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Parameswaran, V. R.

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ADFREEZE STRENGTH OF MODEL PILES IN ICE

by V. R. Parameswaran

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Adfreeze strength of model piles in ice

V. R. Parameswaran

National Research Council of Canada, Division of Building Research, Geotechnical Section,
Ottawa, Ont., Canada K1A 0R6

The adfreeze bond strengths of wood, concrete, and steel H-section piles embedded in fresh-water ice have been measured under constant rates of displacement for displacement rates varying between 10^{-4} and 10^{-1} mm/min (loading rates between 10^{-3} and 10 kN/min). Wood piles showed the highest adfreeze strength (0.6 and 1.8 MPa); that for concrete piles was independent of rate of displacement (average value 0.8 MPa); that for steel H-sections varied between 0.2 and 0.6 MPa. These results were used in estimating the contribution of ice adhesion to the total adfreeze strength of various piles in frozen sand.

L'adhérence développée entre la glace d'eau douce et des pieux de bois, de béton et d'acier en section H a été mesurée sous des vitesses de déplacement constantes et comprises entre 10^{-4} et 10^{-1} mm/min (vitesses de chargement entre 10^{-3} et 10 kN/min). La plus grande adhérence a été observée sur les pieux de bois (0,6 et 1,8 MPa); l'adhérence sur les pieux de béton était indépendante de la vitesse de déplacement (valeur moyenne de 0,8 MPa); celle sur les pieux d'acier en section H variait de 0,2 à 0,6 MPa. Ces résultats ont été utilisés pour évaluer la contribution de l'adhérence de la glace à l'adhérence totale sur différents pieux dans du sable gelé.

[Traduit par la revue]

Introduction

Laboratory measurements of the adfreeze strength of small-scale model piles in frozen sand and silty soil under constant rates of loading and constant load creep conditions have been described (Parameswaran 1978, 1979). The adfreeze bond strength or shearing resistance developed at the interface between a pile and frozen soil has two components: that due to adhesion of ice to the pile and that due to soil grain friction at the pile–soil interface. In an attempt to estimate the contribution of the ice component to the total adfreeze strength of piles in ice-bonded soils, a study was initiated of the adfreeze strength of various kinds of piles in ice as a function of rate of loading and displacement.

These studies will be helpful in estimating the upward force that may be exerted on piles installed in ice-covered waters as part of such structures as wharves, offshore jetties, and drilling platforms. The force imposed by a floating ice cover as a result of changes in water level (caused by one or more of several phenomena such as seiches in large lakes, storm tides in coastal waters, or even winter rainfall) could be sufficient to cause uplift of the piles. To prevent this, the load on the pile and the depth of embedment must be such that the bond between the pile and the ice fails before there is any vertical displacement of the pile. In the present study, the adfreeze bond strengths between ice and wood, steel, and concrete piles were determined in the laboratory.

Experimental Procedure

The equipment and test method were similar to those used earlier to determine the adfreeze strength of frozen sand to model piles (Parameswaran 1978). A schematic diagram of the equipment is shown in Fig. 1. A pile (A) of wood, concrete (cylindrical, 76.2 mm diameter and 305 mm long, smooth surface), or steel (101.6 mm, wide flange H-section, mill finish surface) was placed in a Plexiglas box (B) (inner dimensions $305 \times 305 \times 305$ mm³) and water poured to a height of 190.5 mm. The box was placed inside a cold room at $-6°C$ and the water frozen from all sides. A pencil type heater (H) kept open a small hole through which water could flow from the interior as freezing progressed. This prevented the formation of cracks from excess pressure caused by expansion on freezing. A bent stainless steel sheet (G) prevented excess water from flowing to the area around the pile.

After complete freezing, the box was mounted on the rigid base plate of an Instron universal testing machine (25 000 kg capacity) installed in the cold room. The plug (C) was removed and a DCDT (L) (direct current differential transducer) was mounted under the pile (as shown by the dashed lines in Fig. 1) in such a way that the displacement indicated by the DCDT was the actual displacement of the pile with respect to the ice. The DCDT was connected to a chart recorder and the output (in millivolts) plotted against time as the pile was loaded. The displacement
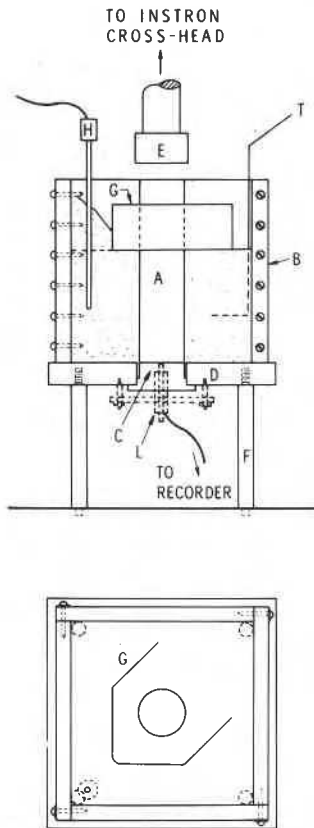
FIG. 1. Schematic diagram of experimental setup to measure adfreeze strength of piles in ice: (A) pile, 76.2mm diam.; (B) Plexiglas box; (C) plug; (D) base plate; (E) compression ram from Instron load cell; (T) thermocouple; (F) supporting legs; (G) stainless steel sheet; (H) heater; (L) displacement transducer.

FIG. 2. Typical load–displacement curves for B.C. fir (1), concrete (2), and steel H-section (3) piles in ice at −6°C; cross-head displacement rate 0.02 mm/min.

from the movement of the Instron cross-head includes (in addition to pile displacement) elastic deformations of the pile, machine elements, legs (F), and flexure of the base plate (D). This aspect has been discussed (Parameswaran 1978). The height of the pile above the ice was measured and the pile pushed out by a ram (E) attached to the Instron cross-head at a constant rate of cross-head motion. The load–displacement curve was recorded on the Instron chart, and tests were conducted at rates varying between 0.0005 and 0.1 mm/min.

Results

Figure 2 shows typical load–displacement curves. Figure 3 shows an H-pile in ice before and after testing. The crack pattern around the pile after the adfreeze bond was broken may be seen in Fig. 3b. From the load–displacement curve, the maximum or peak adfreeze strength for a particular rate of dis-

placement was calculated by dividing the peak load by the adfreezing area (surface area of contact) between the pile and ice. From the peak loads and the times to reach them, nominal loading rates in kN/min were also calculated. Nominal pile displacement rates were calculated from the DCDT displacements and the time corresponding to the peak load. All these data, namely, peak load (kN), nominal loading rate (kN/min), nominal pile displacement rate (mm/min), and peak adfreeze strength (MPa), corresponding to each cross-head displacement rate, are tabulated in Table 1.

Peak adfreeze strength was plotted against displacement rates on a log–log scale, as shown in Fig. 4. The full lines correspond to the cross-head displacement rates and the broken lines are the nominal pile displacement rates calculated from the DCDT output. Figure 5 shows the variation of adfreeze strength with log (loading rate).

For a particular rate of displacement, wood piles showed the highest adfreeze strength (0.6–1.8 MPa) and steel piles the lowest (0.2–0.6 MPa) within the range in which tests were carried out. For these piles the adfreeze strength increased with increasing rate of displacement. For concrete piles, adfreeze strength was essentially independent of rate of displacement within the range in which tests were carried out.

Discussion

For a particular value of adfreeze strength the nominal displacement rate ($\dot{l}$) of the pile with respect to ice (see dashed lines in Fig. 4) is smaller than the

TABLE 1. Adfreeze strength of piles in ice at various loading (displacement) rates

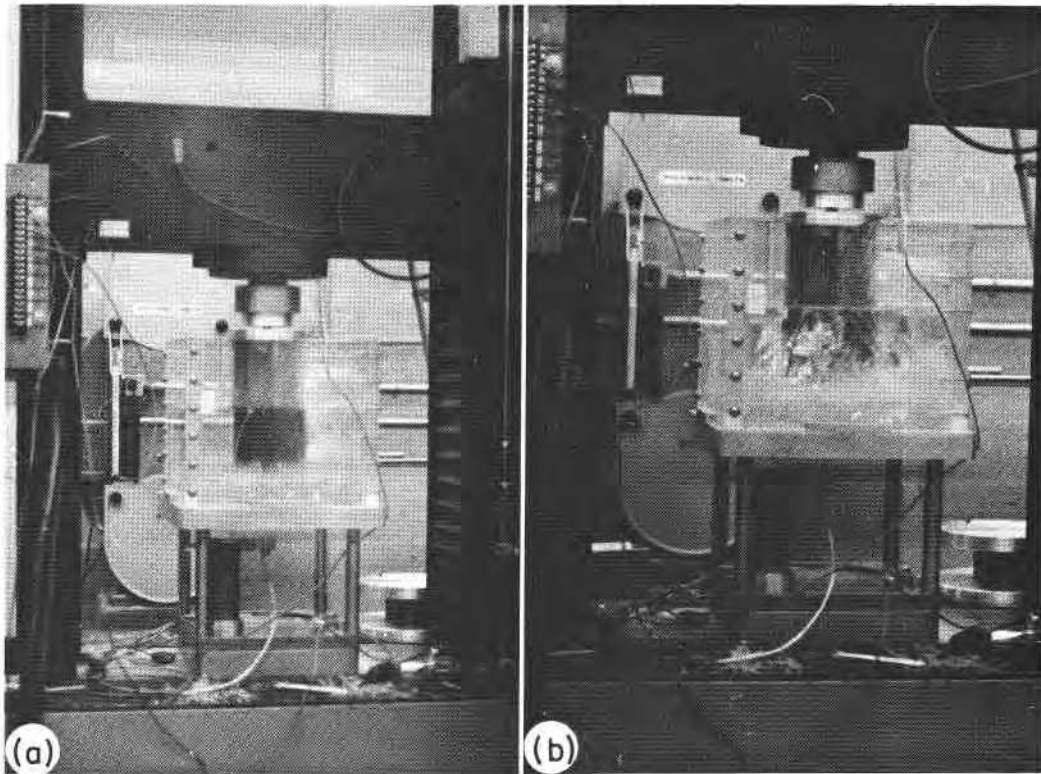| Rate of displacement of crosshead (mm/min)	WOOD						CONCRETE						STEEL					
	Peak load (kN)	Time to reach peak load (min)	Nominal loading rate $\dot{P}$ (kN/min)	Pile displacement at peak load, from DCDT (mm)	Nominal pile displacement rate (mm/min)	Peak adfreeze strength τ_{ad} (MPa)	Peak load (kN)	Time to reach peak load (min)	Nominal loading rate $\dot{P}$ (kN/min)	Pile displacement at peak load, from DCDT (mm)	Nominal pile displacement rate (mm/min)	Peak adfreeze strength τ_{ad} (MPa)	Peak load (kN)	Time to reach peak load (min)	Nominal loading rate $\dot{P}$ (kN/min)	Pile displacement at peak load, from DCDT (mm)	Nominal pile displacement rate (mm/min)	Peak adfreeze strength τ_{ad} (MPa)
0.0005	20.10	4000	5.03×10^{-3}	0.68	1.7×10^{-4}	0.435	39.0	3100	1.26×10^{-2}	0.40	1.3×10^{-4}	0.8616	18.8 24.3	4900 3370	3.84×10^{-3} 6.12×10^{-3}	– –	– –	0.175 0.233
0.001	49.3 39.2	2150 2150	2.3×10^{-2} 1.82×10^{-2}	– 0.84	3.91×10^{-4}	1.110 0.860	29.0 48.5	1160 1480	2.5×10^{-2} 3.28×10^{-2}	0.22 0.23	1.9×10^{-4} 1.55×10^{-4}	0.624 1.117	43.0 38.5 34.6	2050 1684 1394	2.1×10^{-2} 2.29×10^{-2} 2.48×10^{-2}	0.53 0.44	3.15×10^{-4} 3.16×10^{-3}	0.401 0.364 0.327
0.002	33.0 49.5	1000 1050	3.3×10^{-2} 4.71×10^{-2}	– 0.40	3.81×10^{-3}	0.729 1.101	42.35 37.50 39.00	846 1100 810	5.01×10^{-2} 3.41×10^{-2} 4.81×10^{-2}	0.68 – 0.47	8.04×10^{-4} – 5.83×10^{-4}	0.924 0.806 0.862	32.0	978	3.27×10^{-2}	1.02	1.04×10^{-3}	0.305
0.005	54.6	340	1.61×10^{-1}	0.631	1.86×10^{-3}	1.206	39.50	292	1.35×10^{-1}	0.53	1.82×10^{-3}	0.817	35.4	229.5	1.53×10^{-1}	0.42	1.83×10^{-3}	0.342
0.01	64.1	217	2.95×10^{-1}	–	–	1.38	33.5	118	2.84×10^{-1}	0.20	1.68×10^{-3}	0.745	51.8 43.8	160 206	3.24×10^{-1} 2.13×10^{-1}	0.40 0.90	2.5×10^{-3} 4.37×10^{-3}	0.477 0.410
0.02	68.8	125	5.5×10^{-1}	–	–	1.515	34.15 36.75	65 82	5.25×10^{-1} 4.48×10^{-1}	– 0.20	– 2.44×10^{-3}	0.787 0.807	47.3 48.9	72 88	6.57×10^{-1} 5.56×10^{-1}	0.43 0.75	5.9×10^{-3} 8.52×10^{-3}	0.453 0.444
0.04																		
0.05	76.3	55	1.39	–	–	1.641	34.20	24.2	1.413	0.41	1.69×10^{-2}	0.761	54.0	28.2	1.915	0.433	1.54×10^{-2}	0.517
0.10	77.5 85.2	27 24.3	2.87 3.51	0.30 0.44	1.11×10^{-2} 1.81×10^{-2}	1.689 1.857	43.2	13.5	3.20	0.38	2.81×10^{-2}	0.961	59.7	15	3.98	0.35	2.33×10^{-2}	0.580

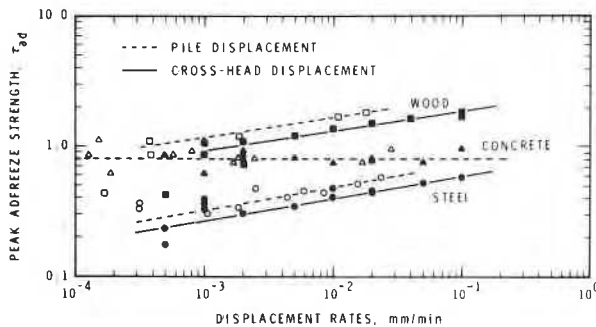FIG. 3. Steel H-section pile in ice: (*a*) before test, (*b*) after test.

FIG. 4. Variation of adfreeze strength of piles in ice with rate of displacement. Solid lines correspond to displacement rates of cross-head, and broken lines correspond to nominal pile displacement rates ($\dot{l}$).

FIG. 5. Variation of adfreeze strength in ice with log (loading rate).

displacement rate ($\dot{x}$) of the cross-head of the Instron testing machine (see solid lines in Fig. 4) by a factor of about 4. This results from the fact that the latter quantity includes the elasticity of the system, consisting of the test set-up and machine elements. As the primary interest is to relate adfreeze strength to rate of displacement of piles, results presented here will be discussed on the basis of the nominal pile displacement rate ($\dot{l}$). Figure 4 shows that the peak adfreeze strenth (τ_{ad}) for wood and steel piles varies

with nominal pile displacement rate ($\dot{l}$) according to a relation

$$[1] \qquad \tau_{ad} \propto (\dot{l})^m$$

where the exponent m given by the slope of the dashed lines has values of 0.1516 and 0.1733 respectively.

In earlier work (Parameswaran 1978) the adfreeze strength (τ_{ad}^s) of piles in frozen sand (Ottawa fine sand containing 14% moisture and compacted to an optimum Proctor dry density of 1700 kg m^{-3} prior to freezing) was also found to vary with displacement

FIG. 6. Comparison of adfreeze strength in frozen sand ($\tau_{ad}{}^s$) and adfreeze strength in ice ($\tau_{ad}{}^i$) at same displacement rate.

rate ($\dot{x}$) of the Instron cross-head, according to an equation of type [1], with the values of the exponent m being 0.1555 and 0.1024, respectively, for wood and steel piles. As the equipment, testing temperature, and method of measuring the adfreeze strength were the same for both frozen sand and ice, it is r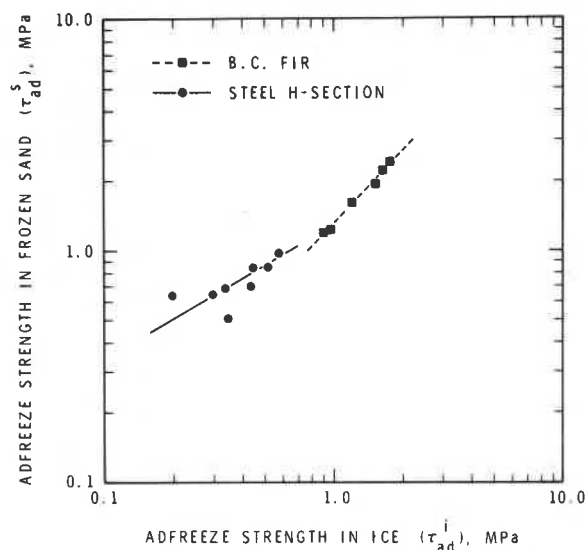easonable to assume that the dependence of adfreeze strength ($\tau_{ad}{}^s$) on the nominal pile displacement rate ($\dot{l}$) in the frozen sand will have the same relation to its dependence on cross-head displacement rate ($\dot{x}$) as in the present case; i.e., nominal pile displacement rate ($\dot{l}$) for given ($\tau_{ad}{}^s$) is smaller than cross-head displacement rate ($\dot{x}$) by a factor of 4. It can therefore be assumed that the values of the exponent m in [1] relating adfreeze strength in frozen sand to pile displacement rate will be the same as those determined from the cross-head displacement rate, namely 0.1555 and 0.1024 for wood and steel H-section piles. Using the superscripts s and i for sand and ice, the relation between adfreeze strength and pile displacement rate can be written as

[2] $\tau_{ad}{}^s \propto (\dot{l})^{m_s}$ for frozen sand

and

[3] $\tau_{ad}{}^i \propto (\dot{l})^{m_i}$ for ice

Thus

[4] $\dfrac{m_s}{m_i} = \dfrac{\partial \ln (\tau_{ad}{}^s)}{\partial \ln (\dot{l})} \Big/ \dfrac{\partial \ln (\tau_{ad}{}^i)}{\partial \ln (\dot{l})}$

At a particular pile displacement rate

[5] $\dfrac{m_s}{m_i} = k = \dfrac{\partial \ln (\tau_{ad}{}^s)}{\partial \ln (\tau_{ad}{}^i)}\Bigg|_{\dot{l}=\mathrm{constant}}$

The values of the constant k, calculated from the values of the exponents in sand and ice quoted previously, are 1.026 and 0.591 for wood and steel piles. Equation [5] leads to

[6] $\tau_{ad}{}^s = A(\tau_{ad}{}^i)^k$

where A is a constant.

Figure 6 shows a log–log plot of the variation of adfreeze strength in ice ($\tau_{ad}{}^i$) with that in frozen sand ($\tau_{ad}{}^s$) for wood and steel piles at constant pile displacement rates. The dashed lines were drawn with slopes equal to the values of k calculated above, that is 1.026 and 0.59 for wood and steel. The data seem to fit reasonably well, although for steel piles some deviations at the lower displacement rates were observed. The values of the constant A calculated from Fig. 6 were 1.3 and 1.2 for wood and steel piles.

The present analysis shows that both peak adfreeze strength for piles in frozen sand containing 14% moisture by weight and peak adfreeze strength in freshwater ice are related by an expression given by [6]. The values of the constants m_s, m_i, k, and A are as follows:

	m_s (Parameswaran 1978)	m_i (Present results)	$k = m_s/m_i$	A
B.C. fir	0.1555	0.1516	1.026	1.3
Steel H-section	0.1024	0.1733	0.591	1.2

Thus, using [6] and the values of the constants given, it is possible to estimate the adfreeze strength of a given type of pile in frozen sand from a knowledge of the value of adfreeze strength for the pile in ice (or vice versa). It should be emphasized that the values of the constants shown in the table are valid only for the particular system under consideration, namely, frozen sand with 14% moisture and the experimental setup described.

On plotting the loading rate ($\dot{P}$, kN/min) against the peak adfreeze strength (τ_{ad}), the best fit was given by the semilogarithmic plot shown in Fig. 5. This plot shows that for wood and steel H-section piles τ_{ad} is related to loading rate by

[7] $\ln \dot{P} = \ln \dot{P}_0 + (\tau_{ad}/n)$

where $\dot{P}_0$ is a constant for a particular pile–ice system, and $n = \Delta\tau_{ad}/\Delta \ln \dot{P}$ is given by the slope of the
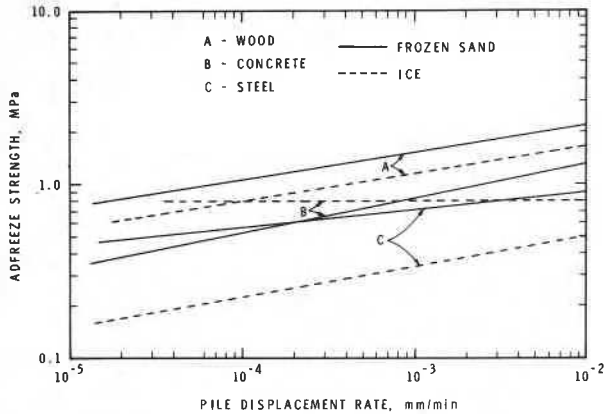
FIG. 7. Variation of adfreeze strength of piles in frozen sand (solid lines) (Parameswaran 1978) and in ice (broken lines) (present results) with nominal pile displacement rate.
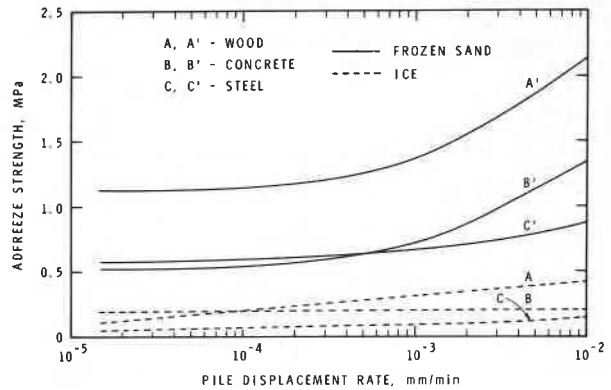
FIG. 8. Variation of total adfreeze strength of piles in frozen sand (solid lines) and contribution due to ice present in sand (broken lines) with nominal pile displacement rate.

straight line. The values of n for wood and steel piles obtained from Fig. 5 are 0.4604 and 0.1294 respectively.

From [7]

$$[8] \quad \tau_{ad} = n \ln (\dot{P}/\dot{P}_0)$$

From [1]

$$[9] \quad \tau_{ad} = (\dot{l}/\dot{l}_0)^m$$

where $(\dot{l}_0)^{-m}$ is the proportionality constant in [1]. Comparing [8] and [9],

$$[10] \quad \ln \left(\frac{\dot{P}}{\dot{P}_0}\right) = \frac{1}{n}\left(\frac{\dot{l}}{\dot{l}_0}\right)^m$$

or

$$\dot{P} = \dot{P}_0 \exp \left(\frac{1}{n}\left(\frac{\dot{l}}{\dot{l}_0}\right)^m\right)$$

Equation [10] gives the relation between the nominal rates of loading and pile displacement. The complex nonlinear relation between loading and pile displacement rates is probably due to the anelasticity of the system, composed of the machine and the pile–ice specimen. In [10], $\dot{P}_0$ is a constant having dimensions of kN/min, $\dot{l}_0$ is a constant having the dimensions of $\dot{l}$, and m and n are obtained from the slopes of the lines in Figs. 4 and 5 respectively. The constants $\dot{P}_0$, $\dot{l}_0$, m, and n are typical for each pile–ice system.

Figure 7 shows the variation of peak adfreeze strength with rate of pile displacement for frozen Ottawa sand as well as for ice. (As mentioned earlier, the pile displacement rates ($\dot{l}$) in frozen sand were estimated from the displacement rates ($\dot{x}$) of the cross-head of the testing machine by dividing the latter by 4.) The adfreeze strength for wood and steel piles is greater in frozen sand than in ice. For pile displacement rates larger than 8×10^{-4} mm/min, the adfreeze strength for concrete piles is larger in frozen sand than in ice, whereas for rates smaller than this the adfreeze strength is larger in ice than in frozen sand. The reason for this apparent anomaly is that ice adfreeze strength is independent of rate of pile displacement or rate of loading (Figs. 4 and 5); it is also probable that the skin friction between the surface of concrete piles and the soil grains is considerably less than that for the other piles at slow rates of loading.

The non-dependence of the adfreeze strength of smooth concrete piles in ice on the pile displacement rate seemed somewhat anomalous. To check this, a few tests were carried out using a smooth, painted steel, cylindrical pile in ice. Preliminary results on these piles also showed such a rate independence of adfreeze strength. On these piles (concrete and painted steel with smooth surfaces), the adfreeze strength probably is decided by the first major crack developed at the pile–soil interface. This propagates reasonably fast along the interface, without much creep occurring at the interface. These results will be published elsewhere.

To estimate the contribution of cohesion of ice and soil grain friction to the total adfreeze strength of piles in frozen sand, the values of ice adfreeze strength shown in Table 1 and Fig. 4 were reduced by a factor of 0.2377. This fraction is the ratio of the volume of water present in sand packed round the pile to a height of 190.5 mm and the volume of water filled to the same height.

Figure 8 shows the adfreeze strength of piles in frozen sand containing 14% moisture (solid lines) and the contribution to this from ice present in the sand (broken lines) on a semilogarithmic plot. The contribution of ice adhesion to total adfreeze strength

of frozen sand, estimated from these curves for
various pile displacement rates, is as follows:

Nominal rate of displacement of pile ($\dot{l}$) (mm/min)	Estimated contribution of ice adhesion to total adfreeze strength of frozen sand (%)		
	Wood	Concrete	Steel H-section
5×10^{-5}	13.3	34.6	8.6
2×10^{-4}	18.0	32.4	10.3
1×10^{-3}	22.2	25.7	12.3
5×10^{-3}	20.0	16.1	12.8

This indicates that at very slow displacement rates
(5×10^{-5} mm/min) ice adhesion is much larger for
concrete piles than for the other piles and that as the
rate increases the soil grain friction is mobilized
rapidly. In contrast, with wood and steel piles the
adhesion component from ice increases slightly with
increasing displacement rate (see also Fig. 8).

The present results may now be compared with
similar ones obtained earlier by other workers in
both laboratory and field and with theoretical pre-
dictions made from the creep rate of ice. Sackinger
and Sackinger (1977) observed a value of 0.97 MPa
for the adfreeze strength of cylindrical steel piles in
ice at $-23°C$ at a loading rate of 0.1 MPa/s. This
corresponds to a loading time of about 10 s prior to
breakage of the adfreeze bond and about three orders
of magnitude faster than the fastest rate at which the
present tests were carried out. In the present tests,
0.1 MPa/s corresponds to a loading rate of 273.6
kN/min, and the present values of adfreeze strength
for steel H-section piles in Fig. 5 (extrapolated to the
rate of 273.6 kN/min) give a value of adfreeze
strength of 0.81 MPa, which is smaller than the value
of Sackinger and Sackinger (1977). This is probably
due to the higher temperature ($-6°C$) in which the
present tests were carried out. Michel (1970) quotes
values of adhesion of ice to various construction
materials as obtained by Freiberger and Lacks (1961)
under a rate of loading of 5 psi/s (2.07 MPa/min, or
94.53 kN/min in the present setup). The adfreeze
strength values they observed for mild steel and wood
were 0.83 and 0.31 MPa respectively. They also
observed that the strength of adhesion of ice to con-
struction materials depends strongly on rate of load
application. In the present experiments the values
under corresponding loading rates were 0.77 and
2.50 MPa. The value for steel piles is close to that of
Freiberger and Lacks (1961), but their adhesion value
for wood is considerably smaller than that indicated
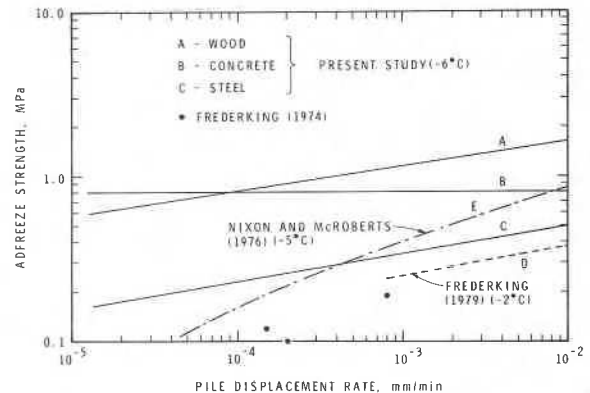by the present result.

FIG. 9. Values of adfreeze strength for piles in ice; compari-
son of present results with those in the literature.

Stehle (1970a, b) conducted short-term as well as
long-term tests on various kinds of piles in ice; from
these data the values of adfreeze strengths (MPa) of
piles (76.2 mm) in ice at $-6°C$ (rates of loading not
specified) were as follows.

In freshwater ice, fast pull-out tests:
    Wood: 2.34
    Steel H-beam: 1.24 (0.54 in slow rate tests)
    Painted steel piles: 0.69
In seawater ice, fast pull-out tests:
    Steel H-beam: 0.40
Values obtained by Tsytovich and Sumgin (1959)
for adfreeze strength of different piles in ice were
as follows:

	Temperature (°C)	Adfreeze strength (MPa)
Ice to smooth concrete*	-5 to -10	0.96
Ice to smooth wood	-1	0.49
	-5	0.61
	-7	1.14
	-10	1.34
	-20	2.16

*This is close to the value of 0.8 MPa observed in the present tests.

This indicates that the adfreeze strength of wood
piles in ice varies almost linearly with temperature.

Frederking (1979) carried out pile pull-out tests at
$-2°C$ at rates varying between 4.2×10^{-3} and 2.1
mm/min. His values of adhesion strength for wooden
piles varied between 0.1 and 1 MPa, for rates varying
between 2×10^{-1} and 6×10^{-1} mm/min. His values,
as well as others, are compared with the present
results in Fig. 9 and Table 2. The three points shown
separately in Fig. 9 are those obtained by Frederking
(1974) in field tests. His values for wood piles (line D,

TABLE 2. Adfreeze strength of piles in freshwater ice

Author	Adfreeze strength (MPa)		Temperature (°C)	Rate of loading displacement
Tsytovich and Sumgin (1959)	Smooth concrete	0.96	−5 to −10	Fast rate
	Smooth wood	0.61	−5	Fast rate
		1.14	−7	Fast rate
Stehle (1970a,b)	Wood	2.34	−6	Fast rate
	Steel H-section	1.24	−6	Fast rate
	Steel H-section	0.54	−6	Slow rate
Freiberger and Lacks (1961) (quoted by Michel (1970))	Wood	0.31		2.07 MPa/min
	Mild steel	0.83		
Sackinger and Sackinger (1977)	Steel pipes	0.97	−23	0.1 MPa/s
Frederking (1979)	Wood	0.1–1.0	−2	4×10^{-3} to 2 mm/min
Parameswaran (present study)	Wood	0.56–1.8	−6	10^{-4} to 10^{-1} mm/min (10^{-3} to 10 kN/min)
	Concrete	0.8	−6	10^{-4} to 10^{-1} mm/min (10^{-3} to 10 kN/min)
	Steel H-section	0.18–0.6	−6	10^{-4} to 10^{-1} mm/min (10^{-3} to 10 kN/min)

Fig. 9) are smaller than the present results (line A, Fig. 9) by a factor of 4.5. The principal reason for this is probably that Frederking's tests were conducted at a mean ice temperature of −2°C, whereas the present tests were carried out at −6°C. As well, Frederking's tests were carried out in a water-filled tank with ice frozen to the sides, so that in addition to shear along the pile–ice interface, bending of the ice plate was also involved. In the present tests the pile was embedded in ice completely supported on the base plate of the box and therefore only shear along the pile–ice interface was involved. The variation of adfreeze strength with rate of pile displacement appears to be almost the same in the present studies as in Frederking's later tests (1979), as may be seen from the slopes of lines A and D. Using [1], the value of the exponent m obtained for various lines in Fig. 9 was as follows:

Present study:
  Wood piles (line A): 0.1516
  Steel H-section (line C): 0.1733
Frederking (1979):
  Wood piles (line D): 0.1710

Line E in Fig. 9 represents the theoretical prediction of Nixon and McRoberts (1976) based on the steady-state creep rate of ice. This curve was derived from an equation

[11] $\dot{u} = A(\tau_a)^{n_1} + B(\tau_a)^{n_2}$

where $\dot{u}$ is displacement rate, τ_a is stress along the pile–ice interface, and A, B, n_1, and n_2 are constants that depend on temperature and pile diameter. For −5°C, values of n_1 and n_2 are 1.92 and 4 respectively. At higher rates (larger than 10^{-4} mm/min) $n_2 = 4$ is the value that governs the pile displacement rate. As may be seen in Fig. 9, if the theoretical prediction (line E) of Nixon and McRoberts (1976) is extrapolated to the higher pile displacement rate region ($> 10^{-1}$ mm/min), it tends to approach the values of adfreeze strength obtained experimentally for wood piles (line A) in the present series of tests. At the lower displacement rate the theoretical prediction deviates from experimentally observed values.

Finally, it is worth noting that adhesion between two materials involves chemical bonding and an associated electrical effect resulting from the formation of an electrical double layer in which one of the materials becomes a donor and the other an acceptor. By this process an electrical potential is generated during freezing of ice to piles, especially metallic piles. One can calculate the charge concentration at the metal–ice interface and the force of adhesion as a function of charge concentration, based on the electronic band theory of solids. Measurement of the electrical potential and the calculation of the force of adhesion have been described by Parameswaran (1980). For a thickness of a double layer of 0.3–0.5 nm and a surface charge density of electrons of 10^{14} m^{-2} (values reasonable enough for the system under consideration), the force of adhesion amounts to 0.1–0.3 MPa. This compares favourably with the adfreeze strength values of 0.2–0.6 MPa obtained for steel in the present experiments.

Conclusions

Measurement of adfreeze strength of various kinds of piles in ice at $-6°C$ shows that wood piles have the highest strength (0.6–1.8 MPa) for nominal rates of pile displacement between 10^{-4} and 10^{-1} mm/min (loading rates between 10^{-3} and 10 kN/min). Smooth concrete piles have an adfreeze strength of 0.8 MPa, irrespective of rate of displacement. Steel H-section piles have adfreeze strength values between 0.2 and 0.6 MPa. The adfreeze strength of wood and steel piles in ice increases linearly with increasing rate of displacement on a log–log scale. Theoretical predictions from steady-state creep of ice extrapolated to high values of pile displacement rates (0.1 mm/min and higher) tend to approach the experimentally determined values for wood piles.

On comparison with adfreeze strength values for piles in frozen sand (containing 14% moisture by weight) reported by Parameswaran (1978), the cohesive component due to ice in the frozen sand is found to be large (about 34% of the total adfreeze strength) for concrete piles at slow rates of pile displacement; as the rate increases, the soil grain friction at the pile–soil interface is mobilized rapidly. For wood and steel piles, the cohesive component due to ice is generally around 13 and 9% respectively for slow rates of displacement of piles; it increases slightly with increasing displacement rate.

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