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DOWNSLOPE SOIL MOVEMENT AT A SUB-ARCTIC LOCATION WITH REGARD TO VARIATIONS WITH DEPTH

P. J. WILLIAMS*

ABSTRACT

Soil movements resulting from solifluction or similar processes have been investigated at Schefferville, P.Q., Canada, where the variation of movement with depth below the surface was specially considered.

Tubes up to 2 m long were inserted vertically in the ground and their subsequent deformation (if any) measured with special probes, which passed down the tubes *in situ*. Some sites proved to be entirely stable despite vegetational characteristics that might have been related to disturbance. Movements at the surface of more than 10 cm/yr. were recorded on a 20° bare slope covered with small stones. Similar large movements were recorded on a lobate terrace-like feature with a general 8 to 10° slope. The distribution of movement with depth was such as to produce a typically concave downslope form in the tubes. The movements varied in intensity and from year to year; they decreased with depth, and were not measurable below about 1 m. Although they are similar to those observed by Rapp and others, they are remarkable in view of the slight slope on which they occurred. Analysis shows that consolidation following frost heave is probably not the sole cause. A stability calculation of the type commonly used for engineering purposes would have given no indication of the occurrence of movements of the magnitude observed. They might have been suspected, however, from geomorphological considerations of the origin of the surface features of the affected area.

SOMMAIRE

On a étudié les mouvements du sol causés par la solifluction et par d'autres phénomènes semblables à Schefferville, P.Q., au Canada, et on a apporté une attention particulière aux variations des mouvements par rapport à la profondeur.

Des tubes ayant jusqu'à 2 mètres de longueur ont été enfoncés verticalement dans le sol et leur déformation subséquente (s'il y en avait une) a été mesurée au moyen de sondes spéciales que l'on introduisait dans les tubes *in situ*. A certains endroits, malgré des caractéristiques de végétation qui laissaient supposer un certain dérangement, on a constate que le sol était complètement stable. On a enregistré des mouvements dépassant 10 cm/an sur une pente nue ayant un angle d'inclinaison de 20° et couverte de petites pierres.

On a constaté des mouvements aussi considérables sur un terrain lobaire en forme de terrasse ayant un angle de déclivité de 8 à 10°. Les mouvements variaient selon la profondeur de telle façon qu'ils déformaient les tubes et leur donnaient une forme de pente descendante typiquement concave. Les mouvements variaient également en intensité et d'une année à l'autre ; ils diminuaient avec la profondeur et il était impossible de les mesurer à une profondeur dépassant environ 1 mètre. Bien qu'ils soient semblables a ceux qu'ont observé Rapp et d'autres chercheurs, ils sont remarquables en raison de la pente peu prononcée du terrain où ils se sont produits. Une analyse montre que la consolidation qui suit un gonflement dû au gel n'est pas la seule cause de ces mouvements. Un calcul de stabilité du type de ceux que les ingénieurs effectuent communément n'aurait pas permis de prévoir l'existence de mouvements tels que ceux que l'on a remarqués. Toutefois, on aurait pu les soupçonner grâce à des considérations géomorphologiques sur l'origine des caractéristiques de terrain de la région.

Descriptions of surface features indicative of downslope movements of soil material due to frost action, known generally as solifluction, occur frequently

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in the geological and geomorphological literature of the arctic and sub-arctic regions. Increasing construction and development in these regions has led to more detailed studies, stimulated by the importance and unusual nature of these natural soil movements as an occasional engineering problem. Measurements of the surface displacement associated with frost action have recently given a clearer understanding of the magnitude of such movements and of the character of the associated surface features (Rapp, 1961). With few exceptions (e.g., Rudberg, 1962) the distribution of the movement below the surface has not been investigated. An instrument has been constructed for this purpose, based on an earlier type (Williams, 1957a) which was substantially developed and modified for the present investigation. It involves insertion of polyethylene tubes of ⅝-in. (1.59 cm) internal diameter, ⅛-in. (0.33 cm) wall thickness, and up to 2 m in length into the ground, and subsequent investigation of their shape, *in situ*, by insertion of a special probe. The probe consists basically of a curvature-sensing element using electrical resistance strain gauges. The instrument is fully described elsewhere (Williams, 1962).

Most investigations described in the literature have been carried out at sites where movement had apparently taken place. The present investigation includes sites where the occurrence of movements was not immediately obvious.

Sites of Investigations

Sites were investigated in the region of Schefferville, P.Q. (Figs. 1a, 1b), in areas with mean annual temperatures of 22 to 23° F[1] (—5 to —6° C), where permafrost occurs discontinuously. The active layer extends, in general, 1.5 to 3 m (5 to 10 ft.) deep.

Site 1, approximately 20 km (12 miles) northwest of Schefferville, is a conspicuous and unusual "terrace" or "lobe-like" feature (Figure 2). Six tubes 1.5 to 2 m (5 to 7 ft.) in length were placed as shown on the plan (Figure 3). The terrace surface had a slope of 4 to 9°, but the bluff was much steeper (Figure 3).

Site 2 is a slope, varying from 5 to 23° (Figure 4) on the east side of Dolly Ridge approximately 5 km (3 miles) northeast of the townsite and covered with alder scrub with isolated spruce (*Picea glauca*), except for patches of grass and moss. Throughout much of the slope, bedrock lies 1 to 2 m below the surface. The woody vegetation shows considerable deformation similar to that sometimes associated in temperate regions with soil movement. Water reaches the surface at the foot of the slope and *Betula nana* is also present there. Six tubes 0.4 to 1.2 m (16 to 48 in.) in length were placed at various points between the foot and the top of the slope in positions with the types of vegetation cover noted above.

Site 3, which is about 300 m southeast of Site 1, is a vegetation-free slope of about 20° (Figure 4) covered with small stones.

Grain-size composition curves for samples from the three sites are shown in Figure 5.

[1]Extrapolated from the mean annual temperature of 24.2° F (4.4° C) measured at the townsite, which is at 200 to 500 feet lower.

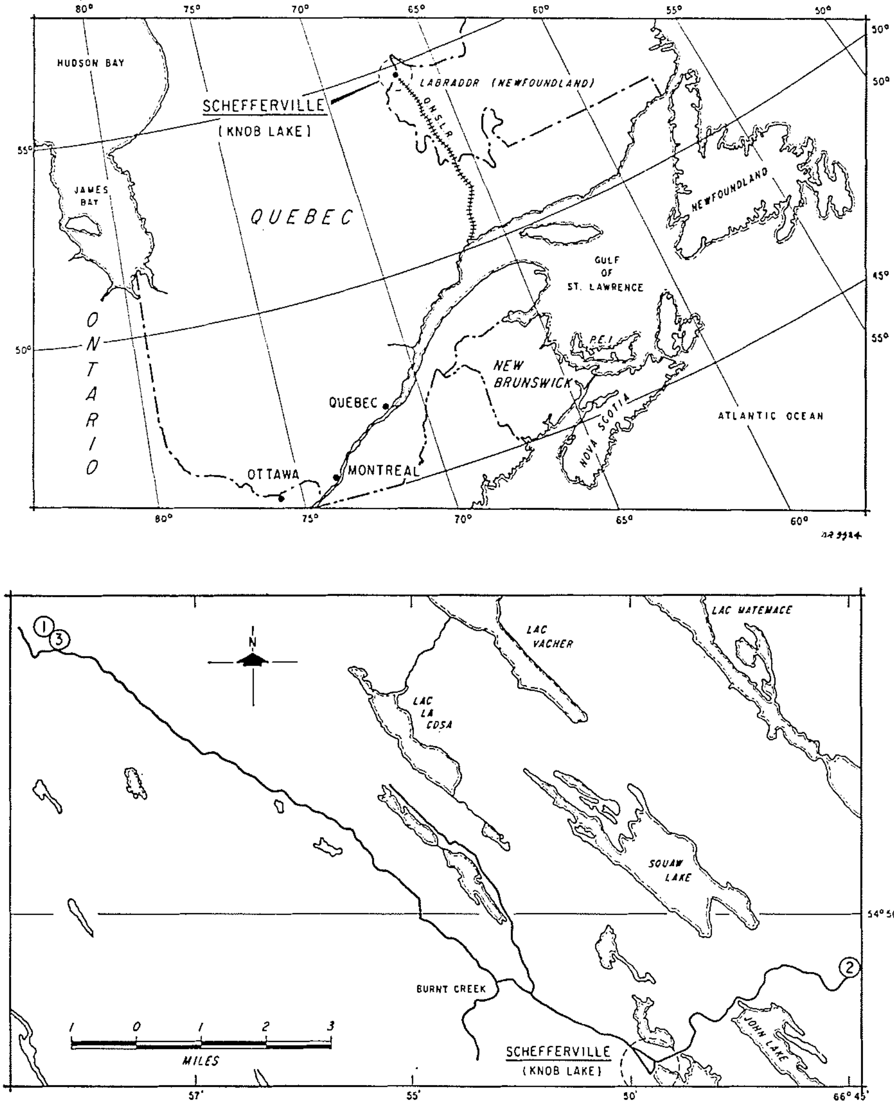


FIGURE 1. Maps showing (a) location of Schefferville, and (b) location of sites at Schefferville

PREPARATIONS AT THE SITES

Tubes were inserted vertically in holes prepared with an auger (Sites 1 and 3) or with a portable pneumatic drill (Site 2, where stones prevented use of the auger). The augered holes were only a few centimetres larger in diameter than the tubes. During placing, the tubes were stiffened by insertion of a brass or wooden rod, which was removed after the holes had been back-filled with a mud slurry. The tubes were heat sealed at the base and closed with corks at the tops.

FIGURE 2. Site 1. The slope investigated is in the foreground where the author is sitting. An assemblage of large boulders lies upslope of this and bedrock appears at the surface of the valley side not seen in the photograph

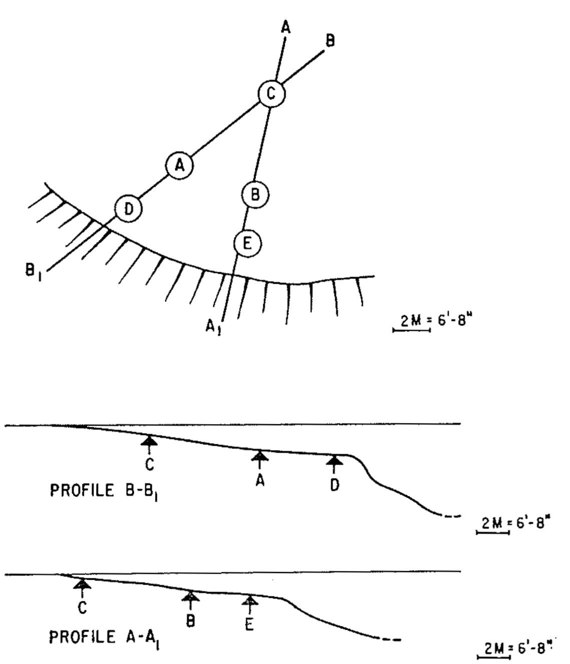


FIGURE 3. Layout of tubes at Site 1, based on linen tape measurements. The two slope profiles are based on accurate levelling. Vertical and horizontal scales are the same.

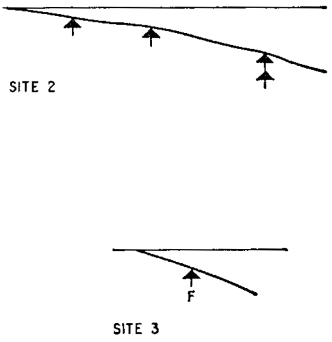


FIGURE 4. Slope profiles at Sites 2 and 3. Profile does not include locations of two of tubes at Site 2.

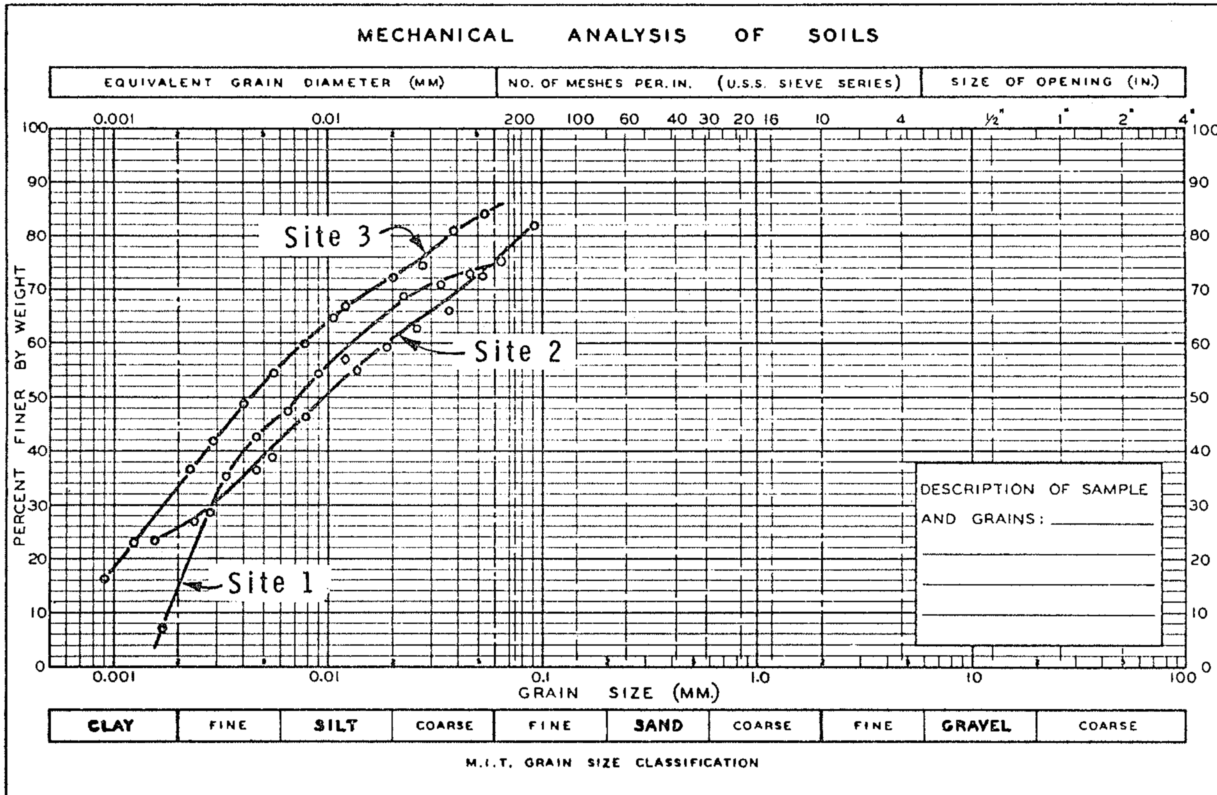


FIGURE 5. Grain size composition curves for the soils at the three sites. All the soils are susceptible to frost heave according to generally accepted criteria (e.g., Beskow, 1935)

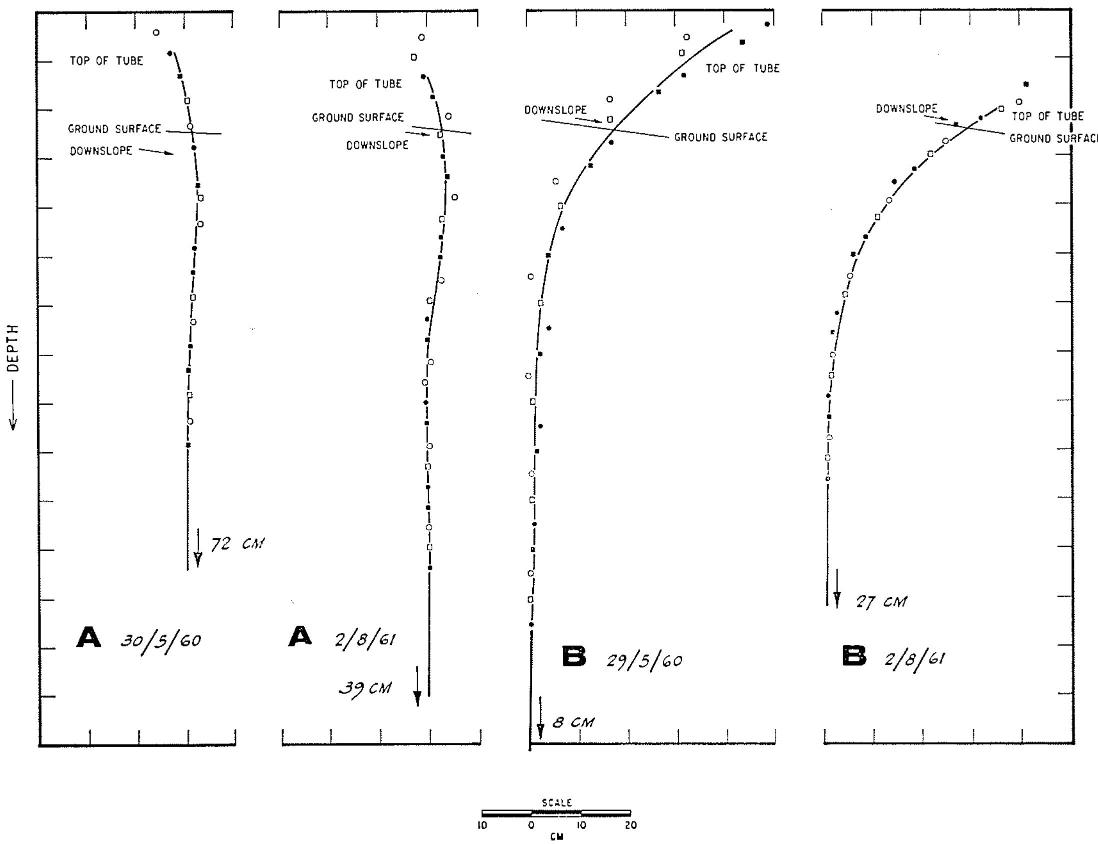


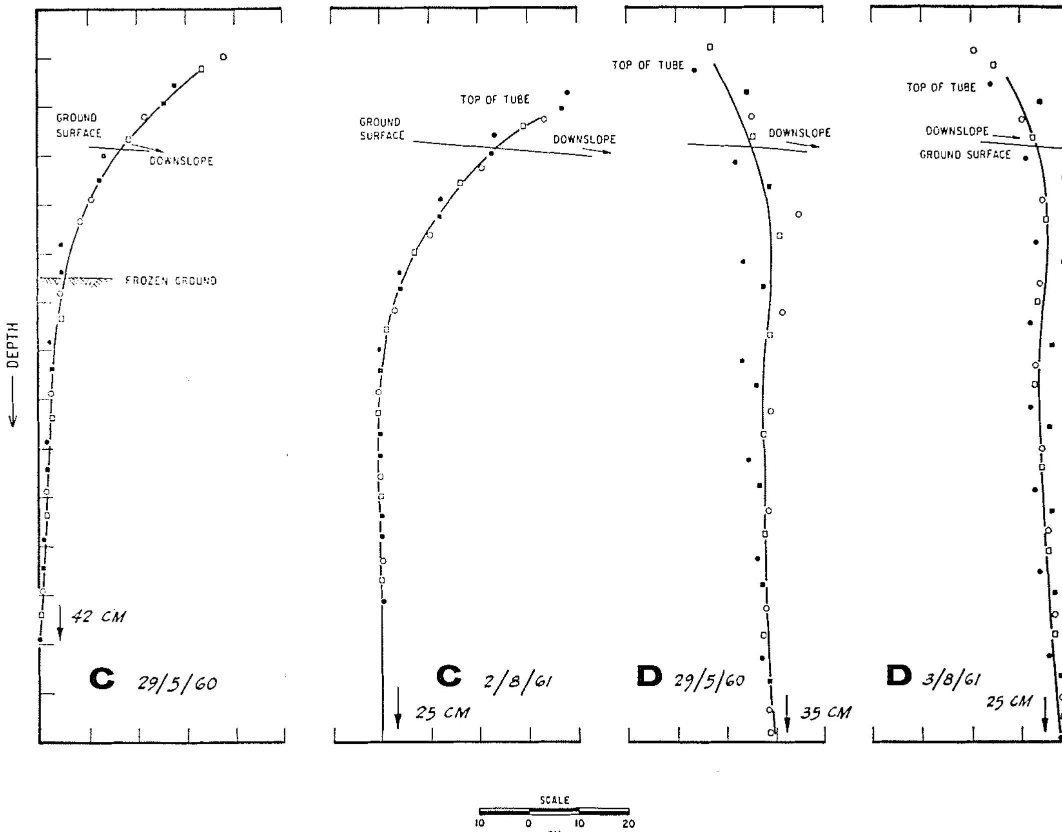
FIGURE 6. Shapes of buried tubes at Site 1 subject to deformation by soil movement. Divisions on axes correspond to 10 cm (3.94 in.). Four series of measurements (repre-

OBSERVATIONS OF SOIL MOVEMENTS

The tubes were placed in 1958 and investigated *in situ* in 1959, 1960, and 1961. No movements were detected at Site 2, although substantial ones were recorded at Site 1. The shapes of these tubes as determined in 1960 and 1961 are shown in Figure 6. The distance to the bottom of the tube is shown where it was not possible to make observations because of obstructions (probably ice) on the tube, or a constriction of the tube due to freezing of the adjacent soil. Observations made in 1959 were of poor quality, but agreed with the displacements subsequently measured. In 1963 the shape of one tube *in situ* was revealed by excavation (Figure 7). The single tube at Site 3 also showed considerable movement by 1960 and 1961 (Figure 8).

DISCUSSION OF OBSERVED MOVEMENTS

The lack of movement at Site 2 illustrates the fact that quite steep slopes (up to 23° in this case) with soil susceptible to frost heave (Figure 5) and



sented by the point symbols ●, ■, ○, □) were made on each tube (for further details see Williams, 1962) on the dates shown.

abundant water may be unaffected by solifluction. It has since been shown that the deformation of woody vegetation at this site is caused by substantial creep movements within the thick snow accumulation during winter and spring (Andrews, 1961).

The movement that occurred at Site 3 is perhaps to be expected. The concave downslope form assumed by the tube (Figure 8) is similar to that generally shown by those at Site 1, where the slope angle is much less. The lower part of the tubes at Site 1 remained straight. When holes were augered in late August (for insertion of the tubes) frozen ground was encountered at about 1.5m (5 ft.). There can be, at most, only a short period of the year during which the ends of these tubes are in unfrozen ground, and it may be perennially frozen. As significant movements are unlikely in perennially frozen material, the lower ends of these tubes can be assumed to be fixed points.[2]

[2]Recent work (*Proceedings, International Conference on Permafrost, 1963*) indicates that frozen ground at temperatures near 0° C and subject to seasonal temperature changes may show "creep" phenomena. In the present case, however, such movements would be much smaller than those observed in the layer subject to total thaw.

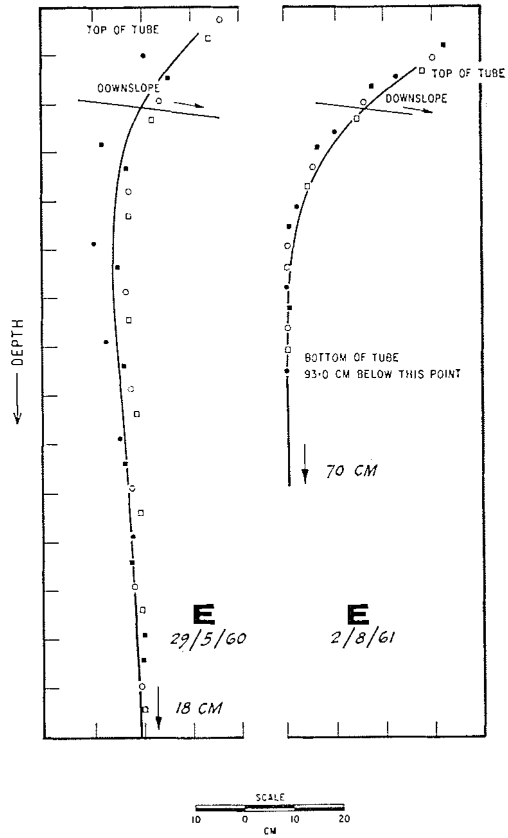


FIGURE 6. (concluded)

The concave downslope form assumed by the tubes shows that not only is the absolute displacement of the upper layers greater than that of lower layers, but the differential movement within each layer increases towards the surface. The slightly convex downslope form apparent in some of the tubes is probably due to their tendency to take on this form following transport to the site in a coil. Only certain tubes were taken from such a coil, and the tendency to assume a curved form seemed very slight at insertion. The convex downslope form may also therefore be related to some corresponding movement of the soil.

The magnitude and profile of the movements and their irregular occurrence resemble certain of the observations of Rapp (1961) and Rudberg (1962), although the latter observations were carried out on much steeper slopes.

Possible causes of the movements observed at Site 1

Normal engineering analysis. When, for engineering purposes, it is necessary to determine whether movement will occur on a given slope, it is usual to make a calculation in which the forces tending to cause movement are compared with those that could be mobilized to resist movement (i.e., the strength of the soil). Such computations take into account slope, water content, pore water pressure, friction angle for the soil, and other factors. Such a computation was carried out for Site 1 (using the procedure in Janbu, Bjerrum, and Kjaernsli, 1956) and it indicated that for failure to occur the friction angle of the soil would have to be considerably less than 30°. The silty nature of the soil indicates that its friction angle is normally much higher. The calculation,

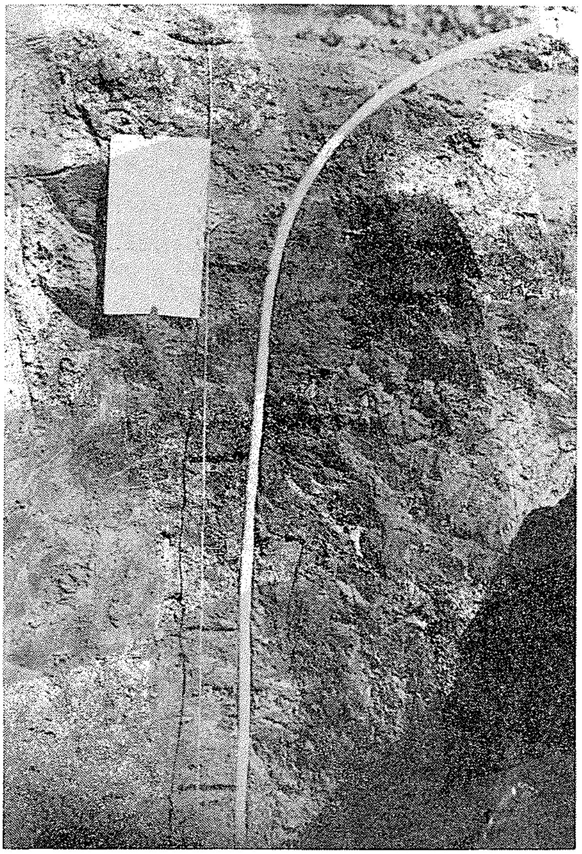


FIGURE 7. Shape of tube C at Site 1 revealed by excavation, August 1963. This can be compared with the instrumental observations for 1960 and 1961 in Figure 5. The grooves cut in the soil are at 1 ft. (30.4 cm) intervals.

furthermore, was made on the assumption that the soil was completely saturated at the time of movement. Even in the spring when there is abundant melt-water from snow, the soil is not, in fact, entirely saturated. The lower parts of the slope were observed to be substantially drier when the upper parts were only appearing under the melting snow. Tensiometers inserted in the thawing ground showed that even in the most recently thawed soil somewhat negative pore pressures occur.

It should be noted that the eventual movements predicted by this kind of analysis involving development of slip surfaces apparently differ in nature from those observed. It can be concluded that movements of this type are not

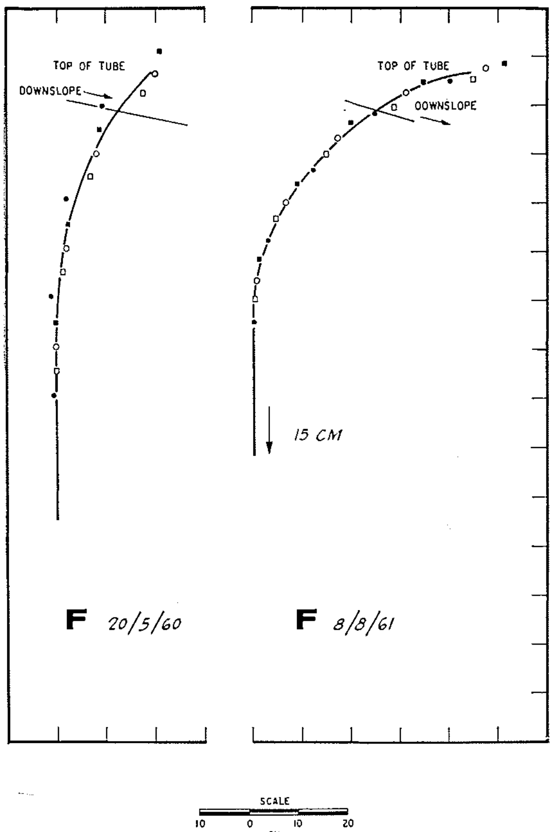


FIGURE 8. Shape of tube at Site 3. For further explanation see Figure 5.

susceptible to conventional stability analysis, which in this case would have led to the conclusion that slope was completely stable.

Effects of frost heave and subsequent consolidation. It is frequently suggested that the volume changes associated with frost heave and subsequent consolidation are responsible for downslope movement (see, e.g., Williams, 1957b).

If it is assumed that frost heave occurs in a direction normal to the slope and that consolidation on thawing occurs vertically, then the downslope movement resulting from one freeze-thaw cycle is given by:

$$L = \tan\beta E \qquad (1)$$

where L is the downslope component of movement

β is the slope angle

E is the frost heave.

In Table I the vertical soil profile at tube C has been regarded as a series of layers 5 cm (1.97 in.) thick. The frost heave per year necessary (according to the above equation) to give the increment of downslope movement measured for each layer is shown as an average value based on the movement over 3 years. The greatest heave occurring in a year in a given layer would thus have to be somewhat greater. Frost heaves of such magnitude, in some cases equivalent to more than twice the thickness of the layer in the unfrozen

TABLE I

Average frost heave per year required in each 5-cm (1.97 in.) layer to produce the observed movement at tube C, site 1, if equation 1 applies

(The slope angle $\beta = 8°$; and the computation is based on the shape of the tube measured in 1961)

Depth of 5 cm layer from surface measured vertically (cm)	Downslope movement 1958–61 of upper surface of layer, ΣL (cm)	Displacement within 5-cm layer, L ($\Sigma L_1 - \Sigma L_2$; $\Sigma L_2 - \Sigma L_3$; etc.) (cm)	Average movement per year, $L/3$ (cm)	Frost heave within 5-cm layer, $(L/3)/\tan\beta$ (cm)
0	28.0	5.5	1.87	13.3
5	22.5	4.5	1.50	10.7
10	18.0	4.0	1.33	9.5
15	14.0	3.0	1.00	7.1
20	11.0	2.5	0.83	5.9
25	8.5	2.0	0.67	4.8
30	6.5	2.0	0.67	4.8
35	4.5	1.5	0.50	3.6
40	3.0	1.0	0.33	2.4
45	2.0	0.5	0.17	1.2
50	1.5	0.5	0.17	1.2
55	1.0	0.5	0.16	1.1
60	0.5	0.0	0.00	0.0
65	0.5	0.5	0.16	1.1

state, are improbable. When frozen, such layers would appear to be ice interspersed with thin layers of soil. Limited sampling gave no indication of such abundant ice. Furthermore, such enormous heaves would probably result within a few years in the ejection of the tubes from the ground. In fact, some tubes were raised but only in some years and by 5 to 10 cm (2 to 4 in.). Except for a surface layer a few centimeters thick, the soil is subject to only one freeze-thaw cycle per year. It can be concluded that consolidation following frost heave is unlikely to be by itself responsible for the movements.

Other effects of the freezing process. It seems certain that the observed movements are associated with the freeze-thaw process, although not in the manner considered above. Compared with stable summer conditions, the soil immediately following thaw is in a very loose state and the cohesion component of soil strength will be much reduced. Similarly, the porewater pressure will probably be higher in relation to the summer condition, tending to reduce the friction component of soil strength.[3] It may be noted that both these effects were allowed for in the computation that indicated the slope to be stable: cohesion was assumed to be nil, and porewater pressures those that would be produced with a water table at the ground surface.

[3]For discussion of these factors in relation to slope stability, see Terzaghi and Peck (1948) or other standard text.

At a few places on the soil surface at the edge of melting snow, meltwater caused shallow mudflows. These, however, were only a few centimetres deep and were generally limited to less than a square metre in area. In fact, even at the time of maximum snow melt, the stability of the surface underfoot was in striking contrast to a solifluction with relatively rapid movement which has been discussed earlier (Williams, 1959).

A further possibility is that the friction angle of the soil is to be regarded as very low immediately following thaw. Both late-lying snow and the raised ground level persisting from the frozen condition tend to increase stresses that can cause movement, although both factors appear to be of relatively little significance. There does not, in fact, seem to be a fully satisfactory explanation at present for the observed movements.

Recognition of probability of movement from surface characteristics

The considerable size of the movements at Site 1, the fact that they would not have been predicted by conventional engineering analysis, and the uncertainty as to their cause, raise the question of whether close acquaintance with sub-arctic landforms could enable recognition of such unstable slopes. In the three to four years before definite observation of movement was made, the site was visited by several geomorphologists experienced in sub-arctic studies. Various suggestions as to the origin of the feature were put forward: that it was a form of moraine, a product of post-glacial stream erosion, or that it was due to solifluction. The characteristics suggesting the last interpretation were the absence of vegetation (suggesting present-day disturbance) a partial resemblance to certain features known to result from solifluction (cf. illustrations in Williams, 1957b), and the difficulty of finding an alternative explanation that would not seriously conflict with other geomorphological evidence. The silty material of which the feature is composed is presumably of fluvio-glacial origin. Its form and location in a small valley believed to be immediately post-glacial appeared to rule out the possibility that the material was in the position it had when originally deposited.

It is hoped that the description and illustrations in this paper will facilitate recognition of similar surface features subjected to continuing soil movements of similar magnitude.

ACKNOWLEDGMENTS

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