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Mechanical properties of seasonally frozen and permafrost soils at high strain rate

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ABSTRACT

Frozen soils, especially seasonally frozen soils, have a great impact on the seismic performance of bridge pile foundations. To account for this impact on pile foundations during seismic events, it is necessary to evaluate the mechanical properties of naturally frozen soil samples. This paper focuses on the mechanical properties of naturally frozen silty soils at a relatively high strain rate. High quality specimens of both permafrost and seasonally frozen soils were prepared by block sampling and machining. Both horizontal and vertical specimens were prepared to investigate the effect of specimen orientation. Unconfined compression tests were performed at temperatures ranging from −0.7 °C to −11.6 °C, at a constant deformation rate corresponding to a strain rate of 0.001/s. Testing results including soil characteristics and mechanical properties such as stress–strain curves, compressive strength, yield strength, modulus of elasticity, strain values at unconfined compressive and yield strength, and strain value at which 50% of the compressive strength is achieved are presented. The impact of temperature, dry density, water content, and specimen orientation on the mechanical properties is discussed. For permafrost, the ultimate compressive strength of horizontal specimens is substantially higher than that of vertical specimens at the same testing temperature and this strength anisotropy is likely due to ice wedge formation, commonly observed in lowland permafrost. In general, the ultimate compressive strength of naturally frozen specimens is lower than that found in previous studies for remolded frozen silty soils.

1. Introduction

It is well known that the ice matrix formed during freezing greatly influences the stress–strain behavior of soils (Andersland and Ladanyi, 2004). It is also well known that frozen soil properties largely depend on temperature, ice/water content, strain rate, dry density, and soil type. Early studies (Sayles, 1968; Sayles and Haines, 1974) mainly focused on the creep behavior of frozen soils (sands, silts, and clays). Akili (1971) studied the stress–strain behavior and strength of frozen fine soils (clay and clayey silt) at varying strain rates. Sayles (1973) and Jones and Parameswaran (1983) studied the stress–strain behavior of frozen Ottawa sand. Watson et al. (1973) conducted a comprehensive study on the thaw settlement and strength of permafrost by using large permafrost core samples taken from the field. Baker et al. (1982) found that a low confining pressure (0 to 0.35 MPa) has little effect on the compressive strength or axial strain at failure. Vinson et al. (1983) conducted a comprehensive study on the dynamic elastic properties of naturally frozen silts from the CRREL Permafrost Tunnel, including both horizontally and vertically oriented specimens by using cored specimens. They found little difference in the dynamic properties between horizontally and vertically oriented specimens, and the confining pressure up to 500 MPa had little impact on the dynamic Young's modulus. Zhu and Carbee (1984) carried out a uniaxial compression test program on remolded frozen Fairbanks silts under various deformation rates and studied the mechanical properties, including uniaxial compressive strength. Andersen et al. (1995) discussed small-strain behavior of frozen sand in triaxial compression tests. More recently, Shelman et al. (2014) conducted an experimental investigation to characterize the effects of freezing temperatures on mechanical properties for seismic design of foundations by using remolded soil specimens of five soil types.

Most existing studies, except Watson et al. (1973) and Vinson et al. (1983), were based on remolded, artificially frozen soil samples, which do not necessarily represent field conditions. Knutsson (1981) showed that frozen soil shear strength properties are sensitive to the sample preparation method. Radd and Wolfe (1979) compared the shear strength of field-frozen samples and laboratory-frozen samples, and found that the field-frozen samples are weaker than the laboratory-frozen samples at all tested temperatures. They identified the major variables that could affect the strength of frozen soils, including freezing conditions, strain rate, and sample orientation and size. There is little study on soil stress–strain behavior at large strain rate

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using naturally frozen samples; nor is there any information on the dependency of frozen soil strength properties on specimen orientation.

Many of the broad cold regions covered by thick seasonally frozen and permafrost soils are located in seismic active zones. Some structural damage during earthquakes has appeared to be directly attributed to the occurrence of frozen ground and ice formation. For example, recent research in Alaska and Iowa has clearly established the significance of frozen ground effects on the seismic response of bridge foundations (Sritharan et al., 2007; Suleiman et al., 2006; Wotherspoon et al., 2010; Xiong and Yang, 2008; Xu et al., 2011; Yang et al., 2007; Yang et al., 2008). It is very important to assess the effects of frozen soil on the seismic performance of superstructures. For this purpose, reliable assessment of the mechanical properties of frozen soils is necessary.

In order to quantitatively evaluate the mechanical properties of undisturbed, naturally frozen silts for seismic design of pile foundations embedded in frozen soils, specimens – including seasonally frozen and permafrost soils of different orientation – were tested at temperatures varying from −0.7° to −11.6 °C at a constant deformation rate corresponding to a strain rate of about 0.001/s. Test results including the ultimate strength or unconfined compressive strength, yield strength, Young's modulus, strain values at unconfined compressive and yield strengths, and strain value at 50% of ultimate strength, or ε_{50}, are presented, and important variables effecting these properties are discussed.

2. Experiment

2.1. Test specimens

The frozen soil specimens tested in this investigation are naturally frozen silts sampled from the Campbell Creek Bridge site in Anchorage, AK (seasonally frozen soil) and the CRREL Permafrost Tunnel in Fox, AK (permafrost). During seismic loading, a pile with its supported superstructure swings back and forth, hence the main loading direction is horizontal. Both vertical and horizontal specimens were prepared and tested to investigate soil orientation impact. Effort was devoted to minimizing the thermal and mechanical disturbances on frozen soil specimens by following procedures described in Baker (1976) and Still et al. (2013). As illustrated in Fig. 1, a vertical specimen (identified by V) indicates that its axis is perpendicular to the ground surface, and a horizontal specimen (identified by H) indicates that its axis is parallel to the ground surface. Assuming uniform soil properties in the same block, at least one vertical and one horizontal specimen were machined from the center portion of the same block for comparison. All specimens were labeled by their sampling site and orientation. For example, C2H1 indicates #1 horizontal specimen, machined from block #2, taken from Campbell Creek Bridge site (seasonally frozen soil). Similarly, P2V1 indicates #1 vertical specimen, machined from block #2, taken from the Permafrost Tunnel (permafrost soil).

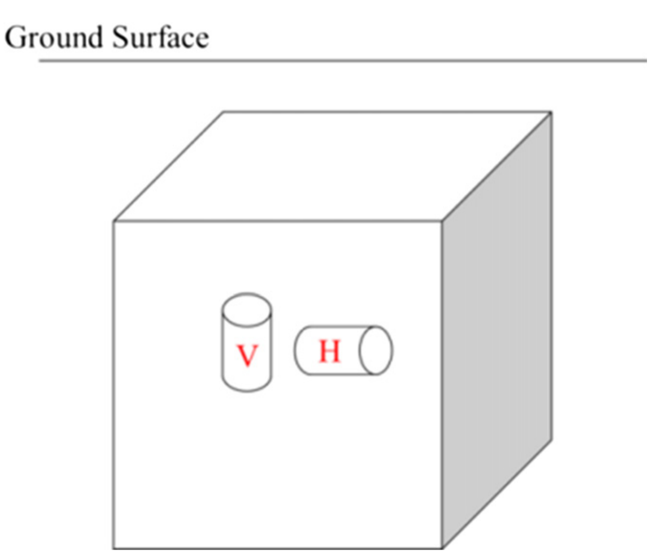

Fig. 1. Illustration of specimen orientation.

Table 1
Representative properties of tested soils.

	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Specific gravity
Seasonally frozen soil (C)	47	44	3	2.44
Permafrost (P)	39	37	2	2.55

A total of 45 seasonally frozen soil specimens (22 horizontal and 23 vertical) and 23 ice-rich permafrost specimens (9 horizontal and 14 vertical) were prepared. Representative properties of tested soils are shown in Table 1. Fig. 2a and b presents the respective grain-size distribution of the permafrost and seasonally frozen soils. Both soils contained large amounts of fines. The permafrost is classified as silt, while the seasonally frozen soil is classified as sandy organic silt, with several specimens being classified as peat because of their highly organic nature. Dry density of specimen ranges from 320 to 780 kg/m^3 for seasonally frozen soil and from 534 to 941 kg/m^3 for permafrost. Water content varies from 86 to 225% for seasonally frozen soil and from 62 to 134% for permafrost soil. With very few exceptions, all samples contained visible ice lenses and were classified as V, according to ASTM standard D4083-89. All specimens, when thawed, can be classified as organic silty soil, with a few specimens classified as peat.

2.2. Testing apparatus and instrumentation

The unconfined compression test was completed using the Universal Testing Machine (UTM-100, following ASTM D7300-06 (2006). The UTM-100 has a temperature chamber that can maintain the temperature as cold as −17 °C. It is recommended that lubricated platens be used whenever possible in the uniaxial compression and creep testing of frozen soils (Ebel, 1985). The lubricated platen consists of a circular sheet of 0.8 mm thick latex membrane attached to the loading face of a steel platen with a 0.5 mm thick layer of high-vacuum silicon grease.

Displacement control was used during the compression test at a strain rate of 0.001/s. As the latex sheets and grease layers compress under load, the axial strain of the specimen should be measured using an extensometer installed near the center of the specimen. A load cell was used to measure axial load and, hence, stress on the specimen. The extensometer and load cell were calibrated before use in these experiments.

3. Observations and specimen modes of failure

Fig. 3a, b, c and d shows examples of test specimens before and after testing. Small ice lenses were found throughout the specimens in both the permafrost and seasonally frozen soils and were distributed non-uniformly. Three failure modes, including bending, bulging and shearing, were observed. Bulging occurred at the top, at the bottom or uniformly. There was no collapsing observed for all specimens. In most cases, small cracks were observed around pieces of rock or ice lenses on the surface of specimens. A majority of the specimens were loaded to an axial strain of at least 15%. However, for safety concerns, some tests were terminated due to excessive bending of specimens. The specimens' failure modes were probably caused by non-uniform density and the asymmetrical mechanical property of the specimen. Water contents of the seasonally frozen soil were mostly above 100%,