

Article

Assessing the State of Structural Foundations in Permafrost Regions by Means of Acoustic Testing

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Abstract: About 60% of the territory of the Russian Federation is covered by permafrost. Additionally, a large share of the country's mineral and hydrocarbon deposits are located in the Arctic. Climate change that has been happening over the past few decades has had a serious impact on the conditions in which permafrost soils are found. Changes in temperatures in permafrost regions, along with the human impact from mining and processing, have led to an increase in accidents caused by the degradation of permafrost foundations. In this situation, timely detection of the degradation of permafrost foundations plays a pivotal role in ensuring the safe operation of buildings and structures. This article contains a theoretical review and describes the results of an experimental study of whether it is possible to use acoustic testing in solving problems associated with monitoring the state of permafrost foundations. In the course of the study, the relationships between the acoustic characteristics and the deformation and strength characteristics of permafrost soils were analysed. The results of the study made it possible to draw a preliminary conclusion that acoustic testing can be used to solve problems associated with condition monitoring of permafrost foundations.

Keywords: permafrost; permafrost regions; acoustic methods; condition monitoring



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1. Introduction

In recent decades, climate change has had a serious impact in regions where the ground temperature continuously remains below 0 °C. These regions are called permafrost regions. According to the data in [1], the Polar Urals have been witnessing a steady increase in atmospheric temperature in both winter and summer, as well as an increase in precipitation in winter, which prevents the ground from cooling down. In central Yakutia, the depth of seasonal thawing has reached 80 cm over the past 28 years [2]. For the Russian Federation, the problem of permafrost degradation is of particular concern because a lot of the country's mineral and hydrocarbon resources are located in the Arctic zone [3,4]. Permafrost degradation puts buildings and engineering structures under threat, as evidenced by emergencies that have occurred in recent times [5–7]. In such conditions, it is vital to timely register when frozen soils become plastic-frozen to ensure the safe usage of buildings and structures.

Currently, there are a variety of methods and tools that have been developed for permafrost monitoring. One of the major methods is temperature control. There are two key approaches to how data is obtained on permafrost temperature: measuring soil temperature profiles, using sensors installed in boreholes [5,8,9], and satellite remote sensing of the earth's surface [10,11]. There are a lot of mathematical models that have been developed to assess temperature distribution in soils [10,12–14]. Regardless of the approach chosen, the criterion for assessing the state is the soil freezing temperature. As a result of the anthropogenic impact on frozen soils, their physical and chemical properties can change. The activation of freeze–thaw processes greatly aggravate this problem [14,15]. It is also important to note the influence of the freeze–thaw cycle affecting the physical and

mechanical properties of soils [16]. Temperature control methods are often used as part of integrated condition monitoring systems [17,18]. Along with temperature, changes in the moisture content of frozen soils, the depth of seasonal thawing, and elevation data on foundations are monitored.

Various methods are used to find elevation data for the foundations of structures, including levelling, differential interferometry, and global navigation systems [19,20]. In a number of cases, deformation control does not allow for obtaining timely and reliable information about the state of the foundation. Frozen soil is a four-phase system that includes solid particles, ice, water, and gas. As a result of thawing, a phase transition of ice into water occurs. As water is almost incompressible, it is necessary that it should drain away and free the pores in order for the soil to settle. In addition, soils can move both upward (when swelling) and downward (when settling) and when such movements compensate for each other, no absolute deformation will be registered.

Recently, geophysical methods for permafrost monitoring have been gaining in popularity. In particular, they are used to monitor the humidity and depth of the layer of seasonal thawing [21,22]. The methods described in [21,22] are based on the difference in the permittivity of water and ice.

As the literature review presented here shows, none of the currently available permafrost monitoring methods make it possible to directly assess the change in the deformation and strength characteristics of soils, despite the fact that these are the key characteristics in the design of structural foundations. In our opinion, this problem can be solved by applying an acoustic method [23,24], since the speed of propagation of an elastic wave is directly related to the elastic characteristics of the medium in which it propagates.

2. Methodology. Problem Statement

2.1. Soil Model Selection

According to the norms and regulations governing the construction of buildings and structures on the territory of the Russian Federation in permafrost regions [25–27], it is mandatory to monitor foundation deformations during the entire life cycle of a structure. The following criterion is used to monitor foundation condition [27]:

$$S_f \leq S_u \tag{1}$$

where S_f is the deformation of the plastic-frozen foundation under the load caused by the structure, S_u is the maximum permissible deformation of the structural foundation for the estimated life cycle, which is determined according to [27].

To calculate foundation settlement, various mathematical models are used. Let us consider two key models: the linear elastic-perfectly plastic Mohr–Coulomb (MC) model [28,29] and the Hardening Soil (HS) model [30–32].

The major disadvantage of the MC model is the invariance of the deformation modulus over the entire stress range. The relationship between stresses and strains in the MC model is described by Hooke’s law [28,29]:

$$\{\sigma\} = [D]\{\varepsilon\} \tag{2}$$

$$[D] = \frac{E_G}{(1 - 2\mu)(1 + \mu)} \begin{bmatrix} A & \mu & \mu & 0 & 0 & 0 \\ 0 & A & \mu & 0 & 0 & 0 \\ 0 & 0 & A & 0 & 0 & 0 \\ 0 & 0 & 0 & B & 0 & 0 \\ 0 & 0 & 0 & \mu & B & 0 \\ 0 & 0 & 0 & \mu & \mu & B \end{bmatrix} \tag{3}$$

$$A = 1 - \mu \tag{4}$$

$$B = (1 - 2\mu) \sqrt{2} \tag{5}$$

where $\{\sigma\}$ is the stress tensor, $[D]$ is the secant elasticity matrix, $\{\varepsilon\}$ is the strain tensor, E_G is the deformation modulus, and μ is Poisson’s ratio.

Unlike the MC model, the HS model takes into account the change in the deformation modulus depending on the stress–strain state. To do this, it factors in three moduli: the modulus of deformation that takes into account stiffness under deviator stress E_{50} , the modulus of unloading and reloading E_{ur} , and the modulus that takes into account stiffness under compression E_{oed} . Each of them depends on the value of confining pressure [30–32]:

$$E_i = E_i^{ref} \left(\frac{c \cos \varphi - \sigma_3 \sin \varphi}{c \cos \varphi + p^{ref} \sin \varphi} \right)^m \tag{6}$$

where $E_i = E_{50}; E_{ur}; E_{oed}$ is the modulus value for a given elementary volume of soil, $E_i^{ref} = E_{50}^{ref}; E_{ur}^{ref}; E_{oed}^{ref}$ is the reference value of the modulus, p^{ref} is the reference pressure, c is adhesion, and φ is the angle of internal friction.

The key factor determining whether it is possible to use one model or another to solve problems of monitoring the state of permafrost soils is the possibility of finding the parameters of the model in the course of field measurements on site. The authors of [29,32–35] analysed the methods used to find soil model parameters. Table 1 summarizes their results.

Table 1. Methods of finding the parameters of soil models.

Model	Parameter	Method
Mohr–Coulomb	E	Triaxial compression, pressuremeter tests
	μ	Oedometer tests
	φ	In-plane shear tests
	c	
Hardening Soil	$E_{50}; E_{ur}$	Triaxial compression
	$\mu; \mu_{ur}$	Triaxial compression
	E_{oed}	Triaxial compression
	φ	In-plane shear tests
	c	
	Ψ	Triaxial compression
OCR	In-plane shear tests	

As Table 1 shows, in order to find the parameters of the HS model, it is necessary to conduct laboratory tests. Direct field methods have not yet been developed.

As for the MC model, Expression (2) and Table 1 show that its parameters can be determined on site. The authors of [28,36] note that the HS model produces better results than the MC model, in comparison with the results of on-site settlement measurements. However, the MC model still produces sufficient results and is widely used in Russia for preliminary calculations [36].

The MC theory serves as a foundation for the deformation theory of plasticity (DTP), in which the deformation modulus E_G depends on the maximum principal stress σ_1 [37]:

$$E_G \equiv E_G(\sigma_1) \tag{7}$$

Therefore, in order to find deformations using DTP, it is necessary to find (7) in the course of tests over the entire range of the stress acting on the soil.

To find the components of the stress–strain state of a permafrost foundation, let us consider a standard model of a permafrost foundation (Figure 1).

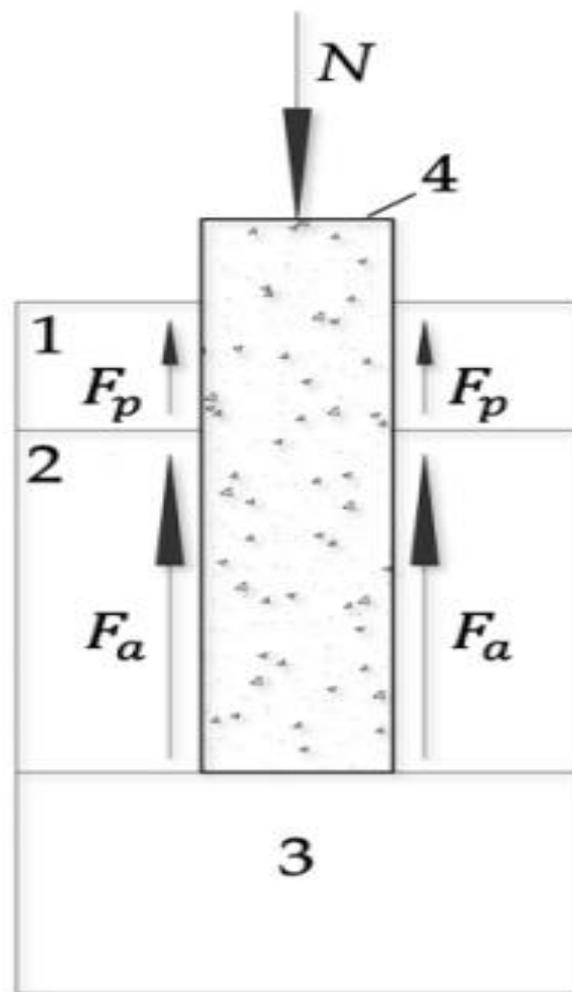


Figure 1. The pile-soil system. 1—zone of seasonal thawing; 2—pile adfreeze zone; 3—soil compression zone; 4—pile foundation; F_a —shear strength in the soil along the lateral adfreeze zone; F_p —frost heaving force; N —load applied by the structure.

The values of the stress tensor components take into account the interface between the soils and the pile (Figure 1). For the zone of seasonal thawing of soils and the pile freeze zone, Boussinesq's solution [38] is applied. As for the soil compression zone, Mindlin's solution is used [39]. In both cases, the stress tensor components depend on the coordinates of the finite element and the resulting load:

$$\{\sigma\} = f(P_i, x, y, z, \mu) \quad (8)$$

where P_i is the resulting load from the structure for different interaction zones (Figure 1), x, y, z are the coordinates of the elementary volume of soil, and μ is Poisson's ratio.

Let us find the resulting load for each pile-soil interaction zone:

$$P_1 = N - F_p \quad (9)$$

$$P_2 = N - (F_p + F_a) \quad (10)$$

$$P_3 = N - (F_p + F_a) \quad (11)$$

F_p (Figure 1) depends on the depth of the layer of seasonal thawing h_s [25]. Therefore, with an increase in h_s , F_p will also change. Similarly, when the soils of the adfreeze zone start thawing, the resistance of the soil along the lateral surface F_a will change. Consequently, the components of the stress tensor also depend on the state of the soils.

Summarizing the above, the following conclusions can be made:

- When condition monitoring a permafrost foundation, it is necessary to monitor not only changes in the deformation characteristics of the foundation, but also in the forces that interact within the pile–soil system.
- In order to use DTP as the foundation of a model for monitoring permafrost foundations, it is necessary to monitor on site changes in $E_G = E_G(\sigma)$, F_p , F_a .

The use of DTP makes it possible to compensate for some of the shortcomings of the MC model, which expands its application range. However, it should be noted that DTP does not factor in rheological properties, which are strongly pronounced in frozen soils [40–42]. These properties need to be accounted for when making a long-term forecast of changes in the state of the foundation. Long-term forecasting of the state of permafrost is a complex problem that requires analysing a significant number of factors and parameters that can change over time, especially when climatic indicators fluctuate and change. In this regard, a question arises of whether it is possible or viable to make long-term forecasts. Therefore, the research we conducted was aimed at providing a rationale for a method that can be used for monitoring the current state of permafrost soils. The method implies analysing the state of soils at a given time and monitoring changes in soil characteristics over time.

2.2. Methods for Finding Soil Parameters

As mentioned above, when condition monitoring of permafrost soils, it is necessary to conduct on-site measurements of the parameters included in the model. Moreover, it is important to measure them directly in the zone of the structure's influence on the soils. Let us consider methods for finding $E_G = E_G(\sigma)$, F_p , F_a .

F_p is found using the value of settlement h_s [25]. To monitor h_s , a lot of methods and instruments have been developed, which is why we do not discuss here the issue of finding F_p .

As a method of finding $E_G = E_G(\sigma)$, let us consider radial pressuremeter (RP) tests. This method is suggested in [43], and it has a number of advantages and disadvantages.

The main advantage is that when soils form different layers, which is typical for the Arctic zone of the Russian Federation, the use of RP makes it possible to find $E_G = E_G(\sigma)$ for each type of soil.

Condition monitoring of permafrost soils implies ongoing monitoring of the deformation and strength parameters of soils. The use of RPs implies loading the soil in a range of stresses ($\sigma_{max}; \sigma_{min}$) during each observation. Soils are characterized by such properties as hysteresis and hardening/softening, as a result of which the deformation moduli found during initial loading and after repeated loading will not be equal. In our opinion, this is the biggest limitation to using RP tests for solving problems of condition monitoring of permafrost soils. Another limitation is that the stresses produced by the pressuremeter chamber are transmitted through soils at distances no longer than 500 mm.

The lateral adfreeze force F_a is determined at the stage of design and engineering surveys. Currently, there are no direct monitoring methods for this parameter. $F_a = f(A_t)$ is found, where A_t is the soil thawing coefficient that is based on the freezing temperature of soils, which is not constant [14–16].

In our opinion, to solve the problems of condition monitoring of permafrost foundations, acoustic testing can be used. This method is currently quite widely used to study the physical and mechanical properties of soils. However, similar to RP tests, acoustic testing has a number of limitations.

In acoustic tests, soil is loaded in the elastic range. As a result of the elastic effect [44], no residual deformations are observed in soils, which, in contrast to RP tests, allows for repeated studies.

The elastic wave passes through the mass of the soil being studied, making it possible to directly study the deformation parameters of soils in a much larger volume of soil compared to RP tests. At present, distances can reach 100 to 150 m. However, when

choosing the dimensions of the volume of soil, it must be understood that an increase in them leads to the averaging of the resulting indicators.

Studying mechanical properties of soils by acoustic testing is based on the mathematical methods of the theory of elasticity. However, in real conditions, soils are not absolutely elastic; the foundations of structures operate in the elastic–plastic range of loads, which is clearly demonstrated by the results of plate load tests [45]. This fact is the biggest limitation for the use of acoustic testing.

An indicator of the deformation properties of soils is the deformation modulus (12):

$$E_G = \frac{\sigma}{\varepsilon_G} = \frac{\sigma}{\varepsilon_e + \varepsilon_p} \quad (12)$$

where E_G is the deformation modulus, ε_G is the relative normal total strain, ε_p is the relative normal plastic strain, σ is the normal stress, and ε_e is the relative normal elastic strain.

At the same time, the result of acoustic testing is the dynamic modulus of elasticity (13):

$$E = \frac{\sigma}{\varepsilon_e} \quad (13)$$

where E is the modulus of elasticity of the medium (soils), σ is the normal stress, and ε_e is the relative normal elastic strain.

From a physical point of view, E and E_G reflect similar properties of soils that characterize their resistance to deformation. However, these indicators characterize different stages of soil deformation, which is the reason why their values are not equal. It should be noted that soils are characterized by the predominance of plastic deformations, therefore, it is true that $E \gg E_G$.

2.3. Problem Statement

The analysis of RP and acoustic tests presented above shows that it is promising to combine them for solving the problems of permafrost foundations condition monitoring. The use of complex multi-parameter testing is one of the key trends in the modern development of non-destructive testing, technical diagnostics and condition monitoring [46]. RP tests make it possible to find the values of the deformation modulus, and acoustic tests can be used to monitor how its values change. To do this, it is necessary to find the relationship $E_G = f(E)$.

There is a number of works that are devoted to the relationship $E_G = f(E)$ [45,47]. These works are similar in that they attempt to find a universal relationship for individual types of soils or rocks. The deformation properties of frozen soils depend on many factors, such as humidity, temperature, particle size distribution, and the chemical composition of water, etc. In addition, as mentioned above, the deformation modulus is not constant and depends on the load acting on the soil. Based on the above, we believe that for the purpose of condition monitoring of permafrost foundations, the relationship between E and E_G should be found for each individual object under study. In our work, we study the relationship $E_G = f(E)$ for soils in a frozen state and the possibility of using this relationship to study thawing soils.

To find the correlation between the deformation modulus and the dynamic modulus of elasticity on site, we propose to equip the standard measuring probe of the radial pressuremeter with a low-frequency transmitting transducer (Figure 2). This method makes it possible to find $\varepsilon = f(\sigma)$ over the entire range ($\sigma_{min}; \sigma_{max}$) for each soil layer (Figure 2) and ensures that there is contact between the transmitting transducer and the borehole wall, which is necessary. Based on the test results, V_p , and $\varepsilon = f(\sigma)$ are calculated for each soil layer over the entire range ($\sigma_{min}; \sigma_{max}$).

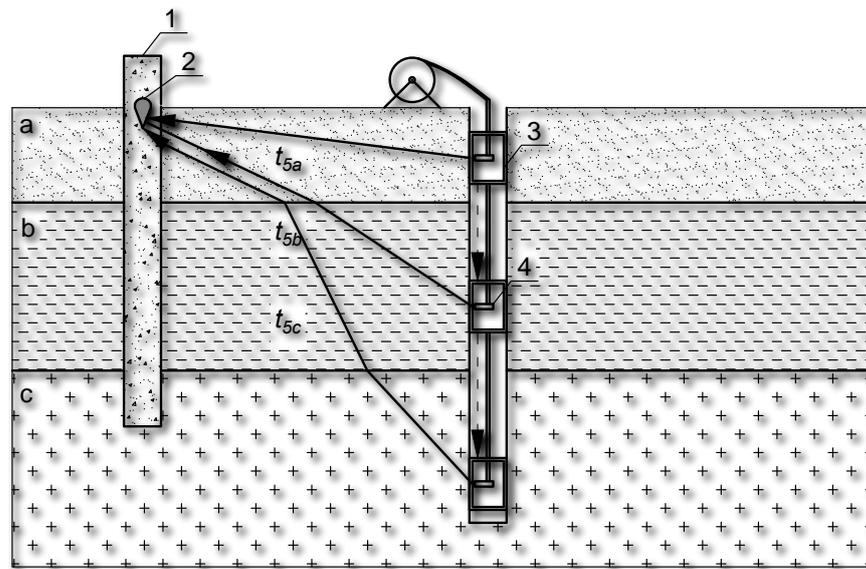


Figure 2. Identifying the deformation characteristics of soils: 1—pile foundation, 2—receiving transducer on the surface, 3—measuring probe, 4—low-frequency transmitting transducer, t_{5a} , t_{5b} , t_{5c} —the propagation period of a beam of the longitudinal spherical wave.

In addition, we propose a method for finding F_a based on the results of acoustic tests. A similar method is widely used for determining the strength characteristics of concrete by acoustic testing [48,49]. This method is standardized [50] and is based on finding $R_c = f(V_p)$ using standard samples, where R_c is the compressive strength of concrete, and V_p is the propagation velocity of the longitudinal wave. During testing, V_p is measured directly on the object being studied, after which R_c is found using the previously found $R_c = f(V_p)$.

To find $F_a = f(V_p)$, we used acoustic testing and in-plane shear testing along the adfreeze zone [51]. Tests were conducted on frozen, transient, and plastic-frozen states. When condition monitoring of permafrost foundations by observing the object under study, V_p is found, after which F_a is found using the relationship above.

Based on the above, two key objectives were set for our experimental study, which will make it possible to draw preliminary conclusions about whether it is possible to use acoustic testing to solve the problems of condition monitoring of permafrost soils:

1. To study the possibility of finding E_G during the thawing of soils by means of acoustic testing using the relationship $E_G = f(E)$ found for the frozen state.
2. To study the relationship $F_a = f(V_p)$ on disturbed samples of frozen sand.

3. Materials and Methods

To reach the research objectives, we prepared disturbed samples of frozen sand. The geometric parameters of the samples were chosen according to the requirements stated in [50,52] (Figure 3). The physical properties of the samples (Table 2) are similar to the properties of soils commonly found in the permafrost regions of the Russian Federation. As a pile simulator, an A500C reinforcing bar was used—GOST [53].

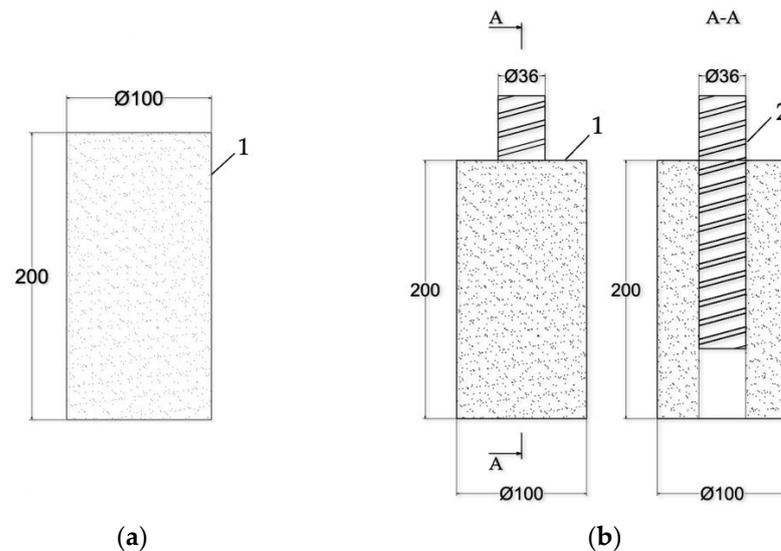


Figure 3. Frozen sand samples: (a) for finding the modulus of total deformation; (b) for finding the shear strength the soil along the lateral adfreeze zone. 1—frozen soil; 2—pile simulator.

Table 2. Physical properties of the disturbed samples of frozen sand.

Soil Type	Moisture, %	Density, kg/m ³
sand	25	1750

Samples were prepared as follows:

- 1 The soil was dried in an oven at a temperature of 100 °C for four hours;
- 2 The soil was sieved to remove coarse parts;
- 3 The soil was moisturized by weight;
- 4 The soil was put in moulds and the samples were weighed;
- 5 The samples was compacted to the required density;
- 6 The samples were left to freeze for 24 h.

Experimental studies were carried out using the Insight 200 electromechanical testing system, equipped with an MTS 651-06E climatic test chamber and a Pulsar-1.1 ultrasonic device (Figure 4).

The studies of the relationship $E_G = f(E)$ were conducted in three steps. First, a temperature of -10 °C was set in the climatic test chamber. Then, a sample of frozen soil was put into it that had been kept in a freezer at a temperature of -10 °C for a day, after which tests were carried out using the uniaxial compression method, as shown in Figure 4a. When the stress value $\sigma = 0.3$ MPa was reached, the propagation period of the longitudinal wave was found by the method of ultrasonic testing (Figure 4a). Based on the results of the experimental studies, the deformation modulus (14) and the dynamic modulus of iontion eshedod for study discussed heres changeoelasticity (15) were calculated.

$$E_G = \frac{\Delta\sigma}{\Delta\varepsilon_G} \quad (14)$$

$$E = V_P^2 \cdot \rho \frac{(1 + \mu) \cdot (1 - 2\mu)}{(1 - \mu)} \quad (15)$$

where E_G is the deformation modulus; ε_G is the relative normal total strain; σ is the normal stress; E is the modulus of elasticity of soils; ρ is the soil density; μ is Poisson's ratio; V_P is the velocity of propagation of the longitudinal wave.

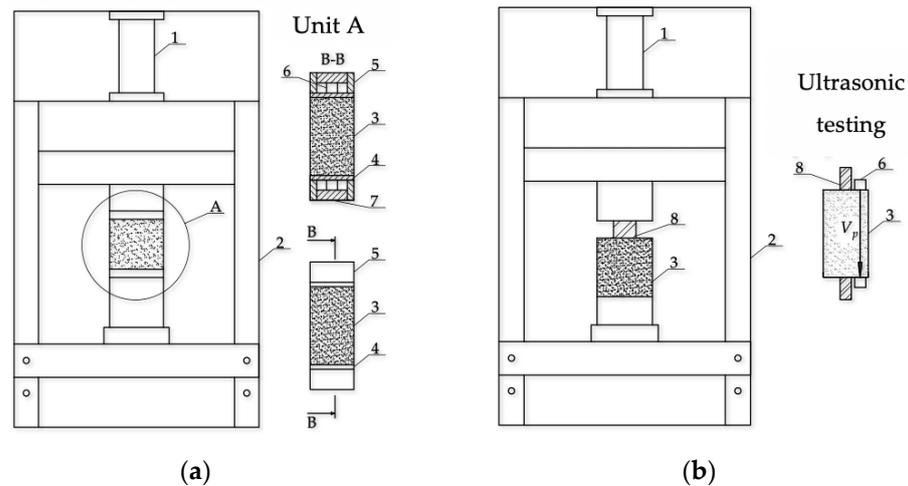


Figure 4. Test installation: (a) for finding the total deformation modulus; (b) for finding the shear strength in the soil along the lateral adfreeze zone. 1—Insight 200; 2—MTS 651-06E; 3—soil; 4—steel ring; 5—steel cylinder; 6—ultrasonic transducer; 7—acoustically impermeable plate; 8—pile simulator.

During the second step, the procedure was similar. The sample was kept in a freezer for a day at a temperature of $-3\text{ }^{\circ}\text{C}$. During the tests, the temperature in the climatic test chamber was also kept at $-3\text{ }^{\circ}\text{C}$. The deformation modulus and the dynamic modulus of elasticity were calculated in the same way as in the first step.

During the third step, the same operations were performed, only the soil temperature was changed to $-1\text{ }^{\circ}\text{C}$ and the temperature in the climatic test chamber was $+2\text{ }^{\circ}\text{C}$.

After the tests, $E_G = f(E)$ was found using MS Excel, where the coefficients of the equation were found by the least squares method.

To study the relationship $F_a = f(V_p)$, twelve identical samples of frozen sand were prepared and kept in a freezer for a day at a temperature of $-10\text{ }^{\circ}\text{C}$ (Figure 4b). Before testing, the sample was put into the test installation (Figure 4b) and kept at room temperature for a certain period (Table 3), after which a load was applied to the pile simulator (Figure 4b). The load was gradually increased until the moment when the pile simulator detached from the soil. The uniaxial compression method was used on nine samples. The remaining three samples were used in acoustic testing (Figure 4b). Before acoustic testing, the samples were also kept at room temperature for the same periods. Based on the results of the tests, the velocity of propagation of the longitudinal wave (16) and the value of shear strength in the soil along the adfreeze zone (17) were calculated.

$$V_p = \frac{L}{T} \tag{16}$$

$$F_a = N \cdot S \tag{17}$$

where L is the height of the sample; T is the propagation period of the longitudinal wave; N is the value of the load at the moment when the pile simulator detaches from the soil; S is the area of the lateral interface between the pile and the soil.

Table 3. Results of the tests aimed at finding shear strength in the soil along the lateral adfreeze zone.

Holding Period	Sample No. 1	Samples No. 2–4	Sample No. 5	Samples No. 6–8	Sample No. 9	Samples No. 10–12
<i>T</i> , min	<i>V_p</i> , m/s	<i>F_a</i> , kPa	<i>V_p</i> , m/s	<i>F_a</i> , kPa	<i>V_p</i> , m/s	<i>F_a</i> , kPa
0	3720	354	3590	341	3633	367
15	3078	167	2950	186	3018	173
45	2154	45	2260	47	2037	52
<i>R</i>		0.97		0.99		0.96

4. Results

Table 3 shows the results of studying the relationship $F_a = f(V_p)$. To analyse the relationship $F_a = f(V_p)$, the correlation coefficient was used.

Based on the results of tests aimed at finding the deformation modulus and the dynamic modulus of elasticity during the thawing of soils, the following correlation was found:

$$E_G = 0.013E + 30 \text{ [MPa]} \tag{18}$$

The values of the deformation modulus and the modulus of elasticity are presented in Table 4.

Table 4. Results of the tests aimed at finding the deformation modulus.

Soil	Method Used to Find <i>E</i>	<i>E</i> by Temperature, MPa		
		−10 °C	−3 °C	(−1 ÷ 0) °C
Sand	acoustic testing <i>E</i>	9800	9300	6800
	Uniaxial compression	163	150	121
	<i>E_G</i> <i>R</i>		0.98	

5. Discussion

The results of the tests aimed at studying the relationship $E_G = f(E)$ showed a strong correlation between E_G and E (Figure 5), which is also evidenced by the value of the correlation coefficient $R = 0.97$. It is worth noting that at the soil temperature $(-1 \div 0 \text{ }^\circ\text{C})$, the value of the deformation modulus decreased by 26% in relation to the value of the deformation modulus found at a temperature of $-10 \text{ }^\circ\text{C}$. A long period of thawing was not considered, since our aim was to provide a rationale for a method that can be used in condition monitoring of permafrost soils to identify the degradation of structural foundations at an early stage. A decrease in the deformation properties of soils by 26% is considered to be critical.

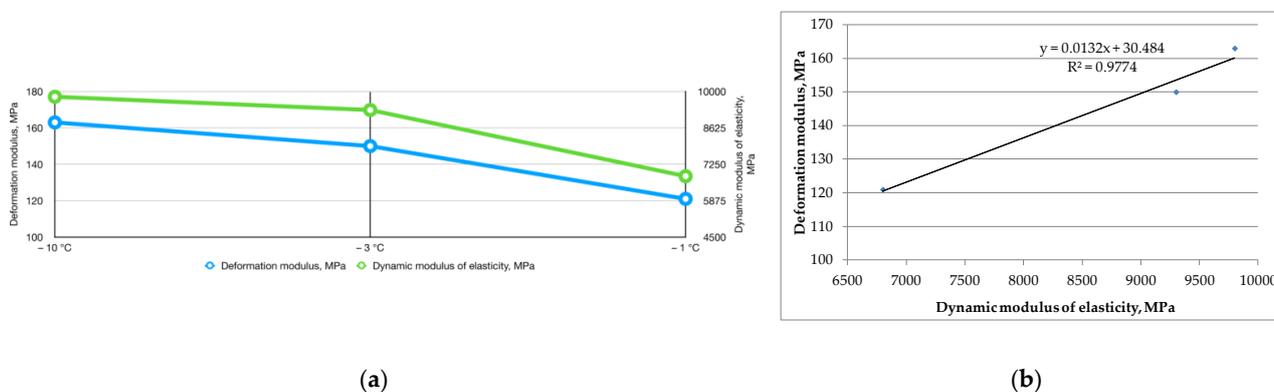


Figure 5. Statistical analysis of $E_G = f(E)$: (a) dependence of deformation characteristics of soils on temperature; (b) dependency regression analysis deformation modulus of modulus of elasticity of soils.

The results of the experimental study of the relationship $F_a = f(V_p)$ that are shown in Figure 6 confirm the assumption that the velocity of propagation of the longitudinal wave and the shear strength of the soil along the lateral adfreeze zone decrease as the soil thaws. The minimum value of the correlation coefficient ($R = 0.96$) signals a significant relationship between these characteristics of frozen soils.

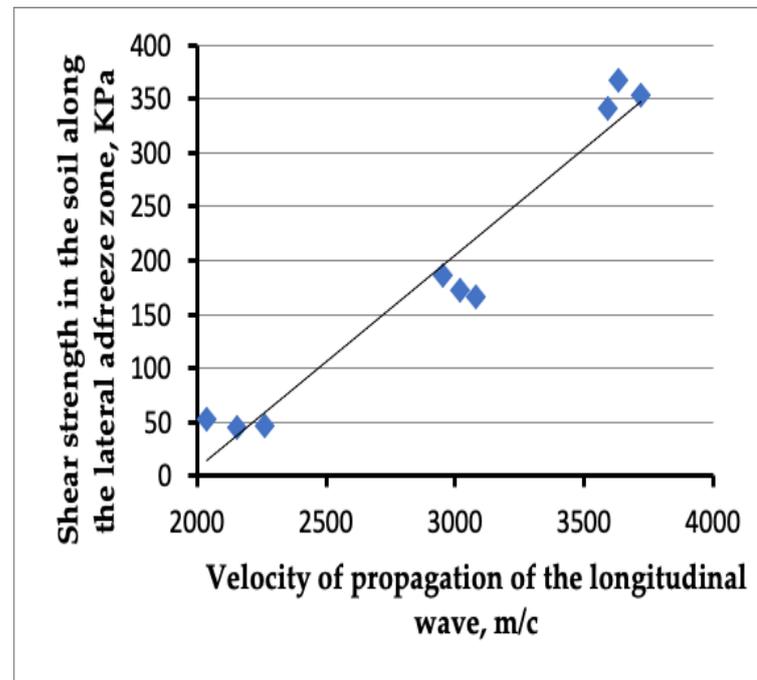


Figure 6. Statistical analysis of $F_a = f(V_p)$.

6. Conclusions

The tests carried out as part of the experimental study discussed here made it possible to draw the following conclusions:

- Using the deformation theory of plasticity makes it possible to factor in the relationship between the deformation modulus and the maximum principal stress.
- Changes in F_a and F_p in the pile-soil system that occur when the soil thaws lead to a change in the resulting load P that is transferred by the structure to the foundation. Taking into account the change in P when condition monitoring of a permafrost foundation allows us to find the correct values of the deformation modulus and the parameters of stress–strain behaviour in the foundation.
- Using the correlation $E_G = f(E)$ established by means of RP tests and acoustic tests makes it possible to monitor the health of permafrost foundations, based on the results of acoustic testing, and prevents soils from demonstrating such properties as hysteresis and hardening/softening.
- The experiments we conducted to study the correlations $E_G = f(E)$ and $F_a = f(V_p)$ showed that these parameters of frozen soils greatly depend on each other, and this dependency can be observed in both frozen and thawing soils. The results enabled us to make tentative conclusions about whether it is possible to use the proposed approach in order to solve the problems of condition monitoring of permafrost foundations. The test results formed the basis of a method that is being developed for condition monitoring of permafrost foundations in buildings and structures.

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