Design of ground freezing for cross passages and tunnel adits

J.A. Sopko Moretrench, A Hayward Baker Company, Rockaway, NJ, USA

ABSTRACT: Ground freezing has been used extensively in the last ten years for the construction of transit tunnel cross passages and SEM tunnels, as well as short adits for utility tunnels. Quite often the ground freezing design requirements are more complex than in conventional shafts. The frozen earth structures are frequently located in urban areas where freezing forces against structures and utilities are common. Additional considerations must be given to frost heave and thaw consolidation. This paper discusses the design procedures related to frost action. Case histories are presented that indicate how frost effects can be controlled with heating pipes, coolant control, insulation methods, and in some cases additional structural bracing. A unique project is discussed where building columns required the installation of a jacking system to accommodate the heave and settlement.

1 INTRODUCTION

1.1 Frost action in soils

When water freezes, the volume increases by approximately nine percent. It is often assumed that the volumetric expansion of soil is as simple as estimating the pore volume and concluding that in a saturated soil this volume will expand by this percentage. Experience and laboratory testing have shown that the process is somewhat more complicated. The soil skeleton will expand when pressure in the ice exceeds the overburden pressure required to initiate separation of the soil skeleton. With sufficient ice pressure, the soil skeleton separates and a new ice lens forms (Andersland & Ladanyi 2004). Typically, the formation of ice lenses requires cyclic freezing and thawing as experienced in nature with seasonal temperature variation. This is not the case in artificial ground freezing. Additionally, ground freezing projects have shorter durations that do not permit the migration of groundwater to the freezing front.

The thawing process begins immediately when the ground freezing refrigeration system is turned off. In nature, the thawing process occurs from the ground surface down, or in in some cases, from a deeper stratum upward. This somewhat simplifies the mechanics of thaw consolidation. In artificial ground freezing, the thaw process begins radially from around each individual refrigeration pipe. As the ice melts and creates an excess of water, excess pore pressures can build up. Before this water can migrate from the frozen zone outward, there is a decrease in shear strength. Surface settlement can also occur depending on the magnitude of ice lenses. However, it must be remembered that the formation of ice lenses on short term artificial ground freezing projects is uncommon (Andersland & Ladanyi 2004).

1.2 Mechanical properties of frozen soil

When designing ground freezing projects, focus is typically given to the strength and thermal properties of the frozen soil. Constant strain rate and constant stress creep compression tests are used to determine the required size of the frozen mass. The thermal properties are evaluated to determine the duration and associated refrigeration load required to form the frozen mass.

A majority of frozen earth projects completed in last 30 years were shafts in remote areas or vacant city lots where frost heave and thaw consolidation were not considered. The design guidelines prepared by the International Symposium on Ground Freezing (ISGF) (Andersland et al. 1991) referred to two testing methods for evaluating the potential for frost susceptibility of soils by using the segregation potential or the CRREL (U.S. Army Cold Regions and Research Engineering Laboratory). These methods provided a qualitive approach to determine whether or not a soil would be subject to frost action but provided no values that could be used to evaluate the potential heave, settlement, or pressure on adjacent structures when artificial ground freezing is used.

These procedures were published well before numerical modeling was used in ground freezing design. Current models such as PLAXIS afford the capability of using the volumetric change in a soil upon freezing or thawing to act as an actual parameter in the input file. One simple method of determining the volumetric expansion is to simply measure the length and several circumferences of the specimen and compute the volume prior to and after freezing.

The volumetric expansion is considered while computing the stresses and deformations of frozen earth structures using PLAXIS. PLAXIS utilizes a system of staged construction in the computation process. One of the stages often labeled the freezing stage is the activation of the frozen soil zone that includes the volumetric expansion. PLAXIS permits the evaluation of the deformations during that phase as shown in Figure 1.



Figure 1. Initial volumetric expansion.

It should be noted that this method only accounts for the primary expansion upon freezing and does not account for the formation of ice lenses, which is not typically considered a factor in artificial ground freezing as previously noted. There are a few problems with the simplification of the described method of measuring frost expansion. Figure 2 illustrates the mechanics of heave during ground freezing.



Figure 2. Frost pressures generated during freezing.

This figure shows the vertical and lateral soil and hydrostatic pressures that resist heave. Different soil types exert varying pressures while frozen and can be measured in a laboratory. Vertical heave can only occur when the pressures generated by the expansion of the pore water through freezing exceed the horizontal and vertical stresses of the in-situ soil conditions. The simplified approach for measuring volumetric expansion does not account for the imposed lateral and vertical in-situ pressures. The author proposes a new method that is a modification of tests developed at Tufts University (Huang & Swan 2017) illustrated in Figure 3.

2 APPLICATIONS IN TUNNELING

2.1 Frozen cross passages



Figure 3. Heave/consolidation cell.

The advantage of this method is that it permits the application of both horizontal and vertical loads, providing a more realistic value of the anticipated in-situ frost heave and thaw consolidation.

Ground freezing is often the only method available to provide temporary earth support and groundwater control for cross passages that are not only very deep but exist in high permeability, cohesionless soils. A typical cross passage ranges in length from 3 to 8 m. Cross Passage 23 on the Seattle Northgate Link Tunnel is illustrated in Figure 4.



Figure 4. CP-23 frozen cross passage.

While the actual design of the frozen earth structure to support the cross passage excavation including structural and thermal analyses is not the topic of this paper, the frost pressures generated by the freezing process warrant discussion. The individual refrigeration pipes can be drilled and installed from within the tunnel(s) as shown in Figure 4 or from the ground surface. Regardless of the method used, the expansion of soil during the freezing process will exert considerable pressure on the segments of the two tunnels.



Figure 5a. Finite element mesh.



Figure 5b. Tunnel displacements.

The three-dimensional mesh shown in Figure 5a is used to simulate the frozen zone. When that zone is activated in the model using a value of volumetric expansion from the laboratory tests, the resulting forces and displacements on the tunnels are computed as shown in Figure b. In this particular application, the volumetric expansion of the frozen soil was 3.1 percent, resulting in maximum forces of 4.28 kN/m² and a maximum displacement of the tunnel segments of 0.017 m. With the knowledge of these forces prior to freezing, sufficient bracing similar to that illustrated in Figure 4 can be installed.

2.2 Frozen tunnel adits

Tunnel adit construction is somewhat similar to cross passage installation but can often be considerably longer. An example of using ground freezing for adit construction at the First Street Tunnel in Washington, DC is presented in Figure 6.



Figure 6. Frozen adit connection.

In this case, ground freezing was used to make the connection from a micro tunneled adit to the main tunnel. The drilling and installation of refrigeration pipes was completed from the ground surface on a roadway laden with utilities including water and sewer lines. The frost susceptibly varies for different soil types. Sand and gravel soils typically exhibit minimal frost heave and thaw consolidation as compared with clay and silt soils (Andersland & Ladanyi 2004).

Review of the soils indicated they were not frost susceptible at this particular location. No mitigation techniques were implemented when the freezing process was initiated but a heave monitoring program was in place. During the initial freezing, unanticipated heaving was observed at the road surface. The contractor was faced with the situation of needing to maintain the freezing system to form the frozen mass at depth while at simultaneously limiting the growth of the frozen zone near the utilities. If it was known in advance that the non-frost susceptible soils would have behaved uncharacteristically and expanded while freezing, protection of the utilities could have been implemented in advance. The most expedient and effective method to limit the growth of the frozen mass and minimize heaving was to insulate the refrigeration pipes in the zone near the affected utilities. This process typically consists of the top 7 to 10 m of the pipe and is installed during the drilling and installation process.

Heave was observed at the road surface during the freezing process. This data was unfortunately not reported until the magnitude of the heave reached a near-threshold level. The heave values are shown in Figure 7.



Figure 7. Frozen adit connection.

As the magnitude of the heave continued to increase, it was necessary to act in order to prevent additional heaving and/or damage to the utilities. Since it was too late to install insulation on the refrigeration pipes, the contractor's only reasonable option was to turn off a few of the redundant refrigeration pipes and then drill/install heating pipes to prevent additional growth of the frozen zone and reduce the size of the already frozen area. Each vertical bar on the graph represents a various phase in controlling the heave. The first bar represents the time at which the contractor was informed that heave was occurring. Five days after notification and confirmation of the data, the redundant refrigeration pipes were turned off. Heave subsided very briefly as the heating pipes were being drilled and installed. The heating pipes were initiated to a depth of 6 m three days later and heave was once again briefly reduced but continued. It was then necessary to heat the ground even deeper to a depth of 12 m. The deeper heating pipes were effective, as shown on the graph.

The heating pipes were essentially the same design of the refrigeration pipes: a steel pipe sealed at the bottom and filled with calcium chloride solution. An electric heating element was installed within each pipe and set to a temperature of approximately 35°C. A time-dependent heat transfer finite element model was used to evaluate the effects of the heat pipes and determine required energy to maintain the 35°C temperature.

This heave was measured at the road surface and not at the utilities. The mitigation using the heating pipes resulted in no measurable heave at the two utilities. After this connection, there were two other zones on the project that required freezing from the ground surface. Due to the unanticipated heave at this site, the refrigeration pipes were insulated on the subsequent projects. There was no measurable ground movement using the insulation.

2.3 Freezing near foundations

It is quite common where ground freezing is used to support excavations near existing building foundations. A large excavation was required within an aircraft factory in the Western United States. The line of refrigeration pipes was very close to existing pipe caps as shown in Figure 8.



Figure 8. Heating pipes to protect pile caps.



Figure 9. Temperature contours with heat pipes activated.

It was necessary to evaluate the geometry, temperature, and electrical power load of the heating pipes in the design phase of the project. This was accomplished using a time dependent finite

element heat transfer analysis. This analysis as presented in Figure 9 presents the temperature after 60 days of freezing. In this model, the heat pipes were considered a temperature boundary condition with the temperature fixed at 35°C. In the model as well during the actual construction, the heating pipes were activated approximately one week before the initiation of the freeze. The actual ground temperatures that were measured during the entire phase of construction were consistent with the modeled temperatures.

Heave at each of the pile caps was measured throughout the entire project. There was no heave during the freezing process nor any observed settlement during thawing. One significant lesson learned from the First Street Tunnel that was applied on this project was the timing of the heating process. On the First Street Tunnel, the heave was not anticipated given the soil conditions. It was not until the freezing was underway that the heave was observed and the heat pipe mitigation plan implemented. As shown in Figure 7, there was significant lag time from the start of the heating until a reduction in heave could be measured.

With that lesson in mind, the modeling confirmed in the field that when the heating pipes are turned on prior to freezing, the freeze will not advance into the warmed zone (provided sufficient heat energy is available).



2.4 Structural bracing to accommodate heave and settlement

Figure 10. Russian Wharf NATM Tunnels.



Figure 11. Load transfer to frozen earth.

In some cases, the frost heave and associated thaw consolidation cannot be prevented or even mitigated, as was the case with the MBTA's Silver Line in Boston, often referred to as the Russia Wharf Project. A binocular-shaped tunnel approximately 13 m wide by 18 m high was constructed under existing buildings in Boston (Lacy et al. 2004). As shown in Figure 10, the tunnel was constructed using NATM techniques under a building that was supported by pile foundations. Ground freezing was used to provide excavation support and groundwater control during construction.

The frozen ground would additionally serve as a medium to distribute the column loads as shown in Figure 10. The soil consisted of a fill layer of organic silts and clays over a silty marine clay. These soils are exceptionally prone to frost heave and thaw consolidation. The load distribution and NATM are shown in Figure 11. Laboratory testing confirmed there would be substantial heaving and settlement during the freezing and post-construction thawing. A jacking system as shown in Figure 12 was installed as a component of the load transfer from the columns to the frozen earth.



Figure 12. Column jacking mechanism.



Figure 13. Effects of jack adjustments.

The jacks enabled the contractor to either lower or raise each building column to compensate for displacements during the various stages of construction. As anticipated, the columns (measured

at the pile caps) began to heave during the freezing. The heave was initially mitigated by restricting the coolant flow to each of the individual refrigeration pipes. This was only a temporary measure and could not accommodate the increased uplift forces caused by the expansion of the freezing ground. As the heave approached the pre-determined threshold limit of 0.003 m, the jacks were activated to lower the columns. Two adjustments of the jacks and continuous cycling of the refrigeration system and coolant flow were required to keep the movements below the threshold limit as shown in Figure 13.

3 CONCLUSIONS

Several aspects related to frost heave and thaw consolidation caused by artificial ground freezing have been discussed. A summary of these issues follows.

Finite element method programs such as PLAXIS can be used to evaluate heave deformations at the ground surface and settlement during thawing. In addition to deformation, these programs can also be used to evaluate the pressure against adjacent tunnels, utilities, and building foundations.

Direct measurement of a soil sample before and after freezing can provide reasonable parametric values for the input in the numeric models. A more accurate method using a triaxial cell and applying vertical loads and lateral pressures is currently being developed and tested.

Heave effects and frost pressures can be mitigated using different techniques. These techniques including deactivating redundant refrigeration pipes, reducing coolant flow or temperature, and installing and maintaining heating pipes.

In unique situations where frost-susceptible soils are present without a way to limit the growth of the frozen soil mass, it is possible to adjust the structure with bracing or a system of jacks to compensate for structural distortion.

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