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PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
UNIVERSITY OF ICELAND
DEPARTMENT OF ENGINEERING AND SCIENCE

MODEL TECHNIQUE FOR THE INVESTIGATION OF ICE FORCES ON STRUCTURES

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I. Introduction

Although several investigations on the prediction of ice forces on structures have been carried out during the last decade, the problem has not yet been solved. The few measurements which have been made of ice forces on prototype piles or piers (Croasdale 1970; Neill 1970, 1972; Peyton 1966; Schwarz 1970; Nevel 1972) merely indicate tendencies, because meteorological and ice conditions, structure dimensions, and other influences which have been studied cover only a small range of possibilities. Theoretical studies without any experimental support or field investigations are dangerous, because assumptions in the analysis about the state of stress and the fracture mechanism of the ice in front of the structures might not be appropriate.

A logical approach to the study of ice forces on structures is, therefore, the use of model tests as a systematic basis for further analytical inquiry. Such a research program was initiated at the Iowa Institute of Hydraulic Research in 1972.

II. Test Facility

The test facility to investigate ice forces on structures basically consists of a 20-ft long, 3-ft wide, and 2-ft deep ice tank. This tank is equipped with a variable speed gear-driven carriage (Fig. 1). A dynamometer is mounted to this carriage, and piles or structures of various diameters and shapes can be attached to it. Contrary to natural conditions, the ice cover is stationary and the carriage with the structure is driven through it. Speeds between 0.004 cm/s and 2.75 cm/s can be obtained by the driving system. These velocities cover a fairly wide range of strain rate ($\dot{\varepsilon} = 10^{-4}$ to 10 1/sec) including ductile and brittle deformation of the ice. A rotational potentiometer and an accelerometer are attached to the carriage. These measure the displacement of the carriage and control the uniformity of its speed.

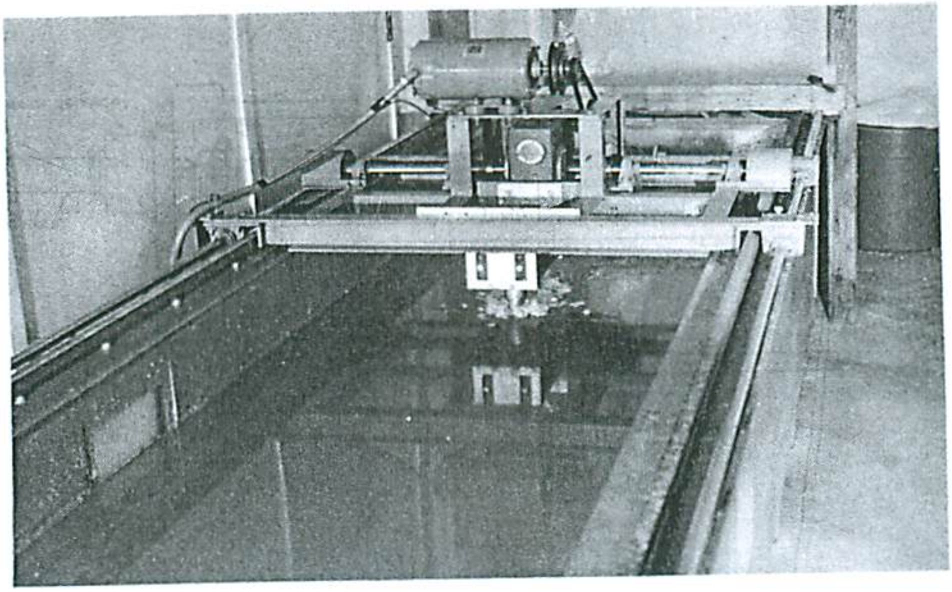

Fig. 1. Ice tank and carriage

The ice forces against the model structures are measured by means of a dynamometer. An outline of this apparatus is given in Fig. 2. The moments from the ice-structure interaction are absorbed by thin (1/50") vertical stainless steel plates and only the horizontal displacements, due to the horizontal forces experienced by the model structure, are transferred by the dynamometer to a load cell. This load cell consists of an adapter and a transducer. The adapter reduces the displacement and the transducer converts the displacement into voltage. The output from this force transducer and other related data are monitored and analyzed, on-line, by the Institute's IBM 1800 computer. The calibration curve of the dynamometer is linear and independent of temperature. The natural frequency of the dynamometer is approximately 200 Hz, which is much higher than the highest frequency of the ice force signals. Ice, air, and water temperatures are surveyed by thermistors, which are also connected to the computer. Up to now circular piles of 0.6 to 4.8 cm diameter have been used for indentation tests, combined with ice thicknesses of 0.6 to 2.5 cm.

The reference strength and other mechanical properties of the model ice are investigated by compression tests on ice prisms with a TINIUS-OLSON testing machine.

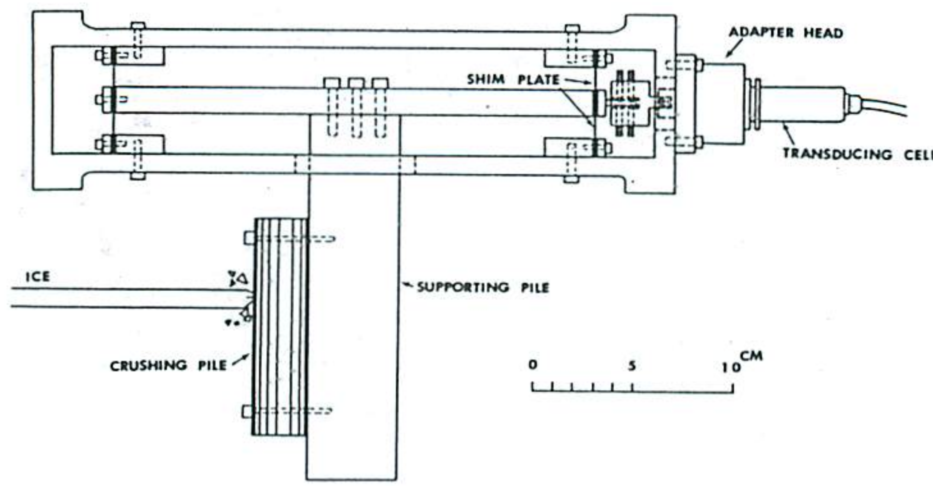

Fig. 2. Dynamometer

III. Model Ice

1. Scale effect

Scale effect is thought to be the dependence of the ice strength on the size of the ice samples. Butkovich (1955) and Butiagin (1966) found that the compressive strength of lake ice increases greatly if the cross sectional area of the sample becomes smaller than 200 cm^2. This phenomenon is commonly explained as an effect of imperfections within the ice so that statistically the strength decreases with increasing volume. Compression tests on our model ice with small crystals (d_{cr} = 0.04 cm) revealed, however, that the strength was independent of the size of the sample, although the cross sectional area of the samples ranged from 100 cm^2 down to 1 cm^2 (Fig. 3). By relating the ice strength not to the cross sectional area of the sample, as suggested by the previous investigators, but to the ratio of the sample diameter d to the crystal diameter d_{cr} (d/d_{cr}), it can be shown that the compressive strength of Butiagin's and Butkovich's tests is also independent of the sample size, if d/d_{cr}—as in our case—is greater than 25 ($\frac{d}{d_{cr}} = \frac{1.0}{0.04} = 25$). This indicates that the compressive strength of ice samples depends not so much on the actual sample size but on the ratio d/d_{cr}. Our compressive strength tests show furthermore that model tests on ice forces on structures can be performed without any influence of the scale effect, provided the size of the ice crystals is scaled down to such an extent that d/d_{cr} (d = diameter of model structure) is at least 25.

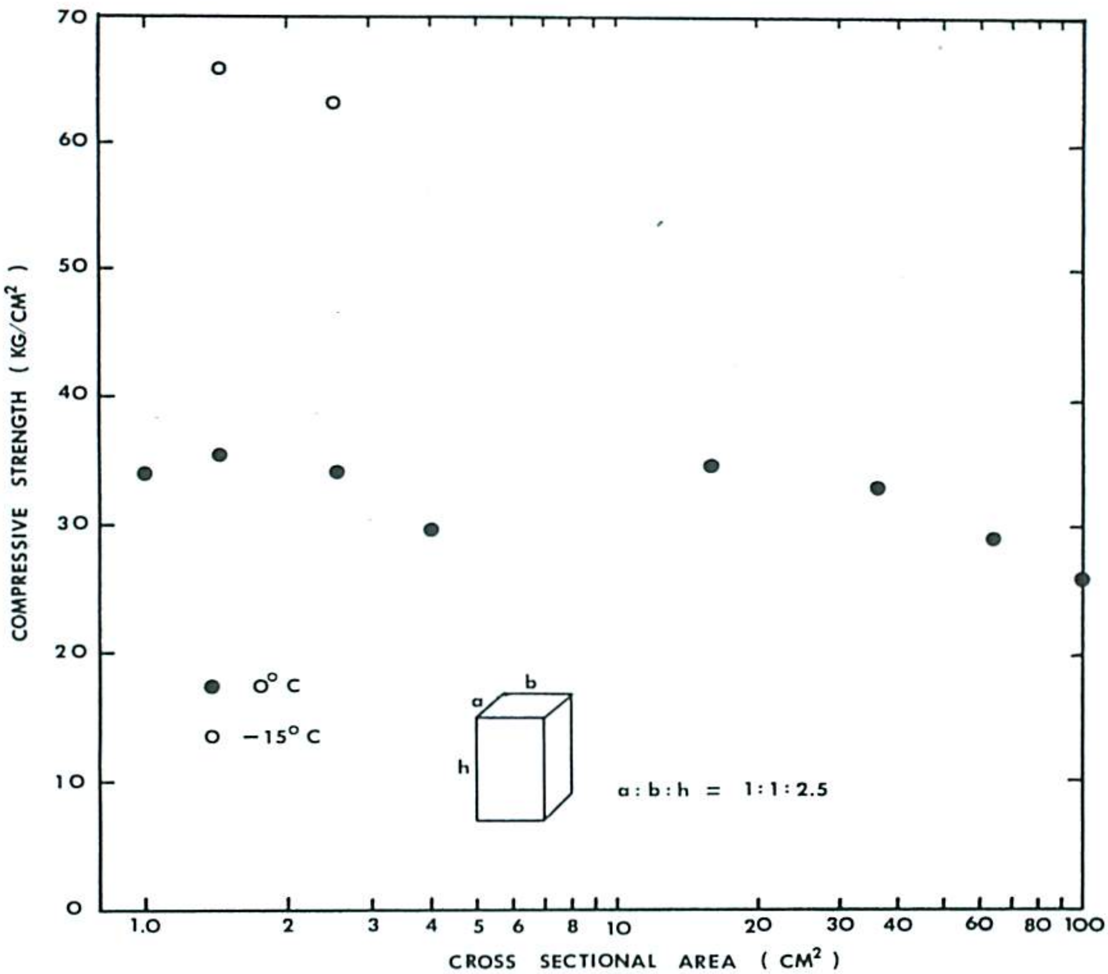

Fig. 3. Relation between compressive strength and cross sectional area of model ice samples

2. Preparation of model ice

For the investigation of ice forces on vertical structures the strength of the ice did not have to be scaled down, because the gravity g has no influence on the results in this case. The preparation of the ice cover, therefore, concentrated on obtaining the necessary reduction in the crystal size. This reduction was achieved by the water-spray method (Lavrov 1969); i.e. water of 1.5°C was sprayed with a commercial spray gun at 60 psi into the air. These droplets froze at -15°C air temperature to form ice crystals. As they settled on the water surface, the frozen droplets initiated the formation of an ice cover. Under the chosen conditions the size of the seeded ice crystals was 0.1 mm; this size, however, depends on the kind of nozzle and on the pressure in the spray gun. A spray volume of 100 to 150 cm^3 water per 1 m^2 water surface was enough to cover the whole water surface completely with small seeded ice crystals.

The ice cover formed in this manner was structurely similar to natural ice: i.e. the crystals in the 2-mm-thick surface layer were randomly oriented.

From there on, the ice grew in the form of vertical columns with horizontal c-axis. The crystal size increased linearly with the depth t and the gradient was approximately the same as in natural freshwater ice.

3. Quality control

The quality of the ice, i.e. the uniformity of its thickness, strength, temperature, and structure and size of the crystals, is dependent on the uniformity of the air temperature, the equal distribution of seeded ice nuclei, and particularly on the uniformity of the air flow conditions above the ice surface. When these requirements were obtained in the ice room the strength of the ice was satisfactorily consistent over the entire length of the ice tank and also from one experiment to the other, the variation being less than ±5%. The strength control was carried out for every ice cover by in situ indentation strength tests; i.e. a standard pile of 2.5 cm diameter was driven under constant conditions (ice thickness h = 0.8 cm, air temperature T = -15°C and velocity v = 1.2 cm/s) through parts of the ice cover. In addition to this, unconfined compression tests were carried out from time to time on samples of the model ice at a strain rate of $\dot{\varepsilon}$ = 0.003 1/sec. This compressive strength was used as the reference strength σ_0 to normalize the pile test data.

IV. Similarity Considerations

Similarity considerations for model studies on ice forces experienced by structures are based on dimensional analysis. The ice force F is assumed to be dependent on the following variables:

$$F = f\,(d,\ h,\ d_{cr},\ v,\ \rho,\ \sigma_0,\ T_i,\ T_w,\ \alpha,\ \beta,\ k)$$

where
- F = ice force
- d = diameter or width of structure
- h = thickness of ice cover
- d_{cr} = mean diameter of ice crystals
- v = velocity of indentation
- ρ = density of ice
- σ_0 = reference strength of ice at 0°C, compressed at 0.003 1/s strain rate
- T_i = ice temperature
- T_w = water temperature at freezing point
- α = shape factor of structure (angle of wedge)
- β = inclination angle of structure
- k = influence of contact between ice and structure

By using the π-theorem, dimensionless groups can be formed and written as:

$$\frac{F}{\sigma_0 dh} = f = \left(\frac{d}{h},\ \frac{d}{d_{cr}},\ \frac{\sigma_0}{\rho v^2},\ \frac{T_i - T_w}{T_w},\ \alpha,\ \beta,\ k\right)$$

If the crystal size of the model ice is reduced to such an extent that the strength of the ice is independent of d/d_{cr}, this term can be neglected.

So far the investigation has been concerned with finding the functional relationship of

$$\frac{F}{\sigma_0 dh} = f(\frac{d}{h}, \frac{\sigma_0}{\rho v^2}, \alpha, k)$$

Examination of temperature and inclination effects on the ice forces will be considered in later studies.

Since ice forces on vertical structures are independent of the gravity, g, freshwater ice with its natural strength was used for the model tests. Some fundamental similarity requirements for these model tests were as follows:

1. The ice cover must have a certain stability in order to guarantee the indentation type of failure without any buckling or bending.
2. The crystal size has to be scaled in approximately the same ratio as the other geometric values, in order to prevent the scale effect and to obtain structurally simulated ice.
3. The fracture behavior of the ice in front of the structure has to be similar to the prototype.

All three similarity requirements were obtained: the ice cover did not buckle during the pile indentation tests as long as the ice cover was at least 7 mm thick and the diameter of the pile was less than 40 mm (requirement 1). The size of the ice crystals was reduced by seeding ice crystals of d_{cr} = 0.1 mm (requirement 2), and the similarity of the fracture of the ice cover was achieved (requirement 3), since a plane horizontal crack in the middle layer of the ice cover in front of the pile was observed

a) in field tests, where the ice cover was up to 80 cm thick,

b) in experiments at CRREL, Hanover, New Hampshire, where the ice was 10 cm thick, and

c) in our indentation model tests, even though the ice cover was only 8 mm thick (Fig. 4).

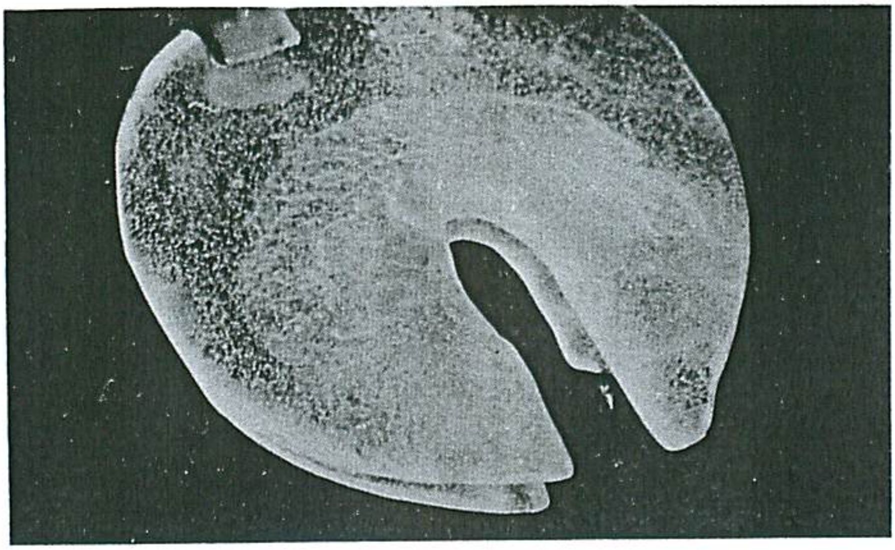

Fig. 4. Plane horizontal crack in the middle layer of a 8 mm thick ice cover

The formation of this horizontal crack and also the whole fracture mechanism in front of the pile was intensively investigated in our model tests. Specially prepared strain-gages, frozen into the ice cover, were used to elucidate the defromation behavior of the ice. It was found that immediately in front of the pile, shear stresses were leading to some vertical micro-cracks, but that the final breakdown of the stress system followed immediately after the formation of a horizontal macro-crack which was perpendicular to the long axis of the ice columns. This crack developed due to tensile strain. The failure of the ice cover, therefore, was governed by tension rather than by shear, although the latter is commonly believed and used as an assumption in theoretical studies. Only at very low strain rates (ductile deformation) shear failure might be dominant; investigations about this question have not yet been finished.

A similar fracture mechanism, namely the ice failure due to tension, was observed by Frederking (1972) in confined compression tests on columnar grained ice. The crack occured also in a plane perpendicular to the long axis of the columns.

V. Some Preliminary Results

Since the investigations on ice forces on structures have not been concluded, only a few sample results can be presented at this time.

1. Effect of strain rate on ice forces

We know from compression tests on ice samples (Carter, 1972; Schwarz, 1970) and also from field measurements (Peyton, 1966) that the strength of the ice depends upon the strain rate. In ice sample tests the strain rate is well defined as the ratio of the compression velocity to the height of the sample ($\dot{\varepsilon} = \frac{v}{h}$). In pile indentation tests, however, the definition of the strain rate is much more complicated, because special attention must be paid to the selection of the characteristic length, by which the velocity of the pile should be divided in order to calculate the strain rate.

Two methods were developed by the authors to obtain the strain rate in case of indentation tests.

a) Fracture frequency analysis: At high strain rates (brittle deformation) the fracture frequency of the ice was used as a measure for the strain rate. This frequency appeared in the test records as a certain number of load-peaks per unit time (Fig. 5). It represents the velocity of the pile divided by a certain characteristic length in front of the pile, where the ice cover was fractured. The fracture frequency, which has the same dimension, $(\text{time})^{-1}$, as the strain rate, was calculated by frequency analysis.

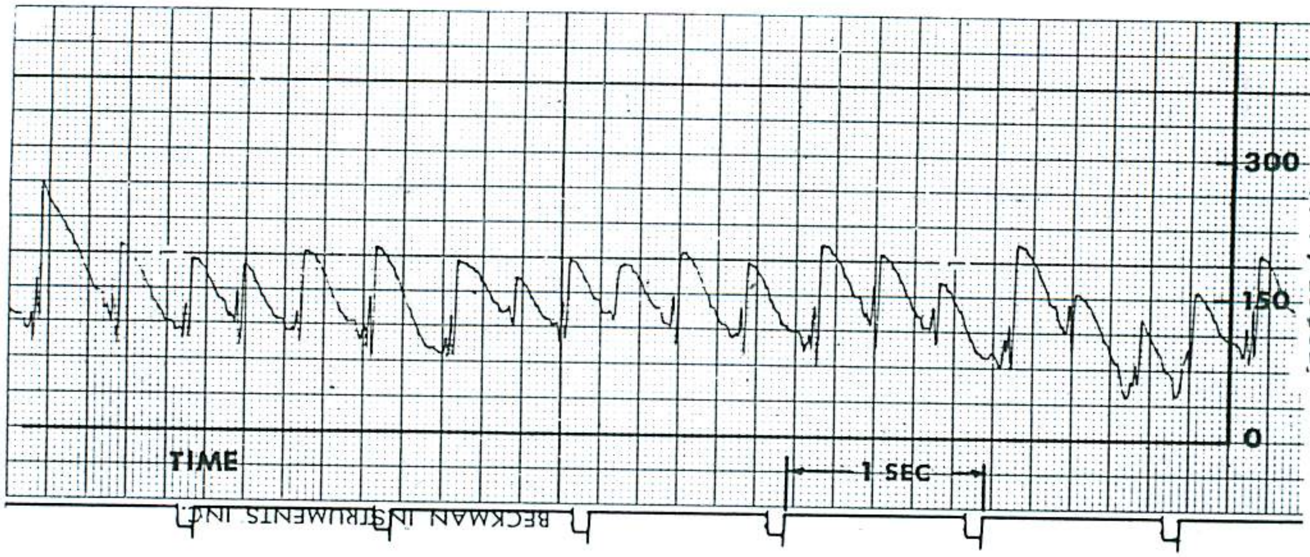

Fig. 5. Force vs time record for brittle deformation

b) Crystal growth effect: The method of fracture frequency analysis to measure the strain rate was only applicable at higher strain rates, when the ice fractured periodically. With decreasing pile velocities the periods became longer and longer until in the ductile deformation range no fracture periods could be identified (Fig. 6). In this velocity range the strain rate was measured by dividing the pile velocity by the length of the plastic deformation region. The identification of this region was obtained by the crystal growth effect. Crystals start to grow after a certain amount of energy per unit volume has been introduced into the ice. This energy input can be as heat or plastic deformation. Crystal growth due to this plastic deformation was used to identify the extension of the plastically deformed region (Fig. 7).

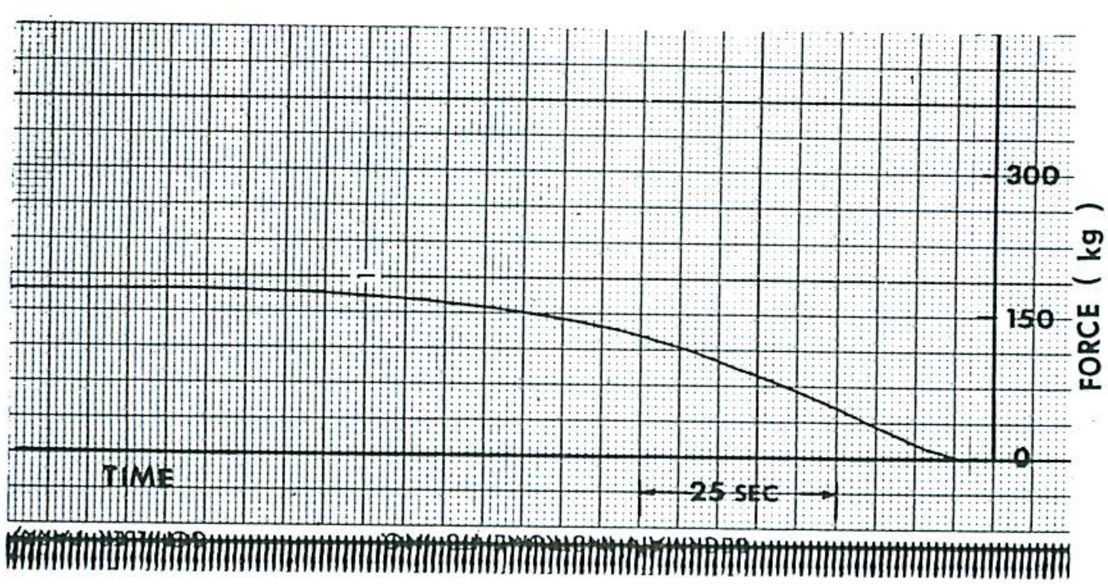

Fig. 6. Force vs time record for ductile deformation

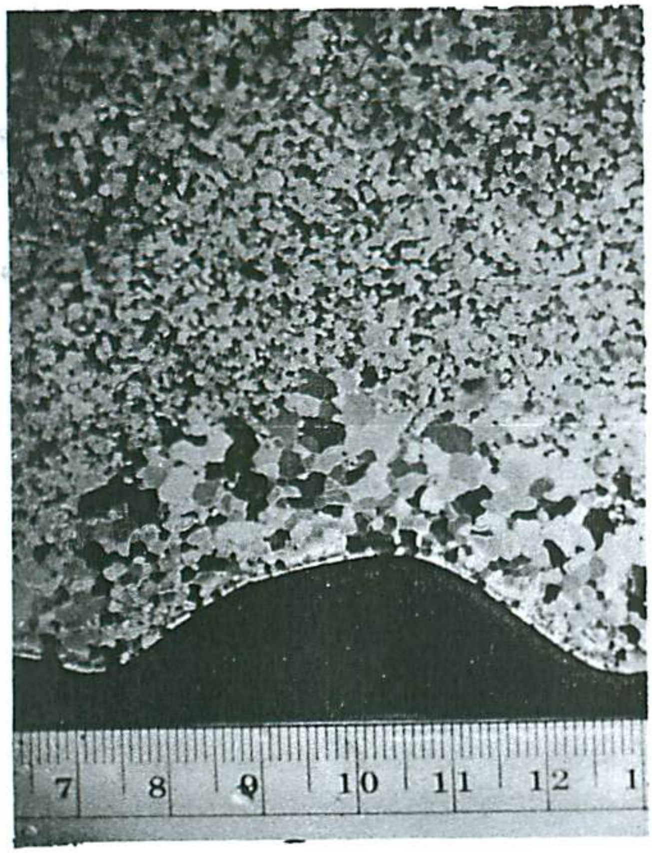

Fig. 7. Grown ice crystals in plastically deformed region

At the transition from brittle to ductile deformation the strain rate was obtained by both methods since the plastic deformation region as well as the fracture frequency could be identified. It was found that the strain rates from both methods were in good agreement.

Using the methods described above to obtain the strain rate for the pile indentation test, it was found that the normalized strength of the ice was increasing with the velocity as long as the deformation was ductile (Fig. 8). The strength reached a maximum at the transition between ductile and brittle deformation, and it decreased to a constant value when the velocity was increased further. A similar relationship between strength and strain rate has been observed by compression tests on ice samples (Carter 1972; Schwarz 1970). The curve in Fig. 8 represents average values of ice stresses for d/h = 3.0, and the strain rate in model. Since the strain rate has a dimension of 1/time, it is dependent on the scale ratio of geometric values. Similar curves were obtained for other d/h ratios. If σ_{90} was considered (i.e. that value of σ, for which 90% of all data show lower strength), the normalized stress did not drop down at higher strain rates, but remained constant after reaching a maximum value (Fig. 8). This result is different from all sample test results and is probably due to the different state of stress between the uniaxial compression test and the three dimensional indentation test.

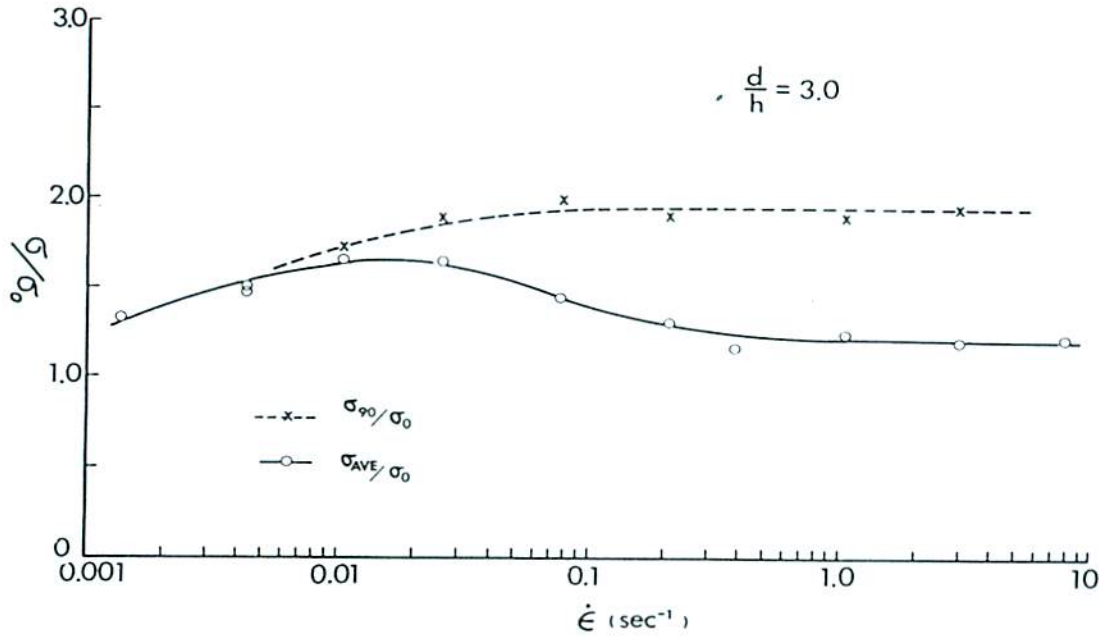

Fig. 8. Normalized ice strength vs model strain rate

2. Effect of d/h on ice forces

The effect of d/h on ice forces was investigated in model tests by varying d/h from 0.2 to 5.3. The ice strength σ_{90} was normalized by the reference strength σ_0 = 35.3 kg/cm^2 (compressive strength of ice prisms at 0°C and $\dot{\varepsilon}$ = 0.003 1/sec). As Fig. 9 shows, the normalized ice strength increased exponentially when d/h was decreased. Within the range of d/h values investigated the ice forces on thin piles are 4 times bigger than on broader piles. If d/h became bigger than about 6 or 7 the ice sheet was no longer stable, buckling occured and bending stresses were causing the ice failure. The results of our model tests were in surprisingly good agreement with model tests using saltwater ice of 3 cm thickness (Afanas'yev et al, 1972) and with experiments using 10 cm thick freshwater ice, which are already in the range of prototype conditions (Nevel, 1973).

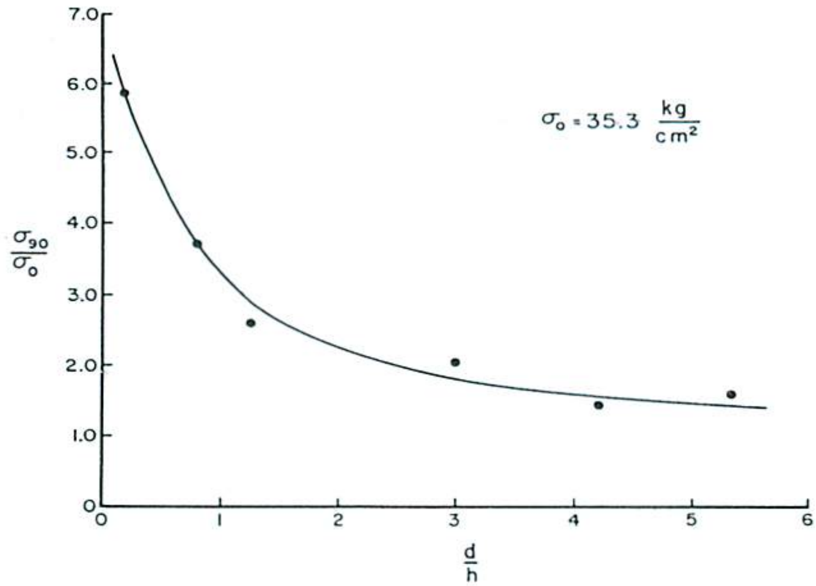

Fig. 9. Normalized ice strength vs d/h

VI. Summary

Model studies for the investigation of ice forces on vertical piles have been accomplished successfully by using frewhwater ice of small crystals but of natural strength. It has been shown that the fracture pattern of this ice was similar to that in prototype and that some preliminary results are in good agreement with data from prototype tests. Investigations on the influence of the velocity and width of the structure, the thickness of the ice, the degree of contact between ice and structure and the influence of a wedge on the ice forces against vertical piles are nearing completion. Model tests on pile combinations and on inclined wedges will be made later on; this study will, however, require a reduction in the strength of the ice.

Special attention has been and will be given to the fracture behavior of the ice in front of the pile and to the studies of basic mechanical properties of the ice. These investigations will provide the background information for further theoretical analysis.

VII. References

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The authors wish to thank all these colleagues for their helpful contributions and cooperation.

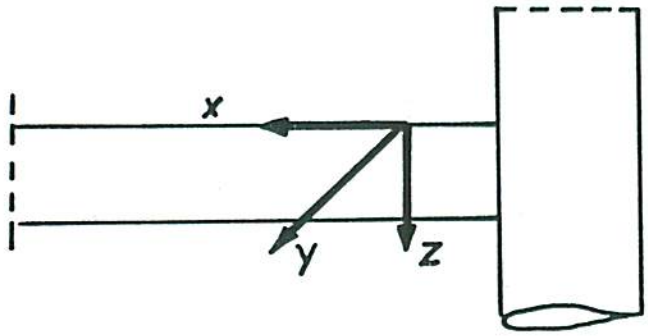
DISCUSSION

Professor R. Parmerter, AIDJEX, University of Washington, Seattle, Washington, U. S. A.:

You mention that the usual failure mode in your tests was a mid-plane crack in the plane of the crack. What is the mechanism that causes critical stress conditions in this plane?

Dr. J. Schwarz, Institute of Hydraulic Research, The University of Iowa City, Iowa 52242, U. S. A.:

The plane horizontal crack in the middle layer of the ice cover is due to tensile strain in the vertical (z-) direction.



Since the lateral strain ε_y is restricted by the confinement, the Poisson's ratio $\varepsilon_z : \varepsilon_x$ is increasing up to 1.0 with increasing pressure until at maximum load the separation crack occurs. The variation of Poisson's ratio was investigated by strain gages, frozen into the ice.

Mr. Norman Arno, U. S. Army Corps of Engineers, Chicago, Illinois, U. S. A.:

Mr. Parker, you have listed several engineering problems in your paper, suggesting that other problems may be important. What, in your opinion, is the engineering problem on which the most effort should be applied to assist in the rational selection of Terminal Facilities on Alaska's Northwest coast?

Mr. W. B. Parker, University of Alaska, Arctic Environmental Information and Data Center, Anchorage, Alaska, U. S. A. :

The most important need at present is to develop a coordinated planning group that can work towards development of facilities that require minimum disturbance of shorelines and seabeds in the coastal areas. The cost of unnesessary disturbance of the easily eroded coastlines can be high.