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Elastic properties of saline permafrost during thawing by bender elements and bending disks

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ABSTRACT

The elastic properties such as small-strain Young's, shear moduli and Poisson's ratio of permafrost are important parameters for analyzing the stress distribution and thaw-subsidence of permafrost and deformation of well casing embedded in permafrost. However, the deep natural permafrost warms up and even thaws due to energy extraction and its elastic properties change significantly with temperature. This paper presents elastic properties obtained by conducting laboratory testing of permafrost samples from the North Slope of Alaska. The testing specimens were conditioned from −10 °C to −2 °C at an interval of 2 °C, and to 20 °C for examining the temperature effects. The bending disks and bender elements were used to measure the compressional wave (P-wave) and shear wave (S-wave) velocities, respectively, for evaluating the small-strain elastic properties during thawing. Measurements were done in both horizontal and vertical directions for assessing anisotropy. The results show that the P- and S-wave velocities from this study partially overlap with in situ measurement data reported in the literature, and tend to be lower due to high salinity and lack of overburden effects, which is stronger on sandy permafrost. Results reveal anisotropy in the wave velocities in all types of permafrost tested, and the small-strain elastic properties of clay and silt permafrost exhibit no sharp change when the temperature crosses 0 °C, likely due to non-uniform freezing point depression caused by the varying and high salinity among specimens. Finally, parameters were provided for predicting the confining pressure dependent small-strain Young's modulus, and regression equations were proposed for predicting the modulus number and exponent in Janbu's model based on permafrost dry density and moisture content.

1. Introduction

Permafrost typically exists to about 600 m deep on the North Slope close to the arctic coast of Alaska (Brown, 1970; DeGeer and Cathro, 1992). The soil strata below 600 m are warmed to above the freezing point by upward terrestrial heat flow. A potential problem exists when warm oil is extracted via a production well from deep reservoirs, or warm fluid is injected via injection wells into deep reservoirs, losing heat as it passes through the permafrost zone, thawing the permafrost and inducing settlement of the soils (Smith and Clegg, 1971; Goodman, 1978; Smith, 1983; Abou-Sayed et al., 1989). Theoretical and analytical studies and laboratory investigations have shown that various thaw-subsidence mechanisms can occur in different types of soils. Goodman (1977) classified these mechanisms into four major categories including stiffness reduction associated with temperature change. Therefore it is essential to evaluate the elastic properties of permafrost during thawing for assessment of thaw subsidence and how it affects the internal stress and strain and the integrity of wells constructed through a thick permafrost zone.

The elastic moduli of permafrost are effected by temperature, water or ice content, dry density, loading ratio and confining pressure (Goodman, 1975; Tsytovich, 1975; Vinson, 1978; Akagawa et al., 1982; Zhu and Zhang, 1982; Al-hunaidi et al., 1996; Andersland and Ladanyi, 2004). Recently there is a renewed interest on the mechanical properties including elastic properties of permafrost as tunnels were excavated through thick frozen soil, road and railway were constructed on, and pipelines were laid in permafrost. Yu et al. (2002) investigated the pressuremeter modulus and shear modulus of frozen soils by conducting in-situ pressuremeter testing, and proposed an equation for mechanical properties prediction considering the effects of temperature

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Fig. 1. Frozen cores (a) and specimens (b). V-shaped ice lens is clearly visible from one specimen.

and water content. Lin et al. (2003) performed a series of uniaxial compression tests of saturated frozen sand at various temperatures and strain rates, and found that the elastic modulus increases with increasing strain ratio and decreasing temperature. Li et al. (2007) analyzed a large set of elastic modulus data obtained by conducting unconfined compression tests of warm frozen clay, and concluded that the normal and logarithmic-normal distributions could well describe its probability distribution. Yang et al. (2008) conducted triaxial compressive tests on frozen saturated saline silty clay, and found that the initial elastic modulus increases with decreasing salinity and temperature. Zhao et al. (2013) found that the elastic modulus for frozen clay increases with increasing thermal gradient in both K_o- and isotropically-consolidated triaxial tests, but the elastic modulus in K_o-consolidated triaxial test is usually greater than that in isotropically-consolidated triaxial test. Zhao et al. (2013) carried out uniaxial compression tests on frozen saturated clay at various temperatures and thermal gradients ranges from 0.125 to 0.75 °C/cm, and concluded that the hardening modulus and uniaxial compression strength increase with decreasing thermal gradient and average temperature, and the thermal gradient has little impact on the elastic modulus. Yang et al. (2015) investigated the elastic modulus and other mechanical parameters of naturally frozen silty soils at a relatively high strain rate, and discussed the impact of temperature, dry density, water content and specimen orientation on mechanical properties. Xu et al. (2016) compared the mechanical behaviors of natural frozen saline silty sand before and after desalting, and found that the initial tangent modulus and the secant modulus of the desalted frozen soil increase with increasing confining pressure and decreasing temperature, and are higher than the ones of the natural saline soil.

The shear wave (S-wave) and compressional wave (P-wave) methods are among the most commonly used nondestructive techniques for evaluating the elastic properties. Both the ultrasonic technique and the bender element (BE) and bending disk (BD, also called piezo disk element, or PDE) technique have been used for shear wave and compressional wave measurement. The ultrasonic technique uses a transmitter to emit an ultrasonic wave to a liquid, which refracts at a certain incident angle on the liquid-soil interface and travel into the soil. By adjusting the incident angle the refracted wave can be controlled to be a compressional wave or shear wave, which can be detected by a receiver for determination of the travel time through a soil (Nakano and Arnold, 1973). The frequency of the wave used is typically in the order of megahertz. This method has been widely applied for elastic property characterization of frozen soils (Barnes, 1963; Nakano and Froula, 1973; Nakano and Arnold, 1973; Thimus et al., 1991; Ling et al., 2002; Sheng et al., 2003; Wang et al., 2006; Christ and Park, 2009; Huang et al., 2013).

The BE and BD method has attracted increasing interest for soil elastic property assessment for its simplicity. In this method, a piezoelectric transducer is in direct contact with the soil specimen and is configured in such a way that it generates either a shear or compressional stress wave, which travels through a specimen and is detected by another piezoelectric transducer for determination of travel time. The frequency of the stress wave is typically in the order of kilohertz and is lower than ultrasonic waves. The measurement method and signal processing technique have seen continuous improvements (Shirley and Hampton, 1978; Dyvik and Madshus, 1985; Brignoli et al., 1996; Nakagawa et al., 1996; Lee and Santamarina, 2005; Leong et al., 2005; Wang et al., 2007; Deniz, 2008; Leong et al., 2005; Yamashita et al., 2009). Recently, Aris et al. (2012) installed BEs in a triaxial cell, and investigated the shear wave velocity of a granular material at horizontal and vertical directions. Eseller-Bayat et al. (2013) provided a detailed BE and BD housing design for measuring the shear and compression wave velocities in fully and partially saturated large sand specimens. Park and Lee (2014) investigated the characteristics of elastic waves and Poisson's ratio in sand-silt mixtures due to freezing, and investigated the impact of saturation on the elastic wave velocity characteristics.

This paper presents elastic property results obtained from testing of permafrost during thawing. The BE and BD method was used to measure the shear and compression wave velocities, which were used to evaluate the small-strain elastic moduli including Young's and shear moduli, and Poisson's ratio. The effect of confining pressure on the P-wave velocity and small-strain Young's modulus were discussed. In addition, a model was provided for evaluating the Young's modulus for thawed permafrost with index properties.

2. Site description and specimen preparation

Frozen cores were obtained from a deep borehole identified as PERM 1 at the DS-2A site on the Greater Kuparuk area of the North Slope of Alaska, as shown in Fig. 1a. A total of about 180-m continuous core was obtained with the in situ lowest temperature of − 10 °C. Three groups with a total of 36 samples, including 11 for clay, 17 for silt, and 8 for sand, were selected from varying depths and prepared for testing. Following established procedures for preparing frozen samples (Baker, 1976; Still et al., 2013), the samples were cut and trimmed in a cold room and machined by using a lathe to right-cylindrical specimens of around 2.75″ diameter. Majority of the specimens have a height to diameter ratio of about 2, as shown in Fig. 1b, except that five of them, i.e. S04, S06, S09, S15 and S16, have a rato between 1.1 and 1.3 due to limited lengths of cores.

Table 1 summarizes the soil sample type, depth, and other properties such as moisture content ω, bulk density ρ, specific gravity G_S, salinity, and Atterberg limits (PL, LL). Most of the permafrost tested are