Physical properties of frozen soils measured using ultrasonic techniques

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ABSTRACT: The velocity of ultrasonic waves traveling in a media reflects the dynamic properties of that media, which should depend on the physical properties. Taking advantage of the easy-operation and non-destructive nature of the ultrasonic technology, it is possible to determine some physical properties of frozen soils indirectly by using this technique, either in the laboratory or in the field. A series of experiments were carried out to obtain dynamic properties of frozen soils and to establish relationships between ultrasonic velocities and unfrozen water contents, as well as the strength of frozen soil. Experimental results have indicated that the strength of frozen soil can be estimated as a function of a single factor by measuring the ultrasonic velocities. Additionally, ultrasonic velocities can be used to predict the unfrozen water content of frozen soil for different temperatures.

1 INTRODUCTION

Sonic waves are generated by propagation of mechanical vibration in media. According to the vibrating frequency, a sonic wave is divided into an infrasonic wave (<20 Hz), an audible wave (20 Hz~20 kHz) and an ultrasonic wave (>20 kHz). As a non-destructive technology, the ultrasonic wave has been widely used in medical inspection, crack detection in metal, and so on. Simply put, the mechanism of ultrasonic detection is to distinguish the physical properties of the detected material through analyzing the propagating features of ultrasonic wave in the material. The higher the frequency of the ultrasonic wave, the better the resolution of detection, because only more than 1/4 wavelength of a “spot” inspected can result in a distinct response to the wave propagation. This is why the ultrasonic wave (not the audible wave) is often chosen as a detecting tool.

The selection of detection frequency is subject to the properties of materials and the detection purpose. Since the 1970’s, researchers have been trying to apply ultrasonic technology to frozen soils. The studies were mainly focused on the understanding of the propagating characteristics of ultrasonic wave in frozen soils. The results indicated that the ultrasonic velocities changed little with temperature in sand (Nakano et al. 1972, Nakano & Arnold 1973), but decreased with increasing temperature in frozen silt (Inoue & Kinoshita 1975, Fukuda 1989), and indicated that the unfrozen water content might be an important factor affecting the ultrasonic velocity in frozen soil (Fukuda 1989, Deschatres et al. 1988, Thimus et al. 1991).

Sheng et al. (2000a) have studied the relationship between unfrozen water content and ultrasonic velocities in frozen Tomakomai silt (in Hokkaido, Japan), and proposed a linear relationship (Sheng & Fukuda 1998, Sheng et al. 2000a). The propagating features of ultrasonic waves in frozen soil reflect the dynamic properties of frozen soils, and the dynamic properties depend on the physical properties. Therefore, the physical index of frozen soils should determine their ultrasonic propagating characteristics. In other words, measuring the ultrasonic velocities in frozen soils may help us to understand the physical properties of frozen soils. Although we can not establish a mechanistic model of the propagation of ultrasonic waves in frozen soils (because frozen soil is a multi-phase material, and each component depends on the others during the mechanical vibration, which makes the micro-vibration in frozen soil complicated), considering frozen soil as a macro-uniform material, it is possible to get some empirical relationships between ultrasonic velocities and macro-physical properties, such as strength or unfrozen water content.

Using the empirical relationships, we can achieve the measurement of physical properties of frozen soils by ultrasonic technology. With this thought in mind, this paper primarily studies the possibility of applying ultrasonic technology to the measurement of physical properties in frozen soils, by comparing ultrasonic velocities with experimental results of mechanical and physical tests.

2 DIRECT DETERMINATION OF DYNAMIC PARAMETERS OF FROZEN SOILS

Dynamic properties of frozen soils are important to geophysical exploration, excavation by blasting, and
design involving vibrating machinery. Sonic propagation in frozen soils is determined by dynamic properties of frozen soils (Young’s modulus, shear modulus and Poisson’s ratio). Elastic parameters should be expressed as follow, as functions of ultrasonic velocities (Bourbie et al. 1987):

$$E = \frac{\rho V_p^2 (3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2}$$  \hspace{1cm} (1)

$$G = \rho V_s^2$$  \hspace{1cm} (2)

$$\mu = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$$  \hspace{1cm} (3)

Here, $E$ is Young’s modulus, Pa; $G$ is shear modulus, Pa, $\mu$ is Poisson’s ratio; $\rho$ is density, kg/m$^3$. $V_p$ refers to longitudinal wave velocity, m/s; $V_s$ refers to shear wave velocity, m/s. Given the density of frozen soil, we can calculate elastic constants from Equation (1) by measuring the ultrasonic velocities of the frozen soil. Figure 1 shows the changes of both longitudinal and shear wave velocities with temperature in Lanzhou Loess. The water content of the sample is 25%, and its dry density is 1.57 g/cm$^3$. Calculated Young’s modulus, shear modulus and Poisson’s ratio are shown in Figures 2, 3. The ultrasonic velocities of both longitudinal and shear waves decrease with increasing temperature, and their Young’s modulus and shear modulus also decreased with increasing temperature. These results display the same trends as the experimental results obtained from a uniaxial strength test (He et al. 1993). The modulus obtained from ultrasonic method is an order of magnitude higher than the results from material test machine. Considering the higher frequency and the lower strain in the ultrasonic method, the higher modulus is understandable. It is not an easy job to determine Poisson’s ratio with a common test machine. However, it is relatively straightforward to obtain Poisson’s ratio for frozen soils by using ultrasonic technology. Compared with normal elastic materials, Poisson’s ratio of frozen soil is somewhat lower, and increases with increasing temperature.

3 UNIAXIAL COMpressive STRENGTH AND ULTRASONIC VELOCITIES IN FROZEN SOILS

Theoretically, the ultrasonic velocities should not directly reflect the strength characteristics of frozen soils. However, when a factor affecting the strength of frozen soil changes, the ultrasonic velocity in frozen soil also changes. If there is a good relationship between the uniaxial strength and ultrasonic velocities, it should be possible to estimate the uniaxial strength of frozen soils by the relationship through measuring the ultrasonic velocities of frozen soils. Inoue & Kinoshita (1975) conducted experiments on ultrasonic velocity and strength for frozen silt and sand with different water content at a constant temperature. Their results indicated that a linear relationship existed between uniaxial compressive strength and shear velocity.

A series of tests of uniaxial strength are conducted for different temperatures in frozen Lanzhou Loess. The dry density of the samples is about 1.57 g/cm$^3$, and water content is about 25%. The results are plotted in
Combining these test results with those presented in Figure 1, the uniaxial compressive strength can be plotted against the longitudinal velocity on the basis of temperature, as shown in Figure 5. It is found that the strength of frozen soil can be expressed as a power function of the longitudinal velocity when changing temperature of frozen soil (longitudinal velocity varies with temperature). The lower the temperature of frozen soil, the faster the ultrasonic longitudinal velocity, and the higher the strength of frozen soil. This relationship between strength and wave velocity in frozen soil makes it possible to estimate the strength of frozen soil by ultrasonic measurement on only one sample, after conducting a few strength tests to calibrate the relationship.

Another experiment was carried out for Tomakomai silt mixed with tire powder (from discarded rubber tire) at different mixing fractions and the same temperature (−5°C). An effort was made to reach about 95% saturation for all test samples. In this case, the unique variable is tire powder fraction. Figure 6 shows the results of strength tests with tire mixing fraction. Based on the tire powder fraction, the relation between strength and longitudinal velocity is given in Figure 7. It is found that the compressive strength of frozen Tomakomai silt has a linear relationship to longitudinal velocity as the mix with the tire powder fraction (details of the experimental results of frozen Tomakomai silt mixed with tire powder may be found in Sheng et al. 2000a, b).

4 UNFROZEN WATER CONTENT AND ULTRASONIC VELOCITY

Unfrozen water content is one of the most important factors affecting the physical and mechanical properties of frozen soils. Understanding the relationship between unfrozen water content and ultrasonic velocities will make it possible to use ultrasonics to determine unfrozen water content (Fukuda 1989). Because the change in unfrozen water content indicates a change in ice content, which plays a cementing role in frozen soils, the change of ice content must result in the change in mechanical properties of frozen soils. The authors have conducted ultrasonic experiments on Tomakomai silt to study the effect of unfrozen water content on the ultrasonic velocities (Sheng & Fukuda 1998, Sheng et al. 2000a). Their results showed a linear relationship between unfrozen water content and both longitudinal and shear wave velocities.

Glass beads, with diameters ranging from 2.2 to 10 μm, is selected to conduct these experiments. A
power function is found between the unfrozen water content and the longitudinal velocity, as shown in Figure 8. The unfrozen water content of frozen soil strongly affects the ultrasonic velocity. The higher the unfrozen water content, the lower the ultrasonic velocity. The existing power function is different from the linear function that was found for frozen Tomakomai silt by Fukuda (1989) and Sheng & Fukuda (1998). This may be a result of the difference in the nature of the materials. The effect of unfrozen water content on the ultrasonic velocity is a complex problem. It involves the structure of frozen soil, the existing form of unfrozen water, and the transforming process for the mechanical wave within each phase in the frozen soil. Leclaire et al. (1994) analyzed the propagating mechanism of an ultrasonic wave in frozen soil using Biot’s theory (Biot 1956a,b). This analysis supposed that unfrozen water in frozen soil was inter-perfoliate. But unfrozen water is generally in a state of separation for most frozen soils, so that supposition is not satisfied by many frozen soil structures. Empirically, the good correlation between unfrozen water content and ultrasonic velocity suggests that there is a possibility to measure unfrozen water content by ultrasonic techniques.

5 CONCLUSION

The propagation of ultrasonic waves in frozen soils responds to the dynamic properties of the material. Taking advantage of the simple, fast, non-destructive nature of ultrasonic technology, the elastic parameters may be measured directly. For a single change in factors affecting the strength of frozen soil, the compressive strength shows a good relationship to the ultrasonic velocity. Unfrozen water content obviously affects the ultrasonic velocity, and a good empirical relationship exists between unfrozen water content and ultrasonic velocity. Of course, many factors, such as ice content, grain size, temperature, as well as structure of soil, may have an effect on the ultrasonic velocity and physical properties. However, for a single influencing factor, the existing relationships between ultrasonic velocity and the physical and mechanical properties make the estimation of uniaxial strength and unfrozen water content possible.

REFERENCES


