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Study on the freezing characteristics of silty clay under high loading conditions

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ABSTRACT

The freezing behaviour of soil in deep alluvium is one of the important issues in artificial freezing engineering. In this paper, an apparatus was developed for studying the freezing characteristics of soil under high loading conditions and the related test procedures were also suggested. Based on this apparatus, a series of one-dimensional freezing tests were also carried out on silty clay under various loading conditions and pseudo temperature gradients. The results show that all soil samples exhibit compression under high loading conditions, and it consists of four stages in which the strain rate is I) very low, II) rapidly increasing, III) decaying and IV) relatively constant. During freezing tests, the freezing front moves downward rapidly during the initial period, and it tends to be stable after 10 h. As the increase of axial load or pseudo temperature gradient, the freezing front moves downward more quickly and lies closer to the warm end at the thermostatic stage. Even under high loading conditions, there is an obvious water redistribution phenomenon, which shows that the water migrated to the frozen part and gathered at the freezing front in the soil sample under the existence of a pseudo temperature gradient.

1. Introduction

In recent decades, underground engineering developed quickly, including underground railroads, deep mines and underground water tunnels. Prior to construction, one of the primary difficulties is how to excavate in deep alluvium, especially when a weak aquifer is involved. Of all the available excavation methods, the artificial freezing technique is particularly suitable for these cases because of its adaptability to complex stratum, its good water-proof performance and its minimal pollution (Hass, 2006; Schmall and Braun, 2007; Wang et al., 2008; Zhou and Zhou, 2012). The freezing behaviour of deep soil, which can bear relatively high ground pressures, is critical to the long-term stability of artificial freezing engineering (Ma and Wang, 2012; Ma et al., 2004).

Over time, various test apparatuses have been developed for studying soil freezing characteristics (Kaplar, 1974; Mageau, 1983; Oliphant et al., 1983; Xu, 1988), such as water migration, ice segregation and frost heaving. In previous studies, many researchers discussed the migration of unfrozen water in freezing soils. Taber (1930) proposed that the water absorbing capacity of soil grains is closely related to the grain size. Beskow (1935) correlated the water absorbing capacity to the height of capillary rise, and Everett (1961) offered the capillary theory, based on thermodynamics, and proposed a method for estimating the water absorbing capacity of soil pores. To explain the formation of the discontinuous ice lens, Miller (1972) proposed the concept of a frozen fringe, where the warmest pore ice was formed. Subsequently, the formation of a freezing front and its development were discussed further (Akagawa, 1988; Gilpin, 1980; Konrad and Morgenstern, 1981; Penner, 1986). Moreover, other scholars observed water migration induced by a temperature gradient in frozen (Mageau and Morgenstern, 1980) and thawing soils (Solomatin, 1994). In reference to ice segregation, a series of mechanisms have been reported, including cementing segregation, repeated segregation, intrusive ice formation and vacuum infiltration. The repeated segregation method proposed by Cheng (1983) was recognised as explaining underground ice formation. Recently, anti-frost heave methods have been reported, such as an intermittent ice segregation mechanism (Zhou, 1999; Zhou and Zhou, 2012; Zhou et al., 2006). In frost heave discussions, previous studies focused mainly on the soil's frost susceptibility and factors influencing soil frost heave. It is believed that three conditions are necessary for frost heave to occur: 1) frost-susceptible soil, 2) availability of water and 3) thermal conditions that will cause a freezing front propagation slow enough to allow water transport (Bronfenbrener and Bronfenbrener, 2010). There are both internal and external influencing factors that affect frost heave; the internal factors include grain size (Johnson et al., 1975), specific surface area (Tong and Guan, 1985), water content (Wu, 1981) and salinity (Bing et al., 2006). External factors include overburden pressure (Arvidson and Morgenstern, 1977), freezing rate (Tong and Guan, 1985) and water supply (Xu et al., 2001).

Most previous studies, however, were carried out on load-free or low-pressure test apparatuses, which are not applicable for deep soils that bear high ground pressures. Thus, there is an urgent need in frozen soil mechanics to develop an apparatus for soil freezing tests conducted under high loading conditions. In this paper, a new apparatus was

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developed for soil freezing test under high loading conditions. Based on this apparatus, the freezing characteristics of silty clay were studied.

2. Test apparatus and the procedures for soil freezing test under high loading conditions

2.1. Test apparatus for soil freezing test under high loading conditions

The main structure of the apparatus is shown in Fig. 1, and it consists of five parts: a sample tube, a temperature-controlling system, a water supplying system, a load-controlling system and a data logger. The sample tube is composed of low-conductivity organic glass, with external and inner diameters of 14.0 and 10.0 cm, respectively. The temperature-controlling system consists of a thermostat, with upper and bottom ends. The thermostat is composed of thermal insulation material, with a capacity of 0.8 m^3; the upper and bottom ends are a metallic material, with a cold-fluid-circulating slot carved in the inner side. By circulating the anti-freezing fluid in the cold bath, the temperatures for the upper and bottom ends can be controlled separately and a certain gradient within the soil can be formed. In the upper end, five circular holes were set in the peripheral direction close to the edge such that a temperature probe and data logger could be connected by a lead wire, whereas in the bottom end, a water supply slot was carved and a metallic perforated plate was placed. A 200-ml measuring cylinder was used to monitor the discharged water before the freezing test. An electric-fluid servo system controlled the axial loading during the testing and succeeded in collecting stress–strain data in real-time.

Compared with previous test apparatuses, the technical advantages of this apparatus are as follows: the O-shaped rubber rings situated between the sample tube and the upper and bottom ends of the temperature controlling system provide good sealing under high pressure; the five circular holes set in the upper end for collecting temperature data prevent the leakage of soil particles under high pressures and reduce the integral strength when opening holes in the wall of the sample tube; and a porous stone, placed on the perforated plate, prevents the leakage of soil particles from the bottom end and allows for a smooth external water supply for the sample under high loading conditions.

2.2. Test procedures for soil freezing under high loading conditions

Before testing, identical initial thermal states were required for all soil specimens, and the consolidation history should be considered before freezing test.

A preliminary test was carried out to determine the time when a relatively stable thermal condition would be reached. After a soil sample was mounted on the apparatus, the thermostat and the upper and bottom ends of the temperature controlling system were adjusted to 5 °C. The temperatures in the different layers of the soil sample were recorded by the probes, and the test results are presented in Fig. 2. As shown in Fig. 2, the temperatures in the different layers all show a rapid decrease after the soil sample begins to cool, and keeps a relatively stable temperature field after 10 h. Therefore, 10 h was taken as the thermostatic time required to reach a cooling temperature of 5 °C.

To consider the consolidation history of soil in deep alluvium, the time required for consolidation of the samples was measured. After cooling the soil sample at 5 °C for 10 h, an axial loading of 2 MPa was applied with a constant stress rate of 15 N/s. Then, it was maintained for 120 h, and the axial deformation was recorded. Fig. 3 shows the axial deformations of the soil samples during the maintaining stage of axial load. As shown in Fig. 3, the axial deformation increases at the beginning of maintaining stage and reaches a relatively stable after approximately 48 h. Based on these data, the deformation after 48 h was determined to be the initial consolidation deformation of the soil sample, which was then subtracted by the total deformation produced in the subsequent one-dimensional freezing process.

The specific test procedures for soil unidirectional freezing test under high loading conditions are suggested as follows:

1) Mount the sample;
2) Adjust the temperature-controlling system to remain at 5 °C until a thermostatic stage is reached;
3) Apply a certain load on the soil sample for 48 h and record the discharged water in real time;
4) Adjust the upper-end temperature to a target value and initiate a unidirectional freezing test under a constant overburden pressure;
5) Remove the soil sample from the apparatus and then measure physical and mechanical properties of the different soil sample layers.

In the following application of the apparatus, the one-dimensional freezing tests were carried out in a closed system. The overburden pressure P consists of 4 levels: 0, 2, 4 and 6 MPa while the cold-end temperatures T_c are -3, -5, -7 and -10 °C, respectively, with a constant warm-end temperature T_w of 5 °C.

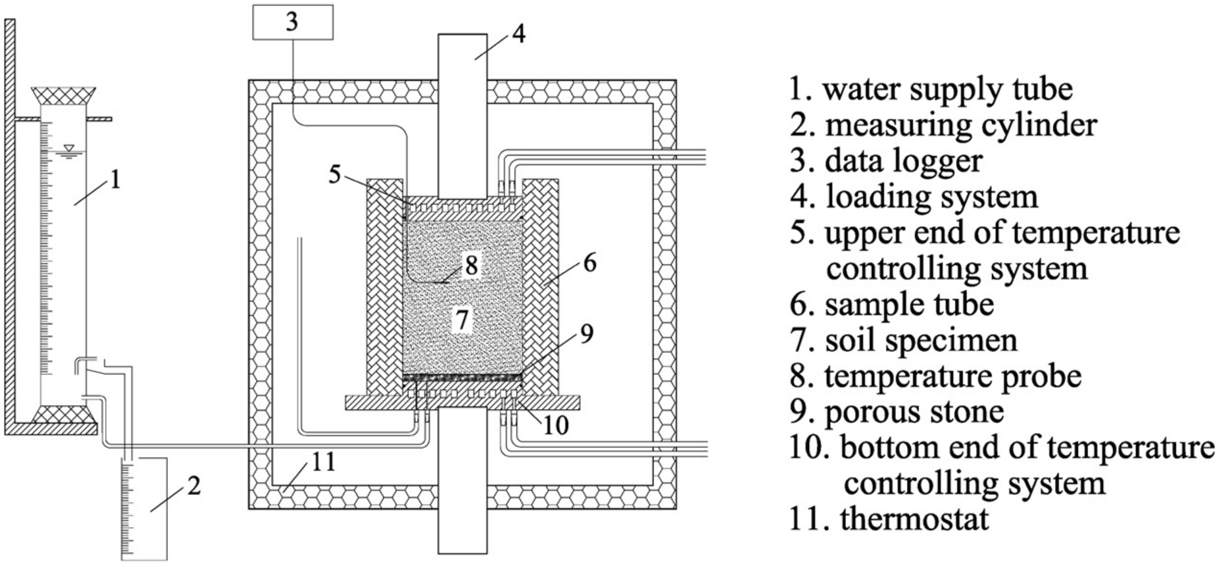

Fig. 1. The soil freezing test apparatus for high loading conditions.