ASSESSMENT OF BUILDING VULNERABILITY DURING THE THAWING OF PERMAFROST SOILS

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Abstract

The development of new Arctic regions in the context of global and local thawing of permafrost soils caused by both local man-made and global natural thermal impacts on the ground necessitates the use of new engineering solutions for the timely prediction and prevention of dangerous uneven deformations in buildings. Uneven building deformations occur due to the reduced stiffness of the soil mass beneath the foundation, caused by the uneven thawing of the soil. It is proposed to assess the stiffness of the "soil-building" system using the dynamic-geophysical testing method.

Keywords: "soil-building" system, dynamic-geophysical testing, natural vibration frequencies of soils, vulnerability of the "soil-building" system, technical condition of the "soil-building" system

I. Introduction

In the Far North, modern multi-story construction has been employed for many years, and it is in no way different from construction in regions without permafrost. However, the use of modern engineering life support systems creates a significant thermal load on the soil mass beneath the buildings, which can lead to uneven thawing of permafrost soils, causing uneven settlement and deformation of the structural framework of buildings (see Figure 1). To prevent potential damage to buildings caused by uneven thawing of the soil, additional diagnostic and monitoring methods are required. These methods should allow for the timely identification of hazardous zones in the soil mass during the investigation, construction, and operational stages, which could lead to deformations in the "soil-building" system [1].

Due to the influence of possible heterogeneities in the soil mass, there is a loss of equilibrium and stability, leading to subsidence, landslides, disruption of hydrological regimes, suffosion, karst phenomena, increased deformation of the "soil-building" system, and a heightened risk of building and structure collapse. To detect potential geological hazards beneath the foundation of a building, investigative methods capable of assessing the soil mass up to depths of 50-100 meters are required [2].

Known geological and geophysical methods do not allow for the quick and reliable determination of the location and magnitude of geological heterogeneities (see Table 1). Geological drilling with soil sampling is a point-based investigation, and to obtain accurate data on the structure, physical and mechanical characteristics, and potential geological hazard zones, the number of boreholes must be maximized, which is impractical in reality. The use of geophysical methods, such as seismic exploration, improves the quality of geological surveys; however, these studies are limited to two-dimensional linear profiles of up to 50 meters in length and 20 meters in depth. The depth of research can be increased by extending the wave source, but this requires additional time and financial resources. The greatest challenge, however, lies in the interpretation of geophysical data and identifying potential geological hazards, which depend solely on the expertise of the geophysicist [3].

Figure 1: *deformation of a building in arctic conditions due to uneven settlement of the "soil-building" system*

Table 1: *comparison of geological and geophysical methods for investigating the physical-mechanical and dynamic parameters of the soil mass beneath buildings and identifying potential geological hazards.*

Criteria	Geological Methods (Drilling and Sampling)	Geophysical Methods (e.g., Seismic Exploration)
Depth of Investigation	Limited to specific borehole depth (can reach 50-100m)	Typically up to 20m, but can be extended with additional efforts
Data Accuracy	High at specific borehole locations	Moderate; relies on interpolation between points
Coverage	Point-based, requires multiple boreholes for broader coverage	Provides continuous profiles along a line, but limited in area
Physical-Mechanical Data	Direct sampling allows precise measurement of soil properties	Indirect; requires interpretation of wave propagation data
Dynamic Soil Properties	Limited, usually not assessed directly	Provides information on soil stiffness, natural frequencies
Geological Hazard Detection	High precision at the borehole location, but limited coverage	Identifies anomalies, but exact nature requires interpretation
Cost	Expensive (especially with a high number of boreholes)	More cost-effective for larger areas, but requires specialized equipment
Time Required	Time-consuming due to drilling and sample analysis	Faster than drilling for shallow studies, slower for deeper studies

Applicability in Complex Terrains	Limited by access for drilling equipment	More flexible; can cover larger and more difficult terrain
Interpretation Dependence	Minimal; results are based on direct soil properties	High; depends on the expertise of the geophysicist
Hazard Detection at Depth	High, but localized to borehole	Moderate, dependent on the depth capability of the equipment

It is proposed to use the dynamic-geophysical testing method for assessing the stiffness parameters of the "soil-building" system.

II. Methods

The experience of applying the dynamic-geophysical testing method shows that, by considering the soil mass as a vibrating body with specific dimensions and depth, one can roughly determine its structure and physical-mechanical characteristics depending on the predominant soil composition and the natural vibrations of the mass.

The technology of dynamic-geophysical monitoring of the "soil-building" system has been widely tested on various objects. This technology allows detecting possible changes in the system's condition. It has been successfully applied for diagnosing "soil-building" systems to identify the risk of building collapse in locations such as Novy Urengoy, Muravlenko, Nizhnevartovsk, the Bryansk region, Yakutia, Altai, the Kamchatka region, Sakhalin, the Ulyanovsk region, and others.[4]

The proposed comprehensive dynamic-geophysical monitoring technology is an integrated measurement and analytical system installed in areas with potential geological hazards. The system consists of a computer with specialized software that collects, analyzes, and processes digital data from sensors placed in the monitored zone according to specific criteria. The system includes a multi-channel analog-to-digital converter (ADC), three-component accelerometers, tilt sensors, water level and pore pressure sensors in the soil, temperature sensors, and others, along with a cable or radio data transmission system from the sensors to the ADC. The composition and number of necessary monitoring system elements are determined based on the monitoring goals.[5]

The criteria developed with the participation of the authors for assessing the stability of the soil mass using the results of dynamic-geophysical observations allow the early detection of unstable equilibrium states of the soil (within hours to days). A sensitive stiffness parameter of structural systems is vibrations. Vibrations of the soil mass, like those of structures, depend on their mass and stiffness. For the soil mass, the equation linking its vibrations to its geometrical and physical-mechanical parameters can be expressed as follows:

$$T_1 = 2{,}63 \times \mathrm{H}\sqrt{\frac{\rho}{G}},\ (1)$$

where:

ρ is the density of the considered block of the soil mass,
G is the shear modulus of the soil mass,
H is the height of the block of the soil mass.

The most convenient parameter for measurements and calculations is the natural frequency of vibrations, which is the inverse of the vibration period. Each type of soil with uniform thickness is characterized by a certain level of weighted average period or frequency of vibrations. The values of fsv vary depending on the thickness, size of the soil mass, and type of soil. For example, for soil with a thickness of 8-10 meters,Tpr = 4H/vs Table 2 provides the physical-mechanical and dynamic parameters of soils.

Thus, by monitoring the period (frequency) of vibrations of the object or the soil mass, it is possible to control their stiffness, including the degree of soil saturation. The stiffness of the soil mass and the building is directly proportional to the squares of the frequencies in the monitored directions.

Table 2: *physical-mechanical and dynamic parameters of soils.*

Soil Type	Density (ϱ), t/m³	Shear Modulus (G), MPa	Elastic Modulus (E), MPa	P-Wave Velocity (Vp), m/s	S-Wave Velocity (Vs), m/s	Natural Frequency of the Soil Mass (f), Hz
Sand	1.6	33.54	15.9	200-500	150-300	2.86
Sandy Loam	1.6	60.38		250-550	120-280	0.7
Loam	1.7-1.75	26.71	5.06	300-600	100-250	1.25
Clay	1.8-2.05	48.16	7.1	1400-2500	400-600	2.1
Wet Clays	Less than 1.5	3-6	1.5	1400	100	1

Thus, to assess the stiffness of the "soil-building" system, it is necessary to:

1. Select locations for sensor placement and perform tests on the "soil-building" system.
2. Obtain the natural frequencies of the "soil-building" system.
3. Calculate the normative values of the natural frequencies of the soil mass beneath the building and the building itself.
4. Calculate the normative values of the natural frequencies of the monitored load-bearing structures.
5. Compare the squares of the natural frequencies of the soil mass and the building, and determine the stiffness deficits by direction.
6. Using the criteria, evaluate the technical condition of the soil mass and the building.

III. Results

In a kindergarten building constructed with a precast reinforced concrete frame and located in Arctic conditions, structural deformations began to appear during its operation due to soil weakening in the foundation caused by thermal exposure. To assess the stiffness of the "soil-building" system, the dynamic-geophysical testing method was applied. For soil assessment, three-component accelerometers of type A1638 were used. By sequentially placing the sensors on the pile cap foundations in the building's basement, as well as on the floors and roof of the building, the natural vibration frequencies of the "soil-building" system were obtained. [5]

Figure 2: *Kindergarten Building Tested Using the Dynamic-Geophysical Method.*

To assess the technical condition category of the building, a comparison was made between the normative values of the building's natural vibration frequencies and the experimentally obtained values.

The potential reduction in the building's stiffness is determined by comparing the normative and experimentally obtained natural vibration frequencies.

Stiffness deficiency is assessed using the following dependencies [4–8]:

$$\Delta fx = ([fx]^2 - fx^2) \times 100 / [fx]^2, \quad (1)$$

$$\Delta fy = ([fy]^2 - fy^2) \times 100 / [fy]^2, \quad (2)$$

$$\Delta fz = ([fz]^2 - fz^2) \times 100 / [fz]^2, \quad (3)$$

where fx, fy, fz are the values of the building's natural vibration frequencies obtained from dynamic tests.

[fx], [fy], [fz] are the standard natural vibration frequencies obtained from the design or calculated values.

Δfx, Δfy, Δfz are the stiffness deficiencies in percentages along the X, Y, Z axes (see Table 2).

Table 3: *Percentage of stiffness reduction (square of the building's natural vibration frequency), depending on the category of technical condition.*

Type of Structure	Percentage of Relative Stiffness Reduction of a Structure in Various Conditions				
	Very good	good	fair	poor	very poor
Reinforced Concrete Frame	0–25	25–43	43–57	57–71,4	71,4–100
Steel Frame	0–16,7	16,7–33	33–50	50–67	67–100
Brick	0–16,7	16,7–33	33–50	50–75	75–100
Wooden	0–20	20–27	27–40	40–67	67–100
For Other Types of Buildings and Structures, Soil Masses Beneath Buildings	0-10	11-30	31-60	61-90	

Based on the test results, the following conclusions were made: The building is in operational condition; however, resonance frequencies between the soil and the building were detected, which may lead to increased vibration amplitudes and the development of structural damage.

To assess possible heterogeneities, loosened areas, and likely zones with reduced soil stiffness, dynamic-geophysical testing was conducted in the building's basement. In Figure 3, the zoning of the soil mass beneath the building is shown. In red zones, stiffness reduction can reach up to 50%, while in yellow zones, it can reach up to 30%. At least two high-frequency anomalies are recorded in the red zones along the axes, while one anomaly is recorded in the yellow zone.

The example considered demonstrates that timely detection of potential zones of stiffness reduction in the soil can be ensured by:[6]

1. Monitoring the soil mass condition to promptly determine its dynamic-geophysical parameters and prevent resonance phenomena from dynamic impacts;
2. Comprehensive monitoring of the "soil-structure" system (parallel control of water levels in boreholes, monitoring the building's geometry and soil surface, etc.);
3. Timely implementation of protective engineering measures, such as installing drainage and stormwater systems to effectively divert groundwater, strengthening the soil, and other measures to enhance the stiffness of the soil mass.

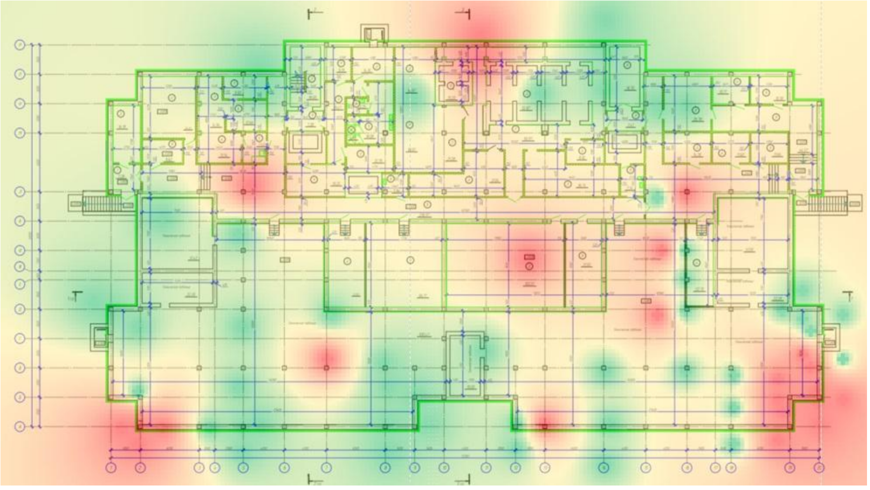

Figure 3: *Zoning of the Soil Mass Beneath the Building Based on Bearing Capacity. In Red Zones, Soil Stiffness Reduction Can Reach Up to 50%*

IV. Discussion

The dynamic-geophysical comprehensive monitoring technology for the "soil-structure" system can ensure the timely detection of geological hazards and assess the potential probability of catastrophic building and structure failures. At the investigation and design stages, it enables the selection of rational engineering measures to enhance the stability of "soil-structure" systems, and during the operational stage, it allows for the control of the effectiveness of these measures.[7]

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