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Experimental and theoretical investigations on the mechanical behavior of frozen silt

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ABSTRACT

The mechanical properties of frozen soil are complicated due to their complex components and sensitivity to temperature, water content and pressure. This study conducts triaxial compressive tests to experimentally investigate the mechanical properties of frozen silt under different confining pressures and at temperatures of −2.0, −4.0, −6.0 and −8.0 °C. Constitutive models, which are used to describe the response behaviors of natural and artificial materials under different loading and environmental conditions, were used as the bases for the description of the mechanical behavior of this frozen silt under external loads. After introducing continuous damage and statistics theories, a statistical damage constitutive model was proposed to reproduce the deformation of frozen silt. The Weibull distribution function was used in the model to describe the propagations of micro-voids and micro-cracks during loading process. The validity of this model was verified by comparing its modeling predictions with the experimental results. It was found that the predictions by this model agree well with the corresponding experimental data.

1. Introduction

The artificial freezing method has been widely used in metro engineering, tunnel construction, mine shaft and other underground engineering activities (Ma et al., 1995; Wang et al., 2005; Li et al., 2006). It has minimal effect on the subsidence disturbances of the ground surface and adjacent buildings, and can also be formed at any ground depth under complex geologic conditions (Cui, 1998; Zhang et al., 2002; Tang and Wang, 2007). Frozen soil has complicated mechanical properties due to its complex composition and sensitivity to temperature, water content and pressure (Ting et al., 1983). The studies on the deformation behaviors and failure mechanisms of frozen soil are important to artificial freezing engineering construction. Therefore, constitutive model, which is used to describe the response of geomaterials under different loadings and environmental conditions, is a key issue in the theory development and numerical analysis for geotechnical engineering.

The choice of an appropriate constitutive model, which will adequately describe the deformation behavior of the material, plays a significant role in the accuracy and reliability of numerical predictions. Since the early 1930s, much effort has been made towards the relationships between load and deformation of frozen soil (Tsytovich and Sumgin, 1937; Zhu and Carbee, 1987; Zhu et al., 1992; Da Re et al., 2003; Li et al., 2004; Arenson and Springman, 2005; Wang et al., 2005; Torrance et al., 2008; Qi and Ma, 2007; Lai et al., 2007, 2008; Shoop et al., 2008; Yang et al., 2010a,b).

Frozen soil is made up of solid mineral particles, ice inclusions, liquid water and gaseous inclusions (Goughnour and Andersland, 1968; Tsytovich, 1985). There are many fissures and cavities in frozen soil, as shown in Fig. 1. The distribution randomness of the micro-voids or micro-cracks in frozen soil causes the great uncertainty and randomness of the mechanical behaviors under an external load. The effect of the inner flaw evolution should be considered in order to study the stress-strain relationship of frozen soil. The probability and stochastic theories, which describe the concepts that are not certain, are used to study the variability of frozen soil. The continuum damage mechanic has been developed to describe the effects of the growth of the micro-voids or micro-cracks on the mechanical behavior of the materials (Murakami, 1983). Recent developments in engineering have brought about serious and enlarged demand for the reliability and safety ranging from civil and structural engineering to automotive engineering, which has caused more interest in continuum damage mechanics and its engineering applications (Murakami, 2012). With the process of loading, plastic flow of the ice and soil particles in the frozen soil occur, which will lead to the microstructure damage of frozen soil. In order to describe the damage deformation behavior, Lai et al. (2009) proposed an elastoplastic damage constitutive model for frozen sandy soil. Lai et al. (2008, 2012) proposed the statistical damage constitutive models to

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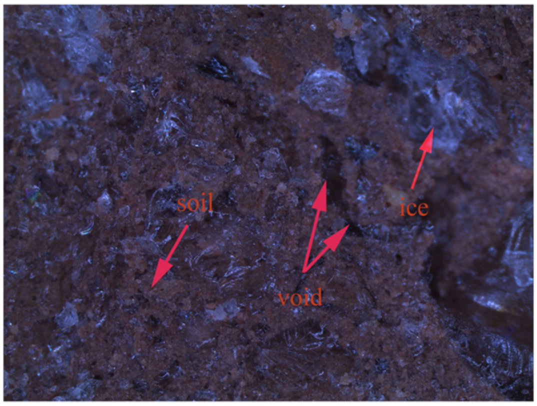

Fig. 1. Electron microscope image of frozen soil (×350).

(a) Before test (b) After test

Fig. 2. Shapes of frozen soil samples.

describe the stress-train relationship of warm and ice-rich frozen soil. Their results showed that the probability and stochastic theories are effective tools to describe the mechanical behavior of warm and ice-rich frozen soil. However, the related theoretical study on the mechanical uncertainty of artificial frozen soil, subjected to low temperature and high confining pressure, has not been found so far.

The purpose of this study is to propose a statistical damage constitutive model to describe the mechanical properties of artificial frozen silt through considering the effects of confining pressure and temperature. Further, the Weibull function is used to describe the random distribution of the inner flaws. The constitutive model is then developed based on a continuous damage theory and the probability and statistics theories. The model parameters are determined by using the conventional triaxial compressive tests and model is verified by experimental data.

2. Test conditions and results

2.1. Experimental samples and method

The test soil used was silt, and its particle distribution is listed in Table 1. The specimens were prepared as cylinders with a diameter of 6.18 cm and a height of 12.5 cm. The specimens had water content of 12.8% and the dry density of 1.85 g/cm^3. Their plastic limit and liquid limit are 15.0% and 23.2%, respectively. The preparation for the specimens observed the following procedure: First, according to the water content of the specimen, the dry silt and the water were weighed for the specimens. Then, the water was added into the dry soil and mixed thoroughly. After the preparations of the soil-water mixtures were completed, the specimen was compacted in a split mold, and subsequently refrigerated at a temperature of approximately −35 °C for 48 h. The specimen was quickly frozen in order to prevent ice lens formations caused by water transmission. At this point, the mold was dismantled and the specimen was subsequently coated with plastic film and covered by an epoxy resin cap to avoid moisture evaporation. The specimen was placed into the pressure cell of the MTS-810, whose confining and axial pressures could be controlled synchronously. The MTS-810 has a capacity of 250 kN in axial force and 20 MPa in confining pressure. Its loading displacement ranges from 0 to 75 mm. Its accuracy is ±3% for long-term measurement and ±1% in short-term measurement. Next, the specimen was placed into the low temperature testing machine for 24 h at the given temperature. Then, the confining pressure was applied to the specimen until the given pressure was reached and kept constant for 5 min. The triaxial shear tests began, and shear strain rate was 1.67×10^{-4}1/s.

2.2. Experimental results and analysis

The typical shapes of the frozen soil samples and stress–strain curves of the frozen silt at the confining pressures and temperatures of −2.0, −4.0, −6.0 and −8.0 °C are shown in Figs. 2 and 3, respectively. It can be seen that the stress–strain curves of the frozen silt experience approximately three stages: an initial linear elastic stage; a nonlinear strengthening stage; and a softening stage. In initial elastic stage, the stress increases linearly with the increase of the axial strain. With the further increase of the axial strain, the slopes of the stress-strain curves gradually decrease in the nonlinear strengthening stage. The slope of the stress-strain curve of the frozen silt gradually becomes negative with the increase of the axial strain in the softening stage. The stress-strain curve presents a strain softening phenomenon during the shearing process under the low confining pressures. Then, the strain softening phenomenon decreases with the increasing of the confining pressure, and even presents a strain hardening phenomenon under the high confining pressure.

The corresponding peak strengths of the frozen silt under different confining pressures are shown in Fig. 4. This figure shows that the confining pressure and temperature greatly affect the strength of the frozen silt. Under low confining pressure $\sigma_3 = 1.0$ MPa, the strength increases from 4.7 MPa to 9.0 MPa as the temperature decreases from −2.0 °C to −8.0 °C. Under the confining pressure of $\sigma_3 = 8.0$ MPa, the strength increases from 11.7 MPa to 16.3 MPa. At a temperature of −2.0 °C, the strength increases from 4.7 MPa to 11.7 MPa, with the increase of confining pressure from 1.0 MPa to 8.0 MPa.

3. Statistical damage constitutive model for frozen soil

The concept of an effective stress proposed by Kachanov (1958) has been used to formulate constitutive equations for damaged materials (Lemaitre and Chaboche, 1990). The effective stress theory postulates that the material damage is caused mainly by the decrease in the load-carrying effective area, due to the growth of micro-voids or

Table 1
Basic physical parameters of silt.

Composition of particle diameters (%)						
>0.50 mm	0.50 – 0.25 mm	0.25 – 0.10 mm	0.10 – 0.075 mm	0.075 – 0.05 mm	0.05 – 0.005 mm	<0.005 mm
0	0.792	22.798	13.50	17.15	35.93	9.83