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Evaluation of the freezing–thawing effect in sand–silt mixtures using elastic waves and electrical resistivity

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ABSTRACT

The purpose of this study is to investigate the effects of the freezing–thawing process on soils using elastic waves and electrical resistivity. Sand–silt mixtures with different silt fractions of 0%, 10%, 20%, 30%, 40%, 60%, 80%, and 100% weight at a fixed degree of saturation of 40% are placed in a nylon freezing cell. The temperature of the sand–silt mixtures decreases from 20 °C to −13.5 °C during freezing and increases from −13.5 °C to 20 °C during thawing. Bender elements and piezo disk elements are used to continuously measure shear and compressional waves, respectively, during freezing and thawing. Four circular electrodes made of stainless steel are used to measure electrical resistivity. For the temperature measurement, a thermocouple is inserted into the specimen. The shear and compressional wave velocities as well as electrical resistivity dramatically change near 0 °C during freezing and thawing for all sand–silt mixtures. After one cycle of freezing–thawing, the elastic wave velocities decrease and the electrical resistivity increases due to the fabric change of the specimens. During the thawing process, the electrical resistivity displays hysteresis behaviors (not elastic wave velocities) from −3 °C to 0 °C. This study demonstrates that elastic waves and electrical resistivity may effectively capture the property changes of the sand–silt mixtures during freezing–thawing.

1. Introduction

Cold regions, including seasonal frozen regions and polar regions, cover large areas of the civilized world, such as the North America, East Asia, and Northern Europe. Because the atmospheric temperature affects the ground temperature, the ground along the frost penetration depth in the cold regions repeatedly freezes and thaws during the winter season. Thus, the freezing–thawing cycles affect various mechanical and physical properties of the ground. Specifically, the spring thaw can damage infrastructures such as pavements, railways, slopes, and buried pipes (Simonsen and Isacsson, 1999). Micro-fabrics or micro-fissures can generate during the freezing and thawing processes of clay soil, which can produce microscopic cracks and voids (Chamberlain et al., 1990; Graham and Au, 1985). Thus, the hydraulic permeability of the soil increases after cyclic freezing–thawing (Chamberlain and Gow, 1979; Kim and Daniel, 1992). The freeze–thaw cycle also markedly decreases the resilient modulus, although the decrease depends on the soil type or density (Lee et al., 1995; Simonsen et al., 2002). Qi et al. (2008) indicated the existence of a critical dry unit weight. When the dry unit weight is lower than the critical dry unit weight, the soil is densified and the cohesion and preconsolidation pressures increase after freezing–thawing; when the dry unit weight is greater than the critical dry unit weight, the opposite phenomenon occurs. Cui et al. (2014) showed that soil becomes looser and pore orientation changes after freezing–thawing. The first of the repeated freezing–thawing cycles has the strongest influence on the hydraulic permeability, and on the changes in soil volume and strength (Boynton and Daniel, 1985; Othman and Benson, 1993; Viklander, 1998; Wang et al., 2007; Yong et al., 1985).

Elastic waves and electrical resistivity have been commonly used in soil science, geotechnical engineering, and geology to investigate the ground. The propagation of small-strain elastic waves provides information about the state of the particulate medium without altering the structure of the medium. Thus, elastic waves have been used to characterize the constituents and structure of soils, including frozen soil (Nakano et al., 1972; Rose, 1999; Santamarina et al., 2001). Note that most of the studies on frozen soil that employ elastic wave velocities were conducted using the immersion ultrasonic sing-around method (Christ and Park, 2009; Fukuda et al., 1998; Wang et al., 2006). However, the elastic waves can only indicate the properties of the post-frozen state when using the immersion method. In addition, the immersion method cannot simulate the natural ground freezing process, in which the ground freezes from the surface to the underground. Thus, the bender elements and piezo disk elements were used to measure the shear and compressional waves, respectively, during freezing (Kang et al., 2013; Park and Lee, 2014; Park et al., 2013).

Electrical resistivity also provides information about soil properties without disturbing the soil fabric. Electrical resistivity depends on

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various soil properties, such as the void ratio, properties of pore water, volumetric water contents, structure of the particles, and pore structure (Santamarina et al., 2001). Many studies have been carried out to investigate the effect of the temperature change on soil (Archie, 1942; Hayley et al., 2007; Seo et al., 2013). Keller and Frischknecht (1966) proposed the relationship between electrical resistivity and temperatures above zero. McGinnis et al. (1973) reported the exponential relationship between resistivity and temperature at freezing temperatures. Park et al. (2014) examined electrical resistivity at various degrees of saturation during soil freezing. However, the effect of the freezing–thawing process on sand–silt mixtures as a function of the silt fraction has not yet been investigated.

This study was performed to investigate the influence of the freezing–thawing process on sand–silt mixtures by examining elastic waves and electrical resistivity. The shear and compressional waves as well as the electrical resistivity were measured during the freezing–thawing of the sand–silt mixtures. Specimens of various silt fractions were placed in a freezing cell. The specimens were frozen at temperatures ranging from 20 °C to −13.5 °C, and the frozen specimens were slowly thawed at 20 °C. This paper first describes the properties of the specimens and the configuration of the apparatus used to measure the shear and compressional waves as well as the electrical resistivity. The results of the experiments are then discussed, followed by the experimental results, and the summary and conclusions.

2. Sand–silt mixtures

2.1. Specimens

Sand–silt mixtures were used as the experimental specimens. The specimens consisted of a mixture of Jumunjin sand and crushed limestone. To minimize the particle size effect, sand that could pass through a no. 30 sieve and be retained in a no. 50 sieve was used. The median particle diameter, D_{50}, of the Jumunjin sand was 0.45 mm. The minimum and maximum void ratios of the sand were 0.57 and 1.02, respectively (ASTM D4253, 2006; ASTM D4254, 2006). The roundness of the sand was angular (Lee et al., 2010a) and the predominant component of the sand was quartz. The specific gravity of the sand (ASTM D854, 2006) was 2.62. The silt was crushed limestone, of which the particle size was less than 75 μm. The D_{50} of the used silt was 19 μm. The minimum and maximum void ratios of the silt were 0.50 and 1.21, respectively. The specific gravity of the silt was 2.68. The size ratio of the sand to silt was $D_{sand}/D_{silt} \approx 24$. The sand and silt properties are summarized in detail in Table 1.

Table 1
Basic properties of specimens.

Silt fraction SF (%)	Specific gravity G_S	Maximum void ratio[a] e_{max}	Minimum void ratio[a] e_{min}	Dry unit weight [kN/m^3]	Total unit weight [kN/m^3]
0	2.62	1.02	0.57	15.40	16.62
10	2.64	0.84	0.52	16.40	17.58
20	2.65	0.81	0.42	17.20	18.22
30	2.65	0.81	0.42	17.30	18.47
40	2.66	0.83	0.43	17.20	18.35
60	2.66	0.99	0.44	16.60	17.82
80	2.67	1.03	0.46	16.40	17.61
100	2.68	1.21	0.50	15.70	16.95

[a] The equation used for the void ratio is as follows.

$$\text{Minimum void ratio}: e_{max} = \frac{G_S\rho_w}{\rho_{d,\,min}} - 1 \qquad (T-1)$$

$$\text{Maximum void ratio}: e_{min} = \frac{G_S\rho_w}{\rho_{d,\,max}} - 1 \qquad (T-2)$$

where G_s indicates the specific gravity of the soil, ρ_w, $\rho_{d,max}$, and $\rho_{d,min}$ are the density of water, the maximum-index density of the specimen, and minimum-index density of the specimen, respectively.

2.2. Specimen preparation

The sands and silts were mixed at different silt fractions. A silt fraction is the ratio of the silt weight to the sand weight ($SF = W_{silt} / W_{sand} \times 100$). The silt fractions were 0%, 10%, 20%, 30%, 40%, 60%, 80%, and 100%. Microscopic images of the mixed specimens are depicted in Fig. 1. The larger, darker particles are sand, and the smaller, white particles are silt. As the silt fraction increased from 0% to 100%, the white silt particles filled the voids between the sand particles and covered the sand particles. The sand–silt specimens were then mixed with water. The degree of saturation of all specimens was fixed at 40%. The specific gravities of the mixtures, which were determined by ASTM D854, 2006, are summarized in Table 1. The maximum and minimum void ratios, which were determined by ASTM D4254, 2006 and ASTM D4253, 2006, respectively, are also summarized in Table 1 and plotted in Fig. 2. As shown in Fig. 2, the maximum and the minimum void ratios of the mixtures are smallest at a silt fraction near 30%. Silt particles filled the void between sand particles, and the void ratios of the mixtures decreased as shown in Fig. 1. However, after all voids between the sand particles were filled with silt particles, the void ratio increased due to the increasing number of silt particles (see details of the binary mixtures in Guyon et al. (1987), Lee et al. (2007), and Lee et al. (2010b)). The mixtures were placed into the freezing cell in three layers as shown in Fig. 3. The mixtures were then compacted using the temping method at a fixed relative density of 70%. The void ratio of the mixtures was also minimized at a silt fraction near 30%.

3. Experimental setup

3.1. Freezing cell

The freezing cell was prepared to measure the elastic waves and electric resistivity during freezing and thawing, as shown in Fig. 3. The freezing cell is made of nylon, which has a low thermal conductivity (0.25 W/m K), excellent insulating properties (breakdown voltage = 24 kV/mm), and high elastic modulus (25 GPa). The inner dimensions of the cell are 100 mm in both length and width and 70 mm in height. The nylon plates of the cell are 25 mm thick. The four walls of the freezing cell are separated to prevent the waves from propagating through the nylon plates.

A pair of bender elements for generating and detecting the shear waves was attached to the side walls, and a pair of piezo disk elements for generating and detecting the compressional waves was attached to the other side walls, as shown in Fig. 3. Both pairs of transducers were installed at a depth of 50 mm from the top of the cell. To measure the temperature in the specimens, a thermocouple was installed at the center of the bender and piezo disk element positions, as shown in Fig. 3.

3.2. Measurement system

The changes in temperature in the sand–silt mixtures were continuously monitored using a k-type thermocouple, which consists of chromel and alumel. These alloys measure the voltage generated due to the temperature change at the point where the two dissimilar conductors contact. The temperature was continuously changed using a data logger (Agilent 34970A) with a precision of 0.001 °C and recorded using a computer, as shown in Fig. 4.

The bender and piezo disk elements generated and detected the shear and compressional waves, respectively. Bender elements have been widely used for laboratory studies due to their superior coupling between the transducer and the soil (Lee and Santamarina, 2005; Yoon et al., 2011). Note that the bender elements have also been applied in the field (Lee et al., 2010c; Yoon and Lee, 2012; Yoon et al., 2008). The dimensions of the bender elements are 10 mm × 5 mm × 0.6 mm (length × width × thickness). The piezo disk elements are also