CHAPTER 93

THE PRESSURE OF FLOATING ICE-FIELDS ON PILES

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SYNOPSIS

In order to determine the maximum ice forces against structures, the compressive strength was investigated by laboratory tests on cubes of several ice species. The results contain the influence of temperature, velocity of deformation and direction of pressure on the cubic strength.

In order to employ these laboratory results for the calculation of structures, a relationship between the strength in laboratory tests and in nature was derived by measuring the pressure of floating ice-fields on a pile of a bridge, which crosses the tidal estuary of the EIDER River.

The investigation leads to an equation, which allows the calculation of ice pressure against piles.

INTRODUCTION

In cold regions the pressure of ice is decisive for the calculation of hydraulic structures. This pressure, however, is still unknown or just in development. It is therefore not surprising that in severe winters hydraulic structures will be destroyed by ice run.

In rivers the danger of ice pressure decreases with time, because the ice run in spring will be controlled by ice-breaker-

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A similar report was given by the author at the 1. Ice-Symposium of IAHR in Reykjavik, September 1970

ships and because the ice formation will be reduced by the heated water of power-stations.

In coastal regions there is no way of keeping the ice forces from structures and just in these locations the question of ice pressure becomes more and more important, for example by the offshore-construction of deep-water harbors, transloading-points for oil, light-houses and bridges.

Intensive ice research was started after World-War II., especially in USA, Canada and Russia with the investigation of fundamental properties of ice (6).

The problem of ice forces on structures has picked up during the last 10 years: KORZHAVIN (3, 1962) developed an equation to calculate the pressure of river ice in spring. This formula is based upon assumptions, which are only derived through laboratory tests. PEYTON (4, 1966) measured the ice pressure on the piles of a drilling-platform in Cook Inlet, Alaska. His qualitative results are in agreement with the investigations of the author. Some experimental work, carried out by oil companies (CROASDALE, 2, 1970) has not yet been published.

A general view about the present situation of research of ice pressure on structures was given by ASSUR (1, 1970) at the 1. Ice Symposium of IAHR, 8 - 10 September 1970 in Reykjavik.

GENERAL CONSIDERATION

The authors investigation (5, 1970) of the pressure of floating ice-fields on piles has been based on the assumption that the maximum pressure of ice is limited by its compressive strength. This strength was first of all ascertained in compression tests on cubes in order to determine systematically the different influences, such as temperature, velocity of deformation and direction of pressure. The received cubic strength can't be immediately employed for designing structures, because in nature the rupture of ice occurs in another way than in our laboratory tests. In nature the contact between ice and structure is, for example, smaller than in the experiments between ice cube and pressure plate. Moreover the shape, the width of the structure and the thickness of ice has an influence upon the strength.

Because the fundamental strength properties nevertheless should be utilized for calculating ice forces, it was necessary to derive a relationship between the strength in laboratory tests and in nature. This was done by measuring the ice-forces on a pile of a bridge.

LABORATORY TESTS

Strength properties were investigated by compression tests on ice-cubes from river, lake and harbor (fresh-water-ice) and from the North-Sea, Baltic-Sea and brackish-water (salt-water-ice).

The edge lengths of the cubes were 10 cm. The tests were performed at ice temperatures of 0^{o}, -10^{o} and -20^{o} C in two different directions (perpendicular and parallel to the growth-direction). The velocity of deformation was varied from $S = 3 \cdot 10^{-3} \frac{1}{sec}$ to $S = 3 \cdot 10^{0} \frac{1}{sec}$. Plywood panels were placed between the cube area and the pressure plate, in order to average out the unevenness on the cube surface, so that the test results scattered only up to ± 5 %.

RESULTS

1. By lowering the temperature, the strength of ice increases at a rate of about.

   $\alpha = 4{,}5$ kp/cm^{2}°C with fresh-water-ice and

   $\alpha = 2{,}5$ kp/cm^{2}°C with salt-water-ice.

   This strengthening is nearly linear down to -20^{o} C. The lesser strength of salt-water-ice is attributed to the liquid brine cells within the ice.

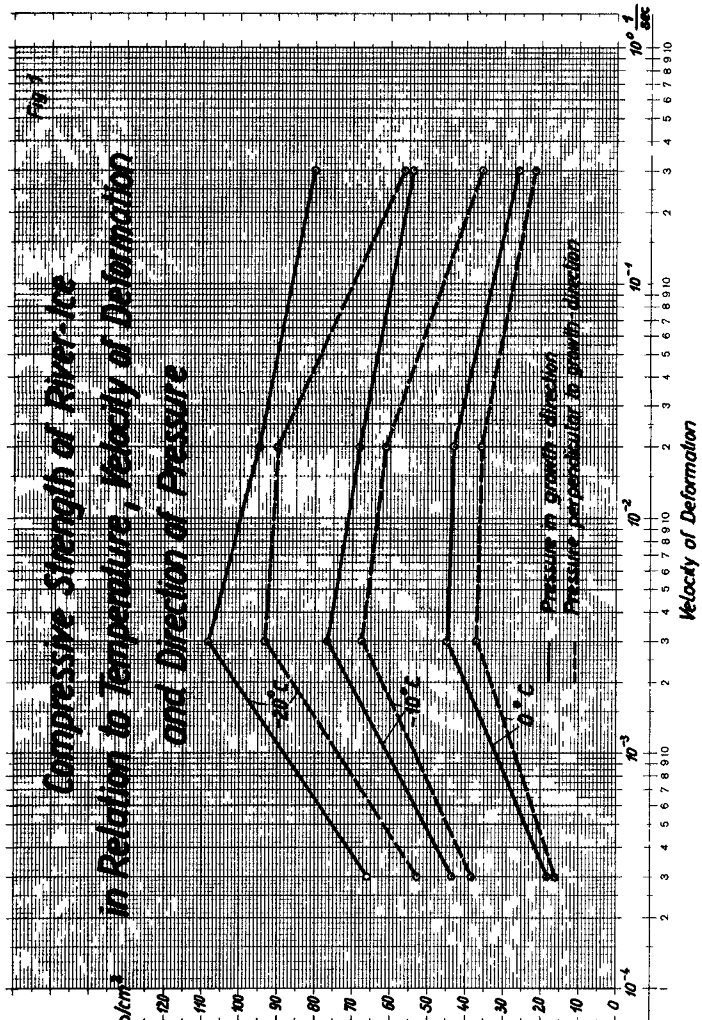


Fig. 1
Compressive Strength of River-Ice
in Relation to Temperature, Velocity of Deformation
and Direction of Pressure
-20°C
-10°C
0°C
Pressure in growth-direction
Pressure perpendicular to growth-direction
Velocity of Deformation
kp/cm²
120
110
100
90
80
70
60
50
40
30
20
10
0
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰ 1/sec

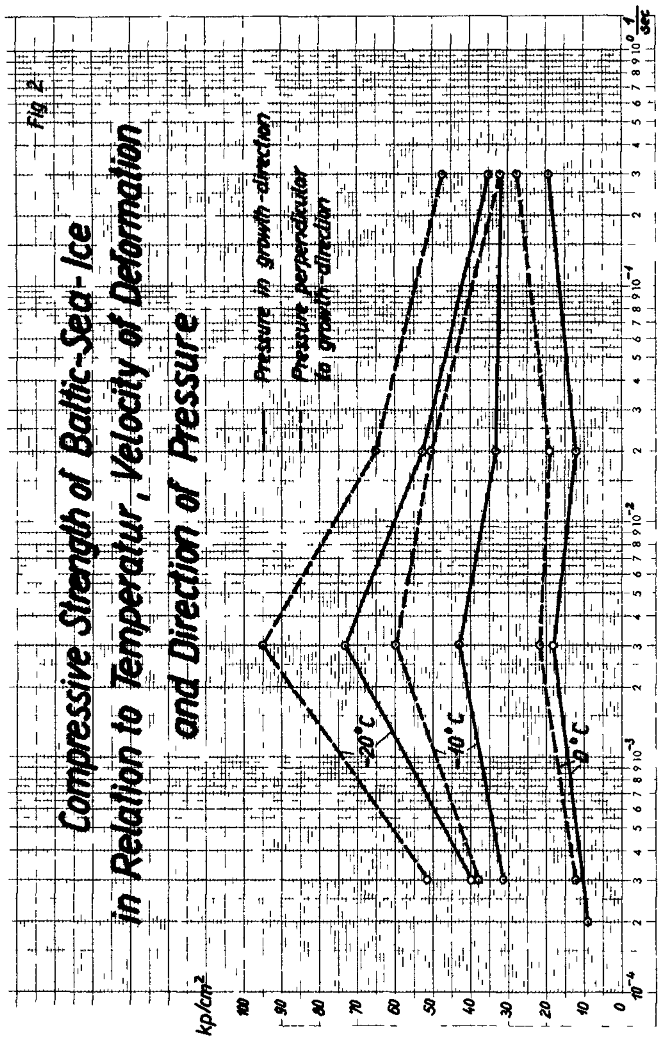


Fig 2
Compressive Strength of Baltic-Sea-Ice
in Relation to Temperatur, Velocity of Deformation
and Direction of Pressure
Pressure in growth-direction
Pressure perpendicular to growth-direction
-20°C
-10°C
0°C
kp/cm²
Velocity of Deformation

2. At a deformation velocity of S = 0,003 $\frac{1}{\text{sec}}$ there is a maximum in strength (Fig. 1, 2). This result is explainable from the deflection-time-curve, shown in Fig. 3. The maximum appears at all ice species at the same strain rate and is more evident, the colder the ice is. The deformation velocity of S = 0,003 $\frac{1}{\text{sec}}$ corresponds to an ice sheet velocity of only a few cm/sec. That means, if the ice temperature is low, the maximum ice pressure in nature is to be expected just before the ice sheet stops.

3. If the pressure acts parallel to the growth direction, the strength of fresh-water-ice is 20 % higher (Fig. 1) than if the pressure direction is perpendicular to the growth direction. With salt-water-ice these relations are just the reverse.

4. Between air-content within the ice and strength exists a nearly linear relation.

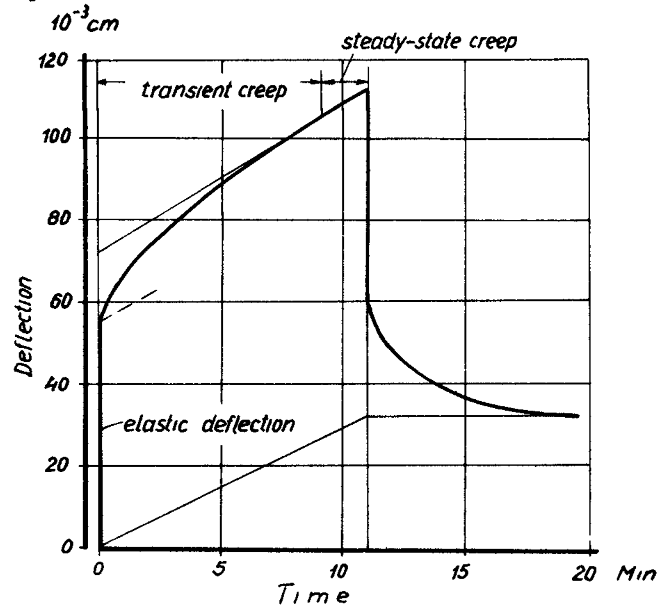


FIG. 3 DEFLECTION OF ICE VS TIME (TABATA, 7)

MEASUREMENT IN NATURE

The compressive strength of sea ice, as occurs in nature, was measured in winter 1967/68 and 1968/69 at a pile of a bridge, which crosses the tidal estuary of the Eider during the construction of a tidal barrier.

Along the entire German coast of the North Sea and also just outside the estuary of the Eider lie large flat areas (wadden ground), where ice fields can grow very quickly. These ice fields float up only at higher tides and then drift with the tidal current against the bridge, where the ice fields are cut up by the piles. In the hereby occuring state of stress the ice strength has maximum values.

The testing instrument consists of a shield with 50 pressure cells (Fig. 4), 5 in each altitude level halfway encompassing the pile (Ø 60 cm). The area of the pressure cells was 15 cm x 15 cm. In some of these pressure cells were situated smaller ones with areas of 25 cm^2 an 50 cm^2 in order to determine the relationship between strength and area of pressure. The shield was fixed on the seaside of the pile (Fig. 5).

FIG. 4 SHIELD WITH 50 PRESSURE CELLS

Insulating the electronic part of the pressure cell against salt water presented a particular problem. It was solved with BOSTIC-NEOSEAL and SILICON-CAOUTCHOUC.

RESULT

In a paper of probability (Fig. 6) the strength of sea-ice in nature, related to several areas of pressure ($\sigma_f \Rightarrow 25$ cm^2, $\sigma_{F'} \Rightarrow 200$ cm^2, $\sigma_\varnothing \Rightarrow 840$ cm$^2 \Longrightarrow$ the whole width of the pile at an ice thickness of 14 cm) was compared with the cubic strength from laboratory tests with the same ice.

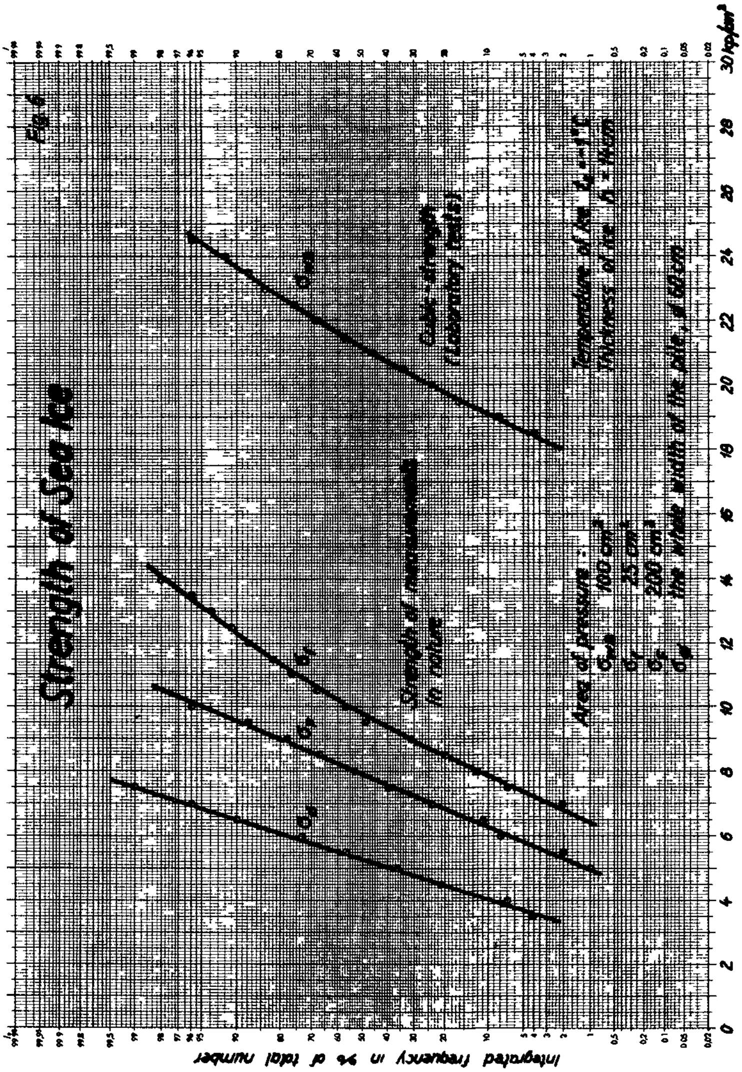
FIG. 5 POINT FOR MEASURING ICE PRESSURE ON A PILE OF A BRIDGE

1. If the pressure is related to an area of F' = 200 cm^2 the compressive strength in nature ($\sigma_{F'}$) is only half of the cubic strength (σ_{WB})

$$\frac{\sigma_{F'_{99}}}{\sigma_{WB_{50}}} = \varkappa_{F'} = 0.5$$

This reduction of the cubic strength is attributed to the incomplete contact between ice and structure. Therefore $\varkappa$ is called contact coefficient, although this value includes the different state of stress in the cube pressure experiment and in nature.

2. If the area of pressure is only f = 25 cm^2, the coefficient of contact increases to $\varkappa_f = 0.56$.


Strength of Sea Ice
Fig. 6
Integrated frequency in % of total number

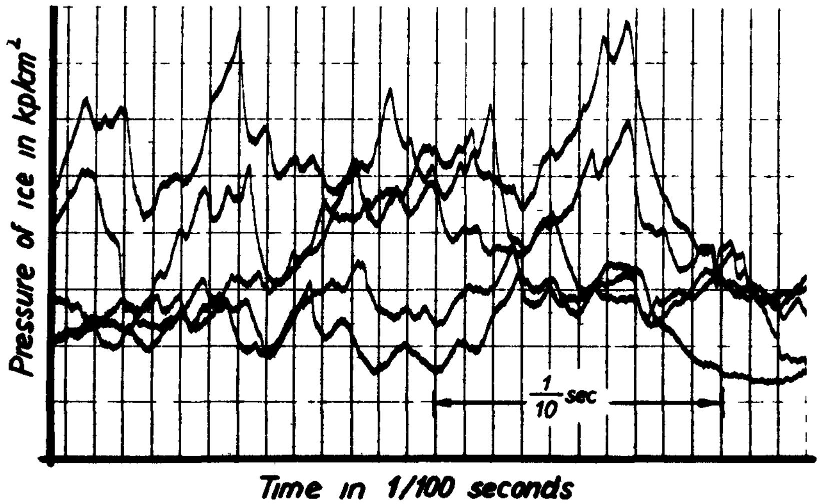


FIG. 7 ICE PRESSURE ON 5 SIDE BY SIDE PRESSURE CELLS

3. Because the peaks of pressure (Fig. 7) occur simultaneously only on 1 or 2 of the 5 side by side load cells - the others being largely unpressured - a second reduction factor from the proportion

$$\frac{\sigma_\phi}{\sigma_F} = 0{,}66 \quad \text{was ascertained.}$$

σ_ϕ is the mean pressure over the whole width of the pile x thickness of ice, projected in the direction of floating. 0.66 takes into account first of all the shape of the structure, but also the increase of the area of pressure from 200 cm^2 to 840 cm^2.

4. From measurements of different thicknesses of ice follows, that the strength of ice increases, if the ratio thickness of ice to width of pile becomes greater (Fig. 8). This is caused by the increase of the

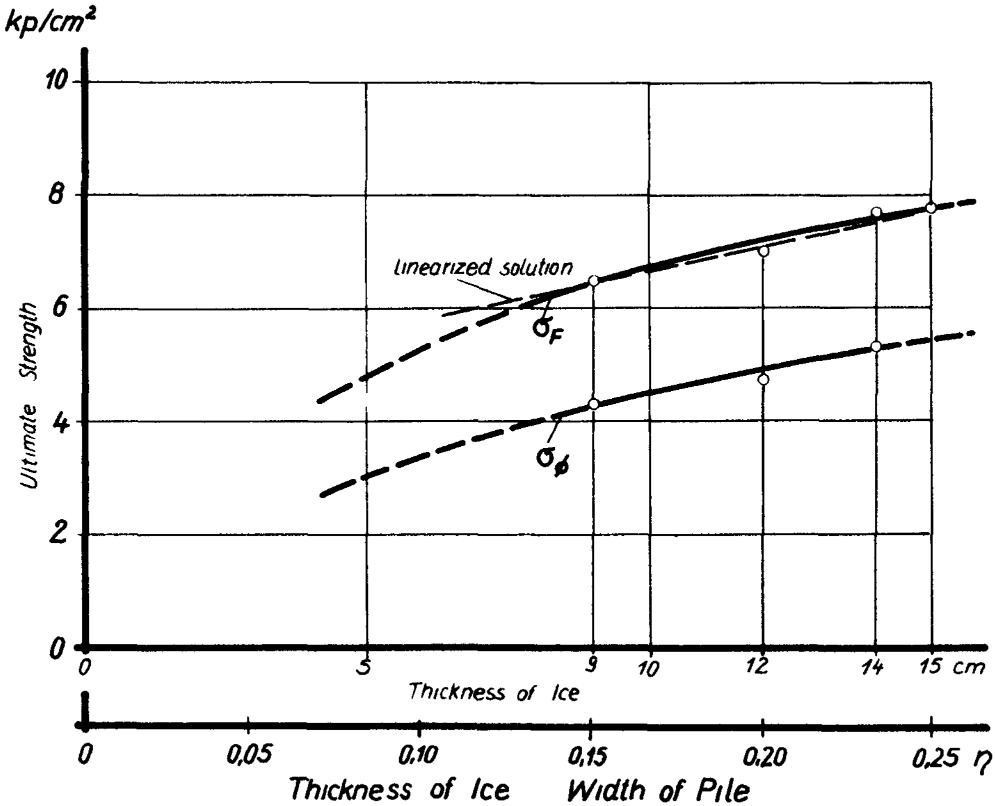


FIG. 8 RELATION BETWEEN ULTIMATE STRENGTH AND THE RATIO THICKNESS OF ICE TO WIDTH OF PILE

threedimensional stress. If the ice sheet grows thicker, the number of planes of shear increases linearly, but also the extension of the planes of shear is lengthend, so that the strength increases exponentially.

5. The pressure of brittle ice with low cubic strength was nearly the same as the pressure of new ice, because of the closer contact between brittle ice and structure. It can be assumed, that the coefficient of contact decreases with lowering temperatures.

From the results of the laboratory tests and the measurements in nature the following equation is derived in order to determine the maximum pressure of floating ice-fields on piles

$$P = \left[0,5 \cdot 0,66(\sigma_{wB}(0^{\circ}\ C) + 0,35 \cdot \alpha(t_L - t_w)) + 12,5(\eta - 0,15)\right] h \cdot b$$

$0,5$ = Coefficient of contact

$0,66$ = Coefficient of form (pile ⌀ 60 cm)

$\sigma_{WB}(0^{\circ}\ C)$ = Cubic strength of ice at 0° C and a deformation velocity of $S = 0,003\ \frac{1}{sec}$

$0,35 \cdot \alpha(t_L - t_w)$ = Influence of temperature

α = Temperature factor

t_L = Air-temperature during the last 24 hours

t_w = Water-temperature

$0,35$ = Factor to get the mean temperature of the ice-sheet (after KORZHAVIN, 3)

$12,5(\eta - 0,15)$ = Influence of thickness in proportion to the width of pile

h = Thickness of ice

b = Width of pile

η = Thickness of ice width of structure

This equation should be extended to higher values of η.

REFERENCES

1. ASSUR, A. Forces Exerted by Ice on Marine Structures. Proceeding of 1. Ice Symposium of IAHR in Reykjavik, 8 - 10 September 1970, will be published in sommer 1971.

2. CROASDALE, K.R. The Nutcracker Ice Strength Tester and its Operation in the Beaufort Sea. Preprints of papers of the 1. Ice Symposium of IAHR in Reykjavik, 8 - 10 September 1970, Reykjavik Juli 1970.

3. KORZHAVIN, K.N. The Action of Ice on Engineering Structures. Publication of the Siberian Department of the Academy of Science of USSR, Novosibirsk, 1962 (in Russian).

4. PEYTON, H.R. Sea Ice Forces. Ice Pressure against Structures. Proceedings of Conference at Laval University Quebec, 1966, Ottawa 1968.

5. SCHWARZ, J. Treibeisdruck auf Pfahle. Mitteilungen des Franzius-Instituts fur Grund- und Wasserbau der Technischen Universitat Hannover, Hannover 1970.

6. WEEKS, W., ASSUR, A. The Mechanical Properties of Sea Ice. Ice pressures against Structures. Proceedings of Conference at Laval University Quebec, November 1966, Ottawa 1968.

7. TABATA, T. Studies of Visco-Elastic Properties of Sea Ice. Arctic Sea Ice. U.S. National Academy of Science. National Research Council. Publication 598. Washington 1968.