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EVALUATION OF IN SITU CREEP PROPERTIES OF FROZEN SOILS WITH THE PRESSUREMETER

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EVALUATION OF IN-SITU CREEP PROPERTIES OF FROZEN SOILS WITH THE PRESSUREMETER

A series of field tests was carried out at a permafrost site near Thompson, Manitoba, to investigate the suitability of the Ménard Pressuremeter as a tool for in-situ determination of the rheological properties of frozen soils. Both short-term and long-term tests were conducted using the standard pressuremeter equipment with only minor modifications. Special care was taken in drilling and preparing the borehole for the tests to minimize the temperature disturbance. By using a newly developed method described in the paper, it was possible to obtain from the tests both the short-term and the long-term strength parameters. The first were obtained from conventional type pressuremeter tests, while the latter resulted from stage-loaded creep tests. In addition to the time dependent strength, the constitutive creep equation of the frozen soil was also established from the pressuremeter creep tests. The pressuremeter technique was found to be quite promising for creep testing of frozen soils. Its main advantages over laboratory methods used for similar purpose is that it is quicker, less expensive and involves a relatively large volume of soil. Its drawback is that it furnishes information on the soil behavior in only one direction, i.e., normal to the axis of the borehole which may be insufficient for foundation design if the permafrost stratum is anisotropic and contains horizontal ice lenses and layers.

EVALUATION IN-SITU DES PROPRIETES DE FLUAGE DES SOLS GELES AU MOYEN D'UN PRESSIOMETRE

Afin de pouvoir évaluer les possibilités d'utilisation du pressiomètre Ménard pour la détermination sur place des propriétés rhéologiques des sols gelés, on a effectué une série d'essais pressiométriques dans le pergélisol près de la ville de Thompson au Manitoba. Ces essais, tant à court-terme qu'à long-terme, furent effectués en utilisant l'équipement standard avec seulement quelques modifications mineures. Le forage du trou, et sa préparation pour les essais, a été fait avec un grand soin pour éviter de déranger excessivement l'équilibre thermique du sol. Les résultats d'essais furent analysés par une nouvelle méthode décrite dans le texte. D'une part, on montre comment, à partir des essais à court-terme, on peut déterminer les paramètres de résistance correspondants. D'autre part, on explique comment, à partir des essais de fluage à paliers, on peut déduire les trois paramètres de fluage fondamentaux, permettant d'établir l'équation constitutive du fluage ainsi que la résistance différée du sol gelé. Cette étude montre que la technique pressiométrique est bien adaptée pour la détermination des propriétés de fluage des sols gelés. Par rapport aux méthodes de laboratoire, ses avantages principaux résident dans le fait qu'elle est plus rapide et moins coûteuse et qu'elle examine un grand volume du sol. Son inconvénient est de ne fournir que des renseignements sur le comportement du sol dans une seule direction, notamment, normalement à l'axe du trou de forage, ce qui peut être insuffisant pour le calcul des fondations, si la strate du pergélisol est anisotrope et contient des lentilles et des couches horizontales de glace.

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EVALUATION OF *IN SITU* CREEP PROPERTIES OF FROZEN SOILS WITH THE PRESSUREMETER

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INTRODUCTION

For the design of foundations and other engineering structures in permafrost areas, there has been a real need for new methods and instruments to determine the properties of frozen soils in the field. A research project was undertaken, therefore, in 1971 to investigate the suitability of the Ménard pressuremeter, as a tool for *in situ* evaluation of the rheological properties of frozen soils. Although the pressuremeter has been used extensively in unfrozen soils and rock, the authors were not aware of any published information that describes its use for investigating the basic creep behaviour of frozen materials.

It appeared that two kinds of problems had to be solved. First, an appropriate testing procedure had to be developed that would permit the necessary creep information to be obtained with minimum physical and thermal disturbance of the ground. Second, a theoretical interpretation method had to be found that would allow the creep information obtained in a test to be put into a useful general form.

The results of the research investigation carried out are presented in this paper.

SOIL CONDITIONS AT THE TEST SITE

Field tests were carried out during July 1971 at a permafrost site at Thompson, Manitoba. Within the depth interval investigated, i.e., between 1.50 and 4.20 m, the soil was a varved clay of low to medium plasticity, composed of dark brown clay layers from 12 to 25 mm thick and tan-colored silt layers increasing in thickness with depth from 25 to 75 mm.

The most significant ice segregation was found in the top 4 m and was usually associated with the dark layers. Ice lenses were mainly horizontal and varied in thickness from hairline to a maximum of about 12 mm. Permafrost temperatures at depths between 1.50 and 9.00 m were fairly uniform, varying between –0.10 and –0.30 °C, throughout the year.

INSTRUMENTATION

The Ménard pressuremeter (Figure 1) is a special borehole dilatometer that has been used for a number of years for *in situ* measurement of stress-strain and strength properties of soils and rocks. It consists of an inflatable probe, composed of two coaxial cells, and a pressure-volume control device that allows a given pressure to be applied to the wall of the borehole and the resulting volume increase of the hole to be observed.

The tests at Thompson were performed with a type G pressuremeter fitted with a pressure-volume control device of 700 cm^3 volume capacity and 0-25 bar pressure range. The NX-size probe had its rubber membrane protected by

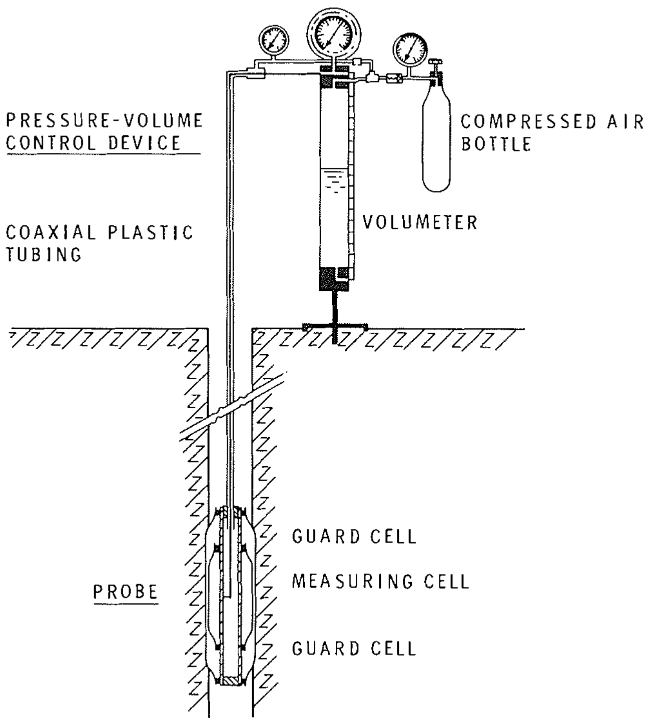

FIGURE 1 Ménard pressuremeter type G. Test setup.

an extensible overlapping metal strip jacket. For creep testing of frozen soils, the following modifications were made to the equipment:

1. A fine adjustment valve was included in the pressure control system, to provide more accurate pressure control when performing long-term creep tests.
2. Three thermocouples were fixed to the outside of the probe, so that the temperature of the soil in contact with the probe could be checked continuously during a test.
3. The complete volumeter assembly was enclosed in an insulated box that was filled with crushed ice to cool the fluid to be injected into the probe during the test.

Previous pressuremeter testing experience in unfrozen soils showed that the quality of results depends greatly on the quality and accuracy of drilling of the borehole. This is even more valid in frozen soils where not only a physical but also a thermal disturbance may occur during drilling. The method used was to auger the hole to about 0.75 m above the required test level. A special sampling tube, having its cutting edge tapered inwards to avoid disturbing the soil surrounding the hole, was then pushed into the frozen soil to make a tight hole for the probe. Owing to high air temperatures (15-25 °C), some thermal disturbance of the relatively warm permafrost at the site could not be avoided during drilling. Temperature checks in the borehole showed, however, that the temperature at the hole wall returned to normal within about 1 h after drilling was completed. One hour was used, therefore, as a normal waiting period before starting each test.

TESTING PROGRAM

Before starting the long-term testing program, several short-term tests were conducted at the site to investigate the general character and strength range of the frozen varved soils. These short-term tests were similar to Ménard's standard or normal pressuremeter tests used in current soil testing practice. For the standard test, the pressure in the probe was increased up to the limit pressure in about 10-20 increments, the pressure being kept constant at each stage for no longer than 2 min. At each stage, volume readings were taken at 30 s, 1 min, and 2 min after the pressure was increased.

After comparing a number of different loading programs for long-term creep testing purposes, it was concluded that the following two types of pressuremeter tests might represent minimum requirements for obtaining the creep information required:

1. A one-stage creep test in which the pressure is brought rapidly to a given level and is left at that level as long as possible. In practice, because deformation is limited by the maximum volume of 700 cm^3 that can be injected into the probe, the total creep time can vary from about 20 min to several hours.
2. A multistage creep test, in which the pressure is brought rapidly up to an initial creep level and then is increased to the limit in several equal stress increments, each kept constant for 15 min.

RESULTS OF SHORT-TERM TESTS

As detailed descriptions of the standard pressuremeter testing procedure including all corrections of pressure and volume readings, as well as the calibration curve determination, can be found elsewhere[1,9] only some typical short-term results and their interpretation will be given here.

Plotting of Pressuremeter Curve

The results of a short-term pressuremeter test are usually plotted as a corrected pressuremeter curve (Figure 2A) defined as:

$$V_m = f(p_c), \qquad (1)$$

where V_m denotes the total volume of fluid injected into the measuring cell from the start of pressure application,

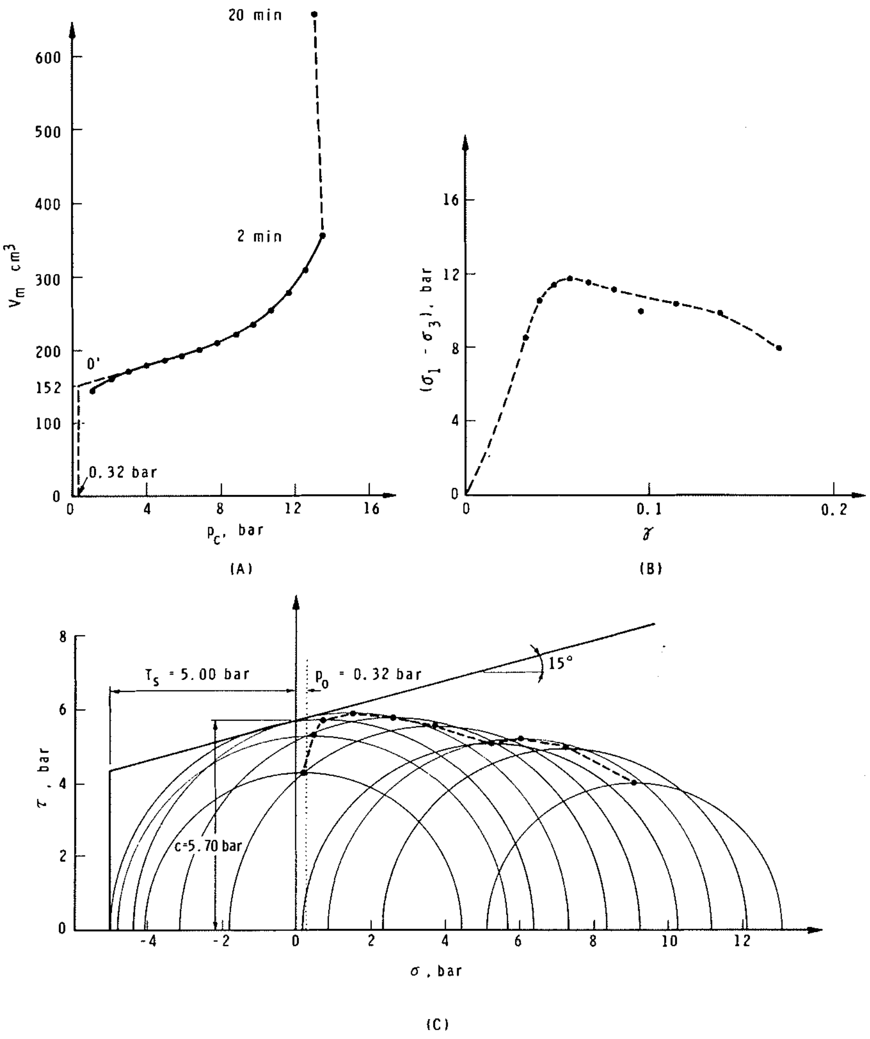

FIGURE 2 Results of a short-term pressuremeter test in a varved silt-clay soil: A, pressuremeter curve; B, stress-strain curve; C, vector curve.

and p_c is the applied pressure that has been corrected for the piezometric head and the extension resistance of the unloaded probe.

The interpretation method adopted in this paper, however, is based on the true pressuremeter curve, such as would be obtained in an ideal test starting from the original ground pressure, p_0. The true pressuremeter curve represents a relationship of the form:

$$\Delta V = f(p_c - p_0), \tag{2}$$

where p_0 denotes the original total lateral ground pressure at the level of the test, and

$$\Delta V = V_m - V_{mo}, \tag{3}$$

where V_{mo} is the volume of the liquid injected in the probe up to $p_c = p_0$. The true pressuremeter curve is obtained from the corrected curve by shifting the origin from 0 to 0′, as shown in Figures 2A and 3A.

Eleven short-term tests were carried out at the Thompson site. Two typical results are shown in Figures 2 and 3, the former obtained in a frozen varved silty soil and the latter in a frozen varved clay.

Interpretation of Short-Term Tests

From a soil mechanics point of view, a frozen soil is essentially a (c, ϕ) material having a relatively high time- and temperature-dependent cohesion and an angle of internal friction that is usually only little affected by time and temperature. Because little is yet known about the true intergranular stresses in frozen soils, c and ϕ are assumed to be total stress parameters. Moreover, if the soil is fine-grained and ice-saturated, the volumetric component of the deformation will be very small and, therefore, may be neglected. With these assumptions, a pressuremeter curve for frozen soil can be interpreted using the method proposed by Ladanyi,[6] the main points of which are given below.

The method is based on a general solution of the problem

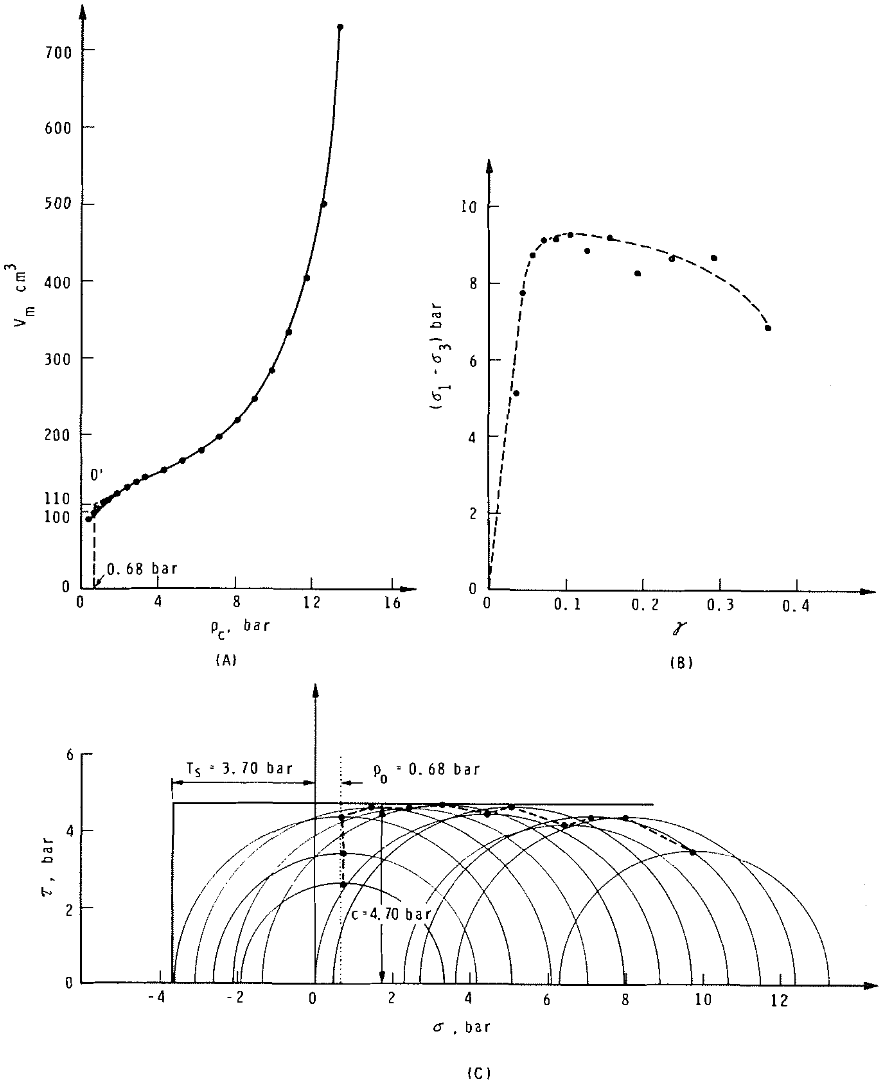

FIGURE 3 Results of a short-term pressuremeter test in a varved clay: A, pressuremeter curve; B, stress-strain curve; C, vector curve.

of expansion of a thick-walled cylinder, which is considered as an assemblage of a finite number of thin concentric cylinders, all of which respond to a common stress-strain law. By inversing the solution, it is found that not only the pressuremeter modulus and the average ultimate strength can be determined from the pressuremeter curve, as shown previously by Gibson and Anderson,[2] but also the whole stress-strain curve of the soil, as well as a vector curve in the Mohr plot.

Stress-Strain Curve

As shown by Ladanyi,[6] it is possible to determine from any two points, i, $i + 1$ of the true pressuremeter curve (Figure 2A), the corresponding mobilized strength, $q_{i,i+1}$, defined as the principal stress difference:

$$q_{i,i+1} = (\sigma_1 - \sigma_3)_{i,i+1}, \tag{4}$$

and the associated average shear strain, defined as the principal normal strain difference:

$$\gamma_{i,i+1} = (\epsilon_1 - \epsilon_3)_{i,i+1}. \tag{5}$$

The principal stress difference can be calculated from the formula:

$$q_{i,i+1} = (p_i - p_{i+1})/(1/2)[\ln(\Delta V/V)_i - \ln(\Delta V/V)_{i+1}], \tag{6}$$

and the principal normal strain difference is obtained from:

$$\gamma_{i,i+1} = (1/2)[(\Delta V/V)_i + (\Delta V/V)_{i+1}], \tag{7}$$

where p and ΔV denote the coordinates of the true pressuremeter curve at the points i and $i+1$, and the current volume V of the borehole is defined by

$$V = V_o + \Delta V \qquad (8)$$

in which

$$V_o = V_{\text{empty}} + V_{\text{mo}} \qquad (9)$$

denotes the volume of the measuring section of the probe at the moment when the pressure in the probe has attained the original ground pressure, p_o. In this study it was found that p_o should be determined or estimated independent of the test, since, contrary to the usual belief, the lateral pressure was usually found to be completely unrelated to the shape of the pressuremeter curve.

It should be noted that the stress-strain relationship obtained by this procedure is valid for constant volume plane-strain condition. It can, however, easily be transformed into the more usual axial symmetry case by using the von Mises yield criterion.[6]

The stress-strain curves obtained by this procedure from the pressuremeter curves (Figures 2A and 3A) are shown in Figures 2B and 3B. Some caution is necessary, however, when such stress-strain curves are compared with those obtained in a triaxial test. In fact, in brittle soils, and often in frozen soils as well, it has been found that a pressuremeter test produced radial cracking of the soil early in the test, leading to an irregular shape of the stress-strain curve.

Vector Curve in Mohr Plot

On the other hand, since both the major principal stress σ_1 (equal to the applied radial stress) and the principal stress difference ($\sigma_1 - \sigma_3$, equal to $q_{i,i+1}$) are known at any moment of the test, the information can be used for plotting a series of Mohr circles and a vector curve in the Mohr plot. In terms of plane-strain information as obtained in the test, the values of the total principal stresses σ_1 and σ_3 for any interval $i,i+1$ of the pressuremeter curve are given by:

$$\sigma_1 = (1/2)(p_{c,i} + p_{c,i+1}), \qquad (10)$$

and

$$\sigma_3 = \sigma_1 - q_{i,i+1}, \qquad (11)$$

where p_c is the applied radial stress and $q_{i,i+1}$ is the stress difference defined by Eq. (6).

Figures 2C and 3C show two such plots obtained for frozen varved silt and clay, respectively. To follow the sequence of Mohr circles more easily, they have been connected by a vector curve, showing the variation of $(1/2)(\sigma_1 - \sigma_3)$ with $(1/2)(\sigma_1 + \sigma_3)$ in the tests.

Although a semigraphical method for plotting Mohr circles directly from a pressuremeter curve has been shown by Ménard,[7] the true meaning of the circles has never been properly understood. To understand what the plot really means, one should remember that in a pressuremeter test the soil responds first in a pseudoelastic manner, attains failure, and then continues deforming in a plastic manner up to large deformations. In Figures 2C and 3C, the pseudoelastic behaviour is reflected by the first two or three circles that increase in diameter but remain concentric, as anticipated by the theory of expansion of a cylindrical hole in an infinite elastic medium.

The following two or three circles are failure circles and correspond to the peak strength of the soil. The remaining circles are all in the plastic domain and correspond to ever-increasing plastic deformations. The diameters of these remaining circles depend, therefore, simultaneously on the strength characteristics of the soil and on its postfailure stress-strain behaviour.

It follows, therefore, that the three kinds of Mohr circles cannot be expected to have one common failure envelope. In fact, one may be justified in drawing one failure envelope over all failure and postfailure circles only if the postfailure behaviour of the soil is very close to the ideally plastic assumption. If, on the other hand, the postfailure behaviour of the soil is either strain-hardening or strain-softening, which is most often the case, the circles will not have a common failure envelope, and the determination of failure parameters c and ϕ from one single pressuremeter curve will be very difficult or impossible. In other words, contrary to the belief expressed by Ménard[7] and Gibson and Anderson,[2] a single pressuremeter test is usually insufficient for determining the failure envelope of the soil. Nevertheless, it is considered that the plotting of both the stress-strain curve and the vector curve, as described herein, is at present the best method available for a proper understanding of a short-term pressuremeter test.

In this study, the Mohr circle plots have been used only for estimating probable lower limits of the short-term tensile strength, T_s, and the cohesion, c. To estimate the two parameters, the Mohr circles were enclosed by a bilinear envelope, composed of a Coulomb straight line and a vertical tension cutoff. For the Coulomb line, a friction angle of 15° was assumed for all silty soils and 0° for all soils composed mainly of clay.

In addition, the values of the pressuremeter modulus, E_p, were calculated from the initial straight-line portions of the pressuremeter curves by using the usual formula valid for incompressible soil:

$$E_p = 3\,\Delta p/\Delta(\Delta V/V). \qquad (12)$$

The overall variation of the three short-term parameters in the tests was approximately as follows:

For frozen varved soil: $250 < E_p < 800$ bar; $5 < c < 14$ bar; and, $1.5 < T_s < 12$ bar.
For the same varved soil, unfrozen: $60 < E_p < 80$ bar; $2 < c < 5$ bar; and, $1 < T_s < 5$ bar.

As expected, a given type of soil is stronger and much less deformable when frozen than unfrozen. It also was noted that the tensile strength of the frozen soil tested was about the same order of magnitude as its peak shear strength. Frozen varved clay was found to be slightly weaker and more deformable than frozen varved silt at the same temperature.

INTERPRETATION OF PRESSUREMETER CREEP TESTS

According to Hult,[3] there are essentially two practical methods for generalizing experimental creep information. The first method, applicable to long-term creep tests in which the steady-state creep strains greatly exceed the instantaneous and primary creep strains, consists of linearizing the creep curves and considering the total strain at any time as being the sum of the pseudoinstantaneous and the steady-state creep strain. The method was applied to the creep of frozen soils by Ladanyi[5] and was used subsequently by Johnston and Ladanyi[4] for generalizing creep information obtained in a series of long-term pull tests performed on grouted rod anchors in permafrost.

The second method, applicable to relatively short-term creep tests, considers the creep information as being essentially of a primary (or "stationary") creep type and attempts to extrapolate it to longer time using a convenient creep curve fitting method. As the creep time that can be realized in a pressuremeter test usually does not exceed several hours, the test should be considered as a short-term creep test to which the second method is applicable.

According to the second method, the creep data obtained in a pressuremeter test can be generalized using the solution to the problem of stationary creep under the internal pressure of a cylindrical cavity of infinite length located in an infinite medium.

The primary creep of high temperature metals, ice, and frozen soils can often conveniently be described by a law of the form

$$\epsilon^{(c)} = K\sigma^a t^b \qquad (b<1), \tag{13}$$

where K, a, and b are temperature-dependent material constants. In this report, Eq. (13) will be written in Hult's[3] notation and is generalized to multiaxial state of stress:

$$\epsilon_e^{(c)} = [\dot{\epsilon}_c(1+\mu)]^{1/(1+\mu)} (\sigma_e/\sigma_c)^{m/(1+\mu)} t^{1/(1+\mu)} \tag{14}$$

where ϵ_e and σ_e are the equivalent creep strain and the equivalent stress, respectively; $\dot{\epsilon}_c$ is an arbitrary, conveniently selected, strain rate; σ_c is the creep modulus in units of stress; and m and μ are creep exponents. The values of creep parameters σ_c, m, and μ can be obtained by a convenient plotting of creep curves as described by Hult.[3]

To solve this problem, it is convenient to introduce into Eq. (14) the transformed time unit:

$$\tau = t^{1/(1+\mu)}, \tag{15}$$

which permits Eq. (14) to be transformed into an ordinary power law:

$$d\epsilon_e^{(c)}/d\tau = K\,\sigma_e^n\,, \tag{16}$$

where

$$K = [\dot{\epsilon}_c(1+\mu)/\sigma_c^m]^{1/(1+\mu)}, \tag{17}$$

and

$$n = m/(1+\mu). \tag{18}$$

The solution of Eq. (16) for the problem of creep expansion of a cylindrical cavity under plane-strain condition can easily be obtained by analogy from the corresponding solution in nonlinear elasticity. Complete solutions of the particular problem can be found in several textbooks.[8]

To process the pressuremeter creep data, the only relationship needed from the solution is the one relating the creep cavity expansion rate with the applied internal pressure, which is, according to Odquist:[8]

$$dr/d\tau = (\sqrt{3}/2)^{n+1}\, K\, r[(2/n)(p_i - p_o)]^n, \tag{19}$$

where r is the current radius of the cavity, p_i is the constant applied internal pressure, and p_o is the pressure acting at infinity. If p_i is replaced by p_c according to the notation adopted for the corrected pressure in the borehole, Eq. (19) can be written as:

$$dr/r = G(p_c - p_o)\,d\tau, \tag{20}$$

where

$$G(p_c - p_o) = (\sqrt{3}/2)^{n+1}\, K[(2/n)(p_c - p_o)]^n, \tag{21}$$

in which K is given by Eq. (17) and n by Eq. (18).

For a finite interval of time at a constant stress, Eq. (20) can be integrated to give:

$$\ln r = G(p_c - p_o)\,\tau + C. \tag{22}$$

Taking $r = r_{i-1}$ at $\tau = 0$, i.e., at the beginning of the considered ith creep stage, the integration constant C can be eliminated, and Eq. (22) becomes:

$$\ln(r/r_{i-1}) = G(p_c - p_o)\,\tau. \tag{23}$$

Since for a cylindrical cavity:

$$(r/r_{i-1})^2 = V/V_{i-1}, \tag{24}$$

Eq. (23) becomes finally,

$$V/V_{i-1} = \exp[2\,G(p_c - p_o)\,t^{1/(1+\mu)}], \tag{25}$$

where V_{i-1} denotes the cavity volume at $t = 0$ (Figure 4), i.e., at the start of a given constant-pressure creep stage, and $V = V_{i-1} + \Delta V_c$ denotes the volume of the cavity at any time t after the step-increase of pressure $(p_c - p_o)$ in the stage i.

To determine the creep parameters μ, m, and σ_c, the semigraphical procedure described by Hult[3] for the primary creep case can be followed. Taking first a natural and then an ordinary logarithm of Eq. (25), one gets:

$$\log[\ln(V/V_{i-1})] = \log 2G(p_c - p_o) + (\log t)/(1 + \mu), \tag{26}$$

showing that pressuremeter creep curves should linearize if $\ln(V/V_{i-1})$ is plotted against time in a log-log plot. According to Eq. (26), in such a plot, the slope of the creep straight lines is equal to $1/(1 + \mu)$ or, from Figure 5:

$$1 + \mu = A/B. \tag{27}$$

The intercept at the unit time ($t = 1$ min in Figure 5) of any creep line, each of them corresponding to a different value of pressure $(p_c - p_o)$, is then equal to $2G(p_c - p_o)$.

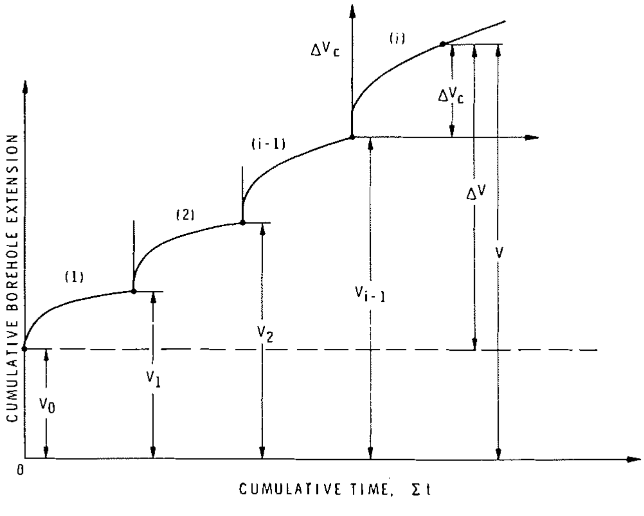

FIGURE 4 Notation for interpretation of pressuremeter creep data.

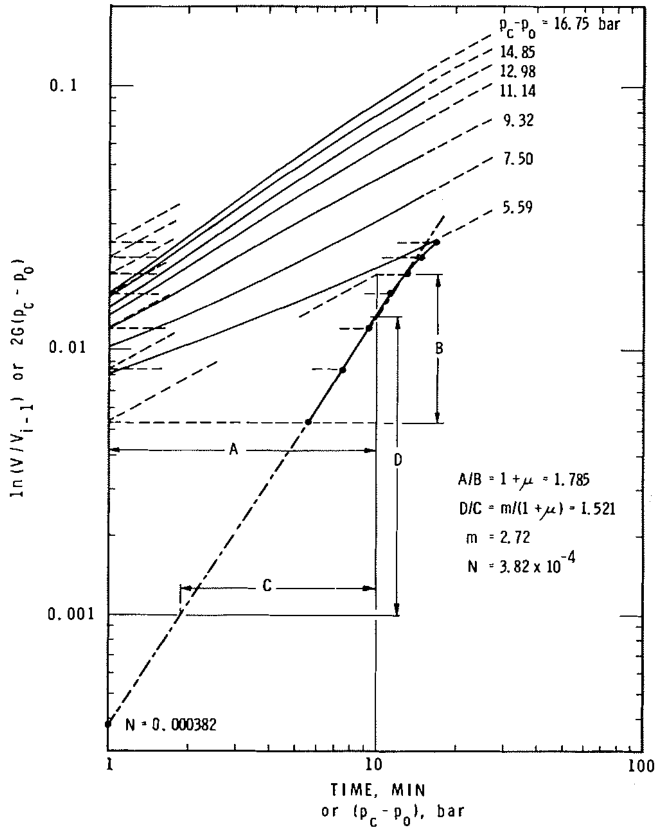

FIGURE 5 Multistage creep test in a varved silt-clay soil. Determination of creep parameters.

To determine the parameters m and σ_c, Eq. (21) may be written as:

$$\log 2G(p_c - p_o) = \log M - n \log \sigma_c + n \log(p_c - p_o), \tag{28}$$

where

$$\log M = \log 2 + (1 + n)\log(\sqrt{3}/2) + (n/m)\log(\dot{\epsilon}_c m/n) + n \log(2/n). \tag{29}$$

Equation (28) shows that plotting $2G(p_c - p_o)$ against $(p_c - p_o)$ in a log-log plot will give a straight line with the slope equal to n. In Figure 5 such a plot is shown superimposed on a plot of $\ln(V/V_{i-1})$ versus time. The new straight line has a slope:

$$D/C = n \equiv m/(1 + \mu) \tag{30}$$

and its intercept N, read at unit value of $(p_c - p_o)$ (at 1 bar in Figure 5), is, according to Eq. (28), equal to:

$$N = M/\sigma_c^n. \tag{31}$$

Since, for an arbitrarily assumed $\dot{\epsilon}_c$, and with known μ and m, the value of M can be calculated from Eq. (29), the value of σ_c is:

$$\sigma_c = (M/N)^{(1+\mu)/m} \equiv (M/N)^{1/n}. \tag{32}$$

Once the creep parameters μ, m, and σ_c have been determined, they can be substituted into Eq. (14) to get a general creep equation of the soil. The equation, subsequently, can be used either for extrapolating the pressuremeter creep data to longer time intervals or, in association with an estimated creep failure strain, serve for predicting the long-term strength of frozen soil. To predict the long-term strength, if ϵ_{ef} denotes the equivalent failure strain and σ_{ef} the equivalent creep strength, then Eq. (14) yields:

$$\sigma_{ef} = \sigma_c\, \epsilon_{ef}^{(1+\mu)/m}\, [\dot{\epsilon}_c(1+\mu)t]^{-1/m}. \tag{33}$$

Figure 5 shows typical creep information obtained in a multistage pressuremeter creep test with 15 min per stage. Figure 6, in turn, shows the result of a one-stage creep test kept at a constant stress for more than 5 h. In the figures, the logarithmic creep measure, $\ln(V/V_{i-1})$, is plotted against the time, t, in a log-log plot, as required for creep parameter determination.

To apply the foregoing analysis in practice, two conditions are necessary: Creep curves should linearize in a log-log plot; and creep curves for different sustained pressures should be parallel to each other.

As can be seen in Figures 5 and 6, neither of the two conditions was completely satisfied in the tests. In fact, the creep curves were found to curve up slightly at low pressures and curve down at high pressures. Moreover, the creep lines frequently were not quite parallel but diverged with increasing time. Nevertheless, they appeared to linearize better in one-stage tests then in multistage tests and showed a tendency to become parallel after about 15 min. With these two experimental facts in mind, it was decided, for the purpose of generalization of creep information, to consider the creep curves as becoming parallel after 15 min in each stage and having a slope ($A/B = 1 + \mu$) average for the considered pressure interval. The creep lines were then projected back from 15 to 1 min to get the values of $2G(p_c - p_o)$, according to Eq. (26). These values were then plotted against $(p_c - p_o)$ to get a set of points through which an average (dash-dotted) line was drawn. The line, according to Eq. (28) to (31) allows the ratio $D/C = m/(1 + \mu)$ and the intercept N at $p =$ 1 bar [Eq. (31)] to be determined. With these values and after calculating the value of M [Eq. (29)], the creep modulus σ_c was finally determined.

In the six tests performed in the frozen varved silt, it was found that the value of $(1 + \mu)$ remained essentially between 1.5 and 2.5, while the value of m varied from about 2 to 4. There was a much larger variation in σ_c, from about 4.5 to 24 bar.

It should be noted that in all creep calculations the arbitrary strain rate $\dot{\epsilon}_c$ was taken as equal to 10^{-5} min^{-1}.

As already explained, when the three parameters are known, one can write both the general creep equation, Eq. (14), and the time-dependent strength equation, Eq. (33). For the test shown in Figure 5, the creep equation has the form:

$$\epsilon_e = 0.87 \times 10^{-3}\, (\sigma_e/4.71)^{2.08} t^{0.64},$$

where σ_e is in bar and t in min, and the time-dependent

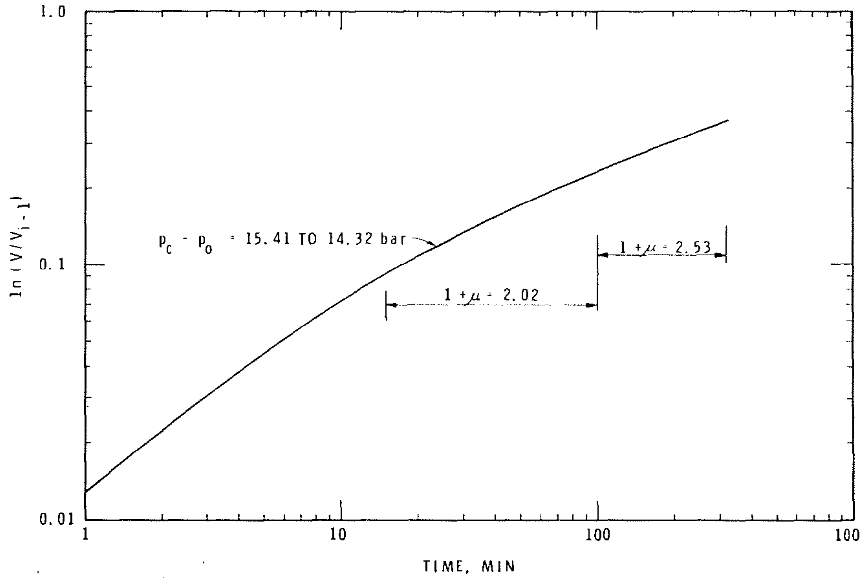

FIGURE 6 One-stage creep test in a varved silt-clay soil. Creep curve.

strength, assuming a failure strain of $\epsilon_{ef} = 0.10$, is given by:

$$\sigma_{ef} = 44.5\,t^{-0.305}$$

with the same units as above. Thus, the soil would have a 30-min strength of 15.8 bar and a 1-year strength of 1.62 bar, i.e., its strength would decrease within a year to about one tenth of its short-term value.

CONCLUSIONS

The study conducted to evaluate the pressuremeter test as a means for obtaining creep information of frozen soils *in situ* indicated that:

1. After some minor modifications, the standard pressuremeter equipment proved to be suitable for performing creep tests under the conditions found at the Thompson site. It is not known, however, how the same equipment would perform at very low temperatures and in some other types of frozen soils, such as glacial till.
2. Methods used to drill and prepare the borehole for the tests were fairly satisfactory. Some temperature disturbance could not be avoided, however, and special attention must be given to this aspect in future studies.
3. A new interpretation method had to be developed in order to make use of information obtained from the short-term tests. This method permitted the determination of short-term strength parameters and the stress–strain curve from each pressuremeter test.
4. A method had also to be found for the determination of creep parameters from the pressuremeter creep data. The method developed proved feasible for the determination of creep parameters of frozen soils *in situ* and the prediction of long-term strength. To obtain sufficient creep information for the proposed method to be applicable, however, it is recommended that, in addition to conventional short-term pressuremeter tests, the following two types of creep tests be performed: multistage creep tests with about 15 min per stage and one-stage creep tests conducted at different pressure levels to check the linearity of creep lines for long time intervals.

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