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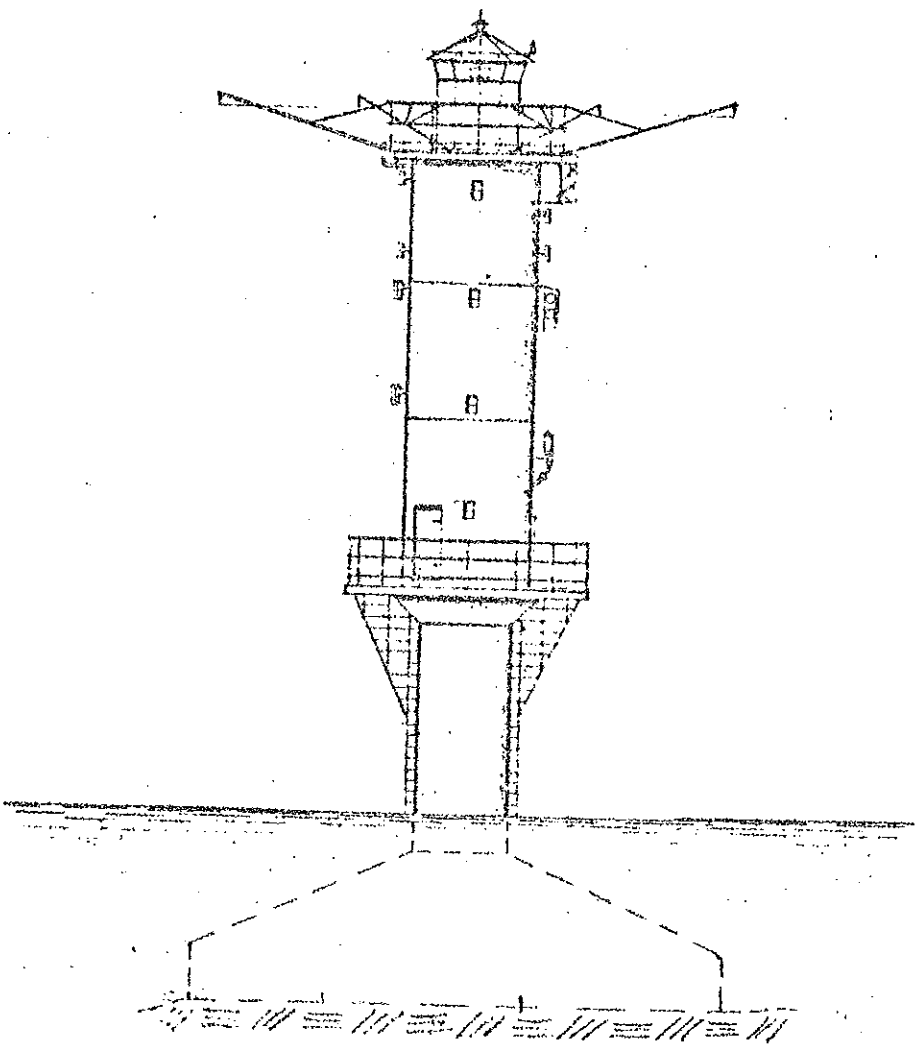
ICE PRESSURE AGAINST LIGHTHOUSES

by

Lars Bergdahl



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Abstract:

Two cases of damage to lighthouses due to ice in the Baltic are reported. Factors influencing the magnitude and the level of the ice pressure are discussed. The crushing strength of the ice and the height of pile-up are distinguished as the outstanding factors.

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ICE PRESSURE AGAINST LIGHTHOUSES

By Lars Bergdahl[1)]

Lighthouses, moorings and other isolated structures in the arctic and temparate seas are exposed to moving ice fields and pack ice. Dimensional criteria and rules for the design has long been needed.

In the Baltic isolated lighthouses have been built in areas with severe ice conditions since the thirties in spite of the fact that little was known about the forces from the ice. Some experiments with wood instead of pack ice was made by Frost [6] in 1941. See figure 1.

Only two of these lighthouses has been damaged by the ice. Thus the other lighthouses are pretty safe, but the probability of damage is very difficult to estimate when you do not even know the force from or behaviour of an ice field with known properties.

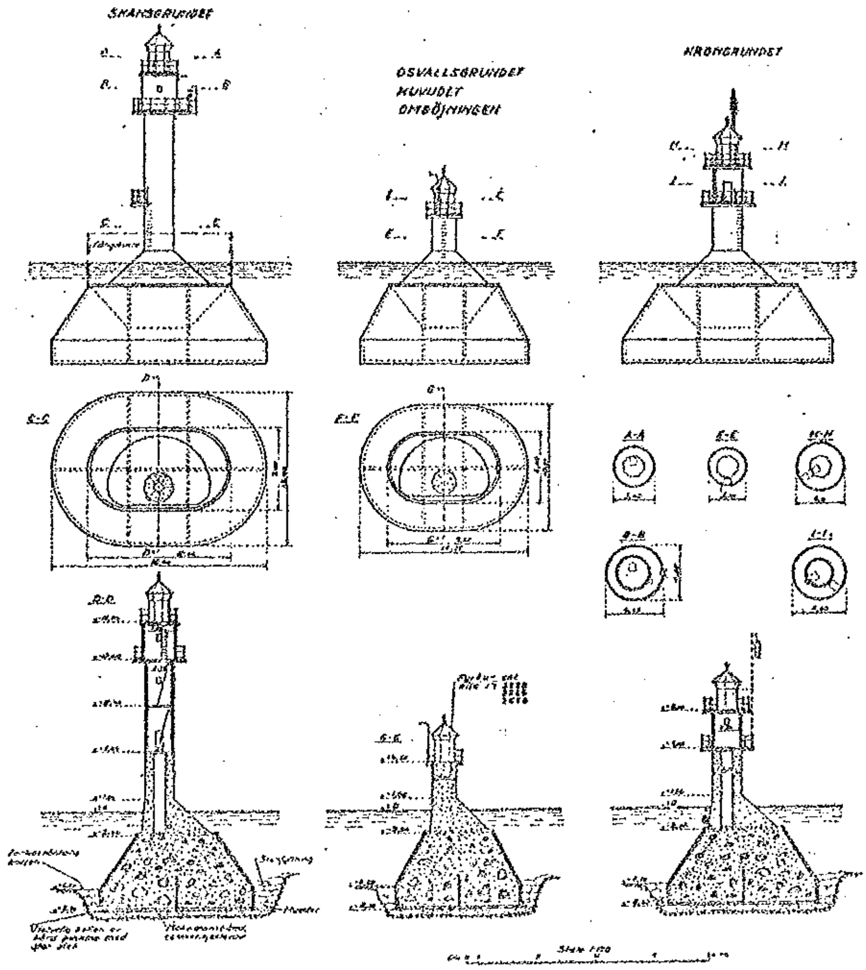

Figure 1 Five lighthouses in Kalmar sund, 1941. From Frost [6]

1) Research engineer Division of Hydraulics, Chalmers University of Technology, Göteborg, Sweden.

Damaged lighthouses

Two cases of damage to lighthouses, due to the ice, are known in the Baltic. One is Tainio lighthouse outside Helsinki in the Gulf of Finland and the other is the lighthouse of Nygrån outside Luleå in the Bay of Bothnia.

Tainio lighthouse consists of a caisson which was sunk on a leveled macadam bed at nine meters depth in the summer of 1966. The lighthouse was finished in october except for the injections of the macadam-bed. This work was postponed to the next summer.

At one occasion in the winter 1966-1967 the lighthouse was pushed 14 m in the ESE-direction. The surrounding ice cover had an estimated thickness of 0.3 to 0.5 m. At the lighthouse, however, the ice was packed up to approximately 4 m thickness against the weatherside and 1 m against the lee side. The sea level was slowly rising and winds were heavy.

The caisson was positioned on radially arranged steel rails. At first these rails could have lessened the friction but in the final stage the lighthouse stopped against some protruding rocks.

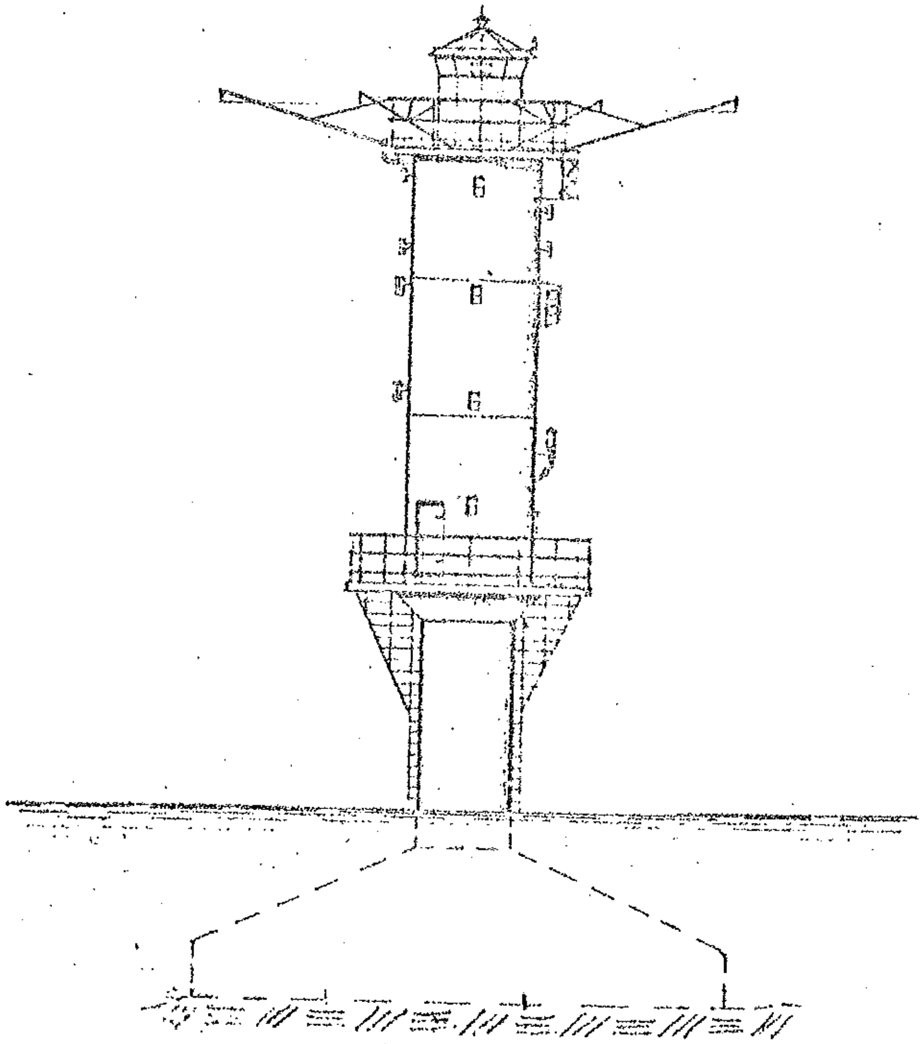

Figure 2 Nygrån 1956.

From Ernstsons and Kjellgren [3]

Hence Löfquist and Palosuo [10] made the following estimation. The friction factor must have been between 0.5 and 0.7 until the lighthouse stopped against the rocks. The weight in water was $8 \cdot 10^6$ N which gives the ice preassure $4 \cdot 10^6$ à $5.6 \cdot 10^6$ N. Divided by the diameter, 3.5 m, of the circular cylinder this gives $1.2 \cdot 10^6$ à $1.6 \cdot 10^6$ N/m.

In the end of april 1969 the lighthouse of Nygrån was broken down by the ice. The type of fracture has been classified as pure bending after inspection by divers. According to Ernstsons and Kjellgren [5] no trace could be found that the lighthouse had moved out of position.

Ernstsons has estimated the yield moment to $8.1 \cdot 10^6$ Nm from the appearance of the fracture. The surface of fracture was one meter under the sea level. So if the force acted at sea level it must have been $8.1 \cdot 10^6$ N. But the fissuring on the tower indicates that the point of action was between one and two meter above sea level. That is the ice pressure could have been as low as $2.7 \cdot 10^6$ N.

The lighthouse was built on sand with a friction factor of 0.60 à 0.75. The weight was $7 \cdot 10^6$ N. This gives a highest probable load of $4.2 \cdot 10^6$ N. That is the resultant force from the ice must have acted at least 1 m above sea level. Inspection sustains this.

The lighthouse had a diameter of 2.5 m. See figure 2. The ice pressure would then be between $1.1 \cdot 10^6$ and $1.7 \cdot 10^6$ N/m.

What actually happened when the lighthouse broke down is not known. But the pack ice must have built up to at least one meter above sea level so that the forces from the surrounding ice fields could act at that elevation. See figure 3.

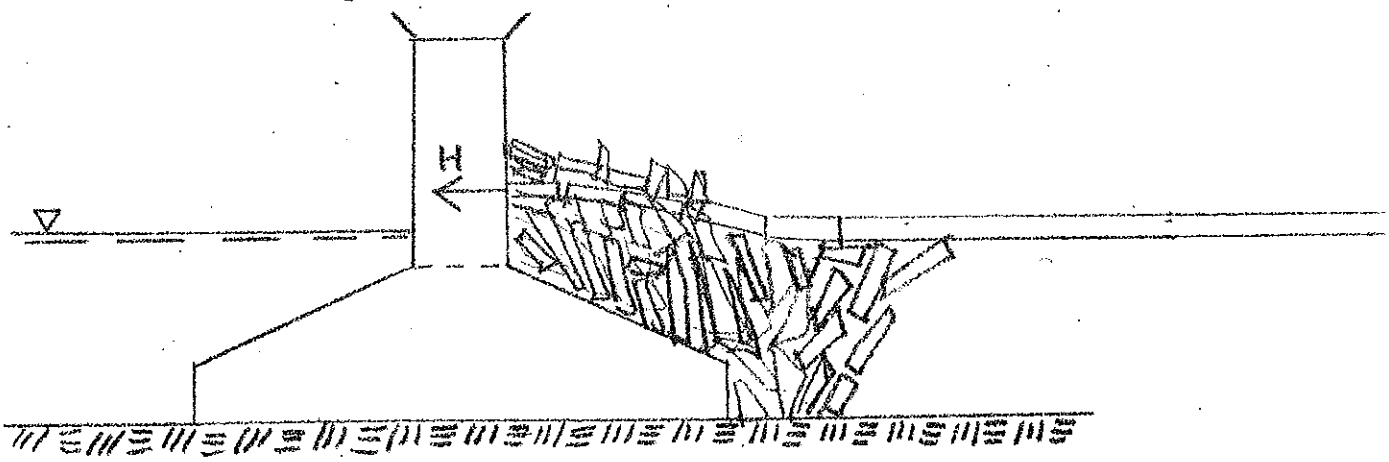

Figure 3 Scheme for the action of the ice.

According to the maritime office of the Swedish meteorological and hydrological institute (SMHI, Larsson) the ice cover in the area most winters reaches a maximum thickness of 0.70 m in the end of March or the beginning of April. The thickest smooth ice cover ever reported in the area is 0.90 m. Salinity in the water is 4.5 to 5 ‰. The institute lacks regular measurements of the ice before the winter 1969/70.

Piling up of ice on coastal structures

Bruun and Straumsnes [4] report of the behaviour of ice against seashores and coastal structures. They draw the following conclusions:

"1) Sloping shores and structures favor ice piling. As a result of wind and current forces, ice may pile up to an elevation of 10-15 m above still water level.

2) Vertical walls do not favor ice piling. If the depth in front of the structure is sufficient the ice does not climb but is rather forced down."

The authors say that they do not know ice piling at depths greater than 6 m but that the magnitude of this "safe" depth in some way must depend on the acutal exposure.

Allen et al. [2] gives an interesting analysis of the relation between horizontal force, P, per unit width of surrounding ice and height of pile up, h.

$$P = \sigma t = \rho g \frac{h^2}{2} \qquad \ldots\ldots\ldots \quad (1)$$

	σ is	the horizontal pressure from wind and currents
	t	thickness of ice
	g	earth accelleration
and	ρ	density of the pile up above water level

The equation (1) could reformulated be useful to estimate the possible height of a pile up.

$$h = \sqrt{\frac{2 \sigma t}{\rho g}} \qquad \ldots\ldots\ldots \quad (2)$$

Experimental data are few and scattered but equation (2) is on the "safe" side. Note that σ must be equal to or less than the crushing strenght.

Nygrån was situated at a depth of 4 m and the foundation was sloping so conditions for ice piling was at hand. The lighthouse will be replaced with a new one of the same shape but able to sustain the ice load at 2 m above sea level.

Estimation of the ice pressure

Several models for estimating the ice pressure exist. They are founded on the mode of failure of the ice. See Korzhavin [7], [8], Nuttall [13], Lavoie [9].

The simplest mode of failure is when the ice field is crushing against a vertical pillar.

$$H = d \cdot t \cdot \sigma_{cr} \quad \ldots\ldots\ldots \quad (3)$$

where
- H = horisontal force
- d = diameter of pillar
- t = thickness of ice
- σ_{cr} = crushing strength of ice

This is the formula used by Swedish authorities [6]. Korzhavin [7] used a variant.

$$H = I \cdot m \cdot k \cdot d \cdot t \cdot \sigma_{cr} \quad \ldots\ldots\ldots \quad (4)$$

Here m is a formfactor due to the shape in plan of the structure. m varies according to table below.

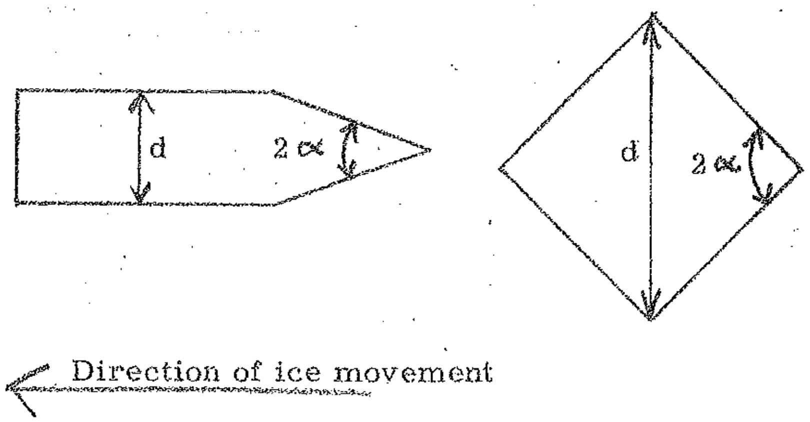

Figure 4 Definition of d and α .

Table 1

2α	45^o	60^o	70^o	90^o	120^o
m	0,60	0,65	0,69	0.73	0.81

I depends on the local buckling and redistribution of forces in the ice according to Korzhavin [8]. Allen [1] calls this an indentation factor, and uses following relation

$$I = 1 + 4/\exp\sqrt{d/t} \quad \ldots\ldots\ldots \quad (5)$$

Korzhavin [7] [8] states that $I \leq 2.5$, that is I has maximum value of 2.5 when $d/t = 1$. See also Nuttall [13].

The contact factor k tells the fraction of contact between the pillar and the ice. This is set to 0.7 to 0.5, but reasons for those values are very doubtful. See for example Schwarz [14].

The crushing strength σ_{cr} depends on the rate of loading, void volume, salt content, temperature etc. See for example Weeks and Assur [15].

Failure due to bending

Failure due to bending is a very complicated fenomena due to the unelastic properties of the ice. Consider a unit width of the structure. The horizontal force P on the structure depends on the vertical force V necessary to break the ice at some distance l, the slope of the structure β, the friction factor $tg\varphi$ between the ice and structure. Sometimes the momentum of the ice is a limiting factor. For definitions see figure 5.

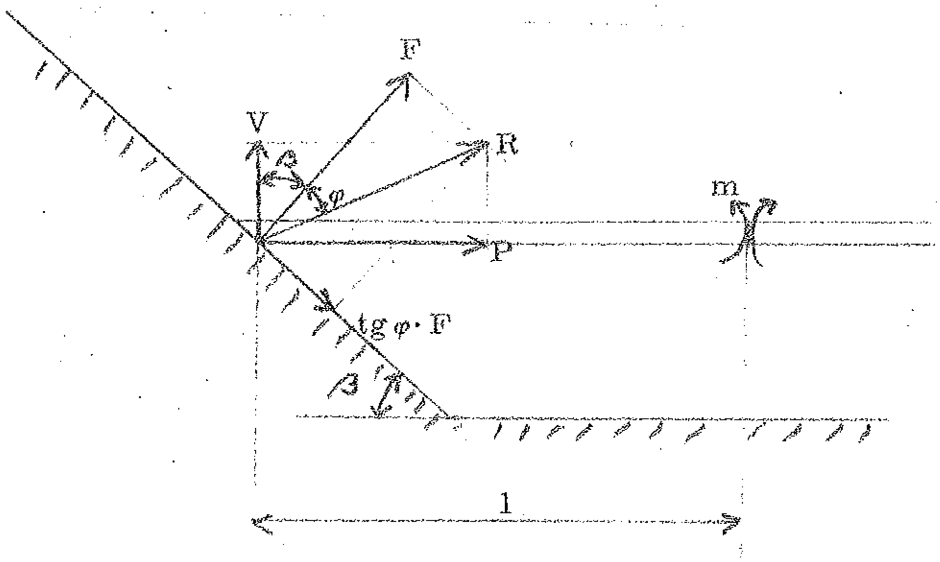

Figure 5 Scetch of forces against the ice sheet

The ice sheet is pressing perpendicular against the slope with a load F. When moving, this gives rise to the friction force $tg\varphi \cdot F$. F and $tg\varphi \cdot F$ can be composed to the resultant R which then is divided into the horizontal force P and vertical force V.

$$R = F\sqrt{1 + tg^2\varphi} \qquad \text{........} \qquad (6)$$

$$V = R \cdot \cos(\varphi + \beta) \qquad \text{........} \qquad (7)$$

$$P = R \cdot \sin(\varphi + \beta) \qquad \text{........} \qquad (8)$$

(7) and (8) give

$$P = V \cdot tg\ (\varphi + \beta) \qquad \text{........} \qquad (9)$$

The unit width load P is limited by equation (4) when neglecting exentricity of loading or by the highest possible value of V inserted into equation (9).

The maximum vertical force can be derived from the positions of cracks and type of failure. The most frequent theories use a model with a tensile crack at a distance l from the structure. See figure 5. The distributed moment m is either hypothetically set to a yield moment $\frac{1}{4}t^2 \cdot \sigma_y$ or an elastic moment $\frac{1}{6} \cdot t^2 \cdot \sigma_s$, where σ_y is a yield stress and σ_s is the bending strength

$$m_y = \frac{1}{4}\ t^2 \cdot \sigma_y \qquad \text{........} \qquad (10)$$

$$m_s = \frac{1}{6}\ t^2 \cdot \sigma_s \qquad \text{........} \qquad (11)$$

The load V per unit width of a long sloping structure is then according to fig. 5.

$$V = m/l \qquad \text{........} \qquad (12)$$

or using equation (11)

$$V = \frac{1}{6}\ t^2\ \sigma_s/l \qquad \text{.........} \qquad (13)$$

A circular sloping structure with a waterline contact radius a, see figur 6, gives

$$V = \frac{l + a}{a \cdot l} \cdot m \qquad \text{.........} \qquad (14)$$

per unit length of circumference or using (11)

$$V = \frac{1+a}{a1} \cdot \frac{1}{6} t^2 \sigma_s \qquad \ldots\ldots\ldots\ldots \qquad (15)$$

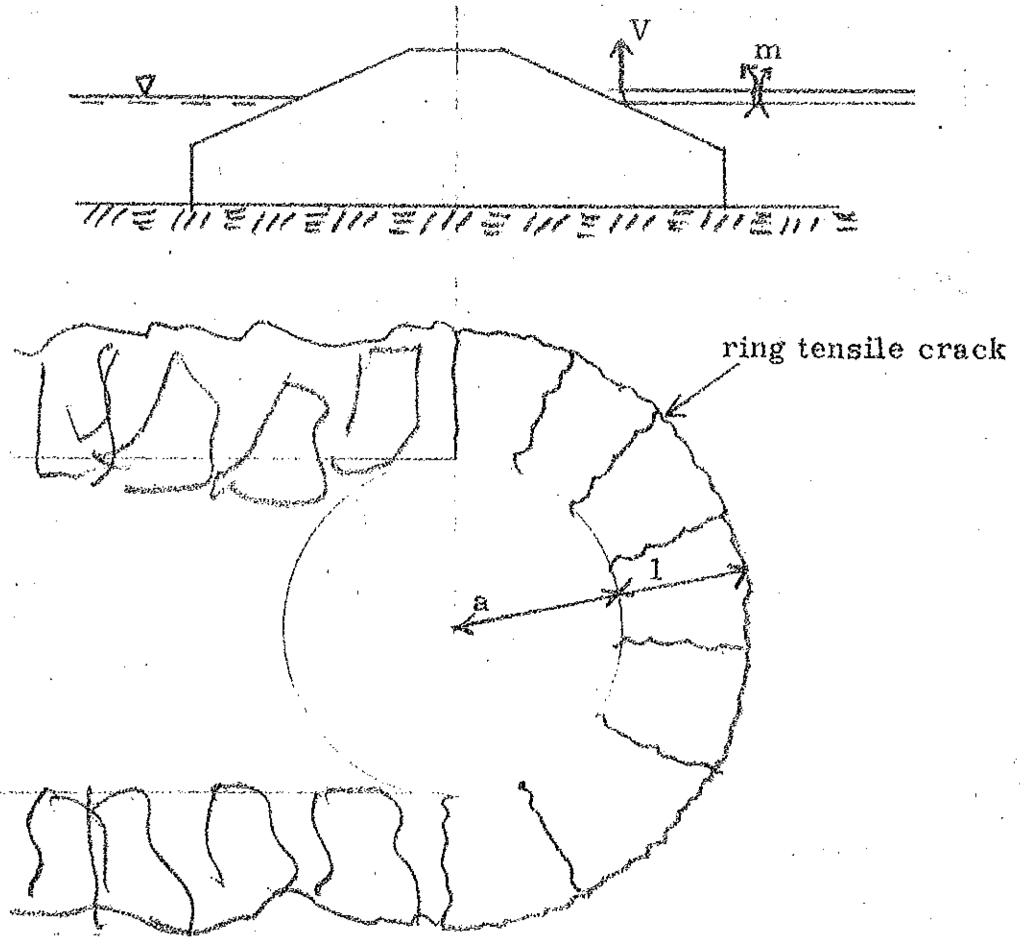

Figure 6 Scetch of the bending mode of failure against a circular structure with sloping sides.

According to Russian engineers [7] the distance 1 is observed to be equal to 3 t. Equations (13) and (15) then degenerate into

$$V = \frac{1}{18} t \cdot \sigma_s \qquad \ldots\ldots\ldots\ldots \qquad (16)$$

and $$V = \frac{(3t+a)}{a} \cdot \frac{1}{18} \cdot t\, \sigma_s \qquad \ldots\ldots\ldots\ldots \qquad (17)$$

(Integration of (17) over the circumference under the conditions below gives

$$2\pi a V = 5.2 \cdot 10^5 \text{ N}$$

which is 25 to 35 percent more than results from theories by Nevel [12], Meyerhof [11] and Assur [3].

Conditions:

E	Elasticity of ice	$3 \cdot 10^9$ N/m^2
t	Thickness of ice	0,45 m
ν	Poisson's ratio	0,33
a	Water line radius or loading radius	4.2 m
σ_s	Bending strength	$6 \cdot 10^5$ N/m^2)

To get the total horizontal load on a circular structure with sloping walls from an ice field being cut by the structure, the component of P, parallell to the movement of the ice field, is integrated over half the circumference. Using equation (9) gives

$$H = \int_{-\pi/2}^{\pi/2} P \cdot a \cdot \cos\alpha \cdot d\alpha = 2 \cdot V \cdot tg\,(\varphi + \beta)\,a \qquad (18)$$

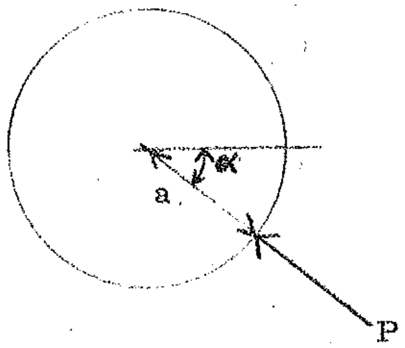

Figure 7 Projection of the force P.

Insert V according to equation (17)

$$H = (3\,t + a) \cdot \frac{1}{9} \cdot t\ \sigma_s \qquad \ldots\ldots\ldots \quad (19)$$

Failure due to shear

Sometimes the vertical force V and hence the horizontal force is limited by the fact that the ice fails by shear instead of bending. Probably the shear cracks will be vertical but due to uncertainties of crystal orientation it is safer to assume it at 45^{o} against the horizon. The necessary vertical force is then per unit width of ice brim.

$$V = \tau_s \cdot t \cdot \sqrt{2} \qquad \ldots\ldots\ldots \qquad (20)$$

where τ_s is the shear strength. This gives analoguously to equation (18)

$$H = 2\,V\,tg\,(\varphi + \beta)\,a = 2\sqrt{2}\,\tau_s t \cdot a\ tg\,(\varphi + \beta) \qquad \ldots\ldots \qquad (21)$$

Proposed design procedure

The first step when designing a lighthouse is to make a geotechnical investigation of the bottom and choose a suitable place. This step should include a consideration of the possibilities to avoid the piling up of ice. Is it cheapest to build it on a deep place, or should it be built in a shallow area and be designed for the pile up?

As a second step prevailing directions of winds and currents have to be found out and the fetch in different directions have to be decided. Also the probability of maximum permissible wind velocity and current velocity should be decided. Ice conditions and ice characteristics in the area should be mapped.

Now an estimation of possible forces in the ice has to be made from the chosen values of wind velocity, current velocity and fetch. At this point we could get an indication of the height of pile up if any. A decision of the shape of the lighthouse must also be made. The mode of failure and the forces from the ice must be weighed against the cost for different shapes.

The example Nygrån

Assume that the fetch of wind and currents was big enough so that the internal force per unit width of the ice was restricted by the crushing strength.

Let $\sigma_{cr} = 3 \cdot 10^6 \text{ N/m}^2$ [13], $t = 0.70$ m and $\rho = 600 \text{ kg/m}^3$

$$(1) \Rightarrow P = \sigma_{cr} \cdot t = 2.1 \cdot 10^6 \text{ N/m}$$

$$(2) \Rightarrow h = \sqrt{\frac{2P}{\rho g}} = \sqrt{\frac{2 \cdot 2.1 \cdot 10^6}{600 \cdot 10}} = 26 \text{ m}$$

The highest possible pile up against a shore would thus be 26 m if the fetch was long enough. Due to the shape of the tower the ice cannot, however, build up to 26 m because the ice is carried away at the sides of the lighthouse.

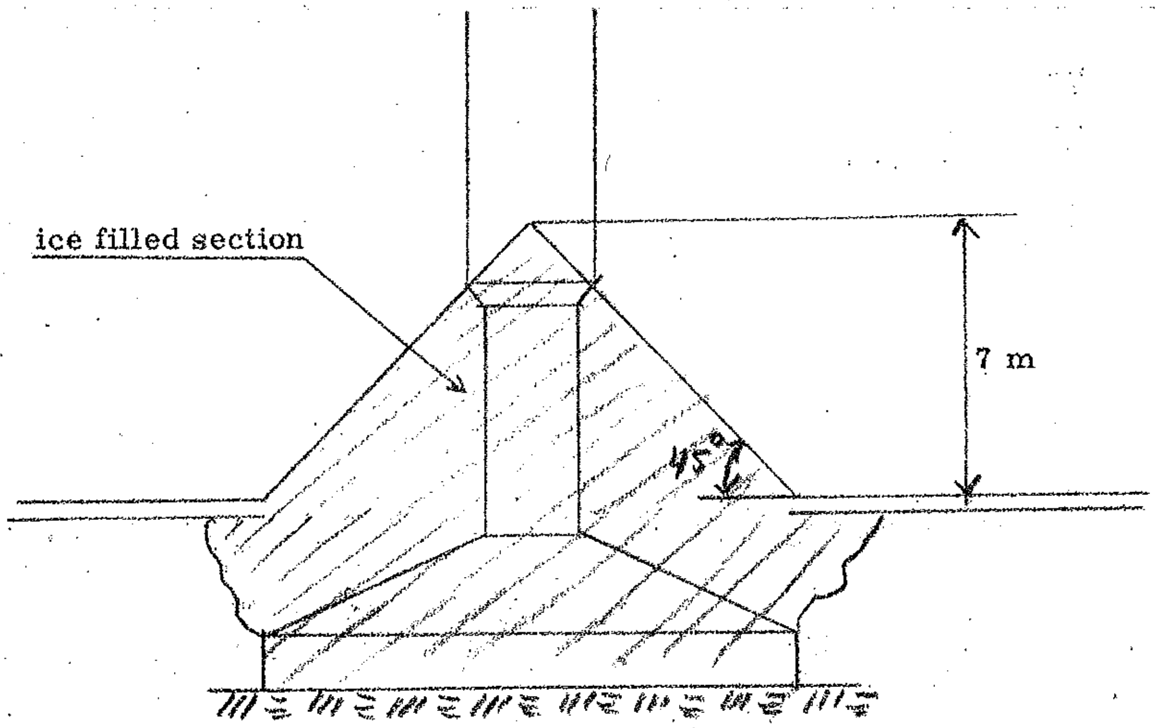

Figure 8 View of the lighthouse in the direction of ice movement.

Still it would seem realistic to count on some overelevation of the horizontal force on the lighthouse tower. Say 2 m above water level.

The horizontal force against the vertical tower would then be calculated according to equation (4). $d = 2.5$ m, $k = 0.7$, $m = 0.80$

$$(5) \Rightarrow \quad I = 1 + 4/\exp\sqrt{2.5/0,7} = 1,6$$

$$(4) \Rightarrow \quad H = 1,6 \cdot 0.8 \cdot 0.7 \cdot 2.5 \cdot 0.7 \cdot 3 \cdot 10^6 = 4,6 \cdot 10^6 \text{ N}$$

That is per meter width of structure: 1, 8 N/m.
The moment at the failed cross section would be

$$M = 4,6 \cdot 10^6 \cdot 3 = 14 \text{ Nm}$$

Note that if $\sigma_{cr} = 10^6$ N/m^2 $H = 1.5 \cdot 10^6$ N or $0,6 \cdot 10^6$ N/m width of structure.

Conclusions

Looking at the calculations in the example Nygrån, it is obvious that there are only two factors that are really important; namely the crushing strength of the ice, and the height and possibility of pile up. Concerning the strength of ice it is not probable that this can be clarified any better because of the variation in nature. See Weeks and Assur [15].

The "critical" depth for pile up according to Bruun and Straumsnes [4], and the interrelation between forces and height of pile up according to Allen [2] must be better decided.

Especially the reduction of pile up due to finit width of structure must be investigated.

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APPENDIX II - NOTATIONS

The following symbols are used in this paper:

a	=	waterline or contact radius
d	=	diameter of structure
E	=	elasticity of ice
F	=	normal force per unit width
g	=	earth accelleration
H	=	total horizontal force against a structure
h	=	height of pile up above water level
I	=	indentation factor
k	=	contact factor
l	=	distance between contact and ring tensile crack
m	=	form factor
m	=	moment per unit width
m_s	=	elastic failure moment per unit width
m_y	=	yield moment per unit width
P	=	horizontal force per unit width
R	=	resultant force per unit width
t	=	thickness of ice
$tg\varphi$	=	friction factor
V	=	vertical force per unit width
α	=	angle in plan
β	=	angle of slope of structure
ν	=	Poisson's ratio
ρ	=	density of pile up above water
σ	=	stress
σ_{cr}	=	crushing strength of ice
σ_s	=	bending strength of ice
σ_y	=	yield stress of ice
τ_s	=	shear strength of ice
φ	=	friction angle