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Technical Paper

An extended hypoplastic constitutive model for frozen sand

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Abstract

This paper presents a hypoplastic constitutive model for frozen sand. The model is obtained by introducing temperature-dependent cohesion and a deformation-related function for strain softening. The extended model is simple in mathematical formulation and contains only eight parameters, which can be easily obtained from conventional triaxial tests. The model performance is shown by simulating a series of triaxial compression tests at different temperatures and confining pressures.
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Keywords: Hypoplasticity; Constitutive model; Frozen sand; Mechanical behavior

1. Introduction

Engineering activities in permafrost regions are on the rise worldwide. For such projects, the strength and deformation of frozen soil plays an important role. There is urgent need for appropriate constitutive models for the mechanical behaviors of frozen soil.

1.1. Previous work on modeling frozen soil

As a special geo-material, frozen soil contains ice and unfrozen water. Such multiphase media show rather complex mechanical behaviors and are difficult to model. Nevertheless, constitutive modeling of frozen soil has attracted intensive research in the past decades. The existing constitutive models for frozen soil can be classified into three categories, namely (1) empirical stress–strain relationships, (2) microscopic models and (3) elastoplastic models. (1) *Empirical stress–strain relationships.* Sayles (1973) analyzed the stress–strain relationship of frozen Ottawa sand based on triaxial shear tests and triaxial creep tests. Zhu et al. (1992) conducted numerous uniaxial compression tests at different temperatures and strain rates on different frozen soils. Then two types of stress–strain equations, namely, elastoplastic and visco-elastoplastic, were proposed for the stress–strain curves. All these efforts helped to understand the mechanical behavior of frozen soil in the early days. However, the application of such stress–strain equations was rather limited, because they were set up especially for certain test condition. (2) *Microscopic damage models.* Such models were developed by introducing a damage variable into the stress–strain equation, which relates the microstructural change with the macroscopic mechanical behavior of frozen soil. Miao et al. (1995) proposed a damage creep model by considering the microstructure of frozen soil in isothermal creep tests. Particle orientation and area reduction were introduced as the damage variables. Based on continuum mechanics and thermodynamics, He et al. (1999) proposed a damage constitutive model for frozen soil, in which a damage threshold and dissipation potential function were studied. Liu et al. (2005) defined a damage function for frozen Lanzhou loess based on the uniaxial

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compression test results obtained with X-ray CT method. They developed a damage constitutive model for frozen soil under uniaxial compression. Ning and Zhu (2007) set up a relationship between the elastic constants of soil, ice and that of frozen soil mass based on the mesomechanics of composite materials. The result was a constitutive model which takes the evolution of damage into consideration. The advantage of these models is that they explain the macroscopic mechanical behavior of frozen soil from a microscopic view. However, describing the damage evolution for frozen soil posed a great challenge to the investigators. (3) *Macroscopic elastoplastic constitutive models.* Cai et al. (1990) separated the total strain rate into viscoelastic strain rate and plastic strain rate components, and proposed a visco-elastoplastic constitutive model for frozen soil, which was suitable for monotonic loading and cyclic loading. Rong et al. (2005) proposed two formulas for calculating the Green stress and Kirchhoff stress, and developed a constitutive model for frozen soils under finite deformation. Based on triaxial compression tests on frozen Qinghai-Tibet sandy soil, Lai et al. (2009) obtained the plastic potential and failure surface with the help of orthogonal flow rule, and then proposed an elastoplastic constitutive model for frozen sand. It should be noted that these models were obtained by analogy with the constitutive models for unfrozen soils within the framework of plasticity theory, which is mainly based on experiments or hypotheses (Li, 2004). Although the constitutive models discussed above have achieved certain degrees of success, some problems remain unsolved. Most models have rather complicated mathematical formulation.

1.2. Brief introduction to hypoplasticity

Recently, hypoplastic constitutive models have become quite popular in describing the mechanical behavior of granular materials. In hypoplasticity, the stress rate is formulated as a nonlinear tensor function of stress and strain rate based on the representation theorem for isotropic tensor functions. Compared with traditional elastoplasticity theory, hypoplasticity has many advantages, such as: (1) the model does not have an elastic range and the stress–strain relationship is incrementally nonlinear from the beginning of loading; (2) distinction between loading and unloading is not necessary, since the loading-unloading criterion is incorporated in the models; and (3) hypoplastic constitutive equations have simple mathematical formulation with few parameters. A number of hypoplastic constitutive models (Kolymbas, 1985; Wu and Kolymbas, 1990; Wu, 1992; Wu and Bauer, 1994; Wu et al., 1996; Herle and Kolymbas, 2004; Huang et al., 2006; Mašín, 2013) have been developed for various geo-materials and can be applied to various boundary problems, *e.g.* retaining walls (Qiu and Grabe, 2012), pile driving (Osinov et al., 2013), tunnel under earthquake (Hleibieh et al., 2014), debris flow (Fang and Wu, 2014a, 2014b) and slope stability (Peng et al., 2015). Hypoplasticity has been proved to be a powerful tool in describing various soil properties, such as nonlinear mechanical behavior, dependence on stress path, shear dilation and strain softening.

1.3. Feasibility of modeling frozen soil with hypoplasticity

Most macroscopic constitutive models regard frozen soil as a homogeneous continuum, with ice distributed uniformly in the soil mass. This makes it possible to model frozen soils with hypoplasticity, which is based on continuum mechanics. Secondly, many test results (Sayles, 1966; Ladanyi, 1981; Haynes and Karalius, 1977; Parameswaran, 1980; Bragg and Andersland, 1981) reveal that the most significant factor which governs the mechanical properties of frozen soil is temperature. This can be attributed to the following two aspects. Firstly, the mechanical properties of ice in frozen soil are strongly dependent on temperature, and secondly the bonding strength of the interface between soil grain and ice is also very sensitive to temperature. From this point of view, the strength of frozen soil consists of two parts, namely the strength of soil skeleton and the ice cementation, see also Goughnour and Andersland (1968). Therefore, when the cementation of ice is taken into account, a hypoplastic constitutive model for frozen soil can be built on the hypoplastic models for cohesionless soil.

2. The extended hypoplastic model for frozen sand

2.1. Hypoplastic constitutive model for sand

In the work by Wu and Kolymbas (1990), a general hypoplastic constitutive model was defined as follows

$$\overset{\circ}{\mathbf{T}} = \boldsymbol{L}(\mathbf{T}, \mathbf{D}) + \boldsymbol{N}(\mathbf{T})\|\mathbf{D}\| \tag{1}$$

where $\mathbf{T}$ is the Cauchy stress tensor, $\mathbf{D}$ is strain rate tensor, $\boldsymbol{L}(\mathbf{T}, \mathbf{D})$ and $\boldsymbol{N}(\mathbf{T})$ are linear and nonlinear isotropic tensor functions with respect to stress $\mathbf{T}$, respectively. $\|\mathbf{D}\| = \sqrt{\mathrm{tr}\left(\mathbf{D}^2\right)}$ stands for the Euclidean norm of strain rate tensor, $\overset{\circ}{\mathbf{T}}$ is the Jaumann rate of Cauchy stress tensor and is defined as

$$\overset{\circ}{\mathbf{T}} = \dot{\mathbf{T}} + \mathbf{T}\cdot\mathbf{W} - \mathbf{W}\cdot\mathbf{T} \tag{2}$$

where $\dot{\mathbf{T}}$ is the time derivative of Cauchy stress tensor, $\mathbf{W}$ is the spin tensor. The Jaumann rate of stress tensor equals to the time derivative when the spin tensor is 0.

In order to obtain a concrete form, model (1) should be subjected to three restrictions (Wu and Bauer, 1994). (i) *Rate independence*. To start with a simple case, the constitutive model is considered to be rate independent, *i.e.* the Jaumann rate of Cauchy stress should be positively homogeneous of the first degree in $\mathbf{D}$. (ii) *Objectivity* under rigid rotation. This requirement can be satisfied when the model is chosen according to the representation theorem for isotropic tensor functions. (iii) *Stress dependence*. Many test results show that the strength and initial tangent modulus of sand depend proportionally on stress level. Hence, the Jaumann rate of Cauchy stress should be homogeneous in $\mathbf{T}$. According to these restrictions, Wu (1992) proposed the following hypoplastic constitutive model for sand

$$\dot{\mathbf{T}} = c_1(\mathrm{tr}\mathbf{T})\mathbf{D} + c_2\frac{\mathrm{tr}(\mathbf{TD})}{\mathrm{tr}\mathbf{T}}\mathbf{T} + c_3\frac{\mathbf{T}^2}{\mathrm{tr}\mathbf{T}}\|\mathbf{D}\| + c_4\frac{\mathbf{T}_\mathrm{d}^2}{\mathrm{tr}\mathbf{T}}\|\mathbf{D}\| \tag{3}$$

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