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Publisher's version / Version de l'éditeur:

Proceedings of the 3rd International Specialty Conference on Cold Regions Engineering. Northern Resource Development, 1, pp. 41-52, 1984-04-04

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Appeared in
Proceedings Third International Specialty Conference
Cold Regions Engineering, "Northern Resource Development"
Edmonton, Alberta, April 4, 5 and 6, 1984
Volume I, p. 41 - 52

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DBR Paper No. 1190
Division of Building Research

Price $1.25 OTTAWA NRCC 23320

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RÉSUMÉ

On a constaté qu'une charge alternée aussi faible que 5% de la contrainte statique accélère le taux de déplacement des pieux enfoncés dans les sols gelés et supportant des charges de longue durée, ainsi que le taux de fluage des échantillons de sol gelé soumis au chargement uniaxial en compression. Cet effet réduit la capacité portante des pieux enfoncés dans les sols gelés et doit être pris en considération pour les calculs de fondations dans les régions de pergélisol.

EFFECT OF DYNAMIC LOADS ON PILES IN FROZEN SOILS

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ABSTRACT

An alternating stress as small as 5% of the static stress was found to accelerate the displacement rates of piles subjected to long-term loads in frozen soils, as well as the creep rate of frozen soil samples subjected to uniaxial loading under compression. This effect essentially reduces the bearing capacity of piles in frozen soils, and has to be taken into consideration in the design of foundations in permafrost areas.

INTRODUCTION

Pile foundations supporting buildings in permafrost areas are subject to static loads due to the superimposed structure, and to dynamic loads from operating machinery within the buildings. Shocks and vibrations from extraneous sources are also transmitted to the foundations through the ground. Conventional designs of foundations in permafrost areas usually take into consideration only static loads and an allowable settlement of the foundation during the anticipated service life of the structure. The bearing capacity of a pile is estimated from the adfreeze bond strength between the pile and various soils (which is determined experimentally from short-term and a few long-term pile load tests) and from the behaviour of existing structures in permafrost areas. The end-bearing capacity for a pile in frozen soils is a function of the compressive strength of the soil material. For ice-rich soils this is very small and usually neglected. The uncertainties caused by variabilities in the type of soil and the moisture content and its distribution in the soil, and those due to the surface characteristics of the pile are normally compensated for by a factor of safety incorporated into the design criteria.

At present, the effects of dynamic stresses are not taken directly into consideration in design. The large safety factor normally used is probably sufficient to compensate for these effects. Although it is known that the mechanical properties of frozen soils and ice are affected by dynamic loading on these materials (Kaplar (1969), Stevens (1975), Vinson et. al. (1978) (a) and (b), Czajkowski and Vinson (1980)) no field studies have as yet been reported on the effect of alternating loads on the rate of settlement of piles in frozen soils. Laboratory studies were undertaken to obtain information on the behaviour of piles in frozen soils under various conditions of load (static and dynamic) and temperature. Preliminary results of these investigations showed that an alternating stress as small as 3 to 5% of the static stress caused a doubling of the displacement rate of wood and concrete piles in frozen soils at -2.2°C (Parameswaran (1982)). This indicated that dynamic loads reduce the life expectancy of a structure to half that which is predicted from static stress alone.

The present paper reports the results of more recent studies on the effect of dynamic stresses on the rate of settlement of piles embedded in frozen soils with free ends, without any end-bearing. Since the total bearing capacity of a pile is a combination of the adfreezing strength at the pile-soil interface and the end-bearing capacity estimated from the compressive strength of the soil under the pile, it was also decided to study the effects of dynamic stresses on the creep of cylindrical samples of frozen soils under uniaxial compression.

EXPERIMENTAL PROCEDURE

The experimental setup to measure the displacement rates of piles in frozen soils under static loads and superimposed alternating loads was described earlier (Parameswaran (1982)). The same creep frame was also used to study the creep of cylindrical frozen soil samples, as shown in Figure 1.

Samples of frozen soil, 75 mm in diameter and about 175 mm in length, were prepared from a natural silty clay obtained from permafrost areas in the Northwest Territories. The dried soil was mixed with water (50% by weight of dry soil) and the resulting slurry was packed into cylindrical cavities cut into a Styrofoam block with a flexible polyethylene sheet lining. The samples were allowed to freeze unidirectionally by exposing the open end to the air inside a cold room kept at -2.2°C. After complete freezing, the cylindrical samples were removed from the Styrofoam block and their ends faced in a lathe. The finished samples were 150 mm long. The ice lenses in the frozen soil samples were distributed uniformly, but randomly oriented. The average moisture content of the samples was about 45%.

For a creep test (as shown in Figure 1), a cylindrical sample (A) was mounted on the steel pedestal (B), and the lever arm (D) was adjusted horizontally, with the load cell (C) above the sample. A hydraulic jack (J) was used to raise and lower the lever arm. The combined weight of the beam (D), the shaker (E), and the loading platform (P) provided the static load on the specimen. Weights could be placed, if necessary, on the loading platform (P) to increase this static load. Dynamic load was applied on the frozen soil sample by the electrodynamic shaker (E). The frequency and amplitude of the dynamic load was controlled by feeding a suitable wave form signal to the shaker from a wave generator and an amplifier. For most tests a sinusoidal wave of 10 Hz was used, as this was close to the critical frequency of vibration for piles in frozen soil determined earlier in the laboratory (Parameswaran (1982)) and observed in the field (Pernica et. al. (1984)). (The term 'critical frequency' is used here to denote the frequency at which the amplitude of vibration, measured by an

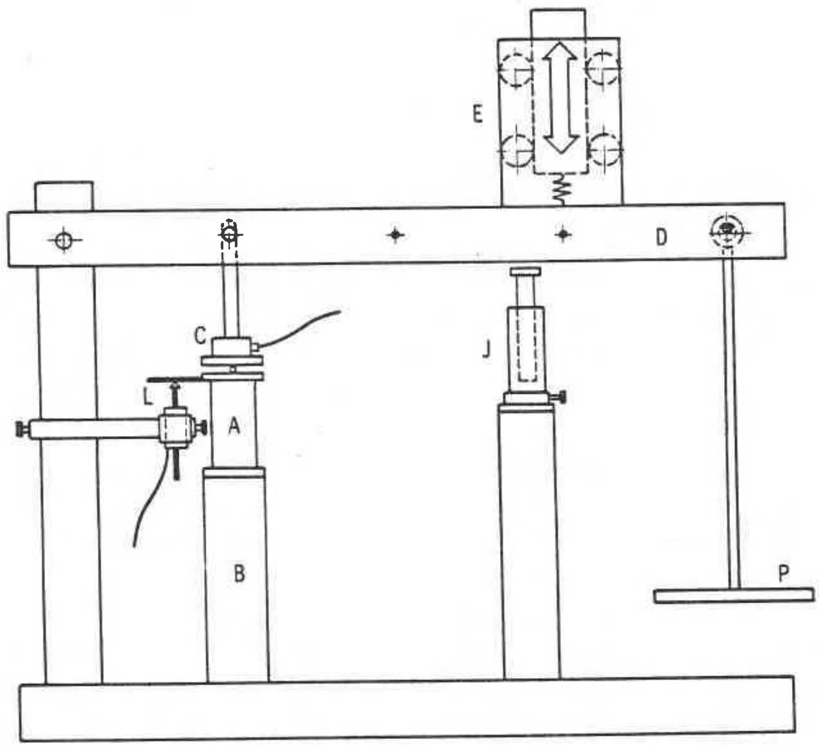

Figure 1. Schematic diagram of the experimental setup to study creep of cylindrical samples of frozen soils. A - frozen soil sample, B - steel pedestal, C - load cell, D - lever arm, E - electrodynamic shaker, J - hydraulic jack, L - linear variable differential transducer (LVDT), P - loading platform

accelerometer on the pile, is a maximum.) The static and dynamic components of the load applied on the specimen were monitored continuously from the output of the load cell (C) on a chart recorder. The deformation of the sample (axial compression) was also recorded on the chart recorder, measured by a linear variable differential transducer (LVDT) 'L'. All tests were carried out at a temperature of -2.2°C ± 0.2°C.

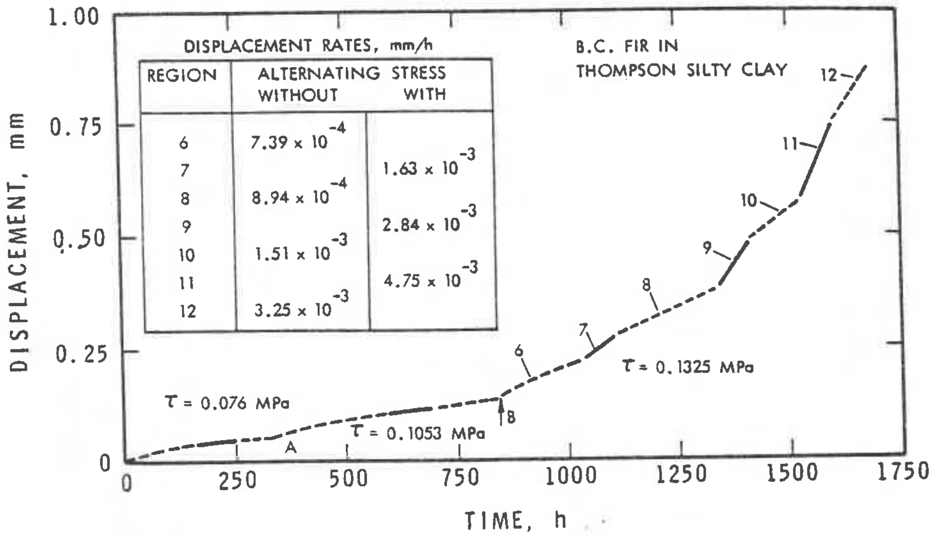

Figure 2. Typical creep curve showing the displacement of a wood pile in frozen silty clay with time

RESULTS AND DISCUSSIONS

Displacement of Piles in Frozen Soils

Figure 2 shows a typical creep curve giving the displacement with time of an uncoated wood pile (made from Douglas fir) in a frozen silty clay. The dashed lines show the displacement under static load alone, and the solid lines indicate the regions where an alternating load (of about 5% of the static load) was superimposed on the static load. The arrows indicate the positions where the static load was increased by adding weights to the loading pan (P in Figure 1). In the early part of the test, the displacement rate of the pile in the frozen soil decreased continuously with time, indicating primary creep behaviour of the frozen soil under shear at the pile-soil interface. After the second load increment (B in Figure 2), the initial displacement rate was still of the primary creep type, as seen in region 6 of Figure 2. A marked increase in the displacement rate of the pile was observed after the shaker was turned on to impose the alternating load. The displacement rate decreased soon after turning the shaker off. In regions 7, 9 and 11, the effect of the superimposed alternating load in enhancing the displacement rate of pile in the frozen soil is clearly seen. The values of the displacement rates with and without the alternating stress, under a constant static stress of 0.1325 MPa at the adfreezing interface between the pile and the soil, are also given in Figure 2. The alternating stress causes the displacement rate to be doubled from region 6 to 7, and to be increased more than 3 times from region 8 to 9, and from region 10 to 11. This would imply that a structure designed only on the basis of static loads for a certain allowable displacement in a given time period will, under combined static and dynamic loads,

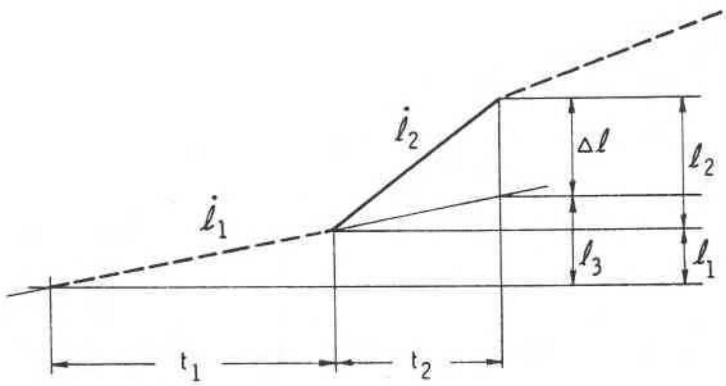

Figure 3. Schematic representation of the displacements with and without a superimposed alternating load

attain that displacement in 1/3 of the design life, if sufficient safety factors are not incorporated in the design.

Different kinds of piles such as uncoated wood (B.C. fir) piles, concrete, and steel pipe piles were tested in various kinds of soils, including a uniform sand (of average grain diameter 0.2 to 0.6 mm) containing 14% moisture (by weight of dry soil), a silty soil with 20% moisture, and a silty clay with 50% moisture. From the displacement rates observed under static loads and with a superimposed alternating load, the increase in pile displacement per cycle of alternating load was calculated as shown in Figure 3, for various static stress levels and displacements.

Let ℓ_1 be the displacement and $\dot{\ell}_1$ be the displacement rate during period t_1 under static stress alone, and let ℓ_2 and $\dot{\ell}_2$ be the corresponding values for a period t_2 with the superimposed alternating stress. Assuming that the displacement rates $\dot{\ell}_1$ and $\dot{\ell}_2$ remain unchanged during the periods t_1 and t_2, and extrapolating the creep curve beyond t_1 to t_2 as shown in Figure 3, the additional displacement ($\Delta\ell$) caused by the alternating load alone is given by:

$$\Delta\ell = \ell_1 + \ell_2 - \ell_3 = (\dot{\ell}_2 - \dot{\ell}_1)t_2 \qquad (1)$$

The increase in displacement per cycle of loading is given by:

$$\frac{d\Delta\ell}{dN} = \frac{(\dot{\ell}_2-\dot{\ell}_1)t_2}{t_2 \times f} = \frac{(\dot{\ell}_2-\dot{\ell}_1)}{f} \qquad (2)$$

where N is the number of cycles of alternating stress applied during the time period t_2, and f is the frequency of loading.

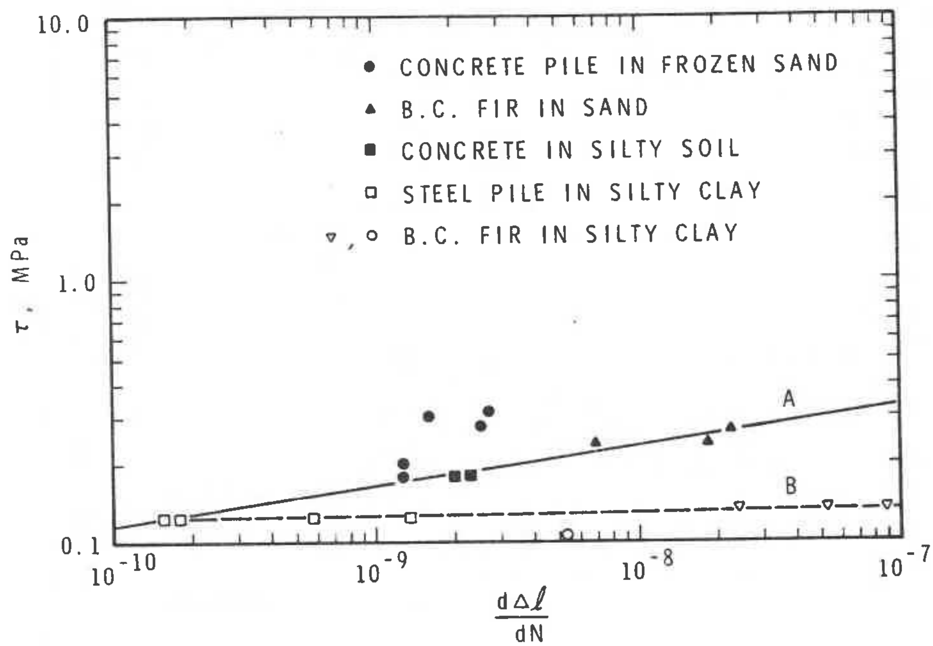

Figure 4. Variation of the increment in pile displacement per cycle of alternating load with mean stress

Figure 4 shows the values of $d\Delta\ell/dN$ calculated for various piles plotted on a log-log scale against the mean stress τ at the pile-soil interface. For piles in frozen sand and silty soil, there is some indication (as shown by line A in Figure 4) that $d\Delta\ell/dN$ increases with mean stress τ as:

$$\frac{d\Delta\ell}{dN} \propto \tau^n \quad (3)$$

where the value of n obtained from the slope of the straight line A was 6.5. In the case of piles in frozen fine grained clayey soils containing about 50% moisture by weight of dry soil, the values of $d\Delta\ell/dN$ varied between 10^{-10} and 10^{-7} mm/min for a very small change in stress about the mean value of 0.13 MPa (line B in Figure 4).

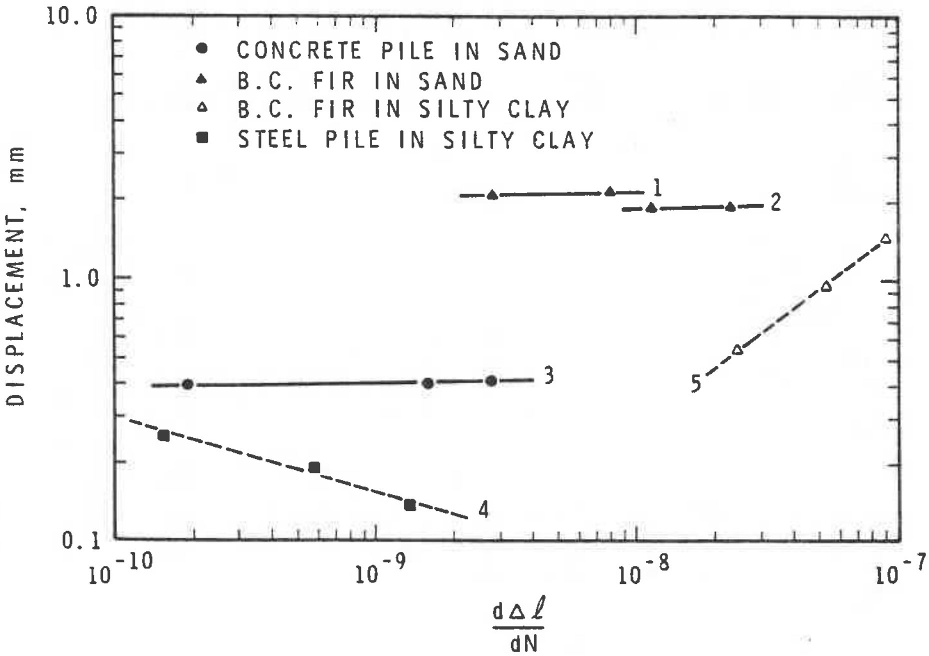

Figure 5. Variation of the increment in pile displacement per cycle of alternating load with displacement

Figure 5 shows the values of $d\Delta\ell/dN$ plotted against displacement of the pile on a log-log scale. The behaviour of piles in frozen sand and silt (lines 1, 2 and 3 in Figure 5) showed that $d\Delta\ell/dN$ increased sharply with displacement ℓ. Lines 4 and 5 for a wood pile and steel cylindrical pile, respectively, in a frozen clayey soil show definite deviations from this behaviour. The limited amount of data obtained so far does not allow one to draw any conclusion or propose a generalized behaviour of piles in clayey soils. Further tests are underway to study the behaviour of piles in frozen fine grained soils under dynamic loads.

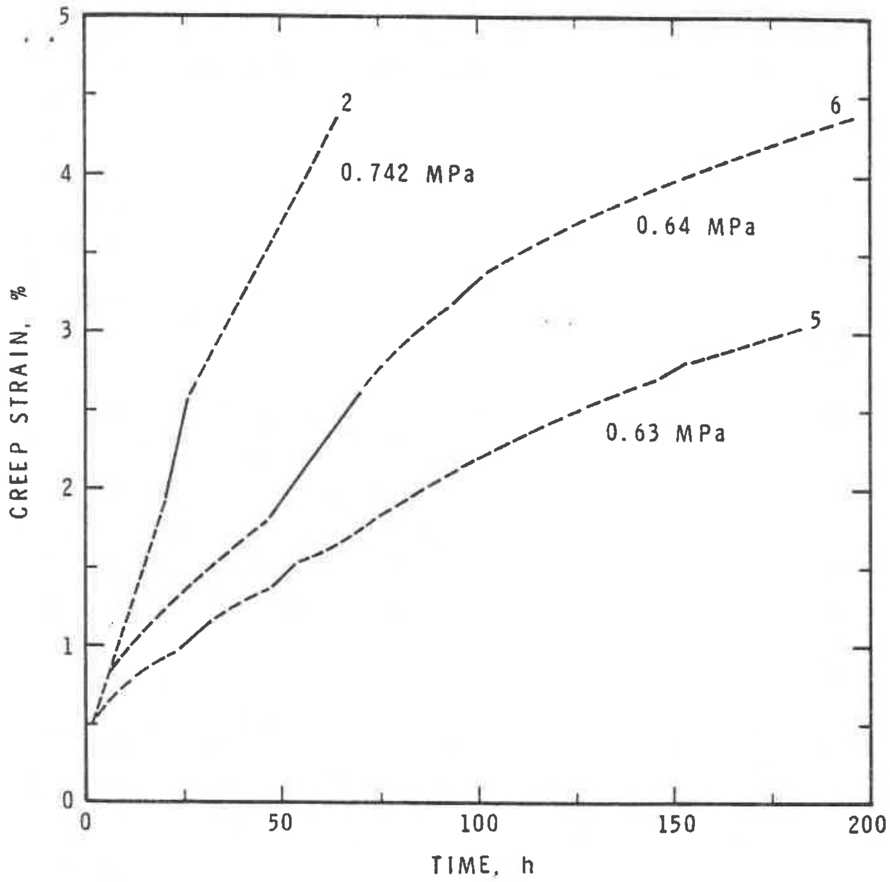

Figure 6. Typical creep curves of cylindrical samples of a frozen silty clay

Creep of Cylindrical Soil Samples

Figure 6 shows typical creep curves for three different samples of silty clay with 50% moisture tested at -2.2°C. The dashed lines show the dependence of creep strain on time under static stress alone, and the solid lines show the creep strain under the combined static and dynamic stresses. The peak-to-peak amplitude of the alternating stress was about 5% of the static stress. Figure 7 shows another sample of the same material tested at a lower mean stress, but for a longer time. The effect of dynamic stress in increasing the creep rate of the samples is obvious in both Figures 6 and 7.

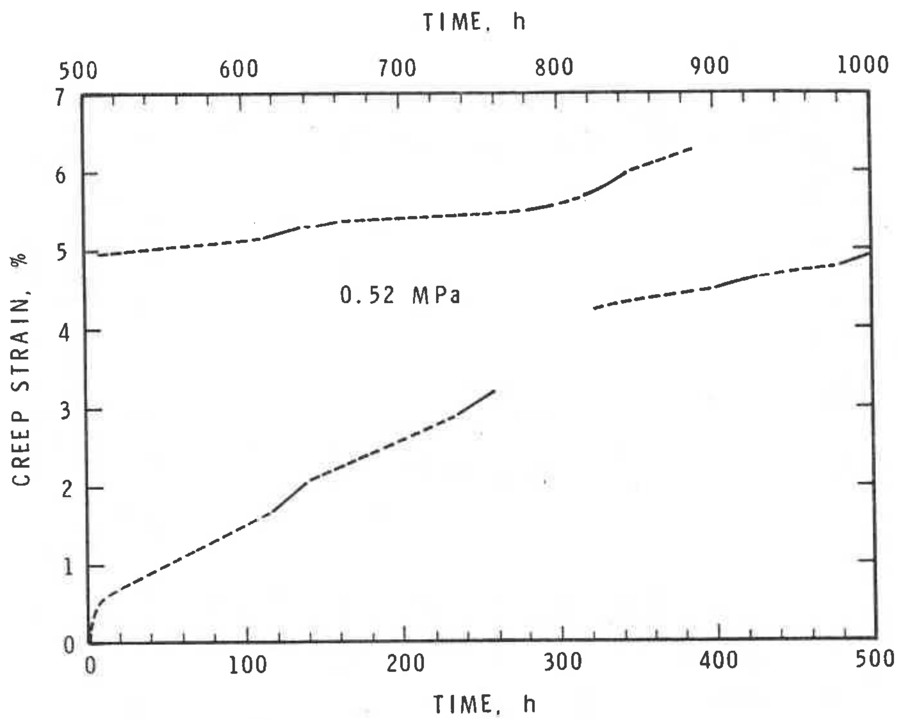

Figure 7. A typical long-term creep curve of a frozen sample of silty clay

Creep rates calculated for various samples with and without alternating stress are plotted against time on a log-log scale in Figure 8. The shaded symbols give the rates under combined static and dynamic stresses, and the blank symbols, the rates under static stress alone. The creep rates ($\dot{\varepsilon}$) under static as well as dynamic stresses decrease continuously with time (t), following a power law:

$$\dot{\varepsilon} \propto \bar{t}^{a} \tag{4}$$

When a = 0, $\dot{\varepsilon}$ = constant, as observed in the early part of the creep curves (for t < 100 hours) for samples 5 and 8 tested under mean stresses of 0.63 and 0.52 MPa, respectively. For the dynamic tests as well as for sample 1 tested under a mean static stress of 0.66 MPa, the value of the exponent 'a' was 0.8. This suggests that the deformation behaviour of the sample is close to that of logarithmic creep (a = 1) in the primary part of the creep curve, which is similar to the behaviour observed in many metallic materials at elevated temperatures. For sample 8, tested for a longer duration at a low mean static stress value of 0.52 MPa, the slope for static creep changes from a value of zero for t < 100 hours, to a value of a = 2 or more for t > 200 hours, which eventually leads to a very low value of creep rate.

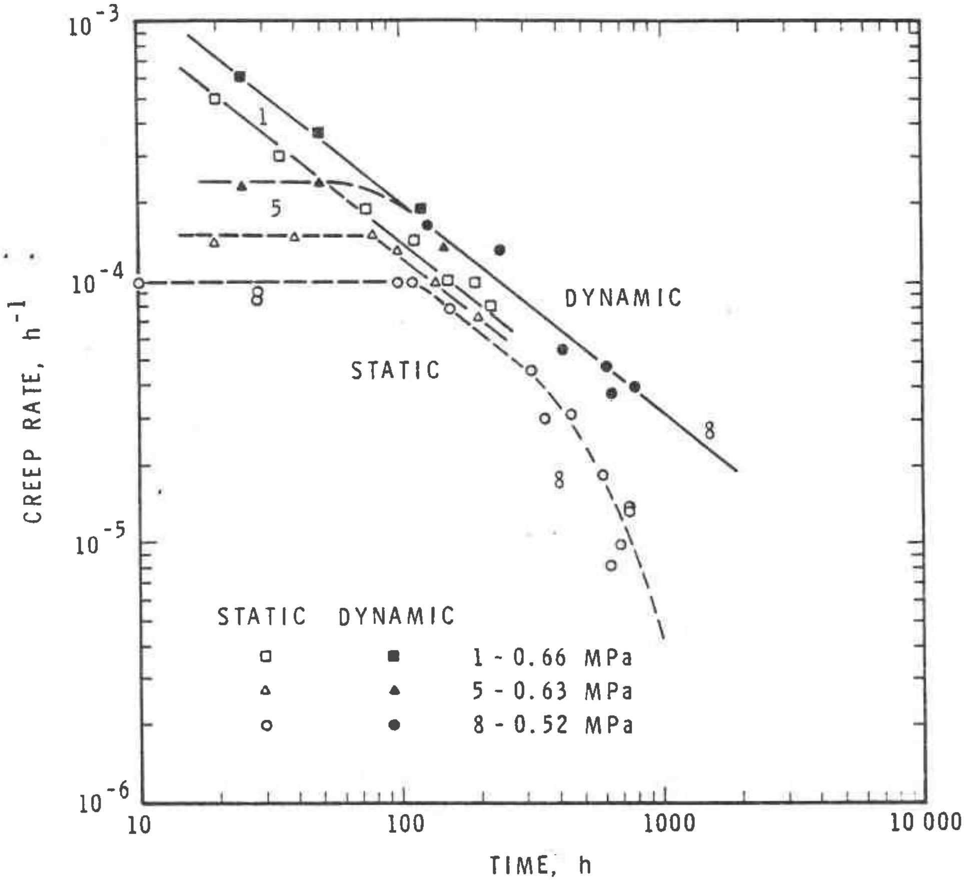

Figure 8. Variation of creep strain rate with time for silty clay under static and dynamic loads

The behaviour depicted in Figure 8 is very similar to the long-term creep behaviour of polycrystalline ice and sand-ice materials (Butkovich and Landauer (1959), Mellor and Testa (1969), Hooke et. al. (1972)), which follows the empirical equation (Weertman (1973)):

$$\varepsilon = A\ t^{1/m} + B\ t \tag{5}$$

where ε is the strain, t the time and A and B are constants for a particular material. Differentiating (5) with respect to time:

$$\dot{\varepsilon} = \frac{A}{m}\ t^{(1-m)/m} + B \tag{6}$$

The value of m obtained by Butkovich and Landauer was 3, which gave $\dot{\varepsilon} \propto t^{-0.66}$. This is close to our present observation, $\varepsilon \propto t^{-0.8}$. Gold (1965) observed values of m = 1 to 2 in some of his columnar grained ice samples. If m = 1, $\dot{\varepsilon}$ in equation (6) becomes a constant, which is the behaviour observed on samples (5) and (8) (Figure 8) for $t < 100$ hours. This suggests that the creep of frozen soils also follows the same empirical equation used to analyze creep of polycrystalline ice.

CONCLUSIONS

A dynamic stress of small amplitude amounting to a fraction of the static stress, enhances the rates of displacement of free ended piles in frozen soils. This indicates that the shear adfreeze strength at the pile-soil interface is decreased by dynamic loading. The creep rate of cylindrical samples of frozen clayey soils (containing about 45% moisture) under uniaxial compression was also increased by a superimposed alternating stress. As the total bearing capacity for piles in frozen soils is a function of both the adfreeze strength at the pile-soil interface and the end-bearing strength of the material under the pile, these effects should be taken into consideration for safe and optimal design of structures in permafrost areas. Since the creep rate is a function of the mean static stress, one way to ensure safety in the design when alternating loads are present is to reduce the static load on each pile by using a larger number of piles under the structure.

In general, the creep of ice-rich frozen soils was found to follow the same empirical equation that was used earlier for polycrystalline ice. This indicates that the creep of frozen soils is essentially governed by the creep of ice in the soil matrix.

ACKNOWLEDGEMENTS

Sincere thanks are extended to Colin Hubbs for performing the tests in the permafrost laboratories of DBR/NRCC. This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

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