The pattern of changes in the velocity of propagation of ultrasonic waves in frozen soil samples during thawing

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Abstract. The locations of mining and processing enterprises in the areas of permafrost distribution are associated with monitoring the state of the ice-ground massif. The monitoring problem is exacerbated by climate change trends, and the reduction of suitable for the existence of permafrost zones. The increase in the number of emergencies associated with the degradation of permafrost soils in the regions of the Republic of Sakha and the Norilsk industrial region are direct evidence of this problem. The main consequences of thawing soils are uneven troughs of subsidence of foundations, frosty swelling, and waterlogging. The article considers the possibility of using the ultrasonic monitoring method in order to monitor the state of permafrost soils, along with existing monitoring methods. Existing methods for monitoring the state of permafrost soils are considered. The results of experimental studies of changes in the velocity of propagation of an ultrasonic wave during the thawing of various permafrost soils, humidity and particle size distribution are presented. It has been proved experimentally that the sensitivity of the speed of propagation of an ultrasonic wave to a change in temperature in frozen soil samples. When the soil passes from a frozen state to a plastic-frozen state, there occurs a sharp drop in the speed of the ultrasonic propagation.

1. Introduction
A significant contribution to the economy of the Russian Federation is made by the extraction and processing of minerals. Most of the mining and processing enterprises are located in the zone of permafrost distribution. For the safe operation of engineering structures, the industrial complex, high-quality monitoring of permafrost soils is necessary since they serve as the basis for the foundations of these structures [1].

The problem of monitoring permafrost soils, relevant for many years, and remains so to this day. Climate change, over the course of a decade, has exacerbated the problem of monitoring the state of permafrost soils. Due to warming, permafrost is being degraded, and the zone suitable for the existence of permafrost is shrinking [2]. Despite the existence of various methods, tools, and devices for monitoring permafrost soils discussed later in this paper, the problem is not yet solved.

According to the rulebook 25.13330.2012 “Soil bases and foundations on permafrost soils” two principles permafrost soils using are allowed. The first principle of construction, on permafrost, is the most common. When using permafrost soils, according to the I construction principle, the frozen state of soils is preserved both during the construction period and during the operation of the engineering structure. Accordingly, when thawing permafrost soils, the foundations of engineering structures give uneven precipitation. This violates the normal operation of the structure [3].
Monitoring of permafrost soils temperature is mainly used to measure and control the temperature of permafrost soils. For this there should be a well bored out and equipped with a garland of temperature sensors (a thermometric scythe and a logger). The logger is designed to read thermometric info [4]. There is a main reason why temperature monitoring, in spite of its popularity, does not allow to finally solve the problem of monitoring permafrost soils is that the transition of permafrost soils from hard-frozen to plastic permafrost can occur at the slightest change in temperature [5].

Another applicable method for monitoring permafrost is surveying. The method provides more information, but has a number of disadvantages. The main disadvantage is that the method is discrete, that is, it does not allow continuous monitoring of the state of permafrost soils. And also, it is worth noting that using this method, precipitation of the bases is recorded, that is, changes that have already occurred, which entailed precipitation of the foundation of the structure [8].

Until now, studies of the propagation velocity of ultrasonic waves in frozen and permafrost soils have been aimed at developing the sounding method of an ice-ground fence constructed to create a waterproof fence with “special” construction methods. In this paper, we consider the possibility of using ultrasonic waves to predict the loss of bearing capacity of permafrost soils. This work should be considered as the initial stage of adaptation of the ultrasonic method for predicting the loss of bearing capacity of permafrost soils. For this purpose, experimental studies of changes in the velocity of propagation of ultrasonic waves during the thawing of permafrost samples have been carried out.

2. Materials and methods
The object of research was samples of sand and loam. At the initial stage, the samples were dried in an oven. Further, the samples were moistened, by weight, by 10%, 20%, 30%. After wetting, the samples were placed in a wooden formwork, cubic in shape, measuring 10x10x10 centimeters. A thermocouple was placed in the center of the sample to measure the temperature of the sample. After laying and compaction, the samples were placed in the freezer for a day, until completely freezing. The temperature of the freezer was -18.5°C. Before each measurement of the propagation velocity of ultrasound, measurements were made on the dimensions of a frozen soil sample using a caliper. Measurement of the transit time of the ultrasonic wave in the samples was carried out by means of the Pulsar ultrasonic device. The determination of the transit time of the ultrasonic wave occurred through sounding. When the sample reaches the required temperature, a receiving and radiating converter attaches to it. Acoustic contact was provided by liquid lubricant. Each measurement cycle consists of 15 measurements. Further, emissions were rejected and the result was determined by the formula:

\[ T_{ot} = \frac{T_1 + T_2 + T_3 + \cdots + T_N}{N} \]

where \( T_{ot} \) is the transit time of the ultrasonic wave through the sample at a given temperature; \( T_N \) – time of each measurement elapsed, rejection of emissions.

The propagation velocity of a longitudinal ultrasonic wave was calculated by the formula:

\[ v = \frac{l}{T_{ot}} \]

where \( l \) is the length of the sample.

When measuring the transit time of an ultrasonic wave, the samples were not loaded. The measurements were carried out at a temperature of \(-15^\circ C\), \(-10^\circ C\), \(-5^\circ C\) and 0°C, the temperature value was determined using a thermocouple, according to the multimeter.

Based on the obtained values of the propagation velocity of the longitudinal ultrasonic wave, the characteristic impedance and volume dynamic modulus of elasticity of the samples were calculated:

\[ Z = v \rho \]
\[ E = v^2 \rho \]

where \( Z \) is the characteristic impedance of the medium; \( E \) – volumetric dynamic modulus of elasticity; \( \rho \) is the density of the sample.
3. The results of the experiments

Tables 1 and 2 show the results of calculations performed during experimental studies.

Table 1. The results of experimental studies of the propagation of a longitudinal ultrasonic wave in frozen sand samples

| t, °C | T₀, μs | V, m/s | Z, MPa·s/m | E, hPa |
|-------|--------|--------|------------|--------|
| −15   | 52.84  | 1950   | 3.11       | 6.1    |
| −10   | 54.62  | 1885   | 3.01       | 5.7    |
| −5    | 70.64  | 1458   | 2.3        | 3.4    |
| 0     | 76.53  | 1345   | 2.14       | 2.8    |

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|-------|--------|--------|------------|--------|
| −10   | 54.62  | 1885   | 3.01       | 5.7    |
| −5    | 70.64  | 1458   | 2.3        | 3.4    |
| 0     | 76.53  | 1345   | 2.14       | 2.8    |

Table 2. The results of experimental studies of the propagation of a longitudinal ultrasonic wave in frozen loam samples

| t, °C | T₀, μs | V, m/s | Z, MPa·s/m | E, hPa |
|-------|--------|--------|------------|--------|
| −15   | 47.56  | 2018   | 3.9        | 7.9    |
| −10   | 49.87  | 1928   | 3.7        | 7.2    |
| −5    | 62.57  | 1529   | 2.9        | 4.5    |
| 0     | 65.73  | 1460   | 2.8        | 4.1    |

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The characteristic form of the obtained dependences, the propagation velocity of a longitudinal ultrasonic wave on the temperature of the samples (presented in Figure 2).

The data presented in Figure 2 shows that regardless of the sample type and its humidity, the value of the propagation velocity of a longitudinal ultrasonic wave, when thawing the soil, decreases. It is also worth noting that in the temperature range from −10°C to −5°C, there is a sharp decrease in the velocity of a longitudinal ultrasonic wave propagation. This is because the thawing of the samples occurred evenly, in the direction from the edges of the sample to the center. Since the thermocouple was installed in the center of the sample, by the time the temperature reached −5°C, in the center of the sample, a significant part of the sample had already thawed. In the temperature ranges from −15°C to −10°C and from −5°C to 0°C, the state of the samples was uniform, frozen or thawed. Therefore, the decrease in the propagation velocity of the longitudinal ultrasonic wave was not so significant.

According to the measurement results, the ultrasonic wave propagation velocity, in order to assess the change in the deformation properties of the samples and assess the change in the degree of resistance of the medium (samples) to ultrasonic vibrations, the dependences of the volume dynamic modulus of
elasticity on temperature and the characteristic impedance on temperature were constructed. A typical view of the obtained dependencies is presented in Figure 3 and Figure 4.

**Figure 2.** A characteristic experimental dependence of the ultrasonic wave propagation velocity on the temperature of soil samples: horizontal - sample temperature, vertical - propagation velocity of a longitudinal ultrasonic wave.

**Figure 3.** A characteristic experimental dependence of the characteristic impedance on the temperature of soil samples: horizontal - sample temperature, vertical - characteristic impedance.
Figure 4. A characteristic experimental dependence of the volume dynamic elastic modulus on the temperature of soil samples: horizontal - sample temperature, vertical - volume dynamic elastic modulus.

4. Conclusion
The course of this work, the sensitivity of the propagation velocity of ultrasonic waves to temperature changes in frozen soil samples was experimentally confirmed. In the process of thawing samples, during the transition of frozen water from an ice state to a liquid state, the propagation velocity of a longitudinal ultrasonic wave decreases. The drop in speed occurs regardless of the type and moisture of the soil, and the nature of the drop in the speed of the ultrasonic wave is similar for all types of samples.

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