A comparison of static and repeated loading tests on natural frozen soils

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The results of static creep tests and repeated loading compression tests on samples of frozen clayey silt, peat, and sand obtained from Cornwallis Island, Northwest Territories, Canada, are reported and compared. Special oversized end platens were used to reduce end effects on the cylindrical test samples.

The development of strains under repeated loading is examined and a semi-logarithmic relation is used to compare static creep rates with repeated loading deformations. Shear stress level and frequency of load application are found to have pronounced effect on the magnitude of the strains which develop under repeated loadings. Continuous deformation rates under repeated loadings are found to exceed static creep deformation rates when the applied stress exceeds about 30 per cent of the short-term strength of the frozen soils. At lower stress levels the repeated loading deformations are comparable to long-term stable creep deformations. Low-frequency repeated loadings (less than 0.5 Hz) are found to cause relatively large deformation rates in frozen soils.

Strain ratio (pseudo Poisson's ratio, ν) measurements show that these natural frozen soils exhibit values of ν less than zero under low stress levels to a maximum value of $\nu = 0.33$ under high stress levels. The common assumption of $\nu = 0.5$ is not considered applicable to natural frozen soils under normal design loadings.

Dans le présent article, sont décrits et comparés les résultats d'essais de fluage sous charge statique et des essais de compression sous charge répétée que l'on a effectués sur des échantillons de silt argileux, de tourbe et de sable gelés obtenus dans l'île Cornwallis (Territoires du Nord-Ouest). On a employé des plateaux très larges, pour réduire les effets des bords sur les éprouvettes cylindriques.

On examine le développement des déformations sous l'effet de charges répétées et l'on emploie une relation semi-logarithmique pour comparer les vitesses de fluage sous charge statique aux déformations résultant de l'application de charges répétées. On a constaté que l'intensité des contraintes de cisaillement et la fréquence d'application des charges avaient un effet prononcé sur l'importance des déformations qui se manifestent en présence d'une charge répétée. On a sussi constaté que les vitesses de déformation continue sous charge répétée dépassaient les vitesses de déformation par fluage sous charge statique, lorsque la contrainte appliquée dépassait d'environ 30 pour cent la résistance des sols gelés à une charge de courte durée. À des niveaux de contrainte moins élevés, les déformations sous charge répétée sont comparables aux déformations de fluage rémanentes. On a observé que les charges répétées de basse fréquence (moins de 0,5 Hz) donnaient lieu à des vitesses de déformation relativement grandes dans les gélisols.

Les mesures du taux de déformation (coefficient modifié de Poisson), montrent que ces gélisols naturels présentent des valeurs ν inférieures à zéro pour des contraintes faibles jusqu'à une valeur maximum de $\nu = 0,33$ en présence de contraintes élevées. L'hypothèse courante d'après laquelle $\nu = 0,5$ n'est pas considérée comme applicable aux gélisols naturels soumis à une charge théorique normale.

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Introduction

Dynamic testing of frozen soils using resonant column techniques (Stevens 1973) and electromagnetic vibration techniques (Kaplar 1963), has been employed mainly to obtain elastic constants under small-amplitude deflections. The major application of such data is in analyzing the response of these materials to earthquake loadings. The tests reported in this paper were carried out by applying repeated loads to frozen soil samples at frequencies between 0.2 and 0.5 Hz while the continuous permanent sample deformations were monitored. The main application of these results is in the analysis of the continuous movements (deformations) of frozen soils adjacent to foundation elements subjected to low-frequency repeated loadings. One example would be footings or anchors for transmission towers on permafrost.

Material Properties

Samples of natural frozen soils were obtained on Cornwallis Island (latitude 75°15′N, longitude 95°00′W) using a portable core drill below the base of a pit dug about 300 mm through the active layer. Ten cores of 76 mm diameter and 200 mm length were recovered from between 200 and 400 mm below the permafrost table in each soil type (clayey silt, sand, and peat). Cores were wrapped in plastic and aluminum foil and placed immediately into freezer chests packed with ice. The coolers were stored in freezers except during air transport to Montreal and ground transport to Kingston. The sand soil had D_{10} = 0.1 mm and a uniformity coefficient of 3.1, classifying as an SP soil in the Unified System. The clayey silt (classified ML) contained less than 10 per cent clay sizes and had a uniformity coefficient of about 10. The organic content of the fine fibrous peat was determined to be between 29.5 and 31 per cent (by both hydrogen peroxide and combustion test methods). The frozen sand was homogeneous, but samples of the clayey silt and peat contained ice inclusions and lensing (Figure 1). Limits in the degree of saturation of test samples are listed:

Clayey silt - 91 to 103 per cent saturated (some lensing)
Uniform sand - 89 to 93 per cent saturated (homogeneous)
Fibrous peat - 88 to 91 per cent saturated (ice inclusions).

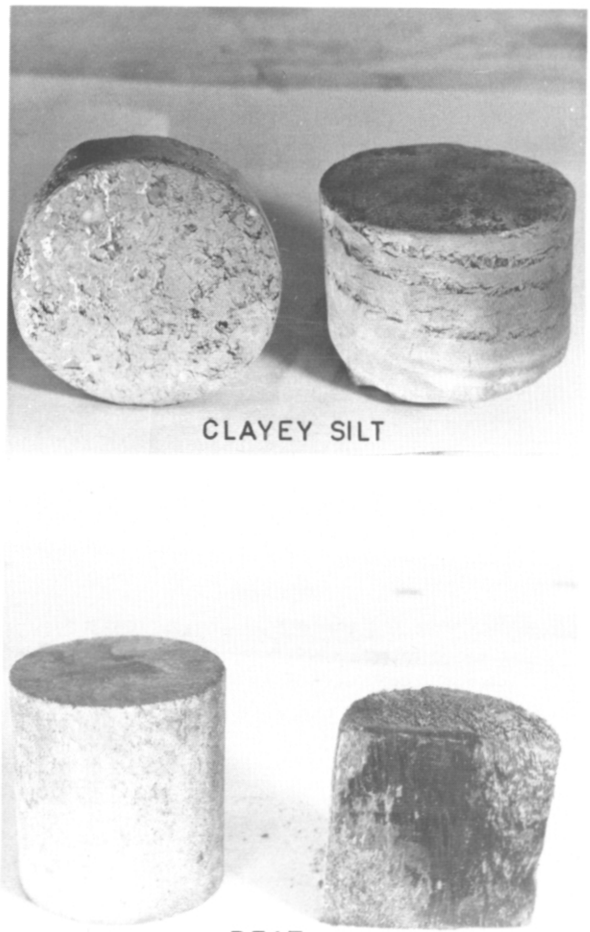

FIGURE 1. Samples of frozen clayey silt and peat.

Equipment and Test Procedures

Commercial rolling diaphragm cylinders (Bellofram cylinders) were activated by air pressure in order to apply static and repeated axial loading on triaxial specimens of frozen soils. To create repeated loadings, a solenoid valve and a timer/counter switch were used to control the flow of air in and out of the loading cylinder. Cell pressures were created by an air pressure introduced in the upper part of the cell so that changes in cell fluid (antifreeze) level could be monitored to determine sample volume changes. This method was used by Baker (1976) and is considered to be sufficiently accurate for the determination of strain ratios for engineering purposes (*see also* a discussion of measurement accuracy by O'Connor and Mitchell 1978).

Dry bottled air was used as an air supply for the loading cylinders in order to prevent icing in the lines, and the cylinder air pressure in the repeated loading tests was monitored by a pressure transducer mounted on the loading cylinder. Axial displacements were monitored by a direct current differential transformer (DCDT) linear displacement transducer mounted in the upper part of the cell. The equipment is shown on Figure 2 and further details of this equipment were described by Trimble (1977). Repeated loadings, using the solenoid switch system, are theoretically of a square-wave form with 50 per cent duty cycle (load

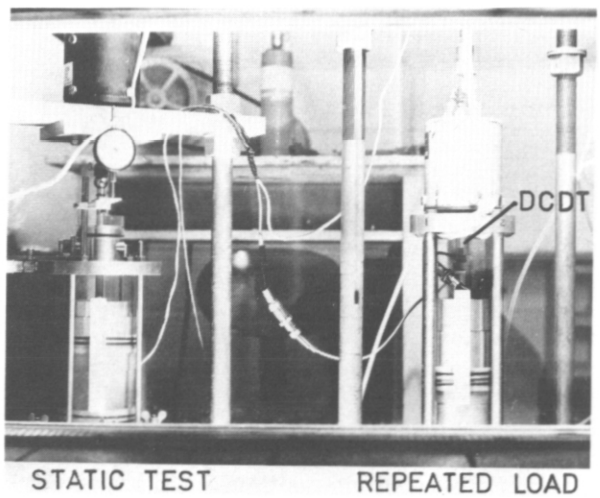

FIGURE 2. View of testing equipment through cold-room window.

on 50 per cent of the time). Measured cylinder pressures, however, showed an exponentially decreasing rate of pressure build-up and an exponential decay of pressure (due to the air flow required to operate the system) such that the full load was on for about 30 per cent of the cycle time, the load was at zero for about 40 per cent of the cycle time, and the load was varying for the remaining 30 per cent of the cycle time (about 20 per cent increasing load and 10 per cent decreasing load). Aluminum loading platens contained 5 mm thick by 85 mm diameter confined disks of frozen soil, similar to the soil being tested, in order to reduce contact stress effects and achieve the desired intimate contact and parallel alignment between the sample and loading platens. Test samples were nominally 76 mm in diameter by 140 mm in length.

An initial series of displacement controlled tests were carried out at a displacement rate of 3.4×10^{-4} mm/s to obtain a reference value for the short-term strength of each of the three frozen soil types. Because the stress–strain relations in these slow tests were of the 'plastic' type, the deviatoric stress at 10 per cent strain was taken as $(\sigma_1 - \sigma_3)_f$. Static and repeated loading creep tests were then conducted at stress ratios, $X = (\sigma_1 - \sigma_3)/(\sigma_1 - \sigma_3)_f$ between 0.1 and 0.84. Since strain-controlled tests indicated no significant differences in test results for cell pressures of 50 to 250 kPa (Trimble 1977) a cell pressure of 150 kPa was selected for all subsequent tests. Static creep and repeated loading tests were done in parallel on identical samples and were continued, for each pair of samples, until the bottled air supply was depleted. All testing was carried out in a cold room at −11°C (±0.5°C) a temperature which is thought to be about 1°C colder than the minimum ground temperature at the sample locations.

Test Results

Typical results from static and repeated (0.5 Hz) loading tests on frozen sand samples at X = 0.5 are plotted on Figure 3. Similar forms of stress–strain relations were noted for other values of X and other materials. The relative magnitudes of the strains in static and repeated loading tests depend mainly on the value of X (material type was of secondary importance under these high-saturation and low-temperature test conditions). All the original data was plotted by Trimble (1977) and the relations are similar to the primary creep relations observed by other

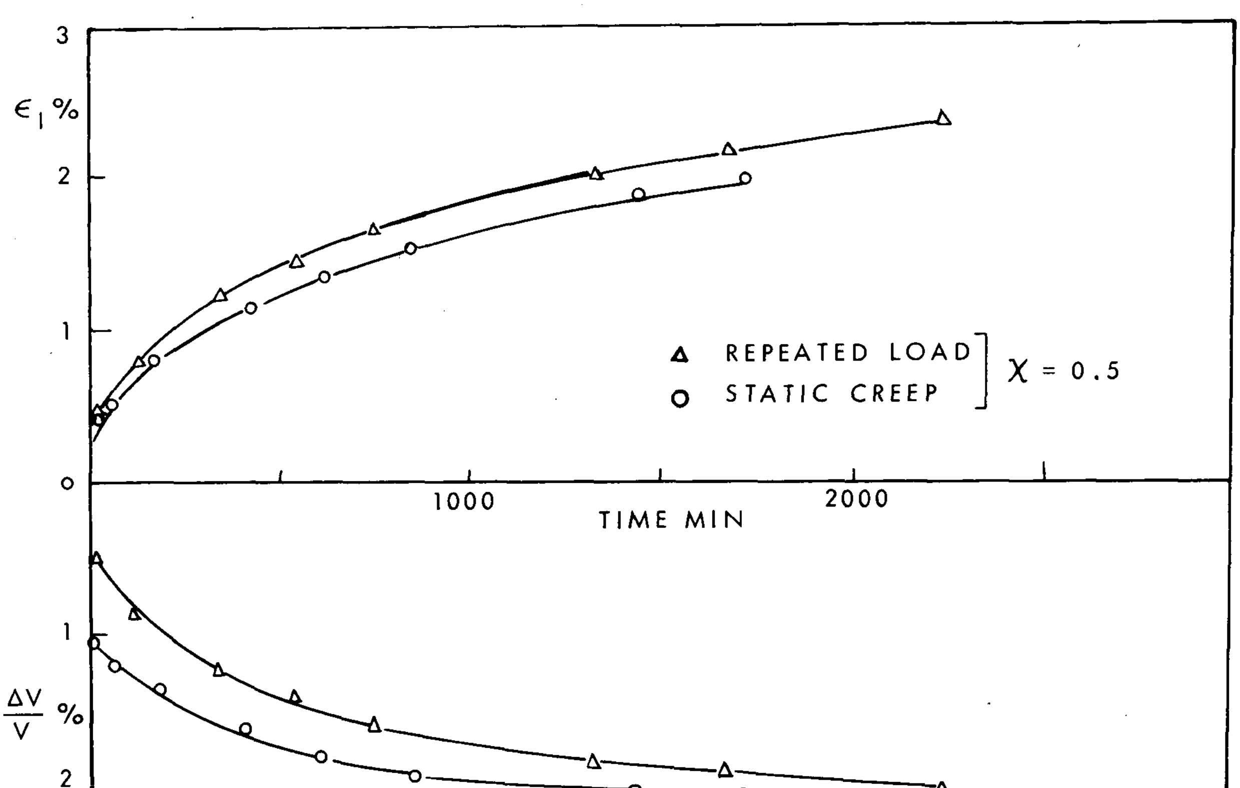

FIGURE 3. Typical strain relations for frozen sand.

researchers except that the volumetric strains are notably higher. Most of the available published data comes, however, from saturated samples prepared in the laboratory and the present data is from partly saturated natural materials. With corrections for ice lensing, the actual degree of saturation of the soil matrix, in many cases, was calculated to be as low as 85 per cent. A strain-increment ratio, $\nu = -\delta\varepsilon_3/\delta\varepsilon_1$ was calculated from test data for all tests and this ratio was found to vary significantly with the material type and value of X. For the clayey silt and sand, ν was found to be negative for $X < 0.3$ (a minimum of $\nu = 0.5$ for frozen sand at $X = 0.1$) and positive for X>·3 (a maximum of 0.33 for frozen sand at $X = 0.5$ and for frozen clayey silt at $X = 0.84$). The calculated values of ν for the frozen peat were negative at all X values. Negative strain-increment ratios are considered to result because these natural frozen materials are not saturated, allowing positive (compressional) strain increments to develop in all directions in response to low-level, deviatoric stress increases. There was no significant difference in ν between static creep and repeated loading tests.

Figures 4 and 5 show typical axial strain rates from static creep and repeated loading tests respectively. This data indicates that most tests were terminated prior to the end of the primary creep stage; the test at X = 0.84 on frozen clayey silt (*see* Figure 5) appears to have attained a nearly constant strain rate, characteristic of secondary creep.

While the deformations obtained in repeated loading tests are comparable to classical creep curves, the effect of applied stress level is more pronounced under repeated loadings. For field applications the long-term deformation rates are of greater significance than the initial primary deformations and may be estimated from the data by plotting axial strains against the logarithm of time (Figure 6). The long-term creep rate ($\delta\varepsilon_1/\delta \log t$) from a creep test can then be compared with that from a repeated loading test. The comparisons are shown on Figure 7 and it is concluded that the frozen peat material exhibits similar long-term creep rates under both types of loading while the other two materials (and in particular the frozen clayey silt) exhibits much larger long-term creep rates under repeated loads (compared to static loads) when the applied stress level exceeds about 30 per cent of the short-term sample strength (i.e. when $X > 0.3$).

The effect of loading frequency was investigated by

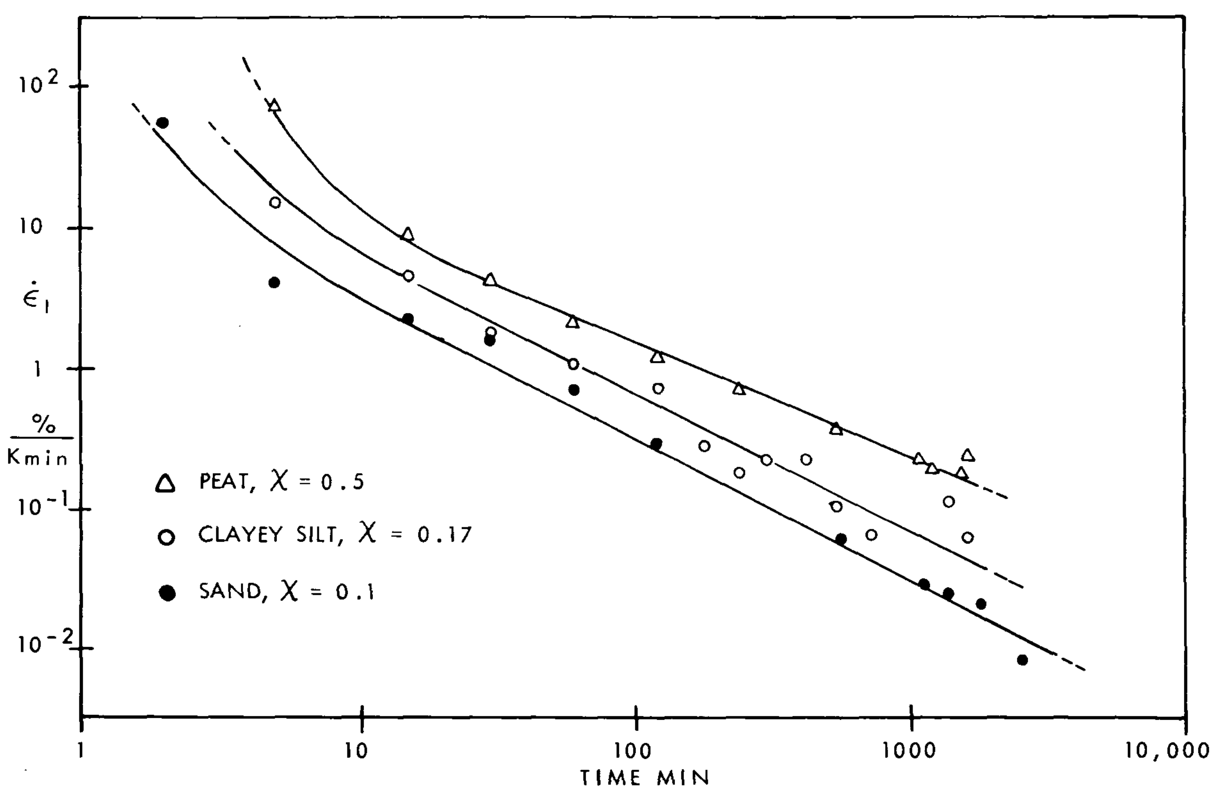

FIGURE 4. Axial strain rates for typical creep tests.

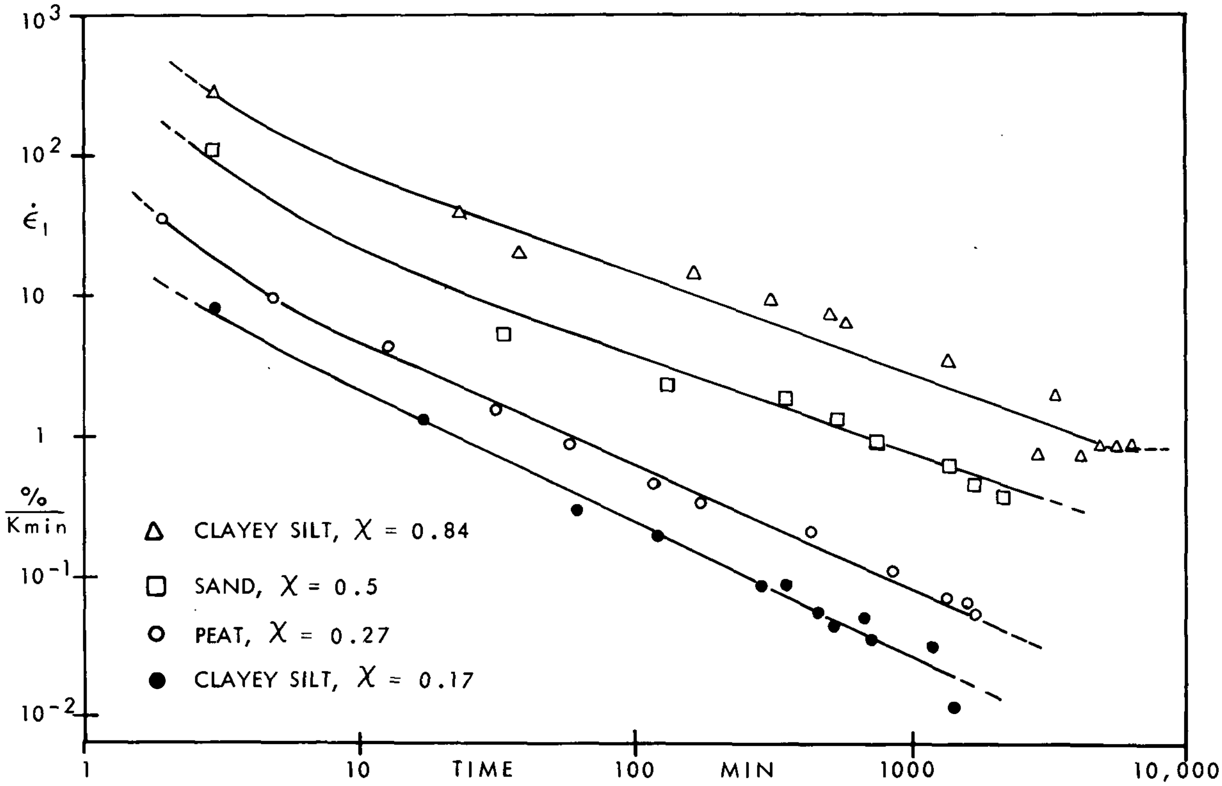

FIGURE 5. Axial strain rates for typical repeated loading tests.

a series of repeated loading tests on frozen clayey-silt samples at 12 cycles/min (0.2 Hz), 18 cycles/min (0.3 Hz), and 30 cycles/min (0.5 Hz). The test data, plotted on Figure 8, show that the creep rate increases as the loading rate is decreased. It is difficult to compare these results directly with static creep test results because the duty cycle of the loading mechanism creates a varying load and the sample is subjected to the full loading for less than one-half the time (approx 35 per cent of the time in this case). To study the response of frozen soil to repeated loadings in more detail, several samples were subjected to manual cycling at about 2 cycles/min. Typical of the response is the data on Figure 9 where each cycle is

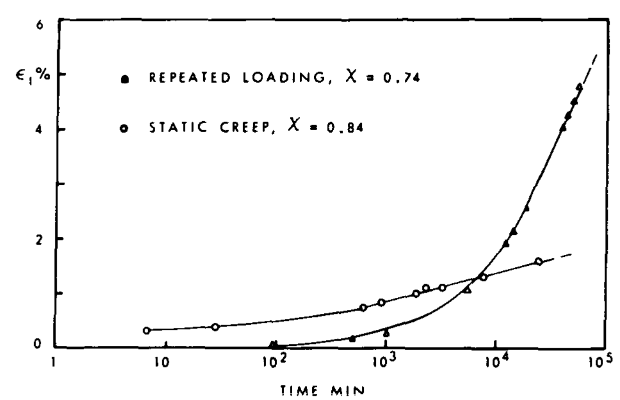

FIGURE 6. Typical axial strains in frozen clayey-silt samples.

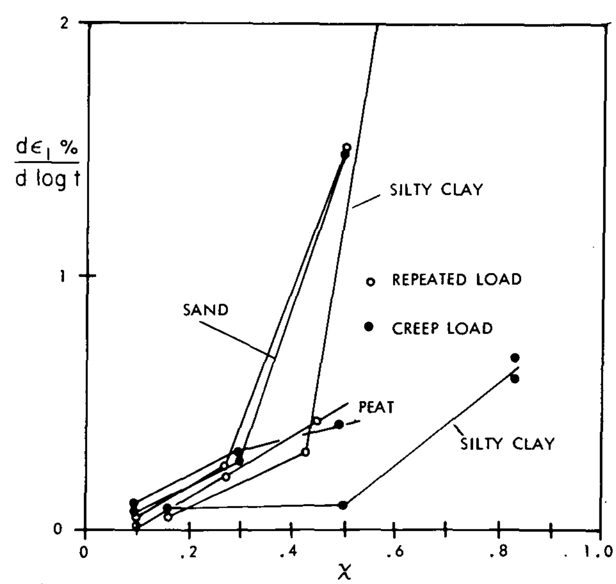

FIGURE 7. Long-term creep rates.

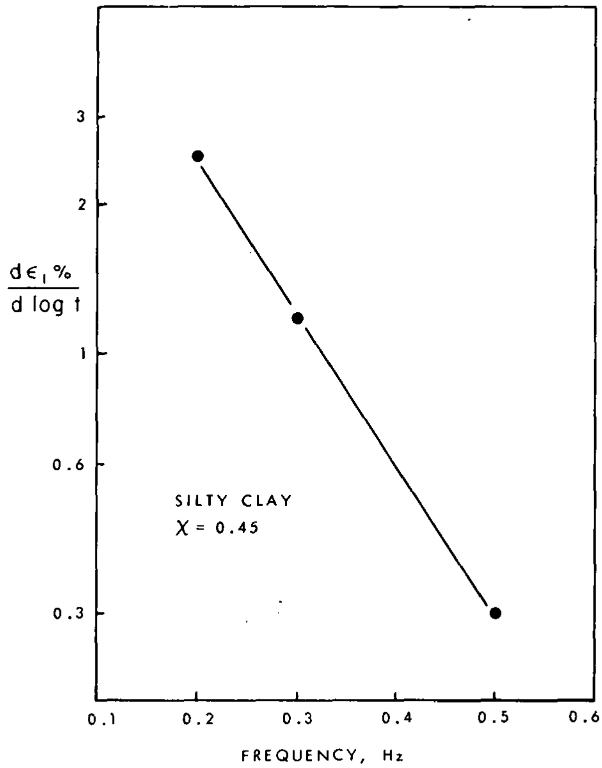

FIGURE 8. Creep rate under various loading frequencies.

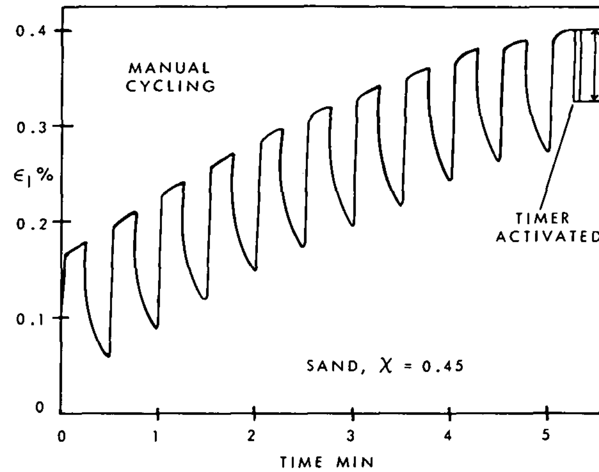

FIGURE 9. Axial strain during manual cycling of load.

characterized by rapid deformation and slow strain recovery. While both the recoverable and the non-recoverable axial strains decrease with increasing numbers of cycles, the large strains which develop during low frequency repeated loading are an interesting phenomenon. These strains may be considered to result from the superposition of concurrent primary deformations caused by each subsequent loading cycle. It is not known whether a continuation of such low-frequency repeated loads would lead to extremely high creep strain rates (*see* data on Figure 8) and failure of the sample or whether the creep rate would reach a stable constant value. The testing reported herein was limited by the number of natural samples available as well as by physical and equipment limitations. Further study of the response of frozen soils to low-frequency repeated loadings is obviously warranted.

Conclusions

The results of comparative static creep tests and repeated loading tests can be used to evaluate the design requirements for foundation elements (in frozen soils) subjected to repeated loadings. Machine loadings as well as wind and/or wave action can create cyclic repeated loadings on foundation elements. Within the physical restrictions limiting the data obtained from this study, the following tentative conclusions are drawn:

1. Repeated loadings at stress levels in excess of about 30 per cent of the short-term strength of a frozen soil generally cause soil deformations in excess of those associated with static creep under the same stress level. For lower stress levels the repeated loading deformations are generally of the same magnitude as (or less than) static creep deformations.

2. The frequency of application of repeated loadings appears to have a major influence on the short-term deformations in frozen soils. Low-frequency loadings (less than 0.5 Hz) can cause large deformations and frozen soils subjected to low-frequency repeated loadings in excess of 30 per cent of the short-term static strength may attain a failure condition in a relatively short time period.

If foundation elements in frozen soils are to experience repeated loadings it is recommended that these loadings be restricted to avoid excess deformations. In some cases, pre-cycling or adjustments during early operations may be a feasible method of reducing the design-life deformations. Results of the tests show that significant volumetric compression occurs during shear testing of these natural frozen soils. This volumetric compressional strain exceeded the axial strain in many cases, particularly at low deviatoric stress levels, and is considered to result, primarily, because the soils are not fully saturated. Lack of complete saturation of the soil matrix in natural frozen soils apparently effects the strain response to stress increases and this aspect of frozen soil behaviour warrants further research.

Acknowledgement

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