Elastic Properties of the Remolded Soil During Freezing and Thawing Cycle By Bender Elements

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Abstract. The elastic properties such as shear moduli and shear moduli of freezing and thawing soil are important parameters for analyzing the stress distribution and thaw-subsidence of freezing soil and deformation of well casing embedded in freezing soil. This paper presents elastic properties obtained by conducting laboratory testing of sand samples from the area of soil. The bending elements were used to measure the shear wave (S-wave) velocities for evaluating the shear moduli during freezing and thawing. Nine pairs of testing specimens were conditioned from 25°C to -25 °C at an interval of 5 °C for examining the temperature effects during freezing and thawing process, respectively. The test parameters included dry density (1.6, 1.8, 2.0 g/cm³) and moisture content (6%, 9%, the saturation). Test results showed that the wave velocities and the shear moduli in all types of specimens tested exhibit sharp change when the temperature adjacent to 0 °C, likely due to non-uniform freezing point depression caused by the varying structure among specimens. The increase of dry density has positive effect on shear modulus. However, the moisture content has a dual effect on the strength of the sand soil.

1. Introduction
Frozen soil contains mineral particles, ice, liquid water, and gaseous inclusions. Since about the early 1970s, the shear modulus of frozen soil has been studied by many scholars [1]. The elastic moduli of permafrost are effected by temperature, water or ice content, dry density, loading ratio and confining pressure [2, 3]. 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 it, and pipelines were laid in permafrost [4].

Extensive investigations into the anisotropy of elasticity in unfrozen soils, including clays and sands, have been conducted regarding shear moduli, through the measurement of shear wave (S-wave) velocity via laboratory testing and field experiments. However, literature reporting the remolded soil during freezing and thawing cycle is fairly limited. This paper presents results related to the shear modulus evaluated by using the S-wave velocity measured on the remolded soil by the BE method during freezing and thawing. The specimens having different dry densities, different moisture contents were conditioned from −25°C to 25 °C at an interval of 5 °C for examining the temperature effects. In the end, factors affecting the shear modulus are analyzed.

2. Experimental methods

2.1 Specimen preparation
The frozen sand soil tests were all carried out by the remolded soil samples, which obtained from a deep borehole on the Zhaogu mine, the soil sample type, depth, and other properties such as moisture content
\( \omega \), bulk density \( \rho \), specific gravity as shown in Table 1. Fig. 1 shows the grain size distributions of representative soil samples.

![Gradation curve of sand and soil particles](image)

**Fig. 1 Gradation curve of sand and soil particles**

| Number | Depth (m) | Moisture content (%) | Bulk density (g/cm³) | Void ratio | Saturability | Specific gravity |
|--------|-----------|----------------------|----------------------|------------|--------------|-----------------|
| L18    | 578       | 17.9                 | 1.79                 | 0.495      | 96           | 2.67            |

For laboratory testing, cylindrical specimens of 6.18 cm in diameter and height about 125 mm were machined, using a representative core of various soil sand types. The soil sand simples were subdivided into nine pairs, the test parameters included dry density (1.6, 1.8, 2.0 g/cm³) and moisture content (6%, 9%, the saturation).

| Soil sample number |
|--------------------|
| No | Dry density (g/cm³) | Moisture content (%) | No | Dry density (g/cm³) | Moisture content (%) |
|-----|--------------------|----------------------|-----|--------------------|----------------------|
| S-1 | 1.6                | 6%                   | S-6 | 1.8                | saturation           |
| S-2 | 1.6                | 9%                   | S-7 | 2.0                | 6%                   |
| S-3 | 1.6                | saturation           | S-8 | 2.0                | 9%                   |
| S-4 | 1.8                | 6%                   | S-9 | 2.0                | saturation           |
| S-5 | 1.8                | 9%                   |     |                     |                      |

2.2 Testing equipment and procedure

The S-wave velocity measurement equipment consists of a pair of BEs, a function generator, a power amplifier with bandpass filters, and a Mixed Signal Oscilloscope. The typical shear waveforms are shown in Fig. 2. Subsequently, the oscilloscope was used to digitize the received signal and compare it with the excitation signal to obtain the travel time.

![Typical signal diagram of bending element test](image)

**Fig. 2 Typical signal diagram of bending element test**

![Bes temperature measurement point](image)

**Fig. 3 Bes temperature measurement point**

The refrigerator and high and low temperature cold bath device constitute the temperature control system. The temperature was decreased in the following increments: The testing specimens were conditioned from −25°C to 25 °C at an interval of 5 °C for examining the temperature effects. The temperature of testing specimens was considered to be the average value of soil surface temperature and soil core temperature. Freezing process is similar to the freezing process operation. Fig 3 shows the temperature monitoring curve and shear wave velocity measurement points in the thawing process.
3. Experimental results and discussion

3.1. Elastic wave velocities

Wave velocity calculation need to determine the travel length and travel time. The travel length can be determined by the diameter of specimens. The determination of S-wave first arrival is difficult due to near-field effects and the interference from repaid P-waves in the system. Majorities of ways minimize the error involved in S-wave first arrival determination and the zero after first bump method was used [5], as illustrated in Fig. 2. The shear wave propagation time of the signal determined by oscilloscope includes two parts, which can be evaluated by the following equation:

\[ \Delta t = \Delta t_1 + \Delta t_2 \]  

Where \( \Delta t \) is the total travel time, \( \Delta t_1 \) is the propagation time of shear wave in soil sample; \( \Delta t_2 \) is the running time of signal in each instrument component, namely system delay.

The calculation formula of wave velocity is as follows:

\[ V_s = \frac{L}{\Delta t_1} \]

Where \( V_s \) is the wave velocity, \( L \) is the diameter of soil sample, \( \Delta t_1 \) is the travel time.

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 [6]. The frequency of the wave use distypically in the order of megahertz. This method has been widely applied for elastic property characterization of frozen soils [7,8,9].

Fig. 4 shows the S-wave velocity variation with temperature for the nine types of soils tested in the horizontal direction. In the freezing and thawing process, the shear wave velocity changing with temperature is mainly divided into three stages, S-wave velocity with basic tend to index the rise of temperature, the temperature in the process of \(-5 \degree C\) to \(5 \degree C\), as the ice crystals into liquid water in the soil, sandy soil specimen strength greatly abate, S-wave velocity of abrupt decrease, while in the process of \(5 \degree C\) to \(25 \degree C\) or \(-5 \degree C\) to \(-25 \degree C\), S-wave velocity reduction is small, basic remain unchanged.

Fig 4 the S-wave velocity variation with temperature for soil

At the same temperature measurement point, the shear wave propagation time in freezing process is obviously longer than that thawing. The shear wave velocity at freezing is obviously higher than that at thawing. The reason is that in the freeze-thaw process, the structure of soil body changes, leading to changes in permeability and porosity ratio of soil body, and changes in pore characteristics of soil body, thus leading to changes in shear wave velocity of soil body. Therefore, the process of freezing and thawing is completely irreversible, which changes the physical properties of soil.

3.2. Elastic properties

Based on the elastic wave propagation theory, shear moduli in horizontal directions were evaluated by using Eq. 3.

\[ G_0 = \rho (V_s)^2 \]  

Where: \( \rho \) is soil density; \( V_s \) is shear wave velocity.
Fig. 5 The relationship between shear wave speed and temperature

Fig. 5 shows the variation of the average S-wave velocities with temperature for the remoulded sand and the trends are similar to those in thawing and freezing process. Moreover, it reveals a similar variation trend with temperature in $G_0$ of all specimens as in $V_s$, as expected. When the temperature crosses 5 °C or belows -5 °C, the elastic properties of specimens including S-wave velocities, shear moduli show gradual variation: Whereas the temperature is between 5 °C and -5°C, those of sand specimens show an abrupt change.

For the sake of exploring investigate the effects of dry density and moisture content on shear modulus of frozen and thawed soil, this study selects - 20 ℃, -10 ℃ and 0 ℃, 10 ℃, 20 ℃ temperature point for data analysis, the five get figure 5-3 shear modulus relation with dry density and moisture content of the graphs.

Fig. 6 Relationship between dry density and shear modulus

Fig. 6 shows the variation of dry density with temperature in this study. Both moduli demonstrate trends similar to the elastic wave velocity of the same type of soil. The shear modulus of sand increases with the increase of dry density, but the amplitude of increase is obviously different. In the case of positive temperature, the difference of dynamic shear modulus of sandy soil with different dry densities is not very great, but the soil samples with high dry density are slightly larger than those with low dry density. When the temperature closes to 0 ℃, the shear modulus of soil samples with different dry densities changed obviously, and it rose in a straight line. When the temperature at minus temperature, the graph - 10 ℃, -20 ℃ shear modulus and the relationship between dry density curve, observed with the increase of dry density, shear modulus increases promptly.

Fig. 7 Relationship between moisture content and shear modulus

Fig 7 shows the relationship between shear modulus and moisture content of frozen sand with the same dry density in the thawing process. As dry density is 2.0 g/cm$^3$ in positive temperature, the shear...
modulus with the moisture content of 6%, 9% and the saturation were 80.1 to 90.0 MPa, 77.1 to 86.5 MPa, 72.4 to 83.1 MPa, the shear modulus with the same dry density decreases with the increase of water content at positive temperature; In contrast to the negative temperature, the shear modulus with the moisture content of 6%, 9% and the saturation were 156.0 to 420.3 MPa, 180.5 to 570.1 MPa, 305.3 to 1400.3 MPa, the shear modulus decreases with the moisture content. It indicates that the moisture content has a dual effect on the strength of the sand soil.

Dual function of the key reasons lies in the influence of pore water in the soil, when a positive temperature conditions, soil samples in the middle of the three-phase body and no ice phase, the strength of the soil is mainly composed of soil structure, soil water content on behalf of the greater the compactness of the lower, so the higher the moisture content of sandy soil in strength under the condition of temperature is lower. When the temperature is negative, the pore water freezes into an ice phase, and the strength of the soil mass is provided by the structure of the soil mass and the ice in the soil. After water freezes, the ice fills the internal void of the soil mass, which increases the compactness of the soil mass and greatly improves the strength of the soil mass.

4. Conclusions
This paper summarizes the small-strain elastic properties of a typical remaking sand soil as the temperature increases from −20 °C to 20 °C by elastic wave velocity measurements. Test application is simple and efficient system of bender elements measured. Based on analyses of the test results, the following conclusions can be made:

(1) While S-wave velocities and dynamic elastic modulus decrease with increasing temperature, their values are not the same in freezing and thawing process, with the general rate of change between 20% and 60%.

(2) When the temperature exceeds 5 °C or is lower than -5 °C, the elastic properties of specimens including S-wave velocities, shear moduli show gradual variation; whereas when the temperature is between 5 °C and -5 °C, those of sand specimens show an abrupt change.

(3) Moisture content has a dual effect on the shear modulus of sandy soil. At positive temperature, the higher the moisture content is, the lower the dynamic shear modulus of sandy soil is; at negative temperature, the higher the moisture content is, the higher the dynamic shear modulus of sandy soil is.

(4) In the process of freezing and thawing, the shear modulus of sand increases with the increase of dry density, but the amplitude of increase is obviously different. When the temperature adjacent to 0 °C, those of sand specimens show an abrupt change. Whereas, the shear moduli show gradual variation.

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