Influence of repeated loading on the behaviour of frozen silty clay

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The results of an experimental study investigating the effects of dynamic loading on the shear strength of frozen silty clay are presented. Specimens were tested at temperatures of −1, −2, and −3°C and under a constant confining pressure of 200 kPa. The mechanical behaviour of the frozen soil subjected to repeated loading is compared with the behaviour of the same frozen soil without the repeated loading history. It was found that the shear strength of the frozen sample subjected to repeated loading decreased by about six per cent at temperatures near −1°C but showed no difference at lower temperatures, i.e. −2 or −3°C. The deformation modulus of the frozen soil increased when subjected to repeated loading. The increase was about 200 per cent at -1°C and 75 per cent at -3°C for the soil tested.

Cet article présente les résultats d'une étude expérimentale des effets d'une charge dynamique sur la résistance au cisaillement d'argiles limoneuses gelées. On a soumis des échantillons à des températures de −1, −2, et −3°C, et à une pression lithostatique constante de 200 kPa. On compare le comportement mécanique du sol gelé sous l'effet d'une charge répétée au comportement de ce même sol non soumis à cet effort répété. On a constaté que la résistance au cisaillement de l'éprouvette gelée soumise à une charge répétée diminuait d'environ 6 pour cent aux températures proches de −1°C, mais ne variait pas aux températures plus basses, comme −2 ou −3°C. Le module de déformation du gélisol a augmenté en présence d'une charge répétée. L'augmentation était d'environ 200 pour cent à −1°C et de 75 pour cent à 3°C pour le sol testé.

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Introduction

The behaviour of soils subjected to earthquakes, traffic loads, explosions, etc. is important in regards to the safety of structures. Such dynamic loads may cause considerable decreases in the strength of soils endangering life and property.

The effects of repeated loading on the strength of unfrozen soils were studied by various investigators. Seed and Chan (1966) and Lee and Focht (1976), for example, observed marked decreases in the strength of unfrozen soil under the influence of repeated loading. The change in the strength of unfrozen soil is closely related to the increase of pore-water pressure induced by repeated loading.

The structure of the frozen soil is more complex than that of the unfrozen soil. Existence of an ice phase and ice cementation bonds play an important role in the behaviour of the frozen soil.

Prokudin and Zhinkin (1973) carried out dynamic tests on frozen saturated specimens at temperatures between 0 and −2.4°C by changing the cell pressure in a sinusoidal form and found that strength decreases under the effect of vibrodynamic loads as compared to static conditions.

Tsvetkova (1960) compared the strengths of frozen and unfrozen soils under repeated loading, and found a strength decrease of 22 per cent for the frozen samples tested under dynamic loads at −0.8 to −1.0°C. Yet no change in the strength of unfrozen samples was observed.

Nadezhdin and Sorokin (1975) found that the strength properties of frozen soil were affected by preloading. The long-term strength was shown to increase and the instantaneous strength was shown to decrease by preloading.

The influence of dynamic loading on the mechanical behaviour of frozen soils could be explained by the existence of unfrozen water in the frozen soil and by the increase of the pore-water pressure as well as the destruction of the structural bonds of ice.

In this paper mechanical behaviour of frozen samples subjected to repeated loading is compared with that of the samples which had not been subjected to repeated loading.

Method

In this study specimens were tested at temperatures of −1, −2, and −3°C in a triaxial test apparatus by applying a constant confining pressure of 200 kPa. In all dynamic tests by repeated loading, specimens were sheared to failure under undrained conditions. In the static test the rate of deformation was 1.143 mm/min.

Topser Red Clay was used throughout the tests. Samples were prepared by compacting with a compaction energy per unit volume equivalent to that of Standard Proctor energy. Following saturation, all samples were frozen at $-20 \pm 1°C$ and then brought to the test temperature. It should be noted that by this process, the amount of unfrozen water in a sample will be smaller than it would be in a sample frozen at -1 or $-3°C$. Specimens have a diameter of 34.3 mm and a height of 71.5 mm. Degree of saturation of specimens was calculated to be between 96 and 99 per cent.

Properties of Topser Red Clay are: $w_L = 0.41$, $wp = 0.23$, $1p = 0.18$, $\gamma_{solids} = 27.3$ kN/m³, $\gamma_{opt} = 17.0$ kN/m³, $w_{opt} = 0.19$ and the grain-size distribution is:

0.42 to 0.06 mm	30 per cent
0.06 to 0.002 mm	51 per cent
Smaller than 0.002 mm	19 per cent

Tests were carried out in a cold room with dimensions of $2.65 \times 1.64 \times 2.26$ m.

Dynamic (repeated) loading was performed with a SBEL SDT - 1000 Dynamic Triaxial Apparatus; load capacity 1000 lbs (4.45 kN). The test set up is the same as in Togrol *et al.* (1977). In such an apparatus, specimens were subjected to one-directional repeated loading with a square-wave form. Liquid paraffin was used in the cell to apply the confining pressure. Confining pressure was kept constant within ± 5 kPa.

Results

A large number of undrained triaxial compression (static) tests on frozen Topser Red Clay specimens with a constant confining pressure of 200 kPa showed that the peak deviatoric stress could be given (for a temperature range of -1 to $-3°C$) as

$$(\sigma_1 - \sigma 3_s)_{max} = 0.977\theta^{0.561}\text{MPa}.$$

θ is the absolute value of the negative temperature in degrees Celsius. And the modulus of deformation could be written as

$$E_S = 33\theta + 0.3\,\text{MPa}.$$

Triaxial compression tests were carried out on samples subjected to repeated loading at various temperatures ($\theta = -1°C, -2°C, -3°C$) and at various loading conditions on the frozen silt. The results strongly suggest the following relationship:

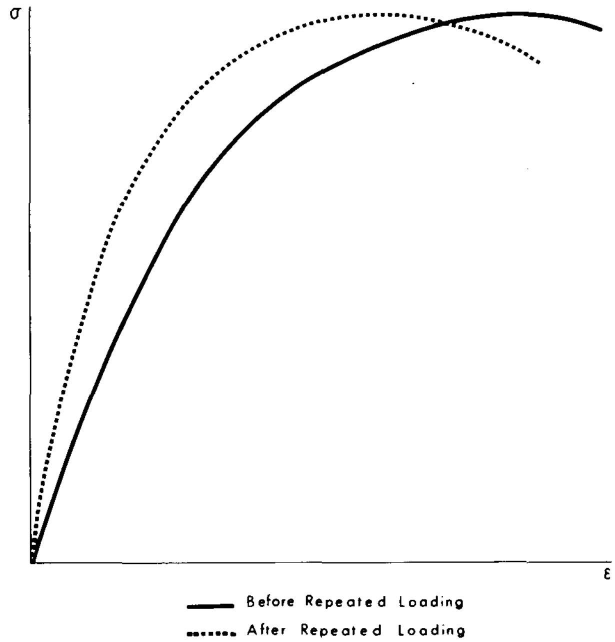

FIGURE 1. Influence of repeated loading on the stress–strain curve.

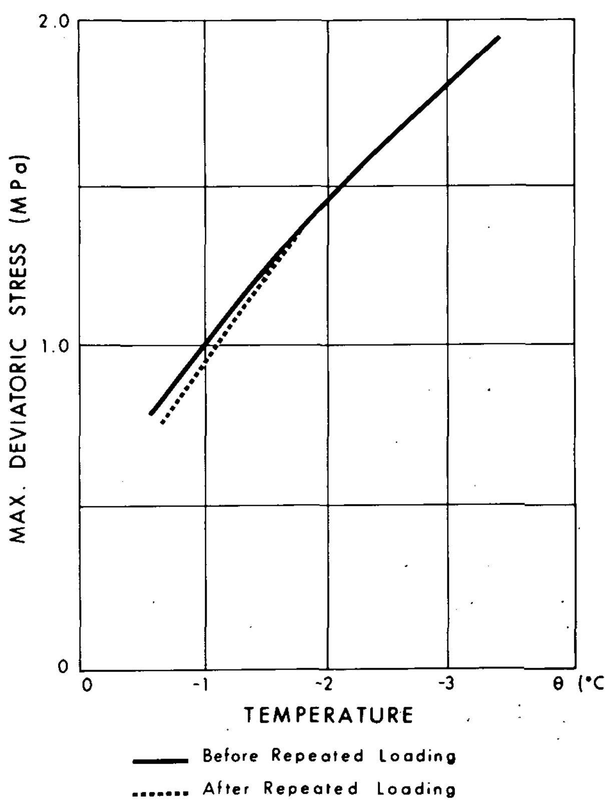

FIGURE 2. Influence of repeated loading on the shear strength at various temperatures.

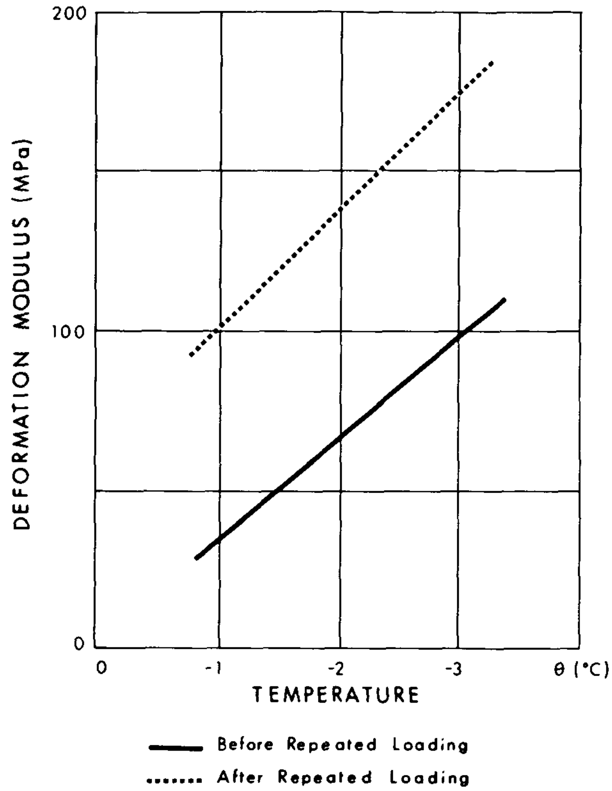

FIGURE 3. Influence of repeated loading on the deformation modulus at various temperatures.

$$(\sigma_1 - \sigma_3)_{max} = 0.922\theta^{0.627}\text{MPa}.$$

The deformation modulus could be given as:

$$E_C = 36\theta + 66\,\text{MPa}.$$

Results of the tests could be summarized as:

(1) Strength properties of frozen soil change under the influence of repeated loading. This change is more pronounced at temperatures just under 0°C.

(2) Stress–strain curve of frozen soil is influenced from the repeated loading (Figure 1). The samples subjected to dynamic stress reaches to failure at smaller strains.

(3) The shear strength of frozen soil when subjected to repeated loading decreases by about six per cent at temperatures near −1°C but shows no difference at lower temperatures, i.e. −2 or 3°C (Figure 2).

(4) The deformation modulus of frozen soil increases when subjected to repeated loading. This increase is found to be about 200 per cent at −1°C and 75 per cent at −3°C for the soil tested (Figure 3).

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