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BY

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Downdrag Loads Developed by a Floating Ice Cover: Field Experiments[1]

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The first phase of an investigation of the vertical forces developed on a structure by a floating ice cover frozen to it is described. It is the objective of this work to develop the theoretical, experimental, and field aspects of vertically acting loads required for the more efficient design of structures subject to such loads. A load frame was constructed that would apply constant upward acting loads to wooden piles frozen into an ice cover composed mainly of snow ice. Load, ice temperatures, and movement of the pile in relation to the ice were measured.

The time-dependent movement of the pile in relation to the ice exhibited creep characteristics, and these results were related to shear creep for grouted rod anchors in permafrost. Results of a previous study for WF steel H-beams in ice were also considered. The steady-state creep displacement rate for wooden piles in ice, rod anchors in permafrost, and WF steel H-beams in ice exhibited a comparable dependence on the constant applied shear stress. The steady-state creep displacement rate of a 100-mm wooden pile in snow ice at −3 °C and under a constant applied shear stress of 180 kN/m² was about 1 mm/day.

L'article décrit la première phase d'une étude des forces verticales développées sur une structure par un couvert de glace flottant gelé sur cette structure. L'objectif de ce travail est de développer les aspects théorique, expérimental et pratique de l'action des forces verticales dans le but d'arriver à un dimensionnement plus efficace des structures soumises à de telles forces. On a construit un bati de chargement pour appliquer des forces d'arrachement constantes à des pieux de bois gelés dans un couvert de glace composé essentiellement de glace de neige. La force, les températures de la glace et les mouvements du pieu par rapport à la glace ont été mesurés.

Les mouvements en fonction du temps du pieu par rapport à la glace ont présenté des caractéristiques de fluage, et les résultats ont été reliés au fluage en cisaillement pour des ancrages injectés dans le pergélisol. Les résultats d'une étude précédante pour des poutres d'acier en H dans la glace ont également été considérés. Les mesures de déplacement en fluage en régime permanent, pour les pieux de bois dans la glace, les ancrages dans le pergélisol et les poutres H en acier dans la glace sont toutes, de façon similaire, fonction de la contrainte de cisaillement appliquée. La vitesse de déplacement en fluage d'un pieu de bois de 100 mm, dans une glace de neige à −3 °C, est soumis à une contrainte de cisaillement de 180 kN/m² était d'environ 1 mm/jour.

[Traduit par le journal]

Introduction

Adhesion of a floating ice cover to a structure can result in the development of vertical loads acting either upwards or downwards. Upward forces develop as a result of buoyancy effects when there is an increase in water level; downdrag loads develop either when water level decreases leaving the ice partially unsupported (*e.g.* draw-down of a reservoir during winter), or as a result of accumulated snow on the surface of the ice. Structures subject to vertical ice loads include bridge piers, navigation aids, wharves, docks, etc. Two specific examples of such structures are marinas, which are usually supported on H-piles or tube piles, and private docks at summer cottages which are often supported on timber piles.

The Geotechnical Section of the Division of Building Research, National Research Council of Canada, has undertaken theoretical, experimental, and field investigations of vertically acting forces imposed by ice with the objective of providing information required for the design of structures subject to such loads. This work complements other programs on frost

[1]Presented at the 26th Canadian Geotechnical Conference, Toronto, Ontario. October 18–19, 1973.

heave forces (Penner 1970) and performance of rod anchors in permafrost (Johnston and Ladanyi 1972). The basic problem is common to these three studies, *i.e.* to establish the dependence of design loads on the mechanical properties of frozen material (ice or frozen ground), geometry of the structure, and natural conditions (temperature, water levels, etc.). As the loading conditions are similar it is reasonable to assume that a single unified theory could apply in all three cases and that it will be possible to compare results from field and laboratory investigations.

The present paper describes the initial phase of the program of investigation on vertically acting ice loads, giving the results for the first two winters of field experiments. Information was obtained on the dependence of pile displacement rate on applied stress for snow ice at a temperature within 10 C degrees of the melting point.

Theoretical Background

Review of the literature indicated that very little information is available regarding the design of pile-supported structures against vertical ice loading or for verification of visco-elastic theories thought to be applicable to this loading situation. Lofquist (1951) has described field measurements made in Sweden and puts forward a theory for predicting vertical ice loads. More recently, Stehle (1968, 1970) reported laboratory and field measurements on the holding strength of piles in ice. And Johnston and Ladanyi (1972) in reporting on field tests of grouted rod anchors in permafrost have presented a theory that relates the pull-out rate of rod anchors to applied stress and anchor radius. This theory is based on a power creep law of the form

$$[1] \qquad \dot{\gamma} = \dot{\gamma}_c \left(\frac{\tau}{\tau_c}\right)^n$$

where τ is shear stress, τ_c and n are experimentally determined creep parameters, and $\dot{\gamma}_c$ is an arbitrary shear strain rate for normalizing purposes. Johnston and Ladanyi defined the shear strain rate $\dot{\gamma}$ of a particle with vertical velocity $\dot{u}$ at radius r by

$$[2] \qquad \dot{\gamma} = -\frac{\mathrm{d}\dot{u}}{\mathrm{d}r}$$

Similarly, the shear stress at radius r as a function of shear stress τ_a on the pile surface of radius a is given by

$$[3] \qquad \tau = \tau_a \frac{a}{r}$$

Substituting Eqs. [2] and [3] in Eq. [1] yields

$$[4] \qquad \frac{\mathrm{d}\dot{u}}{\mathrm{d}r} = -\dot{\gamma}_c \left(\frac{\tau_a a}{\tau_c r}\right)^n$$

Integrating with the pile–ice interface limit of $\dot{u} = \dot{u}_a$ at $r = a$ gives

$$[5] \qquad \dot{u}_a - \dot{u} = \frac{\dot{\gamma}_c a}{n-1}\left(\frac{\tau_a}{\tau_c}\right)^n \left[1 - \left(\frac{a}{r}\right)^{n-1}\right]$$

As r approaches infinity, $\dot{u}$ approaches zero, so that displacement rate at $r = a$ is

$$[6] \qquad \dot{u}_a = \frac{\dot{\gamma}_c a}{n-1}\left(\frac{\tau_a}{\tau_c}\right)^n = \dot{s}_c \left(\frac{\tau_a}{\tau_c}\right)^n$$

Equation [6] is the basis for the analysis of the experimental results now reported. Of the independent variables in this equation, a and τ_a are parameters selected for the experiment and $\dot{\gamma}_c$, n, and τ_c are material properties that characterize the ice. Assuming that there is no slip between the ice and the pile, $\dot{u}_a$ will also represent the vertical movement rate of the pile in relation to a position on the ice cover where the movement rate is zero.

In pull-out tests of piles in ice it was not possible to measure vertical pile movement in relation to a position on the ice where the displacement rate approached zero; *i.e.* where r approached infinity. Of necessity, vertical movement of the pile was measured in relation to some finite position $r = b$ on the ice. The deformation rate $\dot{u}_b$ at $r = b$ evaluated from Eq. [5] and [6] is

$$[7] \qquad \dot{u}_b = \frac{\dot{\gamma}_c a}{n-1}\left(\frac{\tau_a}{\tau_c}\right)^n \left(\frac{a}{b}\right)^{n-1}$$

The ratio of the displacement rate at $r = b$ to the displacement rate at $r = a$ is given by

$$[8] \qquad \frac{\dot{u}_b}{\dot{u}_a} = \left(\frac{a}{b}\right)^{n-1}$$

If the displacement rate at b is much smaller than the displacement rate at a, then the error introduced by determining the pile movement rate in relation to a finite radius b, rather than

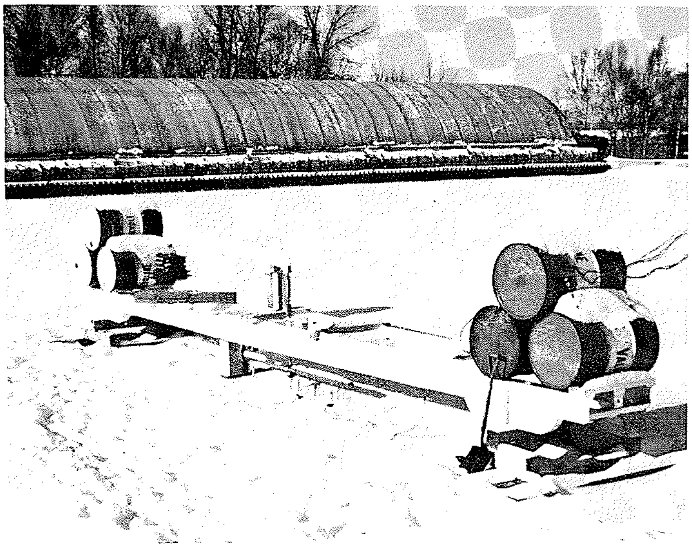

FIG. 1. Loading frame at test site.

to a radius approaching infinity, will be small. Results reported by Ramseier (1971) for creep tests on snow ice suggest a value for n of 3. The maximum value of the a to b ratio in the pile tests was 1/3. The displacement rate at b would therefore be 1/9th the displacement rate of the pile; or the displacement rate $\dot{u}_a$ measured relative to $r = b$ would have a value of 8/9 of its value if it were measured relative to a position of r approaching infinity.

It should be pointed out that this theory assumes that the material (ice or permafrost) is isothermal, isotropic, and homogeneous. Although it is very unlikely that a floating ice cover will meet all these assumptions the use of such a theory is justified because of the paucity of experimental data and lack of a more general theory.

Description of Apparatus and Test Site

The field program was designed to provide information on the rate of pile pull-out under constant load for various load levels and ratios of pile diameter to ice thickness. A reaction load frame supported by the ice cover and using a lever arm system with a force multiplication of ten to apply a constant upward-acting load was constructed (Fig. 1). The 9-m long frame is capable of exerting a force of 30 000 N and has a total weight of 1000 kg. (An ice thickness greater than 200 mm is required for long-term support of this equipment). A shaft supported in low friction bearings transmitted the force from the lever arm down to a load cell attached to the pile. All piles were made of B.C. fir turned to a uniform diameter on a lathe. A threaded rod through the center of the pile connected it to a coupler on the bottom of the load cell.

Figure 2 shows the threaded rod, load cell, and displacement-measuring cross-arm used during the winter of 1972–73. The cross-arm, made up from a 1.5-m long aluminum U-section, was fixed at its center to the load cell. Displacement transducers of the DCDT type attached to the cross-arm measured relative movement between the cross-arm and wooden dowel pins set in the ice. Recording instruments were set up to provide a continuous record *versus* time of the following: vertical load on the pile, relative displacements between the cross-arm and the ice cover at four locations (radii 750, 450, 150, and −750 mm), and ice temperature 150 mm from the pile and about 50 mm below the surface plus air temperature. Ice thickness was measured periodically and samples were recovered to establish the ice type.

The experiments were carried out over the winters of 1971–72 and 1972–73 on the ice cover of the Manoeuvering and Rough Water Basin at the National Research Council Laboratories in Ottawa. This is an outdoor facility, and it was necessary to work with the ice conditions and temperatures that nature provided. Both winters were characterized by periods of mild temperatures and rains in January, conditions that caused the ice cover (for the most part granular snow ice) to increase in thickness from about 200 to 500 mm in a short time. These adverse weather conditions restricted the number of tests that could be conducted.

Test Procedure

A similar test procedure was followed in all cases. A hole with a diameter slightly larger than the pile was augered through the ice cover, and the pile was inserted and allowed to freeze in. There was no

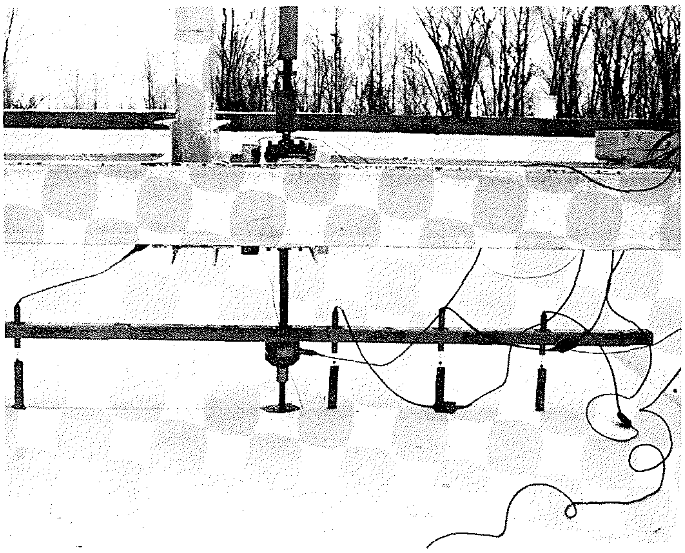

FIG. 2. Cross-arm and load cell in test position.

thickening of the ice adjacent to the pile because of the low thermal conductivity of wood. Before starting the test, a hydraulic jack was inserted to support the lever arm while weights were added to the weight pan. In initiating the test the jack cylinder pressure was gradually released so that there was a smooth application of load to the pile. For each subsequent test the load frame was moved and a new hole prepared for the pile.

Test Results

As there was a general refinement of the instrumentation between the first and second winters, it is reasonable to consider the results of each season separately. Applied stress was calculated by dividing the force on the pile by its surface area in contact with the ice.

Winter of 1971–72

Only two tests on a 50-mm diameter wooden pile were completed. Vertical movement was measured in relation to a point on the ice 150 mm from the central axis of the pile by a single DCDT. Displacement–time results of the first test, at a stress of 185 kN/m^2, are plotted in Fig. 3. (The M's on the abscissa indicate midnight.) Total ice thickness was 460 mm, composed of 150 mm of columnar ice overlain by snow ice. It may be seen that this curve exhibits typical creep characteristics, *i.e.* an initial instantaneous displacement followed by a period of constant rate displacement and a subsequent accelerating displacement to failure. Pull-out of the pile occurred at 12:00 h

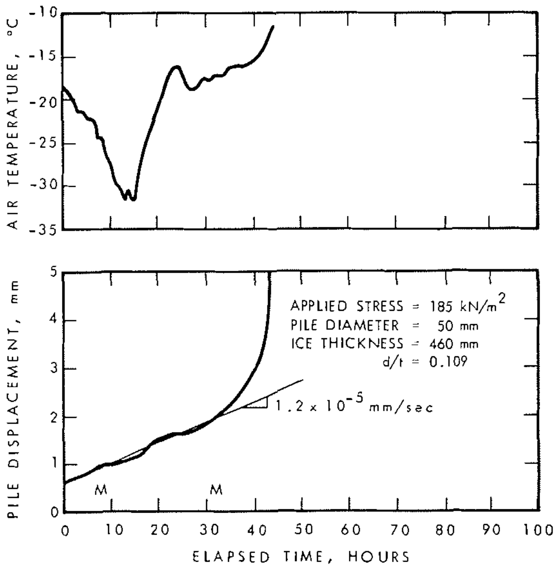

FIG. 3. Test 1-72.

after an elapsed time of 44 h. Air temperatures at a location about 1.5 km from the test site are also plotted on Fig. 3 and indicate that the latter part of the test coincided with a general warming trend. On examining the pile after pull-out, it could be seen that small flakes of ice still adhered to it, suggesting that final failure resulted from a break-down of the ice immediately adjacent to the pile.

Before performing the second test, thermo-

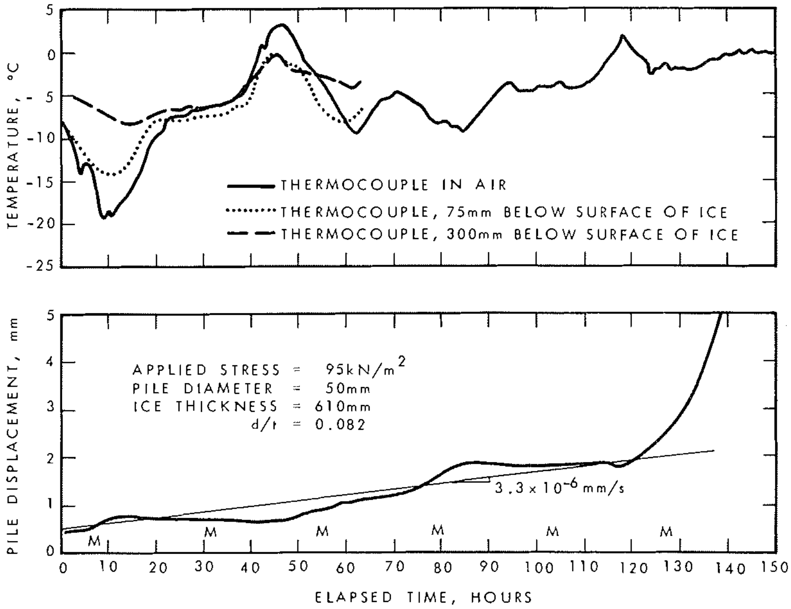

FIG. 4. Test 2-72.

couples were placed in the ice and in the air. The results, at a stress of 95 kN/m^2 and ice thickness of 610 mm, are shown in Fig. 4. Again, the displacement–time curve shows creep characteristics. Pull-out occurred at 18:00 h after an elapsed time of 145 h. It may be seen that at about 45 h the ice temperature was at the melting point. Although there was an increase in the pull-out rate failure did not occur. Note that between 10 and 50 h and 90 and 115 h, both of which followed cold periods, the creep pull-out rate was zero. The final stage of the test corresponded with a general warming trend. At a few points it appears that there was a decrease in pile displacement, possibly due to temperature effects on the load frame and displacement measuring apparatus. The following winter these thermal effects were investigated.

Winter of 1972–73

Three tests were completed on a 100-mm pile. The ice cover comprised 170 mm of columnar-grained ice overlain by snow ice. The force on the pile was continuously measured and was found to be constant over each test period. Relative displacements between the ice cover and the pile were measured with DCDT's at four locations along the cross-arm (Fig. 5A). They were recorded continuously. From these displacement records the movement of the pile in relation to the ice and an approximation of the deflected shape of the ice cover adjacent to the pile were to be determined.

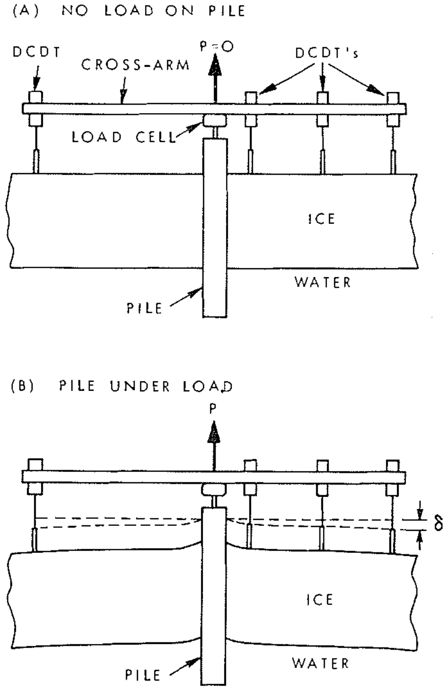

FIG. 5. Schematic of pile and deflection measuring arm.

A preliminary test was done to determine thermal effects on the load and deflection measuring apparatus. The equipment was set up as shown in Fig. 5A, with no load on the pile. Load and displacement were recorded over a 3-day period, but no measurable loads were developed on the pile; from the displacement measurements it was apparent that the cross-arm had tilted and curled to the extent of several millimeters at the ends as a result of temperature changes. On the basis of these preliminary measurements it was decided to measure pile movement in relation to a position 150 mm from the center line of the pile where thermal effects on the cross-arm would be at a minimum. Figure 5B is a schematic of the assumed deflected shape of the ice when load is applied to the pile.

The measured deflected shape of the ice cover immediately after load application is shown in Fig. 6 for each of the three tests. The circles represent measured instantaneous deflections and the dashed line is an approximation of the deflected shape of the ice surface in relation to the cross-arm. Tilting of the cross-arm would explain the nonsymmetric deflections. There is no apparent relation, however, between the deflected shape of the ice and the applied loads, and these attempts at measuring the deflected shape of the ice cover were not successful.

The results of test 1-73, for an applied stress of 120 kN/m^2 and an ice thickness of 510 mm, are shown in Fig. 7. A 2.5-m square of 25-mm bead-board insulation was used on the ice to simulate snow cover. From the temperature results it may be seen that the insulation moderated the effects of air temperature. The displacement–time curve exhibits creep characteristics. Pull-out occurred at 20:00 h after an elapsed time of 105 h, and as in earlier tests final failure coincided with a warming trend.

Test 2-73, run at a stress level of 185 kN/m^2 on 530-mm ice, is shown in Fig. 8. Pull-out occurred at 13:00 h after an elapsed time of 20 h. No insulation was used. It is instructive to relate the results of this test with test 1-72, which was done at the same stress level. The instantaneous displacements are comparable, as are the steady-state displacement rates, but there is a major difference in times to failure.

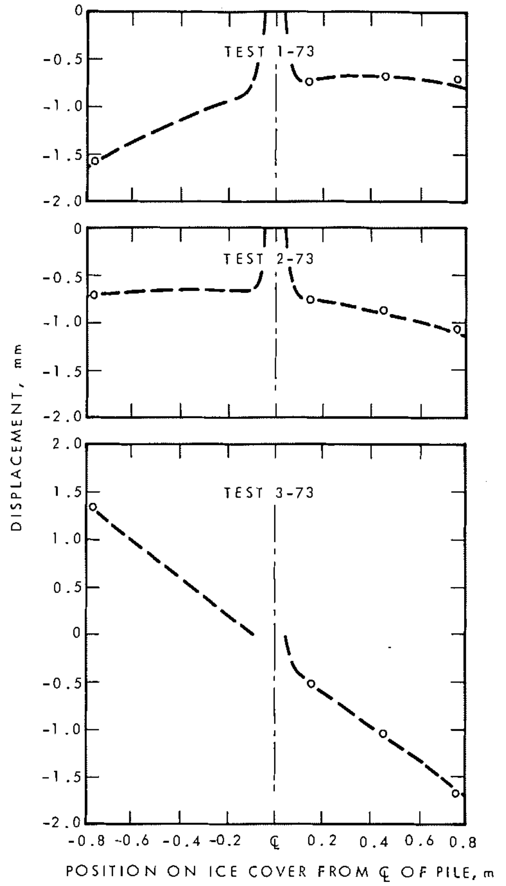

FIG. 6. Initial deflected shape of ice cover.

Figure 9 illustrates the results of test 3-73, done at a stress of 80 kN/m^2 on 570-mm ice. Pull-out occurred at 09:00 h after an elapsed time of 114 h. No insulation was used. There was a much smaller initial displacement and a much lower steady-state displacement rate than in test 2-72, which had only a slightly larger applied stress.

Analysis of Results

Figure 10 is a log–log plot of steady-state creep displacement rate *versus* average applied stress for the pull-out tests over both winters. The results of each test series were fitted to Eq. [6] and the material properties derived therefrom are shown in Table 1.

Given the data, the values of n are in reasonable agreement with the stated value of $n = 3$ for snow ice. Equation [6] suggests that larger diameter piles would have larger steady-

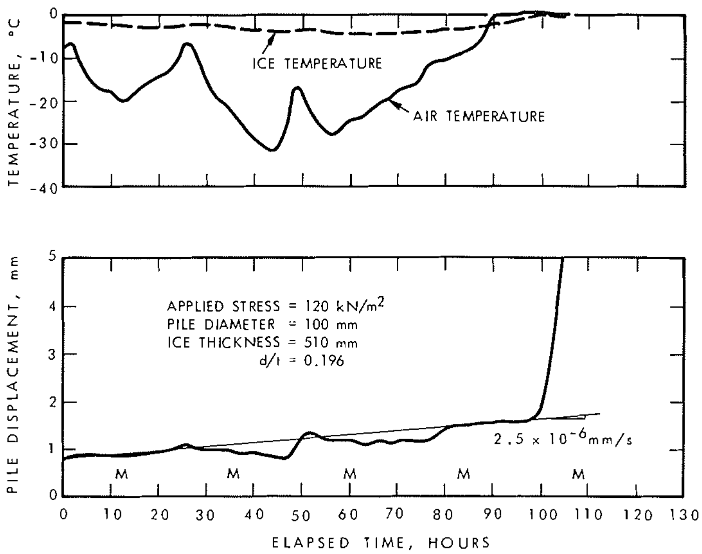

FIG. 7. Test 1-73.

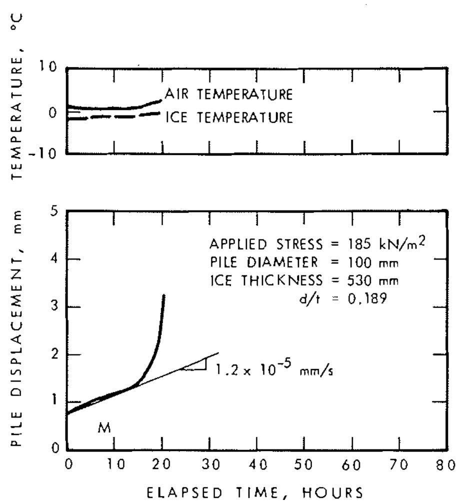

FIG. 8. Test 2-73.

state creep displacement rates for the same applied stresses, but this has not been the case with wooden piles in ice.

Stehle (1970: see Figure 12) indicates that as the temperature approaches 0 °C the type of material in which the pile is frozen, whether ice, sand slurry, or clay slurry, has little effect on pull-out rate. The steady-state creep displacement rate reported by Johnston and Ladanyi (1972) for rod anchors in permafrost at −3 °C and by Stehle (1970) for WF steel H-beams in ice at −1 °C are comparable to the steady-state creep displacement rates measured for wooden piles in ice, *i.e.* in all three studies pile movement is measured in relation to a position on the frozen material that is assumed to be fixed. It seems reasonable to plot the rod anchor results and WF steel H-beam results on the same figure as the wooden pile results. The steady-state creep displacement rates of the WF beams show an increasing displacement rate with increasing effective diameter, as suggested by Eq. [6]. In general, the dependence of displacement rate on applied stress is similar for the pile – frozen material configurations considered above.

Discussion of Results

A review of the results of two winters of field experiments indicates that under constant load the pull-out of a pile exhibits characteristics of creep deformation. Steady-state creep displacement rate is related to applied stress by a power law function. The creep parameter, n, measured in these field experiments is comparable to the value measured in the laboratory for snow ice. Time to pull-out appears to be related to ice temperature as well as to stress level. Time and temperature both influence the pull-out of a pile. Under natural conditions in the field both of these variables are independent of each other, but combine together to influence the rate of pull-out. To separate the influence of these two variables it is possible that laboratory tests under more controlled

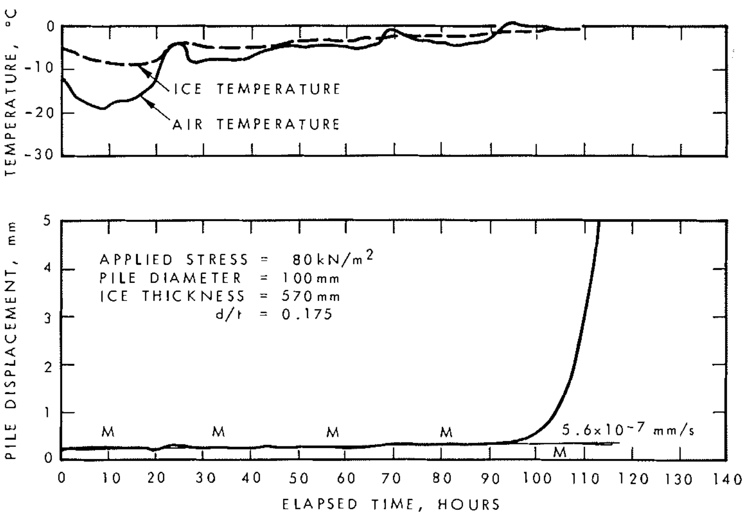

FIG. 9. Test 3-73.

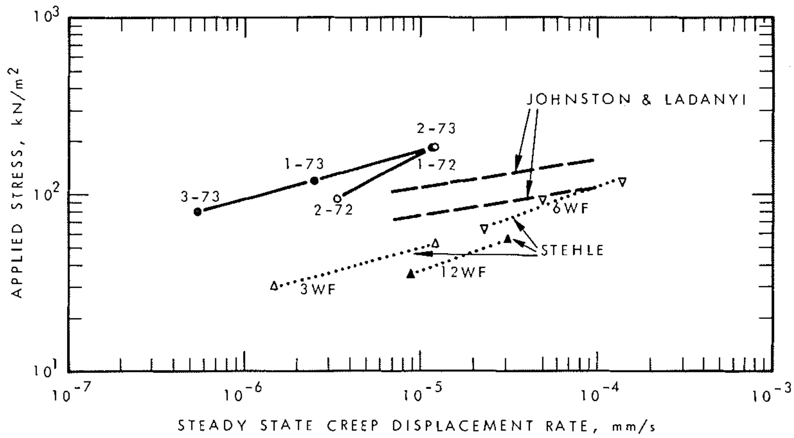

FIG. 10. Steady-state creep displacement rates *versus* applied stress.

TABLE 1. Summary of material property parameters determined from pull-out tests

	Material property parameters		
Test series	n	τ_c	$\dot{\gamma}_c$
1972	1.94	51.3 kN/m²	3.75×10^{-8} s^{-1}
1973	3.65	93.4 kN/m²	5.30×10^{-8} s^{-1}

Note: $\dot{s}_c = 10^{-6}$ mm/s where $\dot{s}_c = \dot{\gamma}_c a/(n-1)$.

conditions will have to be done. These field tests can form a good basis for setting up and evaluating relevant laboratory tests.

The displacement immediately preceding pull-out was 2–3 mm for the 50-mm pile and about 1 mm for the 100-mm pile. This was the only pile diameter effect noted. There was no clear indication of any pile diameter to ice thickness ratio on the pull-out rate of the pile.

Results of analogous tests in ice and frozen ground indicate that there was sufficient similarity to justify comparing results, providing average temperature of the frozen material was between −1 and 0 °C. The displacement rate for a wooden pile frozen into an ice cover of mainly snow ice at about −3 °C under an applied load of 180 kN/m^2 is about 1 mm per day. Natural water level fluctuations in a reservoir are of this order or greater, and it is reasonable to assume that shear stresses developed on wooden piles would be greater than 180 kN/m^2.

Further testing is planned for following winters to explore more fully the effect of varying pile diameters and pile materials. By improving the displacement measuring technique it is hoped that it will be possible to determine the deflected shape of an ice cover. Tests are also planned in which the pile will be moved at a constant rate in relation to the ice.

Acknowledgments

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JOHNSTON, G. H., and LADANYI, B. 1972. Field tests of grouted rod anchors in permafrost. Can. Geotech. J. **9**, pp. 176–194.

LOFQUIST, B. 1951. Lifting force and bearing capacity of an ice sheet. Natl. Res. Counc. Can., Ottawa, Canada. Tech. Trans. TT-164.

PENNER, E. 1970. Frost heave forces in Leda clay. Can. Geotech. J. **7**, pp. 8–16.

RAMSEIER, R. 1971. Mechanical properties of snow ice. Proc. First Int. Conf. Port Ocean Eng. Arct. Cond., Trondheim, Norway, pp. 192–210.

STEHLE, N. S. 1968. McMurdo ice wharf—pullout strength of piles. U.S. Naval Civ. Eng. Lab., Port Hueneme, Calif., Tech. Note N-996.

——— 1970. Holding strength of piles in ice. U.S. Naval Civ. Eng. Lab., Port Hueneme, Calif., Tech. Rep. R-700.