Ammonia Plant Safety
Vol 12.
1969/1970.

Frost Heaves and Storage Vessel Foundations

The size and use of equipment, soil and ground conditions, type of foundation, and economic considerations determine what precautions are necessary to prevent ground heaves.

D. M. Morrison
and
H. T. Marshall
Chicago Bridge & Iron Co.,
Oak Brook, Ill.

A great deal of theoretical and experimental work is being done on frost heave in soils, largely to find solutions to highway frost soil problems. The mechanics of frost penetration and moisture migration in soils is the same, however, whether it occurs beneath a highway pavement or the foundation of a low temperature storage vessel. A low temperature vessel can, under certain conditions, create a temperature condition in the foundation subgrade similar to that existing beneath a highway pavement during sub-freezing weather. This condition can cause an increase in the moisture content of the soil beneath the foundation, the formation of ice lenses in the soil, and, finally, heave of the foundation.

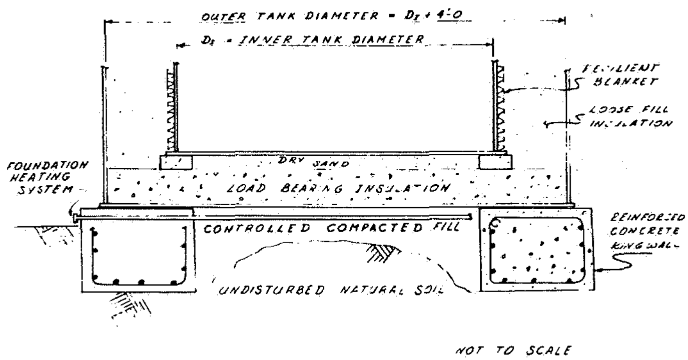

Figure 1. Foundation details for a double wall ammonia storage tank.

Mechanics of frost heave

Low temperature storage equipment is, in general, insulated from its foundation and the soil subgrade. Figure 1 illustrates the foundation insulation of a typical double wall, low temperature ammonia storage-facility. Insulation alone, however, is not sufficient to prevent a lowering of temperature or even freezing of the soil beneath the tank. A system of heating coils is installed beneath the insulation to maintain the soil at the base of the tank at above freezing temperatures. The case histories to follow will show that distress in the structure can result when the foundation soil temperature is allowed to drop below freezing.

Figure 2 shows a situation in which the subgrade beneath a low temperature tank has not been adequately protected from the subfreezing temperatures of the tank product. The figure shows, qualitatively, the isothermal lines which are generated when the temperature at the base of the structure is significantly lower than the mean soil temperature or the temperature of the ground water.

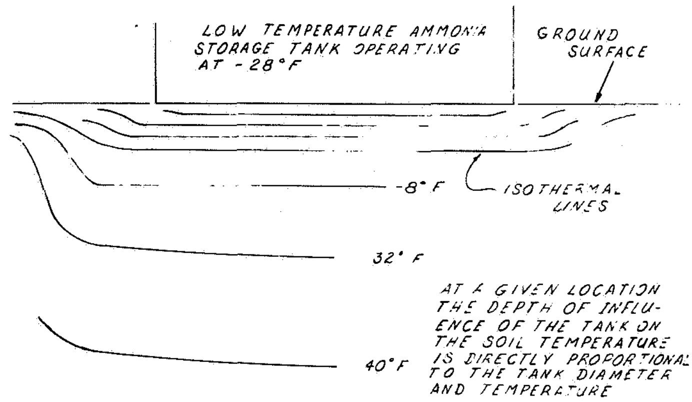

Figure 2. Isothermal lines beneath a low temperature ammonia tank.

If the pores of a soil mass are saturated with water, and if the pore water is frozen quickly, the volume change which occures is due entirely to the expansion of water as it freezes; a volume change of about 9%. In a typical sample of soil having an allowable bearing capacity

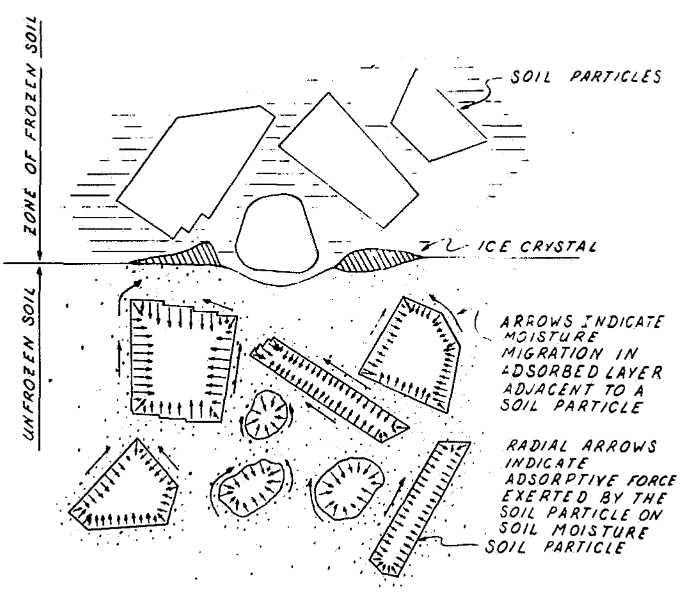

Figure 3. Suction process by which soil moisture is drawn upward to the region of frozen soil.

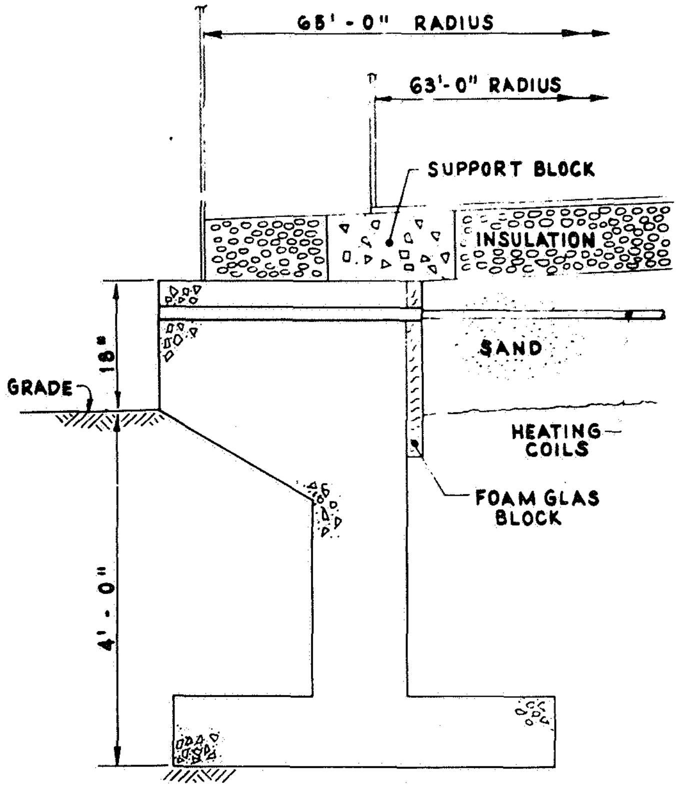

Figure 4. Tank foundation and support system.

adequate to support a flat bottom tank, water-filled voids may account for 40% of the total volume of the soil sample. Freezing of this water would then result in a 3.6% increase in the volume of the soil mass.

Experience with pavement heave, structural foundations, and laboratory experiments have shown that, in many cases, the amount of heave which occurs greatly exceeds that which could be expected from volume change alone. It is known that, in many instances, the lifting or heave of the ground surface, of pavements, and of structures is due to the formation of lenses of ice in the ground. Indeed, in most cases of frost heave ice lenses are the principal factor.

An idealistic view of a system of isothermal lines (lines connecting points of equal temperature) has been presented, Figure 2. It has been demonstrated experimentally, and theories have been developed to show that soil moisture travels in the direction of heat flow. Figure 3 illustrates the suction process by which water is drawn upward to the region of frozen soil where it freezes and thereby contributes to the formation of the ice lenses.

In Figure 3, the arrows pointing inward from the perimeter of the soil particles illustrate the adsorptive force which holds a film of moisture about each mineral grain. The electrostatic force which binds the moisture film to the mineral grain decreases with increasing distance from the surface of the particle. As heat is withdrawn from the ice lens at the base of the frozen zone, water molecules adjacent to the ice crystal, but also part of the adsorbed water film on adjacent soil particles, freeze to the ice lens. The mineral grain which has lost the water molecule must then attract another molecule to balance its adsorptive force. This process gradually draws moisture from the surrounding soil or from the ground water table. The process does not stop until either the supply of available moisture is consumed or until heat flow stops. The ice lenses form parallel to the isothermal planes and grow normal to these planes. Therefore, heave occurs in the direction of heat flow, or generally in a vertical direction.

The thickness of the ice lens is dependent on the balance between the rate of heat flow and the rate at which water can be supplied. As shown above, the supply of water is obtained from the surrounding soil and from the ground water table. If the potential supply of water exceeds the rate of heat removal, the lower boundary of the zone of frozen soil will remain relatively stationary and the ice lens will continue to grow at that location indefinitely. A decrease in the supply of water or, conversely, an increase in the rate of heat flow, will result in the base of the frozen soil zone extending to greater depth where another ice lens may be formed.

The fact that moisture migration and the formation of ice lenses is a continuing process is important. Ice lens formation does not occur just as the soil is first frozen. Ice lens formation is not dependent on a succession of freeze-thaw cycles. If a sub-freezing condition is applied to a soil mass, whether it be at the base of a spread footing, at the base of a pile cap, or a deep well pump, or whether a sub-freezing condition exists beneath a flat bottom low temperature tank, the process is depleted at the greatest depth to which the frozen zone can penetrate.

Case histories

It may now be useful to review a few situations which have demonstrated the theory of moisture migration and frost heave associated with low temperature and cryogenic equipment often used in the air and ammonia industry. The first of these involves an 18,000 ton, 126 ft. dia. double-wall tank for ammonia storage at -28°F. After approximately two years of operation, buckles were noticed at two points in the outer tank, Figure 4.

Investigations revealed that portions of the subgrade under the tank was heaving causing distress to the structure. After taking the tank of service, it was determined that the subgrade in an area between 5 ft. and 10 ft. inside the ringwall was at temperatures below freezing. Elevation profiles across the inner bottom indicated the approximate amount of heave in the subgrade, Figure 5. The curve representing the elevation profile across the bottom has an appearance similar to the inverse of the temperature profile plot, Figure 6. Borings made from the inside of the tank indicated the depth of the frozen soil varied from 2 ft. to 4½ ft. and that there were ice lenses in the clay up to 1½ in. thick. The ground heave under the tank was substantial enough to actually lift the tank shell pulling a portion of the ringwall foundation with it. In one area, there was a void under the ringwall foundation of approximately 3½ in.

Samples of the insulation taken from the tank bottom showed variations in moisture content, which probably resulted from exposure of the insulation during construction. The area surrounding the tank was not adequately drained and ground water was trapped adjacent to the tank. Further investigations revealed that one phase of the three-phase electrical foundation heating system had been inoperative for an indefinite period of time, reducing the capacity of the heating system by approximately 50%.

Several factors leading to frost heave were present here. The silt and clay soil in the area were highly susceptible to frost heave and the normally high water table, plus the increased head from the free-standing water adjacent to the tank, provided the moisture necessary for the growth of ice lenses. Low storage temperature in the tank provided refrigeration to freeze the soil under the tank. Variations in the moisture content of the bottom insulation caused variations in the thermal conductivity which allowed uneven temperatures under the insulation. Unfortunately, the thermocouple control points were not all located in the coldest places and thereby unable to detect that portions of the subgrade were below freezing.

The repair consisted of removing the inner bottom steel, the bottom insulation and most of the outer bottom. Soil under the tank was thawed and holes were excavated around the inside and outside of the ringwall for inspection and for pumping water from under the tank. Thawing the frozen subgrade allowed the heave to settle and the ringwall returned to its original position.

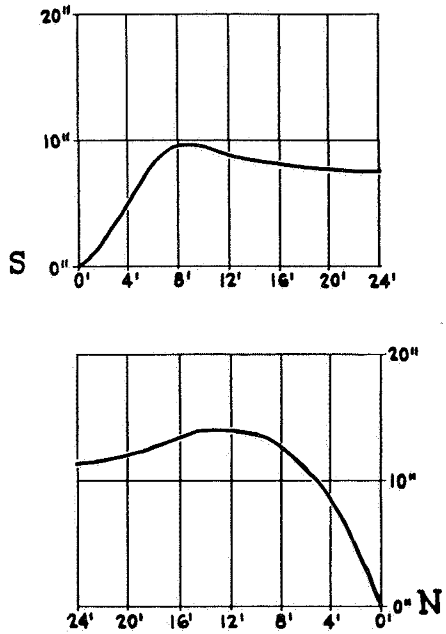

Figure 5. Elevation profile of the inner tank bottom.

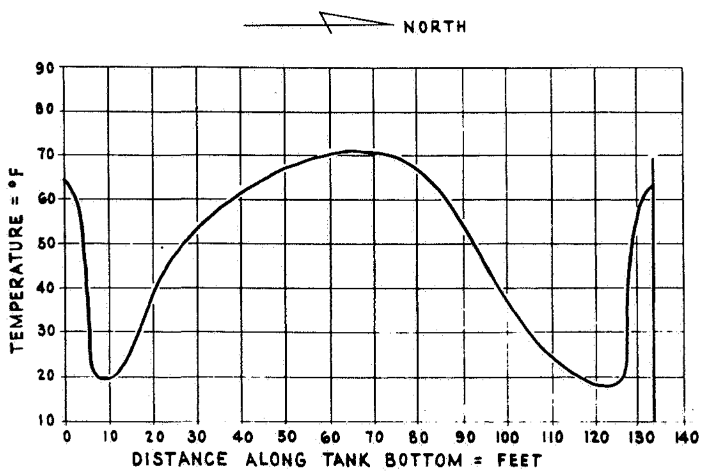

Figure 6. Tank subgrade temperature profile.

Broken and cracked areas of the ringwall foundation were restored. The outer bottom, bottom insulation and inner bottom plates were replaced after recompacting the soil inside the ringwall. The area around the tank was graded for permanent drainage and the foundation heating system was reconditioned before placing the vessel back in service.

Vertical deep well pumps

Frost heave damage associated with low temperature equipment is not limited to large storage vessels. Vertical deep well pumps are frequently used in the ammonia industry for transfer of low temperature ammonia at approximately -28°F. There have been several cases of frost heave associated with these pump installations. One

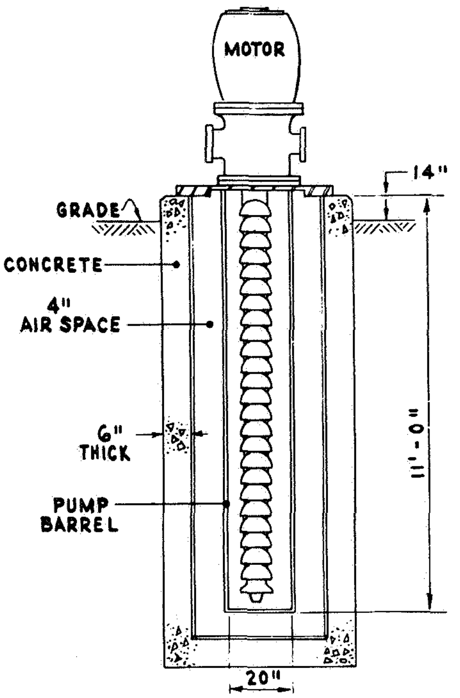

Figure 7. Vertical deep well pump and foundation arrangement.

such instance involved three pumps which were installed in a line on 6 ft. centers. Each pump was in a foundation casing 20 in. inside diameter by 11 ft. deep with an air space provided for insulation between the pump barrel and the foundation casing, Figure 7. Pump foundation heating and additional thermal insulation were not provided since the pump installations were intended for intermittent seasonal operation.

After operating the pumps intermittently for approximately three years, plant operators noticed distortion in the piping around the pumps. It was apparent that each of the three pumps had risen out of the ground by approximately 2 in. The soil report for the facility indicated that the soil around the pumps consisted of gravel, clay, and small amounts of weathered shale and peat. A high water table existed in the area and, at the time of the inspections, considerable water was standing on the ground which would not drain from the area.

A suspicion that the moisture and soil around the pumps had frozen was confirmed by taking several soil borings in the area. The borings indicated the presence of an ice lens of indeterminate thickness located approximately 10 ft. deep and adjacent to two of the pumps. Other areas around the pump casings were cold, but not below freezing. Temperatures taken from the borings were only approximate since the ground could have warmed up slightly in the pump areas during the time interval between taking the pumps out of service and actually making the borings. The lowest temperatures were located in the range of depths between 6 ft. and 12 ft.

There was no positive evidence that an ice lens had developed under the pump foundation casings, however, it was reasonably apparent that some portions of the soil under the casings had been frozen. Based on the data obtained, it is reasonable to assume that the ground had actually been frozen around the pumps from an approximate depth of 7 ft. to approximately 14 ft. below grade. Allowing for 2% to 3% expansion due to freezing would account for the 2 in. of upward heave experienced by the pumps. This is another instance where excessive moisture, frost-susceptible soil, and a low temperature source combined to cause equipment damage.

Repairs were started by disconnecting the pump piping and removing the pumps from the foundation casings. The casings were then filled with water and loaded with large concrete blocks while a heating element was inserted into the water to provide heat for warming the frozen or cold soil. The surcharge remained on the pump foundations until settlement readings indicated that the foundation casing was no longer settling. New elevations for the pumps were slightly lower than the original elevations before heaving.

Permanent heating coils and insulation were added to the pump barrels to prevent additional freezing. After the casing settlement had ceased and water was removed from the casings, the pumps were re-installed and the piping re-connected. The piping was modified to fit the new pump elevations and to remove the stresses in the piping imposed by the pump heaving.

Foundation heating

The question of whether or not to install heating on the foundation of small intermittent service pumps such as these is very difficult. The savings in original cost, operating, and maintenance costs realized by not providing insulation and heating must be weighed against the possible chance of frost damage and associated repair. It is desirable that the owner of the facility participate in this decision since he will have to live with the maintenance and operating costs of a heating system or with any problems which may develop as a result of not heating the foundations.

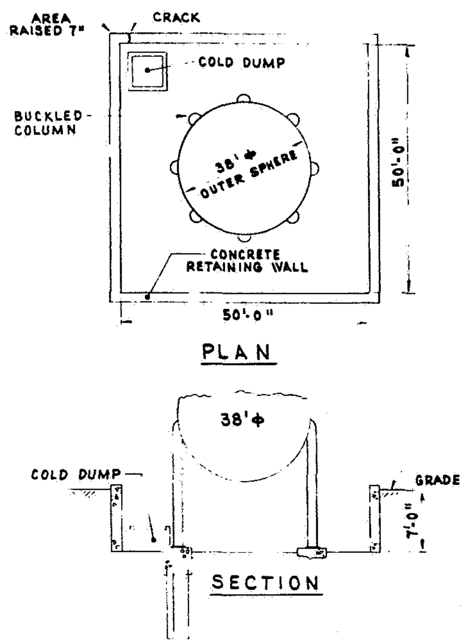

Figure 8. General arrangement of the sphere and pit.

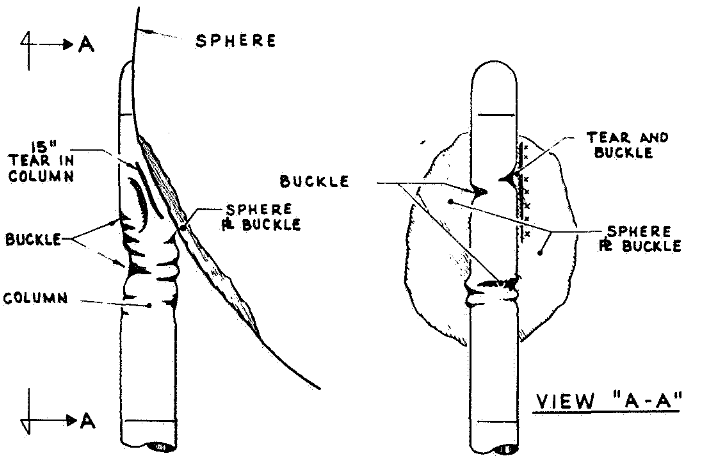

Figure 9. Sphere column sketches showing buckles.

A very unique incidence of frost heave occurred under the foundation of a double-wall aluminum sphere for the storage of liquid oxygen. The inner sphere is 32 ft. in dia. and insulated with 3 ft. of perlite insulation. The sphere is column-supported by eight reinforced concrete piers, each supported by two piles to a depth of about 75 ft. below grade, Figure 8. The sphere and its foundation is located in a hole 50 ft. square and approximately 7 ft. deep. The 50 ft. square hole is surrounded by a concrete retaining wall which holds back the existing grade. A reinforced concrete box, approximately 5 ft. square and protruding out of the ground about 3 ft. is located in the corner of the hole. The concrete box was used for a cold dump for disposal of excess liquid oxygen. After approximately seven years of service, a large buckle developed on the outer sphere due to an abnormal punching load into the sphere from one of the support columns. The column also buckled where it attached to the outer sphere and there was a tear at the connection, Figure 9.

It was obvious from the condition of the concrete box that substantial amounts of liquid oxygen had been dumped over the life of the vessel. The concrete was spalled and broken away in large sections exposing reinforcing bars. It was suspected that the cold dump had caused the ground and the immediate area to freeze and that the frozen ground had heaved and raised the foundation pier under the damaged column. This was verified by completely removing the pier and exposing an ice lens under the pier. The pier had risen approximately 2½ in. due to the ice lens which stopped short of adjacent piers by approximately 2 ft. The depth of freezing was not determined.

Two ¾ in. dia. concrete reinforcing bars connecting each pile with the pier were necked down and completely failed by tension. The upward movement of the foundation pier caused an increase in load in that sphere column which resulted in its buckling. It was also determined that the reinforcing wall around the 50 ft. square hole had risen about 7 in. in the immediate area of the cold dump. In this situation, improper location of the cold dump, rather than the problem of the sphere itself, had contributed to the failure. Failure of the reinforcing bars and damage to the sphere demonstrated the strength of the ice lens. This case adequately demonstrates the fact that tying the pile cap to the piles will not prevent frost heave.

The repair consisted of removing the cold dump, re-pouring the concrete foundation pier, modifying and stiffening the damaged areas of the sphere, and adjusting the sphere so that the columns would carry approximately equal loads. The foundation for this sphere was originally constructed to resist frost heaving due to low ambient conditions, but the foundation design did not anticipate the extremely deep frost penetration from the cold dump which was installed adjacent to the sphere. Alternate methods of liquid oxygen disposal are now used, eliminating the use of the cold dump pit.

Preventive measures

When planning the installation of a foundation for low temperature or cryogenic equipment, there are many considerations affecting site selection and the type of foundation required. Provision of an adequate factor of safety against a bearing capacity failure and limitation of the total and differential settlement of the structure to an acceptable value are the two most important criteria. In addition, it is essential to consider the effect freezing conditions have on the subgrade and the significance of time on this phenomena.

The soil conditions at the site will determine whether the tank or equipment can be supported at grade either on virgin soil or compacted fill, or whether piles or caissons are necessary. Concerning the thermal aspects only, the important distinction is whether or not there is an air space between the equipment and the ground.

Pile and caisson foundations can be designed to support the cold equipment a sufficient distance above grade to premit circulation of air between the ground and the equipment. The air circulation protects the ground from the cooling effects of the cold equipment and no further precautions are necessary. A flat bottom tank supported on a pile cap whose underside is at least 1½ ft. above grade is an example of this type of foundation.

Ringwall foundations for flat bottom tanks and spread footings for other equipment are characteristic of the type of foundations used when the soil at grade has sufficient bearing capacity to support the equipment. When equipment is supported at grade, it is common practice to provide insulation between the equipment and the soil, and a system of heating coils between the insulation and the soil to prevent freezing of the subgrade. The designer and the plant owner must decide for which of the equipment, if any, a heating system is necessary after the soil condition at the site has been determined. Type of soil, depth to the ground water table, and the operating conditions of the cold equipment will determine if a foundation heating system is necessary. The size of the equipment along with the portion of the time that it remains in a cold condition must also be considered.

Silty soils are more susceptible to frost heave than either sands, gravels or clays. Clean sands and gravels exhibit almost no potential to form ice lenses and heave. A water table close to the base of the foundation will result in more ice lens formation than if the water table were at great depths since the lenses require water to grow.

Deep well pumps and their zone of temperature influence are relatively small and are used intermittently. Where the water table is at sufficient depth and the soil surrounding and beneath the pumps is not particularly frost-susceptible, special precautions against frost heave are not required. If fill is required adjacent to or below such an unheated foundation, this material must be non-frost-susceptible. Conversely, the soil beneath a low temperature ammonia tank is subject to long-term cooling and the subgrade is affected to a considerable depth merely because of the size of the structure. In the design and operation of this tank, as opposed to the deep well pump, it must be assumed that the water supply is available at some depth within the zone of influence of the tank and that a process of moisture migration can occur which could lead to the formation of ice lenses with damaging effects.

Finally, in evaluating whether foundation heating will be provided, the safety of the overall system must be evaluated since differential settlement between connected pieces of equipment may jeopardize piping or the adjacent equipment.

Thermal insulation properties

Where insulation is provided between cold equipment and the ground, and particularly where large foundations are involved, the thermal insulation provided in the tank bottom should have very consistent properties which will not be adversely affected by the method of construction. Variations in the thermal insulating properties can result in an uneven temperature profile under the insulation. The uneven temperature profiles are undesirable since the heater control points may not detect localized cold spots. The foundation insulation system, the foundation heating system, the foundation and the structure itself must all be designed to allow for the normal settlements expected in the life of the vessel plus movements due to differential temperatures.

The foundation heating systems should be sized not only to provide heat through the foundation insulation, but also to the surrounding soil. If an electrical system or any other system requiring periodic maintenance is used, it should be installed so that it can be properly serviced. It is for this reason that most electrical heating systems are installed in electrical conduits.

Control systems are necessary to monitor the ground temperature beneath the cold equipment where heating systems are used. The number of temperature indicators chosen should be sufficient to monitor the maximum practical number of points under the foundation. This provides better control in the event that some of the control points are in locations which are not typical of the entire foundation insulation. It is also advisable to provide a means for indicating the concrete foundation temperature. This can often be accomplished in conjunction with the subgrade temperature control system.

If the foundation heating system is electrical, the design of the electrical system should anticipate the full range of voltages which might occur in the area. Electrical heating cables should be selected which can safely operate over the entire range of voltages.

Plant operators should monitor the amount of time that the foundation insulation heater system operates. This can be accomplished by installation of an elapsed time meter which indicates the total hours that the system has been operational. Indicating lights can also be provided to indicate to the plant operators that the heating system is working. A heating system operating more than anticipated may indicate a malfunction of the temperature indicating or heating system, or may indicate that a portion of the insulation has become wetted.

After the initial installation, the owner of a facility involving low temperature equipment foundations should make periodic visual inspections of the equipment, pipe, and structure. This inspection should detect cold spots and damaged equipment insulation. Elevation surveys of pipe supports, cold equipment, as well as other connected structures, should be made to determine if potentially damaging differential movements are occurring.

Functional checks of foundation heating systems should be periodically conducted to verify the heating system operation. Periodic temperature surveys of the subgrade under a cold equipment foundation is useful to detect changes which occur gradually over a period of time.

In summary

Frost heave is a very real and important factor which must considered in the design of low temperature and cryogenic facilities. The size and use of equipment, soil and ground water conditions, the type of foundation, and economic considerations will determine what precautions are necessary to prevent ground heave. It is our belief that competent design, coupled with careful construction procedures, and a regular program of inspection and maintenance can prevent damage to low temperature and cryogenic facilities due to frost heave.