PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
TECHNICAL UNIVERSITY OF NORWAY

# EFFECT OF CONE-SHAPED STRUCTURES ON IMPACT FORCES OF ICE FLOES

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## INTRODUCTION

Since early days waterways have played a very important part in the communication system of Canada and many lighthouses were required in lakes, rivers and in the St. Lawrence Gulf where they are exposed to heavy ice movement. Although for a long time the theoretical knowledge about the ice forces was very limited and sometimes non-existant, a great number of piers for bridges and lighthouses were built. Design and construction were based on the engineers' experience and, perhaps, on their intuition. Certain features of the structures exposed to ice forces became typical, although there was no good explanation for it, and besides some failures there were ample successful structures. In the last decade a relatively great interest has been shown in ice forces on structures. One of the reasons was the oil and gas exploration in the Arctic and a need to design expensive structures exposed to large ice forces.

When a major lighthouse at Pelee Passage in Lake Erie was built in 1857, the engineer reported that he had introduced some novel features in the design of the substructure, namely, nearly circular shape and sloped sides. When this lighthouse burnt down and was replaced in 1902 with a new one, which is still in service, the substructure was protected with a special sixteen-sided cribwork with 45° slopes (Fig. 1) although neither such shapes or slopes were easy to build for a timber cribwork. Early in the history of lighthouses construction sloped surfaces became accepted feature to reduce ice thrust on the lightpiers (Fig. 1). The piers of many bridges in northern countries have been protected by ice-breakers against ice floes for many years. Such a typical ice-breaker is a sloped wedge type structure. No doubt these bridge ice-breakers influenced the design of the shape of the lightpiers.

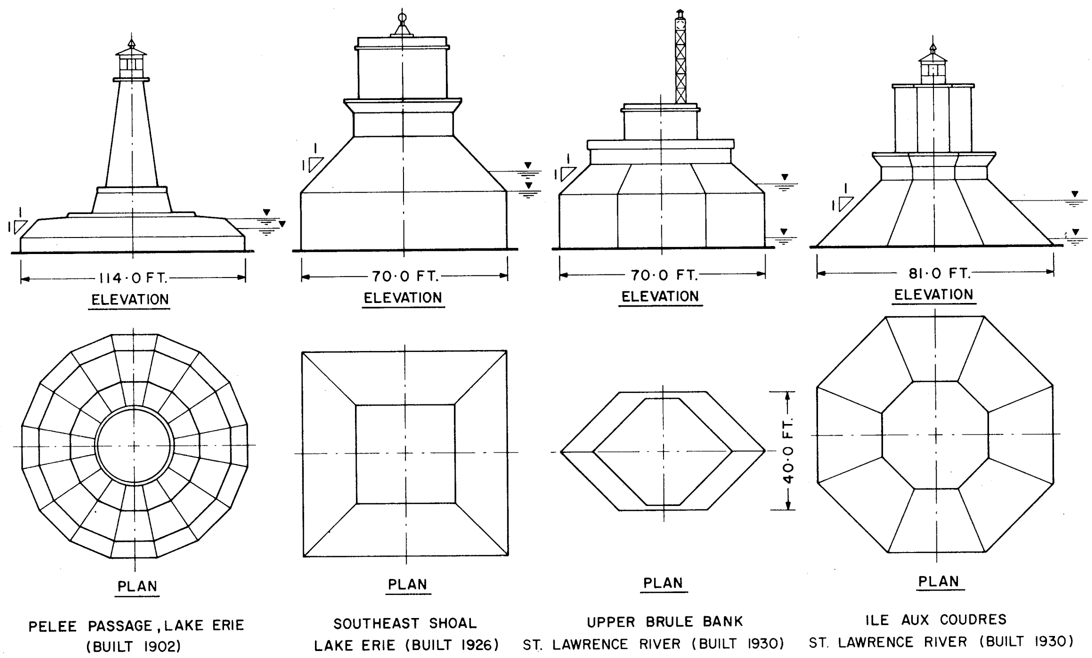


Fig. 1 Typical Lighthouses Exposed to Ice Impact Forces

In 1955 a major lighthouse was built at White Island in the St. Lawrence River near Saguenay River, approximately 100 miles downstream from Quebec City, and a part of it was shaped as a cone. Difficulties occurred in servicing the lighthouse, as the ship could not come close to the lightpier because of the slope, increased currents near the pier and the run-up of waves on the pier slope. Therefore, the other major lighthouse at Prince Shoal in the same area but in deeper water was first designed with two flat sides. But in 1959 the effect of the ice forces on the cylindrical and conical piers were studied in more detail and in a more rational approach, and it was concluded that the cone-shaped structure had a considerable advantage over the other shapes, especially over substructures with vertical walls in reducing the impact forces of floating ice and breaking waves. The stability of the structure with some flat, vertical sides is very unbalanced when ice floes can come from any direction as occurs in some tidal areas where the direction of the currents rotates. Then the stability in the direction of the vertical face becomes appreciably smaller than in the direction of the conical section.

The final shape of the Prince Shoal lighthouse[1] was designed (Fig. 2, 3 and 4) considering the functional requirements, ice, waves, earthquake and other forces, as well as construction and overall economy. A number of other lighthouse piers have been designed and built along the same lines and all of them have been very successful structures.

In 1964-68 a 8-mile long sea crossing between New Brunswick and Prince Edward Island was being designed. Large ice fields under certain wind and current conditions cover the Strait for longer or shorter periods. Extensive ice studies were carried out including elaborate model testing using artificial ice in a laboratory in order to establish the expected magnitude of the ice forces. Various shapes of the piers for a bridge, including the shape of the substructure of the Prince Shoal Lighthouse built in 1962, were tested. It was concluded that the 45$^{\circ}$ conical shape shown in Fig. 5 would result in the most favourable pier loading during the destruction of an ice sheet or of ice ridges.

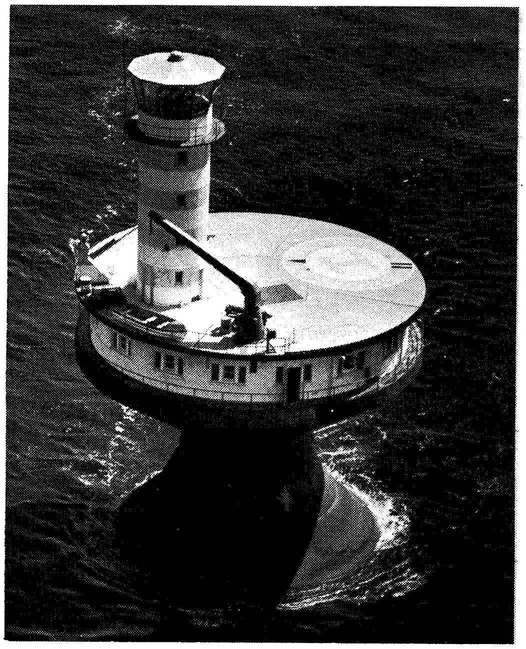

Fig. 2 Prince Shoal Lighthouse General View.

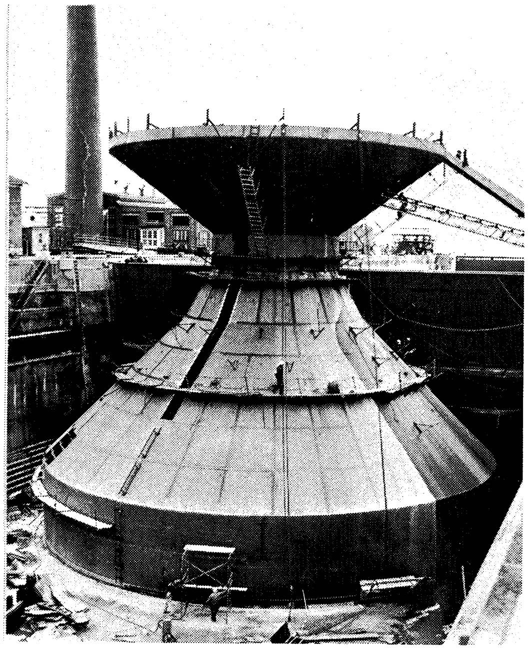

Fig. 3 Caisson for Prince Shoal Lighthouse

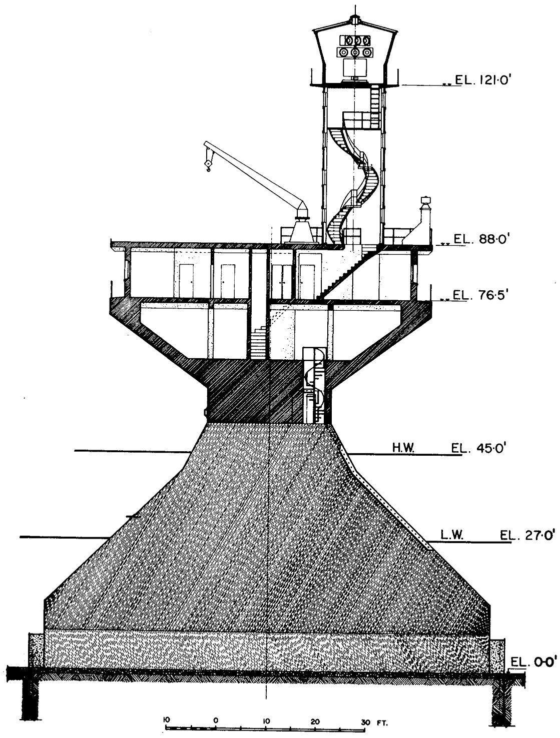


Fig. 4 Cross-section of Prince Shoal Lighthouse.

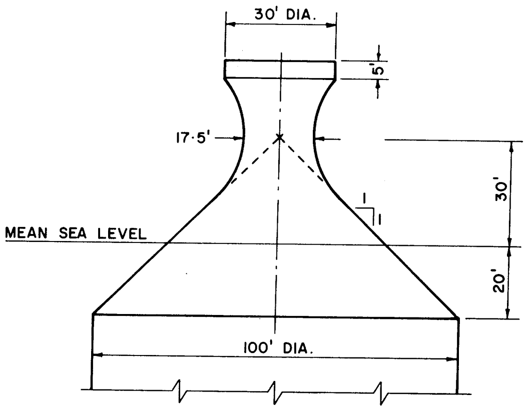


Fig. 5 Northumberland Strait Crossing - Proposed Shape for Piers after Model Testing.

## MODES OF DESTRUCTION OF ICE FLOES

It is assumed that the force developed against structure by moving ice floes is limited only by the strength of the ice, regardless of the size of the ice floes. Four possible modes of destruction of the ice sheet colliding with the pier are: failure by buckling, crushing, shear or bending. The force developed by an ice sheet will depend on which of these modes of failure is taking place.

A vertical cylindrical pier can destroy an ice sheet by introducing buckling or crushing. It seems that buckling is limited to thinner ice sheets, say under $1\frac{1}{2}$ feet thick. The destruction of ice floe by a cone-shaped pier is a much more complex process. Besides the compressive stresses, the inclined surfaces introduce shear and flexural stresses.

### Failure by Crushing

As the compressive strength of ice is much greater than the flexural or shear strength, a failure by crushing, generally, would exert the most severe dynamic load on the structure. This case was assumed for the design of lighthouses after a study in 1959.

The potential force of moving ice floe in the direction of the structure is P. As a result of a collision with a sloped surface, one component of the potential force will act perpendicularly to the surface of the structure, and the other component, tangentially to the surface. The friction between ice and steel plate or smooth concrete is quite small, and the tangential component of the force, generally, may be neglected as being comparatively a small force.

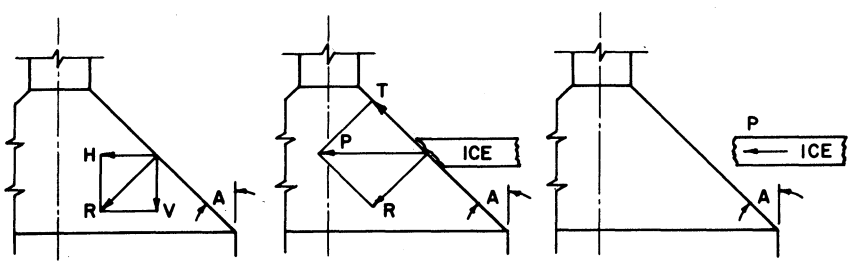


Fig. 6 Mode of Failure by Crushing

The design forces were calculated from the equations:

$$R = m\ n\ b\ h\ q_c \quad (1)$$

$$H = m\ n_1 b\ h\ q_c \quad (2)$$

$$V = m\ n_2 b\ h\ q_c \quad (3)$$

where

R - resultant force on structure perpendicular to the surface

m - shape and contact coefficient, 0.67 for Prince Shoal

n - slope coefficient taken as cos A for R; $\cos^2 A$ for H; cos A sin A for V; A is a slope angle with the vertical

H and V - horizontal and vertical components of R

b - width of the structure, equivalent to the diameter for the circular shape

h - effective thickness of ice sheet

$q_c$ - effective compressive strength of ice.

## Failure by Shear

After the initial crushing of ice on the structure, the vertical component of the resultant force will induce shear stress in the ice sheet. The magnitude of the shear force $F_s$ depends on the penetration depth of the ice sheet into cone:

$$F_s = A_s\ q_s \quad (4)$$

The area $A_s$ of the shear plane in a simplified way could be calculated as half a frustrum of a cone where the small radius $R_o$ is assumed equal to half of the chord corresponding to the penetration depth (Lavoie[2]). Vertical and horizontal components are:

$$V_s = \frac{\sqrt{2}}{2} \quad \frac{A_h}{A_c} \quad A_s\ q_s \quad (5)$$

$$H_s = \frac{\sqrt{2}}{2} \quad \frac{A_v}{A_c} \quad A_s\ q_s \quad (6)$$

where $A_s = \frac{\pi\sqrt{2}}{2} \quad (2\ \sqrt{p(R_o - p)} + h)\ h$ (7)

p - penetration; h - thickness of the ice sheet

$R_o$ - radius of the pier at lower edge of the ice sheet

$A_c$ - contact area of the cone with the ice sheet

$A_h$ and $A_v$ - projected areas

$q_s$ - effective unit shear strength of ice.

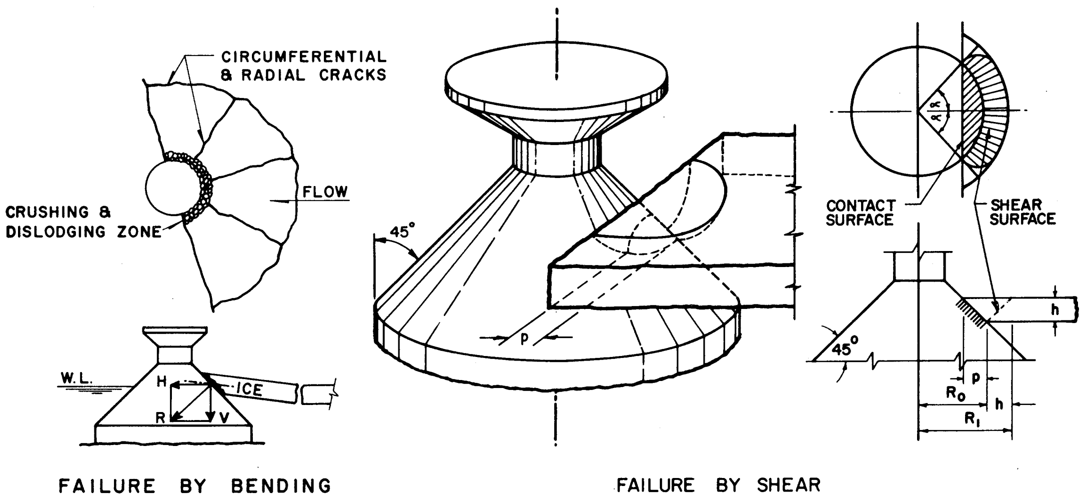


Fig. 7 Modes of Failure by Bending and Shear

Furthermore, the sheared off ice wedge shall be dislodged and this additional force may be expressed as follows[2]:

$$F = M \frac{dv}{dt} \; ; \Delta v_x = v_o \, ( 1 - \cos B ) ; \Delta v_z = v_o \sin B$$

and the horizontal and vertical components of the dislodging force will be:

$$V_d = A_c \frac{w}{g} v_o^2 \sin B \tag{8}$$

$$H_d = A_c \frac{w}{g} v_o^2 \, ( 1 - \cos B ) \tag{9}$$

where B - vertical angle in the direction of the flow

$v_o$ - velocity of the ice sheet

w - unit weight of ice

g - gravity

Failure by Bending

The vertical reaction produced by the cone raises the edge of the ice sheet upwards and induces bending stresses in the ice sheet[2]. Meyerhof's[3] theory of a semi-infinite plate supported on elastic foundation has been applied[2] to estimate the force which would produce the failure along the circumferential crack created by the force acting at the edge of the ice sheet. The basic proposed equation for a special case is[3]:

$$q_t = \frac{(1 + m)P}{(3 + m)h^2} \left[ 8.8 \log \frac{L}{a} + 0.09 - 1.75m + 1.13 (1 + 2m) \frac{a}{L} \right] \quad (10)$$

where $q_t$ - effective tensile unit stress

m - Poisson's ration, 0.33

P - applied load

h - effective thickness of the ice sheet

a - radius of the contact area of the load, assumed equal to half the chord corresponding to penetration

L - characteristic length of relative stiffness

$$L = \left[ \frac{E h^3}{12 (1 - m^2) k} \right]^{1/4} \quad (11)$$

where E - Young's elasticity modulus, assumed 250,000 p.s.i.

k - foundation modulus, 0.036 lb/cu. in.

The model testing indicated a considerable increase in ice load on a pier with the increasing velocity of the approaching floes. It seems that a vertical acceleration of the edge of the ice sheet will accompany the rise of the edge of the floe[4] and increase the load on the pier over that which would occur under slow loading conditions. The magnitude of this dynamic force may be estimated from a relationship:

$$F_a (d + p) = \frac{w}{g} \frac{\pi R_f^2}{2s} h \frac{v_0^2}{2} \quad (12)$$

where $R_f$ - radius to the failure line, $R_f = 1.4L$

s - part of ice area in failure semi-circle which exerts load on pier

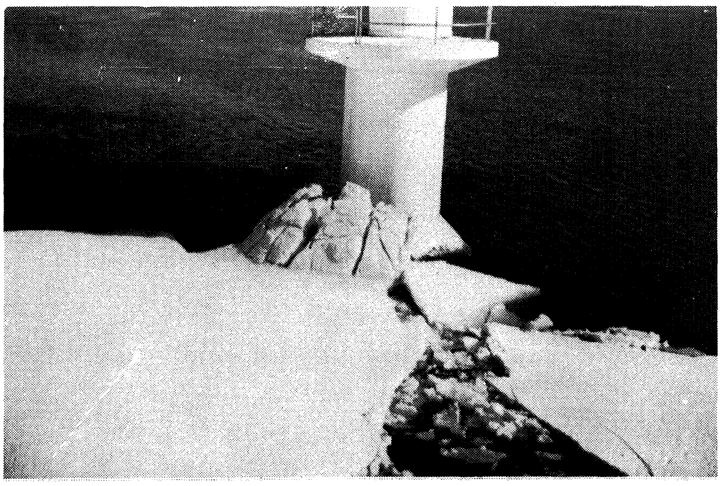

Fig. 8 a

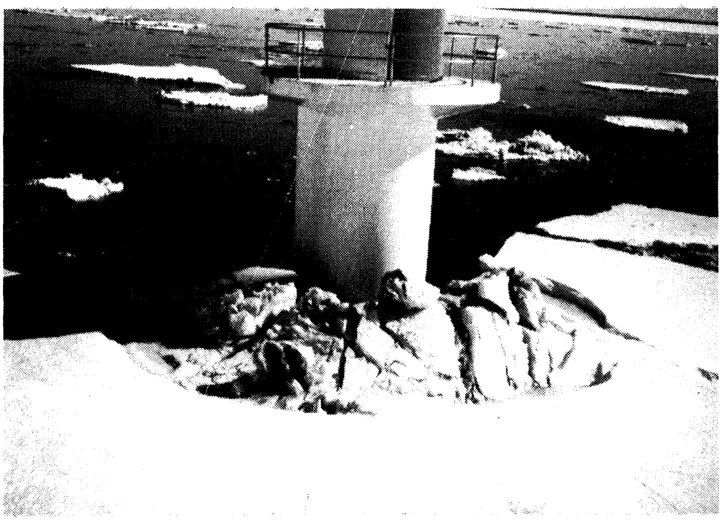

Fig. 8 b

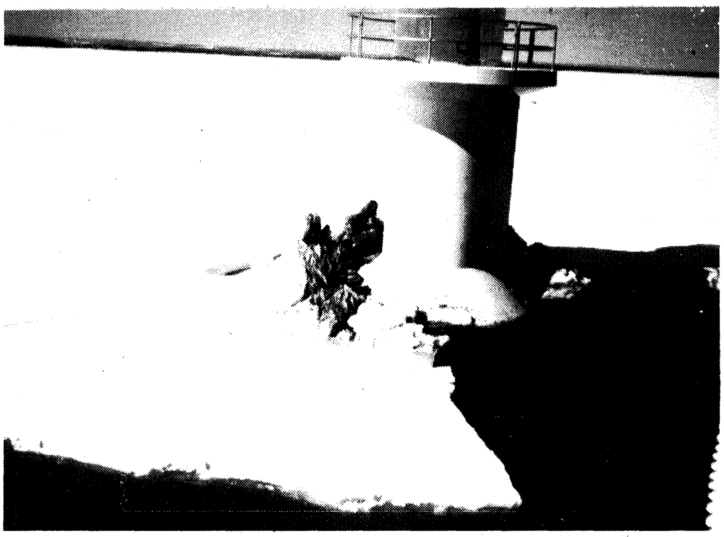

Fig. 8 c

Fig. 8 Interaction between Ice Floes and Conical Substructure of a Light-pier (St. Lawrence River, Lake St. Peter, Canada, March 18, 1971).

d - vertical deflection of the ice sheet

$$d = \left( 1 - 0.89 \frac{a}{L} \right) \frac{v_o}{2.1\, k\, L^2} \qquad (13)$$

Furthermore, the model testing of ice forces for the Northumberland Strait Crossing showed that the loads recorded subsequent to initial impact were considerably, almost twice, larger than the initial impact loads. This was attributed to the weight of the ice fragments leaning on the pier. One can express the magnitude of such load as function of

W - weight of the ice fragments leaning on the structure, and

f - fraction of this weight exerting load on the pier:

$$G = ( f, W ) \qquad (14)$$

## COMPARISON OF FAILURE MODES

Assuming $q_c$ = 220 p.s.i., $q_t$ = 80 p.s.i., $q_s$ = 55 p.s.i., full penetration of the pier into ice sheet, the horizontal forces at a level where the diameter is 50 ft. on a 45$^o$ cone for various failure modes would be:

| | | |
|---|---|---|
| failure by crushing | $H_c$ = | 2,100 kips |
| failure by shear | $H_s$ = | 1,900 kips |
| failure by bending | $H_b$ = | 700 kips |

The figures indicate that the horizontal force on the cone-shaped pier caused by flexural stresses would be about three times smaller than in the case of failure by crushing or shear. These figures show that a failure by shear develops smaller forces when the ratio of unit compressive strength to shear strength is 4. If this ratio, for example, is 3 or less, failure by crushing would occur before failure by shear. The vertical forces induce stabilizing moments, they would be smaller for smaller vertical forces especially, in case of failure by bending. However, for the overall stability of a structure the geometric proportions of the structure, the relation of the height of the application point of the force to the base and the foundation width are important. Generally, the larger the diameter of the base and the closer the acting force to the base, the greater the relative effect of the vertical component of the ice force to the stability of the structure is. The effect of the vertical force is considerably reduced for a relatively tall structure with a small base.

Although it seems, from the above mentioned figures, that the cone-shaped pier destroys the ice floes by introducing flexural stresses in the ice sheet, the proposed method of calculating the forces resulting from failure by bending has many shortcomings. The applied Meyerhof's theory was developed for static conditions and for a force acting downwards as a static load. Actually, the floating ice exerts a horizontal and dynamic force and a vertical acceleration force acts upwards and introduces the rise of the edge of the ice sheet and piling of the ice on the structure. So, three corrections are made to the basic force calculated according to Meyerhof's theory. First, the force is increased because of the dynamic effect of the moving floe against the pier, second, the additional load is added because of the weight of the ice fragments piling on the sloped structure and, third, the tensile or flexural strength of the ice sheet is increased because the ice sheet hitting the slope is in a state of compression.

## CONCLUSIONS

The cone-shaped pier forces the advancing ice sheet to ride up and to break in bending that results in smaller forces on the pier. Also, a part of the load acts downwards increasing the stability of the pier. From the comparative model testings for Northumberland Strait Crossing it appears that the horizontal force on a conical is about four times smaller than on an equivalent vertical cylindrical pier. Calculations according to the three methods described indicate such a ratio to be from 2 for failure by crushing to 6 for failure by bending. However, the proposed method to calculate forces caused by bending is based on too many assumptions to rely on its results.

As a matter of fact, any method of calculation of ice forces still faces uncertainties, as even the basic elements for calculations, as effective compressive, flexural and shear unit stresses, or effective ice thickness cannot be accurately established as yet.

The cone-shaped pier would act differently or its effect would be reduced if the cone slopes would develop a high resistance against an upward sliding of the ice sheet. A possibility for such a case would be formation of high strength ice collars well frozen to the pier. The failure mode by bending would be affected and the ice forces on the structure would be increased to the magnitude of the forces induced by the failure by crushing. Thus the forces calculated from ice failure by crushing would represent the extreme conservative load. Ten years of observations of the two cone-shaped lightpiers in St. Lawrence River Gulf where the tidal range is up to 18 feet showed that the ice collars formed by the splashing water were of soft, porious ice which was easily brushed off by the ice floes. Also, the rising tidal waters melted away these "ice collars".

The cone-shaped pier would have a considerable advantage in breaking advancing ice ridges even if the ice sheet was solidly frozen to the pier[4] and so obstructing the ride-up of the ice on the structure.

Although experience, model testing and theoretical analysis confirm the advantages of a cone-shaped structure, still it is not possible to accurately calculate the magnitude of ice forces on such a structure.

ACKNOWLEDGEMENT

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