Long-term experience of construction and maintenance of buildings on extremely upheaval soils in the conditions of Minusinsk Hollow

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Abstract. The paper presents the experience of the long-term observations on frosty heaving, the construction experience and the state of the structures during 38-40 years of maintenance of the buildings on bearing piles in extremely upheaval soils. The paper describes the experiment of using complex anti-heaving sheath from chemically treated soil as an anti-heaving stabilization. It also presents an example of uneven upheaval deformations of unloaded bearing piles, caused by the discordant bedding of the clayey soil. The paper analyzes the causes of uneven deformations of frosty heaving, the factors influencing the migration and water accumulation, the peculiarities of cryogenic structure formation on the boundary of the interaction of the treated and untreated soils.

1. Introduction
The researched objects are in Minusink Hollow. The climate of the districts is acutely continental. A severe winter gives way to a hot summer. The aim of the study is to research the state of the structures and of the anti-heaving sheath during 40 years of maintenance at the experimental object.

Due to the close level of the ground waters, caused by the backwater of Krasnoyarsk hydropower station and by the periodical water escape from the reservoir of Sayano-Shushenskaya hydropower station, freezing heaving sometimes goes on with forcing migration. This is frequently observed at the development of hollows in the autumn period, when the frost penetration front in winter during construction of the foundations penetrates from the bottom of the hollow into the ground water’s level. The objects in the towns of Minusinsk hollow, Abakan, Chernogoesk and Minusinsk, are exposed to the intensification of migration processes.

The researchers in Tomsk [1], St. Petersburg [2] and Moscow [3] continue studying the soil properties’ changes at the frost penetration – thawing.

The classical example of soils’ frosty heaving in the conditions of forcing migration is the collapse of the workshops of the vocational school № 59 in Abakan [4]. The eastern part of the building collapsed because of the extrusion of the thawing soil from under the foundation’s subgrade in the absence of concrete floors on the soil in the basement (Figure 1). In the western part, where there were concrete floors on the soil, their upheaval, caused by the soil’s extrusion from under the foundation’s subgrade, occurred. The floors near two pillars of the basement floor upheave, cracks and hollows, into which a hand of a person could get, appeared.
Figure 1. The geological section along the longitudinal axis with the scheme of deformation (on the left – the western wing, on the right – the eastern one, the collapsed).

Figure 2. The subsidence deformations of the unfinished building of the vocational school № 59 workshops in Abakan after frosty heaving and soil thawing.

As it can be seen in Figure 2, the pillar with the foundation in the collapsed part of the building fell into the soil for more than 1 meter. In the western part the concrete floors prevented the extrusion of the soil from under the foundation’s subgrade and prevented the loss of the thawing soil’s firmness; the soil before thawing was in the frozen condition.

2. Methods of studying frosty heaving and interaction of foundations in the conditions of extremely heaving soils

2.1. Methodology of the research in the stationary and portable ground hod

Comparison of the carried out researches in the freezers with the researches in the field conditions while studying the deformation of frosty heaving, water accumulation at the frost penetration, and cryogenic textures revealed significant discrepancy of laboratory researches from the processes, going on in the natural conditions [5-6]. To liquidate such a discrepancy there was erected a pavilion with a ground hod in Khakass technical institute (KTI) (Figure 3). The methodology of the research in the stationary ground hod was based on the creation of cyclic thermal contour in the period of negative temperatures of the external air. The soil frost penetration was done at the set depth, and its thawing in
the winter period was done with the help of a heater and powerful incandescent lamps at the airtight closure of the pavilion.

![Figure 3. A general appearance of the stationary ground hod.](image)

The pavilion joins to the building from two sides. The bearing constructions of the pavilion 1 were metallic dismountable poles 2 and purlins 3. The roof 4 and two pavilion walls 5 were made with sandwich panels. Along with this, the roof is easily opened during the period of negative temperatures for the soil to freeze up to the depth of 60 cm. For the thawing the roof is closed, the heaters and powerful electric lamps are switched on. The ground hod is bricked 6, the thickness is 250 mm, sheathed with wooden shields, the fence is blocked with the tow. It protected 7 the soil from the frost penetration in the hod, at the bottom the floors in the pavilion are covered with ceramic stones and asphalt. The water pole in the pressure tank 8 with the capacity of 0.5 m$^3$ regulated the level of the ground waters. Two layers of polyethylene were spread at the bottom of the hod; pipes with the holes for water delivery from the tank were built, and filled up with coarse sand. Sandy-loam soil was laid with the layer-specific compaction over the sand. The sandy loam was brought from the site of Abakan district under construction. The coefficient of water accumulation at that site exceeded fivefold values (Cwa=5.12).

In the carried out researches one of the efficient evaluation criteria of the heaving and soils was the coefficient of water accumulation, which was determined by the ratio of soil humidity after frost penetration to the humidity before frost penetration.

The humidity of the frozen soil after migratory water accumulation increases more than three times. The ice lenses in the frozen soil pierce through discordantly deposited various soil fractions, from sand to loam. For the forming cryogenic structure at the low boundary of frost penetration, it is “indifferent” which soil is ahead: natural, as a rule of an inhomogeneous chaotic bedding, from fine and dust sand up to loam alluvial sedimentation in the rivers of Abakan and Yenisei. The textures showed that in the conditions of the close level of the ground waters the predominant factor is the temperature gradient. The influence factors of mineralogical and granulometric compositions in such conditions are not of major importance. The similar findings are presented in the works of Konrad and Morgenstern [7-10].
The works of the Chinese [11-12] experimentalists also confirm the increase of ice lenses before the front of the thawing layer, stretching under the freezing mass. The experiments of the scientists from Northern China (Harbin) [11] on studying cryogenic textures most persuasively point out the sharp increase of the humidity with the depth of frost penetration. Their results confirm our experiments in the pavilion with the ground hod in the natural condition of frost penetration, as well as in the field sites in Abakan and Sapogovo [4].

In the middle part of the nod there was constructed a resistant system for the research of normal forces of frosty heaving and for static testing of thawing soils by stamps. The resistant system is anchored under the gym foundation. However, portable hods were made at the setting in of optimum temperatures for the migration process and for reaching frosty heaving maximum deformations (research of cryogenic textures). The most important task was the study of cryogenic textures on the boundary of the treated and untreated soils (Figure 4). The creation of the immediate contact of such soils was implemented by putting a polyethylene layer between the treated and untreated soil and its further retrieval before the beginning of frost penetration. The treated soil is the same sandy loam with the introduction of potassium ions from the potassium fertilizer KCl into the absorbing complex [4].

![Figure 4](image_url)

**Figure 4.** The formation of the cryogenic texture on the boundary of the soil treated with potassium fertilizer (KCl) and the untreated natural soil.

Methodology in the portable hods is based on the natural frost penetration at the change of the outer air temperature and of the pressure, which promote obtaining stratified cryogenic texture. This is conditioned by twenty-four-hour temperature fluctuations. It is efficient to use chemical treatment in the portable hods as a single process. This excluded contamination of univalent cations “K” in the stationary hod with salts.

It is necessary to mention that such a cryogenic texture was obtained in the conditions of natural frost penetration in the portable hod at twenty-four-hour temperature fluctuations from -1 to -8 degrees Celsius. Thus, a complex anti-heaving sheath works effectively both as higher and lower the ground waters: above ground waters there is fine-grained chipping, below – there is the soil treated by salt.

According to the similar technology medical storehouses had to be built in the village Askiz. However, digging out three bearing piles demonstrated the absence of a complex anti-heaving sheath. As a result unloaded bearing piles appeared to be hove (Figure 5).
Figure 5. Heaving of bearing piles of medical storehouses in village Askiz, the Republic of Khakassia, Russia.

At present the medical storehouses are handed over to a college, and training workshops are located in the heated storehouses. The soil conditions in Askiz college are presented by alluvial depositions of the river Abakan. Loamy soils (up to two meters of the daily surface) are cobbled with pebble sedimentation. The ground waters in the construction period were in the layer of loamy soil, exposed to frosty heaving. Nowadays the ground waters have dropped, and considering the rise of the planning mark by filling up with the pebble soil by 0.9 m, and are at the depth of 3.4 m.

Nevertheless, the heated object is being maintained at present. The unheated storehouse is in emergency. Thin suspended reinforced concrete panels heave together with the heaving mass. Their rise is conditioned by attaching the panels to the bearing piles with the help of the yokes, which freely move up and down the bearing structure.

2.2 Methodology of the field research
The field researches of frosty heaving at the experimental objects are based on the bay of 18 meter, the step of the bearing piles is 6 m: the civil defense storehouses at the station Orositelnaya (built in 1981); the medical storehouses in the village Askiz (built in 1983).

The first object “The civil defense storehouses at the station Orositelnaya” was visually observed twice a year: before and after frost penetration.

After dismantling wall panels, beams and roofing panels while moving the objects to a new location, the bearing piles of one of the storehouses have been unloaded since 2009.

Since that period the instrumental observations of the unloaded bearing piles have been done.

The technology of creating anti-heaving sheath is as follows: in the center of the pile immersion a leading bore with the diameter of 0.8 m is drilled not less than 0.3 m to the level of the ground waters. Into the bottom of the bore a calculating amount (12 kg for this bearing pile) of potassium fertilizer is backfilled, pebbles with sandy aggregate are filled above the salt. In the process of bearing piles’ immersion the salt is carried along with the clayey soil, including extremely heaving soils, when the front of frost penetration permeates below the level of the ground waters.

Despite presenting the same structure and technology of creating the anti-heaving sheath in the design drawings of the storehouse for medical property in the village Askiz, there was no control of the construction work. Digging out three bearing piles at his object revealed the absence of this technology. Evidently, there was no hole-bore while pile-striker’s working, and the foremaster (irresponsible) ordered to immerse the piles without creating the anti-heaving sheath.
In the period of writing PhD thesis in the Laboratory of Physics and Chemistry of Frozen Soils of Scientific Research Institute of Bases and Underground Construction named after N. M. Gersevanov in the Republic of Khakassia the buildings of the storehouses were constructed according to the technology copyrighted by the author’s certificate of invention SU1101498A1. The first object was built at the station Orositelnaya in 1981.

After thirty years of this object’s maintenance, it was relocated to Chernogorsk. But at one of the storehouses they were not able to pull out the bearing piles, and they continue standing unloaded, being not prone to the influence of the heaving soil (Figure 6).

Figure 6. Bearing piles of the dismantled former civil defense storehouses at the station “Orositelny”, the Republic of Khakassia, Russia.

Guaranteeing the steadiness of the bearing piles with the complex anti-heaving sheath is provided due to the formation of the cryogenic texture on the boundary of the soil treated by potassium fertilizer (KCl) and untreated natural soil with vertical ice lenses. The formation of vertical ice lenses on the boundary of the soil treated and untreated by salt is, in our opinion, conditioned by the accelerated passing of frost penetration front in the treated soil and by the formation of negative temperature non-horizontal wave in the area of the treated and untreated soils interaction.

The parameters of the complex anti-heaving sheath were obtained based on the researches of large concrete foundations models’ interaction; the researches were carried out in the ground hod, the foundations had a freezing array.

Figure 7. The structure of the complex anti-heaving sheath at the station “Orositelny”, the Republic of Khakassia, Russia.
In connection with this, the negative temperature of the treated soil advances the process of ice formation in the untreated soil – an additional energy is formed in the untreated soil (during the ice freezing the crystallization heat releases). That is why the advanced front of the negative temperatures of the treated soil causes the formation of the vertical front of the immigration process’ frost penetration in the horizontal direction.

The Polish scientist Kozłowski [13-14] researched the influence of ion K, Ca and Mg content in bentonite and kaolin on the processes of frost penetration. He also included the review of the works of the Russian scientists Yershov and Grechishech. But he did not mention the works of Tyutyunov and Neresova [15], who are recognized specialists in cryopedology.

The classical works of Orlov and Penner till now are the basis for the research of tangential forces of frosty heaving. It is necessary to mention that Penner in his other works [16] referred to the works of the Russian (Soviet) scientists (Tsytovich, Vyalov, et al.).

3. The results of the research
As it has already been described in the methodology, numerous tests on frost penetration in heat chambers did not give the opportunity to create maximum approximate natural conditions of frost penetration of frosty heaving deformation. In connection with this, the research of cryogenic textures on the boundary of the treated and untreated soils was carried out in the portable hods. The typical appearance of the cryogenic texture on the boundary of these two soils is presented in Fig. 4. As it is evident from the presented photo, on the boundary of two media’s division vertical and inclined ice lenses are concentrated. In the treated soil the ice lenses are absent. What is the reason for the formation of vertical and inclined ice lenses on the boundary of two media’s division? The reason is in the accelerated penetration of the negative temperatures through the treated by KCL (potassium fertilizer) soil and creation of non-vertical front of frost penetration. That is why the humidity migration happens horizontally or with a slight incline away from the horizontal.

Minimal sizes of the anti-heaving sheath were obtained based on the study of the interaction of concrete piles with an anti-heaving sheath in the stationary ground hod [17-18]. The 110 mm size of the non-heaving soil excludes the influence of the heaving array on the unloaded stakes. In the field conditions the size of the sheath of the non-heaving soil was considered to be twice more. The diameter of the leading hole was considered 800 mm. The state of the upper part of the sheath made from fine-grained chipping remained stable, calmatation (silt) during 40 years did not happen. The soil below the bottom hole is lower than at drilling the leader hole, and at the contact with the pile it was in a thawed state. At the same time in the distance of 0.3 m from the pile there was frozen soil with the facility of 80 cm (from the depth 70 cm to 150 cm). Therefore, long-term observations of unloaded bearing piles demonstrated the efficiency of the gravel chipping sheath. Despite extremely heaving soils, during the transformation from a thawing, fluid state into a tight plastic one after the summer stabilization, the sheath kept its own primary state.

For the unfilled sheaths in the village Askiz (cold storehouses) under the load on the bearing piles not exceeding 70 kN the tangential forces of frosty heaving during 38 years did not reach the values, exceeding 0.025 MPa.

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