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# LABORATORY STUDIES OF THE ADFREEZE BOND BETWEEN SMALL-SCALE MODEL PILES AND FROZEN SAND



by V.R. Parameswaran

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The adfreeze strength developed during freezing of cylindrical piles to fine Ottawa sand mixed with 14% by weight of water was measured under constant rates of pile displacement on an Instron testing machine and under constant load [in a creep equipment]. Four types of pile were studied: natural B.C. fir, concrete, steel coated with a red oxide primer, and creosoted B.C. fir. Constant rate tests showed that adfreeze strength increased with increasing loading rate. Preliminary data from the constant load creep tests indicate that the load dependence of the steady-state creep rate for piles in frozen sand agrees with the displacement rate dependence of the adfreeze strengths determined by extrapolation of the results of the constant rate tests. In general, maximum adfreeze strength developed with natural B.C. fir, and the minimum with creosoted B.C. fir.

ÉTUDE EN LABORATOIRE DE L'ADHÉRENCE DUE AU GEL ENTRE DES PIEUX À L'ÉCHELLE ET DU SABLE

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L'adhérence due au gel de pieux cylindriques à du sable fin d'Ottawa contenant 14% d'eau, au poids, a été mesurée sous déplacement des pieux à vitesse constante, dans une machine d'essai Instron, et sous charge constante (dans un appareil provoquant la reptation). Quatre types de pieux ont été étudiés: en sapin de Colombie non traité, en béton, en acier recouvert d'un primaire au minium de plomb et en sapin de Colombie créosoté. Les essais à vitesse constante ont montré que l'adhérence due au gel augmente avec le taux de mise en charge. Les résultats préliminaires des essais de reptation à charge constante indiquent que le rapport entre la charge et la reptation à vitesse constante des pieux dans le sable gelé correspond au rapport entre le taux de déplacement et la force de l'adhérence due au gel extrapolé des résultats des essais à taux constant. Dans l'ensemble, l'adhérence maximale se manifestait avec le sapin de Colombie non traité et l'adhérence minimale, avec le sapin de Colombie créosoté.

ЛАБОРАТОРНЫЕ ИССЛЕДОВАНИЯ СИЛЫ СМЕРЗАНИЯ МЕЛКОМАСШТАБНЫХ МОДЕЛЕЙ СВАЙ С МЕРЗЛЫМ ПЕСКОМ

Сила смерзания цилиндрических свай с мелкозернистым песком, смешанным с 14 вес.% воды, измерялась при постоянных скоростях смещения свай на испытательной машине Инстрон и при постоянной нагрузке /на машине для испытания на ползучесть/. Изучались четыре типа свай: сосновая; бетонная; стальная, покрытая суриком; и сосновая, пропитанная креозотом. Эти испытания показали, что сила смерзания возрастает с увеличением скорости нагружения. Предварительные данные испытаний на ползучесть при постоянной нагрузке указывают на то, что зависимость стабильной скорости ползучести от нагрузки для свай в мерзлом песке согласуется с зависимостью между скоростью смещения и силой смерзания, определяемой путем экстраполяции результатов испытаний. Отмечено, что максимальная сила смерзания развивается при использовании необработанных сосновых свай, а минимальная - при использовании сосновых свай, пропитанных креозотом.

# LABORATORY STUDIES OF THE ADFREEZE BOND BETWEEN SMALL-SCALE MODEL PILES AND FROZEN SAND

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## INTRODUCTION

Pile foundations incorporating an air space between the structure and the ground surface are used extensively in permafrost areas to transfer the structure loads through the unstable active layer to the more stable permafrost. Various types of piles, including timber, steel pipes and H-sections, and precast concrete piles, may be used. Wood piles are the most common, however, because they are available locally in many parts of the permafrost regions. Cast-in-place concrete piles have been used occasionally in special cases. As a rule of thumb, a minimum depth of embedment in permafrost of 3 metres or three times the maximum depth of the active layer during the design life of the structure (whichever is larger) is recommended for piles in permafrost regions.

A pile foundation must resist uplift forces due to frost heave in the active layer and loads due to wind and the weight of the structure. Pile foundations in frozen ground transfer superimposed loads by two mechanisms: end bearing, and shear along the pile (adfreezing). The total bearing capacity of a pile is therefore the sum of the calculated contributions of the two mechanisms. Empirical formulae for these calculations have already been proposed by several workers in the Soviet Union (Vyalov and Porkhaev, 1969), based on their experience in building in the North.

The end bearing capacity of a pile can be obtained from the value of the compressive strengths of the soil determined under confined and unconfined conditions. The shearing resistance developed at the pile-soil interface has two components: that due to adhesion of ice to the pile; and that due to soil grain friction at the pile-soil interface. The supporting capacity for a pile embedded in permafrost results primarily from the shearing resistance at the pile surface. In general, for a pile supporting a structure in permafrost the following condition should be met:

$$P + \tau_f A_f + \tau_d A_d > L - \tau_h A_h - U$$

where P is the end-bearing capacity for the pile, as determined from the compressive strength of the soil under the pile, the cross-sectional area of the bottom end of the pile, and a suitable factor of safety,

$\tau_f$ is the adfreeze strength at the pile-soil interface,

$A_f$ is the pile-soil interfacial area in the permafrost zone,

$\tau_d$ is the frictional drag stress between the pile and the unfrozen soil (if present) over the permafrost zone,

$A_d$ is the pile-soil interfacial area in this zone,

L is the structural load,

$\tau_h$ is the stress due to frost heave in the active layer in the ground

$A_h$ is the pile-soil interfacial area in the active zone,

U is the uplift load due to wind

By knowing the distribution of the allowable adfreeze strength, $\tau_f$, along the length of the pile, the depth of embedment in permafrost required to carry the applied load L can be calculated. Thus it is imperative that $\tau_f$ be determined accurately to permit reliable design of foundations for structures in permafrost regions.

Although measurements of the adfreeze strength between piles and frozen ground have been taken since 1930 (mainly in the Soviet Union), sufficient information is not yet available to make it possible to design for different foundation materials such as concrete, wood, and steel in various soils. The early tests were done by freezing a pile into the ground, then pushing it through or pulling it out of the completely frozen ground at a relatively fast rate and measuring the force required. The results of early work in the Soviet Union from short-term tests have been given by Tsytovich and Sumgin (1959), Tsytovich (1975) and Vyalov (1965). Crory (1966), Crory and Reed (1965) and Sanger (1969) have reported the results of pile load tests in the permafrost regions of North America for adfreeze strength, pile settlement under loads and heave of piles due to freeze-back of the active layer. Some of the tests were short term, and others were carried out over periods of several weeks.

There has been no systematic laboratory measurement of the adfreeze strength between piles and soils. Recently, Laba (1974) measured the instantaneous adfreeze force ("frost grip," as he called it) between frozen sand and concrete under laboratory conditions by pushing frozen sand from an inner cylindrical cavity in a concrete block at a rate of 1.2 mm per minute. These results indicate, in general, that "frost grip" decreased rapidly with increasing porosity, that it increased with increasing ice content in the sand and that "frost grip" increased with decreasing temperature.

Laboratory studies have been initiated on the influence of variables such as loading rate, type of pile and pile surface, temperature, moisture, etc., on the adfreeze strength and bearing capacity of piles in frozen soils. Some preliminary results of measurement of the adfreeze strength developed at the interface between model piles and frozen sand-ice mixtures are presented in this paper.

## EXPERIMENTAL METHOD

### Measurement of Adfreeze Strength under Constant Rates of Displacement

The apparatus used for the experiments is illustrated in Fig. 1. The model pile (A) was 76.2 mm in diameter and 304.8 mm long. Ottawa fine sand (ASTM Specification C-109, passing Sieve No. 30 and retained on Sieve No. 100) mixed with 14% by weight of water was placed and compacted around the pile in five layers, each 38.1 mm thick, to an optimum density of about 1,700 kg $m^{-3}$, as determined by a standard Proctor test. Box (B) was of 25.4 mm thick Plexiglas plates, and the plug (C) and the base (D) were aluminum. The box containing both pile and sand was placed in a cold room (maintained at -6°C ± 0.2°C) for four days to ensure complete freezing of the sand. A thermocouple (T) placed in the middle of the sand was used to determine temperature.

After complete freezing the plug (C) was removed and the pile pushed out by a ram attached to the cross-head of a floor model Instron testing machine (25000 kg capacity) installed in the cold room. Each test was carried out at a constant rate of cross-head movement. Displacement of the pile was taken to be equal to the displacement of the cross-head less the deflection of the plate (D), measured by a dial gauge or a DCDT positioned under the plate near the pile.

Four types of cylindrical piles were studied:

Natural B.C. fir with a smooth surface finish.

Concrete piles with a smooth surface finish. These were cast in the laboratory from a commercial dry mix, Sakrete, to which water was added in the recommended proportion. After casting in Plexiglas tubes having an internal diameter of 76.2 mm and wall thickness of 12.7 mm, the concrete mix was vibrated using an electric vibrator to eliminate as much occluded air as possible. The finished and cured concrete cylinders had a density of 2250 kg $m^{-3}$.

Steel piles made from mild steel tubes having outside diameter of 76.2 mm and wall thickness of 6.35 mm closed at the bottom end with a welded steel plug and at the top by a rubber stopper. These piles were painted with a red oxide primer to prevent rusting in the wet sand.

Creosoted B.C. fir. B.C. fir piles, machined to a smooth surface finish, were creosoted in a high pressure autoclave in the Eastern Forest Products Laboratory, Department of Environment, Ottawa. Following creosoting, the wood was found to have absorbed, on an average, 96.3 kg $m^{-3}$, i.e. each pile would have about 0.136 kg of creosote.

### Results of Constant Rate Tests

When a pile was loaded at a constant rate, the load-displacement curve was very similar to the stress-strain curve for a frozen soil in unconfined compression, as shown in Fig. 2 for an untreated B.C. fir pile. The load reached a peak, then dropped quickly, indicating that the bond between the wooden pile and sand had broken. A similar curve was obtained for concrete piles. For a painted steel pile, the load reached a maximum, then dropped abruptly, indicating a clean shear of the pile from the soil. In Fig. 2 the load decreases less abruptly, indicating that there is still some adhesion at the interface. Adfreeze strength was calculated by dividing the maximum load at the peak of the curve by the surface area of contact between the pile and the soil.

The Instron cross-head speeds were varied between 0.0005 and 0.1 mm $min^{-1}$. At the slowest rate it took about 50 hours to reach a peak, and at the fastest rate only about 30 minutes. Displacement at peak load was about 0.5 to 1.5 mm, depending upon the type of pile and the rate of loading.

Values of adfreeze strength obtained for the various piles at different rates of loading are shown in Table I. Figure 3 gives adfreeze strengths plotted as a function of loading rate on a log-log scale for the four kinds of piles. Adfreeze strength, $\tau_f$, varies with rate of pile displacement $\dot{\ell}$, according to:

$$\tau_f \sim (\dot{\ell})^m$$

or

$$\dot{\ell} \sim (\tau_f)^n$$

The values of m and n, obtained by linear regression analysis, are as follows:

| | m | n = 1/m |
|---|---|---|
| B.C. fir | 0.2234 | 4.48 |
| Concrete | 0.2161 | 4.63 |
| Painted steel | 0.1661 | 6.02 |
| Creosoted B.C. fir | 0.1862 | 5.37 |

The maximum adfreeze strength was for untreated B.C. fir and minimum for creosoted B.C. fir and painted steel piles. The adfreeze strength values obtained for concrete piles were larger than those for creosoted B.C. fir and painted steel, but considerably lower than those for untreated B.C. fir.

### Constant-Load Tests

In actual practice, a pile foundation supporting a structure is subjected to constant loads rather than constant rates of load application. Creep is the process of deformation under such conditions, occurring at the interface between the pile and the soil. To simulate these conditions in model studies, a constant-load creep apparatus was built for which the Plexiglas box with pile shown in Fig. 1 could be used.

Figure 4 is a schematic diagram of the creep frame with the pile inside the sand box. Weights were placed on the loading pan (B). This load was magnified by a factor of 4 at pile A due to the ratio arm (C). The load on the pile was measured by means of a BLH load cell (D) having a capacity of 4550 kg. The BLH load cell was calibrated on the Instron load cell which was, in turn, calibrated by a proving ring.

Two DCDT's, one positioned under the pile and the other under the plate supporting the block of frozen sand, monitored deflections due to the load. Net pile displacement was taken to be equal to the difference between the two deflections.

Results of Constant-Load Creep Tests

Figure 5 shows a typical net displacement-time curve obtained for a painted steel pile. The load on the pile was 1130.57 kg, corresponding to a stress of 2.43 MPa on the pile head and 0.243 MPa along the pile soil interface. This curve resembles a classical creep curve, with a primary region (A) where the creep rate decreased to a steady value, a short secondary region (B) of about 8 hours, for which the steady-state creep rate was $1.04 \times 10^{-4}$ mm $min^{-1}$, and a tertiary region (C) where the creep rate accelerated until failure of the pile occurred after about 34 hours.

The results of preliminary tests are shown in Fig. 6. The straight lines 1 to 4 are extrapolations to the lower-rate regions of the adfreeze strengths vs loading rate lines shown in Fig. 3; the plotted points indicate the rates of motion of the piles in the steady-state creep region under constant load (region B in Fig. 5). In Fig. 6, line 5 for creep of painted steel has about the same slope as line 3, the adfreeze strength vs loading rate. For concrete and creosoted B.C. fir, the data obtained from the constant-load creep experiments are in reasonable agreement with the results of the adfreeze strength tests under constant rates of loading, extrapolated to the lower strain rate regions.

## DISCUSSION AND CONCLUSION

Data available in the literature on the adfreeze strength of piles in frozen soil are meagre, and most laboratory tests to determine adfreeze strength have been done at fast rates (Tsytovich 1975, Laba 1974, Rooney 1976). The preliminary results now presented indicate that adfreeze strength decreases with decreasing rate of loading. Preliminary data from creep tests indicate that the load dependence of the steady-state creep rate for piles in frozen sand appear to agree with the displacement rate dependence of the adfreeze strength determined by extrapolation of the results of the constant rate tests. Long-term creep tests give more realistic values for the long-term adfreeze strengths and hence for the bearing capacities for piles. The results obtained from rapid tests cannot be used to calculate the long-term bearing capacity of piles in frozen soil unless a large factor of safety is used.

Few tests have been carried out to date and further work must be done to determine the behaviour of piles in various soils at different temperatures and to obtain reliable data for design of foundations in frozen soil. Work is in progress in the cold rooms of the Division of Building Research, National Research Council of Canada, on the behaviour of steel H-section piles in frozen sand, group piles (groups of 4 and 6) in frozen sand and piles in frozen natural soils under conditions of constant rates of load application and constant loads.

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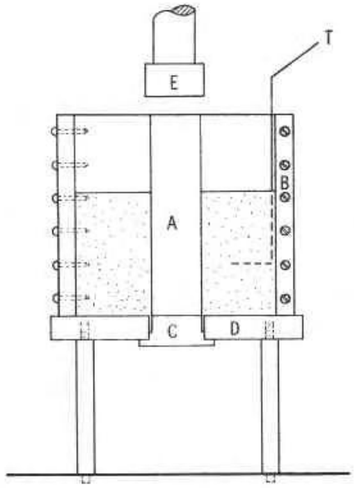
TABLE I

VARIATION OF ADFREEZE STRENGTH WITH RATE OF LOADING

| Cross-Head Speed ($\dot{\ell}$) | Adfreeze Strength ($\tau_f$), MPa | | | |
|---|---|---|---|---|
| mm min$^{-1}$ | B.C. Fir | Concrete | Painted Steel | Creosoted B.C. Fir |
| 0.0005 | 1.140 | 0.525 | 0.497 | 0.403 |
| 0.001 | 1.175<br>1.29 | 0.553 | 0.496 | 0.487 |
| 0.002 | 1.113<br>1.247 | 0.671 | 0.648 | 0.690<br>0.505 |
| 0.005 | 1.61 | 0.733 | 0.677 | 0.720 |
| 0.01 | 1.56 | 0.866<br>0.940 | 0.679 | 0.813 |
| 0.02 | 1.936 | 1.16 | 0.973 | 0.920 |
| 0.05 | 2.231 | 1.293 | 1.026 | 0.875 |
| 0.10 | 2.42 | 1.611 | 1.146 | 1.220 |



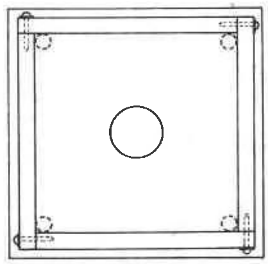



Figure 1

Schematic Diagram of the Experimental Set-Up to Measure the Adfreeze Strength Under Constant Rate of Cross-Head Motion

A Pile, 3" Dia
B Plexiglas Box
C Plug
D Base Plate
E Upper Compression Member from Instron Load Cell
T Thermocouple

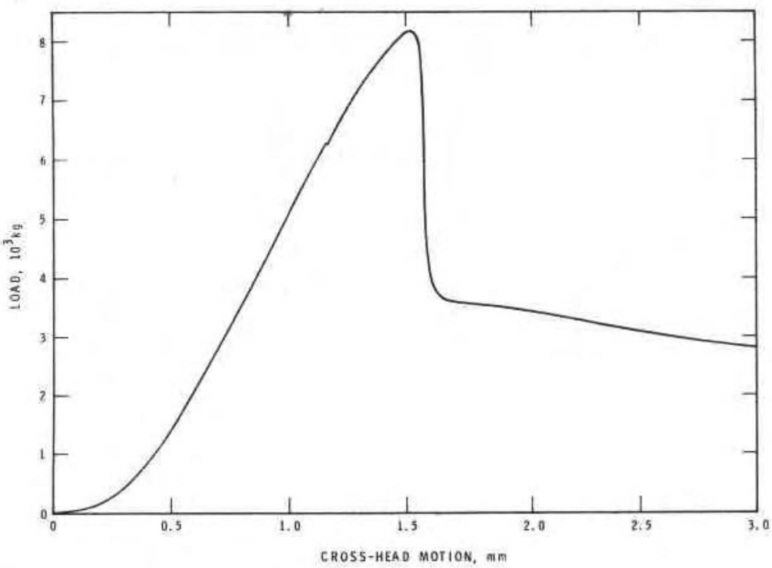



Figure 2

Load-Distance Curve for an Untreated B.C. Fir Pile in Frozen Sand (T = 6°C, Cross-Head Speed = 0.1 mm/min)

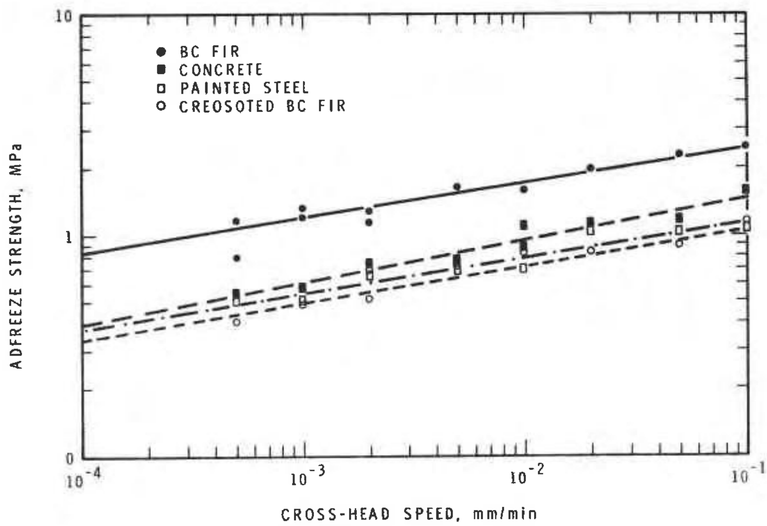



Figure 3

Variation of Adfreeze Strength with Rate of Loading

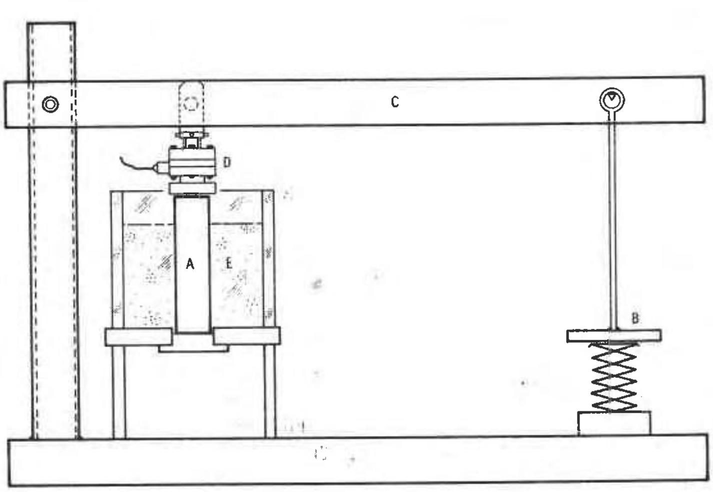



Figure 4

Schematic Diagram of the Set-Up to Study the Creep of Piles in Frozen Sand Under Constant Load (A - Pile, B - Loading Pan, C - Ratio Arm (1:4), D - BLH Load Cell, E - Frozen Sand)

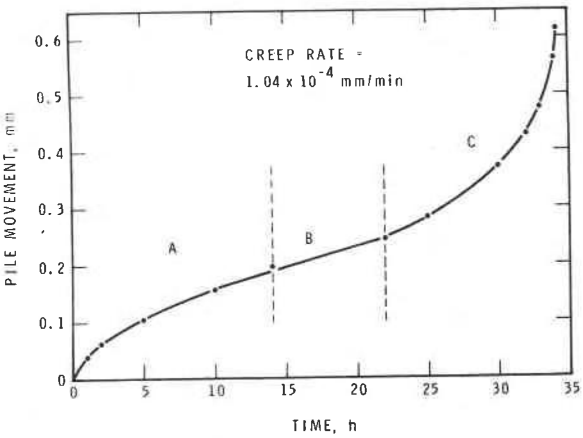



Figure 5

Creep Curve for a Painted Steel Pile in Frozen Sand (T = 6.2°C, Loaded = 1130.57 kg)

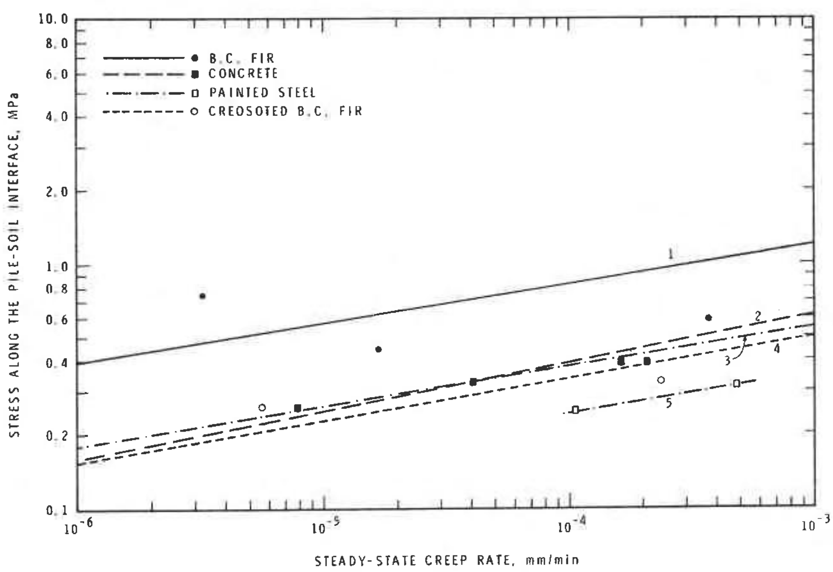



Figure 6

Variation of Adfreeze Strength (Under Constant Load) with Creep Rate in the Steady-State Creep Region