Deformation of building on pile foundation due to frost heave

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ABSTRACT

The city of Arkhangelsk has the complicated geological conditions, particularly wide spread occurrence of soft ground such as peat and mud. The average annual atmospheric temperature is about +0.8°C and that enables the seasonal frost penetration up to 1.8…2.2 m. Usually the frost penetration causes damages to low-rise buildings, road paving, and pipelines. But the authors unexpectedly found in the process of their practical activities deformations of a building supported by 18 meter piles which were caused by the frost heave of a mud. The building is a cooling house designed for fish storage at the temperature of -22…-24°C which has been operated since 1985. It was found by drilling boreholes that the mud under the center of the building was frozen at the depth from 3.8 to 8.1 m. The floor uplift reached 18 cm, the inner columns uplift - 13 cm and the building was taken out of service. The numerical simulation data for 29 years of the building operation period performed by the Geostudio software correlate quite close with the data obtained by drilling the boreholes.

The achieved experience may be useful for construction of ice rinks, cooling houses as well as for regular not heated storage buildings. As for the latter buildings located in the regions with the average annual atmospheric temperature about 0°C the frozen ground layers may continue and their thickness may increase for several years.

Keywords: cold climate, frost heave, pile foundation, frozen soil, numerical simulation

The distinctive features of the environment conditions of the city of Arkhangelsk situated in the Russian subarctic zone is cold climate and wide spread occurrence of weak soils such as peat and mud up to 8…10 meters thickness [7]. The average annual atmospheric temperature is about +0.8°C, the duration of the negative temperature period is about 6 months and that results in deep seasonal frost penetration. The permafrost does not occur here. The ground frost heave damages roads paving, pipelines, low-rise buildings and the weak soil occurrence considerably rises the cost of foundation arrangement [1].

This article studies rather non-typical deformation case of a building erected on 18-meter piles. It was designed as a cooling house for fish storage and the deformation was caused by mud frost heave frozen up to 8 m deep.

The building is single storeyed with reinforced concrete frame 42 m long and 8.4 m high, that forms two 12 m spans. The outside walls are made of haydite concrete panels and have additional inner foam polystyrene thermal insulation. The floors are concrete. To protect the foundation against the frost penetration there was arranged a light gravel layer 0.9 m thick under the floor slab. An electrical heating system was installed in the concrete layer under the light gravel. The building has pile foundation. Because of the 12.7 m mud layer within the site the builders used 18 m long driven sectional piles consisting of 12 m bottom part and 6 m top part.

The refrigeration equipment installed in the building maintained the temperature from -22 to -24°C during the whole operation period. The building was normally operated since 1985 but starting from the late nineties there was detected crack occurrence on the floor, inner brick walls and partitions. By 2012, when the middle columns uplift reached 130 mm and the floor uplift reached 184 mm (Fig.1), the building was taken out of service. The edge columns and the outside walls as well as the adjacent floor sections were not deformed. As it was found out later, the deformations were caused by freezing of frost-susceptible soil due to the foundation heating system failure. The absence of thermometric wells didn’t allow to detect and to repair the defect leaving the building to be operated in the normal way.

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The geological profile consists of the following soils layers:
1. Technogenic sediments – fine wet sand; from 2.1 to 3.2 m thickness;
2. Alluvial marine sediments – fine water saturated sand; from 1.3 to 2.8 m thickness;
3. Alluvial marine sediments – very soft mud; from 1.5 to 3.6 m thickness;
4. Alluvial marine sediments – soft mud with insignificant sand layers; from 9.2 to 9.7 m thickness;
5. Glacial sediments - stiff loam; about 1.0 m thickness;
6. Marine sediments – fine sand of average density; the penetrated stratum thickness is 3.1 m.

To clarify the site geotechnical conditions and to determine the frozen stratum thickness in autumn 2014 two wells were drilled within the building area – one at the edge column and the other at the middle one. One of the wells, 21.0 m deep, passed the whole mud thickness and the other reached the frozen stratum bottom. It was found out that there’s no frozen ground under the outside walls and that the ground temperature is above zero. In the middle part of the building at the depth between 3.8 m and 8.1 m, there are frozen soils – 1.0 m of fine sand and 3.3 m of mud. The temperature of the frozen soil is between −0.3°C and −0.5°C. The section of the building with geotechnical conditions is shown in Figure 2.

The absence of frozen soils in the top part of the section directly under the floor is explained by defrosting for the two last years when the refrigeration equipment didn’t operate in the building.

The obtained data prove that the sand and mud moisture content increased in the process of freezing due to the moisture migration to the freezing front and heaving. The sand moisture increased only slightly - from 16…18% to 19…20% and the mud moisture – from 30…32% to 33…39%. The mud ice content due to visible ice lenses made up 4…5% while the inclusion thickness achieved 2…3 mm.

The test results of the frozen mud samples by compression method are shown in Figure 3. At the first part of the test up to achieving the pressure of 100 kPa the samples were under negative temperature and then the refrigeration chamber was switched off [5, 9]. The mud compressibility factor in the frozen state was from 0.47 to 0.63 MPa⁻¹, the defrost factor was from 0.029 to 0.063 and the compressibility factor at defrosting was from 0.092 to 0.268 MPa⁻¹. Taking into account the obtained data the calculated value of foundation subsidence at defrosting would be from 0.12 to 0.15 m, which approximately corresponds to the detected columns and floor uplift value.

The tests on determining mud degree of frost susceptibility were performed as well. They were completed by means of the special laboratory unit, the description of which was given in the earlier published work [8]. The laboratory unit design complies with the requirements of Russian and foreign standards [2, 6]. The sample freezing was performed at the freezing
Front rate of 10 mm/day; the load applied to the sample was 50 kPa. As the Figure 4 shows the relative deformation of the mud frost heave achieved from 0.05 to 0.068, which corresponds to the medium frost-susceptible soils [3]. The stratified cryogenic structure formed in the samples is shown in the photo (Fig. 5).

The next research step was the forecast of ground thawing time. This objective was achieved by numerical simulation using the module “Temp/W” of the software complex “GeoStudio2012” [4]. Five time intervals were reviewed:
- start of the cooling house and floor heating system operation (1985),
- floor heating system failure (90-ies),
- switching off the refrigeration equipment (2012),
- start of the building examination after two years operation pause (2014),
- complete thawing of the ground (the date is determined by calculation).

The input data were taken based on the following parameters: building geometrical dimensions, soils bedding, atmospheric air temperature annual variation, thermal conductivity and heat capacity of the soils and structure materials as well as the soils and materials moisture content. The thermal conductivity coefficient and the unfrozen water content of the soils were set as function the temperature. Two types of temperature conditions were specified: constant and varying in time.

The constant temperature was specified at the bottom boundary of the ground body, in the cooling house when it was operated as well as at the heated floor. The varying temperature was specified for simulating the weather conditions outdoors and inside the building when the building was taken out of service.

The Figures 6-8 shows the graphical results of the numerical simulation for the ground temperature conditions. The dotted lines are zero isothermal lines.

The verification of the model was carried out by comparing the frozen soil outlines for 2014 by the simulation results with the data obtained in the process.
of additional surveys by well drilling. As it turned out, if to assume that the heating system failure occurred in 1995, the compliance of the frozen soil superface and subface location in the middle of the building, 3.1/8.0 m and 3.8/8.1 m (Fig. 8) are quite satisfying by the calculation and drilling data respectively.

After that, several variants of the soil thawing around the piles were simulated. Every variant involves floor disassembling with removing the light gravel layer. If using electrical heating elements buried around the central pile and maintaining the temperature of 5°C inside of the building, the soil defrosting around the piles will be completed in 40 days (Fig. 9).

If maintaining the temperature of 5°C inside the building without using the buried electrical heaters for defrosting the soil around the piles 3 years will be needed (Fig. 10).

The issue of the pile section joint remains unsolved. The excavation showed that the joints between the pile heads and the concrete caps are in good state. The pile lift, the tip of which was drove into fine sand for 2.0 m, is little probable. Most likely, the frost heave resulted in breaking the pile section joint.

After thawing the ground the top sections of the piles will return in the initial position but there’s a probability that the area of the section overlap at the joint would be insignificant and in this case the pile bearing capacity wouldn’t be sufficient. This would require the foundation underpinning.

This experience may be useful for construction of ice rinks, cooling houses as well as for common not heated storage buildings. As for the latter buildings located in the regions with the average annual atmospheric temperature about 0°C the frozen soil layers may form in the absence of the solar radiation. When designing such buildings it is recommended to perform temperature regime simulation.

REFERENCES

1) Andersland O., Ladanyi B. (2004): Frozen ground engineering (second edition), Chichester, UK, 2004. 364 p.
2) BS 812-124:1989. Part 124. Method for determination of frost-heave. 23 p.
3) Ershov E. (2002): General geocryology, Manual for high school, Moscow, 682 p.
4) Geo-slope International Ltd (2010): Thermal modeling with Temp/W 2007, fourth edition, Calgary, Alberta, Canada.
5) GOST 12248–2010 Soils. Laboratory methods for determining the strength and strain characteristics, 162 p.
6) GOST 28622-2012 Soils. Laboratory method for determination of frost-heave degree, 12 p.
7) Nevzorov A. (2013): The long-term peat settlement under the sand embankment, The 5-th international geotechnical symposium, Incheon, Korea, 403-406.
8) Nevzorov A.,Korshunov A. and Churkin S.(2014): Numerical simulation of laboratory freezing test of frost-susceptible soil, Proceedings of the 8th european conference on numerical methods in geotechnical engineering, Delft, Netherlands, 977-982.
9) SP 25.13330.2012 Soil bases and foundation on permafrost soils. Moscow. 123 p.