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Laboratory investigation on energy dissipation and damage characteristics of frozen loess during deformation process

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ABSTRACT

For investigating the energy dissipation and damage behavior of frozen loess during deformation process under triaxial compression, besides triaxial compression (TC) tests, a series of static triaxial loading-unloading cyclic (TLUC) tests corresponding to the TC tests were carried out under confining pressures from 0.5 MPa to 9.0 MPa at temperature of −6 °C. It could be found from these two types of tests that the loading stages of TLUC test curves and TC test curves almost coincided under different confining pressure conditions. The influence of confining pressure on stress–strain curves of TC and TLUC tests was similar. The TLUC test results showed that energy dissipation occurred in unloading–reloading process and elastic modulus changed with increase of strain. Dissipative energy value increased at first and then decreased with increase of confining pressure. A damage variable was defined based on the fact of the degeneration of elastic modulus. The experimental results also indicated that there existed an initial damage in frozen loess sample before loading. According to this phenomenon, a method for recognizing undamaged state was proposed. The damage threshold value and damage evolution law under different confining pressures were obtained based on the TLUC test results. The influence of confining pressures on damage characteristics of frozen loess was analyzed. The conclusion can be drawn that damage value of frozen loess decreased with increasing confining pressure under lower confining pressure, but with a further increase in confining pressure, the damage value increased as pressure melting and crushing phenomena caused by higher confining pressure levels.

1. Introduction

Continuum damage mechanics (CDM) is a relatively new field that investigates the mechanical response and reliability of materials weakened by many randomly distributed micro-cracks/micro-defects of irregular shapes and random in size and orientation. The degeneration on macro mechanical properties of materials was defined as damage. The damage was irreversible for many materials and coupled with energy dissipation. CDM was pioneered by Kachanov (1958) who introduced a continual variable to describe the rupture process of metal under creep condition. It was later promoted by some other scholars (Krajcinovic, 2000; Lemaitre, 1992; Rabotnov, 1963). By introducing a "damage variable", the change of macroscopic mechanical response of materials, such as the loss of strength and stiffness attributed to micro-defects, can be quantitatively measured. More specifically, the effects of damage on stress–strain behavior of materials can be considered by introducing the damage variable into the constitutive model (i.e. damage model). In order to construct a damage model, three factors related to damage behavior need to be determined. The first factor is the definition of damage variable. The damage variable plays a key role in measuring the change of macroscopic response of materials engendered by evolution of micro-defects. The second factor is damage threshold value. Because the damage behavior of materials involves an irreversible process, damage usually appears together with irreversible deformation. Therefore, the damage threshold value, which is regarded as a damage criterion, is used to judge whether the damage was generated. The third factor is the damage evolution law which is used to quantitatively describe the change of damage with irreversible deformation. The damage behavior can be described by a damage model once the three factors about damage are determined. Therefore, study on the three factors of damage of materials is a key procedure to investigate the damage characteristics of materials and to establish reasonable damage models.

As a special geomaterial, frozen soil has a large number of micro-defects and micro-cracks. Due to the frozen soil were made up of soil particles, ice, unfrozen water and gaseous inclusions, it has more complex meso/micro-structure comparing with unfrozen soil and metal materials. During loading or deformation process, the evolution and propagation of meso/micro-structure will induce energy dissipation and damage in frozen soil, which affect the macro mechanical

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behavior of frozen soil. In order to consider the influence of these micro-defects and micro-cracks and their changes on mechanical behavior of frozen soil, some researchers investigated evolution of meso-structure and micro-structure of frozen soil during deformation process by using scanning electron microscope or CT scanning tests. Wu et al. (1996) used CT scanner to monitor the change of structures in frozen soil during uniaxial creep process. Their results indicated that the strengthening and softening actions of structure in frozen soil were controlled by the initiation and growth of structural defects, which governed the characteristics of creep process. Ma et al. (1997) used CT scanner to investigate the influence of confining pressure on creep process of frozen loess. They found that the confining pressure can restrain the propagation of cracks in frozen loess and enhance the strengthening action between soil particles so that the strengthening of structure occupied a dominant position at unstable and stable creep stages of frozen loess. Miao et al. (1998) applied electronic microscope scanning test to analyze the creep process of frozen soil, and proposed a damage creep model to describe the creep behavior. However, since the internal structure change of frozen soil during loading process can't be observed by the electronic microscope scanning test, the damage evolution law can't be determined by test results. They assumed a function form as the damage evolution law. Ling et al. (2003) monitored the dynamic triaxial compression process of frozen Harbin silt by CT scanner. The micro-deformation mechanism and structure damage of frozen Harbin silt were qualitatively analyzed in their results. All the studies mentioned above mainly focused on the qualitative analysis of the effects of meso/micro-structure on deformation. In order to quantitatively study the damage characteristics of frozen soil, Liu et al. (2002) defined a damage variable for frozen soil by applying the relation between CT number and density. Based on the fact of existence of initial damage in frozen soil, they regarded the production of micro-cracks during loading process as the additional damage. Two calculation methods for two kinds of damage were proposed in their results. By using the definition of damage variable based on CT number, Liu et al. (2005) proposed a damage constitutive model for frozen soil under uniaxial compression condition. Zhao et al. (2012) carried out systematic investigation for damage characteristics of frozen loess under uniaxial compression by using CT scanning technology. At first, they defined relative change with density as the damage variable. According to the relation between density and CT number during deformation process, they proposed a quantitative relation between damage variable and CT number. They adopted the plastic strain corresponding to the obvious change of CT image as the damage threshold value, and investigated the effects of temperature on it. Finally, they proposed a damage evolution law based on their CT scanning tests.

CT scanning test can certainly observe change of meso/micro-structure in frozen soil during loading process. For obtaining reliable test data, besides the high standard experimental operation, this test requires expensive equipment such as CT scanner. Moreover, this test was unable to investigate the energy dissipation behavior during loading process, which is an important index to describe the extent of damage and changes of internal meso/micro-structure. Damage behavior coupled with energy dissipation and changes of internal meso/micro-structure were extensive studied in various materials, which was reported in many open literatures (Buck et al., 2013; Carol and Willam, 1996; Chen and Yuan, 2007; Gosar and Nagode, 2013; Levenston and Carter, 1998; Sufian and Russell, 2013). There are different methods to measure and calculate energy dissipation during damage process. Jie et al. (1998) proposed a theoretical formula to calculate energy dissipation during the thickening process of a single craze in polymers. However, their equation was confined to the case of single craze in materials and was not applicable to the granular materials with various pores. A convenient approach to investigate energy dissipation in materials is cyclic loading test, which was used by many researchers. Padilla-Llano et al. (2014) used a cyclic uniaxial loading test to determine the effects of reversed cyclic loading and cumulative axial deformation on damage and hysteretic energy dissipation for cold-formed steel framing members. In their study, they mainly aimed at the influence of the sample slenderness on the energy dissipation and strength degradation. Crambuer et al. (2013) conducted cyclic three point bending test on reinforced concrete beams. They used different loading paths in their tests, which allowed them to study relation between the hysteretic energy dissipation and damping phenomenon. Cyclic tests have been carried under various loading modes and conditions to observe different responses of materials. In frozen soil, the cyclic tests usually conducted under dynamic and axial symmetric loading conditions to obtain the dynamic parameters and investigate change of temperature in specimen. Recently, Liu et al. (2014) designed an apparatus to conduct the cyclic direct shear test under dynamic condition for frozen soil, which provided a new test approach for understanding the mechanical properties of frozen soil. In this study, a static triaxial cyclic test was presented to investigate the energy dissipation and damage behavior during static deformation process. In substance, the damage of materials can be reflected and measured from the deterioration of the macro mechanical properties. Based on the fact that damage induces energy dissipation and degeneration of macro mechanical parameters (such as strength and stiffness), the deterioration degree of elastic modulus was defined as the damage variable of frozen loess in this study. For investigating the damage behavior of frozen soil from the viewpoint of deterioration of mechanical properties, a series of triaxial compression (TC) tests and corresponding static triaxial loading–unloading cyclic (TLUC) tests have been carried out at temperature of −6 °C. The TLUC test results showed that hysteresis loops formed during unloading–reloading process, which indicates energy dissipation existed in frozen loess during deformation process. Meanwhile, elastic modulus of frozen loess increased with increase of strain at initial loading stage, and then decreased with increase of strain. This phenomenon indicated that there inevitably existed micro-defects/micro-cracks in frozen loess. And the micro-cracks would close during the initial loading stage, which causes the stiffness of frozen loess increase with strain. Based on this, a concept of initial damage was also introduced for frozen loess. To quantify the initial damage value, a method for determining the undamaged state of frozen loess was proposed. Once the undamaged state was defined, the initial damage under various confining pressures can be calculated, and the damage threshold value corresponding to this state also can be determined. The effects of confining pressure on initial damage and the damage threshold value were analyzed. Finally, a damage evolution law was obtained based on the TLUC test data, and the influence of confining pressure on it was considered.

2. Test conditions and procedures

In this study, the test was conducted on a cryogenic triaxial apparatus improved from MTS-810 material test machine. The technical indices and performance parameters of this equipment were detailed by Xu et al. (2011a).

The test material was Lanzhou loess taken from Donggang town of Lanzhou city. The grain size distribution of the tested loess is shown in Table 1. To ensure the homogeneity of specimen, the loess was mixed with 17% moisture content by weight at first, and then kept for 6 h without evaporation. Afterwards, the soil was put in a cylindrical mold to make cylindrical soil specimens with target densities. The specimens

Table 1
Particle composition of Lanzhou loess.

<0.005 mm	0.005–0.05 mm	0.05–0.075 mm	0.075–0.10 mm	0.10–0.25 mm	>0.25 mm
11.21	68.46	14.03	4.54	1.76	0