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A versatile triaxial apparatus for frozen soils

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ABSTRACT

Settlement and damage to infrastructures in permafrost regions depend in part on the mechanical properties of permafrost layers. In order to get a better understanding of the mechanical behavior of frozen soils, a triaxial apparatus was developed with three new features in addition to the traditional functions. The first is the accurate temperature control, which allows temperature to fluctuate within ±0.1 °C during the loading period, and ±0.02 °C before loading, so as to get a better understanding of the mechanical properties of frozen soils under temperatures close to thawing point. The second feature is used to measure K_0 of frozen soils. A highly-sensitive radial strain measurement device was designed and the K_0 state can be accurately maintained by automatically adjusting the radial pressure when radial deformation changes more than ±10 μm. The third is the precise measurement of the volumetric strain through the displacement of axial and radial loading pistons. The capabilities of the triaxial apparatus are shown using a series of test results. It is considered to be a promising tool to investigate the mechanical properties of frozen soils.

1. Introduction

With increasing construction of infrastructures in permafrost regions, the mechanical properties of frozen soil and their dependence on ambient temperature are becoming more important. Many studies have shown that with global warming significant increases in the temperature of permafrost have occurred (Oberman and Mazhitova, 2001; Osterkamp, 2005; Smith et al., 2005; Wu and Zhang, 2008). This inevitably influences the mechanical properties of frozen soil as temperature is one of the main factors determining the mechanical properties of frozen soils (Bourbonnais and Ladanyi, 1985; Wu and Ma, 1994; Zhu and Carbee, 1984). Even small change in temperature will probably lead to serious consequences for engineering constructions, such as creep of high-temperature (MAGT ≥ −1.5 °C) frozen layers (Ma et al., 2008; Qi et al., 2007; Zheng et al., 2010) and instability of slope in permafrost regions (Niu et al., 2004; Niu et al., 2006; Wang and French, 1995). To investigate the influence of temperature on mechanical behavior of frozen soils, triaxial apparatus is essential because of its simple stress state and clear boundary conditions.

Temperature control is the first task for testing on frozen soils. There have been two main cooling methods frequently used for temperature control of triaxial apparatus. The first uses a refrigerating unit to cool the room and as a result the triaxial apparatus in the room, known as the "air-cooling method". This method simplifies the construction of the triaxial apparatus, and avoids the influence of daily temperature fluctuations, but is associated with poor cooling efficiency and precision due to the large cooling volume (the whole room) and instable air stream. In addition, with radial pressure loading/unloading, the piston does positive/negative work on the hydraulic oil, resulting in changes in the oil temperature. This cooling method cannot respond rapidly to such changes. As a result, the sample temperature will show an obvious fluctuation. Some improvements were then made on this method. For instance, a triaxial apparatus was designed with a large volume of cell fluid, which acts as a "buffer" to reduce the temperature fluctuations (Arenson et al., 2004). The temperature control precision, in the environmental chamber (the triaxial apparatus in the chamber), was increased using a small electronic fan and a heating bulb, and the temperature was controlled more uniform with an air pump to circulate the hydraulic oil in the pressure cell (Gregory et al., 2003). Nevertheless, the "air-cooling method" is still poor in the cooling efficiency and the temperature fluctuation more than ±0.1 °C. The second method uses an anti-freeze liquid, the so-called "liquid-cooling method", where the triaxial apparatus is refrigerated by the cooled liquid circulating in the device. However, the precision of this method is influenced considerably by daily temperature fluctuations and heat emission in long-term tests. This kind of device has a higher temperature control precision than the first method. For instance, Hazirbaba et al. (2011) used two cooling baths, one for the temperature at the top and bottom plates and another for the ambient temperature of soil sample. However, the use of a single cooling device for both the top and bottom temperature may induce non-uniform temperatures throughout the soil sample caused by temperature difference between the outlet and inlet of the cooled liquid. From the above, it can be seen that the two cooling methods have their advantages and disadvantages.

As far as the mechanical properties of frozen soil are concerned, two indexes still remain difficult to measure. One is the coefficient

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of lateral earth pressure (K_0) at rest of frozen soils, which is a very important parameter for designing and analyzing geotechnical engineering such as tunnel, mineshafts, and retaining walls. For unfrozen soils, there are mainly three methods used: the oedometer, plane strain or triaxial test, respectively. Among these methods the triaxial apparatus might be more conventionally available. However, frozen soils are much stiffer, and less deformation occurs than in unfrozen soils under the same stress, requiring higher radial pressures to reach the zero lateral strain once a small lateral deformation occurs. Therefore, in order to precisely measure K_0, the controller and loading system for frozen soil should be more sensitive. In triaxial tests on frozen soil, the measurement of K_0 remains difficult and is rarely investigated. The second problem is the measurement of volumetric changes of frozen soil samples. Devices from conventional triaxial apparatus may be applied for frozen samples. However, due to the more complicated structure needed for such devices for use with frozen soils, there are some drawbacks to measure volumetric change precisely, e.g. the leakage of fluid out of pressure cell, base flexure of the cell due to the applied axial load (Gregory et al., 2003), and the relative low resolution of the measurement (Arenson et al., 2004).

The above mentioned require precise temperature control, multi-functions, especially in K_0-state control, as well as the precise measurement of volumetric change for triaxial tests on frozen soil. Here, a versatile triaxial apparatus is presented in which both air- and liquid-cooling methods are combined to increase the precision of temperature control. A very precise radial strain measurement device is used to measure K_0. The volumetric change can be precisely measured and is capable of strain (rate) and stress (rate) controlled loading, with excellent long-term stability. A series of test programs were carried out to show performance of the device.

2. Apparatus description

Fig. 1 shows a schematic of the triaxial apparatus that was designed and completed in 2010. It consists of two major systems: loading system (stress (rate) and strain (rate) control) and temperature controlling system. Details of all the setups and sensors used in the triaxial apparatus are shown in Table 1.

2.1. Loading system

In the system, a steel airtight pressure cell is designed to withstand a confining pressure of about 30 MPa. Aircraft hydraulic oil in the cell is used to reduce viscosity at low temperatures. Another advantage of the oil is that it can avoid corroding the rubber membrane used to seal the spacemen during testing. It also offers the benefit of being nonconductive, which is essential when locating electronic devices such as the temperature sensors and radial strain measurement device within the pressure cell. Radial pressure is applied to the specimen ($D = 6.18$ cm $\times$ $H = 12.5$ cm) through a piston pressing the hydraulic oil into the cylinder. The sample is axially loaded through a hardened steel piston, with a maximum pressure of 100 kN. The piston enters the top of the pressure cell through two O-ring seals. Two O-rings seal the joint between the bottom plate and the pressure cell. The displacement of both the axial and radial loading pistons is recorded by the revolution of servo-motors in terms of angle, which is transformed into distance by an EDC (External digital controller). A load cell is used to monitor the axial pressure, while two pressure sensors to monitor the radial and pore water (for unfrozen soil) pressure. Automated control is carried out by the EDCs (which is manufactured by DOLI Elektronik GmbH in Germany with four control loops and can control the stress and strain on axial and radial directions separately) for data acquisition and closed loop control of testing instruments. A computer with specially developed software allows for simultaneous control of stress (rate) and strain (rate) in both axial and radial directions. The working principles are shown in Fig. 2(a, b, and c). With this system, it is possible to perform conventional triaxial tests, stress path tests, K_0 consolidation, etc.

2.2. Temperature controlling system

To prevent the influence of laboratory temperature fluctuations on the temperature control precision, a high-power air-conditioner is used to maintain the laboratory temperature at around 22 °C, which is also comfortable for laboratory technicians to work in. Three refrigeration circulators are used to control the temperature at the top, bottom and side of the soil sample. Taking into account the cooling loss due to the heat effect of room temperature and pipe lines, the temperature of cooling bath is set lower than the target temperature.

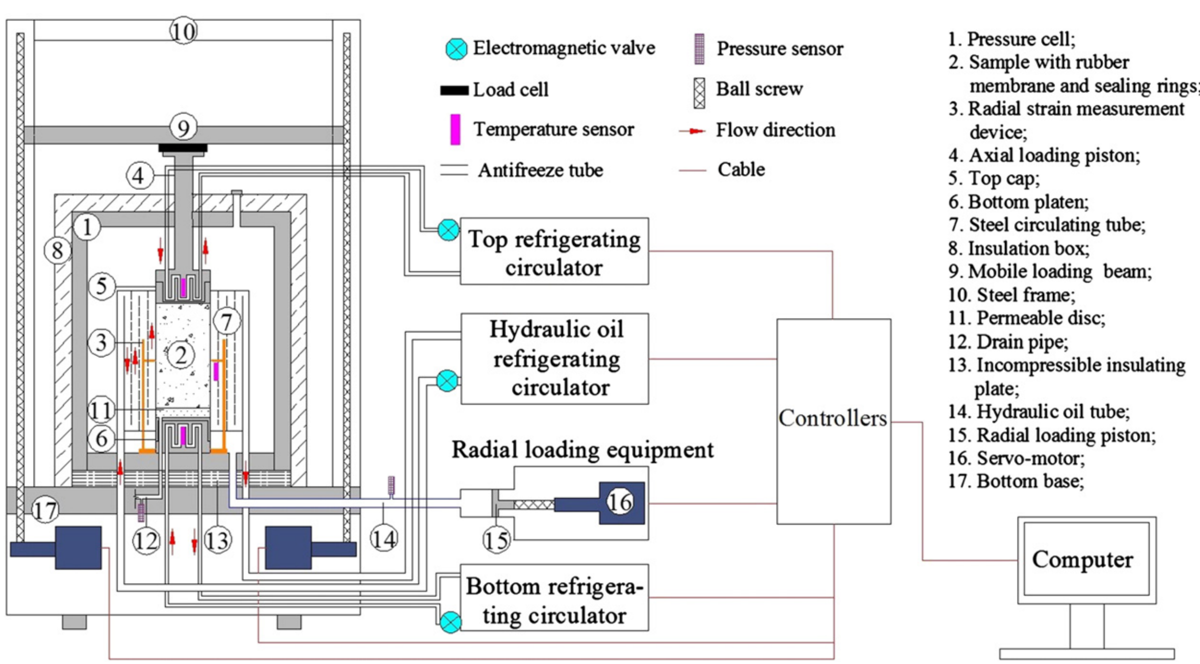

Fig. 1. Schematic of the triaxial apparatus.