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Experimental measurement and numerical simulation of frost heave in saturated coarse-grained soil

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ABSTRACT

A series of 1-D freezing experiments were conducted to simulate frost heave in saturated coarse-grained soil (CGS) with variable fines content. Visible frost heave occurred in CGS that contained a considerable fraction of fines when supplied by an external water source. Near the beginning of the experiments, a small amount of water was expelled, likely due to consolidation of the thawed portion of the sample. As time elapsed, the total amount of frost heave was proportional to the intake of water. Furthermore, frost heave increased linearly as the fines content increased. At higher fines content, frost heave occurred mainly due to water migration and segregated ice lensing. Finally, a simple finite element model that combined thermal and mechanical analyses based on Takashi's equation was developed. The model accurately reproduced experimental results and therefore can be used to simulate and predict frost heave in CGS.

1. Introduction

Frost action is a fundamental problem contributing to the instability of infrastructure embankments in regions of seasonal ground freezing, and often results in railway and highway engineering difficulties. The integrity of pavement and the service life of ballast in cold regions are dependent on the resistance of base and subgrade soils to frost action. Taber (1929) first studied frost heave, and it has since been intensively investigated in laboratory freezing tests and with numerical simulations (Everett, 1961; Miller, 1978; Gilpin, 1980; Konrad and Morgenstern, 1981; Konrad, 2008; Konrad, 1999, 2008; Akagawa, 1988; Sheng, 1994; Remple et al., 2004). There are several modeling approaches for simulating frost heave. These include the hydrodynamic model (Harlan, 1973), rigid ice model (Miller, 1978), and segregated ice model (Konrad and Morgenstern, 1981). These models simulate soil moisture migration and frost heave under different freezing conditions in fine-grained soil, and yield results similar to laboratory tests. However, little is known about frost heave and its simulation in coarse-grained soils.

CGS is generally used as the ballast layer material in railway engineering because it has many favorable properties, including high hydraulic permeability and low susceptibility to chemical and frost weathering (Nurmikolu, 2005). Frost heave susceptibility is typically considered to be a characteristic of fine-grained soils. However, field investigations and laboratory experiments have shown that frost heave occurs in CGS that contain considerable fines fractions. Konrad and Lemieux (2005) found that frost heave reached 10 mm in a pavement structure with a base of granular materials in Québec City. The frost susceptibility of the CGS not only increased with the fines content, but also with an increasing kaolinite fraction. These conclusions have been supported by findings from similar frost heave tests (Reike et al., 1983; Tester and Gaskin, 1996; Bilodeau et al., 2008; Wang et al., 2014). Bilodeau et al. (2008) studied the influence of gradation on the frost heave susceptibility of base granular materials and found that segregation potential was strongly related to a fine particles state parameter, and proposed a model that combined gradation and mineralogical source effects. In contrast to fine-grained soil, CGS behaves very differently during freezing. Capillary forces produced in fine-grained soil are greater than in CGS. Fourie et al. (2007) examined ice formation from water infiltration into a frozen CGS using X-ray computed tomography, and found that fine particles decreased pore dimensions and changed the location of the initial impermeable ice layer.

Frost heave in CGS is often ignored in engineering construction because the magnitude is commonly much lower than for fine-grained soils. However, the maximum allowed displacement of non-ballasted high-speed railway track in cold regions of China is only 15 mm. The safety and serviceability of high speed rail in cold regions therefore depends on strictly controlled track displacement (Sheng et al., 2014). Therefore, it is critical to better understand the frost susceptibility of CGS.

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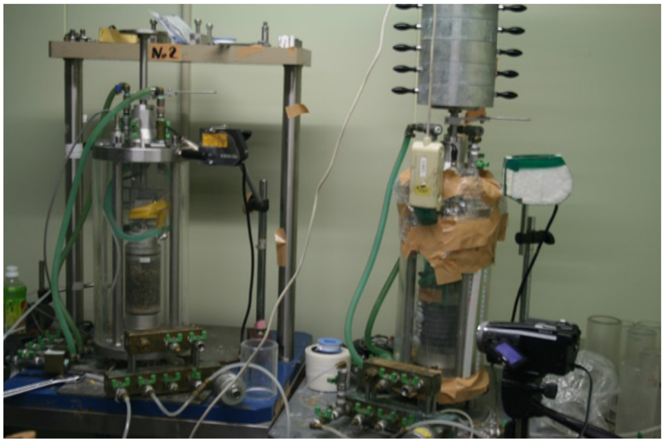

Fig. 1. Frost heave test device in the cold room.

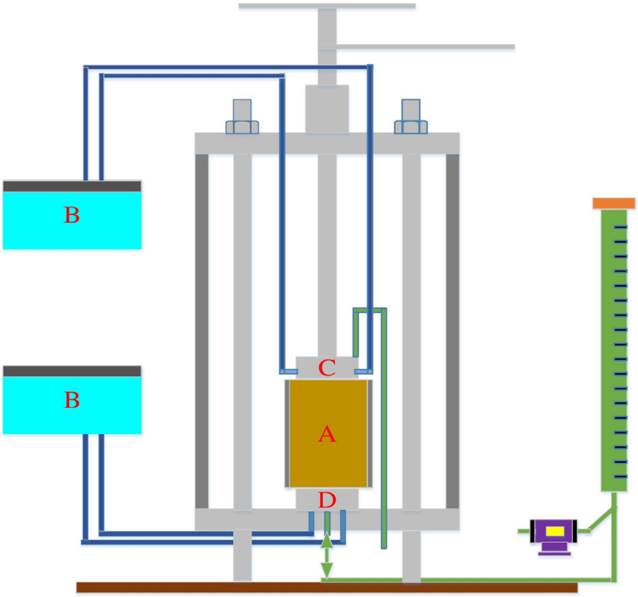

Fig. 2. Schematic diagram of the frost heave test apparatus: (A) soil sample; (B) cold bath; (C) upper pedestal; (D) lower pedestal.

In this paper, we discuss the impact of fines on frost heave susceptibility by adding kaolinite to CGS in an experimental study. We then develop a finite-element model that combines thermal and mechanical analyses, based on Takashi's equation, to simulate and predict frost heave in CGS. The frost heave tests reported in this paper are from preliminary tests carried out at Hokkaido University to evaluate the effect of fines content during soil freezing.

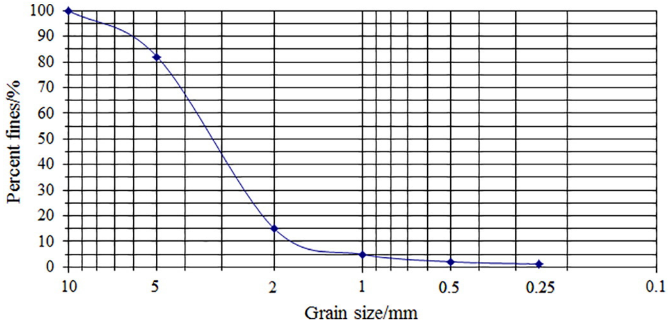

Fig. 4. Grain-size distribution of coarse-grained soil.

2. Experimental methods and testing program

The frost heave test apparatus was composed of four main parts: a frost heave mold, a temperature control device, a water intake and frost heave measurement device, and a data recording system (Figs. 1–2). The frost heave mold is an acrylic cylinder that contains the CGS sample between the lower pedestal, which can move vertically as a piston, and the upper pedestal, which is fixed to the acrylic cylinder. The temperature-controlling device contains two EYELA NCB-3100 cold baths (resolution 0.01 °C), connected to the upper and lower pedestals. For open-system experiments, the water system accurately recorded the liquid inputs. A double-walled burette served as the distilled water reservoir. Before each test, the burette was filled with distilled water from a larger organic glass container. A differential pressure transducer measured the amount of water intake by recording the pressure difference between the base of the water column in the burette and the air. The frost heave measurements were made with a mounted laser to detect soil displacement (1 μm resolution). A clear glass cylinder was placed around the soil to reduce heat exchange between the sample and the laboratory environment, and to allow visual observation of ice lens formation. A camera was mounted near the apparatus and set to take a photo every minute to visually record frost heaving. The frost heave apparatus was placed in a cold room where the temperature was maintained at 1 °C to limit thermal disturbance during the tests. All wires were routed through a hole in the wall of the cold room, and the thermal and laser displacement sensors were connected to an Agilent 34970A multichannel data logger, with measurements recorded at 5 min intervals. All the detailed improvements in our frost heave apparatus was introduced by Margaret et al. (2008).

Crushed rocks blended with fines were used in the frost heave tests (Fig. 3). The sample material was more homogeneous in size and fines content than natural soils used in high-speed railway embankments, so the results obtained from the tests may not reflect exactly frost heave in the field. The coarse particle sizes ranged from 2.5 mm to 5 mm. The fines material added to the CGS was Kaolinite, and had particle sizes <0.075 mm. Grain-size distribution of coarse particle sizes is shown in Fig. 4. The mixture ratio of fines (mass of fines/mass of crushed

(a) Kaolinite fines (b) Crushed rocks

Fig. 3. Kaolinite fines and crushed rocks.