Physical basis of the remote monitoring method of pile foundations of building structures in permafrost areas

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Abstract. The article discusses urgent problems for the northern regions of monitoring the integrity of piles and parameters of the surrounding soil by seismoacoustic and electromagnetic methods and the tasks of remote monitoring for a long time. The possibility of controlling the piles by measuring the intrinsic resonant frequency of the borehole by the acoustic method and the parameters of the surrounding soil using temperature and humidity sensors with an estimate of the tangent of the angle of loss of electromagnetic fields at frequencies of 0.02–1 MHz is estimated.

1. The task of acoustic piling quality control

Due to the intensive development of the northern regions of the Russian Federation, the massive construction of housing and industrial buildings in cities and towns in the conditions of permafrost with installation on a pile foundation, there are real threats of destruction of operating buildings due to violation of the integrity of piles.

This problem can be solved by creating remote automated monitoring systems for pile foundations, requiring the use of modern physical and technical measurement methods and the development of appropriate hardware and software.

The main parameters of piles and surrounding soil, which allow not only to evaluate the current state of objects, but also to diagnose subsequent changes, are the frequency of natural mechanical vibrations of the pile shaft and near pile soil, as well as its temperature and humidity.

To assess the state of piles in Russia, the PDS-MG-4 device developed by Stroypribor (Chelyabinsk) is used, which operates on the principle of recording acoustic signals reflected from the body of a pile upon impact with a hammer.

This portable device is used in construction mode and is operated with the indispensable participation of man. Its cost (about 180 thousand rubles) and the need for the operator to work does not allow the use of this device for the tasks of mass multicast remote monitoring.

Let us evaluate the expected technical characteristics of an automated pile monitoring system. In figure 1 shows a general layout of pile foundations under a building. For remote measurement of the frequency of natural oscillations of piles, seismic receivers or accelerometers are installed on each of them, connected at the outputs to one of the veins of the signal cable.
Figure 1. Layout of sensors for monitoring piles: 1 – soil surface; 2 - pile; 3 - seismic vibrator; 4 - generator of electromagnetic waves; 5 - radiating cable; 6 - grounding; 7 - geophones; 8 - induction sensors; 9 - microcontroller; 10 - radio station for data transmission and control.

A pulsed type vibrator is installed in the center of the structure on the ground or on the base plate, the impact on the soil of which creates Rayleigh seismic waves in the ground, containing up to 95% of shock energy, with a depth of about one seismic wavelength. Under the action of a shock seismic pulse, a longitudinal acoustic wave with a resonant frequency and wavelength corresponding to the relation \( \lambda = \frac{2L}{f} \), where \( L \) is the length of the pile, is excited in each pile. At the speed of propagation of acoustic waves in concrete \( V \), the wavelength is determined as \( \lambda = \frac{V}{f} \).

At \( V=4000 \text{ m/s} \) and \( L=10 \text{ m} \), the wavelength will be \( \lambda=20 \text{ m} \), and the resonant frequency \( f = \frac{V}{\lambda} = 200 \text{ Hz} \).

The appearance of cracks in concrete, for example, in the middle, increases the resonant frequency to 400 Hz, corresponding to the resonance of half the length of the pile.

When using the MG-4 device [1], operating from a blow with a hammer of mass \( m = 1 \text{ kg} \) on a pile, its impact force can be estimated as:

\[
F_c = n \cdot m \cdot g
\]

where \( g=9.8 \text{ m/sec}^2 \) – gravity acceleration;
\( n \) – shock acceleration gain.

At \( n=2; \) \( F_c \approx 20 \text{ kg} \)

To provide the same impact force from a centralized vibrator, it is necessary to create pressure on the pile surface:

\[
P = \frac{F_c}{d \cdot L}
\]

where: \( d \) – pile side width; \( L \) – its length.

This pressure can be determined through the impact force of the vibrator \( F \) as [1]:
where: \( R_0 \) – vibrator baseplate radius; \( r \) – distance from vibrator to controlled pile; \( \alpha \) – loss coefficient in the Earth during the propagation of the Rayleigh wave.

In view of (2), the value of \( F \) should be in the pulse no less than:

\[
F = \frac{\pi \cdot F \cdot R_0 \cdot r \cdot e^{\alpha r}}{d \cdot L}
\]

For example, taking values:
\( R_0 = 0.1 \text{ m}; r = 100 \text{ m}; d = 0.2 \text{ m}; L = 10 \text{ m}; \alpha = 10^{-3} \text{ M}^{-1} \), from (4), we will get:
\( F = 320 \text{ kg} \).

Taking into account the efficiency of the vibrator and the quality of adhesion of the base plate to the ground, the necessary impact force of the vibrator can be 500 - 1000 kg per pulse.

To obtain the necessary signal-to-noise ratio, it is necessary to use the effect of signal accumulation by repeating beats. At the same time, the signal-to-noise ratio in power increases in proportion to the number of strokes during the measurement. The minimum shock repetition period \( T \) is determined by the delay time of the acoustic signal at a distance between the vibrator and the nearest pile \( d_i \). If we take \( d_i = 5 \text{ m} \), and the speed of the seismic wave in the ground is \( V = 2000 \text{ m/s} \), then this time will be: \( t \approx 2.5 \text{ ms} \).

Given the duration of the vibrator pulse \( \tau = 5 \text{ ms} \), the repetition period of the shocks should be at least \( T = t + \tau \geq 10 \text{ ms} \), which corresponds to 100 beats per 1 second.

Since the measurement time during the day can be about one hour, the total number of strokes will be \( n = 3600 \cdot 100 = 360,000 \). This is the potential limit of increasing the signal-to-noise ratio in terms of power and voltage \( \sqrt{n} = 600 \), which makes it possible to raise the spectral density of impact power by this value and compensate for its decrease in a single impact.

If the vibration source is placed on the base plate of the building, for example, in one of the service rooms on the first floor, then the pile will be hit from the end of the pile, the area of which is 25 times less than the side surface area, but this is compensated by a decrease in the attenuation of the seismic wave in the reinforced concrete base plate building.

The implementation of the described method for monitoring the integrity of piles is represented as a multicast encircling system for picking up signals from geophones and their digital processing in the microcontroller of the system, and all the necessary information will be transferred automatically to the computer of the central dispatcher of the city or village via a cellular radio channel.

2. Humidity and temperature monitoring

Next, we evaluate the possibilities of remote control of humidity and temperature of near-pile soil using the electromagnetic method. Measured electromagnetic parameters are selected based on the relevant parameters of engineering geology and hydrology. Geophysical parameters characterizing the cryological state of rocks are: water saturation; soil conductivity \( \sigma \); dielectric constant \( \varepsilon \) and loss tangent \( \tan \delta = \frac{\sigma}{\omega \varepsilon} \), where \( \omega \) is the working angular frequency [2].

The electrical conductivity of rocks \( \sigma \) varies over a very wide range and strongly depends on many petrophysical factors, among which, in the range of positive temperatures, the following are almost equivalent: total rock porosity; pore shape, their size and distribution pattern in the rock volume; degree of pore filling with water, i.e. volumetric moisture content of the rock; state of aggregation of pore moisture; concentration and chemical composition of electrolytes dissolved in pore moisture; the amount and mineralized composition of the colloidal part of the rock.

In conditions of degrading permafrost, the electrical conductivity of rocks, including water and ice, makes it possible to distinguish between frozen and thawed loose rocks. They can be of close importance with non-frozen root (volcanogenic and metamorphic) rocks, however, it is easily determined by
parametric measurements in the surface layer. The presence of even a small level of humidity is sufficient to significantly reduce the resistivity of the rock with increasing field frequency.

The effective electrical resistance $\rho_{\text{ef}}$ and electrical conductivity $\sigma$ of rocks in an alternating current field, obtained with any installation, is well calculated from the measured values of the vertical and horizontal components of the magnetic field and qualitatively characterizes the volume of rocks located in the field of action of the measuring installation (mainly between the transmitter and receiver). To measure $\rho_{\text{ef}}$, one can use the DEMP, EMM equipment with a frequency range of $128 \text{ Hz} – 2.5 \text{ MHz}$ [2].

The dielectric constant $\varepsilon$ varies in a relatively narrow range. Moreover, its value depends on the listed petrographic factors. However, the volumetric moisture content of the rock is dominant, although its mineralogical composition and density also have a noticeable effect. This property of the dielectric constant of rocks is the main advantage as a parameter for determining the natural moisture of rocks, in which the mineralization of pore moisture can vary over a wide range. The dielectric constant also allows you to distinguish between frozen and thawed loose rocks. However, this requires additional time for measuring the elements of the polarization ellipse at each point in the field and then determining $\varepsilon$ using special pallets.

To obtain $\varepsilon$, the existing EMM equipment should be supplemented with tripods with a goniometer device, providing the necessary antenna orientation accuracy.

The dielectric loss tangent is a value that characterizes the total amount of field energy dissipated in it. In this case, one part of the energy is spent on all types of slow polarization in the rock, and the other is spent on through electrical conductivity, i.e. on charge transfer by free ions in soil solutions. Therefore, the value of dielectric losses is not determined only by the value of the through (ohmic) conductivity, but largely depends on the frequency of the field and rock structure. In this case, the structure of the rock should be understood as the amount and nature of the distribution of water in the rocks. The magnitude of the dielectric loss of rocks at a fixed frequency depends mainly on the chemical composition of electrolytes and their concentration in pore moisture, the total moisture content, as well as on the degree of clay content and composition of the clay material [2].

These provisions explain the fact that high-frequency dielectric methods for measuring humidity occupy a dominant position among electrical methods of rock moisture measurement. The tangent of the dielectric loss angle of electromagnetic energy characterizes the moisture content of rocks in a volume corresponding to the dimensions of the measuring installation and can be measured by the phase method.

It is required to study the dielectric properties of the rocks of the studied object in natural occurrence and laboratory conditions.

There is currently no field device; its development and manufacture is required. In the preparatory period, a set of EMM equipment [2] and a serial phasemeter F2-16 can be used as a measuring device.

At the Institute of permafrost of SB RAS (Yakutsk) [4], many years of research have been conducted in the field of studying the electromagnetic field in frozen soils, in particular, using the SEMZ equipment. In the process of research, an empirical parameter was developed for the amplitude attenuation of the intensity of the vertical magnetic component of the harmonic field of a high-frequency vertical magnetic dipole at an optimal frequency of $1.125 \text{ MHz}$:

$$\xi = \frac{\alpha_0 + \alpha_1}{[1 + \alpha_2 \cdot e^{\alpha_3 \cdot L^{0.6}}]},$$

where $\xi$ – amplitude attenuation parameter;
$L^{0.6}$ – volumetric ice index;
$\alpha_0$, $\alpha_1$, $\alpha_2$ – empirical coefficients depending on the place, time and engineering-geocryological conditions for the study of frozen soils.

The task is complicated by the fact that in each case the parameter $\xi$ is determined individually based on a statistical analysis of the totality of the values of this parameter and the ice content of the soils. The approbation of the parameter $\xi$ shows the real possibility of its practical application for solving the
problem of mapping the boundaries of frozen sandy clay soils, as well as the petrophysical task of quantifying their volume ice in the layer of annual heat rotations, which is associated with a large number of field observations.

As is known [2], soil moisture is directly related to its dielectric constant and can be estimated through the loss tangent of high-frequency electromagnetic energy:

\[
tg \delta = \frac{\sigma}{\omega \varepsilon}
\]

In frozen ground, with parameters \( \sigma = 10^{-3} \text{ Sm/m} \), \( \varepsilon = 10 \), \( \operatorname{tg} \varphi = 1 \), the phase shift of the EM signal at 45° is achieved at a frequency \( f = 57 \text{ kHz} \).

According to the data of [3], figure 2 (a, b) shows the dependencies of the \( \varepsilon \) and \( \operatorname{tg} \delta \) parameters of wet sand with electrical conductivity \( \sigma = 10^{-3} \text{ Sm/m} \) on soil temperature at an operating frequency of \( f = 25 \text{ kHz} \).

**Figure 2.** The dependence of the measured soil parameters on temperature at a frequency of 25 kHz: a – the dielectric constant \( \varepsilon \); b – \( \operatorname{tg} \delta \).

As you can see, with the beginning of soil melting, the value of \( \varepsilon \) begins to increase significantly in the range of -5 - 0 °C, and then stabilizes at the level of \( \varepsilon = 60 \). In this case, \( \operatorname{tg} \delta \) drops by a factor of 10.

With an increase in the operating frequency, the ratio \( \varepsilon \omega / \sigma \) increases substantially, which means an increase in bias currents in comparison with conduction currents. Such a dependence of the measured parameter, i.e., dielectric constant, allows not only to evaluate the moisture of the near pile soil, but also the temperature, which makes it possible to avoid the use of thermometers.

The property of the radio wave propagation medium is estimated by calculating the wave number [4]:

\[
K = \beta - ja,
\]

where: \( \beta = K_{1} \left( \sqrt{1 + \operatorname{tg}^{2} \delta + 1} \right)^{1/2} \); \( K_{1} = \omega \sqrt{\varepsilon \mu} \);

\[
\alpha = K_{2} \left( \sqrt{1 + \operatorname{tg}^{2} \delta - 1} \right)^{1/2} \text{ attenuation rate}; \operatorname{tg} \delta = \frac{\sigma}{\omega \varepsilon_{0}}, \quad \text{where} \quad \varepsilon_{a} = \varepsilon' \varepsilon_{0},
\]

\( \varepsilon_{0} = 8.85 \times 10^{-12} \text{ f/m} \) – dielectric constant of air.

The depth of wave propagation from the soil surface is determined by the skin layer, in which the wave field strength attenuates 2.7 times. EM field strength varies with depth according to the law: \( e^{-\alpha \varepsilon} \).

Thus, the parameter \( \beta \varepsilon \) is the phase shift of the wave propagating to a depth of \( \varepsilon \) (figure 3).

At \( \operatorname{tg} \delta > 1 \), \( \beta \) is determined as:

\[
\beta = \sqrt{\frac{\omega \cdot \mu \cdot \sigma}{2}}
\]
If $\tan \delta < 1, \alpha \rightarrow 0, \beta \rightarrow K_1$, which corresponds to a weak dependence of the attenuation of radio waves with depth.

The dependences of the dielectric constant and the loss tangent on the soil temperature indicate the possibility of measuring temperature by an indirect indicator of the phase shift between the signals recorded by the receiving electromagnetic field sensor and the current in the transmitting antenna.

The dependence of the depth of the skin layer of the EM field on the frequency for frozen soil at a temperature of $-15^\circ$ C is shown in figure 3, from which it can be seen that, for relatively small depths $z = 10$ m, it is advisable to work at low frequencies, on the order of $10^{10}$ kHz.

![Figure 3. Dependence of skin depth $\Delta d$ on frequency $f$.](image)

The temperature empirical dependence of the resistivity of gravel-pebble sediment samples of the Kolyma river basin is given [3], which confirms the calculated graphs and generally allows us to conclude that it is possible to measure the temperature of near-pile soil by observing its apparent resistance.

Since $\tan \delta$ depends on two parameters $\sigma, \varepsilon$, their separate observation requires measurements at least at two frequencies - low and high.

From the relation $\sigma \gg \omega \varepsilon$, for example, at $\tan \delta = 10, \varepsilon = 10$ and $\sigma = 10^{-4}$, which corresponds to the parameters of frozen soil, the operating frequency is estimated as $f = 57$ kHz.

At $\sigma \gg \omega \varepsilon$ for melted water, when $\sigma = 10^{-3}, \varepsilon = 50; \tan \delta = 0.1; f_s = 1.14$ MHz.

If we use relative measurements of the two magnetic components of the field $H_x$ - horizontally and $H_z$ - vertically, when excited by a magnetic dipole, then according to [6], the value of $\sigma$ can be calculated at low frequencies $f \leq 20$ kHz:

$$\sigma = \frac{4}{\omega \mu_0 r^2} \frac{H_x^2}{H_z^2},$$

(9)

where $r$ – distance between emitter and receiver.

However, due to the nonlinear dependence of the parameter $\sigma$ on distance and reflections from piles, base plate and soil, the determination of this parameter according to (9) seems complicated and requires individual calculations for each pile.

To measure the parameters $\sigma$ and $\varepsilon$, it is advisable to use the method of electrical exploration using an infinitely long cable, which consists in emitting the primary electromagnetic field with a long grounded line and recording the magnetic field with an induction sensor of the horizontal field component.

Since the amplitude of the signal at the output of such a sensor during field excitation by the cable does not depend on environmental parameters, soil moisture must be estimated by measuring the phase
The dielectric constant of the medium, which directly depends on humidity, in this case will be determined through the measured phase shift \( \varphi \) as:

\[
\varepsilon = \frac{\sigma}{\omega \cdot \tan \varphi},
\]

(10)

It is advisable to place the receiving magnetic sensors in shallow wells (0.5-1 m) between piles in a horizontal plane orthogonally with respect to the exciting cable (figure 1).

During the implementation of the project, the power cable can be laid under the building along it, and the signals of the magnetic receivers will be transmitted via a two-wire communication line to the central microcontroller, and after digital encoding, broadcast via a cellular radio channel to the computer of the city or village dispatcher.

3. Conclusions

1. For the physical basis of a comprehensive method for remote monitoring of pile foundations in permafrost conditions according to the parameters of mechanical strength, humidity and temperature, acoustic control can be laid on the natural frequencies of piles and the measurement of the electrical conductivity and permittivity of the surrounding soil by the electromagnetic method.

2. The implementation of the acoustic control method is represented as the installation in the center of the building on the ground of a pulsed electromagnetic emitter of Rayleigh elastic waves and fixing on the piles of the geophones connected by a cable line to the central microcontroller that calculates the natural frequencies of the mechanical vibrations of all the piles.

3. It is advisable to measure soil moisture and temperature by the method of an infinitely long cable at two operating frequencies, for example, 25 kHz and 1 MHz, which allow obtaining information separately on the parameters of electrical conductivity \( \sigma \) and permittivity \( \varepsilon \).

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