NEW DESIGN METHOD FOR FROZEN EARTH SHAFT SUPPORT

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ABSTRACT

The first documented procedures for designing frozen earth structures are over 50 years old, implemented long before the introduction of the Finite Element Method (FEM). Since that time, the development of three-dimensional models has made the traditional and often over-conservative methods relatively obsolete. This paper discusses a new approach that is largely dependent on the analysis of internal stresses with the frozen structure and comparison to frozen soil laboratory tests. A specific design process is discussed related to initial field investigation, laboratory testing, structural and thermal analysis, and performance monitoring. The design results are compared to case histories in the field that verify the procedure.

Keywords: design, frozen, earth, structures, stresses

BACKGROUND

One of the first documented methods to designing frozen earth retaining structures was by Sangar (1968). Methodical refinements were published by (Harris 1995) and published by the International Symposium on Ground Freezing in 2002 (Andersland et al. 1991). The structural design or thickness of the frozen mass was based on the unconfined compressive strength of the frozen soils. Two simple equations for determining the thickness of a frozen shaft are shown in Fig. 1 and the first two equations below.

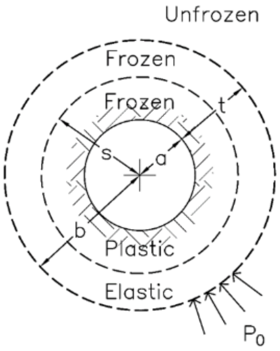

Fig. 1. Description of the variables used in the structural equations

$$t = a\left[0.29\left(\frac{P_0}{q}\right)+2.30\left(\frac{P_0}{q}\right)^2\right] \quad [1]$$

$$t = a\left[(0.29 + 1.42\sin\varnothing)\left(\frac{P_0}{q}\right)+(2.30 - 4.60\sin\varnothing)\left(\frac{P_0}{q}\right)^2\right] \quad [2]$$

Where $s = \sqrt{ab}$.

This method assumed the frozen earth structure was a thick-walled cylinder with shortcomings often leading to conservative results. Inconsistencies with this method (Sopko 1990) include the following. P_o is often the at-rest earth pressure and inconsistent with actual subsurface conditions; it does not account for strain deformation of the frozen structure, pressure generated by the expansion of the soil during the freezing process, and the natural arching of the soils. Secondly, the structure is not a fully open cylinder, it is fixed at the bottom with a cantilevered effect as the soil or rock at the base absorbs some of the stress. Finally, the unconfined compressive strength does not represent the confined state of the frozen soil within the frozen mass.

Once the thickness of the frozen structure is determined, both methods describe a thermal analysis to determine the refrigeration pipe spacing, required freezing time, and associated refrigeration load. The methods for evaluating the thermal requirements are shown in Equations 3-7 and Fig. 2. The time required to have closure of the frozen wall is defined as t_I while the additional time required to form the entire structure is defined as t_2. It is also necessary to evaluate the required refrigeration load (*Kw*) as shown in Equation 6.

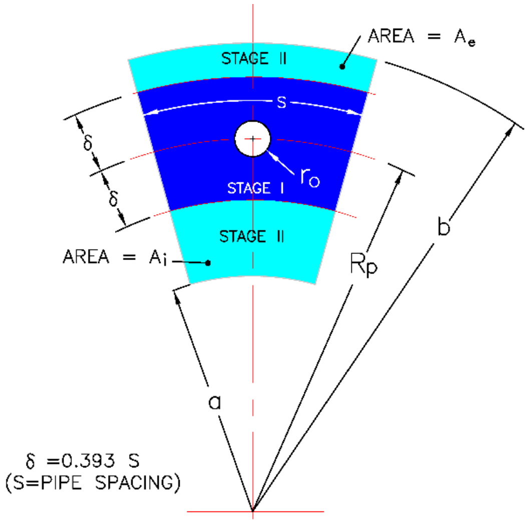

Fig. 2. Description of variables used in the thermal equations

$$t_I = \frac{R^2}{4K_1 v_s}\{(L_I)(2\ \ln\ R' - 1) + C_1 v_s\} \qquad [3]$$

Where K_1 = frozen thermal conductivity of the soil, C_1 = frozen heat capacity of the soil, and v_s = degrees that the coolant temperature is below freezing.

$$L_I = (L + C_1 v_s + 3C_2 v_0) \qquad [4]$$

Where L = latent heat of fusion and v_o = degrees that the initial ground temperature is above freezing.

$$t = t_{IIe} = \frac{1}{2K_1 v_s}(L_{IIe})\left[b^2\ \ln\frac{b}{R_p+\delta} - \frac{b^2-(R_p+\delta)^2}{2}\right] + \frac{C_1}{2K_1}\left[\frac{b^2-(R_p+\delta)^2}{2}\right] \qquad [5]$$

$$Kw = \frac{K_1 v_s}{6685}\frac{1}{\ln R^1}\text{ kw per unit of pipe} \qquad [6]$$

While these equations provide a somewhat reasonable estimate of the required time and heat load, inadequacies become apparent when applied to actual construction projects. Actual refrigeration pipe spacing after drilling is highly variable due to deviations. The equations are suited for a uniform spacing around the shaft perimeter, are pure conduction, do not account for the convection associated with the circulation coolant flow, and use values for frozen and unfrozen thermal conductivity when the value is actually a function of temperature. The coolant temperature is typically warmer for the first week of freezing and then cools off. The equations only use one temperature. This method does not factor in groundwater velocity that can delay or even prevent the formation of a frozen earth wall.

With the advent of numerical methods (particularly the FEM), new methods have been developed and put into practice to perform the structural and thermal designs of frozen earth structures. The value of the numeric models, however, are highly dependent on the material properties used in the input files. These numeric methods have been used, modified, and verified with ground freezing projects since 1985. The standardization of these models in practice requires the standardization of evaluating the parameters which only through a standard practice of field investigation, laboratory testing, instrumentation, and field quality assurance.

FIELD INVESTIGATION

When ground freezing is specified as a method of temporary earth support or groundwater control in an underground project, frozen soil testing is typically included in the Geotechnical Baseline Report (GBR) or Geotechnical Data Report (GDR). In cases where these tests are excluded or ground freezing is selected after the contract documents are published, an additional sampling test and program must be implemented. The field investigation for a ground freezing project should include but not be limited to the following:

1. verification of strata type and elevations by conducting borings as close to the frozen structure as possible that may include standard penetration tests. A clear definition of the strata is required without forgetting highly permeable strata are potential sources for lateral groundwater flow and clay strata are susceptible to time-dependent creep deformation during excavation. While the standard penetration test is good indicator of soil density, using correlations for other parameters can result in inaccurate values;
2. finishing groundwater elevations measured through several tide cycles in the borings as monitoring wells or piezometers. Boring locations should be situated to measure any potential groundwater gradients across the site. Lateral groundwater flow can delay or even prevent the formation of the frozen earth wall. Borings finished with piezometers or monitoring wells across the site can be used to detect ground water gradient. A large gradient coupled with high permeability can result in excessive groundwater velocity;
3. verification of impermeable base stratum, key to vertical excavations. The frozen earth structure should extend into an impermeable rock or soil stratum deep enough to ensure hydraulic and basal bottom stability. In cases where such a stratum does not exist, it is possible to drill and install refrigeration pipes in the interior of the structure to form a frozen bottom plug;
4. index tests including density, water content, grain size, and Atterberg limits;
5. collecting samples for compression testing;
6. an aquifer pumping test.

LABORATORY INVESTIGATION

It is highly important to obtain quality soil samples for testing. While it is possible to obtain quality relatively undisturbed cohesive samples, quality saturate sand samples are difficult to attain. In almost all cases, it is necessary to reconstitute the samples and correlate the SPT values with density using an accepted method. Quality sample preparations for testing are as important as the tests themselves. In addition to the density, two other key components will ensure the samples are fully saturated and frozen using a procedure that eliminates water and ice segregation. This can be accomplished by exposing the base of the cylindrical sample and insulating the top and sides, forcing the freezing in one direction. Freezing from all sides could result in entrapped water and ice in the sample’s center.

The laboratory tests conducted for the design phase include unfrozen triaxial testing and constant strain rate frozen soil compression testing. Typically consolidated, undrained, multi-stage (ASTM D4767-11) triaxial tests are conducted to evaluate the shear strength, friction angle, and elastic modulus of the unfrozen soil. These values are needed to evaluate the lateral earth pressure imposed on the frozen structure when the shaft is excavated. Constant strain rate unconfined compression tests (ASTM D7300-18) are conducted on the frozen soil, typically at -10ºC and -15ºC using a testing apparatus similar to those in Figs. 3a-b.

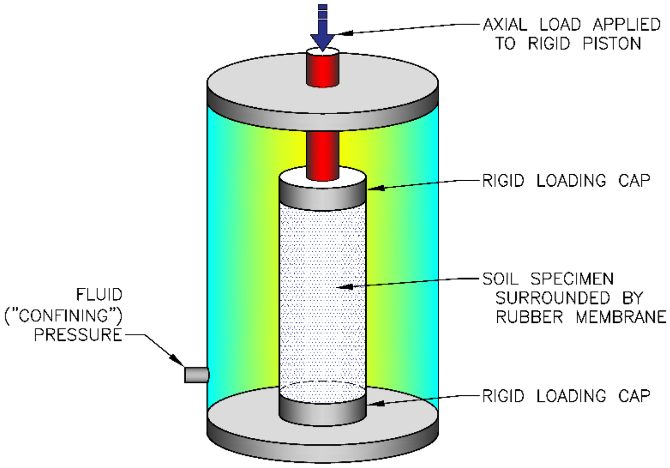

Fig. 3a. Triaxial Compression Cell

Fig. 3b. Compression test load frame in freezer

Testing strain rates can range from 1.0 to 0.1 percent strain per minute. The higher rate will yield a higher strength while the lower rate will yield a lower strength. Research indicates the strength and elastic modulus from this lower strain rate could replace the need for the constant stress creep tests. Results of the constant strain rate test provide an instantaneous or short-term strength and elastic modulus. Frozen soil exhibits time and temperature-dependent rheology; it is stronger at colder temperatures and strength decreases with time. The results of this are used to determine the stress levels in constant stress creep tests. Per ASTM D5520, the recommended stress levels are 0.5, 0.3, 0.3, and 0.1 of the unconfined compressive strength determined by this test.

The constant stress (creep) frozen soil compression test (ASTM D5520-18) is used to evaluate the long-term compressive strength and elastic modulus of the frozen soil. The samples are typically tested as -10ºC and -15ºC. The results of the time versus strain values for each stress level is shown in Fig. 4.

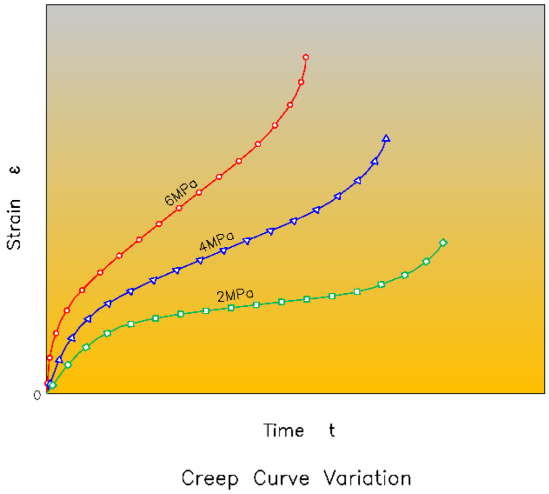

Fig. 4. Results of the constant stress creep tests

It is important the test is conducted long enough to fail the sample; 6 percent strain should be considered failure. It is not uncommon when the actual failure is not readily observed. The creep test data is used to determine the parameters A, B, and C as described by Klein (1981). These parameters cannot be computed unless the samples are run to failure or assumed 6 percent as failure. Once these parameters have been obtained, it is possible to evaluate the unconfined compressive strength (q_f) and elastic modulus E as functions of time as shown in Equations 7-8.

$$q_f(t) = \left(\frac{\epsilon_f}{A * t^C}\right)^{1/B} \qquad [7]$$

$$E(t) = \left(\frac{\epsilon^{(1-B)}}{A * t^C}\right)^{1/B} \qquad [8]$$

Where A, B, and C are creep parameters and ε_f is the strain at which the samples fail. Typically, all stresses fail at the same strain. If not, the failure strains should be averages, or simply use 0.06 (whichever is lower).

FROST HEAVE AND THAW CONSOLIDATION

With more ground freezing projects conducted in urban areas, it is necessary to evaluate the effects of frost heave and thaw consolidation on structures, utilities, and roadways. There are no established and universally accepted laboratory procedures for determining these parameters. Frost heave is typically defined by the primary heave, which occurs instantly upon freezing when the pore water freezes and has a volumetric expansion of approximately 9 percent (note only the water expands 9 percent, not the entire soil mass), and secondary heave. Secondary heave occurs when ice lenses form in fine-grained, frost-susceptible soils. As the freezing front is formed, water migrates towards the front and freezes. Secondary heave is more common in natural, seasonal freezing when there are many freeze/thaw cycles.

The segregation potential test has been suggested as a method for evaluating frost effects on soils. The author has found it a complicated procedure and subject to laboratory mistakes. There is no ASTM standard for this test nor computer program available to use the results. A more positive approach is directly measuring the primary heave and settlement in a device like the one in Fig. 5. This device permits the application of a vertical load prior to freezing. Heave can then be measured followed by settlement upon thawing. Variations of this device are being developed that include a flexible member to permit variation of the later stress. Volumetric expansion and contraction can be determined and used in numerical analysis.

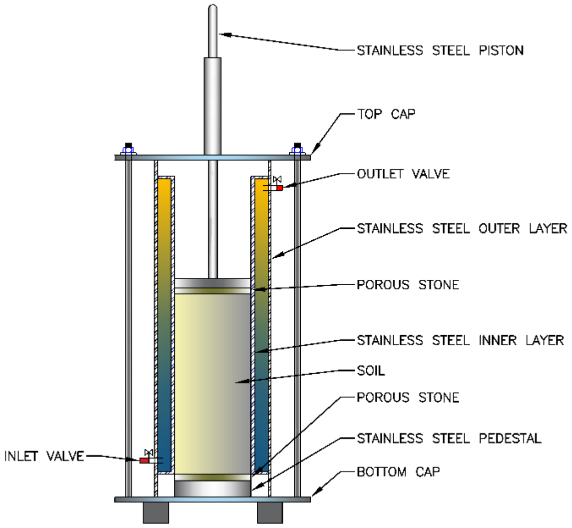

Fig. 5. Volumetric change cell

STRUCTURAL ANALYSIS

Numerical methods, particularly the FEM, permit evaluation of the frozen earth structure and compensate for disadvantages of the equations previously presented. An axis-symmetric model is the most straight forward approach to analyzing a frozen shaft as presented in Fig. 6. The internal stresses of the frozen earth wall section are presented in Fig. 7. The FEM requires an iterative process where different frozen wall thicknesses are evaluated. Fig. 7 shows the hoop stresses defined in Fig. 8.

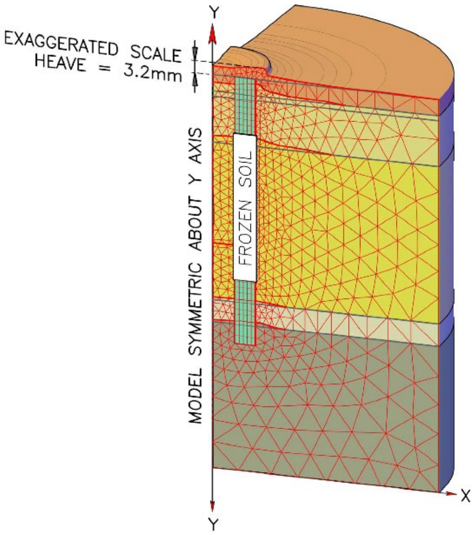

Fig. 6. Axisymmetric FEM model

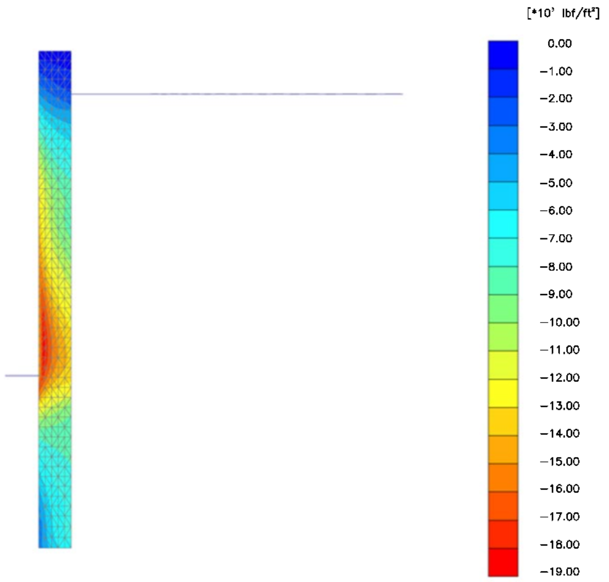

Fig. 7. Stresses within the frozen wall

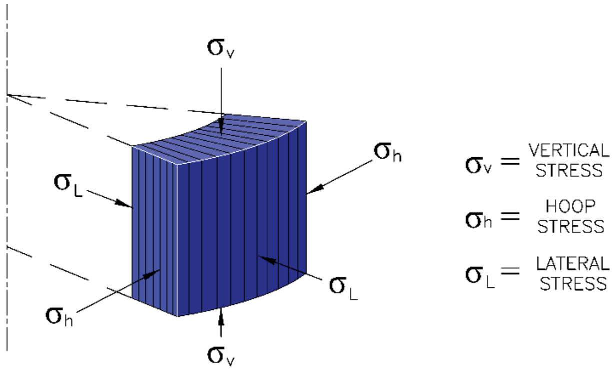

Fig. 8. Definition of Stresses

The hoop stresses are then compared to the long-term strength evaluated in Equation 7. This is a comparison to an unconfined strength when in fact the in-situ frozen soil is subject to lateral confining stresses displayed in Fig. 8. A new approach described by Sopko (2019) is to use this comparison as the factor of safety (F.S.):

$$\text{F.S.} = q_f\,(t)/\text{max hoop stress} \qquad [9]$$

This approach is significantly different than the two traditional approaches. Those methods apply a factor of safety of 2.0 by dividing the unconfined compressive strength by two. This leads to additional conservatism, particularly when the inconsistencies are added to the design. The traditional approaches also consider only a thin-walled cylinder. In practice, it is not uncommon to line the frozen shaft sequentially as the excavation progresses. This method requires the use of staged construction approaches used in commercially available FEM programs.

THERMAL ANALYSIS

Once the thickness of the frozen mass is determined, it is necessary to provide a thermal analysis to determine the spacing of the refrigeration pipes, required time to freeze, and refrigeration capacity required to form the mass in a specified time frame. Figs. 9a-b illustrate a typical FEM mesh used on a recent shaft project. The refrigeration pipe coordinates were taken from a deviation survey completed after the drilling and installation of the pipes. The spacing is not equal, hence the need for the model. Results of the model present the temperature regime after approximately 30 days of freezing. A more specific evaluation of the time is presented in Fig. 10, where actual temperatures are calculated at a node located where the frozen zone extends to the required structural thickness. These figures also compare the modeled temperature to actual data from the project.

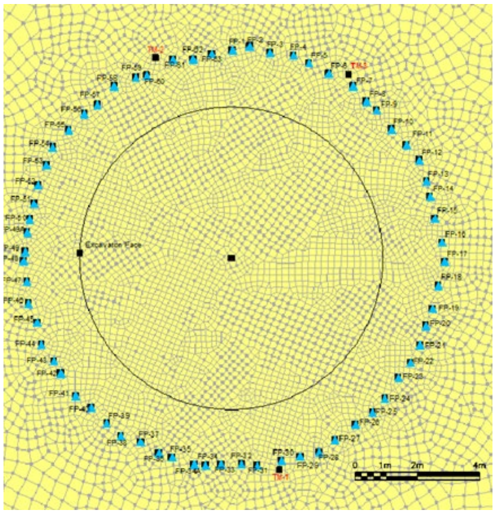

Fig. 9a. Thermal finite element mesh and computed temperature regime

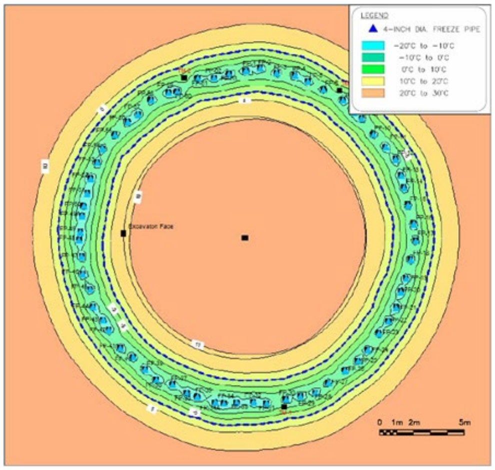

Fig. 9b. Thermal finite element mesh and computed temperature regime

As previously mentioned, lateral groundwater flow introduces heat into the system and can delay or prevent the formation of the frozen wall. Certain FEM heat transfer programs permit the coupling of the thermal model with a groundwater flow program, permitting an evaluation of the heat introduced by the fluid. If the lateral groundwater flow exceeds 1 m/day, the frozen wall will not form using a single row of refrigeration pipes. Fig. 10 illustrates the results of a heat transfer model coupled with groundwater flow. Fig. 11 shows temperature flow. These models provide evaluation of the heat extracted to be included in the design of the mechanical ground freezing system.

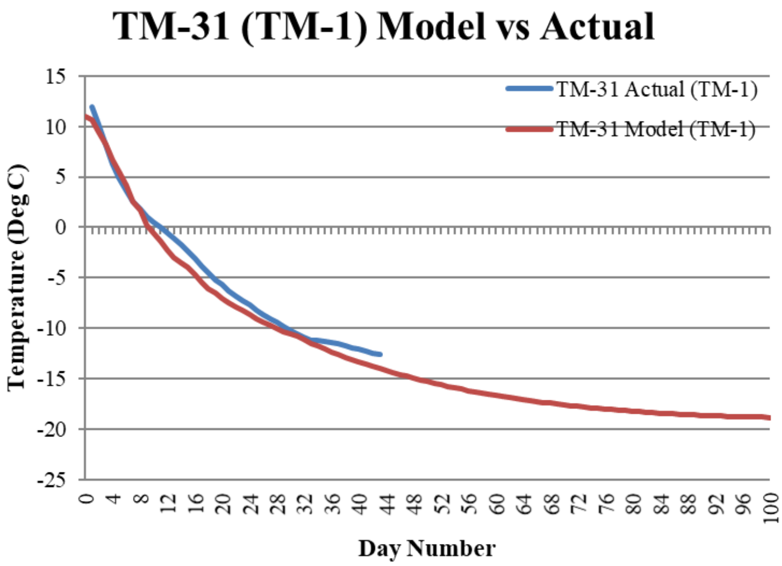

Fig. 10. Time vs temperature plot

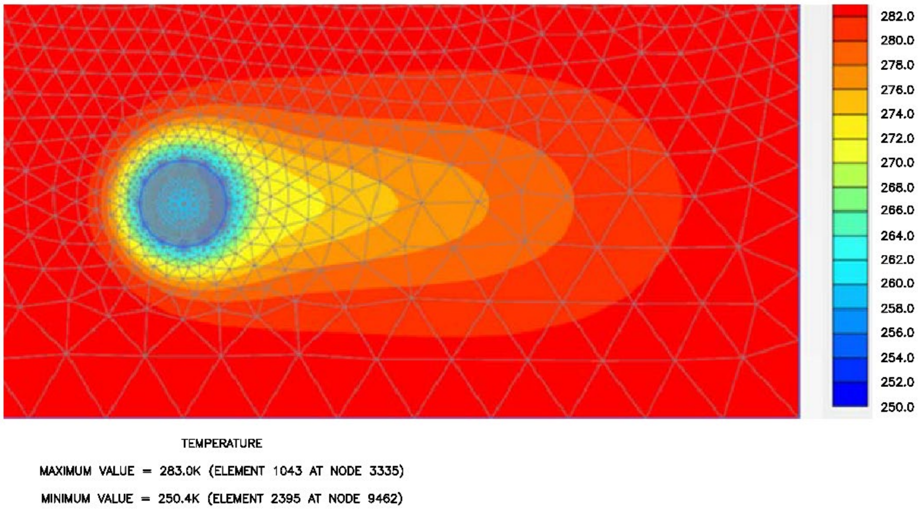

Fig. 11. Temperature plot

INSTRUMENTATION AND QUALITY ASSURANCE

A quality instrumentation system is required to ensure components of the design are implemented and correct. Ground freezing instrumentation systems should measure and record ground temperature and water level, coolant temperature, return temperature from each individual refrigeration pipe, flow rate, refrigeration plant data, and heave and settlement. The data must be evaluated as frequently as practical and compared to the behavior predicted in the analysis.

CONCLUSIONS

The introduction of the finite element method for the structural and thermal design of frozen earth structures has shown advantages over the previously accept methods. It is now possible to model the actual frozen structure instead of free body diagrams that somewhat represent the in-situ geometry and stresses. These methods have been in practice for the last ten years by experienced ground freezing contractors and proven to be effective.

Given quality frozen soil laboratory tests, it is now possible to more reasonably evaluate the factor of safety. This paper presents a summary of the methods used and considers them a starting point for industry-wide acceptance.

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