International Journal of Plasticity 78 (2016) 84–113

Contents lists available at ScienceDirect

International Journal of Plasticity

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

A constitutive model of frozen saline sandy soil based on energy dissipation theory

Yuanming Lai [a, b, *], Mengke Liao [a, c], Kai Hu [a]

[a] State Key Laboratory Frozen Soil Engineering, Cold and Arid Region Environmental and Engineering Institute, Chinese Academy of Sciences, Lanzhou, Gansu 730000, China
[b] School of Civil Engineering, Lanzhou Jiaotong University, Lanzhou, Gansu 730070, China
[c] University of Chinese Academy of Sciences, Beijing, 100049, China

ARTICLE INFO

Article history:
Received 3 February 2015
Received in revised form 10 October 2015
Available online 2 November 2015

Keywords:
B: Anisotropy
B: Mechanical properties
B: Plastic deformation
B: Thermomechanical
Frozen saline soil

ABSTRACT

A series of triaxial compression tests are carried out for frozen saline sandy soil with Na_2SO_4 contents 0.0, 0.5, 1.5, and 2.5% under confining pressures from 0 MPa to 16 MPa at −6 °C, respectively. The test results indicate that, the Critical State Line (CSL) of frozen saline sandy soil is curve and is not through the origin in (p,q) plane, and the soil particles have the properties of initial anisotropic rotational angle and loaded anisotropy in process of loading. In order to describe the deformation properties of frozen saline sandy soil, a new double yield surface constitutive model is proposed based on the triaxial compression tests in this paper. The proposed model contains the influence of salt contents on mechanical characteristics, so it is suitable for describing the stress–strain relation of frozen saline soil. The proposed model has the following properties: (1) By defining a modified effective stress p^*, a critical state strength envelope function is established according to the Modified Cam Clay model. The envelope approximates a straight line under low confining pressures, but it is curve downward under high confining pressures due to pressure melting. (2) The effect of the initial anisotropic rotational angle and loaded anisotropy, during process of loading under plastic volumetric compression mechanism, on yield surface of rotational hardening is taken into account. (3) A paraboloid yield surface function, including the rotational hardening law induced by loading, is proposed under plastic shear mechanism. The universality of the proposed model is verified by the test results of frozen saline sandy soil under different stress paths. Finally, in order to further study the applicability of the proposed model in this paper, the stress–strain relation of the cemented clay is simulated by it. And the influences of the pressure melting phenomenon and the rotational hardening rule on the calculated results of the proposed model are investigated. The research results indicate that the proposed model can simulate not only the mechanics properties of materials whose CSL is straight but also those of materials whose CSL is curved, other than predict the deformation regularity of frozen saline sandy soil well.

* Corresponding author. State Key Laboratory Frozen Soil Engineering, Cold and Arid Region Environmental and Engineering Institute, Chinese Academy of Sciences, Lanzhou, Gansu 730000, China. Tel.: +86 931 4967288.
E-mail address: ymlai@lzb.ac.cn (Y. Lai).

http://dx.doi.org/10.1016/j.ijplas.2015.10.008
0749-6419/

1. Introduction

Frozen soil consists of mineral particles, ice inclusions, liquid water and gaseous inclusions (Tsytovich, 1985). And the frozen saline soil is a type of frozen soil which contains solution of soluble salt and salt crystal. Test results show that the precipitation of salt crystals at negative temperature is strongly sensitive to temperature (Wan and Lai, 2013). Compared with general frozen soil, the structure of the frozen saline sandy soil is changed with the precipitation of ice crystal and salt crystal in the freezing process, so the theoretical modeling of the constitutive relation of frozen saline frozen soil is more complex and difficult than that of other soils. With the development of society and economics, many engineering projects, such as highways, railways, houses, airports and oil pipelines, will be constructed in cold saline soil regions. At present, the study on mechanical property for frozen saline soil is rarely performed, so it is significant and essential to investigate the mechanical behaviors of frozen saline soil for engineering design.

Based on the theory of critical state soil mechanics, Roscoe et al. (1963) proposed Cambridge Clay model for soft soil. Afterward Roscoe and Burland (1968) presented Modified Cam Clay model. Lade and Duncan (1978) formulated a dilatancy model for sandy soil, which is called Lade-Duncan model. Since then, the constitutive model research of geotechnical materials becomes a hot issue. In the case of Rock Mechanics, Khan and co-workers have developed constitutive models to capture elasto-plastic behavior of Berea sandstone under a large range of confining pressures (Khan et al., 1991, 1992). In damage constitutive model study on the brittle material, Shojaei et al. (2013) built a damage constitutive theory based on the dynamic dissipation work method for polycrystalline materials under dynamic loading, and developed a continuum damage mechanics (CDM) constitutive model to describe elastic, plastic and damage behavior of porous rocks (Shojaei et al., 2014). For unfrozen geomaterials, some researchers proposed a lot of strength criteria and constitutive models to solve different engineering problems (Li and Dafalias, 2000; Altenbach et al., 2001; Hashiguchi and Tsutsumi, 2003, 2007; Hashiguchi, 2005; Vorobiev, 2008; Steinhauser et al., 2009; Shen et al., 2012; Xie and Shao, 2012; Yao and Wang, 2014; Mortara, 2015). The deformation behaviors of soils are usually identified by two basic plastic flow mechanisms: one is related to plastic shear, and the other to plastic volumetric compression (Xie and Shao, 2006). In order to describe the two plastic flow mechanisms well, a double yield surface model has been established by combining a cap surface for plastic compression and a cone surface for plastic shear (Peric and Ayari, 2002; Lai et al., 2010). Because of the structural complexity of frozen saline sandy soil, it is difficult to describe the mechanical properties by a single yield surface, so the mechanical characteristics of plastic volumetric compression mechanism and plastic shear mechanism are used to investigate the constitutive relation of frozen saline sandy soil in this paper.

Many researchers have made a lot of researches to describe the mechanical characteristics of general frozen soil (Chamberlain et al., 1972; Bragg and Andersland, 1981; Fish, 1991; Hashiguchi, 2005; Zhang et al., 2007; Lai et al., 2009; Yang et al., 2010; De and Pereira, 2013; Painter and Karra, 2014). By the test and numerical methods and selecting different test materials and theory, the various affecting factors on mechanical behaviors for frozen soil have been studied and different constitutive models have been established up to the present. The more detailed frozen soil test methods and research processes were introduced in the authors' previous works (Lai et al., 2009, 2014). However, it should be pointed out that stress–strain relationship of frozen saline sandy soil is more complex than that of unfrozen soil or general frozen soil. During the freezing process, ice crystals, salt crystals, and soil particles are cemented together to make the frozen saline sandy soil have tensile capacity. The characteristics of frozen soil are similar to that of cemented clay. In the study on mechanical behavior of cemented clay, Suebsuk et al. (2010) proposed a constitutive model, based on the Structure Cam Clay (SCC) model proposed by Liu and Carter (2002), to simulate the mechanical behaviors of cemented clay better. Gao and Zhao (2012) and Nguyen et al. (2014) proposed a modified SCC model and its simulated results agree well with the test results of cemented clay with different cement contents. However, with the increase of confining pressure, the frozen saline sandy soil has a characteristic of pressure melting but the cemented clay does not have it. The pressure melting of frozen soils results in that with the increase of confining pressure, the critical state line (CSL) of frozen saline sandy soil will gradually bend downward, while the critical state line of cemented clay is linear. The critical state line of the frozen saline sandy soil will degenerate as that of cemented clay if the influence of pressure melting is not considered.

During the process of shearing loading or isotropic compression, the unfrozen geotechnical granular materials appear different degree of anisotropic properties (Anandarajah, 2008; Yin and Chang, 2010; Rowshanzamir and Askari, 2010; Liu et al., 2013; Fonseca et al., 2013). Based on theory and tests, many researchers have made a lot of studies on anisotropic properties for granular material and soft soil. Voyiadjis et al. (1995) proposed a granular material constitutive relation based on anisotropic rotating yield surface, and studied the deformation of anisotropic elasto-plastic damage for concrete (Voyiadjis et al., 2008). Cleja-Tigoiu (2000) established an anisotropic finite elasto-plastic constitutive equation by combining the kinematic hardening law of material. Based on test data of soft soils, Wheeler et al. (2003) proposed an anisotropic elasto-plastic constitutive model called as S-CLAY1, in which a rotational yield surface and a rotational hardening law were used, and the sensitivity of rotational hardening parameters was analyzed. In the previous study, it is found that the plastic flow directions does not coincide with the hydrostatic axis (Lai et al., 2009) when the isotropic consolidation was completed and the shearing began, and the initial anisotropy is produced in the process of consolidation. From the triaxial tests of frozen saline sandy soil, it is found that the soil particles generate initial anisotropic angle before shearing loading due to the consolidation pressure. With the increasing of shearing loading, the anisotropic rotational angle of frozen saline sandy soil decreases from initial rotation angle below horizontal axis to zero, and then increases to the maximum rotational angle above horizontal axis.