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Energy dissipation and failure criterion of artificial frozen soil

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ABSTRACT

The failure mechanism of frozen soil is very complicated and shows closely dependence on many factors. A precise physical definition for failure state of frozen silt is not easily quantified. Energy conversion is one of the most important physical principles, and it can be inferred that the failure is the final result of an energy-driven unstable process. The explorations of intrinsic relationships among energy storage, energy release, and strength are important to understand the failure mechanism of frozen soil. In this study, the propagations of strain energy accumulation, dissipation and release are investigated. A framework is established to facilitate the analysis of failure behavior based on energy dissipation and energy release principles, and a new strength criterion is established for frozen soil. According to this criterion, frozen soil starts to fail when the ratio of elastic shear strain energy to elastic volumetric strain energy reaches a critical value. When such an approach is adopted, the problem of modeling failure initiation and propagation of frozen soil becomes greatly simplified.

1. Introduction

The artificial freezing method, which has good water-sealing performance and recoverability of stratum, has been widely used in metro engineering, tunnel construction, mine shaft and other engineering activities in underground (Li et al., 2011; Zhang et al., 2013; Yang et al., 2013; Lai et al., 2014). Frozen soils are made up of mineral particles, ice inclusions, liquid water and gaseous inclusions. The mechanical property of frozen soil is very complicated, and shows closely dependence on many influencing factors, such as temperature, water content, physical characteristics of soil particle, and the interactions among these factors(Arenson and Springman, 2005; Wang et al., 2008, 2011; Bronfenbrener and Bronfenbrener, 2012). Modeling the initiation and propagation of failure behavior of frozen soil is quite complex. Many investigations on the strength theory for frozen soils have been carried out (Ma et al., 1995; Qi and Ma, 2007; Lai et al., 2010; Xu et al., 2011). Most of these strength criteria were obtained from specific experimental results, which are the effective and direct ways to judge whether engineering structures fail; however, these criteria are limited to the specific testing stress state, it is difficult to assess failure behavior for complicated stress condition. In fact, a precise physical definition of failure state for frozen soil is not easily quantified. In order to describe the complicated failure behavior, recently, the strain energy theory has been recalled to predict failure initiation of materials subjected to various loads (Liu, 2009; Xie et al., 2009; Dolinski et al., 2010; Yuan et al., 2013). Energy conversion is an essential physical process, and it can be inferred that the failure of the material is a final result of energy-driven destabilization process. The intrinsic relationships between energy dissipation, energy release, and structural failure are important for understanding the deformation and failure mechanisms of material. Many researches indicated that energy plays an important role in deformation and failure of geomaterials (Sujatha and Kishen, 2003; Hua, 2003; Yu and Yin, 2004). The understanding of the relationship between energy conversion and structural failure is needed, and the studies on capability for energy storage and dissipation could provide valuable references for practical engineering application of frozen soil. However, the researches related to energy description of frozen soil have scarcely been investigated. Our work aims to analyze the energy evolution that occurs during the deformation and failure, and to establish a strength criterion based on energy theory to describe the initiation and propagation of failure behavior of frozen soil.

In this study, triaxial compression and loading–unloading tests are conducted on frozen silt specimens with various confining pressures. The characteristics of strain energy accumulation, dissipation and release are investigated in loading process. Framework to facilitate the analysis of strength characteristic is established based on strain energy principle, and a new strength criterion is proposed for modeling the failure behavior of frozen soil. According to this strength criterion, frozen soil starts to fail when the ratio of elastic shear strain energy to elastic volumetric strain energy reaches a critical value. When such an approach is adopted, modeling the initiation and propagation of frozen soil becomes greatly simplified.

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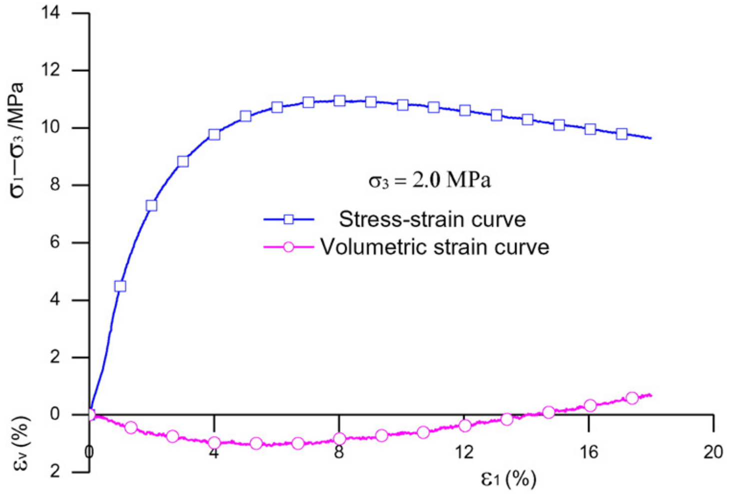
Table 1
Basic parameters of silt.

Composition of particle diameters %							Liquid limit %	Plastic limit %
>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	23.2	15.0

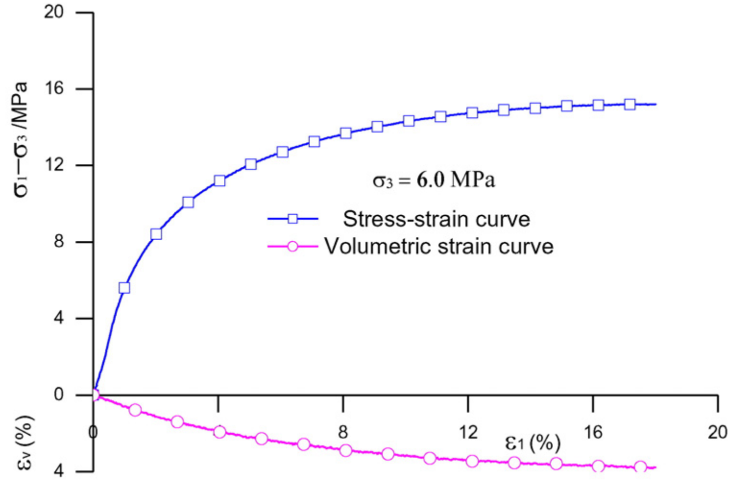
2. Test conditions and results

In this paper, the soil used in test was silt and particle size distribution is given in Table 1. The specimens were prepared as cylinders with 6.18 cm in diameter and 12.5 cm in height. The water content of the specimen tested was 12.8%, and the silt had an optimum dry density of 1.81 g/cm^3. The detailed preparation of specimen has been described by Lai et al. (2010). The specimens were placed into a triaxial pressure cell of at a given temperature and kept constant for 24 h, and were tested by using Servo-controlled MTS810 equipment. Standard triaxial compression tests were carried out, and a constant axial strain rate control of 1.67×10^{-4}1/s was used. Typical stress-strain curves for triaxial compression tests at -8 °C are shown in Fig. 1.

The results show that the stress-strain curve of frozen silt is sensitive to confining pressure. The stress-strain curve shows an initial more or less linearly elastic section. The elastic section is normally followed by bending-over of the curve due to pre-fracture inelastic behavior. The stress-strain curve presents strain softening in loading process under low confining pressures, but presents strain hardening phenomenon under high confining pressures. At the same axial strain, the magnitude of stress greatly increases with the increase of confining pressure, and increase in confining pressure also leads to the strength occurring at a lager strain. The density of the frozen silt is significantly changed during loading process. Inelastic volume changes reflect changes in the microstructure associated with pores or microfissure. The magnitudes of volumetric strain increase with



(a) Typical strain softening and volumetric change curves of frozen silt.



(b) Typical strain strengthening and volumetric change curves of frozen silt.

Fig. 1. Stress-strain and volumetric strain curves of frozen silt for triaxial compression.