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Silt fraction effects of frozen soils on frozen water content, strength, and stiffness

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HIGHLIGHTS

- Strength and stiffness of frozen soils with different silt fractions are evaluated.
- Freezing temperature and frozen water content vary according to silt fraction.
- Strength and stiffness are minimum at the silt fraction of ~30%.
- Peak shear strength is linearly proportional to Vs owing to ice-bonding.
- Residual shear strength is bi-linearly proportional to Vs owing to the silt effect.

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ABSTRACT

The strength and stiffness of soil mixtures vary with regard to the particle composition and the properties of soil mixtures that critically change when water, which is a component in soils, is frozen. The objective of this study is to evaluate silt fraction effects of frozen sand-silt mixtures on the frozen water content, shear strength, and stiffness. The sand-silt mixtures are prepared in a shear box at a fixed relative density of 60% and a fixed degree of saturation of 15% with various silt fractions ranging from 0 to 100% in weight ($W_{silt}/W_{sand} \times 100\%$). A time domain reflectometry (TDR) probe, bender elements, and thermocouple are installed in the shear box, and the direct shear apparatus is placed in the freezing chamber. After the sand-silt mixtures are frozen at −5 °C, the direct shear tests are conducted. The TDR signals and shear waves are monitored before and after the freezing phases for the estimation of the volumetric water content and stiffness, respectively. Test results show that the void ratio, volumetric frozen water content, shear strength, and shear wave velocity are at a minimum near a silt fraction of 30%. As the relationships between the volumetric frozen water content and peak shear strength, as well as between the volumetric frozen water content and shear wave velocity after freezing, are linear, the peak shear strength correlates well with the shear wave velocity after freezing. Furthermore, as the residual shear strength and shear wave velocity before freezing are related to the silt fraction, the residual shear strength is bi-linearly proportional to the shear wave velocity before freezing. This study suggests that the void ratio and frozen water content of sand-silt mixtures are affected by the silt fraction. Thus, the silt fraction effects should be considered for the characterization of the strength and stiffness of frozen soils.

1. Introduction

In natural ground, soil deposits are composed of particles with various sizes, rather than particles of a uniform size, such as clean sands. For the estimation of the particle size effect, numerous laboratory tests were conducted using mixtures with different fine contents, and the porosity of the mixtures depends on the fractional concentration of the sand and fine particles [33,47]. A mixture with a low silt fraction might behave similar to sand, and a mixture with a high silt fraction might behave similar to fines [39]. Thevanayagam and Mohan [41] described that in soils with a low silt fraction, the silt only fills the voids between sand particles, and thus silt has little influence on the major skeleton of sand particles.

The silt effect on the mixture with respect to the strength characterization has been estimated, and the peak shear strength changes with regard to the silt fraction due to different particle arrangements [1,27]. The residual shear strength measured using

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the direct shear test considerably decreased after reaching the peak shear strength for mixtures with low contents of fines [19]. For the uniaxial compression test, the unconfined compressive strength of the mixtures increases, and decreases up to and beyond the specific coarse and fine particle content [29]. Thian and Lee [42] performed a triaxial test, and revealed that the shear strength and elastic modulus of the mixture decreased with an increase in the small particle fraction. Belkhatir et al. [3] conducted an undrained triaxial compression test using mixtures with different silt fractions and relative densities, and demonstrated that the initial relative density significantly affects the peak shear strength, as does the difference in silt fraction. Hsiao and Phan [13] demonstrated that the shear modulus and maximum shear modulus decreased as the silt fraction increased.

The characteristics of mixtures with various particle sizes may change due to temperature variation. The stiffness of a soil mixture specimen rapidly increases when the specimen experiences sub-zero temperatures, and the strength of the frozen mixture gradually increases as the temperature decreases in sub-zero temperatures [31,34]. Zhang et al. [53] demonstrated that the mechanical properties of frozen soils may change with regard to the freezing temperature, and coarse-grained contents may have an influence on the strength due to the different particle size. Kang and Lee [17] investigated the effect of the silt fraction during freezing-thawing using bender elements, and showed that the elastic wave velocity decreased or increased with an increase in silt fraction when the silt fraction is lower or higher than 30%, respectively. However, the variation of the frozen water content, strength, and stiffness of frozen sand-silt mixtures that is related to variable silt fractions have not yet been investigated. Thus, in this study, a direct shear apparatus that was instrumented with time domain reflectometry (TDR) and bender elements is used. Unfrozen water may exist due to the physicochemical characteristics of soil particles [11,14]. In addition, the amount of unfrozen water is dependent on the silt fraction. In this study, the effects of the frozen water content on the shear strength and shear wave velocity are explored.

The objectives of the study are to characterize the effects of the silt fraction in frozen sand-silt mixtures on frozen water content, strength, and stiffness. First, this paper introduces a direct shear box instrumented with TDR probe and bender elements, and the specimen preparation with different silt fractions of 0–100%. The volumetric frozen water content, shear strength, and shear wave velocity, which are measured in the direct shear box, are demonstrated for the characterization of the silt fraction effect. Then, the effects of the silt fraction on the void ratio, volumetric frozen water content, shear strength, and shear wave velocity are discussed. Finally, the shear strengths are compared to shear wave velocity with consideration for the volumetric frozen water content.

2. Experimental setup

2.1. Direct shear apparatus

A new direct shear apparatus is prepared for more accurate measurements of the shear strength. In the new direct shear apparatus, the upper shear box is fixed by four columns to separate the upper shear box from the lower shear box as shown in Fig. 1; as such, ball bearings between upper and lower shear boxes are not required. In addition, the frictional force caused by the ball bearings or shear boxes is effectively removed. The load cell, which is connected to the lower shear box, measures the shear stress generated by horizontal movement of the lower shear box. The inner dimensions of shear box are 70 mm in length and width, and 30 mm in height as shown in Fig. 1. A sensing plate with a thickness of 10 mm is placed on the lower shear box, and the height of the soil specimen is 20 mm. The gap between the upper and lower shear boxes is fixed at 0.5 mm to minimize the loss of the prepared specimen particles and to remove the frictional forces between upper and lower shear boxes. The shear box is made of brass in order to prevent deformation of the shear box during shearing. Furthermore, brass was used to effectively transmit a peripheral temperature into the specimen. Grease is coated on the wall between the specimen and shear box to minimize the adfreeze bond strength. The shear box is located in a freezing chamber to freeze the prepared specimen by controlling the air temperature inside the chamber. For the temperature estimation of the specimens, a thermocouple is installed on top of the sensing plate to measure the temperature during the freezing and shearing phases. Furthermore, a time domain reflectometry (TDR) probe is installed on the sensing plate to measure the reflected electromagnetic signals. The measured electromagnetic signals are used to determine the volumetric water content of the specimen before and after freezing. Thus, the frozen and unfrozen water contents are estimated. The bender elements are installed at the lower part of the upper shear box, which is near the shear plane, to measure the shear wave signals. The shear wave velocities are calculated from the shear wave signals to estimate the stiffness of the specimens during the freezing and shearing phases. Thus, the stiffness variations due to freezing and shearing are evaluated.

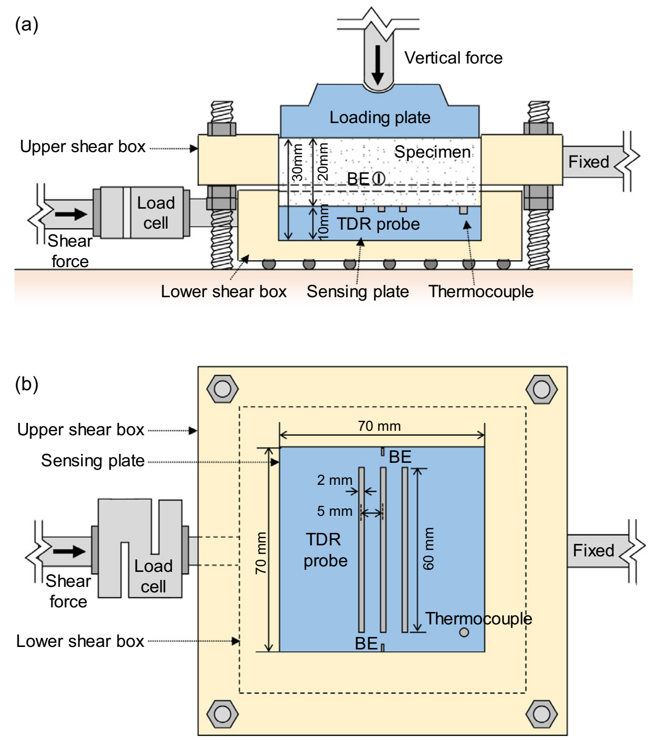

Fig. 1. Direct shear box system: (a) side view; (b) top view. BE and TDR denote the bender element and time domain reflectometry, respectively.

2.2. Time domain reflectometry (TDR) probe

TDR systems have been used as cable testers for the evaluation of wire integrity through the interpretation of reflected electromagnetic signals [9]. An electromagnetic signal is propagated along the cable and reflected at a discontinuous or damaged point. Using the propagation and reflection properties of the electromagnetic signals, TDR systems are used for the estimation of soil properties