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The effect of negative temperatures on the retaining walls of deep pits

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Abstract. In countries with negative winter temperatures, pits and walls of underground structures are subjected to additional forces caused by frost heaving forces. In Russian construction practice, cases of the impact of such forces on the struts and anchors of construction walls are known, which led to the loss of stability of the struts and the failure of the anchors. Obviously, the design of retaining walls in winter should take into account the effect of additional forces caused by frost heaving and their evolution over time. The solution of test problems for an open pit shows that under certain conditions, the forces in the struts can exceed their values by an order of magnitude, determined when taking into account only the active pressure of the soil. Experimental studies were carried out to assess the processes of development of forces in the elements of the retaining walls in winter. The calculated assessment of the temperature fields and the stress-strain state in the excavation walls was performed using the Termoground program. The comparison of results of experimental and calculated data are shown in the article. The comparison of results of experimental and calculated data is shown in the article.

1 Introduction

At present, in conditions of dense urban development, the construction of underground structures is increasingly being carried out to accommodate parking lots, shopping malls, pedestrian crossings, road junctions, etc. In many cities of the world, this task is successfully implemented due to appropriate geotechnical conditions. A number of cities, including St. Petersburg, belong to regions with difficult conditions for the construction of underground structures, such as thixotropic fluid soils, a large number of faults in the underlying strata, as well as the proximity of groundwater to the surface, the presence of natural reservoirs within the city (rivers, canals), congestion of underground utilities and other adverse factors [1-4].

Also, the engineering-geological conditions of St. Petersburg are characterized by the presence of a thick layer (15 - 20 m) of weak clayey soils of fluid or fluid-plastic consistency. With low strength, these soils have a relatively high density, which provides high pressure on the walls of underground structures.

Under favorable geotechnical conditions such as high mechanical characteristics of soils, low groundwater levels, the absence of buildings and structures in the risk zone, the

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development of a pit for the underground part of the structure is carried out with the arrangement of a natural slope. Otherwise, the installation of enclosing structures is required.

When designing an underground structure in the area adjacent to existing structures, the following risk factors should be taken into account, which can lead to deformations of the surrounding buildings [5]:

- Enclosing structure construction technology.
- Change in the level of groundwater in the territory.
- Stability and flexibility of the wall from static loads such as the pressure of the soil, adjacent buildings.

One of the most significant risk factors is the work of the wall when opening the pit, followed by the erection of buildings using heavy equipment [6, 7].

The existing normative methods for calculating retaining walls are aimed mainly at ensuring their strength and stability. In these methods, the loads on the wall, which depend on the strength parameters of the soil, are already known, the bending moments are determined from them, and the section of the wall necessary to ensure the strength of the structure is calculated [8]. From the condition of ensuring the stability of the wall, the required depth of its embedding is determined.

During construction in conditions of dense urban development, the question of limiting the deformations of the surrounding buildings, and, consequently, the retaining walls, becomes more important [9, 10].

In regions with negative winter temperatures, pits and walls of underground structures are subjected to additional forces caused by frost heaving forces [11]. In Russian construction practice, cases of the impact of such forces on the struts and anchors of walls are known, which led to the loss of stability of the struts and the failure of the anchors (Fig.1). Information about the phenomena accompanying the freezing and thawing of soils, and the ways of existing estimates of the deformations developing in this case, is described in detail in the monographs of N.A. Tsytovich (1973), V.O. Orlov (1962) et al.

a) 

b) 

Fig. 1 a) Loss of stability of the pit struts; b) sheet piling anchor failure.

Obviously, the design of retaining walls in winter should take into account the effect of additional forces caused by frost heaving and their evolution over time [12].

The solution of test problems for an open pit shows that, under certain conditions, the forces in the struts can exceed their values by an order of magnitude, determined by taking into account only the active pressure of the soil. At the same time, in some cases, depending on the values of the anisotropy coefficient of frost heaving of the soil, the forces in the struts can change signs to the opposite ones, that is, instead of the compression forces in the struts, tensile forces can also occur [13].

The existing experimental definitions of forces in the elements of the retaining walls are calculated in units.

There are practically no systematic studies of the dependence of the frost heaving anisotropy coefficient on the granulometric composition of the soil, its moisture content, and negative temperatures. With non-one-dimensional freezing, the values of this coefficient approach unity, and sometimes even exceed it, which has a significant effect on the SSS of the freezing massif.

Experimental studies were carried out to assess the processes of development of forces in the elements of the retaining walls in winter.

The calculated assessment of the temperature fields and the stress-strain state in the retaining walls was performed using the Termoground program with a description of the formula basis and the calculation algorithm.

The results of experimental and calculated data allow us to state that it is often necessary to take into account additional forces in the elements of retaining walls caused by frost heaving of soils.

This will make it possible to design a reliable wall without fear of its failure during the predicted course of negative temperatures.

2 The degree of development of the topic

This work considers the effect of seasonally freezing soils on the occurrence of secondary stresses on the fencing of deep pits. In the work, the values of the increase in secondary stresses from frost heaving of soils are determined and compared with the calculated values.

Such scientists as B.I. Dalmatov, N.A Tsytovich. L.V. Chistotinov, V.B. Shvets, N.I. Bykov, V.G. Kondratiev, V.V. Pendin, V.I. Shtukenberg, S.G. Voislav, P.I. Andrianov, A.E. Fedosov, M.I. Sumgin made a great contribution to the study of the phenomenon of frost heaving of soils during freezing, the deformations and forces developing at the same time, the study of the main causes and patterns of deviations of vertical elements, the design of structures that reduce and neutralize the effect of frost heaving forces [14].

The object of study was a single-tier tubular (530x7) strut system of sheet pile metal fencing of a pit with a depth of 9 meters.

The subject of study was forces in the strut system (during the transition from positive to stable negative temperatures) when the stress-strain state of the freezing soil changes.

The purpose of the study was to establish the patterns of interaction between the retaining wall and the soil mass under conditions of negative temperatures and to assess the reliability of modern engineering and numerical methods for calculating the fixed retaining walls in the engineering-geological conditions of St. Petersburg.

3 Materials and research methods

The methodological basis for solving problems was a systematic approach, including full-scale and numerical simulation. Field modeling was carried out at the construction site of a residential building with an underground garage. The building had 9-storeys and 2 underground floors and was located in St. Petersburg, on the Petrograd side, at the corner of Aptekarsky avenue and Instrumentalnaya street.

Calculations of the thermophysical and stress-strain state of soils were performed using the finite element method in the FEM models software package using the Termoground program [15].

To achieve this goal, the following tasks were set and solved:

- the current state of the issue of the behavior of soils under conditions of negative temperatures and frost heaving during the construction of deep pits using retaining walls was studied;
- the current state of the issue of determining the pressure of soils on the enclosing structures (retaining walls), the selection of the enclosing structures of pits and observing the operation of the walls in natural conditions was studied;
- full-scale observations were carried out at the active construction site in St. Petersburg and data were obtained on the stress-strain state of the system “retaining wall – soil massif”;
- comparison of the obtained experimental data with the results of calculations;
- based on the comparison of experimental and theoretical data, a proposal to take into account possible secondary stresses from frost heaving in the system “retaining wall – soil massif” for the engineering-geological conditions of St. Petersburg was formulated.

The author personally performed all the main studies, including setting the goal and objectives of the work, field experiments, interpretation and generalization of the results.

4 Experimental research work

For a more detailed study of the interaction of retaining walls of a deep pit and the soil mass under conditions of negative temperatures, an experiment was carried out at an existing construction site in St. Petersburg.

5 Results

The construction site is located in St. Petersburg, on the Petrograd side, at the corner of Aptekarsky avenue and Instrumentalnaya street.

The site borders on the site and buildings of St. Petersburg Electrotechnical University (LETI). The buildings of the University were built in different years, had different historical significance.

There were a number of cultural heritage sites and several residential and administrative buildings in the zone of influence of the facility under construction.

A residential building of 9-storey and 2 underground floors with an underground garage was under construction. The residential building consisted of 2 buildings.

The depth of the pit of the observed part is ~8.0 m. The length of the sheet pile is 12 m. The strut system is a single-tier strut system. The struts are set at -0.750 (+2.200 abs).

The organization of monitoring of the arising forces in the strut system was implemented by means of string strain gauges, installed on the surface by arc welding, complete with a thermistor, with a measuring range of 3,000 microstrains.

External compressive or tensile forces that were applied to the strut system changed the tension, and, accordingly, the resonant frequency of the vibration of the string inside the gauge. These changes were recorded using an electromagnetic coil attached to the body of the strain gauge. The presence of a built-in thermistor made it possible to isolate the thermal stresses of the structure from the stresses caused by power loads.

The strut system in the area under consideration is a distribution beam (I-beam 50 Sh 1) and a tubing spacer (530x7).

The strut system was installed after the sheet piling was driven in full (from trough-type sheet piles, EVRAZ VITCOVICE STEEL, S 355 GP, VL 606A).

Tensometric sensors (32 pcs.) were installed on the pit struts in the sheet piling (the sheet piling length was 12 m, the pit depth was 8 m) to measure and fix the changing forces in the body of the strut, as well as temperature sensors (32 pcs.) to measure and record the temperature of the outdoor air. Sensors were installed along the perimeter of the cross section of the strut, which made it possible to determine both stretched and compressed zones. The frequency of data collection and recording during the winter of 2018-19 was 1 hour. Thus, more than 80 measurements were performed every hour. A view of the pit with struts and the mounted sensor is shown in Fig. 2.

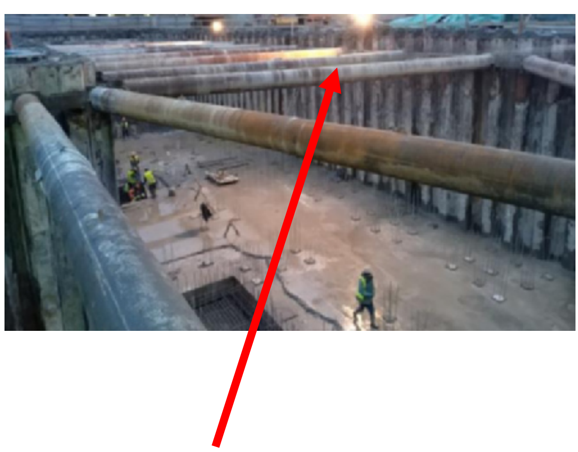

Fig. 2 View of the pit with struts and a mounted sensor.

The engineering and geological conditions of the site from the surface are represented by bulk soils with a thickness of about 2 m, underlain by silty sands 1.7 m thick. Below, fluid loams lie to the full depth. By the beginning of freezing, ground waters lay at a depth of 2 m from the day surface. Thus, with the exception of practically non-frost heaving bulk soils, the sheet pile walls of the pit from a depth of 2 to 8 meters were in contact with heaving (silty sands) and strongly heaving (flowing loams) soils.

The results of measurements of temperatures and forces in one of the struts of the pit at the beginning of the winter are shown in Figs. 3 and 4.

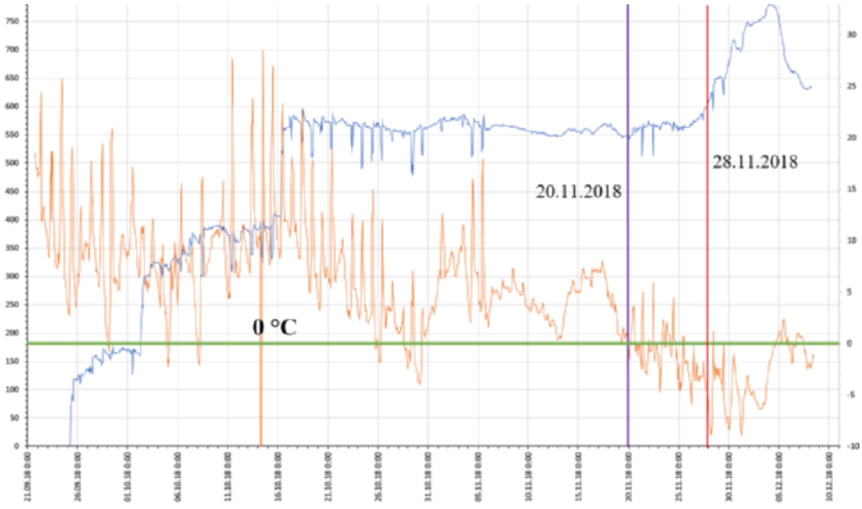

Fig. 3 The dynamics of the growth of forces in strut No. 5 over time.

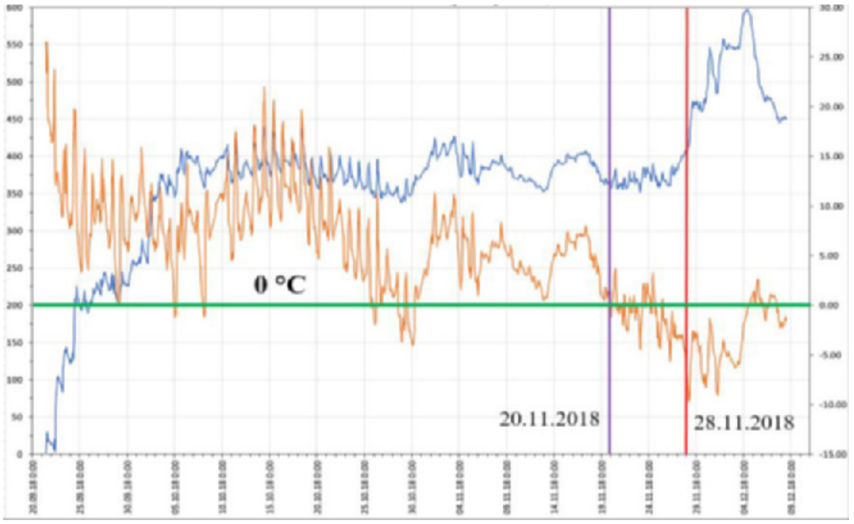

Fig. 4 The dynamics of the growth of forces In strut No. 9 over time.

According to the results of observation and processing of the data obtained, throughout the entire experiment, it can be noted that the excavation of the pit did not dramatically affect the change in the load in the spacers as the changes were uniform throughout the entire observation period at positive temperatures, 204 kN – 383 kN (30 tons), the average growth step was 10 – 15 kN (1.5 tons).

However, with the onset of negative temperatures, when the open walls of our deep pit were frozen, the sensors recorded an additional, accelerated increase in the load on the struts.

As can be seen from the graphs (Figs. 4 and 5), with the onset of a stable subzero temperatures on November 20, 2018, the soil received sufficient freezing and significant changes in the load were observed since November 28, 2018.

The increase in loads on individual struts was from 418 kN to 780 kN (from 42 tons to 78 tons), the average increment was 30-40 kN (3.5 tons).

The maximum value of forces in the strut from frost heaving was 78 tons.

For comparison: from the pressure of the soil mass at positive temperatures with a fully developed pit and ongoing construction and installation works (including from the operation of heavy equipment at the edge of the pit) the increase made up from 360 kN to 385 kN, the average increment was 20 kN (2 tons). The maximum force amounted to 39 tons.

Thus, it can be concluded that due to the forces of frost heaving, with multilateral freezing of the pit, the increase in load (stress) on the spacer doubled.

Such an increase should be considered significant and should be taken into account in design practice.

To assess the stresses in the strut at the end of negative temperatures, temperature and deformation calculations were performed in the Termoground program.

Fig. 5 shows a fragment of the design scheme with the freezing zone highlighted in blue. In the upper corner of the pit, the thickness of the frozen soil, due to the two-dimensionality of freezing, is almost twice the thickness of the frozen layer near the sheet pile wall, which is 0.56 m, which should be considered natural.

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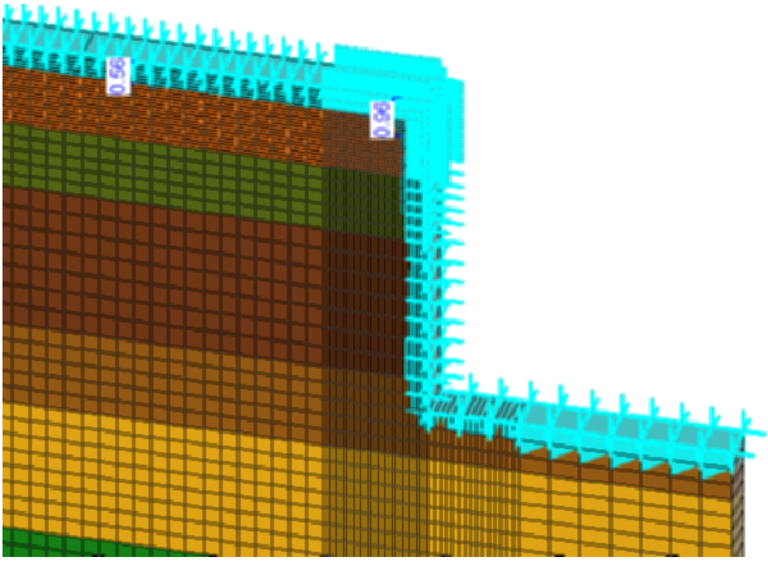

Fig. 5 Fragment of the calculation scheme with the freezing zone (frozen soil thickness in m).

The calculated forces in the strut are shown in Fig. 6.

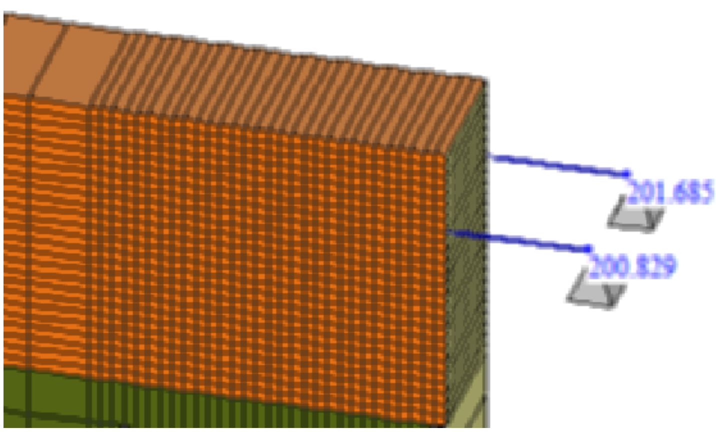

Fig. 6 Forces in the strut, kN.

Fig 7 shows a graph of measured and calculated forces in the strut.

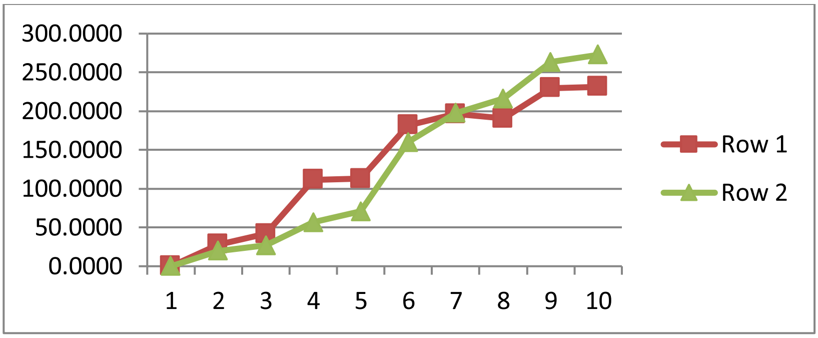

Fig. 7 Graph of the evolution of experimentally measured (row 1) and calculated (row 2) increments of forces in the strut caused by frost heaving.

As can be seen from the calculations, at the beginning of freezing, the calculated and experimental data differ greatly. However, approximately from the middle of freezing up to its end, there is a fairly close agreement between the experimental and calculated data. This makes it possible to use the Termoground program to assess the forces in the elements of the retaining walls subject to frost heaving.

6 Conclusions

The forces of frost heaving begin to act on the elements of the retaining walls almost immediately after the start of freezing of the soil.

The magnitude of the frost heaving forces can be significant, which indicates the absolute need to take it into account in the design, as well as the need for further in-depth research (including at new experimental sites in St. Petersburg).

With the transition of the outside air temperatures to positive values, the frost heaving forces synchronously decrease, however, without falling to zero values.

When calculating the frost heaving forces acting on the walls, one should take into account not only the depth of soil freezing, but also the values of negative temperatures at which the values of the forces can reach maximums.

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