Borehole creep and relaxation tests in ice-rich permafrost

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The experience gained with the pressuremeter creep tests in the last ten years shows that, because of the equipment limitations, one such test can furnish creep data only for relatively short creep times and for a medium range of stress.

Borehole relaxation tests are the alternative to borehole creep tests in the determination of the creep parameters of frozen soils. Their advantage is that the strain is controlled and the stress variation observed, so that there is no danger of exceeding the volume capacity of the cell. Consequently, borehole relaxation tests can easily cover the area of low stresses and can be performed for long periods of time.

The question arises, however, whether the creep parameters deduced from creep and relaxation tests, respectively, are equivalent. A field study, carried out recently at a permafrost site near Inuvik, N.W.T., attempted to answer this question and the principal results of that study are discussed.

Une série d'essais de dilatation de trous de sonde ont été effectués dans du pergélisol riche en glace à Inuvik (T.N.-O.) à l'aide du pressiomètre de Ménard et du dilatomètre de la *Colorado School of Mines* (CSM). Le pressiomètre a été employé pour effectuer des essais à court terme à charge étagée sous contrainte contrôlée et des essais de fluage sous contrainte constante. La cellule CSM a été employée pour effectuer des essais de déformation contrôlée sous charges et retraits de charge étagés et des essais de détente des contraintes. Les paramètres de fluage dérivés des essais de fluage à court terme et des essais de détente des contraintes se comparaient favorablement si l'on considère que des instruments différents ont été utilisés pour les deux types d'essais.

Quoiqu'il soit possible d'effectuer des essais de fluage et de détente des contraintes à long terme dans des trous de sonde dans le pergélisol en procédant avec soin, on a conclu que les résultats doivent être interprétés prudemment et que des travaux complémentaires sont nécessaires afin d'établir si les paramètres de fluage déduits de ces essais sont valides quant à la prévision à long terme du comportement des fondations dans le pergélisol.

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Introduction

Since 1971, several field studies of creep behaviour of frozen soils have been carried out by the author and his collaborators in permafrost regions of Northern Canada. Until very recently, these studies consisted essentially of performing borehole creep tests with the Ménard pressuremeter equipment with the purpose of deducing from them certain basic creep parameters of frozen soils. The procedure used in these studies remained basically the same as that described by Ladanyi and Johnston (1973, 1978).

The experience gained with the pressuremeter creep tests shows that, because of the total volume limitation of the pressuremeter cell, a stage-loaded creep test, with several stages as required for test interpretation, can furnish creep data only for relatively short creep times and for a medium range of stress.

In principle, this limitation can be overcome by performing several closely spaced tests, each of them step-loaded to a different stress level and left to creep for long periods of time. In practice, however, the results of such tests are difficult to combine together because of the variability of properties of frozen soil, even at small distances.

Since the main obstacle to performing long-term stage-loaded borehole creep tests appears to be the limited volume of the cell, one possible solution might be to modify the cell design so that the cell could sustain a larger volume increase without changing its cylindrical shape. This problem, however, has not yet been solved in a satisfactory manner.

Another way of getting the long-term creep information consists in replacing the creep tests by borehole relaxation tests. The advantage of the latter is that, in such tests, it is the strain which is controlled while the stress variation is observed, so that the volume capacity of the cell is never exceeded. As a consequence, borehole relaxation tests can cover easily the area of low stresses and long periods of time.

The question arises, however, whether the creep parameters deduced from creep and relaxation tests, respectively, are comparable. This is the main question which a field study carried out recently at a permafrost site in Inuvik attempted to answer. In this paper the principal results of that study are shown and discussed.

Although the results obtained from the two types of tests were fairly encouraging, it is felt, nevertheless, that a definite answer as to the validity and relative merit of different types of borehole dilatometer tests can only be obtained if a systematic comparative study of such tests is made under well-controlled laboratory conditions. With this idea in mind, several borehole relaxation tests were carried out recently in thick cylinders of ice and their tentative theoretical interpretation was given (Ladanyi *et al.* 1978; Ladanyi 1979*a*). Similar tests are presently underway in thick cylinders of frozen sand.

Theory of Borehole Creep and Relaxation Tests

Elastic Behaviour

If a borehole of radius r_i (Appendix), located in an infinite medium, is expanded or contracted elastically, due only to a change Δp_i of the internal stress p_i, the resulting radial displacement of the cavity wall will be from the Lamé's theory (positive for hole increase under increasing p_i):

[1] $\Delta r_i / r_i = \Delta p_i / 2G$

where

[2] $G = E/2(1+\nu)$

is the shear modulus.

From a measured Δr_i, resulting from Δp_i, the value of G is then

[3] $G = \Delta p_i / 2(\Delta r_i / r_i)$

or, in terms of the volume change of the borehole ΔV, when the Ménard pressuremeter is used

[4] $G \approx \Delta p_i / (\Delta V / V)$

where V is the current volume of the measured length of the cavity (Ladanyi and Johnston 1973).

Failure

All these formulas are clearly valid only until the medium starts failing either by radial cracking, or by plastic zone formation. It can be shown that, in an elastic medium, radial cracking will start when the circumferential stress at the cavity wall attains the tensile strength of the material, which happens when

[5] $p_i \geqslant 2p_o + |T_s|$

where p_o denotes the original horizontal ground pressure, and $|T_s|$ is the absolute value of the tensile strength of the material.

On the other hand, in a Coulomb (c, ϕ) material, which fails in shear rather than in tension, it is easy to show that a plastic zone will be initiated as soon as:

[6] $$p_i \geqslant \frac{2p_o f + c(f-1)\cot\phi}{f+1}$$

where

[7] $f = (1 + \sin\phi)/(1 - \sin\phi)$.

Creep

For an ice-rich frozen soil or ice, the total strain attained after a given time under constant stress can be expressed by

[8] $\varepsilon_e = \varepsilon_e^{(i)} + \varepsilon_e^{(c)}$

where $\varepsilon_e^{(i)}$ is the instantaneous, not necessarily elastic, portion of the total strain, and $\varepsilon_e^{(c)}$ is the creep strain given by

[9] $\varepsilon_e^{(c)} = (\dot{\varepsilon}_c / b)^b (\sigma_e / \sigma_c)^n t^b$

where the subscript e denotes the von Mises equivalent stress and strain, σ_c is the creep modulus corresponding to the strain rate $\dot{\varepsilon}_c$, t is the time, and b and n are creep exponents.

If equation 9 is applied to a problem of an expanding cylindrical cavity in an infinite medium, originally acted upon by an isotropic lateral stress p_o, the radial creep strain rate under a constant stress $p_i > p_o$ is found to be (Ladanyi and Johnston 1973):

[10] $\mathrm{d}r_i/\mathrm{d}t = r_i F b t^{b-1}$

where F is a function of $(p_i - p_o)$, given by

[11] $F = (M/2)[(p_i - p_o)/\sigma_c]^n$

and

[12] $M = 2(\sqrt{3}/2)^{n+1} (\dot{\varepsilon}_c / b)^b (2/n)^n$.

In a stage-loaded creep test, if p_i is the stress applied in the borehole during the stage k, following a smaller stress in the previous stage (k - 1), the resulting radius increase with time is given by

[13] $\ln(r_i / r_{i,k-1}) = F t^b$

or, in terms of the borehole volume

[14] $\ln(V/V_{k-1}) = 2Ft^b$

where $V = \pi r_i^2 L$ is the current volume of the cavity of length L.

Finally, the value of σ_c is given by

[15] $\sigma_c = (p_i - p_o)_N [M/(2F)_N]^{1/n}$

where M is given by equation 12, while $(2F)_N$ denotes the value of $(2F)$ at an arbitrary point $(p_i - p_o)_N$, located on a $(2F)$ vs. $(p_i - p_o)$ straight-line segment in a log-log plot, (Figure 1).

Relaxation

(i) *Method Based on the Aging Creep Theory*: One of the simplest ways for finding from borehole relaxation tests the time-dependent deformation and strength parameters, is to consider that there is a unique and continuous surface in space, relating stress with strain and time. This assumption is known

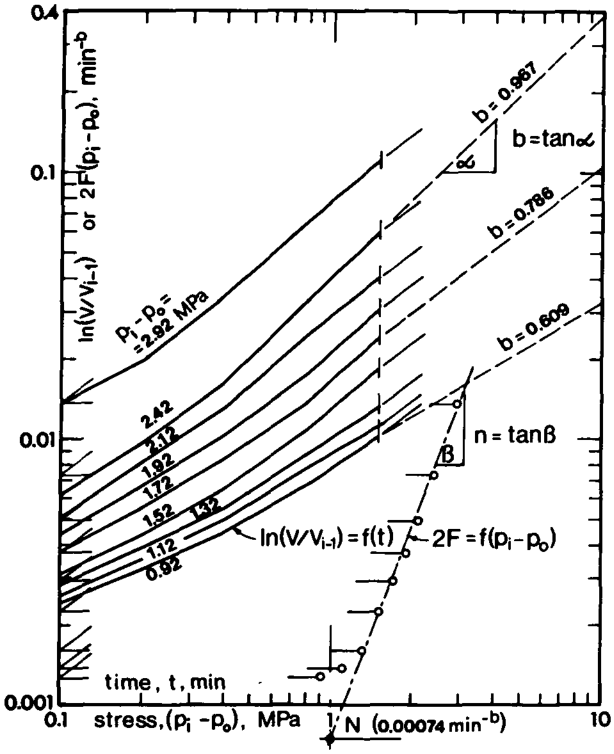

FIGURE 1. Stage-loaded pressuremeter test 214, with 15 min per stage: creep parameter determination.

as the basis of the simplest type of the aging (time-hardening) theory of creep. According to Rabotnov (1966), "relaxation curve predictions based on aging theory are rather poor, but not so bad as to be in severe disagreement with practice".

In borehole relaxation testing, the aging theory can be used in two different manners. In the first one, a step-strained borehole relaxation test is used to generate a series of time-dependent pressure-expansion curves, from which the time-dependent moduli and strength parameters can be deduced by means of a conventional pressuremeter curve interpretation method (e.g., Ladanyi 1979*c*). The second one consists of using the observed borehole relaxation curves for finding the numerical values of some basic creep parameters of the soil. In the aging theory, it is assumed that creep and relaxation are closely related, so that a relaxation curve is nothing else but a creep curve under a continuously decreasing stress, resulting in a constant value of strain. In other words, according to this assumption, any constitutive creep equation can be transformed directly into a relaxation equation by making the creep strain constant and equal to the applied initial strain. In that theory, no consideration is given to the fact that the applied strain may be partially elastic and that the material may have a different behaviour in loading and in unloading. Nevertheless, in spite of these drawbacks, the theory has been found many times in the past to be a useful tool for generalizing the results of stress relaxation tests. For example, in unfrozen soil mechanics literature, this method was used with success by Lacerda and Houston (1973) for describing the results of relaxation tests, carried out on three types of unfrozen soils in triaxial apparatus.

The following method for interpretation of borehole relaxation tests in ice-rich frozen soils, which was first shown by Ladanyi *et al.* (1978), has been found to be simple and easy to use in practice.

According to the aging creep theory, a creep process can be expressed by a family of isocurves (Rabotnov 1966), given by

[16] $\varphi(\varepsilon) = \sigma \cdot \Psi(t)$

where $\varphi(\varepsilon)$ is a strain function, σ is stress, and $\Psi(t)$ is a time function. For including the instantaneous response, it is required that $\Psi(O) = 1$. According to this creep theory, the stress relaxation is then given by

[17] $\sigma = \varphi(\varepsilon)/\Psi(t)$

If, however, one wants to retain the same form of the time function as that contained in equation 9, the condition $\Psi(O) = 1$ cannot be satisfied, but should be replaced by $\Psi(t') =$ constant, where t' is a very short time interval in which the response of the structure is taken to be non-linear elastic. This assumption implies that, at any point and time, the total strain is equal to the sum of a pseudo-elastic strain, corresponding to t', and a creep strain, corresponding to t, where t is the real time. Adopting a similar strain measure as in Ladanyi and Johnston (1973), one can then write for an expanding cylindrical cavity (Ladanyi *et al.* 1978):

[18] $[\ln(V/V_o)]^{1/n} = M^{1/n}[(p_i - p_o)/\sigma_c](t' + t)^{b/n}$

(Note that, for small strains, say for $\Delta V/V < 5$ per cent, and for plane strain, the large strain measure $\ln(V/V_o)$ may be replaced by $\ln(V/V_o) \approx \Delta V/V \approx \gamma \approx 2\varepsilon_1$, where γ is the engineering shear strain). From equation 18 it follows that the family of relaxation curves is defined by

[19] $$(p_i - p_o) = \sigma_c \left[\frac{\ln(V/V_o)}{M(t' + t)^b} \right]^{1/n}$$

where M is given by equation 12.

If the relaxation curves are plotted against the real time t instead of $(t' + t)$, (*in* Figure 6 and 7), they come close to equation 19 only when $t' << t$. For example, if one takes $t' = 0.1$ min, one finds that, at the end of any 15-minute interval, t' is less than

0.7 per cent of t, and the curves are sufficiently accurate for parameter determination.

It will be seen from equation 19 that, when such relaxation curves are plotted in a log $(p_i - p_o)$ vs. log t plot with the strain ln (V/V_o) as the parameter, their slope at the end of interval gives

$$[20] \quad \frac{b}{n} = -\frac{\Delta \log(p_i - p_o)}{\Delta \log t} = \frac{v}{h} \text{ (\textit{in} Figure 6).}$$

On the other hand, if at the same end of interval, where $t = t_i =$ constant, one plots log [ln(V/V_o)] vs. log $(p_i - p_o)$ (*shown superimposed in* Figures 6 and 7) the slope of the line gives:

$$[21] \quad n = \frac{\Delta \log[\ln(V/V_o)]}{\Delta \log(p_i - p_o)} = \frac{h_1}{v_1} \text{ (\textit{in} Figure 6).}$$

When b and n are known, the value of σ_c (for a given $\dot{\varepsilon}_c$) can be determined from any point k on the line ln (V/V_o) vs. $(p_i - p_o)$, by using equation 19:

$$[22] \quad \sigma_c = (p_i - p_o)_k \left[\frac{M\, t_i^b}{\ln(V/V_o)_k}\right]^{1/n}$$

As an additional feature, when equation 19 is applied to two consecutive points of a relaxation curve with co-ordinates (t_1, p_{it1}) and (t_2, p_{it2}), this enables the value of the lateral ground stress to be calculated from

$$[23] \quad p_o = \frac{(t' + t_2)^{b/n} p_{it2} - (t' + t_1)^{b/n} p_{it1}}{(t' + t_2)^{b/n} - (t' + t_1)^{b/n}} \approx \frac{(t_2/t_1)^{b/n} p_{it2} - p_{it1}}{(t_2/t_1)^{b/n} - 1}$$

This formula is clearly valid only for a non-linear viscous behaviour without failure. Moreover, as the determination of a true b/n value requires the knowledge of p_o, the calculation is in fact iterative.

(ii) *Method Based on the Flow Creep Theory*: Compared with the previous solution, the relaxation solutions based on the flow creep theory assume more correctly that, at any moment of a relaxation test, the total strain is always a sum of a creep strain and an elastic strain, the former being continuously transferred to the latter, so that their sum remains constant.

A complete theory of the borehole relaxation test in a thick-walled cylinder, made of a linear-elastic, non-linear viscous material, was developed by Ladanyi (1979*a*), in connection with the borehole relaxation tests in ice. The analysis enabled the creep parameters of ice to be deduced from the tests by using a modified version of the "Reference Stress Method", known in the metal creep literature.

The theory is valid for any material which has a linear-elastic instantaneous response to loading, followed by a non-linear Maxwell type of creep, and which is also linear-elastic during unloading, all independent of the hydrostatic pressure. Experience shows that the behaviour of freshwater ice at temperatures below about $-5°C$ may fit into that category, and this is probably also valid for ice-rich frozen soils at low temperatures.

Finally, it is useful to note that, if the tests are not made in the field, but rather in thick cylinders of frozen soil in a cold room, all the described procedures of parameter determination from creep and relaxation tests remain valid, provided σ_c in equations 15, 18, 19, and 22 is replaced by $m\, \sigma_c$, where

$$[24] \quad m = 1 - (r_i/r_e)^{2/n}$$

and r_e denotes the external radius of the cylinder.

Results of Field Tests

In the summer of 1978, a study of short- and long-term properties of frozen soils was made by the author at a permafrost site near Inuvik, N.W.T., for the National Research Council of Canada. In the study, two kinds of instruments were used: the Ménard Pressuremeter and the CSM Cell dilatometer. Since a detailed description of the site and the instrumentation used in the tests was given by the author in a report (Ladanyi 1979*b*), and in a recent publication (Ladanyi 1979*c*), together with the analysis of all short-term results, this paper will be limited only to the description of creep and relaxation tests and the comparison of their results.

It should, nevertheless, be noted that all the tests have been performed in the depth interval of 1.5 to 2.0 m below the ground surface in an ice-rich soil composed of fine-grained silts and clays. The permafrost table at the site is at about 90 cm below the surface. During the tests, (16 to 31 July, 1978) the ground temperature in the depth interval covered by the tests varied from $-1.5°C$ at 1.5 m to $-2.1°C$ at 2.0 m. During the two-week testing period, the ground temperature decreased by about 0.3 to 0.4°C.

Borehole Creep Tests

These tests were performed with conventional Ménard pressuremeter equipment and a cell of 6-cm diameter with a volume injection capacity of 700 cm^3 and a pressure capacity of 10 MPa.

Altogether, 11 borehole creep tests have been carried out at the site. Among these, three were stage-loaded with 15 min per stage, one was stage-loaded with 60 min per stage, while the remaining seven tests were medium- and long-term creep tests with creep periods of up to, and over, 24 hours in one stage.

Table 1 presents a review of data obtained in these tests. A new hole was drilled for each test, all of them

TABLE 1. Results of pressuremeter creep tests, Inuvik, 1978

Test no.	Depth m	T_{soil} °C	b	b_{av}	n	σ_c ($\dot{\varepsilon}_c = 10^{-5}$/min) MPa	Creep pressure range MPa	Max. time per stage, min	Average loading rate, MPa/min	Range of strain rates, 10^{-3}/min	c MPa	T_s MPa	G MPa
201	2.18	−2.25	0.200				0.58	900					
203	2.26	−2.40	0.549				2.48	240					
205	2.10	−2.20	0.564				1.98	150					
206	1.78	−1.90	0.434				1.48	1310					
208	2.50	−2.50	0.486				0.98	1320					
211	1.98	−2.05	0.523–1.00	0.746	2.430	0.551	0.75–2.35	15	0.0133	0.3–4.3	0.69	−0.73	42.5
214	2.02	−2.10	0.609–0.967	0.786	2.655	0.431	0.95–2.95	15	0.0133	0.7–5.6	0.69	−0.10	36.0
216	1.78	−1.85	0.568–0.895	0.688	2.370	0.734	0.95–2.45	60	0.0333	0.4–1.8	0.69	−0.27	42.6
217	1.90	−2.00	0.377				0.95	1590					
218	1.90	−2.00	0.591–0.729				1.95–2.45	60–75					
219	2.10	−2.20	0.383–0.846	0.780	2.837	0.446	0.95–2.85	15	0.0333	0.6–5.7	0.69	−0.36	38.0

within a circle of less than 100 m in diameter. The depth of the tests varied between 1.5 and 2.26 m, which corresponds to the ground temperature range from −1.5°C (at 1.5 m) to −2.40°C (at 2.26 m). According to the samples taken from some of the boreholes, the soil at that depth is an ice-saturated clayey silt with ice content of 50 to 100 per cent by weight, which corresponds to bulk densities of 1.37 to 1.64 g/cm^3, and dry densities of 0.69 to 1.09 g/cm^3.

Determination of Creep Parameters

The creep information from some typical pressuremeter tests carried out at the site, is shown in Figures 1 to 3. In these figures, the logarithmic creep strain measure, ln (V/V_{i-1}), is plotted against time, t, in a log-log plot. In such a plot, creep curves at each stage most often become linear, which enables the data to be expressed in the form of a general creep equation, such as equation 9.

The procedure for determining the creep parameters b, n, and σ_c from a stage-loaded creep test summarized in the foregoing, has been described in detail elsewhere (Ladanyi and Johnston 1973, 1978).

For the four creep parameters, determined from three 15-min and one 60-min stage-loaded tests, (*see* Table 1) it will be seen that, within the creep pressure range of 0.75 to 2.95 MPa, the exponent b showed an increase with increasing pressure from about 0.38 to 1.00. For determining the values of n and σ_c, an average value of b was adopted. These average values of b (*see* Table 1) are found to vary approximately between 0.7 and 0.8. A general average value for the four stage-loaded tests is $b = 0.75$.

Two remarks should be made here concerning the exponent b. First of all, each creep curve in the log-log plot is not exactly a straight line, but has usually an S-shape. The slope increases during the first 4 min, then remains constant until about 30 min, and finally slightly decreases, especially at lower pressures. This is seen clearly in the 60-min test (*see* Figure 2) as well as on certain long-term creep lines (*see* Figure 3). This means that, by taking an average slope at 15 min, as it is usually done, one might actually overpredict long-term creep strains. Secondly, there is a clear tendency of b to increase with pressure. If one takes an average value of b in the middle of the pressure range,

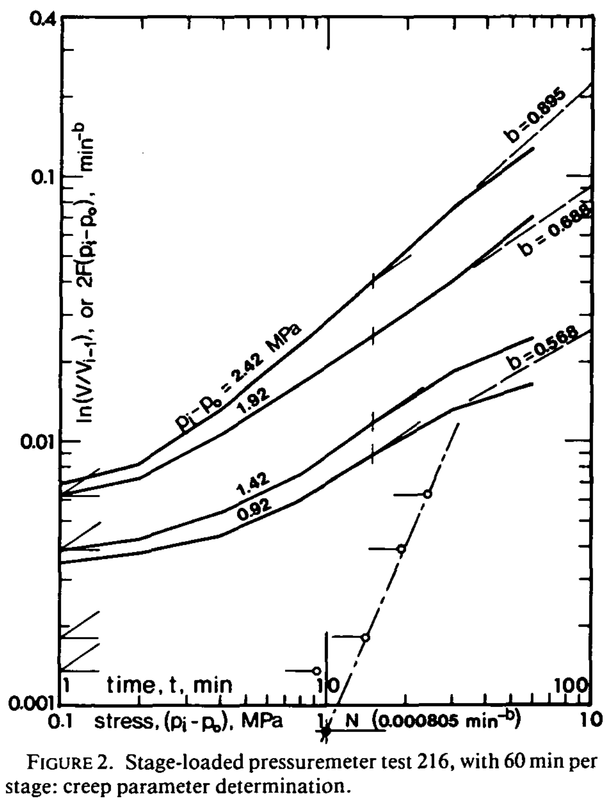

FIGURE 2. Stage-loaded pressuremeter test 216, with 60 min per stage: creep parameter determination.

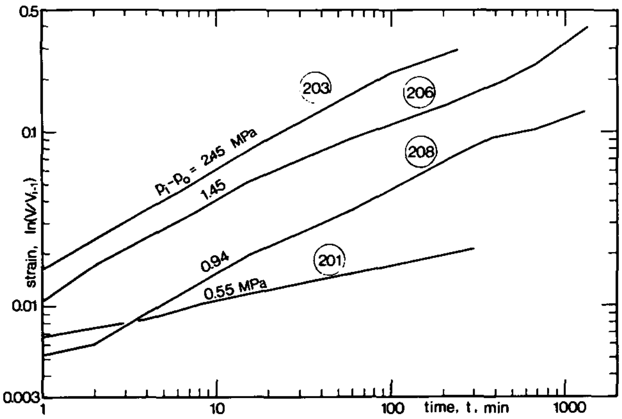

FIGURE 3. Long-term pressuremeter creep tests.

one may overpredict creep strains at low pressures and underpredict them at higher pressures. One possible solution to this problem is to make the exponent b stress-dependent. This would, however, make any direct solution of practical problems rather difficult. Another practically more-acceptable solution is to find separate average values of the three creep parameters for low, middle, and high stress range, respectively, and use those which correspond to the stress range expected in the considered problem. The values of n and σ_c (*see* Table 1) correspond to b average, but it is clear that, from some curves (*as in* Figures 1 and 2), one can get also the values of n and σ_c corresponding to either low or high stress range.

The range and average values of parameters n and σ_c (*see* Table 1) are seen to be:

$$2.37 < n < 2.84, \; n_{av} = 2.57$$
$$0.446 < \sigma_c < 0.731 \text{ MPa}, \; \sigma_{c,av} = 0.541 \text{ MPa, for } \dot{\varepsilon}_c = 10^{-5}/\text{min}$$

Long-term Creep Tests

One of the tasks of this investigation was to conduct long-term tests for long periods of time and over a wide range of loads.

For this purpose, it was first attempted to carry out a stage-loaded test with much longer times per stage. Tests with 30 min per stage have been made before, but one test was made with 60 min per stage (*see* Figure 2), which is probably the limit that can be attained with this equipment if one wants to have at least four stages without exceeding the inflation capacity of the pressuremeter. That test showed that, while at high stresses 15 min per stage may be quite enough, in the low stress range even 60 min creep might still be too short, if one wants to apply the power-law approximation to the creep curves. For low stress range, however, the power law might not be the best solution, and a hyperbolic approximation would probably give a better fit, because, at low stresses, below the long-term strength limit, one can expect to get an attenuating creep and not necessarily continuously increasing creep strains, as implied by a power law.

Four one-stage creep tests were carried out at a wide range of stresses (*see* Figure 3). In some of them it was tried to get over the 24-hour mark, but it usually happened that, during the night, the groundwater from the active layer filled the hole and froze around the probe. This shows that the month of July is not the best time for doing such long-term tests at that site because of the water inflow. A much better situation for such tests would be in April, when the active layer is still frozen.

Nevertheless, these long-term creep tests showed some quite interesting results. Firstly, the creep lines seemed to retain their general slope after 15 min which gives some support to the power-law extrapolation of creep curves. Secondly, the test 201 at 0.55 MPa net pressure, had such a small slope (b = 0.20) that it could have gone for several weeks or even months, had there not been the trouble of water freezing in the borehole. In other words, it is seen that, in spite of its limitations, the pressuremeter can be used without difficulty for long-term creep testing at low pressures, under favorable field conditions.

Borehole Relaxation Tests

These tests were performed with the Colorado School of Mines (CSM) Dilatometer equipment. The dilatometer has a single cell 3.8 cm in diameter and 16.5 cm long which can be inflated by injecting a controlled volume of liquid to increase its original diameter by up to 15 per cent. The system is rated at a pressure capacity of 70 MPa.

In the tests, the volume of the cell was increased in steps and, after each step, the drop of pressure with time was recorded by reading a Bourdon gauge.

Altogether six relaxation tests were carried out with this equipment at the site. Of these, four were multistage medium-term tests with 15 or 30 min per stage, while the remaining two were actually the end stages of short-term loading tests.

Usually, a new hole was drilled for each new test. The depth of the tests varied from 1.52 to 2.13 m, which corresponds to the ground temperature range of −1.52 to −2.2°C. The holes were drilled with a special stainless-steel auger of 3.81-cm diameter, producing clean holes closely fitting the cell.

Before each test, the system was calibrated to determine the volume correction (Hustrulid and Hustrulid 1975), while the membrane correction was determined by expanding the probe outside the hole, similarly as in the case of a pressuremeter. The two corrections were slightly temperature dependent.

More details about the calibration in the present tests can be found in Ladanyi (1979*c*).

A summary of all the results of these tests is shown in Table 2, and certain typical results are presented in Figures 4 to 7.

As mentioned before, four stage-strained relaxation tests were performed: Tests 305 and 307 with four 30-min stages, and tests 309 and 310 with six 15-min stages. The results of these tests were plotted in two different manners. The results of two of the tests (*see* Figure 4) are shown as a set of isochronous dilatometer curves, relating the corrected stress p_i with the logarithmic strain measure $\ln(V/V_o) \approx \Delta V/V \approx \gamma \approx 2\,\varepsilon_1$, with the time as a parameter. As, according to the aging theory, each of these isochronous curves can be treated as a separate pressure-expansion curve, these plots enable one to determine the variation with time of the peak and residual cohesion strength of the soil. These can be determined from the straight-line portions of each isochronous curve, because from any two successive points, i, $i+1$, the mobilized cohesion $c_{i,i+1} = \Delta p_{i,i+1} / \Delta \ln(\Delta V/V)_{i,i+1}$ (*see* Figure 5).

Another way of representing the same data is to plot stress against time, with strain as a parameter (*see* Figures 6 and 7). If the aging (time-hardening) theory is adopted, these plots can serve as a basis for the determination of creep parameters, using the method proposed by Ladanyi *et al.* (1978) (*see* equations 20 to 22 in this paper).

The relaxation lines (*see* Figures 6 and 7) are seen to be remarkably close to straight lines and parallel to one another, which enabled one to determine reliable values of the b/n ratios (*see* Table 2). As shown in Figure 8, this straight-line shape of the relaxation curves in the log-log plot seems to continue for much longer times, probably exceeding 15 hours. Unfortunately, as in the case of pressuremeter tests, freezing of water in the boreholes prevented carrying the tests over-night.

The superimposed $\ln(V/V_o)$ vs. $(p_i - p_o)$ lines (*see* Figures 6 and 7) show some change in slope, giving smaller values of n at low strains and larger values in the high strain range. The values of n (*see* Table 2) correspond to the slopes of tangents to these curves in the middle of the strain range. From b/n and n values, the resulting b values are also shown (*see* Table 2), together with σ_c values calculated from equation 22 at the points of the curves indicated by a larger circle.

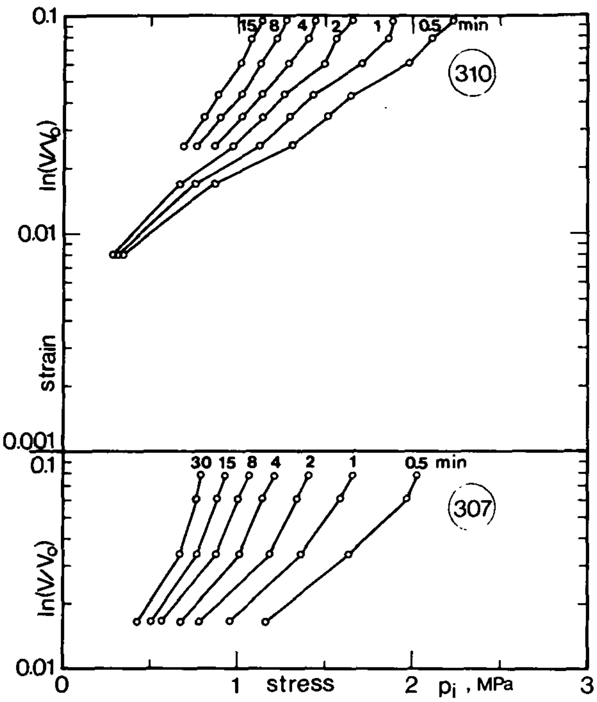

FIGURE 4. Results of stage-loaded dilatometer relaxation tests, plotted as isochronous dilatometer curves.

The values of the three creep parameters deduced from these four tests vary as follows:

$0.473 \leqslant b \leqslant 0.939$, with $b_{av} = 0.633$
$2.25 \leqslant n \leqslant 4.61$, with $n_{av} = 3.205$
$0.134 \leqslant \sigma_c \leqslant 0.459$ MPa , with $\sigma_{c,av} = 0.329$ MPa
for $\dot{\varepsilon}_c = 10^{-5}$/min.

TABLE 2. Results of dilatometer relaxation tests, Inuvik, 1978

Test No.	Depth (m)	T_{soil} (°C)	b/n	b	n	σ_c ($\dot{\varepsilon}_c = 10^{-5}$/min) MPa	Relaxation pressure range MPa	Time per stage, min	Max. relax. time, min	Average strain rate, 10^{-3}/min	G_i MPa	c_{max} (1-minute curve) MPa	c_{res} (1-minute curve) MPa
305	2.13	−2.20	0.204	0.939	4.61	0.134	2.17–0.82	30	30	0.6	150.0	0.556	0.347
307	1.88	−2.00	0.204	0.620	3.04	0.267	2.03–0.43	30	240	0.6	46.6	0.580	0.215
309	1.52	−1.52	0.211	0.473	2.25	0.454	1.90–0.53	15	120	1.2	33.3	0.650	0.300
310	1.78	−1.80	0.171	0.500	2.92	0.459	2.24–0.68	15	300	0.6	51.1	0.720	0.480
312	1.63	−1.70	0.202				0.70–1.64	1	308	9.2 or 17.3	61.7	0.573	0.443
314	1.64	−1.60	0.213				0.23–2.17	1	1482	3.7 or 9.0	48.3	0.580	0.290

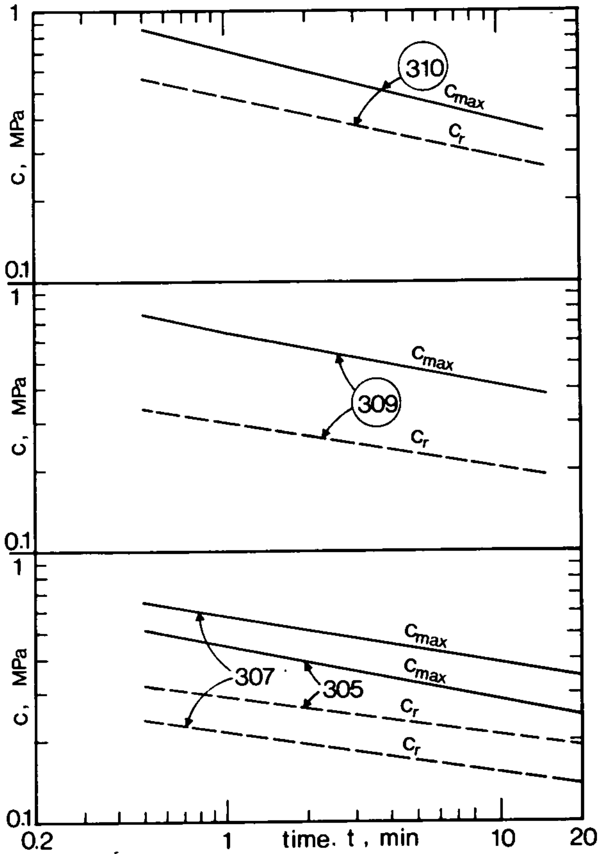

FIGURE 5. Dilatometer relaxation tests: decrease of peak and residual cohesion with time. (From isochronous curves).

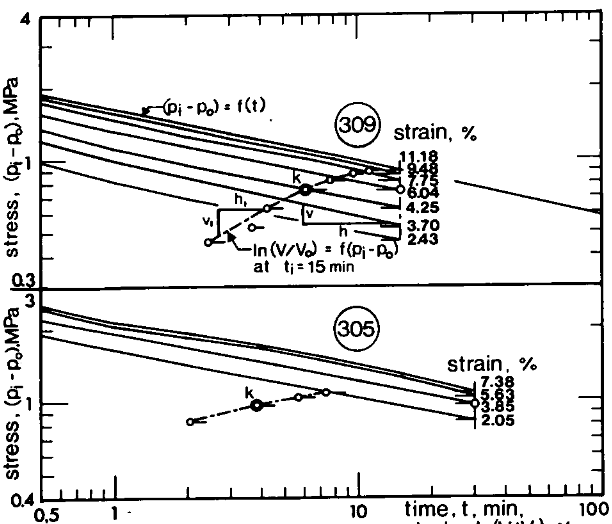

FIGURE 6. Dilatometer tests: relaxation curves from stage-loaded tests.

If one takes away test 305, which seems to fall outside of the normal range, the variation of the parameters is much smaller, and the averages become $b_{av} = 0.531$, $n_{av} = 2.74$, and $\sigma_c = 0.393$ MPa.

The latter average values are closer to those deduced from pressuremeter creep tests, ($b = 0.750$, $n = 2.57$, $\sigma_c = 0.54$ MPa) but still, from relaxation tests, b and σ_c come out smaller and n slightly larger than from creep tests. Whether this difference is due to different kinds of tests, different types of apparatus, different theoretical interpretations, or is simply due to the small number of tests, to these questions only a future, more systematic, comparative study under controlled conditions could give a more definite answer.

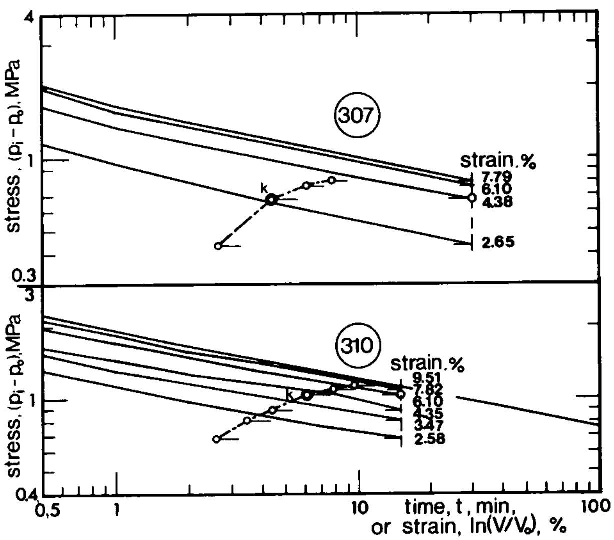

FIGURE 7. Dilatometer tests: relaxation curves from stage-loaded tests.

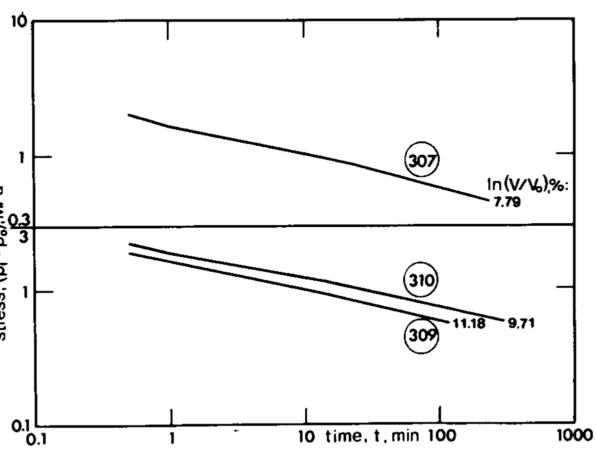

FIGURE 8. Dilatometer tests: long-term relaxation curves.

Discussion and Conclusions

This paper describes the results of a series of creep and relaxation tests carried out at a permafrost site by means of two different types of borehole instruments: the Ménard Pressuremeter and the CSM Cell. Each of the two instruments was found to have its particular area of optimum application: The pressuremeter for performing stage-loaded, stress-controlled, short-term tests, and constant-stress creep tests, and the CSM Cell for stage-loaded, strain-controlled, loading and unloading tests and stress-relaxation tests.

In the area of creep tests, several long-term pressuremeter creep tests were performed covering a wide area of loads. The results show that, at very low stresses, the power law may not always be the best approximation for the strain–time curves. It was also found that creep parameters in the power law may vary with the stress level, which should be taken into account when using such data for design purposes.

A very remarkable advantage of the dilatometer relaxation tests with respect to the pressuremeter creep tests is that, in the former, the long-term relaxation stage can be preceded by any number of shorter stages, enabling from one single test to determine the values of n and σ_c, and to observe in the last stage the variation of the parameter b with time for any desired time interval. In pressuremeter creep tests this is clearly impossible because of the total volume limitation.

A comparison between the creep parameters deduced from the pressuremeter creep tests and dilatometer relaxation tests, respectively, was encouraging, in spite of the different equipment used in the two types of tests. Nevertheless, it is felt that a definite answer as to the validity and relative merit of such borehole expansion tests can only be obtained if they are performed under well-controlled laboratory conditions in thick cylinders of frozen soil.

Finally, even if this study shows that, with a proper technique and care, borehole creep and relaxation tests can be performed for very long time intervals, it should *not* be concluded therefrom that the parameters deduced from such long-term tests will necessarily be valid for predicting the long-term behaviour of foundations in permafrost.

This is because, as found for certain unfrozen soils and more so in frozen soils, these borehole expansion tests contain mainly the deviatoric portion of deformation with only a very small amount of consolidation. It is already known from direct observations (Vialov 1959) that, after a long time interval, even a frozen soil will consolidate below a foundation. Therefore, it is to be expected that a direct extrapolation from any deviatoric creep test will neglect both the deformations due to consolidation and the associated gain in strength. This limitation should be kept in mind whenever using the laboratory or field creep data for predicting the long-term behaviour of foundation elements in frozen soils.

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Appendix

Symbols and Meaning

b = time exponent in the creep equation 9
c = cohesion
c_{max} = peak cohesion

c_r = residual (post-peak) cohesion
E = Young's modulus
f = flow value, equation 7
F = function of $(p_i - p_o)$, equation 11
G = shear modulus
M = function of creep parameters, equation 12
n = stress exponent in the creep equation 9
p_i = internal pressure applied in a borehole
p_o = total lateral ground stress around the borehole
r_i = radius of a borehole
r_e = external radius of a thick-walled cylinder
t = time
T_s = tensile strength of frozen soil
V = current volume of the measuring length of borehole in a pressuremeter test
V_o = value of V at $p_i = p_o$
ε = strain
ε_e = von Mises equivalent strain $= (4\, I_2'/3)^{1/2} = \gamma_{oct}/\sqrt{2}$
$\dot{\varepsilon}_c$ = arbitrary reference strain rate in the creep equation 9
ν = Poisson's ratio
σ = normal stress
σ_c = creep modulus = reference stress for $\dot{\varepsilon} = \dot{\varepsilon}_c$
σ_e = von Mises equivalent stress $= (3\, J_2')^{1/2} = 3\, \tau_{oct}/\sqrt{2}$
φ = stress function, equation 16
ϕ = angle of shearing resistance
ψ = time function, equation 16