Stabilization of pile foundations subjected to frost heave and in thawing permafrost

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ABSTRACT: New techniques have been developed and applied to the stabilization of pile foundations against frost heave. They are: thermal stabilization of soils and control of their freezing rate by means of a new thermo-siphons design, lowering of heaved piles, new pile cross-sections, chemical methods for increasing strength and stability of frozen soils. These techniques have been tested and used in practice.

1 INTRODUCTION

Providing stable support for buildings and structures in cold regions is an important scientific and practical problem. A great number of buildings, roads, dams, pipelines, power transmission towers, etc. have experienced movement or have failed, e.g. in the northern part of Western Siberia there are more than 4000 tilted power transmission towers. The dominant cause is change (violation) of soils thermal conditions under the influence of natural and man-caused factors. This has led to loss of bearing capacity, perennial thawing or freezing and frost heave, with the latter playing the main role.

Different methods are known to protect foundations of structures from heave and settlement, but many of them are not effective technically or economically (Lyazgin et al. 2001). We have developed and applied several new methods: permafrost soils cooling and thermal stabilization (including freezing of thawed soils) by means of a new thermo-siphon design, freezing rate control, lowering of heaved piles, new pile cross-sections, chemical grouting for increasing strength and stability of frozen soils.

2 THE TECHNIQUE FOR SEASONAL AND ALL-YEAR-ROUND FREEZING, COOLING AND THERMAL STABILIZATION OF SOILS

Two-phase, vapor-liquid, thermo-siphons called “thermal stabilizers” (TS) are mainly used in construction as cooling devices (Waters 1973, Waters et al. 1975). A TS transfers heat from its underground part (evaporator) to the aboveground part (condenser) owing to a cyclic process: working fluid evaporates absorbing heat from soil, the vapor lifts and condenses with heat release and dissipation to the ambient air, then liquid working fluid trickles down. Diameters of different TS vary from 10–20 mm to 300 mm, whereas lengths can reach up to 30–50 m and more, with thermal power of up to several kilowatts per unit. Ammonia is used as the working fluid, placed into sealed metallic (usually steel) tube. Vapor-liquid TSs have extremely high thermal conductivity and cooling efficiency, much more than liquid TSs, and their application region is essentially broader.

Since 1993, the “VNIGAS” institute together with the “Inter Heat Pipe” company (Moscow) has been working out and manufacturing new small-diameter TSs. The most interesting among them is the so-called “TMD-5” (Bayasan et al. 2001a). This is the basic model, and several others have been developed subsequent to it. These devices are manufactured from aluminum alloy with a length from 4 to 11.5 m and tube diameter of 28 mm. TMD-5 has an \( \Omega \)-shape evaporator cross-section because an aluminum plate is welded to the tube to increase its cooling surface and rigidity (Fig. 1). So, the cooling surface is equivalent to a circular tube with a diameter of 54 mm.

Two advantages related to aluminum include the high thermal conductivity of aluminum alloys and no need for an anticorrosive coating, which, when combined with the specific internal features of the TMD-5 decrease the turn-on time to 0.8–2.5 hours compared with 8–12 hours for steel TS. That is why during autumn and spring when freezing air temperatures are only experienced at night, steel TS have insufficient time to operate efficiently, whereas fast-response TMD-5 do. In consequence, the active running time of the thermo-siphons increases by 1–1.5 months per year.
TMD-5 devices have small mass (Table 1), so their evaporators are manually installed in oversized predrilled holes backfilled with sand-water slurry. They produce a low temperature gradient (Table 1) and a cylindrical frost bulb in contrast to conical shapes around other types TS. This is especially important for protection against frost heave because heave forces exerted on a cylindrical frost bulb are less than those on a conical one.

The high efficiency of the TMD-5 has been confirmed experimentally, e.g. we froze sweet (not salt) water (+3.8°C) in Tazovskaya Bay (Western Siberia). TMD-5 had been submerged, and at air temperature −25°C after 3 days the diameter of ice cylinder (it was a cylinder – not a cone!) had reached 0.5 m. The mean freezing rate in sweet water was above 8 cm per day (freezing rate of soils would be more). The high freezing rate is one more factor decreasing frost heave, because the latter is known to be maximal at an optimal freezing rate (2–3 cm per day), and it decreases when the rate is either more or less (Rajani & Morgenstern 1993, Lyazgin & Pustovoit 2001).

Experience and computer simulation have shown that, in many cases, a soil cooling during winter only is not enough. All-year-round cooling is needed, and for this purpose we have developed new TSs using thermoelectric modules – semiconductor plates producing temperature differences (of up to 67 degrees) at their opposite faces under low voltage (12 V) from an external source of electricity. One or more such modules are placed at the condenser of the TMD-5 (or other TS model). It permits freezing and cooling of soils during the warm season, whereas for the rest of the time, new TSs are operating in a normal manner. We are manufacturing TS with thermoelectric modules: TTM-01 (power is 50 W) and TTM-02 (up to 500 W). Power may be variable for control of soil temperature and freezing rate. These new devices have been tested, patented and applied at industrial sites in Western Siberia. More information about their properties, technical parameters and test results are presented in Bayasan et al. (2001b, c).

Note that TTMs may be placed into housings with positive air temperature, e.g. closed vaults, where other types of TS are unusable. We have also developed a special adaptation for such cases with a flexible pipe between the evaporator and condenser (both for TMD and TTM). With such a connection, condensers may be placed outside a structure.

The variety of TS types and the wide range of their technical specifications allow them to be installed in different geocryological conditions to prevent frost heaving, as well as thawing. In any case, TSs increase bearing capacity of permafrost soils and provide stable support for civil and industrial structures. Long-term experience confirms these conclusions.

For instance, TMD-5 (above of 5000 units) are successfully used at the objects in Western Siberia:

- gas fields “Medvjeje”, “Urengoyskoye” and “Yamburgskoye”;
- northern parts of pipelines connecting these gas fields with central Russia and Western Europe;
- high-voltage substation in Novy Urengoy and power transmission towers near this town;
- railway “Obskaya–Bovanenko”;
- civil buildings in Salekhard, Labytnangi, etc.
TTMs have been installed at high-voltage substation in Novy Urengoy, TSs with a flexible pipe — in Salekhard and Labytnangi.

We are also developing small-diameter TSs (28–40 mm) for other purposes. Some of the new types are, for instance, longer TSs (25–30 m and more). They may be vertical — for stabilizing dams, soils under water storages or around gas and oil wells, shafts, etc., as well as nearly horizontal — for slab and mat foundations and for great area engineering structures and industrial buildings. TSs with inclined evaporators (below grade) are gaining in popularity for some special purposes. Thermoelectric modules may be attached to any device of these types.

3 LOWERING OF HEAVED PILES

In the northern region of Western Siberia pile foundations are mainly used, and pipe piles are the pile type of choice. Such piles are subjected to frost heaving processes, especially when this has not been considered in design or the construction technology has been violated. Heaving of piles causes considerable damage to different engineering structures, especially to power transmission lines (their total length in this region is more than 4000 km). Because of differential heaving of piles in foundations of towers they lean, and this has led to power interruptions (Lyazgin 2001).

We have worked out, patented and applied the technology for lowering of heaved piles. It does not require removing the tower from the foundation, but temporary underpinning is used. Lowering the pile to its design elevation is performed in two stages. In the first stage soil strength around and under a pile is reduced by mechanical and thermal methods. In the second stage the pile is lowered with the help of one or several vibratory or vibratory percussion devices. Special connections have been developed and patented to set these devices onto a pile. These provide binding rigidity and strength, as well as a high coefficient of energy transmission.

For piles located in permafrost soils, the thawing is applied at the first stage, as a rule using steam injection. The steam is injected into soil under high pressure through injection points – thin tubes with outlets at the bottom part. In this case the thawed soil has high moisture content and low bearing capacity, and soil freezing is needed to strengthen the pile. Thermo-siphons (=thermal stabilizers — see Section 2) are used for this purpose. We have estimated the time interval needed to freeze the soil and to reach the adequate bearing capacity. Depending on the geocryologic and climatic conditions, the time required varies from 7 to 20 days (Lyazgin & Pustovoit 2001).

The calculations and practice show that recovered piles may be unstable also when steam thawing has not been performed. It means that thermal stabilizers have to be applied in this case as well. It is important that freezeback occurs and pile bearing capacity becomes sufficient by the first winter. By the second and third winters soil temperature will decrease and bearing capacity will increase.

This technology has been applied successfully to tilted power transmission towers near Novy Urengoy (Western Siberia). We plan to apply it to other structures.

4 OPEN-PROFILE PILES

Metallic open-profile pile cross-sections have been developed for increasing reliability of foundations, and primarily for their resistance against frost heave. These piles are in use in the northern part of Western Siberia, mainly as foundations of power transmission towers. Open-profile piles with several cross-section shapes have been developed.

Cruciform piles (Fig. 2a) have been used for the construction and renewal of tower foundations at the power transmission lines, with the total length about 2000 km. H-piles are known to be used extensively in frost areas throughout the world, and channel piles are in use now (Figs 2b, c). These two cross-sections are standard, and they are manufactured industrially. Three-blade piles with straight, broken and curved profile (Figs 2d, e, f) have been developed and tested. Curved profile piles are manufactured from pipes cut lengthwise and welded together.

The results of the tests and the long-time operating data have shown that open-profile piles practically are
not subjected to frost heave in contrast to metallic tube piles – the prevailing foundation type in this region. Open-profile piles may be used both in loose and in dense soils, thawed as well as permafrost. We are continuing theoretical and experimental research to advance calculation technique for bearing capacity of open-profile piles and heave forces acting on them. At the present time, stabilization of power transmission towers is the main application of open-profile piles in Russia, but we hope their use will be much more widespread in the future.

5 CHEMICAL PROTECTION AGAINST FROST HEAVE

The investigations showed that we could efficiently stabilize soils and foundations against frost heave and other negative processes using low concentration aqueous solutions of a polymer. The main advantages of polyvinyl alcohol are its unique physico-chemical affinity for water and ice, lack of toxicity, high breaking strength, and some other specific properties. The polymer is chemically and biologically inert. It doesn’t react with acids, alkalis, or petroleum products. It is stable to light and insensitive to repeated freezing/thawing, wetting/drying, and to microorganism activity.

Solution of a polymer is introduced into slurry backfilling the predrilled hole around a pile (in frozen soil), or it is injected into thawed soil under high pressure through injection points.

Changes in the water properties in the presence of polymer molecules result in peculiar formation and growth of ice crystals. Polymer molecules elongate and form fibers both inside the crystals and between them. Thus, the extended lattice forms and reinforces ice and frozen soils during the freezing process. When the soil thaws, the polymer retains its binding power. The composite material turns out to be “sewed” together or reinforced by the fibers and films of the crystalline polymer. The polymer only swells rather than dissolving later on. It gives elasticity and cohesion to this composite material.

We have studied experimentally compressive strength, shear strength and adfreeze strength of composites that had been created by addition of the polymer. The short-term shear strength of ice increased from 0.5 MPa without the polymer to 4 MPa with it, i.e. by a factor of 8 during layer-by-layer freezing, and from 1.8 MPa to 5 MPa, i.e. by a factor of 2.8 during all-round freezing, if all other conditions remain identical. Similar results have been obtained for frozen soils.

The experiments have shown that a pronounced difference is observed during testing for the long-term and the short-term adfreeze strength. Thus, addition of the polymer (0.5% vol.) has increased the short-term adfreeze strength of loam by 40% and the ultimate adfreeze strength by 460%. The adfreeze strength of sand has increased by 30% and 320% correspondingly.

These and some other experimental data have allowed us to evaluate the forces holding piles from heaving (Lyazgin et al. 2001). Table 2 represents these forces for piles cooled by thermal stabilizers during one winter season after lowering these heaved piles (see Section 3). Small polymer supplement is seen to increase these resisting forces, as well as bearing capacity, by 3–5 times. In addition, the polymer decreases heave forces and values.

6 CONCLUSIONS

The methods and techniques described may be used separately. However in most cases it is rational to apply two or more of them simultaneously, e.g. pile lowering may be accompanied by thermal stabilization as well as by soil chemical consolidation. Long-term experience has shown thermal stabilization to be the most effective and universal (multi-purpose) technique. It may be applied in a wide range of geocryologic and climatic conditions. It also permits control soil temperature and freezing rate.

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