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Identification of possible structural defects on piled foundations supporting structures on permafrost soils: Norilsk's Palace of Culture case study

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ABSTRACT

For the safe operation of buildings and engineering structures, and for carrying out restoration work, it is necessary to monitor their technical condition. This paper presents a developed method based on extraction of standing waves from seismoacoustic noise, demonstrating the possibilities of using passive seismic for examining fixity conditions of foundation piles' and determining its sections characterized by a relative increase in stresses using the Palace of Culture (Norilsk) building as the case study. The standing waves were extracted from the recorded acoustic noise by the accumulation of amplitude spectra of a large number of noise recordings. It is shown that the amplitude spectra can be used to reliably determine the fixity condition of foundation piles. The obtained field experiments results are qualitatively consistent with the results of the computer simulation by the finite element method both for individual piles and for the detected foundation anomalies.

1. Introduction

In the northern areas one of the civil engineering features is that the buildings and structures foundations usually installed on piles due to permafrost soils. The usage of pile foundations allows minimize the thermal influence from building foundation to soils and minimizing the risk of their defrosting, which will lead to the deformation of the foundation and destruction of the building.

However, nowadays, the daily average temperatures in northern latitudes are increasing because of climate changes. Temperature increasing leads to partial thawing of soils that negatively affects the fixity condition of pile foundations, causing the individual piles in the thawing zones to lose its stability.

To maintain the frozen state of soils, various technologies are often used, such as cryogels injections [1], into the thawing zone. However, for the effective usage of this technologies monitoring or periodically diagnose the condition is needed.

To date, a large number of various methods for examining engineering structures are used, the use of which makes it possible to present the characteristics of structural components and materials from which they are composed in various geophysical fields. Analysis and interpretation of the observed geophysical fields and anomalies in them allow one to draw conclusions about the state of the structure under study.

The most widely used group of methods for engineering and geophysical survey of the condition of buildings is the class of seismoacoustic methods. Usually, it's ultrasonic inspection of buildings in a large number of its modifications (ultrasonic translucence, reflected wave method, ultrasonic tomography). This method is mainly used for detection of inhomogeneities and voids in the concrete structures (cracks, microcracks, honeycomb structures and cavities) [2-5].

Among the class of seismic methods, the methods that study the response of the examined structure to the natural or artificial direct seismic impact caused by shock, vibration, or earthquake are also common [6,7]. Studying the response of a structure to a seismic impact makes it possible to draw a conclusion about its stability and obtain the amplitude-frequency characteristic of the building's natural vibrations, the analysis of which allows one to determine the presence of defects by monitoring the appearance of additional vibrations, in addition to those that occur at the natural frequencies of the structure [8,9].

In addition to the engineering and seismological survey of a building, it is effective to conduct both mathematical and physical modeling of the

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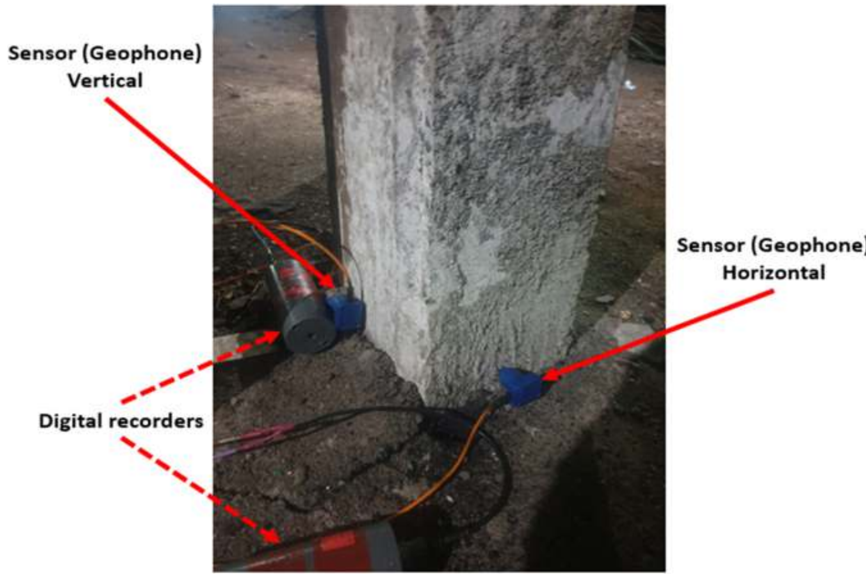

Fig. 1. Horizontal and vertical GS 20DX geophones mounted on the pile surface with Texan recorders (RefTek-125A).

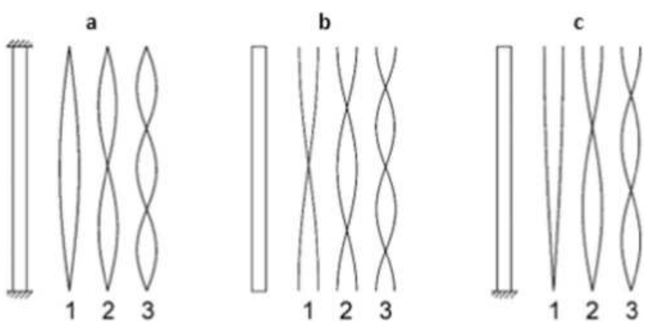

Fig. 2. Schematic representation of the distribution of nodes and antinodes of the first three modes of standing waves in a rod (a) restrained boundary conditions at both ends, (b) in an unrestrained boundary condition at both ends, and (c) in a restrained boundary condition at one end.

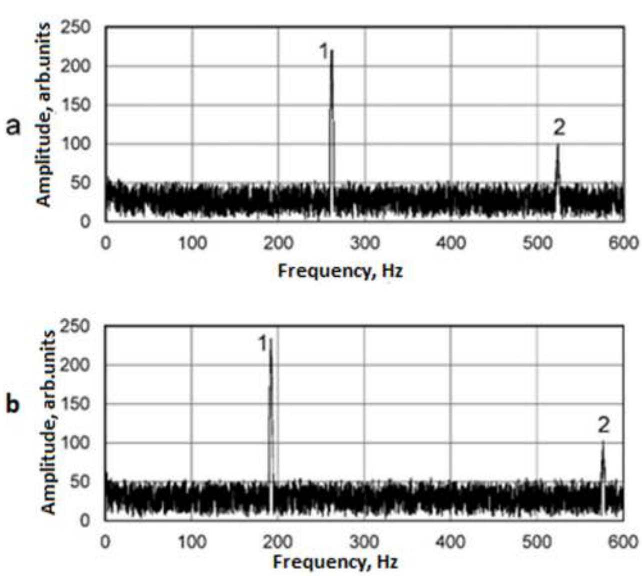

Fig. 3. Examples of amplitude spectra of rod standing waves in piles. The numbers indicate the mode numbers of standing waves. (a, b) – distribution of peaks of standing waves according to formulas (1) and (2), respectively.

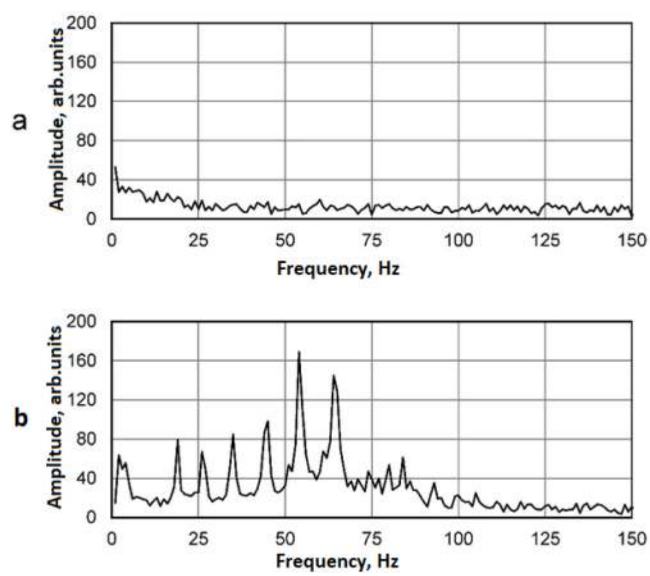

Fig. 4. Examples of amplitude spectra of flexural standing waves in piles for (a) bad piles' fixity, and (b) good piles' fixity recordings from horizontal geophones.

building structure in order to obtain its seismic and vibration characteristics. The least expensive and widely used is mathematical modeling, usually performed using finite element calculation schemes. The finite element approach makes it possible to recreate in detail the geometry and physical properties of structural elements of a structure, which makes one calculate with high accuracy many different building parameters, and predict its behavior and durability under various operating conditions [10-12].

Much more accurate information can be obtained by physical modeling which is a large-scale reconstruction of the structure of the building, followed by its testing with the help of vibrators and industrial explosions located both on it and in the immediate vicinity. However, this approach often leads to the destruction of the model, which is why it is extremely expensive and is used less frequently in practice [13].

The second large class is electromagnetic methods for buildings and engineering structures inspection. The most commonly used are radar

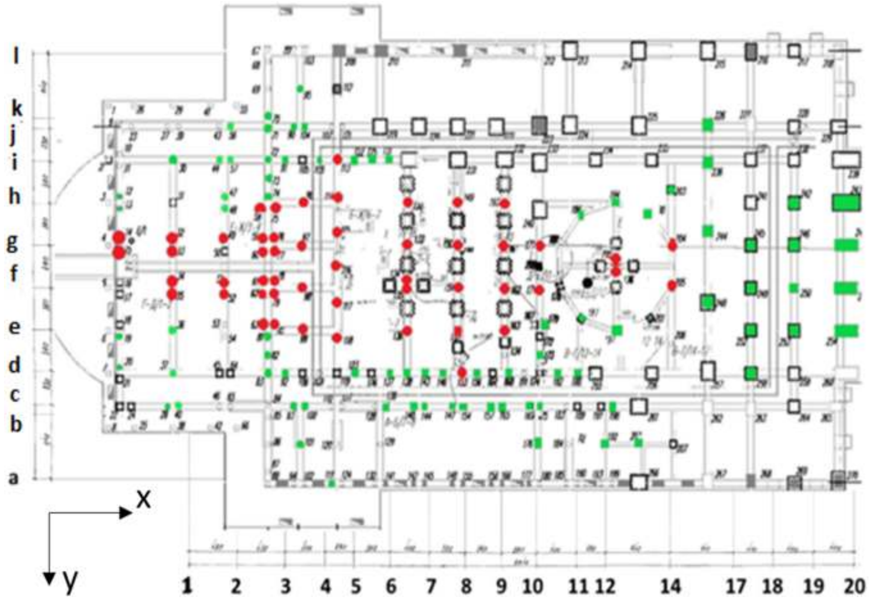

Fig. 5. The layout of the piles. Bad piles' fixity is shown in red, and good piles' fixity piles are in green.

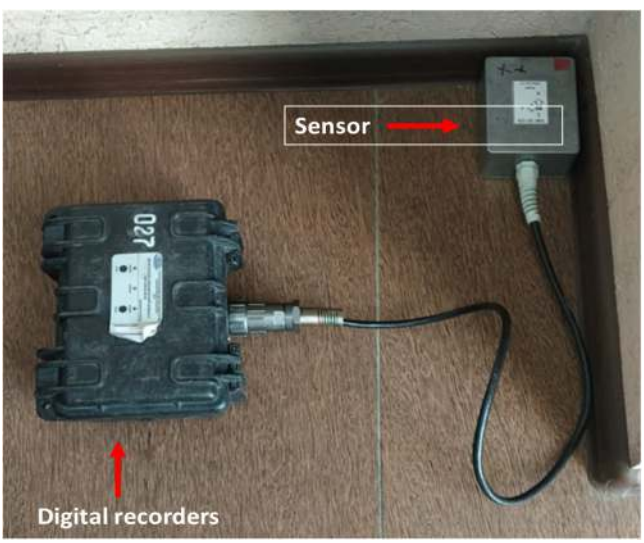

Fig. 6. The recording process on the first floor of the surveyed structure using the Baikal-7 recorder and a three-component GD-10 sensor.

methods in their various forms. Thus, georadar survey (GPR, TWIR) is widely used due to its high performance, which makes it possible to examine the structure in detail in terms of the geometry of the structure (including subsurface) and the positioning of structural connections. Also, radio waves of different frequencies can penetrate various materials, which allows one to focus on specific structural elements (masonry, reinforcement, etc.) [14,15]. With the development of technologies that allow the processing of large amounts of data, satellite interferometry methods that allow tracking absolute structural displacements of structures have become popular in recent years [16]. Along with radar methods, the method of infrared thermography which measures the infrared radiation emitted and reflected from the surface of the object under study is in high demand. This method is usually used to detect thermal anomalies in buildings, which in turn indicate humidity inside wall structures [3,17].

Due to the complexity of use and low noise immunity relative to other methods, magnetic methods of non-destructive testing of buildings and engineering structures are less common. However, some types of defects such as corrosion and fracturing of metal structures, stand out perfectly due to the use of magnetic flux leakage detection (MFL) and eddy current testing (ECT) [18].

In practice, due to the different sensitivity of the above methods to different types of defects, they are often used together [5,19]. The basis for complex field surveys and the creation of computer models are often the results obtained using high-precision photogrammetry or laser scanning (LiDAR). In addition to the basis for the overlay of geophysical data, these methods are used independently for visual flaw detection. Their resolution makes it possible to detect minor defects manifested on the surface of structural elements of a structure, however, they cannot detect hidden internal structural defects [20].

In as much as the above stated methods make it possible to examine the condition of the engineering structure, the need to find realiable and cost-effective methods remains relevant at the present time.

This article demonstrates the possibilities of using the method of extracting standing waves from seismoacoustic noise for examining foundation piles' fixity conditions and determining structural defects sections using the Palace of Culture (Norilsk) building as the case study. The experimental results shows that the proposed method is a cost-effective, reliable and environmentally friendly tool for examining the technical condition of engineering structures.

2. Study object and method of observation

To conduct the research and comprehensive testing of the technology, a defective building located in the northern latitudes was required. Another important factor was the practical benefit for the building owner. It is necessary that after the study the owner could carry out repair work and continue to operate the building.

The Palace of Culture of the ZF of PJSC MMC Norilsk Nickel (Leninsky Prospekt, 9, Norilsk) was considered as the study object for this research because of its cultural importance and obvious presence of defects, which is important for benchmarking the method. To study the natural vibrations of the structural components of the object, the above-described method was used, based on the extraction of standing waves from seismoacoustic noise. The technique consists of the accumulation of a large number of amplitude spectra of noise recordings, as a result of which peak sequences corresponding to families of standing waves of different types appear on the averaged (or accumulated) spectra.

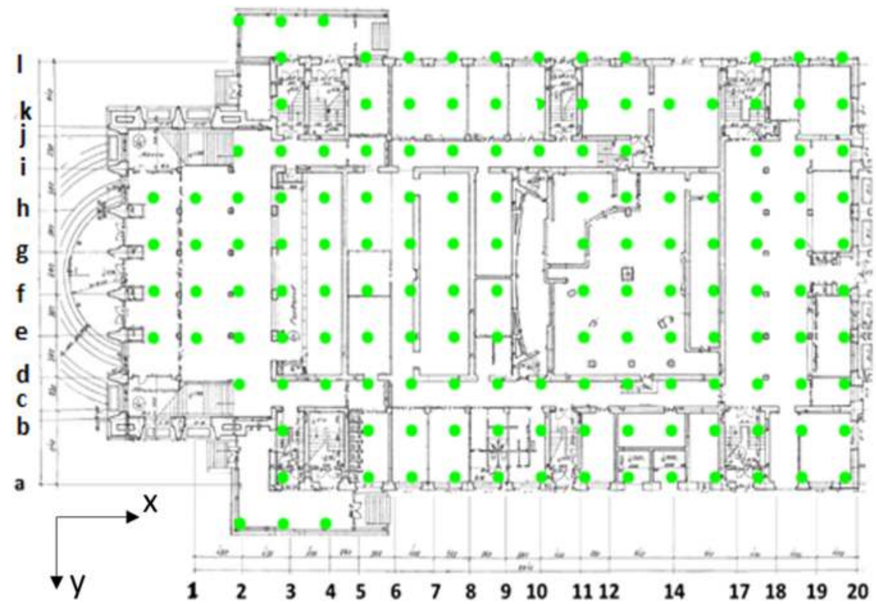

Fig. 7. Sensor installation sites on the first floor of the Palace of Culture.

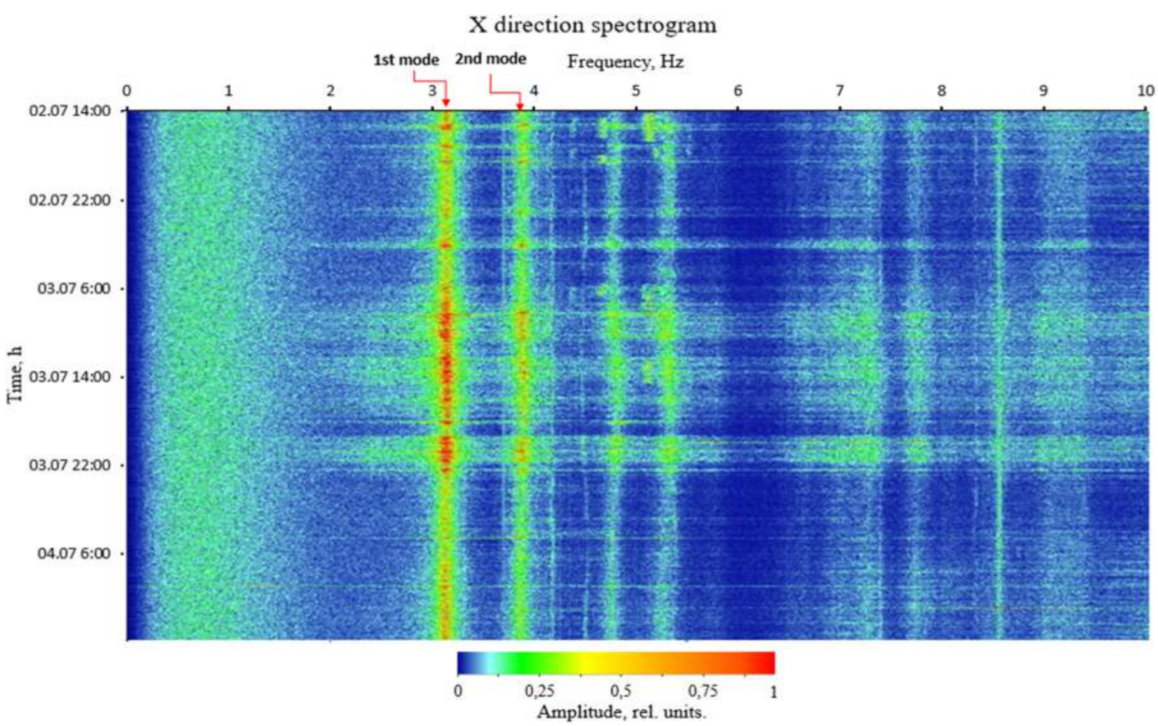

Fig. 8. Spectrogram for the X component.

The method of diagnosing the piles' fixity on which the foundation of the building under study is installed is reduced to the sequential execution of the following operations.

1. Recording of noise recordings on the object under study to extract standing waves in them using two sensors – a statically fixed (reference) and a movable one.
2. Normalization of the noise level of the moving sensor to the level of the reference one for each measurement.
3. Splitting noise recordings into blocks (in our case, 8192 counts).
4. Fourier transformation for each block and averaging the obtained amplitude spectra by summing them.
5. Identification of standing waves on averaged amplitude spectra.
6. Representation of the obtained results in graphical form (averaged spectra, distribution maps of piles' good fixity and bad fixity, amplitude-frequency distribution maps for various modes of standing waves, etc.).
7. Comparison of the obtained experimental results with the results of mathematical modeling by the finite element method of natural frequencies of the structural elements of the structure.

In the described series of experiments, the registration of seismoacoustic noises was carried out in the summer. Horizontal and vertical GS 20DX geophones with a natural frequency of 10 Hz and single-channel

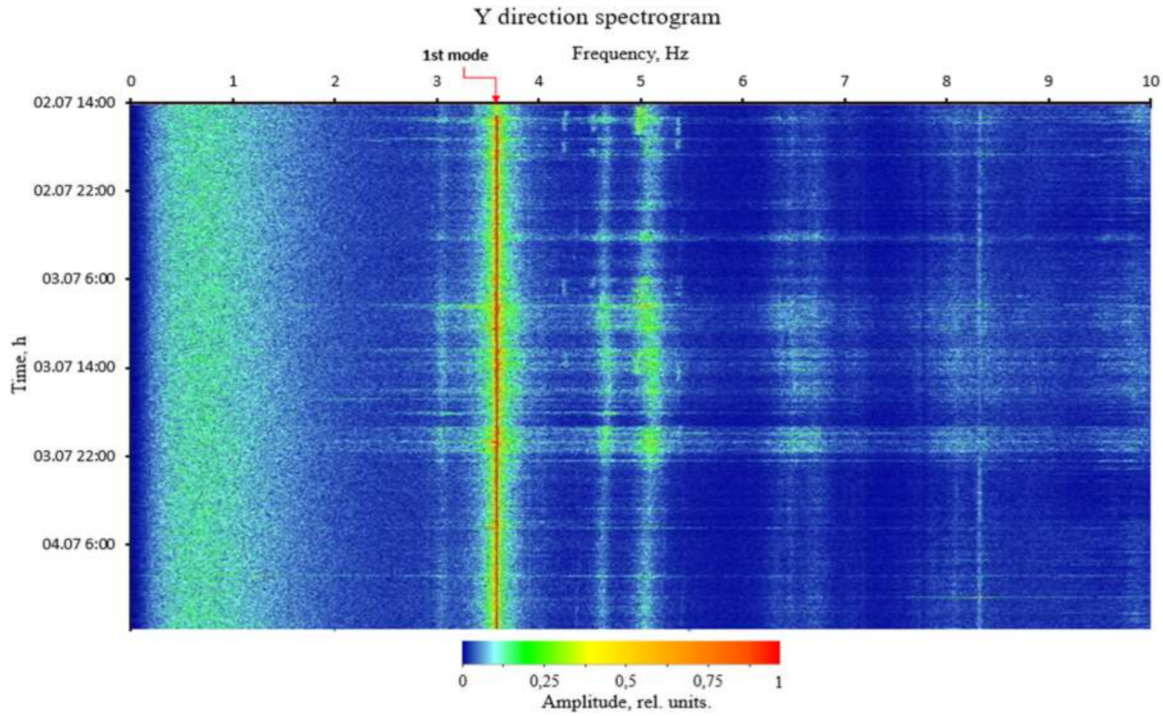

Fig. 9. Spectrogram for the Y component.

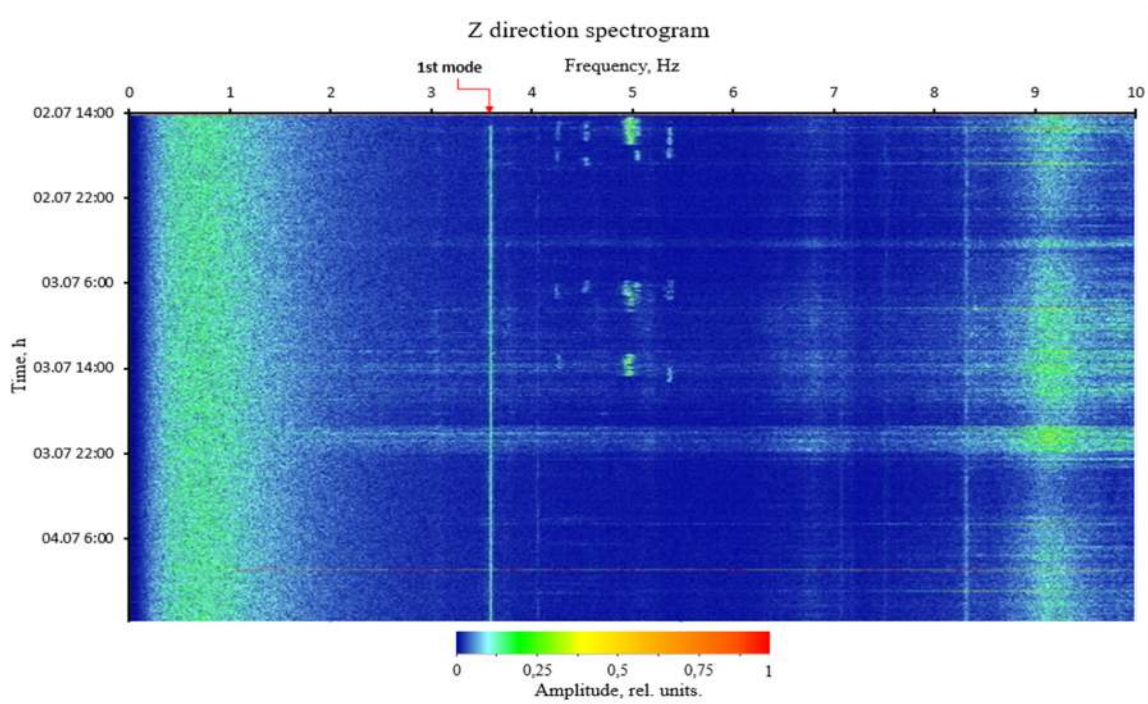

Fig. 10. Spectrogram for the Z component.

autonomous TEXAN digital recorders (REFTEK-125A) with a sampling frequency of 10 kHz were used for recording (Fig. 1). The choice of these recorders is justified by a lower level of internal noise, in comparison with other available recording equipment, which significantly improves the quality of output data [21].

In the object under study, the noise was recorded on the outer side surfaces of piles by horizontal and vertical geophones. To improve contact, in some cases, the sensors were additionally fixity with a rigid clamp. The duration of continuous recording at each observation point was 15 min (Fig. 1).

3. Justifications of diagnosing the piles' fixity condition using elastic standing waves

When assessing the technical condition of buildings and structures built on permafrost, one of the main objectives is to diagnose the fixity

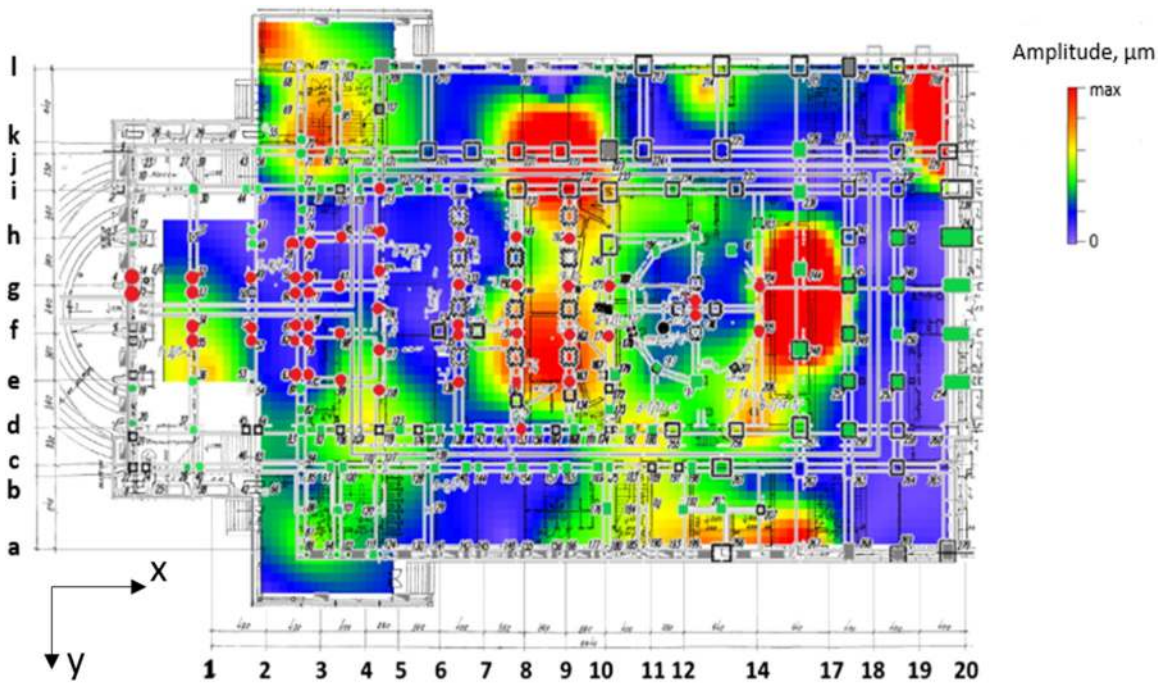

Fig. 11. Joint visualization of the spatial distribution of the amplitudes of natural vibrations of the building in the lowest mode on the Y component and the pile field.

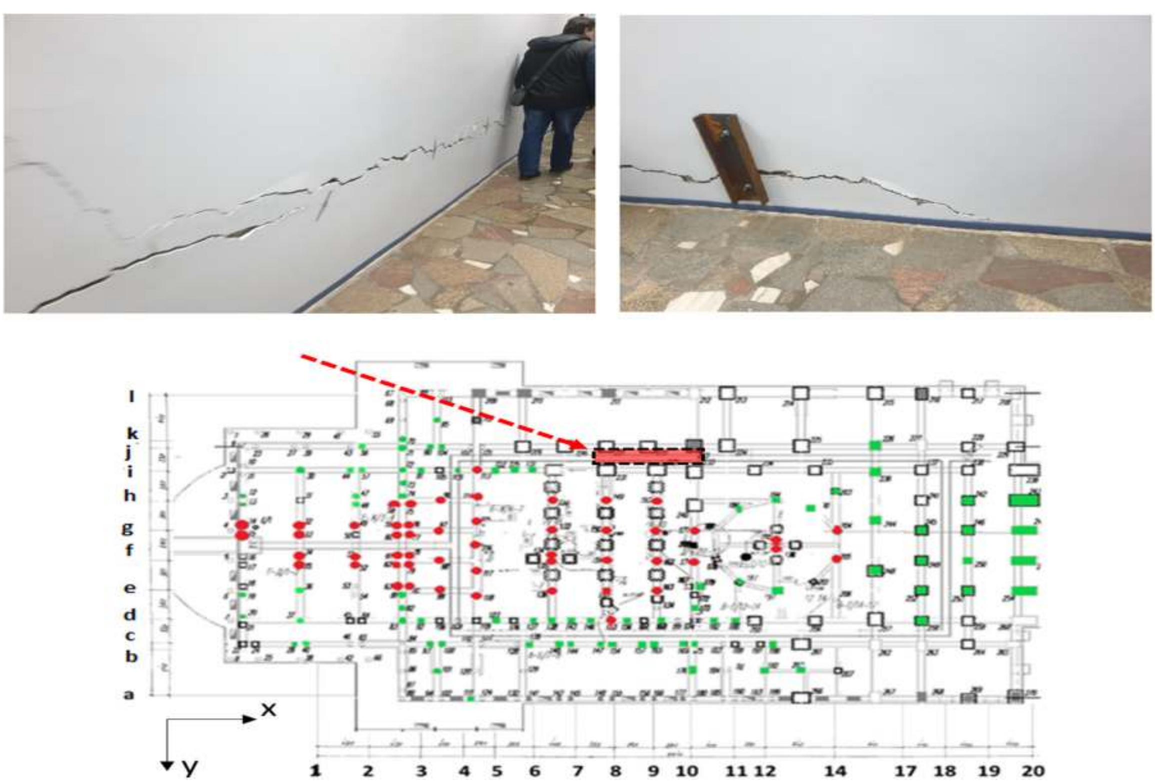

Fig. 12. Examples of cracks on the ground floor (Location highlighted in plan).

condition of piled foundations supporting structures. Piles in the first approximation can be considered homogeneous rods, thin in comparison with their length. If elastic vibrations are excited in a rod in any way, then as a result of interference of reflections from its ends, standing waves are formed in it [22].

If there is a hard fixity on both sides of the rod, displacement nodes should form at its ends. Since the distance between the nodes is equal to half the wavelength, then an integer number of half-lengths of waves fits along the length of the rod (Fig. 2a), and its natural frequencies are determined by the formula [23].

$$f_n = \frac{nV}{2L}, \quad (1)$$

where n – standing wave mode number, V – propagation velocity of

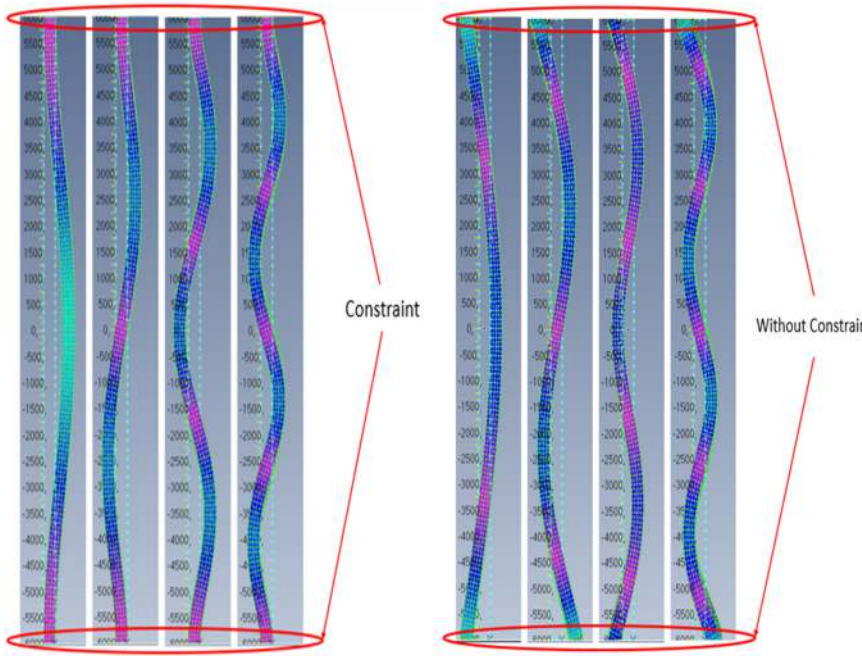

Fig. 13. The first four flexural modes of vibrations are rigidly fixed at both ends of the pile and natural flexural vibrations of a rigidly loose pile.

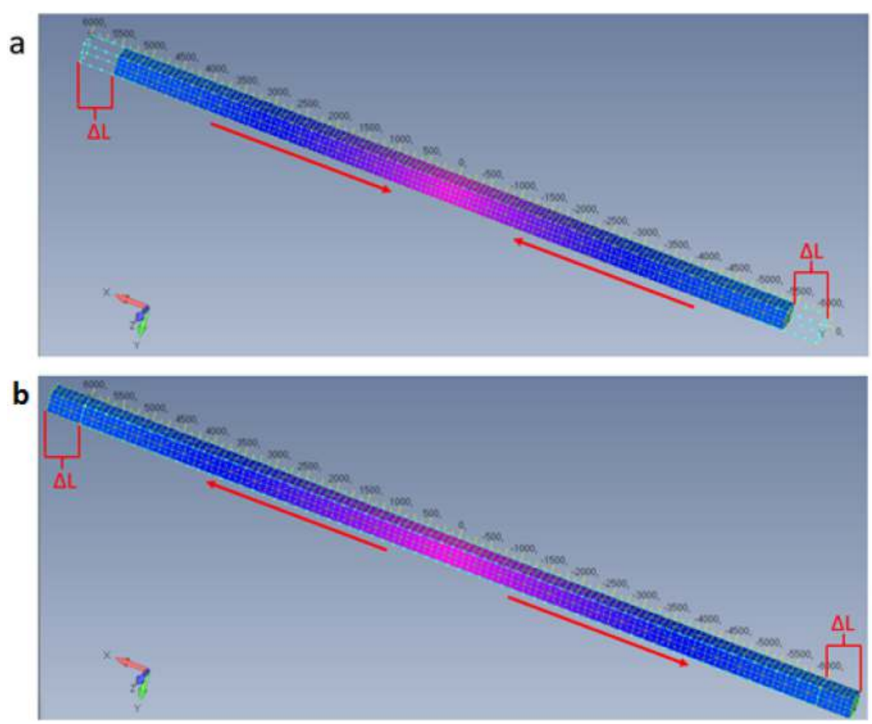

Fig. 14. Schematic representation of longitudinal compression-expansion for the lowest mode in an unfixed pile: a – compression phase, b – expansion phase.

interfering elastic waves, L – rod length. In the case of an unrestrained boundary conditions at the ends of the rod, antinodes are formed at its ends, the distance between which is also equal to half the wavelength, therefore, the natural frequencies of such a rod are also determined by the formula (1) and an integer number of half-lengths of waves fit along the length of the rod (Fig. 2b).

If the rod has a restrained boundary condition only from one end, then a node is formed at this end and an antinode is formed at the unrestrained end, and an odd number of quarters of wavelengths are placed on the length of the rod (Fig. 1b). Natural frequencies, in this case, are determined by the formula [23].

$$f_n = \frac{(2n-1)V}{4L}. \quad (2)$$

The type of standing waves is determined by the type of interfering waves, therefore, in principle, standing waves of different types can exist in rods, in particular rod and flexural waves. In the first case, for standing waves of at least several lower orders, the velocity V in formulas (1) and (2) can be considered independent of frequency and equal to the value of the propagation velocity of longitudinal compression-

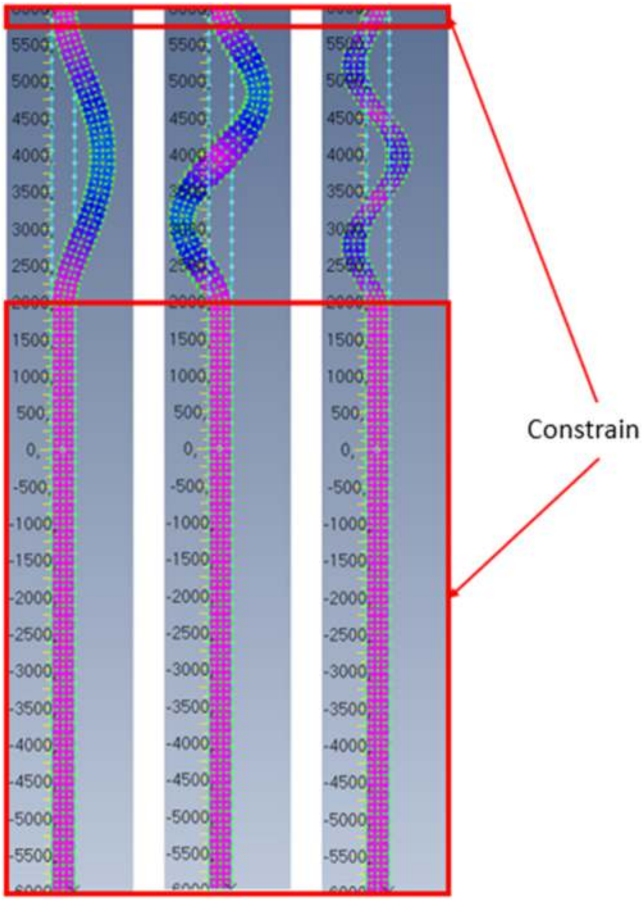

Fig. 15. Three lower flexural vibration modes of the upper section of the pile with good fixity. Sections from −6000 to 2000 mm and the upper end were fixed.

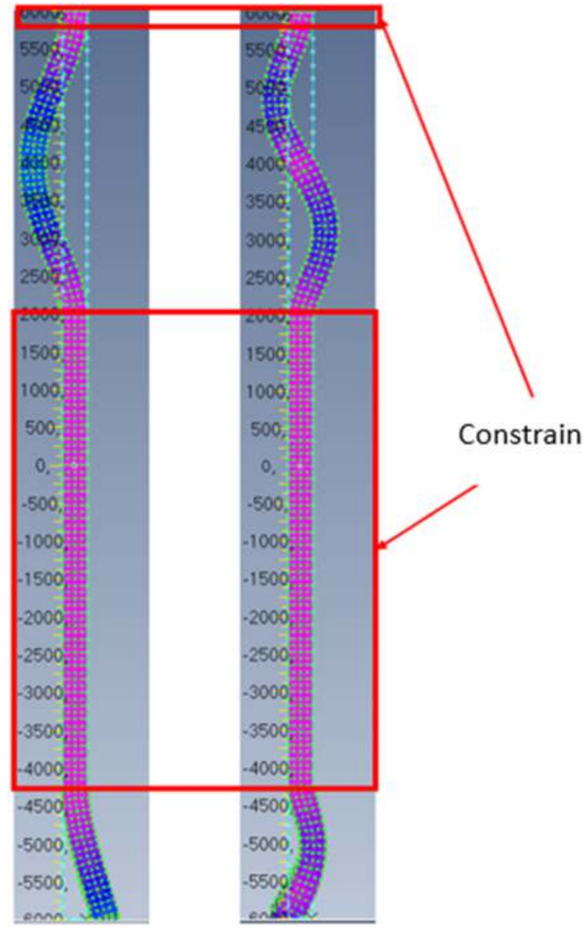

Fig. 16. The first two flexural modes of vibrations of the upper and lower sections of the pile showed that the fixity was lost at the bottom. Sections from −4250 to 2000 mm and the upper end are fixed.

expansion vibrations in thin rods V_b (rod velocity). This is explained by the fact that experiments [24] show that the dispersion (frequency dependence) of the velocity of longitudinal waves in rods made of high-quality material is practically absent for wavelengths exceeding the diameter of the rod by an order of magnitude or more. The consequence of the absence of rod velocity dispersion is the regularity of the spectral peaks of rod standing waves on the frequency axis – the interval Δf between adjacent peaks (natural frequencies) for lower-order modes is equal to the frequency of the lowest mode for formula (1) and twice the frequency of the lowest mode for formula (2):

$$\Delta f = (f_{n+1} - f_n) = V_b/2L. \quad (3)$$

For flexural standing waves, the situation is more complicated, the velocity V in formulas (1) and (2) is equal to the velocity of flexural waves $V_f(f)$ which is characterized by strong dispersion (frequency dependence) in the low-frequency range. Accordingly, the distribution of spectral peaks on the frequency axis in this case has a quasi-regular character. Nevertheless, the features of the distribution of spectral peaks on the frequency axis can be diagnostic signs for assessing the technical condition of the pile foundations of buildings and structures.

Taking into account the above, one of the methods of diagnosing the technical condition of buildings and structures in the areas of permafrost distribution can be based on the analysis of the natural frequencies of piled foundations supporting structures. Various methods can be used to determine these frequencies, including those with active or vibrational sources. In several studies [25-29], a passive method based on the registration of seismoacoustic noises and the accumulation of their amplitude spectra to extract standing waves from the noise field was used to determine the natural frequencies of various engineering and engineering-geological objects. The methodological approaches described in the above works were also used in this study.

3.1. Pile foundation inspection results and discussion

A study of all 133 piles supporting the foundation of the structure was carried out at the object under study. When processing the experimental data, the noise records recorded on each pile were divided into blocks with a duration of approximately 0.82 s (8192 counts), and the amplitude spectra of these blocks were calculated and accumulated. As a result, sharp peaks which corresponded to modes of the compression–expansion type according to formulas (1) or (2), appeared in the amplitude spectra after recording vertical components. Fig. 3 shows examples of the distribution of peaks corresponding to the first two modes of the rod (longitudinal in the rod) standing waves on the frequency axis.

For the first spectrum (Fig. 3a), the frequencies of the first and second compression-expansion modes are 261.7 Hz and 523.1 Hz, which corresponds to formula (1). The peak frequencies in the second spectrum (Fig. 3b) are 192.2 Hz and 576 Hz, which agrees with formula (2). With a known rod velocity in the pile, formula (3) can be used to determine the length of the pile. Measuring the rod velocity in several piles gave an average value of 4460 m/s. Using this velocity and the frequency difference of the first and second modes in Figs. 3a and 3b, it is possible to calculate the length of the piles of which the obtained values were 8.52 m and 11.6 m, respectively. Consequently, the length of 117 of the studied 133 piles was determined. It was not possible to determine the

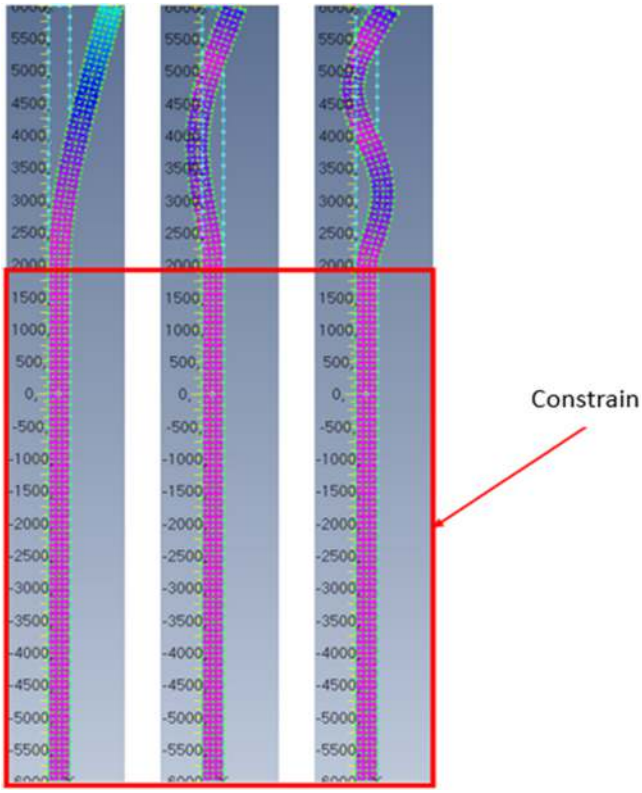

Fig. 17. Three lower flexural modes of vibrations of the upper section of the pile under the bad fixity condition of the pile to the grid beam. Fixed sections from −6000 to 2000 mm.

length of another 16 piles since they have good fixity with rocks, the acoustic stiffness of which is similar to the stiffness of concrete, which excludes the reflection of elastic waves from the lower boundary of the pile.

In the part of the foundation located on rocks, provided the pile is firmly fixed in the rocky ground, it is very difficult to determine the length of the pile since there is no sharp reflecting boundary at the base of the pile (the acoustic stiffness of the pile material and rocks are similar). However, in this case, the piles had good fixity conditions. As a result of processing the data obtained from horizontal geophones, averaged amplitude spectra were also obtained (Fig. 4).

It can be seen that the amplitude spectra obtained from the data of the horizontal geophones differ from those obtained as a result of processing the data of the vertical component. The averaged amplitude spectra obtained from records on bad piles' fixity show quasi-regular sharp peaks corresponding to flexural standing waves. Such quasi-regular peaks are not observed on the spectra obtained from measurements on good piles' fixity, which indicates the absence of a shear component of vibrations in such piles. Fig. 5 shows the layout of the foundation piles of the object under study. The piles recognized as bad piles' fixity according to the results of the survey are displayed in red, and good piles' fixity in green.

In the second stage of the work, the spatial distribution of the amplitudes of the natural vibrations from the lowest modes of the building foundation was constructed. The work was carried out using Baikal-7 seismic recorders and three-component GD-10 sensors with a natural frequency of 5 Hz (Fig. 6).

Fig. 7 shows a map of the location of sensors during the examination on the first floor of the Palace of Culture. Continuous recording was carried out for each observation point for 15 min.

For each observation point, the data was recorded and processed in accordance with the algorithm described above for extracting standing waves from microseismic noise. As a result of processing, the amplitude-frequency characteristics of the natural vibrations of the base of the structure were obtained.

The frequencies of the first three vibrational modes were determined for the X and Y components, and only the frequency of the first mode of natural vibrations was determined for the Z component. The values of the natural vibration frequencies for all three components were as follows:

- X component: 3 Hz, 3.8 Hz, 5.2 Hz.
- Y component: 3.6 Hz, 5.12 Hz, 6.32 Hz.
- Z component: 3.6 Hz.

Examples of spectrograms obtained as a result of data processing utilizing a windowed Fourier transform in a sliding time window of 100 s in size with a step of 50 s over a long measurement period (three days) are shown in Figs. 8–10.

After analyzing the data obtained for each of the sensors, the amplitude distributions over the foundation area were constructed for each of the natural frequencies of the foundation of the structure. With joint visualization of the amplitude distributions of natural vibrations at different frequencies and a map of the location of good and bad piles' fixity, it can be seen that the zones with high vibration amplitudes are distributed along the edges of sections with good piles' fixity. Fig. 11 shows the spatial distribution of the amplitudes of natural vibrations along the Y component at a frequency of 5.12 Hz with a mapped pile field (good and bad piles' fixity). Zones with high amplitudes indicate high stress values in these areas, which inevitably leads to the deformation of the structure, and the appearance of cracks which can cause its destruction.

Cracks are observed in many areas of the building with high natural vibration amplitudes (Fig. 12).

4. Vibrations of pile structures based on the results of mathematical modeling

To describe the modes of flexural natural vibrations and the modes of longitudinal compression-expansion vibrations characteristic of foundation piles, models of piles mainly used in construction in permafrost zones, models of drilling piles SMT 12–32, produced according to the standard "Series 1.011.1–8 m" were created in the Ansys finite element computer modeling system.

Pile geometrical parameters: $12000 \times 320 \times 320$ mm, cement concrete material. The elements of the calculated grid are tetrahedra with a face length of 160 mm at the top and 226.2 mm at the base. With these calculation parameters, several models were created corresponding to various types of fixity of the building pile in the ground and fixity with the overlying grid beam.

Fig. 13 presents the first 4 modes of flexural vibrations characteristic of any extended beam-type objects rigidly fixed at both ends and without fixation. It can be seen that the fixed ends of the beam (marked with a red oval) are stationary, and the amplitude of their vibrations is equal to zero. Such sections correspond to the nodes of standing waves (natural vibrations of the beam). At the same time, the beam bends between them and there is an alternation of sections characterized by the maximum deviation (antinodes) from the vertical axis and the absence of deviation (nodes).

In the absence of fixity at the ends of the beam, vibrations also occur, and the ends cease to be nodal points and are also characterized by oscillatory deviations from the vertical axis.

Thus, the presence or absence of flexural vibrations at the points that must be fixed according to the project is a reliable diagnostic sign of the quality of the beam fixity in the surrounding medium (soil, concrete, etc.). On the amplitude spectra of standing waves, the presence or absence of such vibrations is manifested by the presence or absence of quasi-regular peaks, which indicates, respectively, the good or bad fixity

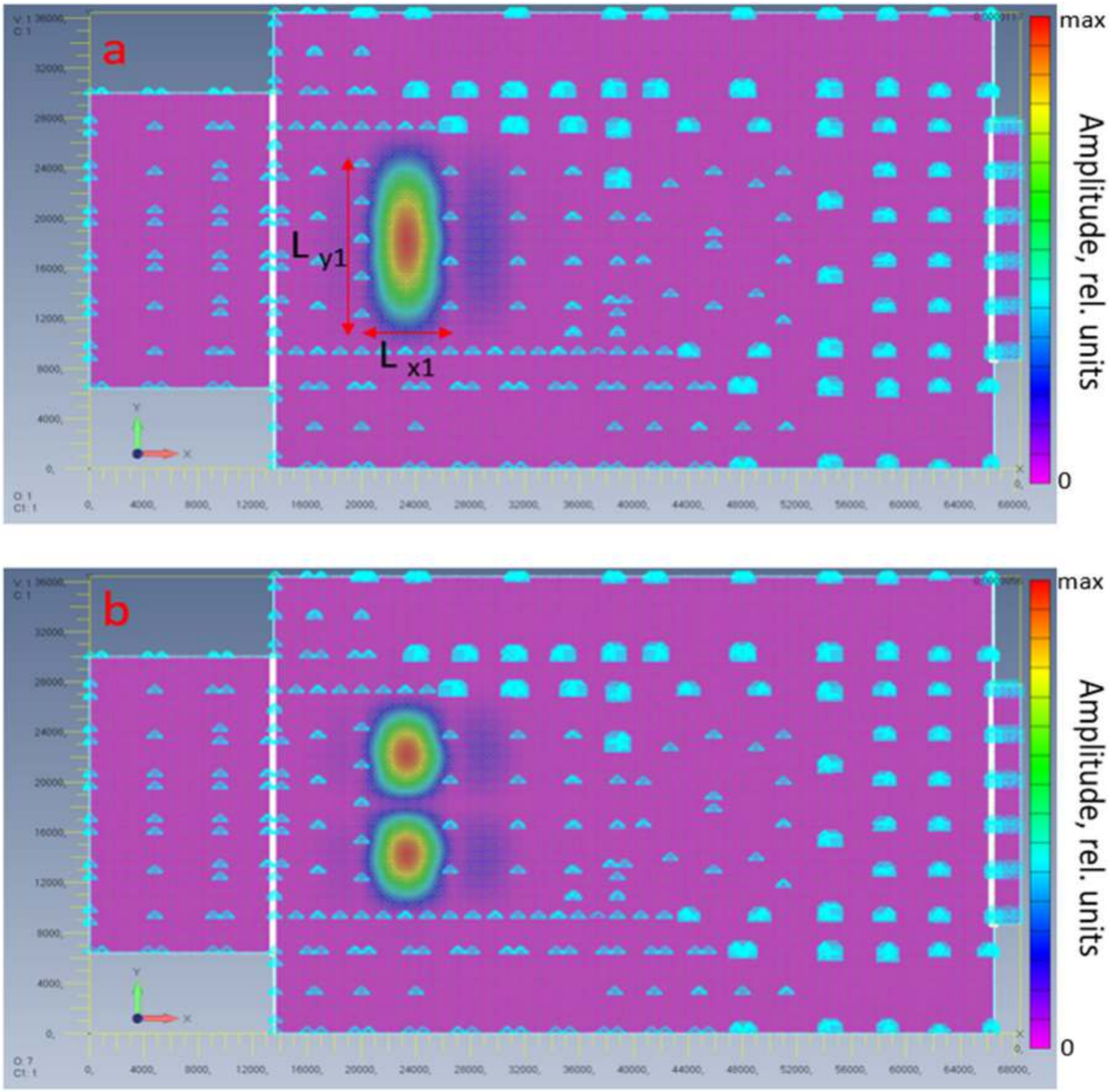

Fig. 18. The first two modes of vertical natural vibrations of the foundation model with good piles' fixity on the site X: 4–6, Y: B-I (see the building plan in Fig. 5). a is the first mode with a frequency of 2.56 Hz, b is the second mode with a frequency of 2.94 Hz. Piles are marked in blue in accordance with the building plan L_{x1} and L_{y1} indicating the size of the area located between the anchors.

condition of the pile.

In addition to the flexural modes of natural vibrations, less intense modes of longitudinal compression-expansion can be formed in piles (an example of such vibrations is shown in Fig. 14). The frequency of such vibrations depends on its length, in addition to the rod velocity at a known rod velocity, which makes it possible to determine the length of the pile by analyzing the natural frequencies on the amplitude spectra of standing waves using formulas (1) or (2).

In addition, it is worth noting that in Figs. 13–14, the displacement amplitudes are given in relative units for better visualization. In reality, such vibrations can be recorded only with the help of high-precision equipment.

In the building under study, several types of fixity in foundation piles can be distinguished:

1. Good fixity is when the pile is fixed in the ground to the design depth and attached to the grid beams.
2. Bad fixity is when the thawing of permafrost occurred from above.
3. Bad fixity in the ground is when thawing of permafrost occurred from below.
4. Bad connection to the grid beams.

If the pile is well fixed (see Fig. 15) it is assumed that its lower part (from −6000 to 2000 mm) is rigidly fixed in the ground and the upper end is rigidly attached to the grid beams.

In this case, the presence of flexural vibrations will be observed only for a section from 2000 to 6000 mm (type 1), while at the upper end of the pile there are nodes of standing waves. An increase in the length of the oscillating section provided that the pile is driven 8 m below the soil surface, may indicate a possible thawing of the upper part of the permafrost soils and weakening of the fixity from above (type 2).

In the case of the thawing of permafrost soils from below, the fixity of the lower part of the pile is lost (see Fig. 16).

Here, in addition to flexural vibrations in the area from 2000 to 6000 mm, also present in the area from −6000 to −4250 with antinodes at the lower end of the pile, which indicates the loss of pile's fixity at its base (type 3). Also, an increase in the length of the oscillating sections, in case of their difference from the design, indicates the loss of the pile's fixity.

If reliable fixity with the grid beam is lost, the presence of vibrations

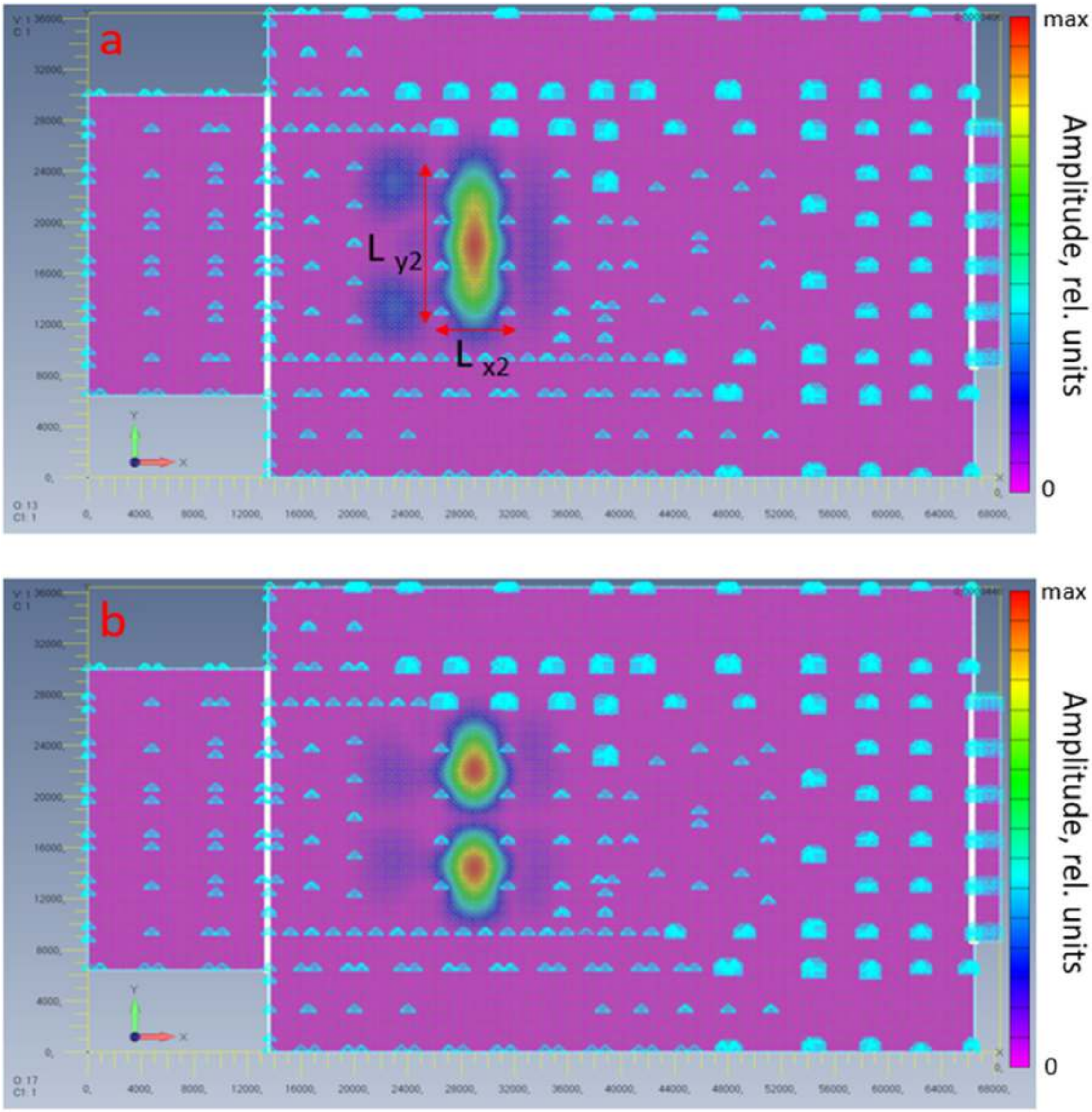

Fig. 19. The first two modes of vertical natural vibrations of the foundation model with good piles' fixity on the site X: 6–8, Y: B-I; a is the first mode with a frequency of 3.73 Hz, b is the second mode with a frequency of 4.04 Hz. The locations of the piles are marked in blue. L_{x2} and L_{y2} denote the dimensions of the area located between the anchors.

will also be a characteristic of the upper end of the pile (type 4). But in this case, the antinodes of flexural standing waves will be observed at the upper end of the pile (Fig. 17).

In addition to the types of fixity loss described above, piles may be in contact with others that are a combination of the types described above.

5. Numerical modeling results of the foundation of the palace of culture building

To construct the distribution of the amplitudes of natural vibrations corresponding to the intact foundation of the Palace of Culture building in Norilsk, its computer simulation was performed by the finite element method in the Ansys software package. The model scale and the location of the support piles, which ensure rigid fastening of the foundation at the installation sites, corresponded to the real object. The model material of piles and foundations is cement concrete. The calculated grid is uniform and includes 1115315 elements. The elements of the calculated grid are isosceles tetrahedra with a long edge of 200 mm. The calculation was carried out based on the Lanczos algorithm [30].

The plan of the foundation model with pile installation sites is shown in Fig. 5. As a result of the simulation, the spatial and frequency distribution of natural vibrations of the structure in all three orthogonal directions (X, Y, Z) in the range from 2.5 to 6.6 Hz was obtained. The support piles of the foundation are nodal points at which there are no vibrations. The volume of the foundation located between the piles fluctuates freely. An example of the distribution of the amplitudes of natural vibrations obtained from the calculation results is shown in Figs. 18–19.

In the example presented, it can be seen that the frequencies of the vibration modes of the section shown in Fig. 18 are lower than in Fig. 20 (2.56 Hz and 3.73 Hz for the first and 2.94 Hz and 4.04 Hz for the second, respectively). This is explained by the fact that the linear dimensions of the oscillating section bounded by piles in the first example (L_{x1} and L_{y1}) are larger than in the second (L_{x2} and L_{y2}).

Thus, natural vibrations of the structure are distributed over its entire area and have a frequency that is greater than the smaller linear dimensions' vibrations between the piles' fixity boundaries. The amplitude of such vibrations is small (and decreases with increasing

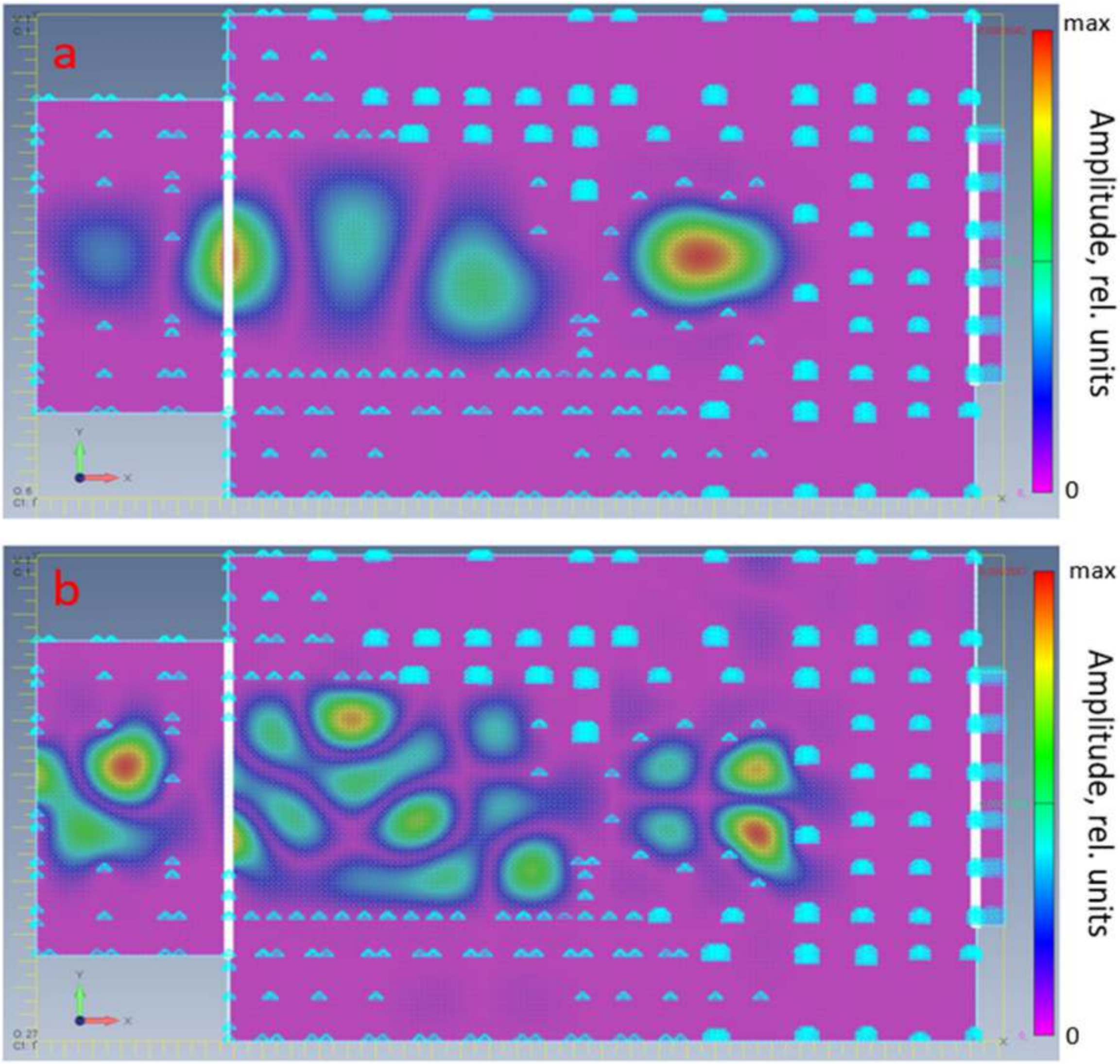

Fig. 20. The first two modes of vertical natural vibrations of the foundation model bad piles' fixity. The location of bad piles' fixity corresponds to position 1 in (Fig. 5). a are vibrations in the range from 1.03 to 1.53 Hz, and b are vibrations in the range from 3.14 to 4.27 Hz.

frequency) and does not pose a danger to the integrity of the structure.

In the calculated range from 2.5 to 6.6 Hz, the 80 lowest modes of natural vibrations of the structure were determined, taking into account the integrity of all foundation supports, which reflects the distribution of silent vibrations in the plan. The simulation results were taken into account when processing the obtained field data to isolate structural vibrations caused by the bad fixity of the foundation piles from the normal field of the natural vibrations obtained in the course of mathematical modeling. However, despite the coincidence of the calculated location of the anomalies with the results of a field experiment, the vibration frequencies are different, which is explained by changes made during the operation of the building (other than the original architecture of the building) and already existing defects, the presence of which was not taken into account when creating a mathematical model of the foundation.

Based on field measurements, it was found that 51 piles had bad fixity conditions. Taking into account the location in terms of bad piles' fixity, a mathematical model of the damaged building of the Palace of Culture was created with parameters similar to those of the undamaged model. The bad piles' fixity was taken into account by the lack of rigid fixity at the locations of such piles. A composite high-quality image showing the vibrations of the foundation at various frequencies is shown in Fig. 20.

Fig. 20 shows that the vibrations cover a large area in the central part of the building, exactly where the bad foundation piles' fixity are located. Thus, these areas are a free oscillating surface like a membrane and the load that should have been on the piles located within the bad fixity areas is redistributed to the piles and supporting structures of the building along the perimeter of these areas. Such a redistribution of the load can significantly reduce the seismic resistance of the building and lead to the destruction of load-bearing structures due to the constant impact of loads exceeding the design ones.

6. Conclusions

During the examination of the pile foundation of the Palace of Culture building in Norilsk, the state of 133 piles was studied by the method of passive microseismic monitoring based on the allocation of standing waves, for each of which the nature of their fixity was determined. It was found that 51 piles had bad fixity conditions, which can be interpreted as a violation of the piles' fixity of the building, the lack of support on the base, and the hanging position of the pile. The lengths of 117 piles were determined. However, it was not possible to determine the length of 16 piles, since they have a good fixity to the rocks, which excludes the reflection of elastic waves from the lower boundary of the pile.

An analysis of the location of the bad piles' fixity piles showed that they are all under the building, closer to the "left" edge of the building on the project plan. The experimental results obtained have shown that the method of extracting standing waves can be successfully used to detect the piles' fixity conditions. Standing waves can be extracted from the noise field by accumulating a large number of amplitude spectra of noise signals.

At a qualitative level, this distribution is consistent with the results of the computer simulation by the finite element method. The fact that under the influence of acoustic noise, flexural standing waves are formed horizontally on some piles and absent on other piles, indicates the absence of hard fixity with the rock mass.

It is shown that the analysis of standing waves of vertical compression-expansion arising in a pile under the influence of noise makes it possible to examine its length and qualitatively evaluate the ratio of acoustic stiffnesses of the top and bottom of the pile, which is also a diagnostic sign indicating the absence of hard fixity with the rock mass.

Competing Interests

No potential conflict of interest was reported by the authors.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

The data that support the findings of this study are available upon request.

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