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QUANTITATIVE INVESTIGATIONS OF SOIL MOVEMENT IN FROZEN GROUND PHENOMENA **

Sommaire

Les études quantitatives des phénomènes du sol gelé comprennent des mesures linéaires ou volumétriques des mouvements du sol. Ces études sont généralement expérimentales, exigeant certains instruments et des observations répétées. Les résultats, quoiqu'ils ne soient pas toujours très précis, permettent d'obtenir: (a) une interprétation correcte de ces mouvements comme processus géomorphologiques et (b) des renseignements qui peuvent être appliqués d'une manière satisfaisante aux problèmes géotechniques.

On a décrit les méthodes et les résultats d'un certain nombre d'études. On a mis au point une nouvelle méthode pour déterminer les mouvements souterrains. Cela comprend des mesures répétées concernant la déformation d'un tube enterré, qui donnent le profil vertical de la vitesse. Une sonde sensible à la courbure est placée dans le tube. On peut ainsi détecter, à partir de la surface, toutes les déformations du tube. La sonde comprend principalement une bande sensible aux efforts à laquelle sont fixées des jauges à résistance électrique. On peut détecter les courbures de la bande grâce aux indications données par les jauges. La forme de douze tubes enterrées à des angles différents a été vérifiée à plusieurs reprises. On a constaté que les mouvements se sont produits dans une forme topographique dont l'origine était douteuse.

The occurrence of considerable movements of soil material as a result of cold climates has long been recognized, and has given rise to a large literature on solifluction, patterned ground and allied phenomena. Only recently, however, have careful observations been made of the rates of movement of material involved.

These observations have been stimulated by the need for appreciation of the significance of such mass movements. Correct interpretation of many minor land forms has been hampered by ignorance of the quantities of material that could reasonably have been moved in the time available. Furthermore, the increasing development of the arctic and subarctic and the associated refinements in building and other construction work means that the recognition of these movements and of their size and nature is becoming a matter of practical importance.

In many cases the movements are associated with the development of easily recognized surface features which are conspicuous throughout most of the year. In other cases there is no obvious surficial indication of the susceptibility of the soil to movement in its natural state.

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SOME RECENT INVESTIGATIONS

The most widespread and fundamental form of movement is that of frost heave, in which expansive and contractive movements occur more or less perpendicular to the ground surface as a result of freezing and thawing. Largely because frost heave is also common in areas of quite moderate climate, many investigations have been made into its magnitude, effects and causes, especially from the engineering point of view (see, e.g., Beskov 1935; Penner 1958) and it will not be further discussed here.

There are many types of lateral or downslope movement. A comprehensive review of Scandinavian work has been prepared by Rapp, 1960 a (which also covers movements not essentially related to ground freezing).

Repeated measurements with tapes of the position of wooden stakes (Dahl 1956) showed very localized movements of 10 cm/yr in a vegetation covered slope. Slight wrinkling of the soil surface was noted. Extensive observations have recently been carried out by Rapp (1960b) using similar methods. Scattered movements of 10—20 cm/yr occur even on slopes with a considerable cover of sedges, grasses and other vegetation. Some of the larger movements are associated with wet areas, or with moderately defined terrace features. Rudberg (1958) recorded movements of painted stones of 9—12 cm/yr under similar conditions. Washburn (1947) with a line of stakes across a very well-defined solifluction terrace showed movements of 3 to 6 cm/yr. In somewhat similar terraces, excavations investigated by the author showed a buried humus layer extending back for 13 m, and progressively decomposed from the front of the terrace (Williams 1957a cf. pl. 2). Since the humus layer represented vegetation over-run by the advancing terrace an average movement of 0,3 cm/yr can be postulated for post-glacial time. With the use of specially constructed probes buried in the ground, movement downslope from a snow patch (pl. 1) was recorded as it occurred (Williams 1957b)[1]. Movements of 25 cm took place during the spring thaw, and were detectable to a depth of 75 cm. In contrast, an example of the minor modification of a marginal drainage channel in post-glacial time is shown in plate 2.

So-called rock glaciers, large boulder accumulations which commonly have a "tongue" or "flow"-like form have been investigated by Chaix (*in* Kesseli 1941) and Michaud (1950). Both recorded occasional movements of 100 to 300 cm/yr, although a few cm/yr was common. Debris tongues are smaller features but are also largely composed of loose

[1] A recent paper by Zhigarev (1960), discusses these probes, and describes an instrument constructed by him for a similar purpose. The apparatus described later in the present paper is designed to overcome certain deficiencies of these earlier types.

rock material, and movement of stakes from 2 to 19 cm were recorded in three days (Dege 1943). Gradwell (1957) noted 2 to 8 cm/yr movement downslope in small stone stripes on 2° to 5° slopes. On 10° slopes movement from 10 to 20 cm/yr occur. Miller, Common and Galloway (1954) observed that stone stripes re-formed two years after they had been destroyed. Investigations by Schmid (1955) in a more temperate climate, showed movements of small stones and finer materials of 1 to 1,5 cm/yr down a vegetation free slope.

The many forms of patterned ground are the results of various movements and sorting processes, and the term is usually restricted to features occurring on level or near-level ground. In most cases the cumulative effect of the soil movements in patterned ground is less marked: prolonged development of patterned ground does not give rise to any great depth of moved material, in contrast to that thought to have accumulated at the foot of many solifluction slopes.

Measurements by Black (1960) showed an increase in width of 0,5 to 1 cm/yr in ice wedges in polygonal ground. Maximum rate of movement of marked stones in small stone polygons was observed to be 10 cm/yr by Michaud and Cailleux (1950), also Michaud (1950), in 2 of 6 polygons investigated. Comparison of photographs of stony earth circles taken annually, showed individual movement of small stones of 1 to 2 cm/yr (Williams 1959). It indicated that stony earth circles take 10 or more years to form. No changes could be perceived in successive photographs of frost hummocks over a period of 6 years. The technique has also been used by Sandberg (1960) on several features.

Vialov (1957a and b) has conducted laboratory investigations into the deformation of frozen ground under various temperatures and pressures. His observations of the effect of prolonged loading and the decrease in strength with time indicate an important field of study.

With few exceptions, the measurements made in the field refer only to the surface of the ground. It is apparent that several of the features described above merely involve the disturbance of a shallow surface layer. More significant both from the geomorphological and engineering points of view are the occurrence of downslope movements involving layers of soil perhaps 2 m in depth. Rudberg (1960) has shown the nature of movements which occur down to about 50 cm, by excavation of plastic capsules, buried one above the other to a depth of about 100 cm. An apparatus rather similar in purpose has recently been developed which in addition permits repeated determination of the distribution of movement with depth (or vertical velocity profile).

APPARATUS FOR THE DETERMINATION OF SUBSURFACE MOVEMENTS

A plastic tube about 1,5 cm internal diameter and 0,15 cm wall thickness is buried perpendicular to the ground surface with the top of the tube exposed. It is assumed that soil movement will deform the tube. Curvature of the tube throughout its length is then determined at intervals by the insertion of a specially constructed probe. Ideally, the lower end of the tube should be placed below the maximum depth reached by the movements. An accurate survey of the exposed top of the tube provides one fixed point. If the tube is inserted straight and any inclination measured the position of the base is also established.

The probe is cylindrical and of approximately the same diameter as the internal diameter of the plastic tube. Made of an epoxy resin it includes a spring steel strip of about 0,1 cm thickness, on which are mounted electrical resistance strain gauges (fig. 1). Any curvature of the probe sets up a strain in the steel strip which is detected by the strain gauges. It can be shown that, with slight approximation, the strain set up in the strain gauges is proportional to the curvature of the steel strip and hence of the probe.

Leads from the gauges pass along a narrow semirigid tube attached to the probe and of suitable length, and are led into a resistance measuring bridge placed on the ground surface [2]. The resistance of the strain gauges is proportional to the strain, and with the aid of a calibration table the bridge readings are easily converted into a measure of curvature.

To determine the longitudinal profile of the tube a series of readings are taken with the probe at successive positions up the tube. By integration

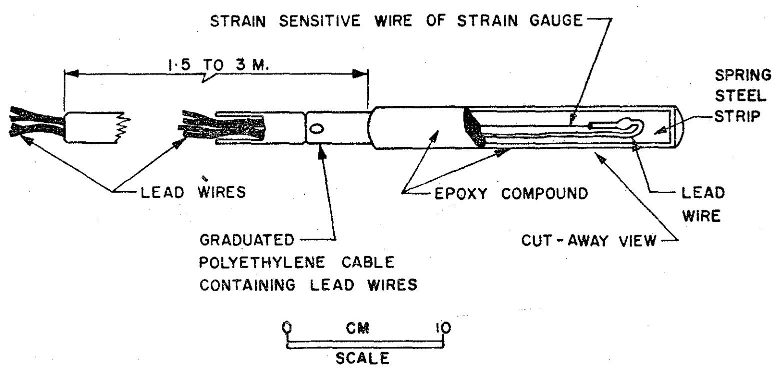

Fig. 1. Probe for determination of shape of buried tubes

[2] A number of portable bridges are produced especially for use with strain gauges.

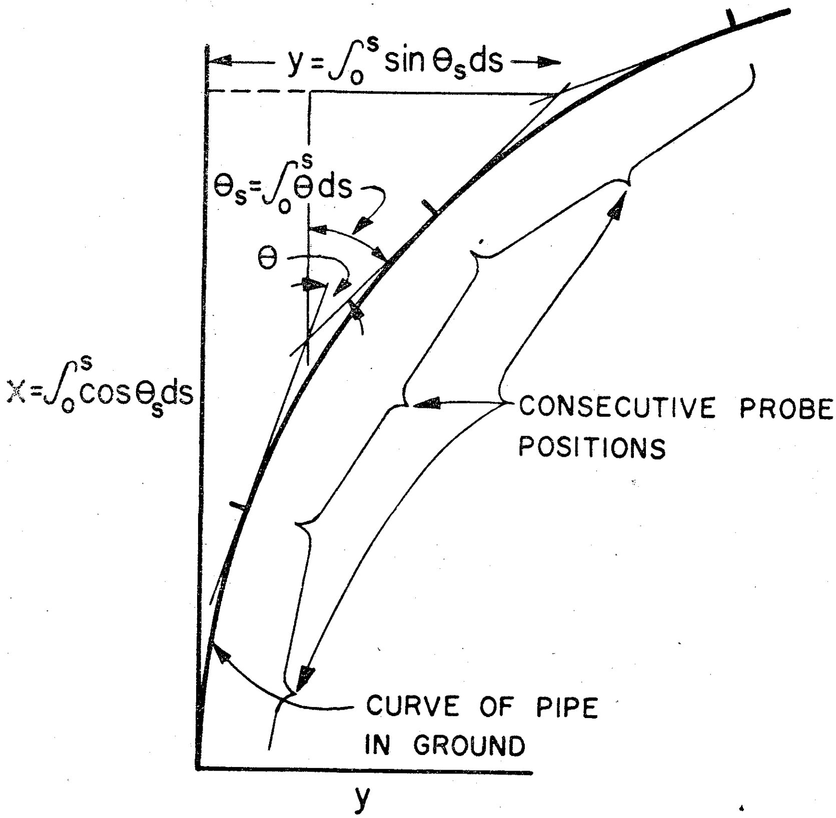

Fig. 2. Diagram illustrating calculation of results, showing short lenght of tube

of the readings the shape of the tube is reconstructed. The calculations are illustrated in figs. 2 and 3. The co-ordinates X and Y are obtained for successive points up the tube and these are plotted to give the shape of the tube.

There are inaccuracies inherent in the use of this method of determining the shape of the tube. The most satisfactory length of the probe has been found to be about 20 cm. Probes of this length cannot give a true value if the curvature is at all irregular. Constrictions of the tube and difficulties associated with the use of fairly sensitive electrical equipment under field conditions also lead to a certain scatter in the readings. A pair of gauges is used in each probe to compensate for possible errors due to changes of temperature. Figure 4 shows four series of determinations made on the same tube at one time, and illustrates the reproducibility of the readings. By drawing in the curve which most nearly corresponds to all four series, in most cases a reasonable representation of the shape of the tube is obtained. If the positions of the probe down the tube are changed by $\frac{1}{4}$ of the probe lenght, for each of the four series, possibility of error due to irregularities of curvature is reduced. If the position of the ends of the tube are known, and the reconstructed curve fitted to these, errors of under 15% are usually obtained in the Y co-ordinate. For most cases where movements are of the order of cm/yr observations of this accuracy have significance at the present time, while the nature of the vertical velocity profile (whether concave or convex downslope) and the depth to which movement occurs are equally of interest.

This method further assumes that deformation of the tube corresponds to the movement of the adjacent soil. From simple theoretical considerations (Williams 1957) this appears probable. Were movements of the soil to take place by development of shear planes the tube could not satisfactorily illustrate this. Rudberg's (1960) investigations with separate capsules provided supporting evidence of the absence of significant shear planes in one type of solifluction.

Twelve plastic tubes have been placed on various slopes in the Schefferville area of Labrador, Canada. Over two years, no movement except some minor displacements due to winter ice growth has been detected in any tubes placed in a steep slope, where adjacent alders and spruces showed markedly deformed trunks and branches. Other investigations showed that the latter was due to the creep of large masses of snow in winter (Andrews 1960). Several tubes placed in a peculiar lobe-like feature whose origin was in doubt have indicated movements of several centimetres near the surface (cf. fig. 4).

Many tests of alternative methods of design of the probe and of interpretation of results have been made and will be reported elsewhere, but the apparatus as described has proved the most satisfactory. Some further modifications to the probe design are envisaged, which may facilitate its use and the attainment of greater accuracy.

PROBE POS	STRAIN READING	θ (FROM CAL. TABLE)	$\theta_s = \int_0^s \theta ds$	$\cos \theta_s$	$X = \int_0^s \cos \theta_s ds$	$\sin \theta_s$	$y = \int_0^s \sin \theta_s ds$
0	000	0° 0'	0° 0'	1·0000		0000	
1	-·115	2° 48'	2° 48'	·9988	1·0000	·0488	0000
2	-·223	4° 24'	7° 12'	·9921	1 9988	·1253	·0488
3	-·159	3° 26'	10° 38'	·9828	2·9909	·1846	·1741

Fig. 3. Example of calculation of results

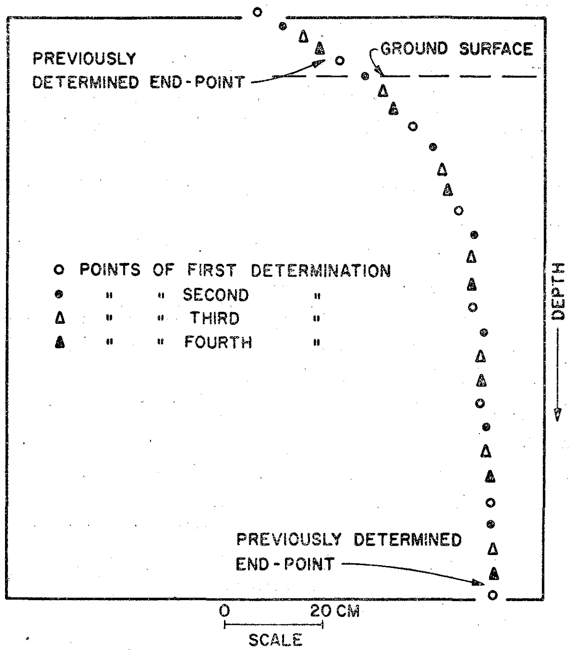

Fig. 4. Four determinations of the shape of a buried tube made on the same occasion at Schefferville, P.Q.

The positions of the points are adjusted to fit the known end--points of the tube. (The shape of the tube is represented by that line most nearly corresponding to all four determinations)

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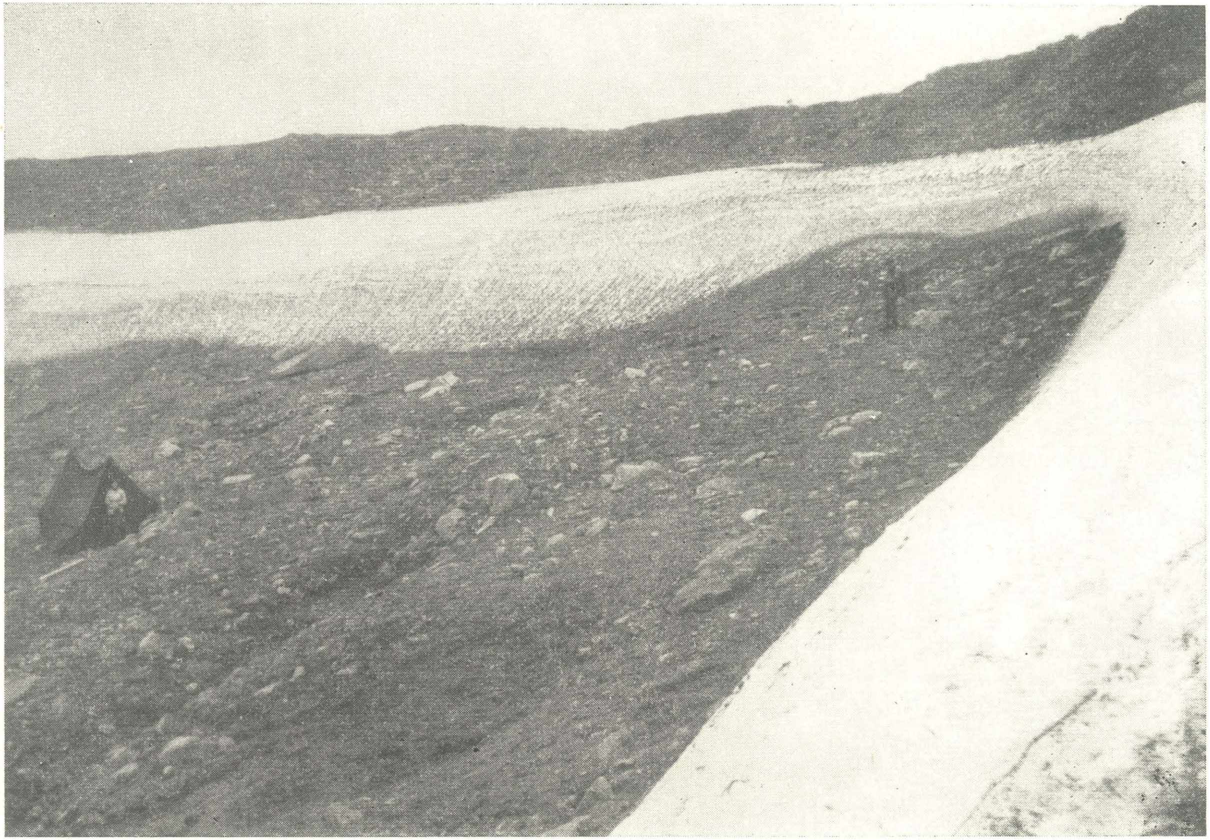
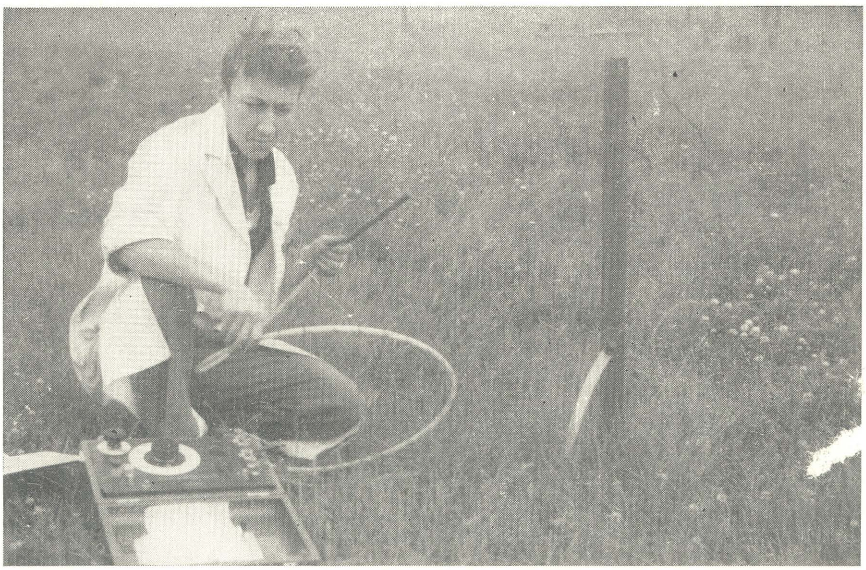


Pl. 1. Solifluction downslope of late-lying snow patch. Movements of 25 cm were recorded during spring

Pl. 2. Modification of ice-marginal drainage channel by solifluction, Ilmanndalen, Rondane, Norway



Pl. 3. Apparatus for determining subsurface movements. The top of the buried tube is seen near the post; the man is holding the probe