III.1. REVIEW OF CONSTRUCTION TECHNIQUES AND MAINTENANCE PROBLEMS IN ZONES OF DISCONTINUOUS PERMAFROST IN NORTHWESTERN CANADA

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Experience with a variety of types of construction in northwestern Canada during recent years has shown that the zone of sporadic or discontinuous permafrost is much more extensive in area than has been generally appreciated. In many respects, construction problems resulting from frost in the ground are more difficult in zones of discontinuous permafrost than is the case in areas of continuous permafrost. This paper deals with several types of construction problems peculiar to zones of discontinuous permafrost and illustrates some of them with case histories from the author's experience over the past several years.

The first problem, of course, is to identify the existence of permafrost at a given site. A characteristic of all permafrost in the zone of discontinuous permafrost in northwestern Canada is that in its undisturbed natural environment it is in a state of retrogression. It may, therefore, be found in what appears to be a solidly frozen state; or it may be found in a partially thawed condition in which free water is mixed with ice, a condition colloquially known as "rotten" permafrost. In fact, excessively wet zones can be found in a soil profile where there appears to be no ice but the water and soil temperature is exactly 32°F. In general, therefore, one must be prepared to recognize all possible physical mixtures of ice and water within the range from solidly frozen soil to soil in which the ice has melted but the free water from the ice lenses has not had sufficient time to drain away and permit the soil to consolidate under the weight of over-burden above it.

In engineering practice the conventional procedure for a site investigation is to put down one or more test boreholes, visually log and sample the soil, and if necessary run a series of laboratory tests on the samples to estimate the mechanical properties of the soil. Many investigators have assumed that these procedures will readily identify discontinuous permafrost. Unfortunately, however, experience has shown that even experienced engineers may fail completely to identify partially frozen soil by these methods. In fact, cases are on record where even solidly frozen soil has not been recognized. The conventional practice for foundation investigations is therefore not adequate in zones of discontinuous permafrost. The procedures must be augmented by additional checks.

In our experience there are three additional checks that are of prime importance, and that in our view should always be included in site investigation procedures in areas of potential discontinuous permafrost. The first of these is that the mean annual air temperature should be estimated from the Climatological Atlas published jointly by the National Research Council and Department of Transport and checked by available local air temperature data. If the mean annual air temperature is between about 30 and 32°F., discontinuous permafrost is to be expected rather than continuous permafrost. Areas only some 200 miles north of Edmonton, Saskatoon or Winnipeg are known where the mean air annual temperature is within this range. In areas having a mean annual air temperature within this range, however, retrograding permafrost will usually be found only under a thick organic cover with tree growth, or on the northerly exposures of hills and stream valleys having relatively heavy vegetation growth on them.

The second important check involves the natural moisture content profile in test holes at the site. These should always be determined in areas suspected to have retrograding permafrost. One or more bulges towards the wet side in the natural moisture content profile, particularly if the moisture contents in the "bulge" exceed the liquid limit for the soil, are positive indications that permafrost has recently existed at the site, and that the conditions are not yet in equilibrium following melting of the ice. The Thompson area in northern Manitoba is one where this procedure is frequently very effective. The recently thawed layer of permafrost in this area appears to have been of the order of 30 to 40 feet in thickness. "Rotten" permafrost is sometimes identified, but more frequently the natural moisture content profile will show excessively wet soil.

The third essential check is that soil temperatures should always be measured with a thermometer at the bottom of the test hole at intervals as it is progressed. Temperature readings at or just below 32°F are also positive indications that the soil has only recently thawed and the conditions may not yet be in equilibrium.

If frozen soil or melting ice are encountered, or if the subsoil moisture in a zone in the profile has not yet stabilized following melting of the ice, it is impractical to attempt to maintain the present conditions indefinitely into the future. Retrogression from the solidly frozen state will continue despite anything done on the surface short of providing mechanical refrigeration to refreeze at least a portion of the permafrost zone. This is in contrast to the situation in colder zones of continuous permafrost, where it may be quite practical to take steps to maintain the soil in a frozen state indefinitely into the future.

If permafrost in any of its stages of retrogression is encountered at a site, then a set of unconventional design conditions must be superimposed on the usual design practice. Unfortunately, a general answer for these additional conditions does not exist except to the extent that it must be recognized that conditions of retrogression will continue and probably at an accelerated rate as a result of the construction work that is to be undertaken.

From the foundation point of view, a standard procedure is to use a piled foundation with the piles extending through the recently frozen zone to act in bearing and/or friction in the underlying more stable soil. Timber piles have been the most widely used in the permafrost zone under consideration. These can be steam jetted through frozen soil, but experience has shown that they can readily be driven through permafrost in an advanced state of retrogression. The use of a piled foundation under such circumstances requires a structural ground floor or basement floor. No advantage results with these conditions in raising the building above the ground surface to provide outside air circulation. In fact, such an air space can be detrimental to the extent that frost penetration during the winter below the ground surface under the building may irregularly lift the piles by frost heaving.

The usual site preparation such as clearing, stripping off the organic cover and providing surface drainage will invariably increase the rate of deterioration of the permafrost. Settlements of the order of several inches, or even of a few feet, may result at the surface. It is difficult to analyze rationally the rate at which thawing and consolidation will proceed at a given site, because a heat transfer problem is superimposed on the consolidation problem. The problem can be handled mathematically by modern computer techniques, but difficulties arise in assigning accurate numerical values to the several parameters involved in the numerical solution. These include accurate values for the specific heat and thermal conductivity of the soil, the soil moisture content, the permeability and consolidation characteristics of the soil as well as the variation in at least the mean daily temperature at the surface of the ground for the period during which thawing and consolidation will progress.

Experience has shown, however, that the major portion of the movements occur within a year of the site preparation work. This leads to a procedure that has proven to be advantageous and economical from several points of view in the site development. The site can be cleared in the spring of the first year and left exposed during the following summer. In the fall a mat of compacted soil from 3 to 5 feet in thickness is placed over the building area and the following summer the building is completed. The foundations can then be spread footings placed on the mat. It is unrealistic to assume that all settlements will be completed during the one-year period, but the mat has the effect of reducing the magnitudes of the residual differential settlements that may develop following completion of the building. These can frequently be accommodated by modest expense in stiffening the building frame, and under exceptionally poor conditions it is possible to build into the foundations provision for jacking and shimming the structure if the differential movements become intolerable. In many circumstances the use of the mat makes it possible to eliminate the necessity of the ground floor being a structural slab.

The problem frequently arises as to the stability of higher embankments such as may be involved in earth dams or dikes, high railroad or highway fills, etc. if these are built on retrograding permafrost, or even on stable permafrost. In areas of discontinuous permafrost it again must be anticipated that the effect of the structure will be to increase the rate of deterioration of the permafrost and that within a year or two the permafrost will thaw below the structure. During this period, however, the structure must be capable of assuming substantial differential settlements.

The concept of many engineers is that under such circumstances complete instability will develop within the zone of frozen soil as it thaws and therefore a foundation failure is inevitable. This would be the case if the mass of frozen soil thawed instantaneously. Experience has shown, however, that such anticipated foundation instabilities do not, in fact, develop. The reason for this appears to be that thawing develops slowly and as it progresses consolidation and stabilization of the recently thawed soil also proceeds. A rational analysis to determine the minimum conditions of stability that will develop is not possible with present knowledge, but experience in several such circumstances indicates that it is very much more favourable than would result if the frozen soil were suddenly completely thawed. The problem, therefore, in the construction of embankments on frozen soil is not one of foundation stability within the zone of frozen soil, but rather is one of accommodating the differential movements that will develop during thawing and subsequent soil consolidation.

Figure 1 shows cracks due to differential movements produced on the downstream slope of a dam caused by thawing of permafrost below the slope. This dam was built partially on rock and partially on retrograding permafrost. The cracks shown developed the year following construction of the dam. No maintenance was done on these cracks and they subsequently appear to have been self-healing.

The performance of this particular dam, however, pointed up two additional pertinent factors. One was that at two locations "sink holes" developed on the crest. These were circular depressions about 4 or 5 feet in diameter in which settlements of the order of a foot or two occurred with a sheared face around the perimeter. The second abnormal behavior involved a thin horizontal seepage zone through the dam over a length of 20 to 30 feet caused by bridging of the crust of several feet of frozen soil below the crest. The reservoir was filled after freezing temperatures had set in, and it appeared that as the line of seepage rose in the embankment some settlement of the newly saturated soil occurred. The zone of horizontal seepage developed along the line of seepage. It was possible to lower the reservoir level for the remainder of the winter, and the following summer the seepage zone healed itself with no maintenance work being done. Obviously, however, with the possibility of such defects occurring, the use of a zoned cross-section for a dam in such circumstances is much to be preferred to a homogeneous embankment of fine-grained soil. The zoned cross-section would have much superior self-healing characteristics as compared to the homogeneous fill.

Figure 2 shows a longitudinal crack in a clay dike about 20 feet high that was deliberately built on frozen muskeg. A core section was cut through the frozen muskeg during the winter and backfilled with clay. The embankment was subsequently built on the frozen soil. The cracks shown developed the following summer and are due to differential settlement between the clay filled core and the thawing muskeg. It is pertinent to note that no instability developed in the muskeg. No maintenance work was done on these cracks. They appeared to seal themselves following surface run-off. In this case, the construction of the dike on frozen muskeg appeared to result in more favourable performance than if it had been built under summer conditions with the muskeg unfrozen.

Figure 3 shows a repeater station in which differential movements of 22 inches occurred between the opposite ends of the building due to thawing of permafrost in organic subsoil. This is an example in which the original site investigation did not detect the existence of permafrost. One test hole on the building site identified 4 feet of organic soil underlaid by "hard till". The thickness of organic soil was correct at the test hole, but at the west end of the building there was no organic soil while at the east end there was 16 feet of organic material. The foundation design provided for the removal of the organic soil and its replacement with gravel backfill. The building is only 30 by 60 feet in plan, and the design provided for a lightly reinforced concrete floor slab supported on the gravel backfilling. All of the organic material was not removed at the east end during construction presumably because the sub-contractor assumed that he had only contracted to remove 4 feet, not 16 feet of organic material.

The building is not large, and the first reaction is that possibly the most expedient procedure would be to move it bodily to a new foundation. It does house expensive equipment, however, and its continuous operation is essential to the operation of an important communications system. It was therefore decided that efforts should be made to improve the existing foundations.

The floor slab was not structurally strong enough to lift it off the ground. The first step, therefore, was to jack needlebeams from the side across under the slab. These were shimmed against the bottom of the slab and held at the ends by a new concrete edge beam. At the end of this operation the slab was structurally capable of being lifted off the ground and supported as desired. Ten-inch diameter pipe piles were then jacked down into the underlying till under the maximum load that could be developed using the building as the reaction. These were subsequently filled with concrete, and the building was levelled by jacking on the new piles.

Temperatures taken at the bottom of the boreholes showed the temperature of the till to be below freezing. There was no assurance that there was no ice segregation in the till and in view of the high end bearing pressure on the piles it was anticipated that settlement of the piles might occur if heat from the building ultimately thawed the till at the base of the piles. It was not considered desirable to leave a space for outside air circulation below the building because of the possibility of moisture condensation on the floor inside the building. It was decided therefore to make provision for jacking the building from the new piles if future settlements made this desirable.

The details of the jacking arrangement are shown in Figure 4. Three-foot lengths of 6-inch pipe were fabricated with a cap on the top through which 2-inch diameter rods 2 feet long were threaded. Two of these 6-inch pipes were welded to brackets on the sides of each pile, and in the final adjustment of the level of the building the threaded rods were turned up against steel bearing plates on the bottom of the concrete edge beam. The arrangement of the two 6-inch pipes on each side of the piles leaves room for jacks by which the slab can be raised and the threaded rods adjusted in the future if necessary.

This installation has now gone through one summer and two winters. Additional settlements have occurred during the summer and some heaving occurred during the second winter. An adjustment with the jacks was successfully undertaken during the second winter. If thawing of the permafrost below the building continues, insulation between the floor slab and ground surface may be advisable.

A large variety of engineering problems occur in areas of discontinuous permafrost. It is not possible to generalize on solutions applicable to all circumstances. A basic knowledge of the conditions that may exist in the soil in zones of retrograding permafrost is essential, however, for a proper solution of the resulting engineering problems.

FIGURE 1

CRACKS IN DOWNSTREAM SLOPE OF EARTH DAM BUILT ON PERMAFROST

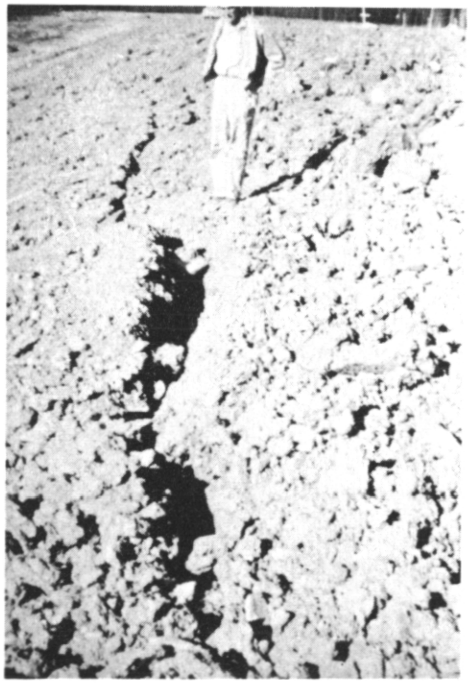

FIGURE 2

CRACKS IN AN EARTH DIKE BUILT ON FROZEN MUSKEG

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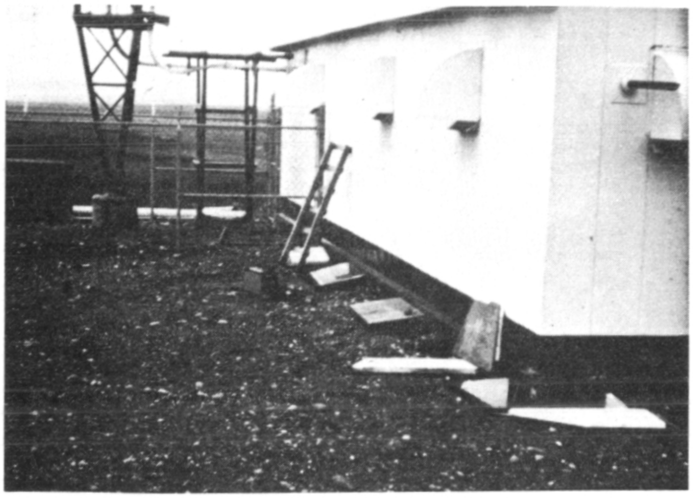

FIGURE 3

BUILDING SUBJECT TO 22 IN. OF DIFFERENTIAL SETTLEMENT DUE TO THAWING PERMAFROST

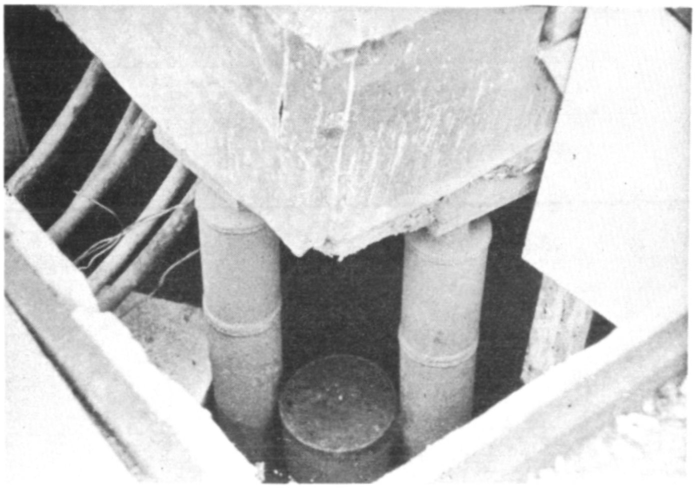

FIGURE 4

DETAILS FOR JACKING BUILDING FOUNDED ON PERMAFROST

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Discussion

G.S.H. Lock remarked that he is interested in the references made by the author to analytic methods of solving permafrost problems. His main interest in permafrost is heat transfer and it is surprising that comparatively few of the people interested in permafrost tackle the problem from the heat transfer standpoint. Whatever the ultimate aims in studying permafrost and its behaviour, it is a heat transfer problem. Actually, it is not really such a unique problem as is generally believed. It is only one example of conduction heat transfer by conduction with change of phase. There are many other important examples of this, such as the casting of metals, ablation of missiles during re-entry, de-icing of helicopter blades, etc. These are all problems of the same heat transfer type. The permafrost problem is not an easy one to solve but no more, or less, difficult than many others, such as those stated above. Examination of recent literature on heat transfer by conduction with change of phase reveals that in these other areas, investigators are not so reluctant to use mathematical techniques, and they continue to obtain useful results. In the past, this reluctance seems to have been associated with the difficulty in measuring the values of the various important parameters, such as thermal conductivity. With the support of surveys such as those described by R.J.E. Brown, there must be a more deliberate effort to treat the problem analytically in order to understand the phenomenon more fully and improve the ability to predict its behaviour. Lock asked the author what is the role of analytic methods in solving permafrost problems. Methods include mathematical techniques involving exact solutions and numerical solutions, analogue solutions, and small-scale experimentation. Next year the Department of Mechanical Engineering, University of Alberta will be in a position to study a few problems using these techniques. In particular the thawing of permafrost beneath lakes and rivers will be considered.

The author replied that permafrost research has not been carried out at the University of Alberta since 1949 because facilities were not available to obtain numerical parameters which was the next logical step. The U.S. Corps of Engineers initiated investigations in 1947 and it has derived solutions on a semi-empirical basis.

K.A. Linell added that CRREL supported studies at the Massachusetts Institute of Technology from 1950 to 1955. CRREL has derived semi-empirical methods of analysis which represent some comprising but they are satisfactory for engineering purposes. These have been supplemented by electric and hydraulic analogue computer programmes. These programmes were used by the Canadian Department of Transport in the design of the airfield in Inuvik, N.W.T. A manual in excess of 100 pages is presently being prepared for engineers by the Corps of Engineers containing mathematical methods, tables, and direct analytical solutions for building foundation and airfield design.

R.M. Hardy stated that there is no problem to solving a mathematical problem but knowledge of the accuracy of the physical parameters used in the problem is required. The depth of frost penetration can be obtained but in the discontinuous zone where permafrost is in a delicate thermal state, it is difficult to assign values to such parameters as thermal conductivity. K.A. Linell remarked that CRREL usually uses Kersten's data. These values are approximate but CRREL can determine precise thermal conductivity values if necessary. This is seldom done because of the high cost involved. Hardy asked how CRREL handles degree days of freezing and thawing, and temperature fluctuations. K.A. Linell replied that degree days are difficult; for example, a change of 50 degree days is possible within a few miles if changes in relief or some other factor occur. Thus errors could be introduced if data from a weather station 10 miles distant were used. Instruments would be required at each site which raises the question of how much money is available to pay for the required information. The depth of thaw can be estimated within 6 to 9 inches but conditions vary from year to year. Freezing index values are based on a minimum of 10 years of observations. If values are only available for one year, then they are correlated with records of nearby stations.

G. Lutz asked whether analogue methods are carried out from the one or three-dimensional point of view. K.A. Linell replied that most analogues are one-dimensional but they can be expanded to three.

O.F. Simonsen felt that analogue computers do not provide the solution. They are very complicated and few organizations, consulting engineers, etc., have them available. He asked what requirement there is for programs and wondered if numerical analyses would be better. Do the oil companies have any demand? The author replied that the U.S. Corps of Engineers has published numerical solutions of problems. These are quite suitable now but the demand for computer programs will increase. At present, computer programs are very expensive.

R.A. Hemstock asked what would be the maximum depth that permafrost would be encountered in areas of receding permafrost. He asked also whether there are cases of permafrost at great depth which is receding. Hardy replied that ice crystals had been found to depths of 60 feet in areas where permafrost had not been expected. This ice was the last remnant of permafrost in the area. There is evidence that frozen zones alternate with unfrozen zones. Hardy reported that he had never run into conditions where it could be concluded that the frozen zone had migrated downwards in the process of equilibrium conditions developing under the present temperature regime.

R.A. Hemstock also asked to what depth investigations should be conducted to obtain permafrost information required for engineering design purposes. R.J.E. Brown remarked that the permafrost that he described in his paper yesterday was close to the ground surface. It is virtually impossible to detect permafrost at depth without subsurface investigations because of the lack of surface indicators. G.H. Johnston added that the existence of permafrost islands at depths of 15 to 20 feet such as those at Thompson, Manitoba, could not be predicted by surface features such as vegetation. He added that investigations should be extended to a depth equal to the dimensions of the building being designed and also to the depth of climatic influences. These vary from one area to another but one might think in terms of exploration to a depth of 20 feet. At Thompson this was rather critical because it was found that some houses were built on permafrost islands. The question arose as to how subsequent building failures could be avoided. Regulations were established which required the contractor to carry out an investigation on each lot, consisting of a hole at each of the corners and at the centre of the building site. These holes were put down to a depth of about 20 feet. If permafrost was found, the lot was left vacant. For larger buildings, it might be desirable to put down test holes to a depth equal to the width of the building.

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