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RÉSUMÉ

L'auteur a étudié le fluage cyclique des sable saturé et argiles gelés en superposant des charges alternantes sur une charge de compression statique moyenne posée sur les échantillons. Le chargement cyclique a accru considérablement la vitesse de fluage de ces matériaux, ce qui pourrait s'expliquer par l'augmentation de la teneur d'eau non gelée résultant de l'énergie thermique transitoire produite par cyclage mécanique. On a observé que l'incrément de déformation par cycle augmentait proportionnellement à l'accroissement de la déformation du sable gelé, tandis qu'il diminuait dans les argiles gelées, montrant une tendance à la résistance progressive à la déformation.

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Cyclic creep of frozen soils

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Abstract

Cyclic creep behaviour of frozen saturated sand and frozen clays was studied by superimposing alternating stresses over a mean static compressive stress on the samples. Cyclic loading increased the creep rate of these materials considerably, which could be due to the increase in unfrozen water content generated by the transient thermal energy produced by mechanical cycling. The strain increment per cycle was found to increase with increasing strain in frozen sand, whereas it decreased in frozen clays, showing a tendency for strain hardening.

Introduction

Creep or time-dependent inelastic deformation of frozen soil materials has been studied to some extent as a function of temperature and stress, and attempts have been made by several authors to fit the experimental creep data to classical creep equations developed from the observed behaviour of many viscoelastic materials, in particular metals and alloys. For designing foundations in frozen ground, the bearing capacity of the frozen soil has to be known, which depends on the creep characteristics of the frozen soil. In general, the long-term creep strength of the soil under constant stress is used for design. In practice, however, foundations are invariably subjected to various kinds of dynamic stresses from intrinsic and extraneous sources, in addition to static stresses due to structural loads. Rapid changes in mechanical stresses could also cause thermal changes in the soil, altering its creep behaviour.

It has been shown that small dynamic stresses do indeed increase the displacement rate of a pile foundation in frozen soil (Parameswaran, 1982; 1984), but to date, the effects due to dynamic stresses are taken care of by using an ignorance factor (a safety factor) in the design. Knowledge of the dynamic mechanical properties of frozen soils is sparse, except for some information on the dynamic moduli (Kaplar, 1969; Stevens, 1975; Vinson, 1978(a); (b); (c)). Due to the lack of such knowledge and uncertainties in this area, design of foundations has to be extremely conservative. A better understanding of the deformation behaviour of frozen soil materials under dynamic loading or combined loading, and the use of such information in life prediction analysis, will result not only in less conservative design rules, but also in the enhanced reliability of a structure. This will lead to a reduction in the factor of safety, thereby reducing the cost of hardware, as pile materials can be more effectively used. The challenges, therefore, are in the dynamic creep area where there is a need to develop constitutive equations to depict the behaviour of frozen soils and also the need to generate more experimental data on various frozen soils. This paper is a small step in this direction and discusses recent results obtained from cyclic creep tests on some frozen soils.

Experimental Procedure

Materials and Sample Preparation: Cylindrical samples were made from three different materials: Ottawa sand (ASTM Specification C-109 passing sieve No. 30 and retained on sieve No. 100, and having a grain diameter of 0.2 to 0.6 mm), a natural clay from Inuvik, N.W.T. and a silty clay from Thompson, Manitoba.

Cylindrical samples of frozen sand were prepared in split plexiglas molds. The sand was compacted in layers, at an optimum moisture content of 14%. The mold was then connected to a vacuum pump to remove entrapped air. After evacuation the sand was saturated with deaerated distilled water. The specimens were then frozen uniaxially in the mold kept inside an insulated box with the top end exposed to the cold room air, maintained at -10°C. The water expelled during freezing was removed from the bottom through a capillary tube containing a heater wire. After freezing, the ends of the cylindrical sample were trimmed and faced on a lathe inside the cold room. The finished test specimens contained about 20% moisture and had a bulk density of about 2040 kgm^{-3}.

Cylindrical samples of the natural clays from permafrost areas (Inuvik, N.W.T. and Thompson, Manitoba) were prepared by mixing the dried soil with water (50% by weight of dry soil) and packing the resulting slurry into the cylindrical cavities of a styrofoam block that was lined with polyethylene sheets. The samples were allowed to freeze unidirectionally by exposing the open end to the air inside the cold room. After complete freezing the cylindrical samples were removed from the styrofoam block and their ends trimmed and faced on a lathe. The ice lenses in the frozen soil samples were distributed uniformly, but oriented randomly. The average moisture content in the samples was about 45%.

The finished test specimens had diameters of 50.8 mm (2 in) and 76.2 mm (3 in), and length to diameter (L/D) ratios slightly greater than 2.

Equipment and Test Method: A diagram of the experimental set-up to study the creep of frozen soil samples is shown in Fig. 1. A cylindrical test specimen (A), wrapped in a cellophane jacket with a thermocouple (T) attached to it, was mounted on a pedestal (B), and the lever arm (D) was adjusted horizontally with the load cell (C) above the specimen. A hydraulic jack (J) was used to raise and lower the lever arm (D). The combined weight of the beam (D), the shaker (E), and the loading platform (P) provided the static load on the specimen. Weights were placed on the platform (P) to increase the static load in some tests. Dynamic load was applied on the frozen soil sample by an electrodynamic shaker (E). Larger cyclic loads were applied by an electrohydraulic shaker (H) (shown in Fig. 2). The frequency and amplitude of the dynamic load was controlled by feeding a suitable sinusoidal wave form signal to the shaker from a wave generator and amplifier. Dynamic loads with frequencies of 10 Hz and 15 Hz, and peak-to-peak amplitudes of up to 10% of the static load, were used.

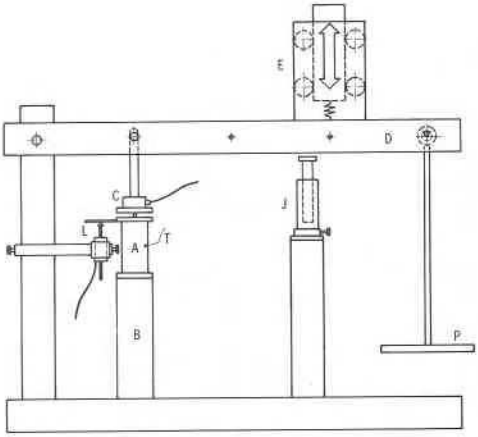

Fig. 1 Apparatus to study creep of frozen soils.

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 dynamic load was also monitored accurately using an oscilloscope having a camera attachment. The deformation of the sample (axial compression), measured by a linear variable differential transducer (LVDT) 'L', was also recorded on the chart recorder. All the data from each test, such as the temperature of the sample, room air temperature near the specimen, the static load on the sample, and axial deformation, were also logged at regular intervals (1 to 2 hours) through an automatic data acquisition system using a desk top computer, and the stress, strain, and strain rate of the sample were calculated for every reading. Tests were carried out at -2.5°C and -10°C, the temperature of the sample being monitored by small thermocouples (T) attached to the sample. Prior to starting a test, the temperature of the sample was allowed to come to equilibrium with the room temperature.

Figure 2 shows the experimental set-up inside the cold room and Fig. 3 shows a close-up view of the specimen and LVDT.

Results and Discussions

Figure 4 shows typical creep curves depicting the variation of axial strain with time for frozen samples of Thompson clay, Inuvik clay and saturated sand. The regions with and without the superimposed alternating load are shown by the dashed and full lines. The effect of alternating load in increasing the creep rate is obvious in these figures, as shown by the increase in slope of the creep curves in these regions. The increments in creep strain and strain rate are particularly marked in Figure 4(c) for the frozen sand sample subjected to a much larger stress than the other two samples. Figure 5 shows the corresponding creep rate curves for these samples. The values of the creep rates with and without alternating stress, the increments in creep strain per cycle of load, strain at the beginning of cycling and the stress on these samples are given in Table 1. The strain increment per cycle ($\Delta\varepsilon/\Delta N$) decreases with increasing strain for the Thompson clay samples, whereas it increases with increasing strain for the frozen sand. This suggests that cyclic stressing causes strain hardening in frozen clay, whereas in frozen sand, it causes softening with increasing strain. For Inuvik clay, which was of much finer grain size than Thompson clay, there was not much variation in the value of ($\Delta\varepsilon/\Delta N$) with strain ($\varepsilon$). Consolidation occurring under cyclic stress could contribute to strain hardening of the clay samples, while the softening observed in the frozen sand samples could partly be due to dilation.

All the tests reported here were carried out in a cold room at a temperature of $-2.5°C \pm 0.5°C$. A few tests were also done at $-10°C$, but at this lower temperature there was hardly any increase in creep rate due to cyclic loading. If the peak-to-peak amplitude of the alternating load could be increased, there is a possibility that one could observe the influence of cyclic loading at the lower temperature too. To study the effect of changing the frequency of loading, some tests were also done at 15 Hz, and in some tests, alternating stresses of both 10 Hz and 15 Hz were superimposed intermittently. The effect of the alternating stress was much less pronounced at the higher frequencies than that at 10 Hz. This could be due to the limitation of the machine and present set-up, where the stress amplitude decreases as frequency of loading is increased.

Plastic deformation of frozen soils is mainly due to the viscous flow occurring in the ice phase. At any temperature, unfrozen water is always present in the soil at the interparticle

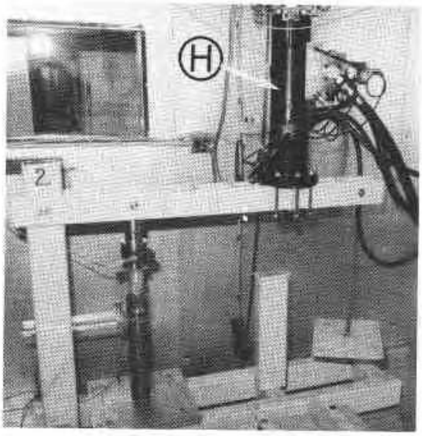

Fig. 2 Inside the cold room: (H) is the electrohydraulic shaker.

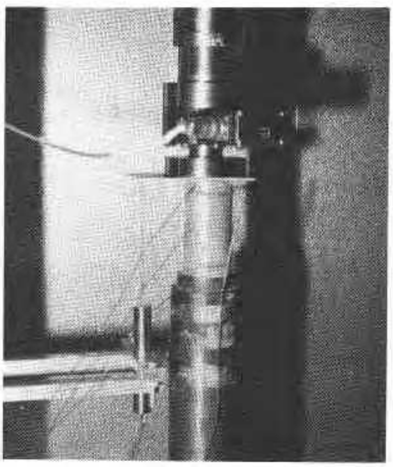

Fig. 3 Close-up of test specimen and LVDT.

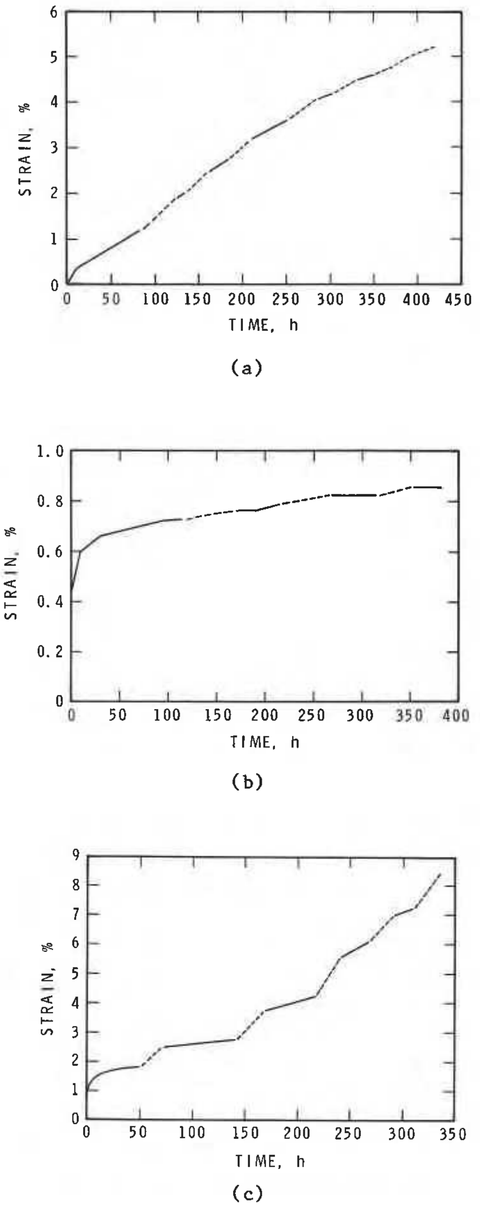

Fig. 4 Variation of axial strain with time.
(a) Thompson clay (Temperature: -2.5°C; moisture: 45%)
(b) Inuvik clay (Temperature: -2.5°C; moisture: 45%)
(c) saturated sand (Temperature: -2.5°C; moisture: 20%)

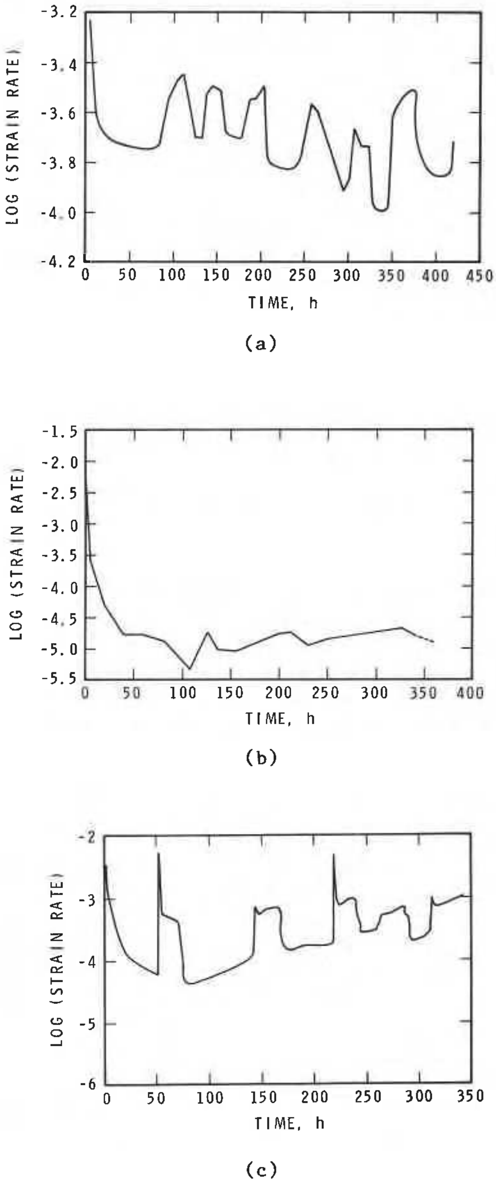

Fig. 5 Variation of strain rate with time.
(a) Thompson clay (Temperature: -2.5°C; moisture: 45%)
(b) Inuvik clay (Temperature: -2.5°C; moisture: 45%)
(c) saturated sand (Temperature: -2.5°C; moisture: 20%)

TABLE 1: Dynamic Creep Data from Three Representative Samples

Test No.	Material	Mean Static Stress σ_m(MPa)	Peak-to-peak alternating stress σ_a(MPa)	Creep Strain Rates Without (Shaker)	Creep Strain Rates With (S^{-1})	Strain Increment per cycle (10^{-9})	Strain at start of cycling (%)
10	Thompson Clay	0.534	0.032 (~6%)	3.21×10^{-8}	5.31×10^{-8}	2.10×10^{-9}	1.27
				3.31 "	5.19 "	1.88 "	2.04
				3.26 "	4.94 "	1.68 "	2.77
				2.88 "	3.91 "	1.03 "	3.67
				2.26 "	3.18 "	0.92 "	4.20
				1.94 "	2.44 "	0.50 "	4.64
15	Inuvik Clay	0.833	0.013 (~2%)	8.10×10^{-10}	2.20×10^{-9}	9.23×10^{-11}	0.73
				13.9 "	1.95 "	5.62 "	0.79
				0	2.32 "	2.32 "	0.82
30	Ottawa Sand	2.237	0.224 (~10%)	1.48×10^{-8}	8.66×10^{-8}	7.18×10^{-9}	1.90
				1.39 "	10.70 "	9.27 "	2.48
				2.84 "	14.9 "	12.06 "	3.50
32	Ottawa Sand	2.609	0.330 (12.6%)	6.19×10^{-8}	10.3×10^{-8}	4.10×10^{-9}	5.91
				2.47 "	9.94 "	7.47 "	7.84
				2.83 "	7.57 "	47.8 "	8.77

junction; the amount is higher, the closer the temperature is to 0°C and the finer the grain size of the soil. This unfrozen water decreases the interparticle friction stress, decreases the viscosity of the soil, and provides paths for diffusive flow in the soil. The unfrozen water can also migrate along the particle interfaces from regions of high stress to those of low stress and decrease the strength of the soil. Input of mechanical energy, as in cyclic loading, could increase the thermal energy in the soil by a hysteretic effect and cause an increase in the amount of unfrozen water content. In frozen soils it is probably this mechanism that accelerates creep during cyclic loading, above the threshold stress. In the present experiments there was also evidence of an increase in temperature of the sample during cycling, as shown in Figure 6 for a sand sample. The dashed portions of the lower curve denote the periods of cyclic stressing, and the corresponding temperatures, measured by a thermocouple embedded in the middle of the test specimen, are shown in the upper curve. In this test the cyclic stress was applied by a heavy electro-hydraulic shaker with a peak-to-peak load capacity of 1360 kg. The temperature of the test specimen was found to increase by almost one degree during cycling.

In many materials such as metals and ceramics, creep at high temperature is associated with the generation and accumulation of point defects (vacancies) and voids. During cycling more point defects are formed than under static stress and these could cause acceleration of creep deformation. These vacancies and voids are nucleated at grain boundaries or grain-particle interfaces due to stress concentrations and elastic accommodation. The failure pattern under high temperature cyclic loading was also found to be different from classical creep or fatigue failures in that cracks frequently follow grain boundaries and particle-grain interfaces. It is possible that in frozen soils voids could be generated at the

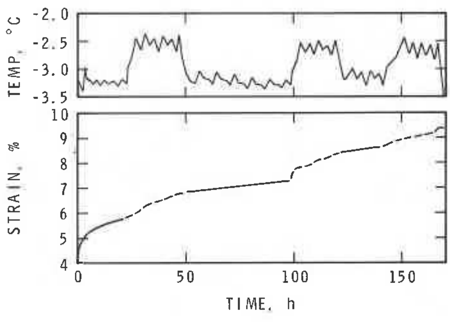

Fig. 6 Effect of cyclic stress on temperature of frozen sand.

interparticle junctions and cracks could be propagated along the interphase boundary regions where unfrozen water could be present. In unfrozen soil materials, the cyclic creep effect is more complicated due to the influence of water, but cyclic creep has been found to decrease with increasing load cycle and moisture content due to consolidation (Holubek, 1969; 1970).

The input of thermal energy caused by mechanical cycling and the amount of unfrozen water produced can be roughly calculated. The electrodynamic shaker has a force rating of 133 N with a maximum stroke capability of 159 mm (6.25 in) peak to peak. If we use the rms value of peak force and 50% of stroke as the operating level, the mechanical energy input per cycle is $0.707 \times 133 \times (15.9/2) \times 10^5$ dyne-cm, which is approximately equal to 7.5 joules per cycle or 1.786 calories. This could cause melting of 1.786/80 = 2.23×10^{-2} g of ice producing about 0.024 cm^3 of water. If this water is assumed to be distributed uniformly around the soil grains in a test specimen, it can be calculated, using the specific gravity of sand and the moisture content of the sample, that a layer of water of thickness equal to 100 A° (10 N.m) will be formed. Not all the mechanical energy will be converted to thermal energy, and even if only a fraction is converted to heat that will cause melting of ice, sufficient unfrozen water will be formed in several hundred cycles to cause accelerated viscous creep of the frozen soil samples.

Conclusions

Creep rate of frozen saturated sand and clays under compressive loading was increased considerably by superimposed alternating stresses of amplitude up to 10% of the mean static stress. This could be attributed to the increase in the amount of unfrozen water caused by transient thermal energy produced by mechanical cycling of the material. Such increases in creep rates caused by cyclic loading could reduce the bearing capacity of foundations in frozen soils, and could necessitate an increase in the value of the safety factor to be used in the design of foundations in permafrost areas.

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