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ICE DISTRIBUTION IN PERMAFROST PROFILES

BY

P. J. WILLIAMS

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REPARTITION DE LA GLACE DANS LE PROFIL PEDOLOGIQUE DU PERGELISOL

SOMMAIRE

L'auteur a examiné des carottes provenant de forages profonds effectués dans le pergélisol spécialement pour déterminer leur lithologie et la présence de lentilles de glace. Il a constaté que l'augmentation localisée de la teneur en eau et la formation de lentilles de glace correspondaient aux prévisions découlant d'essais de pénétration de l'air dans les sols. L'auteur tient compte des conditions géomorphologiques particulières au lieu précis du forage et des résultats de recherches récentes menées en laboratoire sur la congélation du sol.

Ice distribution in permafrost profiles¹

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Soil samples from deep drill holes in permafrost have been analyzed with particular regard to lithology and ice occurrence. The occurrence of moisture accumulation and ice lensing was found to be compatible with predictions from air intrusion tests on the soil materials. Regard is paid to the special geomorphological conditions at the drill sites, and to recent findings in laboratory research on soil freezing.

Introduction

As the scope of engineering works in permafrost regions increases, it becomes important to know the characteristics of the frozen ground lying at depths of several meters or tens of meters. In the construction of dams, foundations for high buildings, etc. the amount of segregated ice and excess moisture in the frozen state occurring at depth is of relevance to the stability of the ground.

The relationships between soil type and amounts of ice lensing and excess moisture (which together constitute frost heave), are now quite well known in a general way for situations where the frozen ground lies within a meter or two of the surface. The grain-size composition of the soil is a useful guide to the amount of lensing (heaving) to be expected. It is also known, however, that overburden pressure and the availability of moisture have significant effects on the amount of lensing. Highway engineers have long used somewhat arbitrary rules, gathered from their field experience, to allow for the effect of the latter factors. Thus it appears that the grain-size criteria cannot without further consideration be extended to the case of soils at much greater depths.

Recent research has given a better understanding of the mechanism of frost heaving (see Williams 1967, for example). On the basis of laboratory and theoretical studies, a new procedure, the air intrusion test (Williams 1966, 1967) has been developed for determining the susceptibility of soils to frost heaving. An important feature of this procedure is that the particular site conditions of pore-water pressure and overburden pressure are explicitly involved. Limited field experience has shown it to be of value in the interpretation of the frost susceptibility of near-

surface materials. The question therefore arises as to whether analysis, and possibly prediction, of the occurrence of ice lenses and moisture accumulation at greater depths (as in permafrost) are now possible, using this procedure.

Good field observations of the ice distribution in deep boreholes are scarce, but in 1961 and 1964 a series of exploratory drill holes were made in permafrost in the Mackenzie Delta area. These were made under the direction of G. H. Johnston and R. J. E. Brown of the Division of Building Research, National Research Council of Canada, who have long experience in such work. The observations made are therefore of particular value. They have been in part described elsewhere (Johnston and Brown 1964, 1965, 1966). Many of the samples obtained have been analyzed in the laboratory, using the air intrusion procedure. In this paper the results of these analyses are compared with the ice occurrences as observed in the field.

Field Observations

Holes were drilled at two locations in the Mackenzie Delta, an area described in detail by Mackay (1963). The holes referred to below as MD2 and MD4 were situated in a lowland area between a small lake and a channel of the Mackenzie River (68°17' N. lat., 133°50' W. long.) (Fig. 1). The groundwater table generally lies within a meter of the ground surface; a high water mark on trees shows that it occasionally reaches 2 m above the ground surface. The underlying material was sandy silt sediments for about 55 m (180 ft) and a dense clay containing some small pebbles between this and bedrock, which occurred at about 70 m (230 ft) (Johnston and Brown 1964). Permafrost occurred throughout these holes, which extended to about 60 m (195 ft) (MD2) and about 35 m (115 ft) (MD4).

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FIG. 2. Values for hole MD2 of 0.42 (air intrusion value) $= P_i - P_w$ as a function of depth: sample contained no segregated ice (open circle); sample contained small amounts of segregated ice (open circle enclosing broken cross); sample contained conspicuous amounts of segregated ice (solid circle). Several determinations at one depth are shown by broken circles. Also shown are the curve of overburden pressure less porewater pressure (dashed line) and moisture contents (small solid circle).

FIG. 3. As Fig. 2, for hole IU 1.

FIG. 4. As Fig. 2, for hole IU 6.

FIG. 5. As Fig. 2, for hole IU 4.

FIG. 1. Aerial photograph showing location of boreholes, MD series, Mackenzie River Delta, Northwest Territories. Note the characteristic geomorphological indications of lateral migration of the channels. (RCAF photograph A 12857-276)

Permafrost was absent below the lake in a hole drilled to 73 m (240 ft).

Little ice segregation was recorded in holes MD2 and MD4. This is further illustrated in Fig. 2; the moisture contents presented in this figure also show that little migration and accumulation of water had occurred during freezing except in the near-surface layers, where substantial accumulation occurred.

The holes referred to below as IU 1, IU 4, and IU 6 were situated about 260 m (850 ft), 4 m (13 ft), and 15 m (45 ft) respectively, from a small lake about a mile outside the delta and about 107 m (350 ft) higher. There is probably no permafrost below the lake (none being found in a hole at the edge of the lake to 17 m (54 ft)), and none to 97 m (320 ft) under the lake. The depth of the bottom of the frozen ground increases with distance from the lake: it was observed at about 20 m (65 ft) in hole IU 4, at about 38 m (125 ft) in hole IU 6, and at 89 m (293 ft) in hole IU 1. The groundwater table is generally within 1 to 2 m of the surface. From 1 to 11 m (35 ft) of organic silt overlies 30–46 m (100–150 ft) of dense stoney till. Mineralogical analyses are given in Table I. Bedrock is thinly stratified shale.

TABLE I
Grain size and composition, Sample IU 4–54.5*

Size range	% by weight	Composition
> 2 μ	49	Mainly quartz, with chlorite, illite, and little smectite
2–0.2 μ	26	Quartz (25%), illite, chlorite and smectite
< 0.2 μ	25	Approx. equal amount illite and smectite, trace of chlorite, no quartz

*Analysis by J. E. Gillott.

Much more ice segregation occurred in these holes. As shown in Figs. 3 and 4, ice segregation and high moisture contents (associated with migration of water during freezing) occur not only in the near-surface layers but also at intervals down the profile, although less so with depth. It is also seen that ice segregation occurs in many cases without any increase in moisture content.

Laboratory Tests and Analysis

Background

Frozen samples for moisture content determinations were collected in small tins. The tests

were carried out shortly afterwards in conventional manner. Moisture content therefore means both ice and unfrozen water.

The other test results shown involve the air intrusion procedure, which will be only briefly explained here; further details are given in Williams (1967), and Geonor (1967). The air intrusion test is carried out in an apparatus with which the pressure of air p_a necessary to displace water throughout a sample is observed. The pore water pressure p_w is known and the "air intrusion value" is $p_a - p_w$. This quantity is a characteristic of the soil and results from capillary action:

$$[1] \quad p_a - p_w = \frac{2\sigma_{aw}}{r_c}$$

σ_{aw} is the surface tension air–water, and r_c is the radius of the largest continuous openings or channels, through a statistically representative combination of the soil particles (Williams 1967, p. 82).

It has further been shown that when a soil freezes and the frost line penetrates downwards, the pressures of the ice (p_i) and the water (p_w) at the frost line differ, and

$$[2] \quad p_i - p_w = \frac{2\sigma_{iw}}{r_c}$$

where σ_{iw} is the interfacial tension ice–water. Combining Eqns. [1] and [2] it is possible to obtain $p_i - p_w$ from a measurement of the air intrusion value $p_a - p_w$:

$$[3] \quad p_i - p_w = \frac{\sigma_{iw}}{\sigma_{aw}} (p_a - p_w)$$

p_i is approximately equal to the overburden pressure (Williams 1967), and p_w , the water pressure developed at the penetrating frost line, may therefore be obtained for the soil and depth in question. If p_w is lower than the pore-water pressure as defined by the ground water level and depth, there is a hydraulic gradient towards the frost line with a resulting accumulation of water in the freezing soil, and probably growth of ice lenses. If p_w is not lower, there is no ice segregation or accumulation of water (no frost heaving).

If a sample is taken from a depth Z , in material with a bulk density γ_s , and if the soil water conditions are hydrostatic with groundwater level at the ground surface, ice segregation and water

accumulation are to be expected at that depth if

$$[4] \quad Z\gamma_s - Z\gamma_w < p_i - p_w = p_a - p_w \frac{\sigma_{iw}}{\sigma_{aw}}$$

where $\frac{\sigma_{iw}}{\sigma_{aw}} = 0.42$

In Figs. 2-5 the dashed lines show $Z\gamma_s - Z\gamma_w$. Various values of γ_s were used, corresponding to field determinations carried out on samples from various depths. Thus γ_s is to be regarded as a roughly average value for all material to each depth Z . Hydrostatic pore water pressures are assumed in each case, with the groundwater level at the ground surface.

If the value of $p_i - p_w$ obtained from the air intrusion test on any sample lies to the right of the dashed line, then following the reasoning above, ice segregation would be expected for that sample *in situ*. It would not be expected if the value lay to the left. These circumstances only apply, however, if the theory given above correctly and completely defines the conditions for ice accumulation, and if $Z\gamma_s$ and $Z\gamma_w$ accurately define the *in situ* confining and pore-water pressures immediately prior to freezing at the depth in question. Consideration of these matters is given in the discussion below.

Test Results

The results obtained from the air intrusion tests on samples from the boreholes are shown in Figs. 2-5. The nature of the air intrusion test is such that it is particularly suited to fine-sandy and silty soils. It is within this range of soil that difficulty is most commonly experienced in the application of conventional grain-size criteria for determination of frost susceptibility in highway engineering. In the present case, many of the samples were of clay-rich material, and such soils have high air intrusion values. The air intrusion value apparatus available cannot be used to determine air intrusion values of above 4 kg/cm². Samples with higher air intrusion values (that is, where $p_i - p_w = (p_a - p_w) \times 0.42 > 1.7$ kg/cm²) are indicated by an arrow attached to the circle.

Interpretation of some other samples with fairly high air intrusion values is also difficult. Particular attention must then be given to the rate of testing and to the choice of scales for plotting of results (Geonor 1967). In addition there is a

tendency for air to leak into the drainage water. In each case, therefore, such leakage was carefully recorded and if necessary the test discarded. Some of the coarser-grained samples contained significant quantities of organic matter, also making interpretation somewhat uncertain. The slurring of the material before the test is carried out does not in general influence the air intrusion value significantly. The value is proportional to a linear dimension (r_c , Eqn. [1]) of the pore system, and minor volume changes of the sample will have a correspondingly small effect. In addition, at the moment of air intrusion the applied air pressure often gives a consolidation pressure not too different from that *in situ*. In all cases, the margin of uncertainty is less than 20% of the measured value and thus has no significance when shown graphically (Figs. 2-5).

Air intrusion tests were carried out on most of the samples from the holes to a depth of about 30 m (100 ft) (Figs. 2-5). Some unfortunate gaps in sampling occurred because of technical difficulties in the field. As the air intrusion values generally range through about four orders of magnitude (i.e. about 10 kg/cm² for fine clays down to perhaps 0.01 kg/cm² for sands), a logarithmic pressure scale has been used. The samples tested for air intrusion value were all examined individually at the time of drilling. Where there was no visible ice segregation this is indicated by an empty circle. Where there were one or two ice layers less than $\frac{1}{8}$ in. in the sample, or a larger layer adjacent to it, this is indicated by radial ticks. Where there was more marked ice segregation this is indicated by a solid circle.

The distribution of these different types of circles together with the numerous moisture content determinations give a good picture of the ice segregation and moisture accumulation at different depths. Wherever the moisture content is substantially above the general value, it can be assumed that an accumulation of moisture occurred at freezing; this usually gives rise to ice lenses, although in some cases there is a more or less uniform distribution of the ice through the sample. On examination of the samples, field observations, and the moisture contents from hole MD4 it was apparent that similar results to those for MD2 would be found. Air intrusion tests were therefore not carried out on these samples.

Finally the heterogeneous nature of the sampled materials, and the relatively small quan-

tities used for air intrusion and moisture content tests must be noted. This introduces a degree of uncertainty into individual observations, which is not, however, great enough to invalidate the general nature of the results.

Discussion

The observations in Fig. 2 show remarkable correlation with theoretical prediction. All the samples represented there would be highly frost-susceptible on the basis of conventional grain-size criteria, but the air intrusion values are such that the values $p_i - p_w$ lie to the left of the theoretical curve. Thus in accordance with the simplest analysis neither ice lensing nor moisture accumulation would be expected in the case of these samples. With only quite significant exceptions neither ice lensing nor moisture accumulation in fact occurred. No samples were available from the upper 3 m (10 ft) of the profile for determination of air intrusion value. However, the uniformity of the sediments permits extrapolation to these layers and it is virtually certain that the air intrusion values would lie to the right of the theoretical curve. Ice segregation and moisture accumulation would be expected and seem, from the moisture content determinations, to have actually occurred.

The soils of boreholes in the IU series consist mainly of clay-rich materials. This results in relatively high air intrusion and $p_i - p_w$ values. In these materials ice segregation occurred in the permafrost at most depths; it was observed at 89 m (293 ft) in hole IU 1. However, examination of the field moisture contents shows that in many cases (e.g. Fig. 5) ice segregation is not associated with moisture accumulation.

These clay-rich materials are quite compressible. The same conditions apply for the segregation of ice and moisture migration to the penetrating frost line as described earlier, and are represented by the theoretical curve separating the two regions in the depth versus $p_i - p_w$ graphs. Ice segregation occurs here even when, from the simple considerations, it would not be expected, for the following reason. When the temperature of the already frozen ground is lowered below that of the frost line, higher values of $p_i - p_w$ occur; p_w in this case is the pressure of the unfrozen water in the frozen soil (Williams 1967, pp. 39–45). At lower temperatures in such clay-rich materials, there is still a very significant

quantity of unfrozen water (p. 11). It has been shown experimentally that with falling temperature the higher values of $p_i - p_w$ cause slow migration of unfrozen water to ice segregations in preference to freezing of such water within the pores. Associated with this migration there is a consolidation (shrinkage) of the soil itself (while the ice segregations enlarge) (pp. 27–35).

Hoekstra (1966) has shown the rate of water migration to be very slow, but it would be expected to occur substantially on a geological time scale. There may thus also be some slow transference of moisture from outside the permafrost to give some increase in the bulk moisture content; however, this would be very limited. The moisture content observations give some evidence of this (e.g. Fig. 3).

There are two further effects which would require displacement downwards of the theoretical curve. The pore-water pressures at freezing at the different depths might not have been hydrostatic. Artesian pressures can arise below permafrost (Williams 1965; Cederstrom 1963). This is improbable for the MD series as will become apparent. The assumption that the ice pressure p_i (Eqn. [3]) is equal to the overburden pressure $Z\gamma_s$ may be incorrect for ice lenses aligned vertically, as were observed in the deep clay-rich layers. On the other hand, the vertical lenses may well have developed as a result of shrinkage in conjunction with growth of horizontal lenses that lay outside the sample. The occurrence of the latter would justify the use of $Z\gamma_s$.

One further problem presents itself. The simple explanation given above of the results observed appears at first sight to be incompatible with the geological history of the delta area (i.e. the MD series of holes) as presently understood (Johnston and Brown 1965). Deposition of silt in the delta was thought to have occurred at an average rate of about 5 mm (0.2 in.) thickness each year, over the last 7000 years. Climatic conditions appropriate for the existence of permafrost have presumably persisted throughout that time. Thus it might be supposed that the permafrost in boreholes MD2 and MD4 was formed from the bottom up as the layers of sediments were deposited. At the time of deposition and freezing of each layer there would not be the overburden and pore-water pressures assumed in the determination of the theoretical curve (Fig. 2).

This is incorrect, however. Characteristic for a delta is a continual lateral migration of the river channels as the sediments are laid down (Fig. 1). Both field observations and theoretical calculations (Brown *et al.* 1964) show that the permafrost is in general absent below lakes and rivers. This is because of the effect of the water body on the thermal regime. As the channels in the delta slowly migrate they cause the disappearance of the permafrost beneath them. Thus although the climatic conditions of permafrost have persisted continuously over thousands of years, the permafrost at any particular point is only as old as the time since a channel or lake last lay above it. This period of time would often be less than 1000 years in the delta. 'Holes' through the permafrost will have occurred at all times of interest. They prevent the occurrence of artesian pressures, and make it probable that the assumed water pressures $Z\gamma_w$ are correct.

Thus the freezing of materials in boreholes MD2 and MD4 occurred relatively recently and when the overburden and pore-water pressures at each depth were not substantially different from the present. The observations are thus in agreement with the predictions from analysis of air intrusion values.

Conclusions

1. Conventional grain-size criteria are not appropriate for the prediction of occurrence of frost heave at depths greater than a few meters.
2. The distribution (or absence) of ice accumulation and frost heave at depth in silty soils was found to be in accordance with predictions based on air intrusion value determinations.
3. The distribution of ice segregations in clay-rich materials that are compressible is also explainable, provided allowance is made for the slow migration of unfrozen water that is to be

expected in such frozen materials over periods of many years.

4. The effect of depth in limiting ice lensing and moisture accumulation in permafrost is demonstrated.

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