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Adfreezing Strength of Ice to Model Piles

by V.R. Parameswaran

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Adfreezing strength of ice to model piles

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Results of tests to determine the adfreezing strength of freshwater ice to piles having different surface characteristics show that adfreeze strength increases with increase in the rate of displacement and loading of the pile. Surface coatings such as creosote on wood piles and paint and silicone sealer on metallic piles drastically decrease the adfreezing strength of ice.

Key words: adfreezing strength, displacement rate, ice, loading rate, model piles, surface coating.

Des résultats d'essais pour déterminer la résistance de l'adhérence par le gel de la glace d'eau douce aux pieux ayant différentes caractéristiques de surface démontrent que la résistance de l'adhérence croît avec la vitesse de déplacement et de chargement du pieu. Des recouvrements de surface tels que la créosote sur les pieux de bois, et la peinture et le scellant de silicone sur les pieux métalliques diminuent de façon drastique la résistance de l'adhérence de la glace.

Mots clés : résistance de l'adhérence par le gel, vitesse de déplacement, glace, vitesse de chargement, pieux modèles, recouvrement de surface.

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Introduction

In designing pile foundations for offshore structures in ice-infested waters the adfreezing strength between piles and the

ice frozen to them is a prime consideration. Upward forces are exerted on piles by a floating ice cover when water levels change, and these forces can be sufficiently large to cause uplift of the piles. To prevent uplift, the load on a pile and the

FIG. 1. Schematic diagram of experimental setup to measure adfreeze strength under constant rate of crosshead motion.

depth of embedment in the soil at the seabed should be sufficient to ensure that the bond between the pile and ice will fail before the pile is displaced vertically. Conversely, if structures are to be built on pile foundations over huge ice bodies such as the Greenland or Antarctic ice sheets or in ice-rich frozen soils, the adfreezing bond between the ice and the pile should be sufficiently large to give adequate bearing capacity. Thus, for design of pile foundations in ice-covered waters and ice-rich soils a knowledge of adfreeze strength of ice to piles is absolutely essential.

Knowledge of the strength of adhesion of ice to substrates is also essential in designing structures exposed to severe winter conditions, including heavy snow and ice accumulation. Aircraft wings and windshields and ship structures are regularly coated with deicing agents to reduce ice accretion. Solar panels exposed to icing weather can also be coated with deicing agents to ease the removal of ice. The adhesive strength of ice to roofing materials governs their performance in service as well. If the adhesive strength is larger than the breaking strength of the roofing material itself, the latter will be damaged during ice removal. Thus, a study of adfreeze strength of ice to various materials and the effect of such factors as rate of displacement and loading, coatings, etc., will be very useful.

Results of laboratory measurements of the adfreezing strength of freshwater ice to three kinds of small-scale model piles (uncoated, cylindrical wood and concrete, and steel H-section) were presented earlier (Parameswaran 1981). The results were compared with those from laboratory and field measurements reported in the literature. A list of these references was appended to the earlier paper (Parameswaran 1981). The present tests are a continuation of the earlier ones and are designed to determine the effect of surface finish and surface coatings on the adfreeze strength of ice to substrates.

Experimental procedure

The equipment and test method were the same as those described earlier (Parameswaran 1981). The model piles tested

FIG. 2. Variation of adfreeze strength (τ) of ice on creosoted wood piles: (a) displacement rates, (b) loading rates. The broken lines in (a) and (b) represent the results on uncoated wood piles from earlier tests (Parameswaran 1981).

in the present experiments were as follows:

1. creosoted wood (B.C. fir) piles;
2. steel piles, cylindrical as well as H-section, with a smooth surface coat of enamel paint;
3. piles made from dense, hard tropical woods such as basralocus, ekki, manbarklak, and wallaba;
4. wood piles covered with bituminous materials (asphalt, asphalt and gravel, or Derbygum, a prefabricated, reinforced, modified roofing membrane);
5. aluminum, cylindrical piles and H-sections, uncoated or with a silicone coating.

All the cylindrical piles were of 76.2 mm diam. and 304.8 mm length. The H-section piles were 304.8 mm long, with a depth of section of 101.6 mm, width of flange of 100 mm, and web thickness of 6.35 mm. The outer diameters of the piles coated with asphalt and gravel varied between 95 and 105 mm; those covered with Derbygum had outer diameters of about 85 mm.

Figure 1 shows the experimental setup in the cold room for measuring adfreeze strength of ice to piles. Pile A, cylindrical or H-section, was placed in freshwater in a Plexiglas box, B, 0.305 m to a side and allowed to freeze in a cold room maintained at a temperature between -6 and -10°C . As freezing occurred from all four sides of the Plexiglas box as well as from the bottom aluminum plate and the exposed water surface, the structure of the ice consisted of some columnar grains

FIG. 3. Variation of adfreeze strength (τ) of ice on painted steel piles: (a) displacement rates, (b) loading rates. The broken line in (a) represent the result for uncoated steel H-section from earlier tests.

near the surfaces, but the bulk of the ice was equiaxed in structure, especially around the pile. Following complete freezing, the box with supporting legs, F, was placed on the base plate of a universal testing machine (250 kN capacity) installed in the cold room. The supporting plug, C, was removed, an LVDT (linear variable differential transducer), L, was mounted under the pile, and the pile was pushed out at a constant rate of displacement by the ram, E, attached to the load cell of the machine crosshead. The output of the load cell and the LVDT were fed to a data logger and microcomputer and the load-displacement curve was plotted. From the peak load, the peak adfreeze strength for that particular rate was calculated by dividing by the adfreezing interfacial area between pile and ice. A nominal pile displacement rate was calculated by dividing the displacement at peak load by the corresponding time required to attain it. Most tests were carried out at a temperature of -6°C ; some of those on roofing materials and aluminum were carried out at -10°C .

Results and discussion

Results of tests are presented in Figs. 2–6, peak values of adfreeze strength plotted as a function of displacement rate as well as loading rate on a log-log scale. For a fixed rate of movement of the machine crosshead the actual displacement rate of the pile itself, as measured by the LVDT mounted under the pile, was considerably smaller, owing to the elasticity of the machine and the experimental setup of the pile-ice sys-

FIG. 4. Variation of adfreeze strength (τ) of ice on piles made from hard tropical woods: (a) displacement rates, (b) loading rates. The broken line in (a) represents the results for uncoated B.C. fir from earlier tests.

tem. Both the machine rate and the actual pile displacement rate are plotted against adfreeze strength in Fig. 2a. In subsequent figures only the pile displacement rates are shown. Typical values of peak adfreeze strength measured at various displacement rates for different kinds of piles are given in Table 1 (not all the tests are reported).

Creosoted wood piles

Figure 2a shows the variation of adfreeze strength with machine crosshead speed as well as nominal pile displacement rate calculated from the displacement at peak load. Also shown for comparison is the variation of adfreeze strength of ice on uncoated wood piles obtained from earlier tests (Parameswaran 1981). Adfreeze strength for the creosoted piles increased rapidly with increasing displacement rate in the lower rate region (10^{-4} – 10^{-2} mm/min) and more slowly at the higher rates. Adfreeze strength for coated piles was smaller than that for uncoated piles by a factor of 2 or more in the lower displacement rate region ($<10^{-3}$ mm/min), but the values approached those for uncoated piles when the piles were loaded at a faster rate ($>10^{-2}$ mm/min).

Figure 2b shows that adfreeze strength increases with increasing rate of loading. A straight line was fitted on a log-log plot by the method of least squares.

Painted steel piles

Figure 3 shows the adfreeze strength values for ice on steel

TABLE 1. Typical values of adfreeze strength of piles in ice at various displacement (loading) rates (not all test results shown)

Pile material	Machine crosshead speed (mm/min)	Temperature (°C)	Nominal pile displacement rate (mm/min)	Nominal loading rate (kN/min)	Peak adfreeze strength (MPa)
Creosoted B.C. fir pile	0.0005	-6	1.08×10^{-4}	5.58×10^{-3}	0.394
	0.005	-6	9.53×10^{-4}	1.36×10^{-1}	1.024
	0.04	-6	4.08×10^{-3}	1.22	1.574
	0.1	-6	1.31×10^{-2}	3.03	1.698
Painted steel cylindrical pile	0.0005	-6	9.07×10^{-5}	1.23×10^{-2}	0.405
	0.002	-6	3.24×10^{-4}	5.33×10^{-2}	0.803
	0.005	-6	8.01×10^{-4}	1.44×10^{-1}	0.712
	0.02	-6	2.54×10^{-3}	7.82×10^{-1}	0.948
Painted steel H-section	0.002	-6	3.84×10^{-4}	5.07×10^{-2}	0.368
	0.05	-6	7.74×10^{-3}	2.06	0.425
	0.1	-6	1.06×10^{-2}	4.72	0.517
Uncoated aluminum cylinder	0.01	-10	8.81×10^{-4}	0.42	0.614
	0.1	-10	1.23×10^{-3}	4.74	0.788
Aluminum cylinder coated with silicone	0.001	-10	1.49×10^{-3}	1.47×10^{-3}	0.005
	0.01	-6	1.61×10^{-3}	0.12	0.029
	0.1	-6	5.73×10^{-3}	0.88	0.037
Uncoated aluminum H-section	0.001	-10	2.77×10^{-4}	2.35×10^{-2}	0.282
	0.001	-10	1.01×10^{-4}	3.11×10^{-2}	0.269
	0.01	-10	1.00×10^{-3}	0.33	0.294
	0.1	-10	2.58×10^{-3}	3.51	0.286
Aluminum H-section coated with silicone	0.01	-6	7.93×10^{-4}	7.38×10^{-2}	0.014
	0.1	-10	1.2×10^{-2}	0.11	0.002
Asphalt on wood	0.001	-6	6.62×10^{-4}	3.16×10^{-3}	0.138
	0.01	-10	4.14×10^{-3}	0.16	0.521
	0.05	-6	1.74×10^{-2}	0.77	0.318
Asphalt and gravel on wood	0.001	-6	6.08×10^{-4}	4.35×10^{-3}	0.252
	0.01	-6	5.64×10^{-3}	1.03×10^{-1}	0.368
	0.05	-6	2.72×10^{-2}	0.61	0.491
Wood covered with Derbygum	0.001	-10	2.28×10^{-4}	1.34×10^{-2}	0.378
	0.01	-10	2.48×10^{-3}	0.20	0.475
	0.10	-10	1.77×10^{-2}	2.03	0.614
Tropical wood piles Basralocus	0.001	-6	3.12×10^{-4}	2.05×10^{-2}	0.768
	0.01	-6	1.87×10^{-3}	3.44×10^{-1}	1.206
	0.05	-6	1.66×10^{-2}	1.35	0.932
Ekki	0.001	-6	1.25×10^{-4}	3.11×10^{-2}	1.003
	0.01	-6	1.77×10^{-3}	0.33	1.070
	0.05	-6	7.36×10^{-3}	2.13	1.780
Manbarklak	0.001	-6	2.42×10^{-4}	3.03×10^{-2}	1.150
	0.01	-6	1.53×10^{-3}	3.92×10^{-1}	1.491
	0.05	-6	8.65×10^{-3}	1.94	1.720
Wallaba	0.001	-6	1.86×10^{-4}	3.11×10^{-2}	1.155
	0.01	-6	1.45×10^{-3}	0.39	1.601
	0.05	-6	1.74×10^{-2}	1.85	1.635

FIG. 5. Variation of adfreeze strength (τ) of ice on wood piles covered with different roofing materials: (a) displacement rates, (b) loading rates. The broken line in (a) represents results from uncoated B.C. fir obtained in earlier tests.

cylindrical piles and H-sections, both coated with a smooth enamel paint, as a function of the actual pile displacement rates and loading rates. Again, for comparison, the values of adfreeze strength of ice on uncoated H-section piles (Parameswaran 1981) are shown as a function of displacement rate of the pile. No data are available for uncoated steel cylindrical piles.

For painted cylindrical steel pipe piles, the adfreeze strength of ice increased with increasing displacement rate in the slow rate region, but at higher displacement rates the increase was very small. This could be due to the smoothness of the painted surface and inability to mobilize surface friction. Figure 3b shows, however, the adfreeze strength increases with increasing loading rate for both cylindrical piles and H-sections. The lines shown in the figure were fitted through the data points using the principle of least squares.

Considering H-section steel piles, the adfreeze strength increased with increasing displacement rate and the behaviour of coated and uncoated piles did not differ appreciably. This could be due to the inherently rough mill finish surface of the H-section, which cannot be made smoother by paint alone. The adfreeze strength was much smaller for the H-section piles than for the cylindrical piles, although the former had a much rougher surface.

The peak load that a painted cylindrical steel pile could support before failure varied between 36 and 57 kN for displace-

FIG. 6. Variation of adfreeze strength (τ) of ice on smooth aluminum piles: (a) displacement rates, (b) loading rates.

ment rates between 0.01 and 0.1 mm/min. The corresponding values of peak load for a painted steel H-section were between 38 and 54 kN. The cross-sectional area of the steel pipe piles was about half that of the steel H-sections. Thus, in instances where adfreezing strength of ice is utilized for bearing capacity of pile foundations in ice or ice-rich soils, considering weight of steel used, pipe piles are more economical than H-sections. The lower adfreezing strength of ice to H-sections, compared with that to cylindrical piles, can probably be attributed to higher stress concentration leading to the initiation of failure at the sharp edges of the H-section, thereby reducing adfreeze bond strength.

Piles made of dense, hard tropical wood

In response to a request from a supplier of tropical wood products, cylindrical piles made from four different tropical woods, ekki and manbarklak from Western Africa and wallaba and basalocus from South America, were tested for adfreeze strength in ice. The results are plotted in Fig. 4. It indicates that at lower displacement rates some of these tropical wood piles (wallaba and manbarklak) show peak adfreeze strengths slightly larger than those of B.C. fir, although at the higher displacement rates the values approach those for the latter.

Wood piles covered with bituminous roofing and waterproofing materials

Three kinds of piles were tested:

1. wood piles covered with a thick coating of asphalt (~ 10 mm);

2. wood piles covered with asphalt and gravel;
3. wood piles covered with Derbygum (a prefabricated, reinforced, modified roofing membrane) 5 mm thick.

The tests were designed to evaluate the adfreeze strength of ice to roofing materials. If the strength of the roofing material itself is smaller than the adfreezing strength of ice to the materials, there will be a tendency for the roofing material to fail by fracture if a crack is initiated and propagated in the ice for some reason (such as thermal contraction or impact, or during ice removal from roofs).

Variation of adfreeze strength for the three types of pile, including displacement rates and loading rates, is shown in Fig. 5. For comparison, adfreeze strength for ice on uncoated wood piles is also shown. The asphalt-coated wood pile shows adfreeze strength values six times smaller than the corresponding values for uncoated wood.

Following examination of the piles during and after the tests, it was found that failure occurred between the ice and asphalt; no slippage was noted between the wood and asphalt. The measured adfreeze strength was indeed that between asphalt and ice. With piles coated with asphalt and gravel there was a tendency for a few gravel particles to be dislodged from the pile surface during test, and some slippage occurred between the wood and asphalt, although peak load corresponded to failure of the ice-asphalt interface.

Aluminum piles with smooth surfaces

Uncoated aluminum piles, both cylindrical and H-section and some with a silicone coating (Dow Corning #1890 RTV), were tested for adfreeze strength in ice. The tests were designed to determine the effect of silicone coating in decreasing the adhesion of ice to aluminum structures exposed to severe winter conditions.

Figure 6 shows the variation of adfreeze strength with displacement rate and loading rate. As observed earlier for steel piles, adfreeze strength values for H-section piles was much smaller than the corresponding values for cylindrical piles. The difference can probably be again attributed to stress concentration and initiation of failure at the sharp edges of the H-section. It may also be seen that adfreeze strength on the H-piles did not increase much with increased displacement rate or loading rate. Values of adfreeze strength were much smaller than the corresponding values for steel piles, probably because aluminum piles, both cylindrical and H-section, have a much smoother surface finish.

When the aluminum piles were coated with a silicone material (Dow Corning RTV sealant), adfreeze strength dropped to very low values, 0.002–0.03 MPa, that is, one to two orders of magnitude smaller than values for uncoated piles. This indicates that silicone coating is very effective in reducing ice adhesion to surfaces, at least for the short term.

Figures 2–6 show, in most instances, a linear increase of adfreezing strength (τ) with displacement rate ($\dot{I}$) and loading rate ($\dot{P}$) when plotted on a log-log scale, indicating a power law relation between the quantities:

$$\begin{aligned} \tau &= A(\dot{I})^m \\ [1] \quad \ln(\tau) &= \ln(A) + m \ln(\dot{I}) \end{aligned}$$

and

$$\begin{aligned} \tau &= B(\dot{P})^n \\ [2] \quad \ln(\tau) &= \ln(B) + n \ln(\dot{P}) \end{aligned}$$

TABLE 2. Values of A , m , B , and n in [1] and [2]

Pile material	A	m	B	n
Creosoted B.C. fir	3.657	0.230	1.206	0.211
Painted cylindrical steel	1.784	0.115	0.932	0.106
Aluminum cylinder (silicone)	5.425	0.954	0.043	0.250
Painted steel H-section	1.093	0.155	0.464	0.116
Uncoated aluminum H-section	0.423	0.053	0.302	0.033
Asphalt on wood	1.346	0.277	0.464	0.188
Asphalt and gravel	1.146	0.207	0.564	0.155
Derbygum	1.218	0.151	0.598	0.114
Basralocus, Ekki, Manbarkalak, Wallaba	2.086	0.082	1.518	0.121
Uncoated B.C. fir*	5.248	0.242	1.590	0.177
Uncoated steel H-section*	0.832	0.119	0.500	0.135

*Results from earlier tests (Parameswaran 1981).

where m and n are power law exponents and A and B are constants. Results of the present tests as well as those from earlier ones on uncoated wood and steel H-section (Parameswaran 1981) were fitted to [1] and [2] using a log-log least squares fit program; the values of A , m , B , and n so obtained are shown in Table 2. Values of m obtained for wood piles (uncoated, creosoted, asphalt coated, and with asphalt and gravel) were in the range 0.2–0.28, whereas for steel piles (cylindrical and H-sections, coated as well as uncoated) m was in the range of 0.115–0.155. Uncoated piles made from dense tropical wood and aluminum H-section had very low values of m , showing a very slow variation and hence very small dependence of adfreeze strength on displacement rate.

It should be noted that the values of adfreeze strength shown in Table 1 and Figs. 2–6 are upper-bound values for the corresponding displacement rates. They were measured while piles were being pushed through the ice in the box under somewhat confined conditions. If, however, piles are pulled from ice, the adfreeze strength can be much smaller than the values quoted above (Frederking 1974, 1979). In actual practice in ice-infested waters, as a pile is loaded the ice sheet around it is subjected to bending as well, and radial cracks propagate from the centre of load application. This can lead to much lower values of adfreezing strength between pile and ice cover. Owing to scale effects and the semiconfined conditions of the laboratory tests, it will be necessary to carry out field tests of piles in ice-covered waters in order to obtain more realistic values of adfreeze strength for design purposes.

Conclusion

Adfreeze strength of ice to piles made of various materials such as wood, steel, and aluminum increased with increasing displacement rates of the piles, rates varying between 10^{-4} and 10^{-1} mm/min. The bearing capacity per unit weight of a pipe pile (nominal diam. 100 mm) was much larger than that of an H-section (100 mm flange $\times$ 100 mm depth), although the latter had a much rougher surface. Lower adfreeze strength on the H-section could probably be attributed to stress concentration and failure initiated at the sharp edges of the H-section.

Creosote coating on wood piles reduced adfreeze strength at lower displacement rates, but at higher rates of loading there was little difference in the adfreeze strength values for creosoted and uncoated piles. A coating of bituminous roofing and waterproofing material on wood piles reduced adfreezing strength by a factor of 4–6; and silicone coating on aluminum piles drastically reduced adfreezing strength by a factor of 10–100 (to values as low as 0.002 MPa) when compared with that of an uncoated aluminum surface.

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