Frost Action on Small Footings

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Frost heave of small footings is a periodic trouble at transformer stations of the Ontario Hydro Electric Power Commission. Warped transformer pads, opened switches and distorted service boxes are among the disturbances arising during the winter months. This paper summarizes the results of laboratory and field investigations, made during the last 4 years, to determine ways of controlling footing heave.

Initial laboratory tests indicated that the grip between frozen soil and concrete was of the order of 400 psi. at - 10 F. These results confirmed measurements made in Siberia approximately 18 years ago. During the last two winters various proposals for heave control were tried on an installation of small footings, placed in a frost susceptible soil 40 miles north of Toronto. Low temperature grease, polyethylene covers, gravel backfill, and soil treatment with a waste product of the pulp and paper industry were among the measures used to reduce the grip between the frozen soil and concrete. Reaction to the heaving forces was also provided by subjecting the footings to various loads or by equipping them with enlarged pads below the frost line.

During the winter of 1951—52, untreated footings having a buoyed weight of approximately 150 lb. heaved as much as 4 inches; greased footings moved about this amount. Frost penetration that year was 12 inches. The following winter was mild and the maximum heave of untreated footings was less than 2 inches. Less movement was obtained under higher loads, however, and footings equipped with concrete pads did not move at all. The greased footings under loads of 350 lb. and above did not move.

An analysis of the frost heave problem, based on these observations, resulted in the preparation of an approximate chart which indicates the bearing pressure required to overcome footing heave. It suggests that the cross-section of footings within the zone of freezing should be made as small as possible, consistent with the structural strength of the concrete. Below this depth the footings should be enlarged to transmit the footing load to the soil safely. The use of low temperature grease was also recommended for special applications such as conduits etc. where a reaction force is not obtainable. Field observations are continuing to assess the resistance of these footings under more-severe winter conditions.

● THIS paper deals with the problem of frost action on and associated heave of small footings founded below the zone of freezing. Footing heave is a nuisance problem that besets many of the transformer and distributing stations of the Ontario Hydro and other utilities each winter, causing switches to be opened, the distortion of service boxes and other minor disturbances.

To date measures for controlling these movements include the provision of footings with smooth, tapered sides to reduce the vertical component of the heaving force and gravel backfill to discourage the formation of ice layers. A satisfactory solution for meter houses has been obtained by placing each footing in a grease-packed sleeve. However, most of these frost-control proposals have been ineffective, and a more-thorough study of the problem was begun early in 1950.

INITIAL STUDIES

In order to ascertain the magnitude of the forces associated with footing heave, the first step in the investigation was to measure the grip which develops between frozen soil and concrete. This was done using the simple arrangement shown in Figure 1. Saturated soil was placed inside the hollow concrete prism and frozen for 24 hours at - 10 F. The specimen was then placed in a compression machine and the force required to free the frozen plug

was measured. The sample was loaded rapidly to avoid excessive plastic flow. Values obtained ranged from 304 to 495 psi., indicating that the grip of frozen soil is quite considerable.

When forces of this magnitude are involved, the practice of tapering footings would be relatively ineffective against heaving and actually appears to be based on faulty reasoning. Even though some reduction is obtained by inclined sides, this advantage is offset by the greater surface area exposed to the frozen ground.
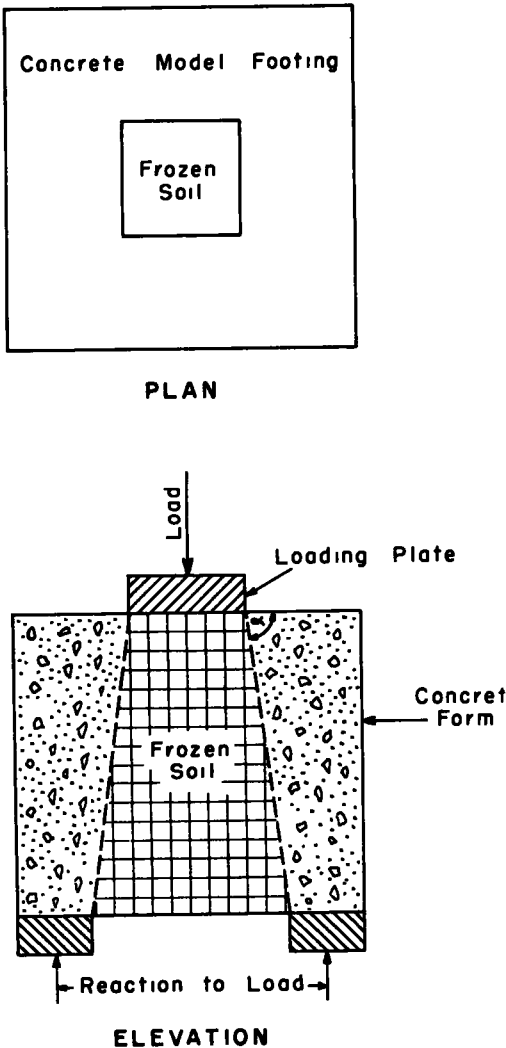

PLAN

ELEVATION

Figure 1. Apparatus used to determine the bond between frozen soil and concrete.

FIELD TESTS

During the past 2 years, experiments designed to test several proposals for con-trolling heave were conducted on a footing model installation in soil known to be sus-ceptible to frost action.

The treatments used in the test program were made on footings 8 inches square and 4 feet deep. In one set of tests, the elimi-nation of the rigid grip of the frozen soil was sought by the application of low-temperature grease to the sides of the footings or by wrapping the footings with polyethylene sheet. In other tests the formation of ice layers in the soil was discouraged by back-filling with gravel or by treating the soil with waste liquor from the pulp and paper industry. Various loads or methods of anchorage were also applied to the models to determine the resistance which must be provided to prevent their movement. A general layout of the site and sketches of the various treatments are shown in Fig-ures 2 to 4.

During the winter of 1951—52 untreated footings in the installation were heaved as much as 4 inches, although the maximum frost penetration did not exceed 12 inches. Last winter was even milder and ground movement was only half the previous value. Ground temperatures in the zone of freezing did not fall below 32 F. Under these mod-erate freezing conditions, complete pro-tection was obtained for the greased foot-ings under a load of about 350 lb. In gen-eral, other treatments provided some relief but appeared to be inadequate for permanent protection. Figure 5 presents the maximum heave of each footing under various loads during the winter of 1952—53.

The most-promising and most-practical arrangement for controlling frost heave, as indicated by these tests, is a footing constructed with an enlarged base below the frost line. In this installation, a base approximately $3\frac{1}{2}$ times the footing width gave the desired anchorage against heave. Its effectiveness is well illustrated in the inset of Figure 5.

ANALYSIS OF FOOTING HEAVE

The resistance to frost heaving, pro-vided by the addition of sufficient footing load, suggests that a rational approach to heave control can be found. Therefore, the following analysis of the problem was made in the hope that it might lead, at least, to an approximate method of design against frost action. The process of heaving prob-ably occurs in a manner similar to that
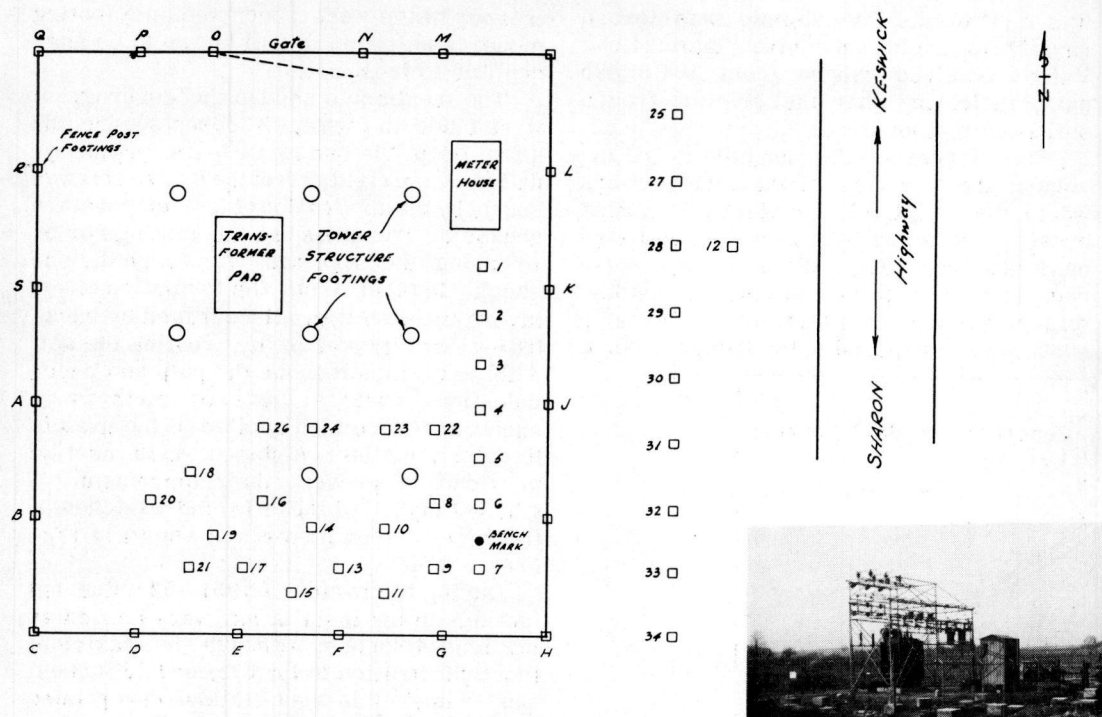
Figure 2.   Sketch showing the location of the footing models.

outlined in Figure 6. This sectional sketch illustrates a footing rigidly gripped along **XY** by a layer of frozen soil, t inches thick. The heaving force, pushing up on the frozen layer and therefore on the entrapped footing, is generated in the thin zone of freezing as pore water expands into ice. In this example it is assumed that the footing is loaded sufficiently to resist these forces and that consequently the frozen soil is held down in its vicinity. The magnitude of the heaving forces is probably proportional to the restraint applied to the frozen soil layer; therefore, the upward
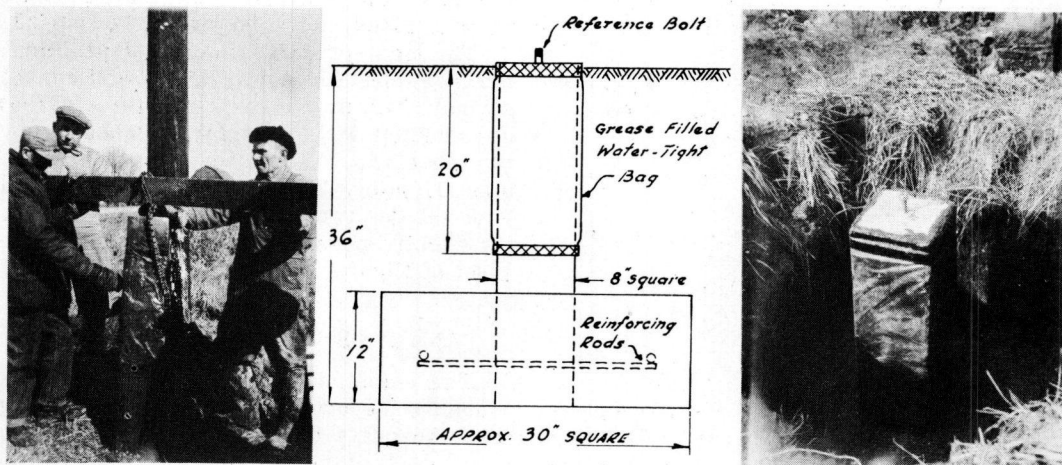

Figure 3.   Sketch and photograph (right inset) showing a footing with an enlarged base and protected against frost action by a grease-filled water-tight polyethylene bag.   Left inset - Lowering a greased treated footing into position - 200 lb. pedestal added after installation.

Figure 4. Sketch showing an anchored footing with a polyethylene cover. Left inset - Lowering a polyethylene covered footing into position. Right inset - Anchored footing showing wrinkling of polyethylene cover as ground heaved.

Figure 5. Chart showing how footing heave was reduced by load (All loads estimated for anchored and enlarged base footings). Inset - Photograph of the heave resistance of enlarged base footings. Surrounding ground heaved up approximately 2 inches.

force will be greatest near the footing and very small near the point of inflection of the frozen layer. By assuming that the pressure distribution is triangular and equal to the uplift resistance, W, of the footing, the maximum bending moment of the ice layer can be calculated readily. When a footing is continuous, the resultant heaving force will act at a third of the distance, L, between the side of the footing and the point of inflection of the frozen soil.

suggest that this distance, L, is approximately 10 times the frost depth, t. ("Lifting Force and Bearing Capacity of an Ice Sheet" B. Lofquist Technical Translation TT-164 National Research Council of Canada). The same relationship can be assumed for frozen soil, which can reasonably be expected to deflect in the same manner as lake ice; the bending moment, M, exerted at the contact surface xy of a continuous footing will then be
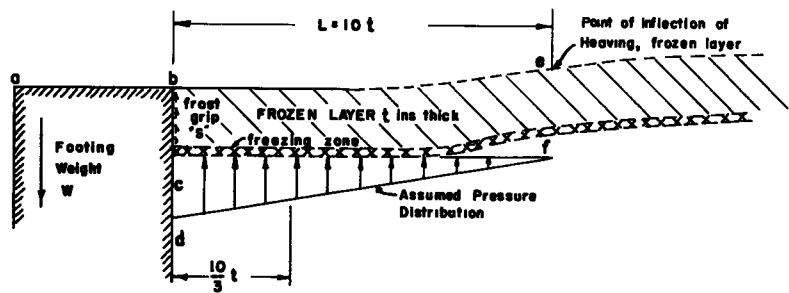

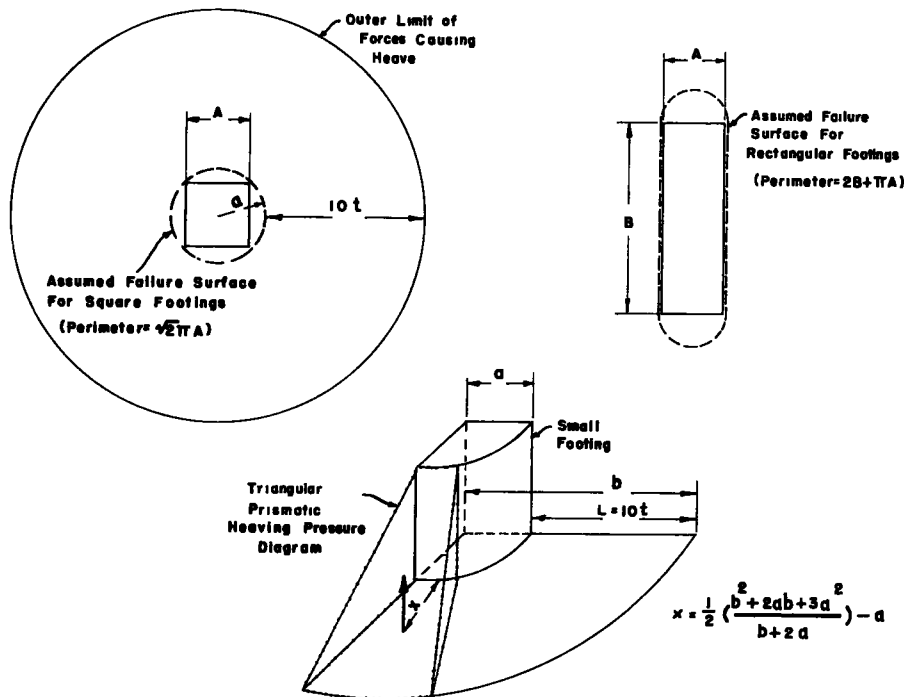Figure 6. Sketch showing mechanics of heave of a continuous footing.

Figure 7. Sketches showing assumed failure surfaces and pressure distribution for square and rectangular footings.

Measurements obtained by Lofquist, of Sweden, of the deflection of lake ice around piers during periods of rising lake levels,

$$\frac{10}{3} \text{ Wt. in in. -lb.}$$

The moment of resistance of the frozen

soil at this surface is equal to the product of the section modulus of the frozen ground and the frost grip, f, along xy. Using the value f = 400 psi., the ultimate bending resistance, M_r, along a footing of perimeter P becomes 66.7 Pt^2 in.-lb. Hence the load, W, required to prevent heaving of a continuous footing is equal to 20 Pt lb.

$$\sqrt{\frac{A}{2}}$$

Any segment of the heaving-pressure diagram bounding this circle will have the shape of a triangular prism with a center of gravity located at a distance from the circle:
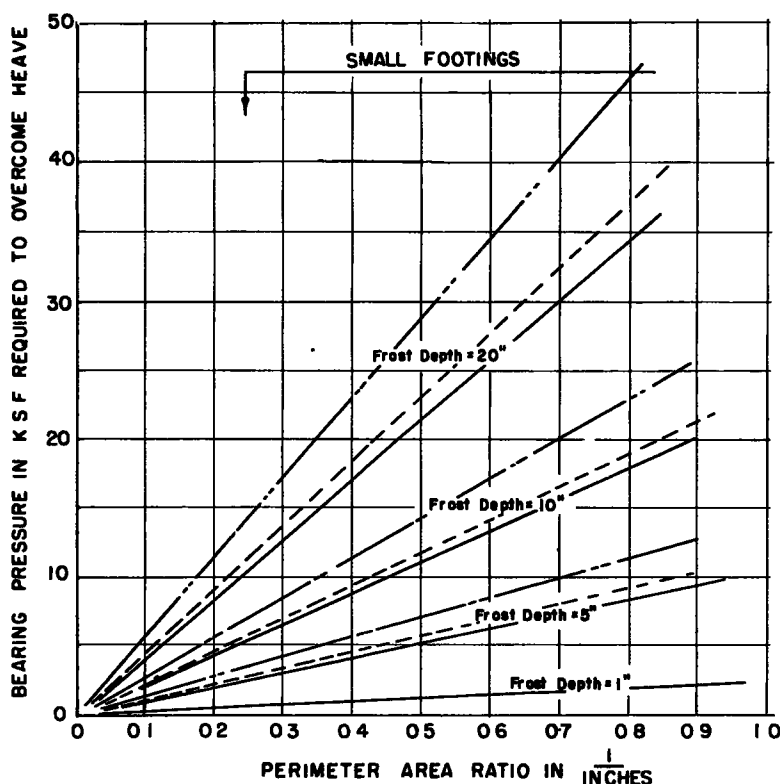

Figure 8. Chart indicating the bearing pressure required to overcome footing heave, (frost grip S = 400 psi.).

Unfortunately, because the distribution of the heaving forces becomes quite complex, this simple method cannot be used for the accurate calculation of the loading required to resist heaving of small square and circular footings. An approximate estimate however, can be obtained by slightly modifying the analysis. As indicated in Figure 7 the zone in which the heaving forces are confined about a small footing probably comprises a ring L = 10t inches wide. The bending moment is assumed to be most critical along the surface indicated by the broken lines; for a square footing of width A the length of this surface is the circumference of a circle of radius

$$X = \frac{1}{2} \frac{b^2 + 2ab + 3a^2}{b + 2a} - a$$

where $a = \dfrac{A}{\sqrt{2}}$, and b = a + 10t

The bending resistance developed around the perimeter, P, of this critical section is again approximately 66.7 Pt^2 in.-lb. Therefore the footing load, W, required to resist heave will be

$$\frac{66.7\ Pt^2}{X}$$

The chart in Figure 8 indicates, for various depths of frost penetration, the bearing pressure necessary to overcome

footing heave. The size of the footings is expressed by the ratio of their perimeter to area, a quantity which becomes larger as the size of the footings decreases. It is immediately apparent from the chart that the bearing pressure required for small footings is much higher than can be applied safely to most soils. Since it is unlikely that small footings would be designed to withstand such high bearing pressures, they require some special treatment or modification to make them invulnerable to frost action.

PROPOSED FROST-HEAVE CONTROL MEASURES

Although small footings are susceptible to frost heave when they conform to orthodox design, a simple modification should provide the necessary resistance. To achieve this resistance the cross-section of the portion of the footing within the zone of frost penetration should be as small as possible; reference to Figure 8 will assist the selection of proper footing size. Below the frost zone the base of the footing can be enlarged to transmit the load safely to the soil.

For such applications as ground-entry point of cables and conduits, where adequate heave resistance cannot be obtained by design or loading, grease-packed sleeves should provide immunity from frost action. Sleeves can also be used to protect the benchmarks and monuments established by surveyors. In many instances these reference points have approximately the same dimensions as the footing models used in the present experiments and therefore are highly vulnerable to frost action.

Discussion

HAMILTON GRAY, Soils Engineer, Maine Highway Department—The subject of Trow's investigation is one which has also interested the writer for a number of years, primarily because it seems to offer a relatively inexpensive way of accumulating fundamental data on frost action for the purpose of obtaining a more-complete understanding of this phenomenon. This is not to imply that the investigation lacks considerable practical value, since although the actual cost of the type of installation studied by Trow is relatively small, the total investment in all similar installations represents a large sum of money. Similarly, when such an installation requires maintenance or some form of rehabilitation as a result of frost action, the cost is not excessively great. However, such maintenance is required on many similar installations. Therefore, in the aggregate, the necessary expenditures total a large sum.

Figure A illustrates the principles studied by Trow. The upper part of the pedestal or pier in this figure is subject to what has been concisely termed "adfreezing" of soil to its lateral surface, and as the frozen ground is moved upward by the expansion of ice or by the development of ice layers at the freezing line, a force termed by Trow "frost grip" tends to raise this portion of the pier upward also. The frost grip creates a reaction in the soil adjoining the pier below the zone of freezing, in the form of a vertical compressive stress in excess of that normally created by the earth overburden about the pier. The nature of the variation of this stress is unimportant here. It is designated by "excess soil pressure" in Figure A.

If the load P applied to the top of the pier is insufficient to overcome the lifting tendency of the frost grip, tension represented by the force T in the diagram will develop in cross-sections below the frost line. In other words, that portion of the pier which is being elevated by the rising soil tends to pull along with it the lower portion. This tendency to move the lower portion is resisted by the weight, W, of this lower portion and by soil pressure on the upper surface of the footing.

That the frost grip usually proves more than capable of moving the lower portion of the pier and its footing seems to indicate that the unfrozen soil between the frost line and the upper surface of the footing is compressed under the action of the excess soil pressures. The amount of compression will depend upon the magnitude of the excess pressures, as well as upon the inherent compressibility of the intervening soil.

Upon the release of the frost grip during thaws, the excess compressive stress in the soil diminishes at an unknown rate. The footing, however, having been elevated through a distance approximately equal to

the compression of the soil, often does not return to its original position. This is attributed to the fact that soil may squeeze or fall inward from the sides of the cavity which the raising of the footing creates. This intruding soil serves to prevent the bottom of the footing from returning to its original position, hence, there is a net annual increase in elevation, never greater than the maximum displacement during the winter, which accumulates from year to year so that the elevation of the pier progressively increases. Of course, if the pier fractures under the action of the force T, its upward movement will be accelerated in future years.
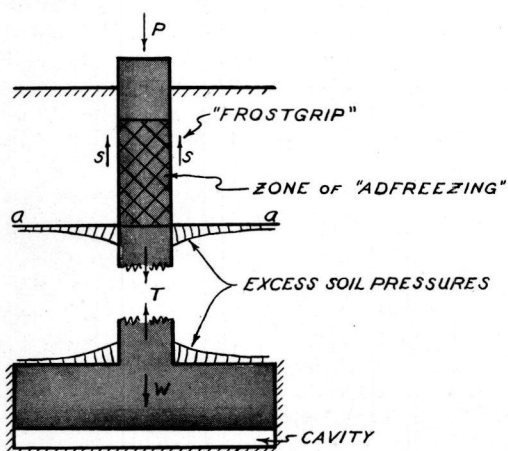

Figure A.

There does not appear to be any limit to the displacement of such a pier until it has been almost wholly ejected from the ground. Stone bounds and similar monuments have been found lying prone upon the ground. Others defining street boundaries have been uplifted unevenly and acquired a resultant tilt displacing their tops by nearly a foot. Invariably this displacement is away from the street and is attributed to the more-energetic frost action which accompanies regular removal of snow insulation by street clearing.

An entirely similar process would seem to explain the annual spring crop of stones with which farmers have to contend in cultivating soil derived from glacial till. No matter how completely the stones are removed from the ground surface, additional ones will appear within a year or two, having been raised by frost action from various depths beneath the ground surface.

Examples of the type of behavior dis-

cussed herein are numerous in any locality where the frost penetrates normally to depths exceeding a few inches. Figures B, C, and D illustrate culvert head walls which have been displaced or broken by frost action either upon the head walls themselves or upon the culverts which in turn move the head wall. In Figure D the culvert has broken through the surface of the shoulder and part of the pavement, as well as having moved the head wall entirely out of position. Rupturing of head walls just above the culvert crown is common and suggests that the culvert pipe is moved more energetically than would be the head wall itself.

Figure E illustrates a door stoop, the outer edge of which was supported on concrete cylinders embedded in the ground. This photograph was taken during the first winter after construction. The posts did not return in the spring to their original position; consequently, the owner will be ultimately faced with the necessity of removing at least the top portions of these posts in order to permit him to open his front door. Presumably the builder believed that these posts, extending to a depth of 5 feet, would never move.

Figure B.

Referring to Figure A, the principles which have been applied in Trow's efforts to seek a solution to this problem can be summarized as follows: (1) Reduction of the soil motion by the use of admixtures which will reduce or eliminate soil freezing and heaving or through the use of non-frost-susceptible soils. (2) Reduction of the area over which the moving soil is in contact with the pier or anything attached to the pier (adfreezing area). (3) Reduction of the force (frost grip) transferred from the moving soil to the pier by interposing a weak material between the two. (4) Op-
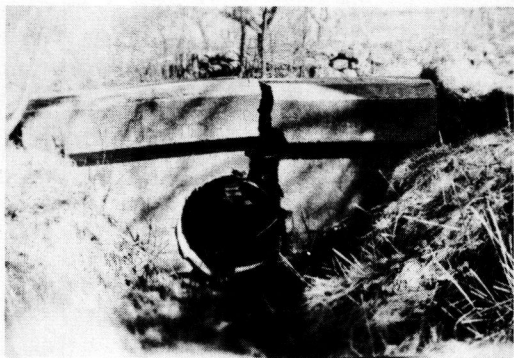
Figure C.

position to the lifting effect either by countering it with a downward load P of substantial magnitude or by providing a footing or enlarged base so that the uplift produced by frost heaving creates a downward reaction on the pier by the footing.

There are certain types of construction (such as culverts, monuments and bench marks for surveying purposes, and very-lightly loaded buildings) for which it is not possible to apply a sufficient downward load P to effectively prevent displacement. Furthermore, even though sufficient load can be applied to reduce the maximum displacement each winter to a small value, this does not ensure that the accumulation of net annual displacements will not eventually become serious.

It is frequently stated that if a wall, post, or pier is extended below the maximum depth of frost penetration it will not be moved by frost action. Just where this misconception originated is unknown. Possibly, it was derived from experience with buildings in which the heat loss through basement walls is adequate to prevent freezing of the outside soil to the surface

Figure D.

of the wall. It is, of course, known that if freezing develops beneath the bottom of a footing or wall extremely large loads are required to counteract the lifting tendency of the ice. Quite possibly the more-favorable behavior which resulted from eliminating this particular kind of freezing was sufficient to establish a belief that satisfactory construction could be obtained by placing the bottoms of walls and footings below the depth of maximum frost penetration.

It is likewise widely claimed that the use of a substantial batter, often referred to as "frost batter", will suffice to counteract the tendency for heaving. This claim is based by some on a belief that the batter itself prevents the adhesion of frozen earth to the pier. Experience with battered piers suggests that this is an erroneous concept and certainly the results of the type of test illustrated by Figure 1 in
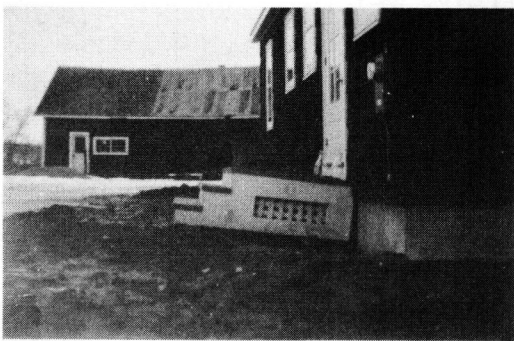

Figure E.

Trow's paper should suffice to emphasize the inaccuracy of this viewpoint. On the other hand, if such a battered pier is urged upward by soil expanding near its top, the continued batter below the freezing zone will induce soil reactions acting downward on the lower portion of the battered object.

Again experience indicates that this downward reaction is insufficient to be wholly effective. Specifically, the downward reaction will increase only as the pier moves upward against the soil and so creates passive earth pressure. Thus the earth is not rigid and must deform if it is to offer a reaction to the upward motion of the battered surface. The use of an enlarged lower portion, footing, or boot on a pier would appear to be more effective than the batter, but experience again indicates that even such a method is not reliable.

Figure F.

Max elevation, Winter 1952-53: ————
Reading, May 7, 1953: ———————

PEA STONE   TILE-DRAIN   PEA STONE

CLAYEY SILT FILL   GRAVEL FILL   CLAYEY SILT FILL

CLAYEY SILT

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Observations of the behavior of light buildings without basements which are supported by short timber posts or concrete piers indicates that certain of these posts or piers periodically move to a much greater extent than others, even though the soil conditions appear to be uniform throughout the building area. Many concrete posts or piers with battered sides extending well below the maximum depth of frost penetration have been observed to move progressively until the supported structure is badly distorted.

In one instance a canning factory was supported on cedar posts approximately 20 percent of which moved upward during each winter and remained in an elevated position after each spring thaw. It was then only necessary to saw off a few inches from the top of each such post to relevel the sills and floors of the building. Eventually such posts worked almost entirely out of the ground and had to be replaced. It appears fortunate in this instance that the support was of timber rather than concrete and that the maintenance work could be done when canning activity was nil.

In planning an additional building for this particular site, which was underlain by a glacial till consisting primarily of clay containing many stones, it was recommended that if posts or pedestals were to be used they be surrounded by granular material which, in turn, should be drained by means of clay tile. Owing to the very heavy floor loads, approximating 600 lb. per sq. ft., it was found that such a type of construction would be approximately 50 percent more expensive than the utilization of a compacted gravel fill upon which a concrete floor slab could be directly laid. The cost of supporting the structure on piers not surrounded by drained gravel would have been approximately equal to the cost of a slab placed upon gravel fill but would not have offered the certainty of satisfactory performance inherent in the use of gravel fill.

Similar observations also indicate that when such structures are supported on posts bearing upon pads which rest on the surface of the ground, less trouble results than when the pads are buried. In the former case, loss of contact between post and pad is unusual, whereas in the latter they soon part company. Hence, although the building may become distorted during heaving weather, the original grades are likely to be regained automatically when the ground thaws, and there is no net annual increase in elevation. Certainly the annual maintenance of this type of construction is less than where releveling must be accomplished each spring.

One form of protection not mentioned in the paper consists of supporting loads on steel rods or pipes which bear upon a pad or plate located below the frost line. A pipe of larger diameter, used as a loose sleeve extending from above the ground surface to the pad or plate, will move with the heaving ground without transferring any reaction to the smaller rod or pipe. This method is commonly used in northern New England for supporting light loads and is effective until the sleeve has been elevated so that its upper end is in contact with the supported structure. Thereafter the sleeve itself may tend to force the structure upward, although if the buried pad or plate is securely anchored to the smaller rod this will help to resist upward motion. If wet earth or water collects between rod and sleeve and freezes, the sleeve becomes useless, and in certain soils, the sleeves may corrode fairly rapidly. However, the great majority of such installations appear to function in a thoroughly satisfactory manner.

Figure F illustrates typical installations, some of them rather similar to Trow's piers, which have been observed for the past 2 years. The lower portion of this figure shows experimental culverts under which various types of bedding have been utilized in order to determine the one most effective in reducing frost displacement. Where granular bedding has been used, certain beds (D) have free-draining outlets, while the other beds are simply laid in trenches without outlets.

Culverts which are not deeply buried tend to move upward progressively from winter to winter until they eventually become exposed at the roadway surface. Prior to that time upward displacement of the roadway surface over the culvert necessitates frequent maintenance, and during winter this results in a bump in the pavement surface. The upper portion of the figure illustrates various small piers and cylinders, some placed without any antiheave treatment and others installed in various ways intended to counteract movement by frost. All piers extend to a depth of 4 feet below ground surface. The smaller objects are either standard con-

crete cylinders (C) or hollow steel cylinders with capped ends (S) of the same dimensions as the concrete cylinders.

It should be realized that only the accumulated behavior over a period of several years will furnish a reasonable indication of the effectiveness of various types of design. The results shown on the figure, which apply to a single year's observations only, indicate the maximum upward displacement occurring some time in the late winter or early spring. The resultant displacement representing the sum of the annual net increases in elevation appears to be more important from the economic standpoint than the maximum displacement attained in any single winter, although in certain types of installations the magnitude of displacement during the winter alone will be sufficient to cause considerable damage.

The immediate conclusion to be drawn from the data shown in Figure F is that while some designs appear more effective than others, none of those adopted have proven wholly effective. Whether in the course of 5 or 10 years there will be marked differences in the observed accumulated displacements remains to be seen. Owing to the differences in behavior which are commonly observed within a small area, such as may be covered by a single building, it is probable that behavior of various designs should be placed upon a statistical basis. In other words, the behavior of a substantial number of piers of a given design is likely to be somewhat erratic and the relative frequency of unsatisfactory behavior as compared with similar frequency with respect to a different design would provide a criterion for recommending one in preference to the other. It may prove impracticable to establish a design which is 100 percent effective at all times. This is particularly true in view of possible deficiencies in workmanship.

Consequently, it is the writer's belief that Trow's work should be encouraged and extended in order that erratic behavior may not play an important part in the conclusions which may be drawn from such investigations.

In addition to the culvert behavior illustrated in Figure F, observations have been made on similar installations under actual roadways. In some cases behavior is contrary to what would logically be expected, and the difficulty has been traced to movement of benchmarks constructed of con-

crete in accordance with some of the pier designs also shown in Figure F. We are thoroughly convinced that the only completely trustworthy benchmarks that should be used in making wintertime observations are those which are established on bedrock or upon substantially constructed heated buildings. Any monuments, irrespective of their design, tend to greater or less displacements whenever they are surrounded by freezing soil.

The installations and observations illustrated by Figure F have been made at the University of Maine. They represent part of a project which has been largely financed by a grant from the University's Coe Research Fund. The corrugated metal culvert pipes were generously provided by Bancroft and Martin Rolling Mills of Portland. For an associated similar project, corrugated metal pipe was furnished by the New England Metal Culvert Co. of Boston and concrete pipe by the Hume Pipe Co. of New England.

PHILIP KEENE, Engineer of Soils and Foundations, Connecticut Highway Department—The author is to be commended on presenting an interesting paper containing valuable data on a subject seldom investigated experimentally in the past. It is to be hoped that he will continue to work on this project and that Nature will provide him with colder winters than those of recent years so that his remedial devices will be severely tested.

The writer was asked to give in this discussion an account of differential frost heaving of a highway pavement that was related to the presence of pipe culverts of various sizes under the pavement. The highway is a part of Route 15 in Hartford, Connecticut, known as the Wilbur Cross Highway, where it crosses a flat swampy area called the South Meadows, located in the southeast corner of the city. The highway is a four-lane expressway with a 10-foot raised median strip of grass. The section studied is about a mile long. The pavement is on a low fill 4 to 7 feet high. The pavement is 9 inches of concrete, but not reinforced, laid in 1942. Subbase is 12 inches of bankrun gravel throughout. The embankment is chiefly organic clayey silt taken from the ditch excavations on both sides and from nearby borrow areas. Ground-water table under the pavement is 5 to 6 feet below pavement.

The bankrun-gravel subbase is a red gravel of Triassic origin, having approximately the following gradation:

100% passing 5-inch sieve
60%   "   ¼ "   "
20%   "   No. 40 "
10%   "   No. 100 "
8%   "   No. 200 "
2% so-called clay sizes

The portion passing the No. 40 sieve has not sufficient plasticity to permit making a plastic limit test but that passing the No. 100 sieve was slightly plastic.

The silt is a gray organic clayey silt apparently deposited during past floods of the Connecticut River, whose normal stream bed is 1/2 mile east of this swamp. The top of swamp is about 3 to 7 feet above normal river level. The clayey silt contains about 15 percent of fine sand 55 percent of the so-called silt sizes (greater than 0.005 mm.), and 30 percent of the clay sizes. Its liquid limit ranges from 37 to 26 and its plastic limit is about 24. Its natural water content varied between 45 percent and 26 percent of dry weight, but in the embankment its water content is normally about 21 to 32 percent. Standard Proctor density is about 101 pcf. at 22 percent optimum water content.

My attention was first called to cracks in the pavement in October 1944. As the pavement surface at the cracks was flat then, differential frost heaving due to the so-called chimney action was suspected. All cracks are transverse to the parkway. There are 30 cracks, of which half extend a full pavement width (two 12-foot lanes) and half are only half width (one 12-foot lane). Of these, all but three are above or close to cross culverts. There are one ore more cracks in the pavement above or close to each of the four large (36-inch and 48-inch) cross culverts and similar cracks as 15 of the 29 small (12-inch) cross culverts. The 12-inch culverts extend only under two lanes and the cracks appear only in the lanes under which the culvert is located. The 600 feet of longitudinal culvert caused no cracks.

In January 1945, 100 points were painted on the centerline of northbound and southbound lanes. Elevations were read on them four times during that winter and the following spring. Most of the points were located at a crack or at transverse joints near the crack, to furnish a profile of differential heaving extending for 25 to 50 feet on each side of a culvert. These readings verified the belief that excessive differential heaving at the culverts created a condition that resulted in the cracks. Furthermore, the worst differential heaves become obvious to the motorist during the latter half of severe winters.

At this site the three requirements for frost heaves were present: cold temperature, silty or clayey soil, and high water table. The pavement heaved rather uniformly (½ inch to 1½ inches) between culverts, causing only three cracks in the mile of pavement. At the cross culverts, differential heaving (in excess of the uniform heaves) varied from ½ inch or 1 inch of rise in 10 feet to 1 inch or 1½ inch of rise in 15 feet or 20 feet. At the culverts, cold air inside the pipe apparently created an additional frost zone adjacent to the pipe circumference. The larger-diameter culverts caused more differential heaving and worse cracking of the pavement than the small culverts. The large culverts were less clogged with snow, had a larger zone of frost adjacent to their outer surface, had a larger cross-section area for cold air per square foot of outer surface, and had a horizontal opening at each end, whereas the 12-inch culverts connect at one end to two inlets which rise vertically to horizontal gratings at the gutters.

Pavement cracking at the 12-inch culverts was absent when the distance from top of pipe to bottom of subbase was more than about 24 feet. Also, it was absent when top of pipe was more than about 5 feet above ground-water table. Therefore, for conditions like those on this project, a rule might be established for cross culverts that when (1) average distances from top of pipe to top of pavement is less than 4 feet for pipes under 24 inch diameter or less than 5 feet for pipes 24 inches and larger and (2) pipe invert is less than 4 feet above wet ground (or ground-water table, in the case of cuts and shallow fills), the pipe shall be surrounded by a 12-inch ring of gravel fill. This assumes the fill or cut material is a badly frost-heaving soil-silt or clay. If it contains a substantial amount of coarser material, the gravel fill can be omitted. The gravel fill should not be extended up to the pavement or subbase, as that would result in a depression if the highway heaves uniformly.

This treatment is not needed for longitudinal culverts, as they apparently have much weaker chimney action. It is not needed for bridges and box culverts having an earth fill above, as their roofs are too high above the ground-water table and they are designed to avoid an accumulation of surface infiltration.