results relating to the modified model with the data on time-dependent deformation developed in rock specimens.

Keywords: Time-dependent; Rock; Numerical modeling; FLAC; Hardening model; Marl

1. Introduction

The time-dependent deformation behavior of rock masses has a significant impact on the stability of rock slopes and underground structures (Tsai, 2007). This deformation might begin few minutes after excavation and continue for up to several years. Thus, the identification and modeling of time-dependent behavior of rocks and rock masses is of great importance in rock engineering. A basic task in the mechanical description of the time-dependent deformation of a certain material is to define deformation as a function of time, stress and temperature (Tomanovic, 2006). Since the change in temperature for fundamental needs in building most rock structures, especially tunnels and underground openings, is limited, the effect of temperature in rock mechanics is often neglected.

Various kinds of constitutive equations have been developed on the behavior of geomaterials, following different assumptions and principles. Elastic or reversible deformation is one of the assumptions considered in classic models. The classic visco-elastic models can be represented by a series of springs and dashpots connected in parallel and/or in series. The constitutive laws in these types of elastic models simply try to relate the current strain rate to the current stress rate in order to define creep deformation in rocks through analytical formulations. Many researchers have used these models to determine tunnel face convergence (Sakurai, 1978; Zhifa et al., 2001; Kontogianni et al., 2006, Dai, 2004; Fahimifar et al., 2010). To enhance

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Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2015.10.003
0038-0806/

visco-elastic models, a number of rheological models have been proposed, including a visco-elastic and an elasto-plastic component to simulate time-dependent and time-independent behaviors of rocks, respectively (Swift et al., 2001; Guan et al., 2008).

Experimental results of creep tests have shown that creep deformation of rock materials is not completely reversible. In fact, irreversible deformation is observed even at low stress levels (Cristescu and Hunsche, 1998). In contrast to the visco-elastic models, assuming fully irreversible strains for the primary, secondary and tertiary stages of creep curve, some researchers proposed visco-plastic models to evaluate long term stability of rocks, mainly rock salts, in underground excavations (Malan, 1999; Wallner et al., 1983; Liao et al., 2004; Erichsen and Werfling, 2003). Furthermore, researchers have used experimental approaches to evaluate visco-plastic behavior of rocks on the basis of creep tests performed on rock samples (Cristescu and Hunsche, 1998; Li and Xia, 2000; Lajtai, 1991; Jin and Cristescu, 1998; Maranini and Yamaguchi, 2001; Munteanu and Cristescu, 2001; Tsai, 2007). The functions defined in this category of mathematical models, such as failure surface and visco-plastic potential function are entirely extracted from the available experimental data, by finding evolution of irreversible stress work. However, the weakness of fully visco-plastic models has been demonstrated by experimental creep tests, including unloading and reloading tests during which reversible creep deformation of rocks occurs (Tomanovic, 2006; Hoxha et al., 2005; Shao et al., 2003).

Considering both the elastic and plastic time-dependent features of rocks, a number of rheological models have been introduced along with the fully elastic or plastic models. Tomanovic (2006) developed a new visco-elastoplastic model to define the creep behavior of marl samples after unloading and reloading. Sterpi and Gioda (2009) also proposed a rheological model composed of a visco-elastic Kelvin–Voigt unit and a visco-plastic unit, connected in series. The equations of this model were worked out by considering the squeezing condition, which may develop in deep tunnels, and written for the biaxial state of stress. As the model was applied to a series of laboratory tests for stress levels below the plastic threshold, the model simulated creep deformation as the primary elastic with a horizontal asymptote. For a stress level above the threshold, secondary creep occurred followed by tertiary creep, which are both plastic deformations.

Generally, the purpose of visco-elastoplasic models is to develop an exact description of time-dependent deformation not only after loading, but also after total or partial unloading and reloading which are particularly significant for stress conditions in rock masses surrounding tunnels. The rock mass around tunnel is in unloading path during excavation, and experiences reloading path when it is supported by a lining. Regarding this fact, this paper represents a constitutive model to simulate the creep behavior of soft rocks under different stress levels at the loading, unloading and reloading phases. For this purpose, the elasto-viscoplastic model proposed by Sterpi is modified. The modifications are made to enhance modeling of secondary creep at low stress level and to calculate unloading and reloading creep deformations. A non-linear elasto-plastic model is also proposed for short term, time-independent deformations.

The governing equations of the models are worked out and implemented in numerical finite difference code (FLAC) using the built-in FISH language for constitutive models. For verification purposes, these models, the models were applied to a series of experimental data found in the literature which describe the creep deformations in two phases of loading and unloading. A comparison between the predictions provided by the models and the experimental data is also provided.

2. Model description

2.1. Elasto visco-plastic model

The deviatoric behavior proposed by Sterpi and Gioda (2009), as schematically illustrated in Fig. 1, consists of a visco-elastic Kelvin–Voigt and a visco-plastic softening unit connected in series. Kelvin–Voigt unit is characterized by shear modulus G^{el} for instantaneous deformation, and visco-elastic parameters including shear modulus G^{ve} and viscosity coefficient η^{ve}. The visco-plastic unit is characterized by Mohr–Coulomb parameters and a viscosity coefficient η^{vp}. Also Sterpi and Gioda assumed that volumetric response of a rock is time-independent and is described by a bulk modulus B^{el} of the elastic spring and also plastic slider.

Assuming an isotropic material, the constitutive model presents a threshold to separate the elastic deformation from the plastic creep one. For stress levels below this threshold,

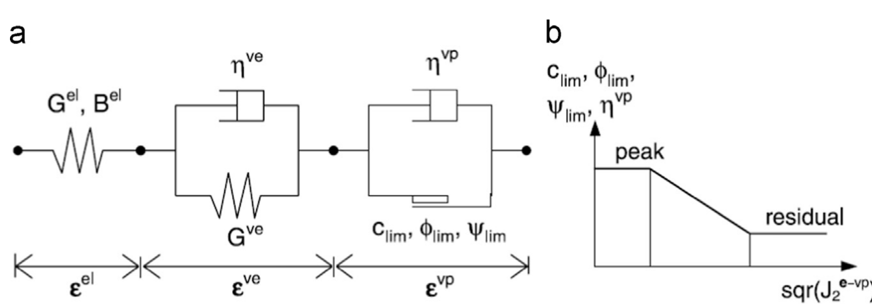

Fig. 1. Rheological model proposed by Sterpi with associated parameters (a) and variation of visco-plastic parameters with the 2nd invariant of deviatoric visco-plastic strains (b).