II.1. ENGINEERING PROBLEMS AND SITE INVESTIGATIONS IN THE DISCONTINUOUS PERMAFROST ZONE

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The purposes of this paper are to define the discontinuous permafrost zone, to outline briefly some of the more important engineering problems which are encountered in this zone and finally to describe some site investigation methods and techniques used to obtain information of soil and permafrost conditions. These comments are not directed to any specific engineering project but are meant to apply to all, be it a route location or an individual building site.

DEFINITION

From papers presented in Session I it is evident that the discontinuous zone covers a large part of the permafrost region and that within this zone the existence and condition of perennially frozen ground can vary widely. Although areas underlain by permafrost can be subdivided or classified in several ways based on, for example, the distribution of frozen soils, ground thermal regime, ice content, type of frozen soil, etc., there are two main features by which the discontinuous zone can be delineated. In this paper, therefore, which is concerned primarily with the Canadian permafrost region, the definition of the discontinuous zone is based on the occurrence of permafrost and the temperature of the frozen ground.

Within this zone, as can be inferred from the term "discontinuous", perennially frozen areas exist together with thawed or unfrozen areas - in contrast to the continuous zone where permafrost is found everywhere and generally to great depth beneath the ground surface. The distribution of permafrost varies considerably from the southern boundary, where unfrozen areas predominate and frozen ground occurs mainly as scattered or isolated patches or islands, to the northern reaches of this zone where permafrost is extensive and frozen ground predominates. The distribution varies not only in areal extent but also vertically, that is in thickness. Thus, permafrost may be only a few feet thick (generally found at the southern limit) or it may extend to considerable depth - say 100 to 200 feet - in the more northerly areas of the zone.

The other feature of particular importance in defining the discontinuous zone is the mean ground temperature, i.e. the temperature just below the zone of seasonal variations. This too, can vary appreciably being influenced by a number of factors. In general the mean ground temperature decreases with increase in latitude. In the southern fringe the mean ground temperature in permafrost bodies is slightly below 32°F, say from 30 - 32°F. Further north in the discontinuous zone, where permafrost is thicker and more widespread, the mean ground temperature may range between 23°F and 30°F.

In summary, the discontinuous zone may be defined in broad terms as that portion of the permafrost region in which perennially frozen ground occurs together with unfrozen areas and is not more than about 200 feet thick and the mean ground temperature just below the depth of seasonal variation ranges from about 23° to 32°F.

ENGINEERING PROBLEMS

(a) Important Features:

There are several characteristics of permafrost which are of particular importance in connection with engineering problems in the discontinuous zone. The most obvious, and yet most unpredictable in many ways, is the distribution of perennially frozen ground - ranging from random or patchy in the southern fringe to widespread further north. Associated with the areal occurrence is the variation in thickness of permafrost - from about one or two feet to more then 100 feet. The depth to the upper surface of permafrost (i.e. the permafrost table) can also vary widely - from one or two feet to as much as 10 feet or more. In some cases, the active layer, that is the depth below the ground surface which freezes and thaws seasonally, may not extend to the permafrost table and therefore an unfrozen layer or residual thaw layer exists above the permafrost table throughout the year. Another feature of importance is the mean ground temperature of perennially frozen materials found in this zone. Normally the temperatures are close to 32°F - that is near thawing.

Most of Northern Canada was glaciated and as a result the predominant soils are fine-grained silts and clays or fine sands or combinations of the three. Organic materials also occur extensively. All these soils are generally frost susceptible and, in addition, when perennially frozen, contain much ice - even in the southern fringe. Not all moisture is in the form of ice, however, particularly when ground temperatures are between about 28° - 32°F. Many fine-grained materials will have a significant unfrozen water content.

Drainage is poor in many areas of the discontinuous zone due primarily to the underlying or adjacent impervious permafrost resulting in an abundance of moisture and saturated materials in the active layer. In addition, groundwater may be found within the permafrost and can significantly affect the ground thermal regime.

(b) Problems:

The features just described are of paramount importance in that each is a potential source of trouble to the engineer if not duly considered prior to design and construction. For example, the relatively unpredictable nature of permafrost occurrence, particularly in the southern fringe, is a real problem in the siting of structures. A number of examples can be cited where a building was located such that a portion of it was underlain by a permafrost island. Thawing resulted in large differential settlements and ultimate failure of the structure. The problem is compounded when the permafrost table lies at some depth, say 10 feet or more, below the ground surface - in which case it may not be expected or discovered during initial site exploration.

Perhaps the most important and difficult problem to be faced, however, is in anticipating or determining the changes that will take place in the local environment due to construction or disturbance in an area. Permafrost is particularly sensitive to thermal changes. Any natural or man-made change, however slight, in the environmental conditions under which permafrost exists will greatly affect the delicate natural thermal equilibrium. In the discontinuous zone, because of the "warm" (that is, just below 32°F) temperature of the frozen ground, any disturbance or change in the local environment for example, the stripping of the surface cover or erection of a building, usually results in thawing of the previously frozen ground unless preventative measures are adopted. In some cases the active layer may be increased and/or the permafrost table lowered; at least a "warming" (but not necessarily thawing) of the permafrost might be expected.

Although frozen soil provides excellent bearing for structures, its strength properties are greatly reduced with increase in temperature and if thawed, it may lose its strength to such an extent that it will not support even light loads. The most serious problems arise with those soils having large ice contents. Great variations in the physical - mechanical properties of the soil occur when the material changes from the frozen to the thawed state.

Thawing of ice laden soils results in an abundance of moisture which, if not able to drain, is available for ice lensing when frost susceptible materials freeze. An increase in the depth of thaw due to disturbance of the local conditions is accompanied in many cases by an increase in the depth of frost penetration. Thus, additional material (previously frozen) is subjected to frost action and the result may be significant foundation movements.

The selection of suitable foundation designs and construction techniques for use in permafrost areas is normally based on one of the following approaches: (a) neglect of permafrost conditions may be applicable in perennially frozen dry gravels and coarse sands or bedrock; (b) preservation and utilization of the frozen condition to support the structure throughout its life; (c) pre-construction thawing and pre-consolidation of perennially frozen soils - with removal and/or replacement of detrimental materials if necessary; (d) thawing of the frozen ground expected during the life of the structure with differential settlement anticipated - foundation design takes these into account.

All of the points previously noted with respect to permafrost in the discontinuous zone greatly influence and must be considered in the selection of foundations and construction methods. It is essential, therefore, that adequate site investigations be carried out so that permafrost conditions can be properly evaluated.

SITE INVESTIGATIONS

One of the first questions to be answered when a site in the discontinuous permafrost zone is under consideration is - does permafrost exist there and if so where and under what conditions? If permafrost is present, then what are the characteristics and properties of the frozen ground and what effects might be expected if construction work is undertaken.

Some general assumptions can be made with regard to the distribution of permafrost, e.g. thawed zones are usually present under bodies of water such as lakes or rivers, and in some cases, under very wet, marshy depressions; permafrost may be present under south facing slopes but at great depth, or it may not exist in coarse granular materials. In general, however, the distribution and condition of permafrost particularly in the southern fringe, is relatively unpredictable.

Climate controls the broad pattern of permafrost distribution. The variations in thickness and temperature at depth and the patchy occurrence of perennially frozen ground cannot be explained, however, by climatic differences alone. These variations appear to be governed largely by local variations in micro-climate and such features of the terrain as relief, drainage, vegetation, snow cover, and soil type.

Careful pre-planning of a field investigation in the discontinuous zone is necessary if much time and effort (and survey costs) are to be saved or reduced. A thorough study, including compilation of pertinent information of the area to be evaluated should be made beforehand. An awareness of the features which influence the distribution and properties of perennially frozen soils and the factors which may affect design and construction is essential. An appreciation of the local climate and geology of the study area is of particular value.

Air photos provide a most valuable aid for preliminary planning and site evaluation. The air photo serves as a map and surface features on this map (together with a knowledge of the climatic and geologic history of the area) when properly identified and/or interpreted can yield a wealth of information on subsurface conditions. Soil types and permafrost conditions can be inferred from or are indicated by relief (and landform) vegetation and drainage characteristics. Colour tones on the photographs can provide further clues. A complete air photo study will consist of a critical analysis of the region as a whole followed by a detailed steroscopic examination of photos covering specific areas.

Papers presented in Session I show how relief, drainage, and vegetation characteristics are closely linked with permafrost distribution. Topographic position (both macro and micro) of a locality is perhaps the most important feature related to permafrost occurrence which can be recognized on an air photo and assists greatly in predicting permafrost conditions. In the discontinuous zone details of the relief such as slope, exposure, configuration of landforms are important in the determination of frost and permafrost phenomena. If the photographic scale is sufficiently large, then micro details such as, for example, the small differences in elevation between peat hummocks or peat plateaux and adjacent ground, and localized small-scale thermokarst and slumping features, can be identified and evaluated.

Although the relatively dense forest growth which is found in many areas of the discontinuous zone may mask surface features on an air photo, the vegetation in an area is a most important factor in terrain analysis. The resultant effect of all significant, chemical, and biological factors are expressed in the vegetation. Certain vegetation associations, noted in the papers in Session I, have been found to be closely related to subsurface conditions and permafrost occurrence and, therefore, when considered together with topographic position, soil texture and drainage can serve as fairly reliable indicators.

In general the surface drainage pattern is little altered by the presence of permafrost. Local drainage patterns and characteristics seen on an air photo do, however, provide useful clues. The thawing effect of water, either standing or flowing, on the occurrence and thermal regime of permafrost is great because of its heat storage capacity and powers of erosion.

Special features such as mud boils, mud flows, solifluction lobes, thermokarst, etc., are further important elements on an air photo which will provide information of ground ice occurrences, unstable thermal regime, severe frost susceptibility, etc.

Most surface features associated with permafrost are the result of a complex relationship between a number of different factors and processes such as climate, geology, freezing and thawing, slope and exposure, and drainage. It is clear that the information gained from an air photo can be expressed in qualitative terms only and its value depends to a great extent, on the experience of the air photo "reader" or "interpreter" and his ability to recognize, interpret, and analyze what he sees. At its present stage of development air photo interpretation can not be a substitute for field sampling and inspection. It is, however, a most valuable asset in the planning of field investigations and the selection (or elimination) of particular sites for detailed study, and cannot be overlooked.

Areas or sites are subdivided during the preliminary study (primarily through the air photo studies) on the basis of similar relief, drainage, and vegetation characteristics. Detailed field investigations are then carried out in these selected areas to check predictions made previously and to determine actual subsurface conditions.

The determination of the occurrence and distribution of perennially frozen ground is the most important aspect of the field programme. Geophysical methods to determine the depth to and extent of perennially frozen ground have had increasing applications in permafrost areas. Seismic refraction soundings appear to be suitable for determining the upper limit or depth to permafrost; electrical resistivity methods are most useful in determining the thickness of permafrost.

The factors which appear to control the existence of permafrost are also assessed at this time. The depth to which seasonal freezing and thawing penetrates (active layer) and rate at which these processes take place, the depth to the permafrost table, the thickness of permafrost (if possible), the presence of taliks (unfrozen zones) within the perennially frozen ground and the movement of subsurface water are additional factors that must be determined. The occurrence and types of ice segregation and the various materials with which they are associated must be known and delineated. Last, but not least, a knowledge of the ground thermal regime (i.e. ground temperature) is essential to describe permafrost conditions.

Detailed records of subsurface conditions are required at actual sites finally selected for construction to assist in the design of foundations. In particular the form and extent of ice segregation should be noted in detail. Subsurface investigations to examine and obtain samples of perennially frozen materials can be carried out in several ways. Naturally occurring exposures and hand-boring methods will provide general information to relatively shallow depths. Testpits and core drilling allow detailed examinations of soils and ice segregation to be made to greater depths. Testpits have particular application to site exploration in areas covered with deposits of stoney tills or gravel. An important advantage of this method is that it permits the frozen soil and the ice segregation to be examined in the undisturbed condition. Testpits can be excavated at any time of the year to depths of 20 to 30 feet and are normally advanced using compressed air or gasoline engine powered jack-hammers. Core drilling methods and techniques to obtain undisturbed frozen samples are widely used for extensive investigations to depths of 20 feet or greater. Although coarse-grained materials have been successfully sampled using special refrigeration equipment and techniques, drilling methods are most applicable in fine-grained soils. Good cores of undisturbed material can be obtained and samples taken for moisture (ice) content and unit weight determinations and the identification and classification of soils encountered.

For most engineering projects subsurface information should be obtained to depths of at least 30 feet although in some cases it may be desirable to go deeper, say to 50 feet. Certainly in the extreme southern fringe area where permafrost is expected to be relatively thin, the lower boundary of the permafrost should be determined. It is within the top 30 feet, however, that most problems, for example due to frost action or thawing resulting from disturbance, will be encountered. In addition, ground temperature observations should be made to a depth of at least 20 feet - the local climate has a significant influence on the ground thermal regime to at least that depth. Not only should the mean annual ground temperature be recorded but also the amplitude or annual variation at specific depths. This can vary considerably and is dependent on, for example, surface cover, soil type and moisture content. A knowledge of the ground thermal regime is most important and temperature installation must form a part of any field survey.

When permafrost conditions have been adequately defined and duly considered and evaluated, then a suitable foundation design can be selected. To assist the designer (and this is dependent on the time element, i.e. if the site work is carried out sufficiently far in advance of actual construction), valuable information can be gained by making actual test installations at the site. For example, should pile foundations be under consideration, then field studies might include an evaluation of pile placing techniques and pile-load and pullout tests to determine adfreezing strengths. Test fills might be constructed for road and airstrip design purposes. Bearing capacity tests of frozen ground might also be included. In addition construction methods and techniques particularly with regard to excavation and handling and placing of frozen and thawed materials might be developed.

Some of the more difficult problems faced by the engineer working in permafrost areas are encountered in the discontinuous zone. The patchy distribution and the very sensitive thermal nature of perennially frozen ground are basically the main reasons for these problems.

The more important factors to be considered when projects are undertaken in this zone have been outlined and the need for site investigations emphasized. Information which is required for design and construction purposes and methods used to obtain this information have been briefly described.

Discussion

T.A. Harwood reminded the audience that the National Air Photographic Library in Ottawa is unique in the world having complete airphoto coverage of Canada from an altitude of 30,000 feet. Some photographs in northern Canada (Mackenzie River valley) were taken as early as 1928 and thus provide a valuable historical record. Regional offices are being established where it will be possible to obtain photographs from Ottawa. He mentioned developments in the use of infra-red and ultra-violet filters and their possible application in mapping permafrost. Harwood referred to the occurrence of fossil permafrost features hundreds of miles south of existing permafrost. For example, relic features have been found in the Paris Basin in France.

G. Hollingshead asked for an explanation of the formation of the distinct horizontal lenses in varved clays. The author explained that varved clays consist of alternate bands of clay-sized and silt-sized materials. The existence of ice in horizontal layers results from the water moving more easily through the silt than the clay as freezing occurs. The lensing mechanism is connected with the rate of penetration of the freezing plane and the amount of available water. At the location of a lens, the freezing plane was probably stationary for a period of time and water was drawn toward it through the silt.

W.F. Iwanson asked for information on drilling equipment used in permafrost areas and what core recovery was obtained. Johnston replied that standard drilling equipment with a few minor modifications was used. Drilling can be carried out using water in canvas bags. Diesel fuel gives very good results in winter when air temperatures are low and eliminates the danger of frozen cores being thawed. Core recovery is excellent in fine-grained soils using water or diesel fuel. Coarse-grained soils can be cored using diesel fuel in air temperatures below 0°F.

J.R. Rettie asked whether the drilling by the National Research Council in permafrost at the Kelsey Hydro Station in northern Manitoba was carried out without drilling fluid. The author replied that no drilling fluid was used. Kelsey is located in the southern fringe of the permafrost region where temperatures in the varved clays are between 31°F and 32°F. The investigations were conducted to determine the depression of the permafrost table under the forebay. Shelby tubes were pushed through the plastic soils with the hydraulic drill head. Ice layers were penetrated by pushing or rotating the tube. Soil samples were taken at intervals of 1 to 2 feet.

D.A. Lindberg asked whether it was possible to differentiate between seasonally frozen ground and permafrost when soil sampling in winter. Johnston replied that in some cases it is difficult to determine any differences. Variations in ice segregation between the two layers may provide an indication. There may be no ice segregation at the permafrost table.

K.A. Linell remarked that the CRREL standard procedure is to use Shelby tubing with a 5-foot long drive sampling spoon to a depth of 25 feet in permafrost down to a temperature of about 25°F. This method works best in winter. Sampling can be carried out also with a drop hammer.

G.S.H. Lock stated that permafrost conditions at building sites can be assessed by drill holes but he wished to know how information on the thermal conductivity of perennially frozen soils could be obtained. The author replied that M.S. Kersten carried out laboratory investigations on the thermal conductivity of soils several years ago but little work has been carried out in recent years. K.A. Linell added that devices consisting of a small heating unit and probe to measure the response to thermal conductivity in the laboratory and in drill holes are available.