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Research Paper

Effect of hydro-thermal behavior on the frost heave of a saturated silty clay under different applied pressures

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HIGHLIGHTS

- Effect of hydro-thermal behavior on the frost heave of saturated soil were analyzed.
- Applied pressure restricts the water migration and frost heave of freezing soil.
- The water intake occurs when the rate of freezing front drops to a critical value.
- The shut-off pressure at which no water flow into or out of freezing soil was obtained.

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ABSTRACT

Civil engineering buildings are often damaged by frost heave of ground soils in cold regions. The hydro-thermal behavior is a key factor in determining frost heave of soils during freezing process. Moreover, the frost heave is also strongly affected by overburden pressure and external water source. Here, a series of one-directional freezing experiments with a water supply under different applied pressures were carried out to study the effect of hydro-thermal behavior on the frost heave of a saturated silty clay. Four different pressures were applied on the top of each soil sample, respectively, i.e. 50, 150, 300 and 500 kPa. The experimental results indicate that the frost heave of the supplied water is the main component of the total deformation for each soil sample with a water supply. However, the increased applied pressure can restrict water migration, and reduce frost heave during soil freezing process. Furthermore, for the saturated silty clay under different applied pressures, only when the advance rate of the freezing front drops to a critical value, the water intake begins. The start time of the water intake is also delayed with the increased applied pressure. Besides, the shut-off pressure of the saturated silty clay, at which no water flow into or out of the soil sample, is obtained based on the relationship between the critical advance rate of freezing front and the applied pressure.

1. Introduction

The hydro-thermal behavior has significant effect on the frost heave which is induced by ground freezing, and often causes damages to cold region buildings such as subgrades, tunnels, pipelines, canals, and line towers [1–5]. It is well known that soil freezing is a complicated process of heat transfer, water migration and frost heave. The water migration to a freezing front changes the thermal regime of the soil, and is the main cause of the frost heave in frost-susceptible soils [6,7], especially for the soils with sufficient water supply [8]. Water migration and frost heave are affected by many factors, including soil type, overburden pressure, cooling rate and groundwater table [9–14]. Generally for the ground soil, the overburden pressure always exists due to overlying soil layers and buildings, so it is very necessary to consider the effect of overburden pressure on freezing characteristics of soils in the construction of cold regions engineering.

So far, some research has been performed on the effect of overburden pressure on frost heave of soils [10,15–20]. Beskow [18] found that externally applied pressures cause a decrease in the rate of frost heave of silty soils during freezing. The overburden pressure can also influence the water flow in a freezing soil, and an overburden pressure, at which no flow of water into or out of a freezing soil, is defined as shut-off pressure [10,19]. Arvidson and Morgenstern [19] provided a linear relationship between the overburden pressure and the flow of water into or out of a freezing soil, and found that the tested soils exhibit only one shut-off pressure for a given set of freezing conditions. The migrated water to freezing front will cause the formation and accumulation of ice

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in a freezing soil [20]. Concerning the influence of overburden pressure on the relationship between rate of frost heave and cold-side temperature, Penner and Walton [12] found that ice accumulation rates at various overburden pressures tend to converge with decreased cold-side temperature, and the maximum rates of ice accumulation under low pressures occur at temperatures closer to 0 °C than those under high pressures. Loch and Kay [17] studied the water flow and the ice formation in saturated silts under different temperature gradients and overburden pressures. Three models of water flow in freezing soils, i.e. capillary model, hydrodynamic model and the secondary frost heaving model, were evaluated, and it was found that they cannot be adequately explain some mechanisms when a pressure is applied.

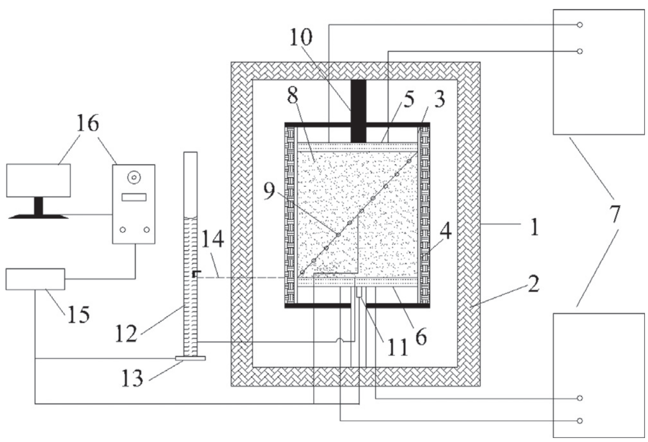

Fig. 1. Schematic of the freezing-thawing test apparatus. 1-outer test chamber, 2-insulated wall, 3-inner test chamber, 4-insulated material, 5-top cold plate, 6-bottom cold plate, 7-cooling baths, 8-soil sample, 9-temperature sensor, 10-load piston, 11-displacement sensor, 12-Mariotte flask, 13-electronic balance, 14-supply water level, 15-data logger, and 16-computer.

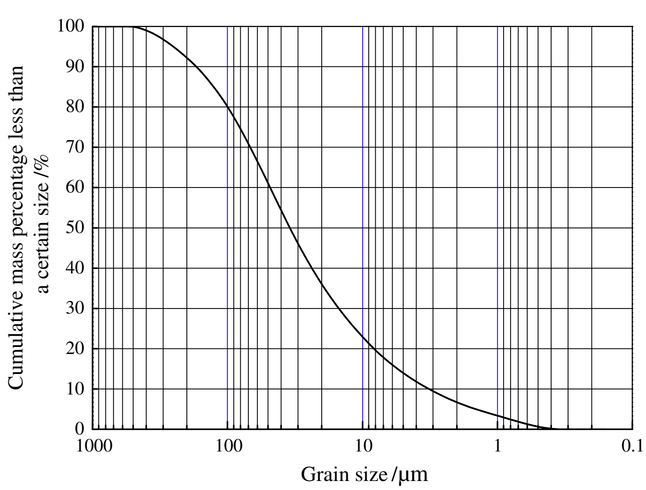

Fig. 2. Grain-size distribution of the silty clay.

When external pressures are applied to soils subjected to open-system freezing, segregational frost heave is inhibited [10]. The relationship between applied overburden pressure (or shut-off pressure) and the net change in pore water volume of a saturated soil during an open-system freezing was recommended as additional criteria for assessing soil frost susceptibility and it provided a basis for evaluating the role of applied surcharge in controlling frost heave associated with freezing conditions [19].

It is also essential to consider the overburden pressure in models for numerical simulations of freezing soil. Hopke [21] presented a model for coupled heat and water transfer in freezing soils considering the effect of overburden. The model predicts the observed rapid decline of frost heave rate with increased overburden. Gilpin [22] developed a model to predict frost heave rates as a function of the basic soil properties (thermal conductivities and particle size) and the externally applied boundary conditions (surface temperatures and overburden pressure). It is assumed that the soil skeletons are separated and allows the formation of a new ice lens when the ice pressure exceeds the overburden pressure plus an additional separation pressure, required to initiate separation of the soil skeletons. The discrete ice lens method presented by Nixon [23] can predict the effect of change of overburden pressure on the predicted heave rate. Konrad and Duquennoi [24] presented a one-dimensional frost heave model to exhibit the water transport in incompressible saturated and solute free soil, and the model also predict the effect of overburden pressure on the frost heave rate. Lai, et al. [25] found that temperature gradient, applied pressure and cooling temperature have significant effect on the frost heave and water migration of saturated soil under no-pressure water supplement by laboratory investigation, and then proposed a hydro-thermo-mechanical model with the variables of temperature, porosity and displacement. At relatively high applied pressures and relatively warm surface temperatures, there is no water migration, and freeze of the available water occurs within the pore spaces, with no accompanying deformation induced by segregated ice growth of migrated water [26].

As discussed above, the frost heave is often affected by many factors, e.g. the applied pressure, water supply, cooling rate, etc., which make it more difficult to understand the coupling relationship among heat transfer, water migration and frost heave during soil freezing under different applied pressures. Although some achievements have been gained, some improvements still need to be made. In this study, a series of one-directional freezing experiments were carried out to study the effect of hydro-thermal behavior on the frost heave of a saturated silty clay under different applied pressures. This will benefit the prevention and reduction of damages caused by frost heave for civil engineering buildings in cold regions.

2. Experimental setup

2.1. Experimental equipment

The freezing-thawing apparatus (Fig. 1) was used to test the temperature, water supply and frost heave of soil samples. The apparatus included outer and inner test chambers, a

Table 1
Experimental conditions of the soil samples.

Condition	Dimension ($h \times d$) (mm)	Initial dry density (g/cm^3)	Initial water content (gravimetric) (%)	Initial temperature (°C)	Applied pressure (kPa)	Temperature boundary (°C)		Freezing time (h)
						Top	Bottom	
1	110 × 100	1.68	22.30	+2.0	50	−2.0	+2.0	96
2	110 × 100	1.68	22.34	+2.0	150	−2.0	+2.0	96
3	110 × 100	1.68	22.37	+2.0	300	−2.0	+2.0	96
4	110 × 100	1.68	22.16	+2.0	500	−2.0	+2.0	96