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Characteristics of elastic waves in sand–silt mixtures due to freezing

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ABSTRACT

The objective of this paper is to characterize the properties of the compressional and shear waves resulting from the freezing of soil. After the sand–silt mixtures with different degrees of saturation (5%, 10%, 20%, 40% and 100%) are prepared in nylon freezing cells, the temperature of the specimens decreased from 20 °C to −10 °C. During the freezing of the soil, three pairs of piezo disk elements and bender elements, installed at three different locations along the depth, are used for the continuous measurement of the compressional and shear waves. The three properties of elastic waves, represented by velocities, resonant frequencies and amplitudes, are monitored continuously. Significant increases are observed in both of the elastic waves near the temperature of 0 °C. As the specimens freeze, the influent factor of the compressional wave velocity changes from the degree of saturation to the ice bonding. After soil freezing, the critical factor that affects the shear wave velocity turns from the confining stress into ice bonding and contact size. The variation of the resonant frequency of the elastic waves according to the temperature and degree of saturation is similar to the variation of the velocity of elastic waves. After soils are frozen, the Poisson's ratio decreases with an increase in the degree of saturation with ice. This study provides fundamental information about the change of properties of elastic waves in soils due to freezing.

1. Introduction

Water in soils is frozen below the freezing point, and ground freezing produces an increase in the soil volume. The volume change of the soils yields significant damage to geotechnical structures including railroads, pavement, and foundations (Andersland and Ladanyi, 2004; Guy et al., 1999; Hartmark, 1978). The change of temperature according to seasonal variation should therefore be taken into account in geotechnical engineering (Campanella and Mitchell, 1968). Ice-lenses formed in the frozen ground melt when the temperature is higher than the freezing point. Thawing of the frozen ground may weaken the ground strength due to the increased water content and the decreased density (Andersland and Ladanyi, 2004).

Various experimental studies have been performed to characterize frozen soils including frost heave, the shear behavior of frozen soils, dynamic soil behaviors, and permeability. Tester and Gaskin (1996) estimated the frost heave rate according to the fine content and Konrad (1999) suggested a prediction method for the amount of the frost heave based on a geotechnical soil index. The shear behavior of frozen sandy soils was dependent mainly on the ice strength in pore, the soil strength before freezing, the effective stress, and the bonding strength between the soil and the ice matrix (Alkire and Andersland, 1973; Andersland and Ladanyi, 2004; Chamberlain et al., 1972; Czurda and Hohmann, 1997; Goughnour and Andersland, 1968). The volume change in fine-grained soil was measured to determine the change of permeability due to the freezing-thawing cycle (Chamberlain and Gow, 1979; Eigenbrod, 1996).

The measurement of elastic waves also helps with the understanding of the constituents and the physical structure of frozen soils (Nakano et al., 1972). Deschartres et al. (1988) evaluated the unfrozen water and the ice content of frozen soils using an analytical solution based on the elastic wave velocities suggested by Wood (1941) and Wyllie and Gregory (1956). The mechanical properties and the dynamic moduli of frozen soils were estimated using elastic wave velocities (Baker and Kurfurst, 1985; Stephenson, 1978). The elastic wave velocities of various frozen soils including sand, silt, clay and loess were measured in cold liquid (kerosene) using piezo ceramic transducers (Christ and Park, 2009; Wang et al., 2006). Frozen soils should be submerged in kerosene. The shear waves in liquid were indirectly obtained through mode conversion. The traditional elastic wave measurement method may characterize only the properties of the completely frozen state. The submerged method may not simulate natural heat transfer, which occurs from the surface to the underground. A new elastic wave measurement method is required for the more accurate characterization of the soil properties during soil freezing.

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The objective of this study is to investigate the characteristics of sand–silt mixtures under freezing conditions using elastic waves in freezing cells, which reflect the condition of the frozen ground due to the temperature change. In this study, three properties of the compressional and shear waves including velocities, amplitudes, and frequencies continuously measured during temperature change from 20 °C to −10 °C are discussed. Five sand–silt mixtures at different degrees of saturation (5%, 10%, 20%, 40%, and 100%) were prepared. A freezing cell was manufactured to decrease the temperature of the specimens from the top to the bottom. This paper consists of specimens, the experimental setup, experimental results, discussion and analysis, and summary and conclusions.

2. Specimens

2.1. Specimen properties

Sands and silts were used in this study. First, sieved Jumunjin sand, which passed sieve no. 30 and remained in sieve no. 50, was used. The median size of the sand particles was 0.45 mm. The maximum void ratio (ASTM D4253, 2006) and minimum void ratio (ASTM D4254, 2006) of the sand were 0.82 and 0.56, respectively. The specific gravity (ASTM D854, 2006) of the sand particles was 2.62. Second, the silt was a crushed limestone with a particle size of less than 75 μm. The maximum void ratio and minimum void ratio of the sand–silt mixtures were 0.74 and 0.47, respectively. The specific gravity of the sand–silt mixtures was 2.57. The specific gravity and the maximum and minimum void ratios of sand–silt mixtures were smaller than the comparable value of the sand.

2.2. Specimen preparation

Five specimens, with different degrees of saturation, were prepared by mixing the sand, the silt and the water. The weight fraction of the silt (% of silt $= W_{silt}/W_{sand} \times 100\%$) was 10%. The relative density of the sand–silt mixtures was 70% ($\gamma_d = 16.3$ kN/m^3). The degree of saturation for each specimen was 5%, 10%, 20%, 40% and 100%. For unsaturated specimens (degree of saturation S = 5%, 10%, 20%, and 40%), the sand-silt-water mixture was placed into the freezing cell in four layers, and was compacted by applying the modified tamping energy. The number of compactions for each layer was adjusted according to the degree of saturation. The accumulated compaction energy was therefore greater at the bottom of the freezing cell than at the top. For the preparation of the fully saturated specimen, the sand-silt-water mixture was boiled to remove the air bubbles from the specimen. The sand-silt-water mixture was then water-pluviated into the freezing cell, which was filled with de-aerated water, and the freezing cell was lightly tapped to control the relative density.

3. Experimental setup

3.1. Freezing cell

A high-strength nylon cell ($E = 25 \times 10^9$ N/m^2) for freezing the specimens of the sand–silt mixtures is represented in Fig. 1. The cell consists of five nylon plates to minimize the vibration propagating through the nylon plates, as shown in Fig. 1 (a). The inner dimensions of the cell are 100 mm in width, 100 mm in length and 200 mm in height. The thickness of each plate is 25 mm, to minimize lateral deformation due to the volume change of the freezing soils. Piezo disk elements were used as the compressional wave transducers, and bender elements were used as the shear wave transducers. Three pairs of piezo disk elements and three pairs of bender elements for the measurement of the compressional and the shear waves were attached on the side walls along the depth: top (T), middle (M) and bottom (B), as shown in Figs. 1 (b) and (c).

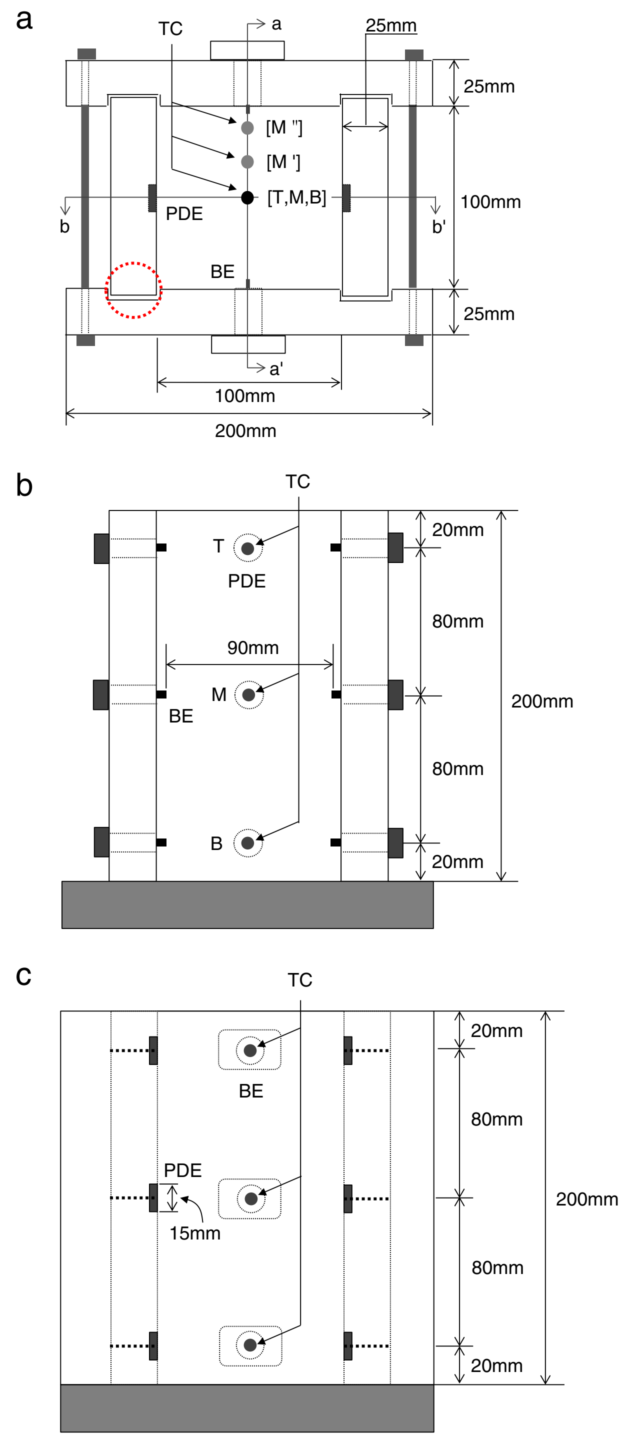

Fig. 1. Freezing cell with bender elements and piezo disk elements: (a) top view; (b) side view along a–a′, section; and (c) side view along b–b′, section. BE, PDE and TC denote the bender elements, the piezo disk elements, and the thermocouples. T, M, and B denote the location of the sensors at top, middle, and bottom.

3.2. Test procedure

The compressional and the shear waves were measured continuously at the top, middle, and bottom of the specimen to investigate the characteristics of elastic waves as the temperatures of the specimen decreased from 20 °C to −10 °C. The temperature of the specimen was measured continuously by thermocouples. Thermocouples were