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Please note

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Cold storage buildings and ice rinks frequently encounter trouble from frost heaving. It is not unusual to find curling rinks with 2 to 3 inches of irregular heave, and cold storage buildings have been observed where the centre of the floor has heaved more than a foot. Although uniform heaving will have little effect on the use of curling or skating rinks, irregular differential heaving must be avoided. Only a small amount of it can be accommodated by ice making techniques, and the structure itself may suffer damage. Cold storage buildings or rinks used year round will eventually suffer serious damage if the freezing plane is permitted to move into frost-susceptible soil where moisture is present because of the subsequent continuous build-up of ice. This Digest discusses methods that can be employed to avoid or alleviate these troubles. It should be pointed out, however, that differential settlement can be caused by poor building design or poor workmanship, which will also cause uneven floors and ice surfaces, and damage the structure.

Mechanism of Heaving

Heaving problems generally occur as the result of imperfect understanding, during design, of the nature of frost heave. For heaving to take place two conditions are necessary, in addition to sub-freezing temperatures. As discussed in **CBD 26** these are:

1. a fine-grained material (soil) through which moisture can move, and
2. a supply of water.

In fine-grained soils such as silts and clays moisture is continuously drawn to the freezing plane where it forms ice lenses. These lenses physically lift the soil above them, thus causing heave at the ground surface. It should be emphasized that this type of heave, due to formation of ice lenses, is not related to the very much smaller volume change of water frozen *in situ*. In general, fine sands, silts and clays are susceptible to heaving and coarse sands and gravels are not. The frost susceptibility of a soil can often be determined by comparing its sieve analysis with that of a soil known to be frost susceptible.

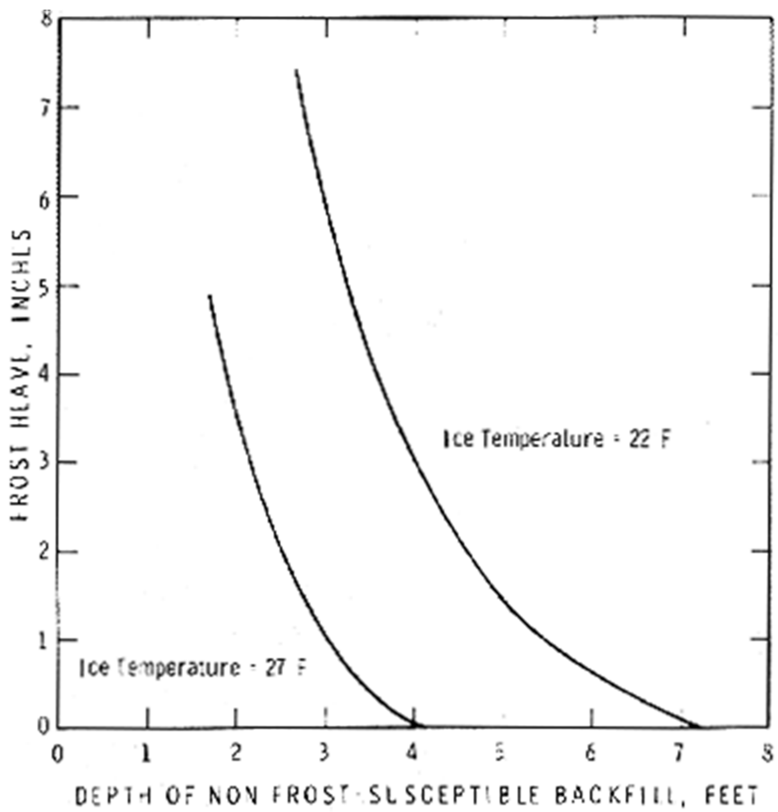

Figure 1. Maximum possible frost heave at end of a six-month cold period (average off-season temperature = 60°F)

By way of illustration of the extent of frost heave that can occur under ice rinks, Figure 1 gives calculated values of maximum possible heave after six months of operation for a saturated clay sub-soil overlain with well-drained non-susceptible back-fill of different thicknesses. The two curves shown are for ice temperatures of 22 and 27°F, the off-season temperature in the building averaging 60°F. It should be emphasized strongly that the assumed conditions of extremely frost-susceptible soil and a high water table will very seldom, if ever, be encountered in practice. Consequently, the frost heaves given in Figure 1 should be considered representative of maximum limits only. It should also be noted that the brine temperature of the refrigeration system is usually 4 or 5 F deg lower than the ice temperature. With these factors in mind, it can be seen that as much as 5 1/2 inches of heave can occur under a rink with an ice temperature of 22°F and 3 feet of non-frost-susceptible soil over the frost-susceptible material.

Methods of Preventing Frost Heave

If more than one site is available, one that has a non-frost-susceptible soil should be chosen. Very often, however, the site is fixed by other considerations, making it necessary to take suitable precautions to prevent frost heave. Basically there are two methods of doing this: either replace the frost-susceptible soil or prevent it from being frozen by supplying heat or insulation, or a combination of both. In addition, every effort should be made to ensure maximum drainage.

Rinks and cold storage buildings can be separated into two classes: those that operate on a seasonal basis and those that operate on a continuous basis. The depth of frost penetration under buildings operated continuously can amount to tens of feet, depending on the inside design temperature, the average outside air temperature and the plan area of the building. With seasonal operation, the freezing plane will normally extend several feet into the ground in the winter and recede during the summer. For simplicity, this paper will deal with the two cases separately.

Permanent Operation of a Building at Sub-Freezing Temperatures

Figure 2 shows the temperature distribution under a long narrow building of width, w, as it would occur after a number of years of operation. In this particular case the mean annual ground temperature is assumed to be 48°F (Ottawa) and the building is maintained at -10°F (cold storage) or 22°F (ice rink). For the cold storage, the freezing plane (32°F) is found to be at a depth of 1.16 w under the centre of the building and for the ice rink, at a depth of 0.36 w. Thus, if the building were 60 feet wide, the maximum depth of frost under the centre would be 70 feet for the cold storage and 22 feet for the ice rink. The temperature distribution with different inside and outside temperatures can easily be established from Figure 2 by noting that there are just ten lines of constant temperature given and the temperature change between any two lines is one-tenth of the difference between the building temperature (floor or ice) and the mean annual ground temperature. It is also helpful to note, in considering ground thermal problems generally, that heat always flows perpendicular to lines of constant temperature between the outside ground surface and the building floor.

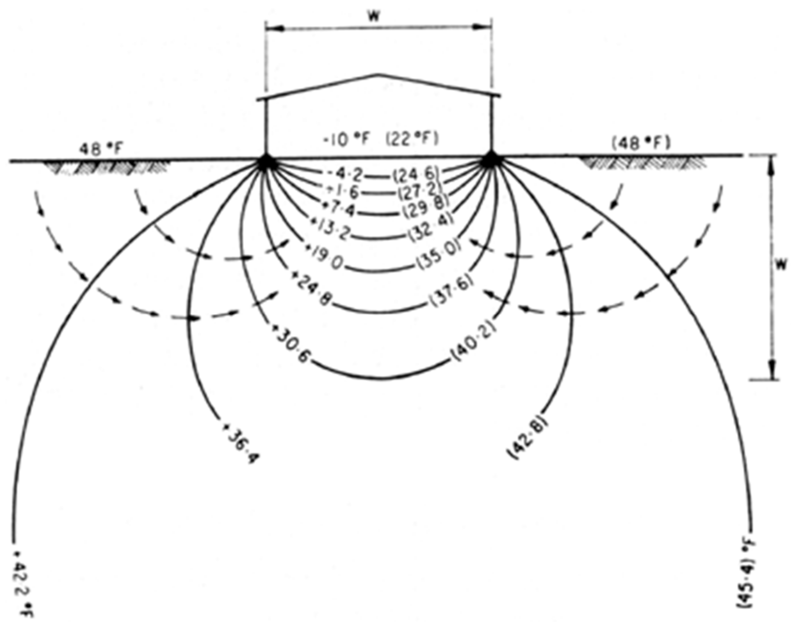

Figure 2. Ground temperature regime under a cold storage building maintained at -10°F or 22°F in a region where the mean annual ground temperature is 48°F (arrows show heat flow direction)

Use of Insulation to Prevent Ground Freezing

It would not be economical to replace the frozen regions in the previous example by nonsusceptible material. Consideration must therefore be given to reducing the depths required by using insulation and supplying heat. The effect of insulation can be judged by noting that for steady-state problems 1 inch of insulation is thermally equivalent to about 2 feet of soil. Thus, freezing could be entirely prevented under the cold storage building by 35 inches of insulation and under the ice rink by 11 inches. Actually, less insulation is required near the edges of the building, so that with tapering the average thicknesses required would be about 24 and 7 inches, respectively. It must be emphasized that only high quality, moisture-impermeable insulation is suitable for below-grade application, and that its cost usually prohibits use in such large quantities.

Use of Soil Heating Systems

Penetration of the freezing plane into the ground can be controlled by providing heat to compensate for that removed by the refrigeration system, while maintaining the desired conditions inside the building. The amount of heat required and the installation costs of the heating system can be minimized by the application of insulation or an equivalent thickness of non-frost-susceptible back-fill between the heating conduits and the building floor. Although with some combinations of insulation and heating it may not be necessary to replace any of the frost-susceptible soil, the use of 1 or 2 feet of non-frost-susceptible soil generally provides for proper drainage of the site and, in many cases, space for the heating system. The final decision on the design should be based on economic considerations.

Table I gives calculated duct temperatures and heat flow requirements for a warm-air system designed to prevent freezing under a 3-inch layer of insulation, with 8-inch diameter ducts on 10-foot centres located with their centrelines 1 foot below the insulation layer. Because 1 inch of insulation is thermally equivalent to 2 feet of soil, the same values would be obtained with the ducts located below 6 feet of back-fill. For other duct sizes and spacing arrangements the reader should follow the method of calculation given in NRC 5095, which was used to calculate the values given in Table I.

Table I. Duct Temperature and Heat Flow Requirements to Prevent Freezing Under Low-Temperature Buildings
(4-inch-thick concrete floor and 3 inches of insulation (equivalent to 6 feet of soil) with 8-inch diameter ducts on 10-foot centres with the centres 1 foot below the bottom of insulation)

Building floor temperature, °F	20	10	0	-10
Duct temperature, °F	41	48	56	63
Heat flow* per lineal foot of duct, Btu/hr	11	20	30	39

* The heat flow is independent of duct size, thus the figures apply to any duct or electric cable.

Ice Rinks and Seasonal Operation

The maximum depth of frost under a rink depends on the ice temperature, the duration of the ice season, the average air temperature in the building during the summer off-season, and to a lesser extent on the thermal properties of the soil. Figure 3 summarizes calculated results and gives the maximum depth of frost penetration in average coarse-grained material for two values of ice temperature (22 and 27°F) as a function of ice season duration and average building air temperature during the off-season.

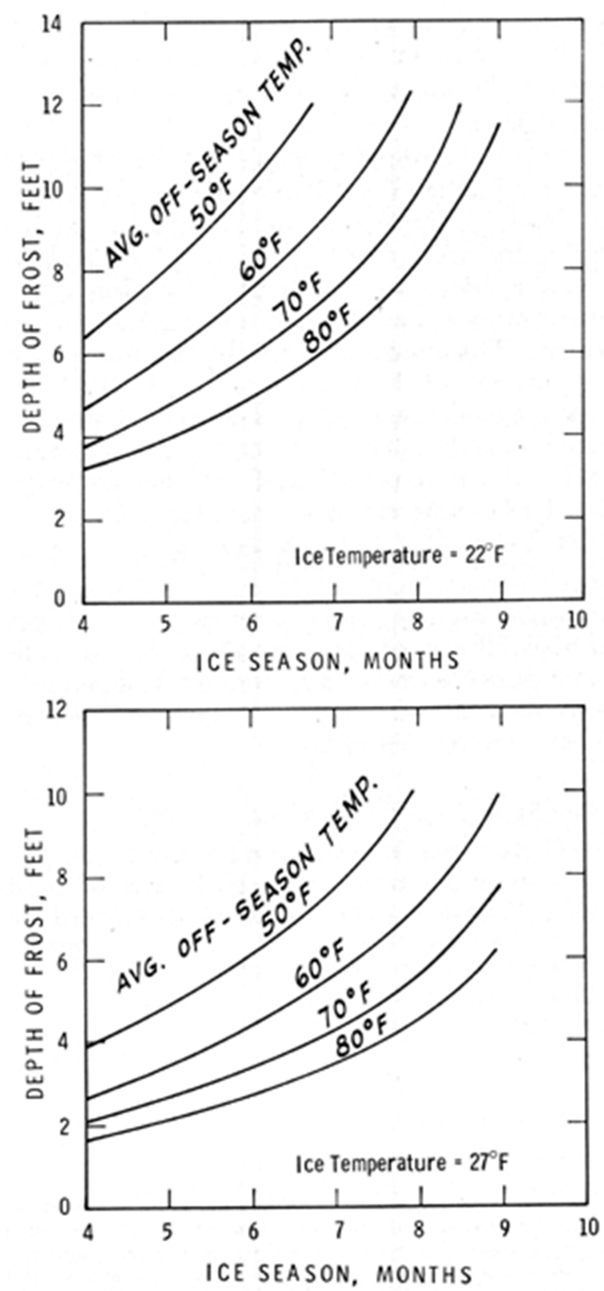

Figure 3. Frost penetration under ice rinks

It is to be noted particularly from Figure 3 that for average Canadian conditions, in which the average off-season temperature is about 60°F, the frost depth for an ice temperature of 22°F lies between about 7 feet for a six-month season and 12 feet for an eight-month season. The corresponding depths for an ice temperature of 21°F are 4 feet and 7 feet, respectively. Consequently, the amount of excavation and back-fill required for frost-susceptible soil can be considerably reduced by keeping the ice temperature as high as possible.

It is not imperative that the freezing plane never penetrate frost-susceptible sub-soil. For example, Figure 1 indicates that if only 5 feet of back-fill is used for a rink at 22°F, the maximum possible heave is 1.5 inches. It should be remembered that Figure 1 represents uncommonly severe conditions.

Insulation and Soil Heating Systems

Either insulation or soil heating can be used to prevent or limit the extent of frost heave. The economic merits of each must be determined for individual situations, however, as was outlined for the permanent operation of the building at sub-freezing temperatures.

Alleviating Frost Heave Problems and Extending the Operating Season

Some reduction in frost heave in existing rinks can be obtained by raising the ice temperature during the colder months. In addition, Figure 3 shows that frost penetration can be reduced by raising the temperature in the building during the off-season. For example, if frost heave occurs with 5 feet of back-fill (or 2½ inches of insulation), then increasing the average off-season air temperature in the building from 60 to 80°F should eliminate the heaving. It is also apparent that supplementary heating can be used to extend the operating season. For example, increasing the off-season temperature to 80°F would allow a 7½- to 8-month season instead of a 6-month season. Probably the best method of raising the average off-season air temperature is to melt the ice and warm the frozen ground at the end of the season by circulating warm brine through the system.

Conclusion

Provided the mechanism of frost heave is understood, difficulties associated with it can be prevented at reasonable cost. For plants operated continuously at below-freezing temperatures it is probable that the most satisfactory solution is to provide heat. In plants operated on a seasonal basis the use of non-frost-susceptible back-fill and insulation may be preferable.