Cold Regions Science and Technology 133 (2017) 70–81

Contents lists available at ScienceDirect

Cold Regions Science and Technology

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

Cyclic direct shear behaviors of an artificial frozen soil-structure interface under constant normal stress and sub-zero temperature

Lianzhen Zhao [a,b], Ping Yang [a], Lai-Chang Zhang [b], J.G. Wang [c,*]

[a] Department of Civil Engineering, Nanjing Forestry University, Nanjing 210037, Jiangsu, China
[b] School of Engineering, Edith Cowan University, 270 Joondalup Drive, Joondalup, Perth, WA 6027, Australia
[c] School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 221116, China

ARTICLE INFO

Article history:
Received 25 December 2015
Received in revised form 13 September 2016
Accepted 31 October 2016
Available online 02 November 2016

Keywords:
Frozen soil-structure interface
Constant normal stress
Cyclic shearing
Sub-zero temperature
Normal displacement
Damage model

ABSTRACT

The soil-structure interface between structures and frozen soil ground is an important element to the structure safety in permafrost regions. This interface is usually subjected to a constant normal stress and cyclic shear loadings such as seismic, wind, and wave loadings. Hence, the cyclic direct shear behaviors of this interface have critical impacts on the safety and durability of the structure. This paper investigated the cyclic direct shear behaviors of an artificial frozen soil-structure interface under four constant normal stresses and four sub-zero temperatures by using a large-scale multi-functional direct shear apparatus. Cyclic shear stress and normal displacement were measured under normal stresses of 100, 300, 500, and 700 kPa and at sub-zero temperatures of −2, −6, −10, and −14 °C, respectively. These measurements revealed the following mechanical properties of this artificial interface: (1) The maximum shear stress is always observed in the initial stage of the first cycle. This maximum shear stress is linearly related to the normal stress. (2) Both the internal friction angle and the cohesion of this interface at the maximum shear stress decrease with the increase of sub-zero temperature. (3) The internal friction angle decreases with further cycles. This angle becomes significantly smaller in the stabilized cycles than that in the first cycle. (4) The maximum dilation measured by normal displacement is always observed in the first cycle. This dilation is decreasing with higher normal stress and at lower sub-zero temperature. However, the final normal displacement always contracts and its magnitude increases with the increase of normal stress or the decrease of sub-zero temperature. Finally, a simple damage model is proposed to describe these behaviors of this artificial interface and its performance is checked through its prediction for experimental data.

1. Introduction

A frozen soil-structure interface is an important element to the structure safety in permafrost regions as well as artificially frozen soils for tunnel excavations. The interface refers to the contacting thin zone between structures and the adjacent frozen soil (DeJong et al., 2006; Silva et al., 2013). It transfers loading between the structures and the ground. Because the structures and the adjacent frozen soil have significant difference in stiffness, strength and thermal properties, this interface is extremely vulnerable to any damage induced by complex external loads such as seismic or wind loads (Donna et al., 2016). Therefore, for the structure safety, interface properties under different normal stresses and sub-zero temperatures are important design parameters (Feng et al., 2016; Lai et al., 2016). The interface performance varies with constraint conditions, such as constant normal stress. A constant normal stress condition refers to that a constant normal loading is applying on the interface. This is very common because a constant normal loading is transferred between the structures through the frozen soil-structure interface. Under a constant normal stress, this interface may be also subjected to a cyclic shear loading such as wind or seismic load in its tangential direction. Therefore, it is necessary for the safety design of the structures in permafrost regions to understand the cyclic direct shear behaviors of an interface under constant normal stresses at sub-zero temperatures.

Frozen and unfrozen soils have significant differences in mechanical and thermal properties due to the existence of ice (Assur, 1980; Li et al., 2011; Zhu et al., 2011; Liu et al., 2013; Zhang and Michalowski, 2015; Li et al., 2016; Zhou et al., 2016). Tsytovich and Sumgin (1937) found that the uniaxial compressive strength of frozen soils was considerably greater than the strength of unfrozen soils under the same normal stress. Tsytovich et al. (1981) further observed a significant change in strength when sub-zero temperature was between −16 °C and −0.5 °C. A power function was found to be able to describe the relationships between sub-zero temperature and uniaxial compressive strength (Sayles and Carbee, 1981), compressive strength (Zhu, 1987), and tensile strength (Zhu and Carbee, 1987) of frozen soils. Li et al. (2001) found that strain rate and sub-zero temperature were two key

---

* Corresponding author.
E-mail addresses: nuswjg@yahoo.com, jgwang@cumt.edu.cn (J.G. Wang).

http://dx.doi.org/10.1016/j.coldregions.2016.10.011

parameters to influence the compressive strength of frozen soils, where a linear relationship was observed between compressive strength and sub-zero temperature. Based on dynamic triaxial tests of frozen clay, Zhu et al. (2010) found that the axial strain rate increases with dynamic stress ratio and temperature rising, while the strain rate decreases with the increase of frequency and moisture content. The maximum dynamic shear modulus decreases with the rise of frozen temperature and the decrease of confining pressure. The maximum damping ratio increases as temperature, frequency and confining pressure increase. Czurda and Hohmann (1997) evaluated the effects of different frozen conditions on the shear strength of soils with high clay content through a series of direct shear tests in laboratory. They found that the cohesion of ice determines the shear strength of frozen soils. After conducting triaxial compressive tests under confining pressures of 0 to 18 MPa at a temperature of −4 °C, Yang et al. (2010) revealed that the strength of the frozen soil initially increases with confining pressure, but decreases beyond some confining pressure (such as 10 MPa in their experiments). Rist et al. (2012) conducted a series of inclinable shear box tests with permafrost sands and found that the grain size of the permafrost is one of the decisive factors for the angle of mobilised interface friction. Liu et al. (2014a) found that both peak shear strength and residual shear strength of frozen soil-concrete interfaces had a positive linear dependency on normal stress but a negative linear dependence on sub-zero temperature. These investigations showed that the mechanical properties of frozen soils largely depend on sub-zero temperature, normal stress, strain rate, ice content, and soil type. Therefore, sub-zero temperature and normal stress are two important factors to frozen soil strength.

The mechanical properties of unfrozen soil-structure interfaces have been well investigated (Liu and Ling, 2008; Zhang et al., 2010; Kwak et al., 2013; Liu et al., 2014b; Toufigh et al., 2014; Duriez and Vincens, 2015; Donna et al., 2016). For examples, Desai et al. (1985) conducted various static and cyclic tests to measure the mechanical properties of a concrete-sand interface at room temperature. They developed a cyclic direct shear apparatus which has a cross section of 31 cm × 31 cm for shearing. They found that the internal friction angle of this interface increases in proportion to the initial density of the sand. They also found that the interface stiffness increases in proportion to normal stress. Zhang et al. (2011) observed the volumetric change of a soil-structure interface under shearing through a large direct shear apparatus. They found that this volumetric change has both reversible and irreversible components. The reversible component of dilatancy depends on the direction of shear stress, while the irreversible component comes from the failure of the unfrozen soil due to cyclic shearing. Hamid and Miller (2009) improved a conventional direct shear device to measure the shear properties of an interface when the soil was unsaturated. They found that the cohesion of the unsaturated soil was greater than that of the interface. Moreover, the cohesion of a rough interface was smaller than that of a smooth interface. By using a larger direct shear apparatus (the cross section of the shear box being 30 cm × 31 cm), Lee and Manjunath (2000) investigated the friction angle of the interface between uniform sand and three woven and nonwoven geotextiles. They found that the reduction of peak shear strength in the soil-geotextile interface was caused by the structural deterioration and physical damage of the geotextiles. Hossain and Yin (2011) completed a series of direct shear tests to investigate the effect of grouting pressures on the interface between weathered granite soil and cement grout, under both saturated and unsaturated conditions. They found that: 1) the stress-strain curves have hardening behaviors under various normal stresses, and the shear stress of the interface increases with normal stress; 2) the shear strength of the interface increases with grouting pressure when the suction is low; while the shear strength decreases when the suction is relatively high. Through a series of monotonic shear tests, DeJong and Westgate (2009) found that the deformation of interface was heavily affected by the physical and mechanical properties of the sliding zone soil. Cai and Xu (2015) proposed an interfacial fracture criterion for interface cracking and for interfacial debonding based on the nominal strain energy density of interface. On this sense, the mechanical properties of the unfrozen soil-structure interface cannot be directly applied to the frozen zone (Donna et al., 2016). It is necessary to investigate the mechanical properties of a frozen soil-structure interface.

The mechanical properties of a frozen soil-structure interface under a constant normal stress and cyclic shear loadings have not been investigated so far. By using our large-scale multi-functional direct shear apparatus (called DDJ-1 hereafter), this study measured the mechanical properties of an artificial frozen soil-structure interface under constant normal stresses and at various sub-zero temperatures. A cyclic shear load was applied to the interface. In the laboratory tests, cyclic direct shear stress and normal displacement were measured under four normal stresses (100, 300, 500, and 700 kPa) and at four sub-zero temperatures (−2, −6, −10, and −14 °C). The maximum shear stress was observed in the initial stage of first cycle and its relationship with normal stress was studied. The effect of sub-zero temperature on both internal friction angle and cohesion of the interface at this maximum shear stress was investigated. Further, the evolution of internal friction angle with cycles was explored. The maximum dilation was observed in the first cycle and its dependence on normal stress and sub-zero temperature was discussed. The relationships of final normal displacement with normal stress and sub-zero temperature were investigated. The rest of this paper is organized as below. Section 2 describes the specimen preparation and testing procedure. Section 3 discusses the measurement results for shear strength, maximum dilation, final normal displacement under different normal stresses and sub-zero temperatures. Section 4 proposes a simple damage model to describe the mechanical behaviors in the first cycle and subsequent cycles. The conclusions are drawn in Section 5.

2. Specimen preparation and testing procedure

2.1. Large-scale multi-functional direct shear apparatus (DDJ-1)

The DDJ-1 system is briefed here. Fig. 1(a) presents the schematic diagram of DDJ-1. This DDJ-1 has four sub-systems: specimen holder or shear box, loading system, measurement system and temperature controller. The shear box system holds specimens and provides space for loading and measurement. The loading system includes horizontal loading servo motor and vertical loading cylinder. The measurement system consists of horizontal and vertical load sensors, horizontal and vertical displacement sensors and temperature sensor. The record devices such as computer and AD/DA adaptors are also included in this system. Temperature control is provided by the refrigerating system. The accuracy of temperature collection and control at the frozen soil-structure interface is crucial to reliable test results. Fig. 1(b) shows the locations of temperature sensors. They were installed at 5 mm down from the interface. Such an arrangement considered the feasibility and accuracy of temperature measurement.

2.2. Specimen preparation

Specimens were prepared with typical Nanjing silt, and its parameters are listed in Table 1. A 2.713 kg of oven-dry Nanjing silt and 0.651 kg of water were well mixed together for 5 min to obtain a remolded silt sample. The saturation degrees of water and ice in the frozen silt are all 24%. The remolded silt sample was then wrapped with plastic film and stored for another 48 h before use. The well-mixed remolded soil sample was filled into a shear box with the dimension of 200 mm long, 100 mm wide, and 86 mm high through a layer-by-layer method. Total three layers were divided and each layer was uniformly compacted to 29 mm in height for the sample weight of 1.121 kg. The surface of the top layer was smoothed flat. Such a procedure for specimen preparation can keep the specimen consistency and uniformity.