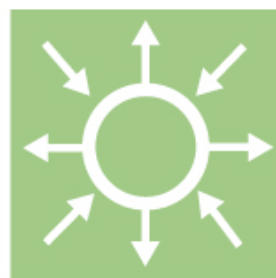


# Recommendations for design of offshore foundations exposed to ice loads

Elforsk rapport 09:55



Lennart Fransson and Lars Bergdahl

April, 2009



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## Preface

A good understanding of ice conditions and ice loads is essential in order to make proper construction of foundations for offshore wind power in the Baltic Sea. Earlier recommendations are published by Lars Bergdahl 2002. The work presented in this report consist an update of these recommendations with current new research and data.

Assumed ice action is based on experiences from damages on Swedish and Finnish lighthouses as well as on resent full-scale measurements in Sweden, but it is also in line with the Canadian and Russian standard and the published comments to these standards.

The applied practices and basic assumptions behind design of bridge pears, lighthouses and offshore constructions were originally created without much knowledge of ice mechanics. Now when these guidelines have been applied for a long time they have become valuable from an empirical point of view. Design rules for bridge piers have for instance not caused any essential setback, whereas a few small lighthouses have been damaged even though similar original guidelines for lighthouse were used.

Because of the stochastic nature of ice, loads on conical foundations have not been reduced to the low levels that many resent investigations have indicated. The uncertainty lays in the question whether a bending failure of the ice sheet always will take place. In general, it is difficult to establish relevant ice conditions and ice scenarios associated with design loads. On the other hand it is possible to calculate the magnitude of the ice load with a sufficient confidence once the ice conditions are defined.

The report comprises recommendations, description of ice loading mechanisms and ice statistics from the Baltic Sea. It should be possible to make at least a preliminary design of a vertical or a sloping foundation with help of this compilation. Additional data on specific ice conditions at a certain site will however improve the ice design considerably.

This work has been financed by the Swedish Energy Agency within the programme Vindforsk II, as project V-225 with Swedish Energy Agency project number 30434-1. The report has been written by Lennart Fransson at Luleå Technical University together with Prof. Lars Bergdahl at Chalmers.

Stockholm, June 2009

Anders Björck  
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## Sammanfattning

En rekommendation för att rätt kunna beräkna islaster mot havsbaserade vindkraftverk presenteras tillsammans med en beskrivning av isens brottmekanismer och statistik över isförhållanden i svenska hav. Vid dimensionering av fundamenten ska horisontell och vertikal last från istäcket beräknas baserat på istjocklek, isens hållfasthet och konstruktionens egenskaper. Det är i detta sammanhang viktigt att skilja på isförhållandena inomskärs i den fasta isen och den mer dynamiska issituationen som råder längre ut till havs. I den mån det finns uppmätta islaster mot vertikala konstruktioner ska det statistiskt grundade effektiva istrycket (lasten dividerad med isens tjocklek och fundamentets bredd) vara vägledande. Islaster mot lutande eller koniska fundament kan beräknas med hjälp av plasticitetsteori endast om man kan göra troligt att isen alltid sönderdelas genom böjning. Detta är inte alltid fallet i områden med hoppackad drivis eller isvallar. Vindkraftverken ska kontrolleras för en oscillerande islast om dess grundfrekvens kan antas ligga nära konstruktions egenfrekvens. Detta gäller för såväl koniska som vertikala fundament.

## Summary

A recommendation for better estimations of ice loads on offshore wind power generators is presented together with informative sections on ice loading mechanisms and statistics on ice conditions in Swedish seas. When the foundations are designed horizontal and vertical loads from the ice sheet shall be calculated based on ice thickness, ice strength and properties of the structure. It is then important to distinguish between ice conditions in the landfast ice zone and the more dynamic ice situation further out from shore. As far as measured ice loads on vertical structures are available the probabilistic effective ice pressure (load divided with ice thickness and foundation width) shall serve as guidance. Ice loads against sloping or conical structures can be calculated using plasticity theory only if it is plausible that the ice fails by bending. That is not always the case in areas of pressure ridges or compacted ice. Offshore wind power generators shall be checked for oscillating ice loads if its main frequency can be assumed to be close to the natural frequency of the structure. This applies to both conical and vertical foundations.



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# 1 Recommendations for ice design

## 1.1 Introduction

Ice loading is a severe and decisive load case in waters with winter climate. The occurrence of ice must be assessed at offshore sites in lakes and seas in North America, northern Europe and northern Asia. Moving ice can induce large foundation loads and cause catastrophic failures for offshore wind turbines.

The magnitude of the ice forces shall be estimated taking into account local ice conditions and water levels as well as ice movements, and to the size and form of the foundation. The following ice loads shall be assessed:

- horizontal load due to temperature fluctuation in a fast ice cover (thermal ice pressure)
- horizontal load from moving ice floes
- pressure from hummocked ice
- vertical force from fast ice covers subject to water level fluctuations.

The following eight approaches, codes, recommendations, guidelines or draft, are used today in ice design (Mättänen and Lilja, 2005):

1. API, API RP 2N (1995), Recommended practice for planning, designing, and constructing structures and pipelines for arctic conditions, American Petroleum Institute
2. CSA, CSA 471-04, (2004), Canadian Standards Associations,
3. GL, GLO-03-319, (2003), Germanischer Lloyd, Guideline for the construction of fixed offshore installations in ice infested waters,
4. IEC, 61400-3 IEC (2004), WG3, Recommendations for design of wind turbine structures with respect to ice loads.
5. RIL, RIL-144, (2001), Finnish civil engineers association, Guideline for the loading of structures.
6. SNiP, SNiP 2.06.04.82\* (1995), Russian national standards,
7. VSN, VSN 41.88 (1988), Russian national standards
8. ISO, Draft ISO 18806 Arctic Offshore Structures Standard

In addition there are other types of design recommendations that have been important in the present recommendation. E.g. the Swedish ice load recommendations for bridge piers (Löfquist, 1987).

## 1.2 General

Ice loads are normally assumed to occur at an arbitrary water level between MHW and MLW if no specific statistical analysis has been carried out. For structures including cones sensitive to the water level, statistical data for water level fluctuations at winter conditions, should be collected in order to identify the design water level range determining the height of the cone. The foundations in this annex are assumed to be constructions with a circular or

rectangular waterline cross-section including vertical cylinders and cones constructed of concrete or steel.

In lakes or in the sea close to the coastline, the ice sheet is normally not moving after having grown to a certain thickness. Loads originating from moving ice shall be checked up to this thickness. Loads from thermal pressure, arching effect and vertical lift shall be checked for thicker ice covers due to later growth.

In areas where moving ice is expected, the loads from moving ice shall be calculated for all seasons and be considered to act in the directions of the current and wind. The wind direction shall be considered to be independent of the motion direction of the ice. A dynamic time simulation of the load case is usually required. The possibility for dynamic locking of the ice breaking frequency to the wind turbine eigenfrequency and to other turbines in a wind farm shall be considered. Model tests can be used as part of an assessment.

### 1.3 Choice of ice thickness

The ice thickness,  $h$ , shall be based on analysis of statistical data from a local ice atlas or similar document (SMHI och Havsforskningsinstitutet, 1982, Westring, 1993, National Ice Center, [www.natice.noaa.gov](http://www.natice.noaa.gov), National snow and Ice Data Center, [www.nsidc.org](http://www.nsidc.org)). In most cases a combined evaluation of ice thickness and crushing strength is to be carried out. For wind turbines in the open sea the thickness shall be chosen corresponding to a 50 year recurrence period. For wind turbines in archipelagos and lakes, the thickness of moving ice shall be chosen to correspond to "Normal winters" and fast ice cover thickness corresponding to the 50 year recurrence period.

Below is an equation to estimate the ice thickness at the end of a frost period if temperature statistics but no ice statistics are available:

$$h = 0,032 \sqrt{0,9 K_{\max} - 50} \quad \dots(1)$$

where  $K_{\max}$  is the absolute value of the sum of 24 hours mean temperatures that are less than 0°C in a frost period (degree days) after the first freeze over.

### 1.4 Load Cases

The following loads shall be applied if relevant for the site.

- horizontal load from fast ice cover originating from temperature fluctuations
- horizontal load from moving ice floes
- pressure from hummocked ice and ice ridges
- vertical force from fast ice covers subject to water level fluctuations.

#### 1.4.1 Horizontal load from fast ice cover originating from temperature fluctuations

Thermal ice pressure shall only be considered in lakes and in brackish seas. In the open sea with saline water like the North Sea the thermal ice pressure can be neglected.

Unilateral thermal ice pressure will be largest on the outer wind turbine foundations in a wind farm, and shall be assumed to act from land towards the open sea or from the centre of a wind power farm, radially outwards. If an icebreaker makes a channel through a fast ice cover under thermal pressure the ice will expand towards the open channel and forces according to Eq. (2) can occur.

The thermal force can be written (Löfquist, 1987, Haapanen et al., 1997)

$$H_t = f_t D \quad \dots(2)$$

where  $D$  is the diameter or the width of the foundation at the water line  
 $D$  is set to 4 m if  $D < 4$  m.  
 $f_t$  is the force per unit width of foundation

The force  $f_t$  is set to 300 kN/m for stand-alone foundations or for outer foundations in a windfarm. For foundations behind the outer row or inside a windfarm  $f_t$  is given the value 100 kN/m.

#### 1.4.2 Horizontal load from moving ice

##### a) Empirical ice load based on full-scale measurements

Vertical structures can be designed based on measurements of the effective ice pressure defined from  $p_{eff} = H/(Dh)$ , where  $H$  is measured horizontal ice load,  $D$  is the width of the vertical structure and  $h$  is average ice thickness. Full-scale data of ice loads on the lighthouse Norströmsgrund in the Gulf of Bothnia can be found on [www.ltu.se/norstromsgrund](http://www.ltu.se/norstromsgrund) and the effective pressures can thus be calculated. A strong dependence of the contact area was found, resulting in  $p_{eff} = 4$  MPa on a 1 m contact width and  $p_{eff} = 2$  MPa on 10 meter width.

##### b) Theoretical ice load based on ice crushing strength

If no relevant field data is found the method originally introduced by Korzhavin should be applied. The water level shall be checked for the specific site during ice conditions, in order to find the relevant vertical level of action for the resulting pressure.

The maximum static force due to ice crushing against a vertical structure is

$$H_d = k_1 k_2 k_3 D h \sigma_c \quad \dots(3)$$

where  $k_1$  shape factor for the shape of the foundation on the ice impact side,  
 $k_2$  contact factor for the ice contact against the foundation,  
 $k_3$  factor for the ratio between ice thickness and the foundation width,  
 $D$  is the width of the foundation at the water line,  
 $\sigma_c$  crushing strength of the ice

Ice crushing strength  $\sigma_c$

The ice crushing strength should be determined from statistical data of crushing strength. The available data shall be corrected for the actual temperature and brine content in order to carry out a statistical analysis of the reference crushing strength (Christensen and Skourup, 1991).

In case no local ice data are available the crushing strength can be chosen as given below which are values typical for the Northern Baltic Sea and Arctic Canada:<sup>1</sup>.

$\sigma_c = 3,0 \text{ MPa}$	for ice in motion from wind and current at the coldest time of the year
$= 2,5 \text{ MPa}$	for moving ice at a very slow motion caused by thermal expansion or shrinking.
$= 1,5 \text{ MPa}$	for ice during spring at temperatures near the melting point
$= 1,0 \text{ MPa}$	for partly deteriorated ice at temperatures near the melting point
$= 0,5 \text{ MPa}$	for saline first year ice in the open sea, as e.g. in the North Sea.

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<sup>1</sup> The above referred values are in accordance with the Canadian bridge standard (1978) which gives values in the range 0.7 – 2,8 MPa. The Soviet standard (1976) states a width 0.44 – 1.47 MPa. The above given values can be seen as conservative. (Roads and Transportation Ass. of Canada, 1981)

### Shape factor $k_1$

If the foundation can cut the ice floe instead of only crushing it at the impact point, the shape factor  $k_1$  is given values:

$$k_1 \quad \begin{aligned} &= 1 \text{ for rectangular shape} \\ &= 0.9 \text{ for circular shape} \end{aligned}$$

### Contact factor $k_2$

The contact factor covers the fact that ice under continuous crushing is not in contact with the whole nominal area  $Dh$  except at the start of the movement when it is completely frozen to the foundation.

$$k_2 \quad \begin{aligned} &= 0.5 \text{ when the ice is continuously moving.} \\ &= 1 \text{ when the ice is frozen to the foundation surface} \\ &\quad \text{at the time the ice is starting its movement.} \\ &= 1.5 \text{ when the frozen ice is locally increased in} \\ &\quad \text{thickness around the foundation. Alternatively, the} \\ &\quad \text{thickness } h \text{ is chosen as the ice thickness in the} \\ &\quad \text{immediate vicinity of the foundation instead of} \\ &\quad \text{referring to the undisturbed ice field.} \end{aligned}$$

### Aspect ratio factor, $k_3$

The aspect ratio factor takes the three-dimensional stress state in the contact point into consideration. If the ice is thin in comparison with the diameter of the foundation the stress state can be considered to be two-dimensional. When the ice is thick it is three-dimensional with confined vertical and horizontal deformation. This is considered by Afanasev's factor

$$k_3 = \sqrt{1 + 5h/D} \quad \begin{cases} h/D \leq 1 & \Rightarrow & 1 \leq k_3 \leq 2.5 \\ h/D > 1 & \Rightarrow & k_3 = 2.5 \end{cases} \quad \dots(4)$$

### Vertical level of action for the horizontal load

If there is a risk of ice piling up against the foundation, the height of load action shall be increased with 0.2 times the water depth at depths smaller than 6 m.

### Sloping Shapes

For sloping structures, e.g. wind turbine towers with ice cones, when the ice fails by bending Equation (6) below by Ralston (1977) can be used as is also recommended by API (1982). The equation is valid for slope  $0^\circ < \alpha < 70^\circ$ , where  $\alpha$  is the slope measured from the horizontal plane. The equation gives lower forces than Equation (3) for crushing failure.

It should be warned that conical structures may not give economical designs as

- 1) the bending-failure mechanism is not valid for an ice cover frozen to the foundation at the start of ice motion and

- 2) that the ice cover may slide up or down the conical part and hit the foundation at a level where it is vertical.

The horizontal load for ice being up-bended is

$$H_b = A_4 \left[ A_1 \sigma_f h^2 + A_2 \rho_w g h D^2 + A_3 \rho_w g h (D^2 - D_T^2) \right] \quad \dots(5)$$

The vertical downward load is

$$V_b = B_1 H + B_2 \rho_w g h (D^2 - D_T^2) \quad \dots(6)$$

where  $A_1, A_2, A_3, A_4, B_1$  and  $B_2$  are dimensionless coefficients which are functions of the ice-to-cone friction coefficient  $\mu$ , and the cone angle  $\alpha$ . The coefficients are given in the graphs in Fig. 1.

$\sigma_f$	= flexural strength of ice, not less than $0,26 \sigma_c$
$h$	= thickness of ice sheet
$\rho_w$	= density of water
$g$	= the earth acceleration
$D$	= water line cone diameter
$D_T$	= cone top diameter (equal to tower diameter)

For cones down-bending the ice, the same formulas applied exchanging  $\rho_w$  for  $\rho_w/9$  and the vertical force has an upward direction.

The above formulae may be used if the height of the cone exceeds one ice thickness from top of ice (up-bending cone) or bottom of ice (down-bending cone). Due consideration to water level variation has to be taken. For double sided cones the forces may be estimated as described above except for forces directly on the tip. For a sharp tip the horizontal force shall be increased by a factor 2, and for a round tip the forces shall be increased by a factor 3 (Gravesen et al., 2003).

#### Friction

The dynamic ice-to-cone friction coefficient  $\mu$  may be set to:

$$\begin{aligned} \mu &= 0.15 \text{ for a cone of concrete/corroded steel and} \\ \mu &= 0.10 \text{ for a cone of new or painted steel.} \end{aligned}$$



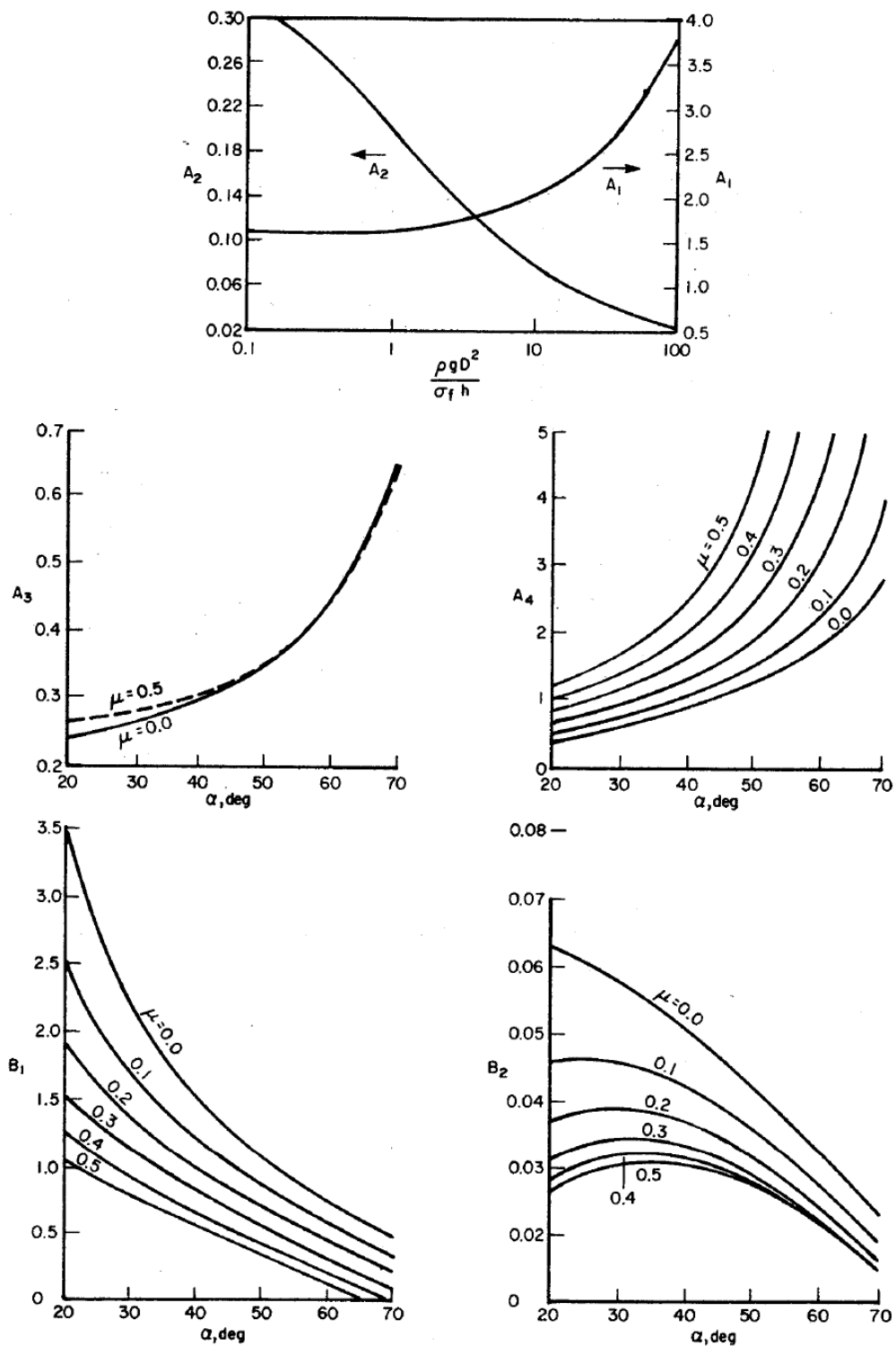


Fig. 1 Ice force coefficients for plastic limit analysis (Ralston, 1977, graphs from Michel, 1978).

### 1.4.3 Wind and current induced load

The load from wind or current on an ice floe can be estimated with

$$H = C_d \rho \frac{U^2}{2} A \quad \dots(7)$$

where for wind

$$C_d = 0.004$$

$$\rho = \rho_a = 1.3 \text{ kg/m}^3$$

$U$  = free stream velocity at 10 m above ice surface

and for water

$$C_d = 0.006$$

$$\rho = \rho_w = 1000 \text{ kg/m}^3$$

$U$  = free stream velocity at 1 m below the ice lower surface

$A$  = area of the ice floe.

The wind and/or current load is limited by the crushing or bending failure of the ice against the foundations according to Equations (3) or (5). The combined drift forces from wind and current should be based on a statistical analysis of site data.

## 1.5 Vertical load from fast ice cover

The vertical load in case of fluctuating water level with a fast ice cover frozen to the foundation is limited either by the shear strength at adhesion to the foundation surface,  $V_\tau$ , or by the bending strength if the ice is failing by bending in a ring around the foundation,  $V_b$ . (Tryde, 1980)

The lower of the two alternatives is decisive and shall be used.

$$V_\tau = A \tau \quad \dots(8)$$

where  $\tau$  = adhesive shear strength

$A = \pi D h$  is the contact area for a circular vertical foundation.

The adhesive shear strength,  $\tau$ , can be set to 0.8 MPa for steel – fresh water ice, to 0.3 MPa for steel – saline ice (Oksanen, 1982), and to 1 MPa for concrete – saline ice (Cummeraert and Muggeridge, 1988).

$$V_b = 1.5\sigma_f h^2 \left\{ 1.05 + 2\frac{r}{l} + 0.5\left(\frac{r}{l}\right)^2 \right\} \quad \dots(9)$$

where  $h$  = the ice thickness,  
 $\sigma_f$  = the flexural strength of ice, not less than  $0.26 \sigma_c$   
 $r$  =  $D/2$  the radius of the foundation  
 $l = \frac{Eh^3}{12(1-\nu^2)\rho_w g}$  = the characteristic bending length  
 $\nu$  = Poisson's ratio of the ice  
 $\rho_w$  = water density and  
 $g$  = acceleration of gravity.

## 1.6 Pressure from ice ridges

Very large loads can occur if ice ridges enclosed in a moving ice sheet press on the foundations. Such an ice ridge consists of ice fragments and can contain consolidated ice fragments frozen together to 2–3 m thickness. Loose blocks below and above the consolidated ice give little contribution to the ice load.

The loads are roughly estimated either with the assumption that the ice is crushed or that the ice ridge is bent in the horizontal plane to failure. It is generally not recommended to put wind turbines in areas with risk of ice ridging.

## 1.7 Dynamic loading

The wind turbines shall be checked for dynamic effects from ice loading. At some locations along the Swedish coast the duration of severe ice crushing may be several weeks each winter. Below some simplified equations are given for dynamic load simulation which can be used if statistical data or measurements are not available.

The time-varying load from moving ice on vertical cylindrical foundations may be approximated by a sinusoidal function as

$$H_{dynv} = H_d \left( \frac{3}{4} + \frac{1}{4} \sin(f_N t / (2\pi)) \right) \quad \dots(10)$$

where  $H_d$  = the horizontal crushing load from moving ice, Equation (3)  
 $t$  = time  
 $f_N$  = the wind turbine structural natural frequency. Both 1<sup>st</sup> and 2<sup>nd</sup> modes should be checked.

The dynamic effects is strongest when a buckling type of failure occurs, which induces strong variations in the ice force (Fransson and Lundqvist, 2006, Yue and Bi, 2000)

A criterion for tuning is (Singh et al. 1990)

$$\frac{U}{(D \cdot f_N)} > 0.3 \quad \dots(11)$$

where  $U$  = ice floe speed and  
 $D$  = is the diameter of the foundation at the water line.

The time-varying load from moving ice on conical foundations ( $\alpha \geq 30^\circ$ ) may also be approximated by a sinusoidal function as

$$H_{dynk} = H_b \left( \frac{3}{4} + \frac{1}{4} \sin\left(\frac{f_b}{2\pi} t\right) \right) \quad \dots(12)$$

where  $H_b$  = the horizontal bending failure load from moving ice from Equation(5)  
 $t$  = time  
 $f_b = U/Kh$  where  $U$  is the actual speed of the ice floe and  $4 \leq K \leq 7$ . The  $K$  which gives highest load shall be chosen.

### 1.7.1 Impact load

Loads from impact of a large ice floe should be checked with a transient load approach as suggested below.

$$H_s(t) = \begin{cases} \frac{Ut}{D} H_d & \text{for } t \leq D/U \\ H_d & \text{for } t > D/U \end{cases} \quad \dots(13)$$

The load is for small ice floes limited by the momentum of the ice floe.

### 1.7.2 Stochastic simulation

A complement to using the Equations (10), (12) or a triangular shaped function is to base response simulations primarily on ice model tests as described below. From such model tests time series describing the stochastic ice load may be available. It is warned, however that the dynamics of the structure sometimes not be scaled correctly in the model tests. As ice model

tests usually only generate load time series corresponding to a few minutes prototype load it is required to extend the measured time series (Gravesen et al., 2003) to obtain a few statistically independent 10 minutes simulations of the dynamic ice load.

Independent ice load and wind forces time series are then simulated in a dynamic turbine model using an appropriate recurrence period for the combined event of wind velocity and ice thickness and motion.

### 1.7.3 Requirements on model testing

Model tests may be carried out with artificial ice. Usually the results are scaled on the basis of a Froude modelling law scaling the forces by  $\lambda^3$ , bending and crushing strengths with  $\lambda$  and time by  $\lambda^{0.5}$ . For vertical foundations severe dynamic interaction between the ice load and the oscillations of the structure may occur and then it is required to model the resonance frequency, the damping and the stiffness of the structure exposed to ice loads correctly. For conical foundations limited dynamic interaction occurs, so stiff model test results may be used to generate the dynamic ice load input to a stochastic simulation (Gravesen et al., 2003).

## 1.8 Local ice pressure

The foundation shell shall be designed for the following local ice pressure:

$$p_{local} = \sigma_c \left( \frac{5h^2}{A_{local}} - 1 \right)^{0.5} < 20 \text{ MPa} \quad \dots(14)$$

where  $A_{local}$  = local area considered.



## 2 Ice loading mechanisms

Ice loads on base structures of wind-power plants can be

- horizontal load from fast ice covers due to temperature fluctuations, *thermal ice pressure*,
- horizontal load from drifting ice,
- pressure from hummocked ice and ice ridges and
- vertical load from fast ice covers due to water level fluctuations.

### 2.1 Thermal ice pressure

Newly formed, thin ice covers in fresh water have a temperature close to the freezing temperature of water. As the ice cover grows thicker the temperature in the upper surface of the ice will decrease, however, and the ice surface will therefore tend to contract and tensile stresses will result. The tensile stresses will be balanced by compressive stresses in the underside of the ice cover or by tensile stresses on banks and structures. At moderate cold the ice will have time to yield by creeping, see Figure 1.

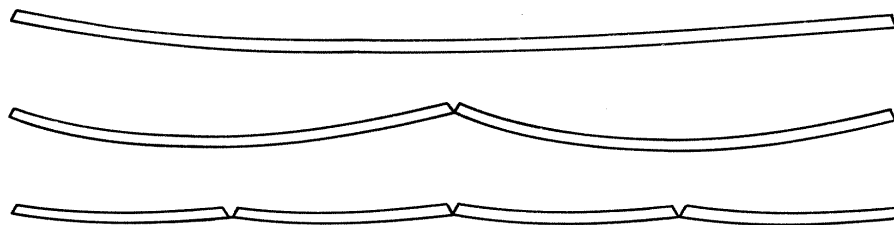


Figure 1. Bending and cracking of a floating ice cover at fast lowering of the air temperature. (Bergdahl, 1978)

In the wider cracks water can penetrate from below and freeze to ice. Later on, when the air temperature rises again the ice cover will try to expand but due to the new ice in the cracks large forces will occur against steep shores, followed by buckling of the ice cover, shoving up on beaches or shoving over adjacent ice fields. Examples of expanding ice sheets are shown in Figure 2.

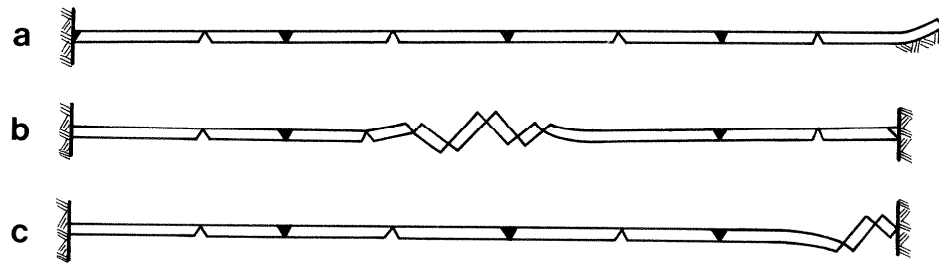


Figure 2. Example of expanding ice covers

- a) shoving up onto a beach
- b) folding out on a lake and
- c) buckling against a steep bank. (Bergdahl, 1978)

In fresh waters the pressures can become substantial. For Northern Sweden possible pressures are given up to 500 kN/m and for Southern Sweden 250 kN/m width of structure. Pressures around 240-300 kN/m have been experienced from field measurements in the USA and Sweden. (Löfquist 1987)

Saline ice with salinities above 0,5 % has a negative coefficient of expansion and therefore thermal ice pressure will be of no concern in Skagerrak, Kattegat, and the Baltic Proper, but could arise in the Gulf of Bothnia, Sea of Botnia, the Gulf of Finland and the archipelago of Stockholm.

### 2.1.1 Estimation of thermal ice pressure

It is difficult to estimate thermal ice pressure due to the complicated rheological behaviour of ice, but also due to widely varying outer conditions like air temperature changes; initial ice temperature; temperature increase in the ice cover which is a function of wind speed, sun irradiation, air transparency, snow on the ice etc; and to what extent water has penetrated into the cracks. (Bergdahl, 1978; Bergdahl and Wernersson, 1978; Fransson 1988). For example, the temperature distribution in ice covers with and without snow is shown in Figure 3. The influence of solar radiation is shown in Figure 4 and the corresponding calculated thermal ice pressure is given in Figure 5.



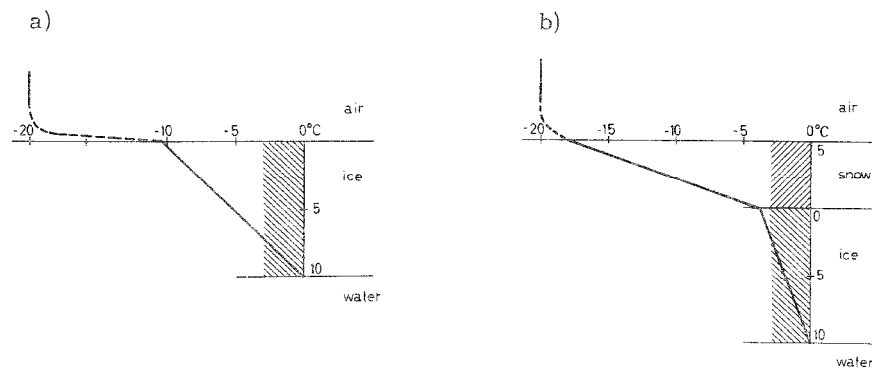


Figure 3. Examples of temperature distributions in a 10 cm thick ice cover  
a) without snow and b) with 5 cm snow. (Bergdahl, 1978)

Air temperature	-20°C
Wind speed	2 m/s
Vapour pressure	0.03 Pa
Cloudiness	4/8
Irradiation (night)	0

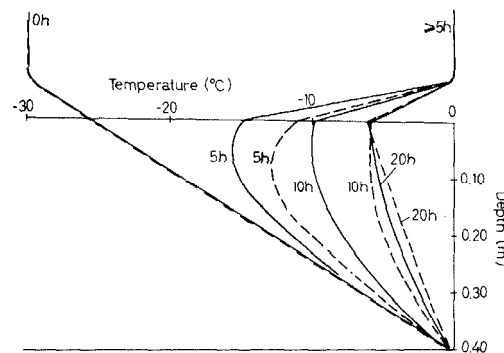


Figure 4. Example of warming of a 40 cm thick ice cover without sun, continuous graphs, and with sun, dashed graphs. The same increase of air temperature, vapour pressure and wind speed in both cases. (Bergdahl, 1978)

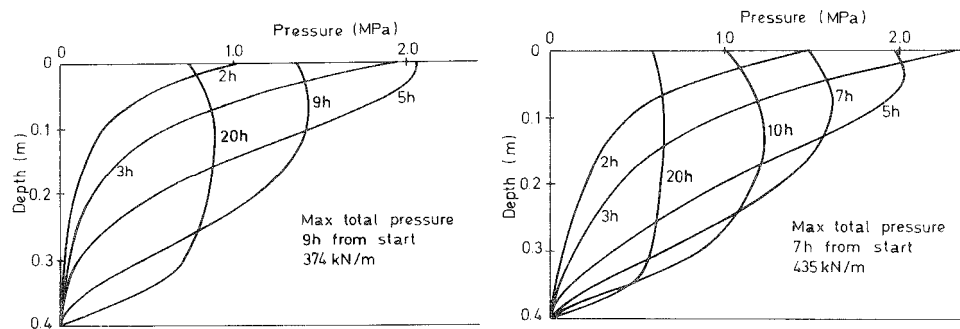


Figure 5. Pressure distributions arising in an ice cover due to warming and restricted expansion. Left figure in overcast and right figure in sunshine corresponding to continuous and dashed graphs in Figure 4. (Bergdahl, 1978)

### 2.1.2 Thermal ice pressure on foundations for wind power plants

If a wind power plant is placed in a lake or in a landlocked part of the sea, the thermal ice pressure will be horizontally isotropic, and gives then no resulting ice load, but the shell of the structure must be able to sustain the pressure.

Usually wind power plants would be placed somewhat off the coast – which is the purpose – and further off the coast there is open water or a lead for ships towards which the ice cover can expand without resistance. The expansion of the ice cover is then only restricted by the foundations of the wind power plants themselves. If the coast is steep and the distance to land is a few hundred metres the forces against the foundations will be so large that the ice will crush, buckle or, at low deformation rate, deform viscously against the foundations.

An example that forces can be large is the incidence at the bridge Hjulstabron in the lake Mälaren in 1953, when the southern bridge column was pressed into contact with the opening part of the bridge, so that the bridge could not be opened. The air temperature had risen  $14^{\circ}\text{C}$  (from  $-20^{\circ}\text{C}$  to  $-6^{\circ}\text{C}$ ) in 12 h, and the 22 cm thick ice cover had expanded towards the broken fairlead under the bridge. The force was estimated to 3 MN or 270 kN/m width of the column by Haggård (1958), see also Löfquist (1987). Another example is the four beacons installed on pile groups in Mälaren in the autumn of 1975, which were damaged the first winter by ice expanding towards a broken fairlead. In this case forces were estimated to between 200 and 800 kN and the ice pressure to between 100 and 270 kN/m the width of the pile groups. (Vattenbyggnadsbyrå, Sweco, 1976). From Canada a case was reported by Barnes (1928), see also Ashton (1986).

Thermal ice pressure can arise between land and the foundations and between the foundations themselves. In the former case the pressure is directed from land towards the open sea. In the latter case the force is

directed radially outwards from the centre of a group of wind power plants. At sloping beaches the ice cover and material from the beach can be shoved far up on land due to repeated thermal ice thrusts. Due to water level fluctuations at steep banks or foundations the ice cover can become layered, because the ice cover may hang on to the structure, and the ice cover can then increase to more than double its thickness away from the structure.

## 2.2 Horizontal loads from moving ice

Assume a scenario in which a fast ice cover has been formed and grown in thickness around a structure. Observe then first the phenomena at the onset of ice motion caused by e.g. wind or on-setting currents.

### 2.2.1 Static Load

Static ice loads on a structure are assumed to reach a maximum just before the ice is about to move. This is not always the case because stress release may come earlier due to radial cracks or creep buckling. If the contact between the ice and the structure is smooth the stress distribution becomes rather uniform after a certain loading time due to viscous creep and creep crushing. The highest stress level is a function of uniaxial compressive strength  $\sigma_c$  and the degree of confinement  $k_c$  of the ice in front of the structure. From plasticity analysis it can be proved that this confinement coefficient  $k_c$  is between 1 and 3. These assumptions make it easy to calculate the static ice load as

$$F_{static} = k_c \sigma_c Dh, \quad \dots(15)$$

where  $k_c = 1 - 3$  and  $\sigma_c$  is the average uniaxial compressive strength of the total ice thickness. The experimental procedure for testing ice strength must be designed to emulate ductile ice behaviour or creep crushing for mild or deteriorated ice. The load should be applied horizontally (perpendicular to the growing direction). For fresh-water ice the strain rate should be less than  $10^{-3} \text{ s}^{-1}$  in order to produce yielding. Finally it is important to perform the tests as quickly as possible after sampling in a controlled temperature and humidity to maintain the original ice properties. It might be so that it is better to test larger volumes of ice than small samples if the crystals are big. Still it is not believed that there is any strong size effect on the compressive strength. Therefore also the static ice pressure is assumed independent on size of the pressure area if the confinement is constant.

Numerical simulations of static ice loads on fixed structures can be used to compare different geometrical shapes of the structure in a given ice situation. Sand (2008) has developed a nonlinear finite element analysis where plasticity and crushing is allowed. This method has shown good agreement with results from full-scale measurements.

### 2.2.2 Dynamic load from a moving ice sheet

#### Ice crushing against vertical structures

If the driving force is sufficiently large ice floes are crushed against vertical structures when they are moving. The driving force in the Gulf of Bothnia comes from the wind and the drifting velocity is at most 3% of the wind velocity, usually less than 0.6 m/s. In other ice covered oceans current and tidal variations also contribute to the ice drift. Ice is an extremely brittle material even close to the melting point and thus brittle ice crushing is the most common failure mode. Fracture mechanical behaviour implies that the process is highly dynamic causing substantial vibrations to almost any structure in interaction. These vibrations may lead to ice-induced resonant oscillations on flexible structures. Such oscillations are only limited by the damping in the system and may cause a total collapse of an otherwise imposing structure.

The classical approach to this problem involves empirical studies of variations of the effective ice pressure defined as the ice load  $F$  divided with the projected ice contact area ( $Dh$ ). Even though the ice quality and temperature are kept constant it has been found that the effective pressure becomes different depending on the load situations. The following geometrical factors are often assumed to affect the effective ice pressure  $p_{eff}$ :

1. aspect ratio between structure width and ice thickness ( $D/h$ )
2. structure width  $D$
3. ice thickness  $h$
4. pressure area ( $Dh$ )

For narrow structures the aspect ratio is important and must be considered. As an example a 300 mm steel tube was pushed with an icebreaker through level ice in the Luleå harbour resulting in an effective pressure that increased from 3.5 MPa to 5.7 MPa when the ice thickness increased from 0.2 m to 0.5 m. This corresponds to an aspect ratio of 1.5 and 0.6, respectively (Fransson et al. 2008).

Wide structures (wider than usual foundations) imply that a larger volume of ice is involved in the crushing process and one might expect some type of size effect. It is also possible that the ice thickness has an effect on the effective pressure and this question is closely linked to the influence of pressure area. Full scale measurements have shown that the effective pressure decreases with pressure area (Sanderson, 1988) but it is not clear how the dependency is distributed amongst  $D$  and  $h$ .

In order to understand the true nature of ice crushing it is necessary to study the contact phenomena going on in the ice. Ice crushing experiments with transparent indenters have shown that *high pressure zones* develop at the centre of the contact area (Joensuu & Riska, 1988; Fransson et al. 1990). The maximum pressure in these small zones is probably limited only by pressure melting. Average pressure during ice crushing is typically less than 1/10 of these peak pressures. The impact of a strong pressure gradient on the contact area seems to be the explanation why continuous ice crushing changes to

intermittent crushing with creep deformation when the process is too slow to maintain the high pressure.

Even though ice crushing is still poorly understood, Fransson & Stehn (1993) proposed that the load from ice edge crushing is limited due to horizontal cleavage cracks in front of a vertical structure. The failure load  $F_{split}$  is given by

$$F_{split} = k_w K_{ic} D h^{0.5}, \quad \dots(16)$$

where  $k_w$  is a function of the relative width ( $w=a/h$ , see Figure 6) of the high pressure band,  $K_{ic}$  is the fracture toughness of ice,  $D$  is the width of the indenter and  $h$  is the ice thickness. It should be noted that the formula predicts that the effective ice pressure  $F/Dh$  is proportional to  $h^{-0.5}$ . It has been known for decades that measured average ice pressure is decreasing with the pressure area  $Dh$  but it is still discussed among ice engineers exactly how this pressure decrease can be explained in full scale.



Figure 6. Horizontal cracks in an ice cover due to pressure concentration.

In nature ice pressure can be limited by many other failure modes (bending, splitting or collapse of weak ice in inhomogeneous ice). The load during ice edge crushing at very high speed with stiff indenters seems to be limited by small-scale axial splitting but it is unclear how the load is related to the ice thickness. Crushing load is often characterised as a saw-tooth curve where the force drops faster than it builds up. For wider structures this high frequency variation is superposed a quasi-static load level usually referred to as *ice extrusion* pressure. The structure is then always in contact with the ice edge. An example of measured ice pressure variations due to ice-induced vibrations of Lighthouse Norströmsgrund is shown in Figure 7.

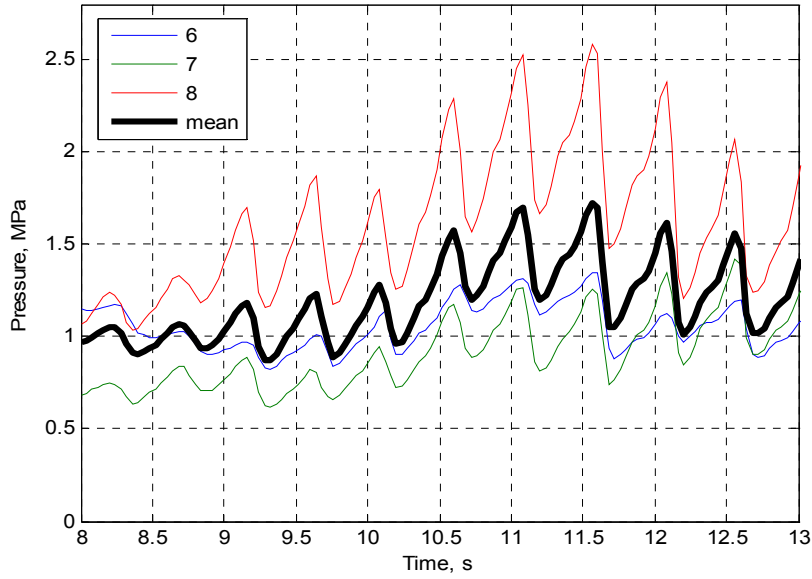


Figure 7. Oscillating ice pressures on Lighthouse Norströmsgrund.(Fransson & Lundqvist, 2006)

#### Upwards bending failure

For a wide structure with an inclined foundation a moving ice sheet will slide up until it breaks in upwards bending. The total horizontal load on a sloping structure comprises mainly two parts: *breaking load* and *ride-up load*. The relationship between horizontal and vertical forces (H and V) on a sloping structure is given by

$$H = N \sin \alpha + \mu N \cos \alpha \quad \dots(17a)$$

$$V = N \cos \alpha - \mu N \sin \alpha, \quad \dots(17b)$$

where  $\alpha$  is the slope ( $\alpha = 90^\circ$  is a vertical structure),  $\mu$  is the friction coefficient and N is the normal force (normal to the foundation wall), see also Figure 8. The bending strength for ice  $\sigma_f$  is typically around  $\frac{1}{4}$  of the crushing strength. When the ice is lifted up at the edge it will crack at a certain distance (proportional to the characteristic length) from the structure. The breaking load  $H_{break}$  is written

$$H_{break} = C_1 \frac{\sigma_f}{l} D h^2, \quad \dots(18)$$

where  $C_1$  is a function of friction and slope and  $l$  is the characteristic length of a floating ice beam.

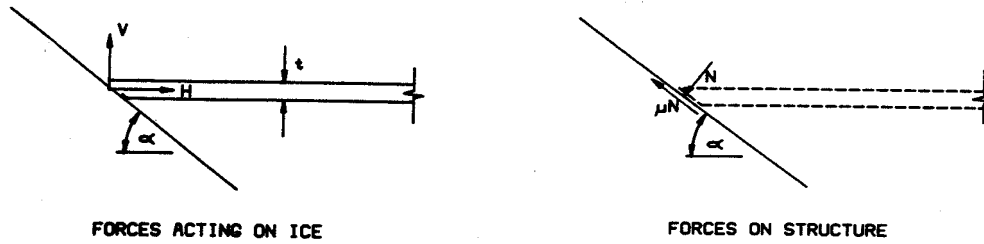


Figure 8. Breaking forces on a sloping structure. (Croasdale, 1980)

Seen as a two-dimensional process (as for a wide structure) it is relatively easy to show that the breaking load is proportional to  $h^{5/4}$ , see Eq.(18). The average ice pressure will thus increase with ice thickness. Thick ice is always possible in deep waters as long as pressure ridges or other thick ice features are present. Then the ice failure mode will change to ice crushing on some distance from the structure.

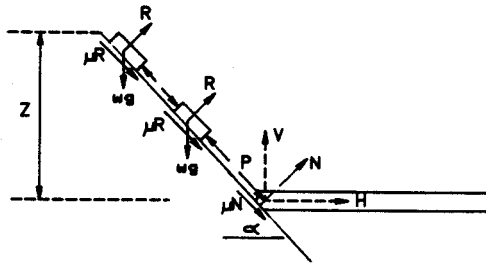


Figure 9. Ride-up forces on a sloping structure. (Croasdale, 1980)

The ride-up load is a function of the height  $Z$  that the weight of the ice floes has to be pushed up the wall of the foundation. This is a process that depends on time and eventually friction may increase drastically if it is cold enough for the floes, snow and water to refreeze on the structure. The ride-up load  $H_{ride-up}$  can be expressed as

$$H_{ride-up} = C_2 Z \rho_{ice} g D h, \quad \dots(19)$$

where  $C_2$  is another function of friction and slope, different from  $C_1$ . The effect of friction is quite significant which can be illustrated by the following example with a structure inclined to  $\alpha = 45^\circ$  sustained to a uniform ice. Lets (a) assume  $\mu = 0.1$  and (b)  $\mu = 0.5$  and that the other parameters remain constant. The effect of friction for a two-dimensional structure is given in Table 1 by the variation of constants. In this case the loads are more than doubled if the friction increases from 0.1 to 0.5. The friction effect becomes exponentially higher for steeper structures which leads to the conclusion that this simplified analysis should be avoided when  $\alpha > 50^\circ$ .

**Table 1.** Effect of friction on a sloping structure 45 deg.

$\mu$	$C_1$	$C_2$
<b>0.1</b>	0.8	1.7
<b>0.5</b>	2.0	4.3

For a narrow conical structure the breaking pattern is somewhat different from the two-dimensional case. First of all the ice sheet will crack in the radial direction out from the structure and the ice wedges are then bended upwards to failure at a fairly constant distance perpendicular to the structure. If the ice sheet is thick bending of circular cracks becomes harder after that the initial crack has been developed because a geometrical mismatch along the crack. Another difference is that the breaking load is more dominant compared with the ride-up load and thus the ice strength becomes more important. All together analytical solutions become more difficult to achieve which leads to the use of empirical formulas based on physical model experiments with various conical structures and ice conditions, etc. An early example of an empirical formula (Afanasev et al.1973) for narrow upwards-breaking cones was based on small-scale experiments with 3.5 cm thick ice. The breaking load  $H_{break}$  was calculated as

$$H_{break} = \frac{S_x \tan \alpha}{1.93l} \sigma_f h^2, \quad \dots(20)$$

where  $S_x$  is the length of the circumferential crack given as

$$S_x = 1.76 (D/2 + \pi/4), \quad \dots(21)$$

where  $D$  is the cone diameter at the water level and  $l$  is the characteristic length of an floating ice sheet. Several experimental studies have shown that the horizontal load for a narrow conical structure can be expected to depend on  $h^2$  and also Eq. (20) tends to do so when  $D \ll l$ . Ice pressure will then increase with  $h$  until other failure modes than upwards bending limit the pressure level on the structure.

### 2.2.3 Radial splitting

When an ice floe hits a narrow structure, vertical or sloping, cracks tend to propagate radially. The distance these cracks may travel can be several kilometres if the ice is cold and brittle. Therefore smaller ice floes will be split into two halves or into more segments when the load becomes high enough. It is difficult to estimate the load associated with radial splits because the tensile stress depends on brittleness, confinement and size of interacting ice floes. In a river during spring break-up radial splitting usually limits the maximum ice load on the bridge pier if the width of the pier is made small enough. The ice strength also has to be low in most rivers before the ice is



able to move. One might also think that splitting will be promoted if the foundation is designed like a sharp arrow. With the assumption that radial cracks are propagating due to stress concentrations at the contact zone it seems likely that the splitting force is proportional to  $(D_{floe})^{0.5}$ , where  $D_{floe}$  is a certain width of the approaching ice floe perpendicular to the ice movement.

#### 2.2.4 Non-simultaneous failures

For wide structures it is obvious that the pressure peaks measured on different small contact widths will not always occur at the same time. From this trivial observation it is a long way to the conclusion that it will never happen. For a stiff structure the ice pressure is only a function of the ice failure process. But as the structure deforms or moves all parts on the total width can be locked-in, i.e. the structure may experience resonant oscillations. If so, all peak pressures are likely to be in phase with each other. The failure process itself is also far from random, even though it appears to be. Maximum ice pressure is assumed to depend on the measuring width  $L$  according to

$$p^{\max} = p_0 \left( \frac{L}{L_0} \right)^{\alpha}, \quad \dots(22)$$

where  $p_0$  is the ice pressure measured on a width  $L_0$   
 $\alpha$  is a negative exponent ( $-0.3 < \alpha < -0.1$ )

Yielding at the corners of a narrow structure is a more confined process than yielding at the front of a wide structure. One must remember that the confinement is only complete in a situation where the structure is surrounded by an uncracked ice sheet as in the static loading case. A load increase as a function of the aspect ratio ( $h/D$ ) can be expected in connection with continuous crushing on vertical structures due to the observed higher maximum pressure levels at the corners of a flat indenter (Fransson & Nyström, 1994). This effect was pronounced on a distance equal to the ice thickness from each corner. Narrow cylindrical structures are affected by the same phenomena but the pressure distribution over the structure width is different. Extrusion of crushed material prevents the pressure to go below a certain minimum level independent on structure width. Very little is known about how this extrusion pressure level varies with ice thickness and velocity on wide structures. As shown by the two diagrams in Figure 10, the ice pressure peaks are higher when measured on a width of  $L = 1.21$  m compared with measurements on  $L = 9.5$  m.

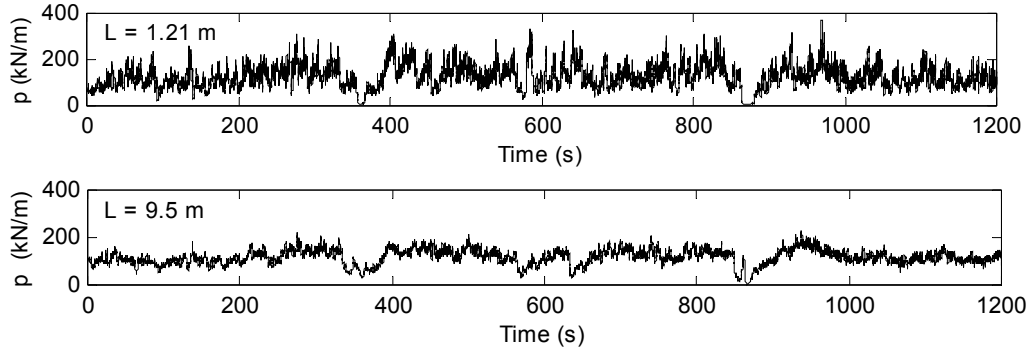


Figure 10. Pressure variation on segment 1 ( $L = 1.21$  m) and on the total measuring width ( $L=9.5$  m). Measurements on lighthouse Norströmsgrund.

Measured ice pressure levels at Norströmsgrund varied over the winter season depending on ice thickness and stability of the surrounding ice cover. Sixteen events with ice pressure were studied and the peak pressure as a function of contact width was obtained using Eq. 22. One example of how the pressure  $p_0$  ( $L_0 = 1$  m) and the coefficient  $\alpha$  is evaluated is shown in Figure 11.

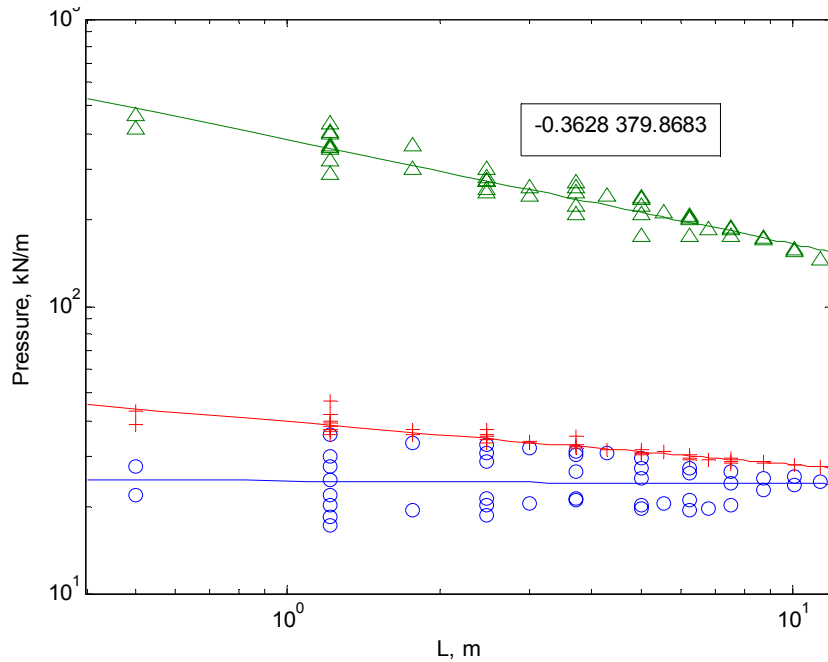


Figure 11. One example of 16 events 2000, where 7-9 panels were sustained to ice pressure. Max pressure (triangle), Standard deviation (+), average pressure (o),  $p_0 = 380$  kN/m and  $\alpha = -0.3628$ .

Peak pressures for short (1m) and long contact widths (10 m) during the whole season 2000 are shown in Figure 12.

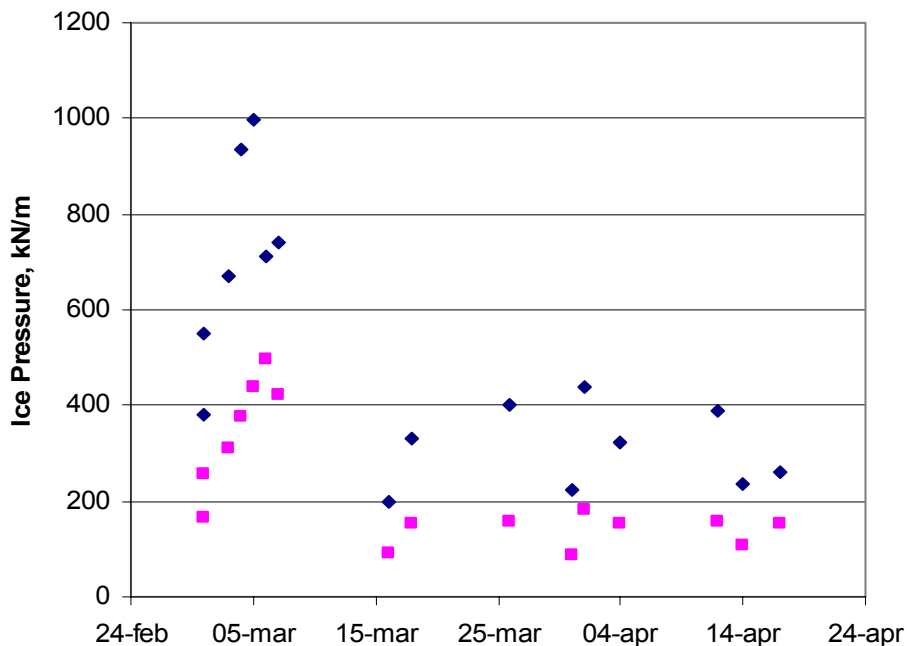


Figure 12. Seasonal variations of ice pressures on 1 m contact width (blue) and on 10 m (red). Max level ice thickness (0.3m) was reached in the middle of March. Measurements on lighthouse Norströmsgrund, 2000.

### 2.2.5 Loads experienced in practice

#### Impulsive loading

Impulsive loads have been estimated from damages on bridge columns in Canada and China. In Canada a case when a bridge column was displaced is reported. The crushing strength was for this case estimated to 1 MPa using the simple equation for effective pressure  $p_{eff} = H/(Dh)$  with  $H$  as the estimated sliding force. In China a case when a bridge column was almost turn over by an estimated force of 3 MN corresponding to an effective pressure of 1.8 MPa. (Löfquist, 1987).

At sea many ice floes can be very large. Haapanen et al. (1997) report that ice floes easily can be  $30 \times 30 \text{ km}^2$  and as the drift speed may be between 0.5 - 1 m/s (1 - 2 knots), it is understood that the forces become large when hitting a structure. Smaller floes smaller cold ice floes split after the first impact and large ice floes will be penetrated under continuous crushing or bending failure as described above.

#### Horizontal loads from large ice fields driven by current and wind

Load caused by continuous passage of ice floes or rather ice fields constitutes probably the most important load case in seas where ice covers are formed. Some few experiences of damaged structures due to such loading are reported the Gulf of Bothnia and The Gulf of Finland.

In the Gulf of Finland the light house Tainio was displaced around 14 m over a smooth rock at erection just before the base was to be injected. The ice load was estimated to between 4 and 5.6 MN and the linear horizontal pressure to between 1.15 – 1.6 kN/m of the structure diameter 3.5 m. (Löfquist, 1987) The light house foundation was a sandfilled, circular concrete caisson moulded on land, towed and sunk into place.

Engelbrektsson (1975, 1987) also lists the following cases:

- NYGRÅN

Caisson light house built in 1958 off Rönnskär in the Gulf of Bothnia. Its tower was broken off completely in the winter 1968-1969. The horizontal load could be estimated to around 4 MN and the linear ice pressure to 1.6 MN/m of the tower diameter 2.5 m.

- BJÖRNKLACKEN and BORUSSIAGRUNDET

These twin light houses were erected in 1969 in a completely weathered area of the Gulf of Bothnia, where ice motion often is severe. In the spring of 1970 it was detected that both light houses had been displaced, Björnlacken around 10 cm and Borussiagrundet some cm. The bases of the light houses were then strengthened by post-tensioned anchor cables into the rock. At noon 4 April 1985, however, Björnlacken's anchor cables were disrupted its caisson was displaced 17 m and the tower was tilted 12°. At inspection it was judged that the anchor cables were completely intact before the rupture and they showed no sign of corrosion. The ice thickness was measured to between 1.4 and 1.5 m in the vicinity of the lighthouse and the horizontal load was estimated to 10.9 MN, the linear pressure to 3.75 MN/m of the diameter 2.9 m and the effective pressure to 2.6 MPa. (Engelbrektsson, 1987; Fransson och Danielsson, 1985)

- KEMI 1 and 2

Kemi 1 and 2 were two light houses made by towers of circular steel tubes hammered into the sandy bottom and filled with compacted sand erected in 1973 off Kemi. They were severely damaged already their first winter in place. The initial damage was caused by ice impacts followed by resonance vibrations. The resonance vibrations damaged the superstructures and the lanterns. Finally one of the lighthouses was broken close to the sea bottom. This breaking was judged to be caused by overload not by fatigue. Therefore the maximum horizontal ice load at the water level could be estimated to at least 4.4 MN and the linear pressure to 2.2 MN/m of diameter 2 m. (Styrelsen för vintersjöfartsforskning, 1974). Both light houses were replaced by similar but stronger structures and provided with superstructures isolated from vibrations. The vibration isolation is shown by e.g. Haapanen et al. (1997).

## 2.3 Loads from hummocked ice and ice ridges

Ice ridges are common in areas of the Baltic where wind-power plants are expected to be erected. Ice ridges appear when drifting ice is pressed together by wind and current and in combination with water level changes. The thickness of the ice ridges can become up to 25 m in the Gulf of Bothnia and 5 m in the Southern Baltic and on the West Coast of Sweden. They appear often in shallow water or when the moving ice meets obstacles as e.g.

skerries, lighthouses and wind power foundations. Loads from newly formed ice ridges are not large, but the ice ridges can rise high. Up to 14 m has been noted and such ridges could block entrances to wind power towers and destroy ladders and external landing platforms. (Haapanen et al., 1997) The risk for such accidents is not completely negligible even on the Swedish West Coast. For instance, in the 1950s a beach restaurant close to Falkenberg was damaged by ice piling up onto the beach. Sometimes ferries in the Sound and in the approaches of Göteborg are experiencing difficulties with ice ridges.

### 2.3.1 Ridge formation

Due to a combination of thermal and dynamic processes a variety of ridge formations can be observed in first-year ice. Wind and wave action are the principal driving forces that create these features which has such an importance for design of structures in ice as well as for ice navigation. The ridge formations can be sorted after ice concentration and breaking resistance. The strength of the ridges depends mainly on size and the degree of consolidation, i.e. how much of the ridge that is frozen together. All ridges are thicker than the surrounding level ice which can be utilized as a method to detect them from satellite images or from automatic air-borne ice thickness measurements. *Pressure ridges* are the single-most important ridge type for design of structures. It is believed that thermal cracks or wave cracks is the weak line that breaks and initiates the ridge when the ice sheet is under lateral pressure. Once the process has started it will remain as a weak zone for a long time. Ice floes are gradually broken (similar to upwards bending against a sloping structure) and will slide on top of each other. The final geometrical shape depends on the size and quality of the broken ice floes and the magnitude of the driving force. When the ridge grows to a certain size, equilibrium is reached and new ridges are formed elsewhere. Then the pressure ridge may be idealized as shown in Figure 13.

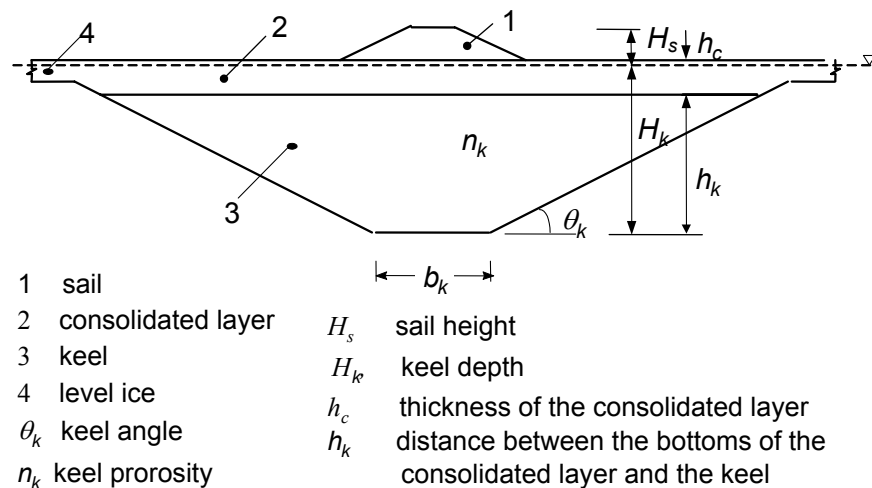


Figure 13. Idealized geometry of a first-year pressure ridge

The ice portion observed over the water level is referred to as the *sail* and the portion under the water level is called the *keel*. The number of pressure ridges is usually high in the Gulf of Bothnia, which is a major problem for winter shipping. Due to prevailing southern and western winds the entrance to the harbours becomes clogged. A typical pressure ridge in the Northern Baltic is formed from 30 cm level ice and can be more than 10 m deep with a sail height of 2 m.

### 2.3.2 Experienced effects for loads

At for instance Björnklacken, described above, there was an ice ridge of 1.4 m height and 3 m draught (keel depth) on the wind side. The thickness of the consolidated ice cover was estimated to 1.4 – 1.5 m, while the surrounding ice cover had a thickness of around 1 m (Engelbrektsson, 1987; Fransson and Danielsson, 1985).

Another important effect may be that an ice cover pressing past a foundation forms an ice ridge and finally the oncoming ice cover slides up on the ridge and attack the wind power plant on a higher level giving a much larger overturning moment than expected, although the force is normal.

In the case of Nygrån the light house tower failed in bending 1 m below the water surface at the connection to the larger-diameter bottom caisson. The tower was designed for a load of 3.75 MN acting 0.5 m above the water surface. However, the ice piled up to a large height so that the force resultant acted at the level 2 m above the water surface. Possibly the ice had frozen together to make the force large (Bergdahl, 1971; Engelbrektsson, 1975).

## 2.4 Vertical load from fast ice cover

At water level changes, vertical loads can arise on the wind power foundations if the ice has frozen to the foundation. At falling water level this is normally not a problem because the weight of the ice cover hanging on the foundation gives a downward load. At rising water level the load will be directed upwards and is governed by the volume of the trough formed around the foundation at the rising of the surrounding ice cover. The vertical load will for thick ice covers be limited by the fact that the ice will crack and water can well up through the ice. For small-diameter structures the load will be limited by the shear strength or adfreezing shear strength. The lifting load is only of interest for minor structures like boat bridges, dolphins, piles and the like. For road bridges it is normally not important. (Löfquist, 1987). According to Haapanen et al. (1997) also wind power plants are heavy enough to resist lifting loads

## 2.5 Icing

Icing of wind power plants occurs at cold windy weather with open water. It can give the following effects: (Engelbrektsson, 1975)

- weight of the ice,
- increase of wind drag,
- forces from falling ice and
- locking of moving parts.

Germanischer Lloyd (1995) gives the icing thickness to 30 mm with the density 900 kg/m<sup>3</sup>. The Norwegian Petroleum Directorate (1994) gives two independent different load cases. See Table 2, one for sea spray and the other for precipitation. Icing will not be considered further in this report.

**Table 2.** Ice loads with annual probability of 10<sup>-2</sup>. (Oljedirektoratet, 1994)

	Ice caused by seaspray			Ice caused by rain/snow	
	56°N to 68°N	North of 68°N	Density	Thickness	Density
5 m – 10 m	80 mm	150 mm	850 kg/m <sup>3</sup>	10 mm	900 kg/m <sup>3</sup>
10 m – 25 m	Linear reduction from 80 mm to 0	Linear reduction from 150 mm till 0	Linear reduction from 850 kg/m <sup>3</sup> till 500 kg/m <sup>3</sup>	10 mm	900 kg/m <sup>3</sup>
Över 25 m	0	0	-	10 mm	900 kg/m <sup>3</sup>

## 3 Ice statistics

### 3.1 Brackish ice

The water in the Baltic Sea has a salinity of 3-10 psu and Baltic sea-ice becomes more like fresh-water ice even if there are important differences. Salinity decreases as we go north with the lowest salinity in the Gulf of Bothnia. In the Luleå inner archipelago the ice is similar to lake ice with a land fast ice cover, but further out wind, waves and salinity (3 psu) makes the ice look like ordinary sea ice. Due to the shallow waters it is difficult to find water as warm as + 4°C, which implies that mixing of the water body is present during the ice formation. It should however be noted that the salt is not expelled from the growing ice in same amount as for ordinary sea ice, the salinity of brackish ice is about 1 psu in young ice. Pancake ice and snow-ice are commonly observed and these ice types are more saline than the columnar ice. In mild and snowy winters it happens that the ice cover becomes flooded due to the overburden. Freezing of the flooded snow involve concentration of brine in the intermediate water layer. Therefore the bonds between the layers become weak in mild temperatures. In the case of rafted ice the process is somewhat different because it is only a thin water layer between the floes that has to freeze. Rafted ice layers can thus consolidate over the season and reach a strength that is comparable with level ice.

### 3.2 General ice statistics

The Baltic Proper is completely covered by ice every 30 years in average, and land fast ice, ice ridges and pack ice occur every second to every fourth year. Similar conditions occur in the Kattegat and the Skagerrak, while the sea between Sweden and Finland and the Gulf of Finland are ice covered almost every year. A chart over the probability of ice is copied in Figure 14 below. Ice ridges with a thickness of around 5 m occur every tenth year in the Baltic Proper. Grounded piled-up ridges will probably occur more often, e.g. in the Strait of Kalmar off the shore at 4 – 5 m water depth. In the Bothnian Sea ice ridges are regularly occurring with draughts of 20 – 25 m. Much of the information below is taken from SMHI and Havsforskningsinstitutet: *Climatologic Ice Atlas for the Baltic Sea, Kattegat, Skagerrak and Lake Vänern (1963-1979)*, 1982. Another publication from SMHI: "Isförhållanden i svenska farvatten under normalperioden 1961-1990" (Ice conditions in Swedish Waters during the normal period 1961-1990, Westring, 1993) contains later information about ice occurrence but not much about ice thicknesses. Later statistics can be ordered in digital form from SMHI. In "Svensk Lots Del A" (Swedish Pilot Part A) there is also an authoritative and well written chapter on ice conditions. (Sjöfartverket, 1992).



Probability of ice occurrence, in percent  
Sannolikhet för isforekomst, i procent  
Jään esiintymistodennäköisyys, (%)

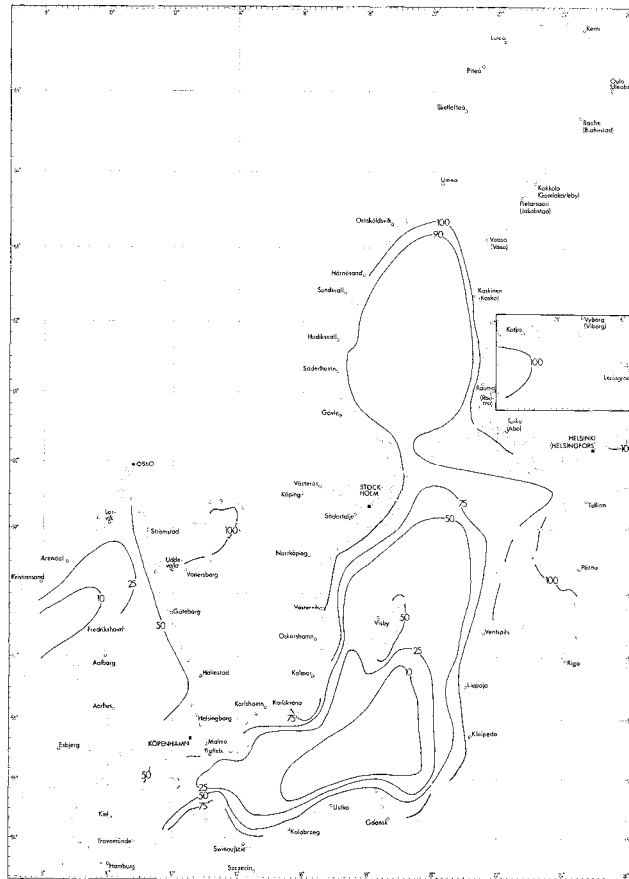


Figure 14. Idealized geometry of ice occurrence in percent (SMHI and Havsforkningsinstitutet, 1982. See also Svensk Lots, 1992)

When studying sea ice one must distinguish between fast ice and moving ice. Fast ice is even ice covers frozen to the coast and locked in archipelagos. It occurs mostly inshore from the 5-15 meters depth curve. This ice develops rather fast during the freezing period and will then be rather stationary during the rest of the ice season. Haapanen et al. (1997) points out that in the Eastern Gulf of Bothnia the land fast ice will stop moving when it has become thicker than around 30 cm, and although it later in the season may become 80 cm thick and sometimes up to 1.3 m it is assumed to lie still until it starts moving again in the spring. It is then deteriorated and the loads on structures may not be so large. According to Haapanen wind power plants should only be built in areas known to have land fast ice.

In contrast the moving ice is of dynamic nature. Wind and current make it move and deform. During severe storms it can move 20 – 30 km in a day. Ice

floes of several kilometres diameter are interrupted by leads and wakes. In the middle of the winter the open water will freeze fast and new ice will form. The deformation process causes ice bands of ice fragments, hummocked ice and ice ridges.

### 3.3 Occurrence of ice

According to the homepage of the Swedish Board of Shipping and Navigation (2008) the ice winters are classified into "mild", "normal" and "severe". The basic factor in the classification is the extent of the coverage of the sea surface by ice. Some other factors affecting shipping are also included, such as the length of the ice period, the navigation problems under the influence of wind and current etc. The Graph in Figure 15 shows the maximum extent of the ice in the Baltic, the Skagerrak and the Kattegat from 1900 to 2008. The graph confirms that the Baltic Proper is completely covered by ice every 30 years as an average. During the 20<sup>th</sup> century The Baltic was completely covered by ice four times, last the winter 1986/87. In Figure 16 the maximum ice coverage this first-year is shown.

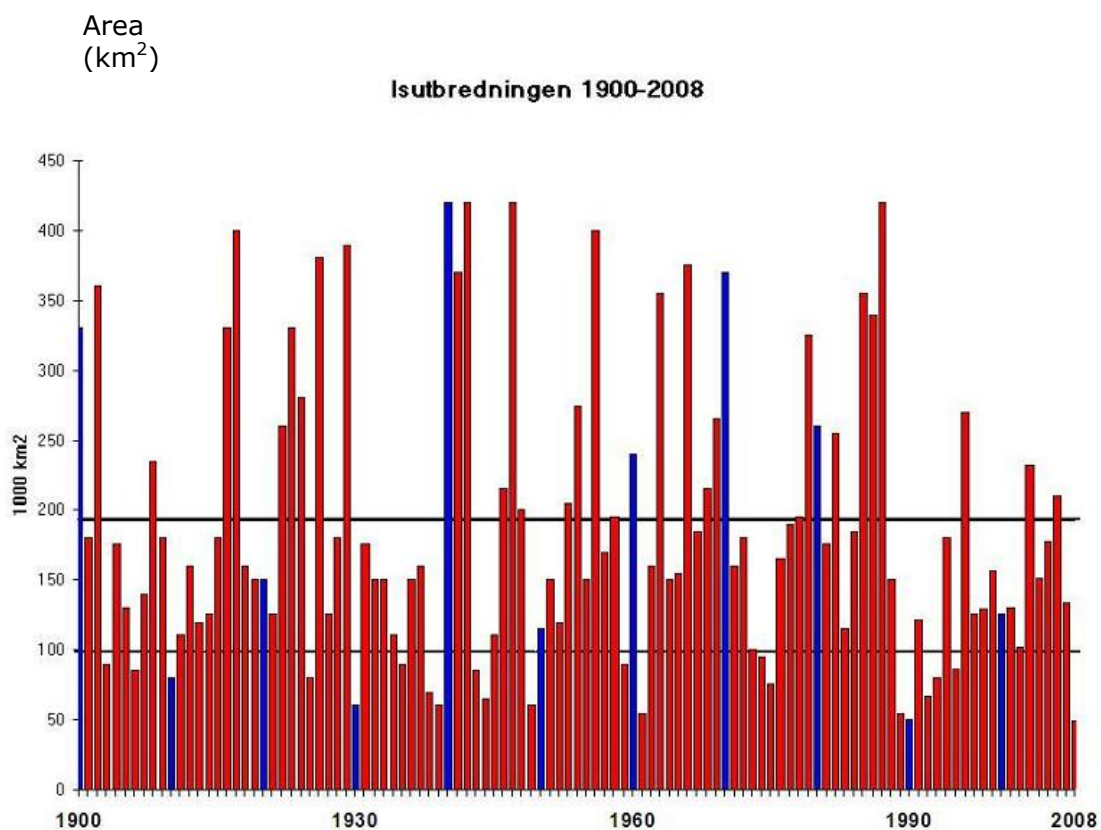


Figure 15. Graph over the ice coverage during the winters 1900-2008. The graph shows the maximum extent of the ice in the Baltic, Kattegat and Skagerrak over the years. The limit between "mild" and "normal" ice winter is drawn at 98 000 km<sup>2</sup>. The limit between "normal" and "severe" ice winter is drawn at 193 000 km<sup>2</sup>. (Courtesy the Swedish Board of Shipping and Navigation) <http://www.sjofartsverket.se>

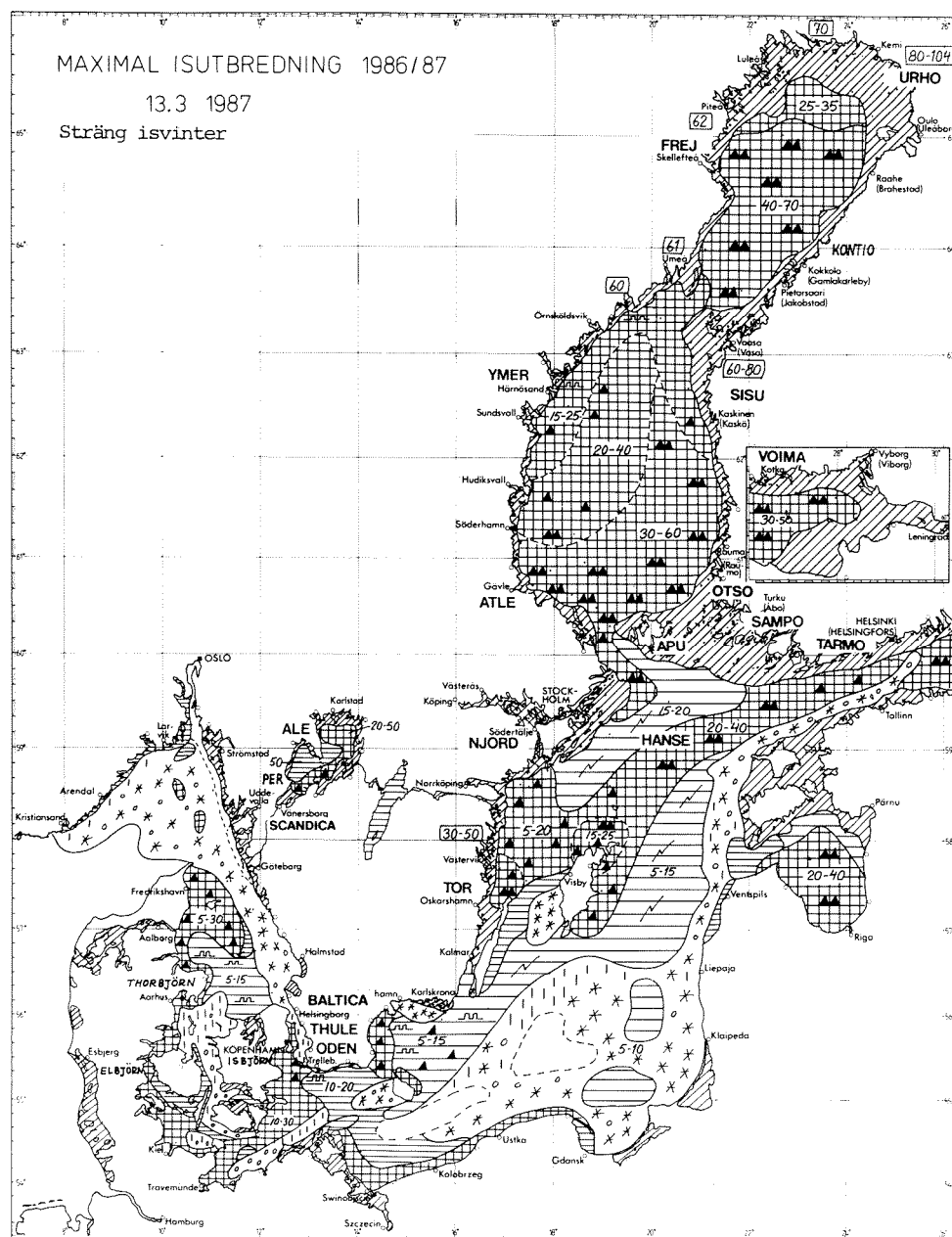


Figure 16. Maximum ice coverage the winter of 1986/87. The italic numerals give the thickness of floes or fast ice in cm. From *Sammanfattning av isvintern och isbrytarverksamheten 2000/2001*, Sjöfartsverket och SMHI (Lundquist & Gullne, 2001)

### 3.4 Ice thickness, ice period etc.

The Climatological Ice Atlas of SMHI and Havsforskningsinstitutet (1982) covers the 16 years between 1963 and 1979 and is based on observations the 1, 11 and 21 day every month. The observed areas are shown in Figure 17. They are all situated off the coast and one may have reason to assume (Thor, 2001) that the ice is thicker closer to land.

In Table 3 below some information is summarised from the climatological ice atlas. In the table the 16-year means of measured ice thickness at the date of maximum ice thickness during winters with ice and maximum observed ice thickness. Often it occurs late in the seasons and one can suspect that it is somewhat deteriorated by sun and warm air. As a comparison Table 4 with ice thicknesses from Svensk Lots are given (Sjöfartsverket, 1992). The maximum ice thicknesses in Table 3 corresponds approximately to severe winters landlocked areas in Table 4, while mean ice thicknesses corresponds to normal winters in landlocked areas.

**Ice thickness distribution areas**

Områden för vilka istjockleksfördelningen beräknats  
 Jään paksuuden jakautumia vastaavat alueet

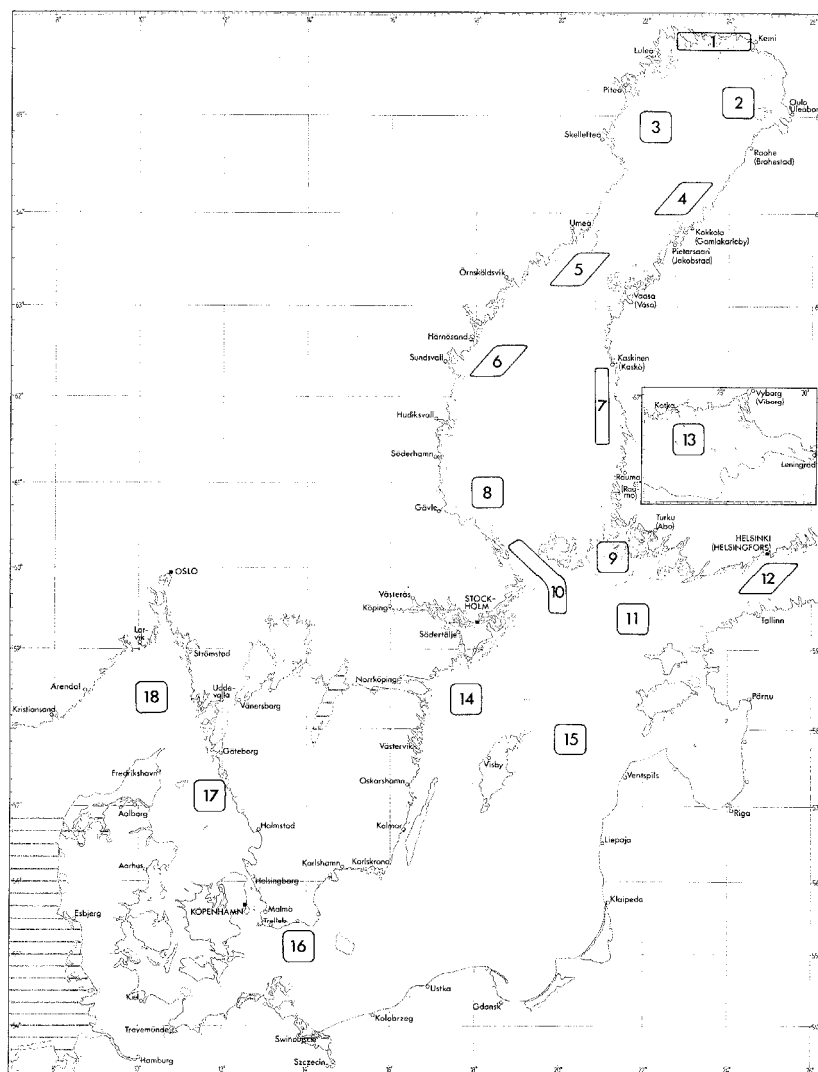


Figure 17. Ice thickness distribution areas. (SMHI and Havsforskningsinstitutet, 1982)

**Table 3.** Ice thickness and ice frequency at sea in some of the areas shown in Figure 17. (Own summary of the information from SMHI and Havsforskningsinstitutet, 1982)

Position	Area	Mean of measured ice-thickness for dates with maximum thickness different seasons. (cm)	Max. (cm)	No of years ice was present at the position of the total 16 years
<b>ENE Skellefteå</b>	3	52	> 73	16
<b>SSE Umeå</b>	5	28	57-72	16
<b>E Sundsvall</b>	6	30	31-42	12
<b>ENE Gävle</b>	8	28	> 73	12
<b>Between Åland and Sweden</b>	10	28	> 73	9
<b>E Bråviken</b>	14	27	43-56	6
<b>ENE Gotland</b>	15	16	21-30	3
<b>S Ystad</b>	16	11	21-30	3
<b>W Varberg</b>	17	11	21-30	4

**Table 4.** Mean ice thickness (cm) in severe, normal and mild winter.(Sjöfartsverket, 1992)

	Severe winters		Normal winters		Mild winters	
	Open sea	Landlocked	Open sea	Landlocked	Open sea	Landlocked
<b>Gulf of Bothnia</b>	70-80	80-90	40-60	60-70	20-40	40-50
<b>Northern Sea of Bothnia</b>	40-60	60-70	20-30	40	10-20	20
<b>Southern Sea of Bothnia</b>	30-50	40-60	20	20-30	ice free	10-15
<b>Northern Baltic</b>	30-50	30-50	10-20	20-30	ice free	ice free
<b>Southern Baltic</b>	10-30	20-30	ice free	10-20	ice free	ice free
<b>Skagerak &amp; Kattegatt</b>	10-20	20-30	ice free	10-15	ice free	ice free
<b>Vänern</b>	20-50	40-60	10-20	30-40	ice free	10-15
<b>Mälaren</b>	Approximately like the landlocked parts of Vänern					

## 4 Water levels

In Svensk Lots Part A (Sjöfartsverket, 1992) there is a short description of water levels and land rise, which is recommended for study. Here we only reproduce values with characteristic water levels around the coast of Sweden and very short notes of the underlying causes, see Table 5. Due to large local variations the information in the table below should be interpreted with caution. In the table one can see that water levels from 1 m above the mean level to 1 m below the mean level are not uncommon. This may be important for designing against overturning moment, for lifting forces and vertical position of ice breaking cones.

**Table 5.** Characteristic water levels. (Sjöfartsverket, 1992)  
 HHW = Highest high water = highest recorded water level  
 MHW = Mean high water = mean of all yearly maxima  
 MW = Mean water = mean of the whole series of observations  
 MLW = Mean low water = mean of all yearly minima  
 LLW = Lowest low water = lowest recorded water level

Characteristic water levels (cm)					
Station	HHW	MHW	MW	MLW	LLW
Kalix (1974-1983)	+ 181	+ 100	0	- 80	- 140
Furuögrund (1916-1981)	+ 153	+ 79	0	- 70	- 120
Ratan (1892-1983)	+ 137	+ 78	0	- 70	- 122
Draghällan/Spikarna (1898-1983)	+ 132	+ 68	0	- 56	- 90
Björn (nedlagd) (1892-1975)	+ 136	+ 73	0	- 52	- 81
Forsmark (1889-1983)	+ 160	+ 75	0	- 55	- 90
Stockholm (1889-1983)	+ 120	+ 61	0	- 46	- 68
Landsort (1887-1983)	+ 99	+ 54	0	- 44	- 68
Marviken	+ 101	+ 60	0	- 45	- 75
Visby	+ 88	+ 48	0	- 40	- 70
Ölands norra udde (1887-1983)	+ 135	+ 65	0	- 42	- 80
Kungsholmsfort (1887-1983)	+ 133	+ 74	0	- 65	- 94
Simrishamn	+ 160	+ 85	0	- 85	- 135
Ystad (1887-1983)	+ 167	+ 90	0	- 93	- 144
Klagshamn	+ 140	+ 86	0	- 74	- 102
Viken	+ 160	+ 90	0	- 70	- 120
Varberg (nedlagd) (1887-1980)	+ 145	+ 96	0	- 64	- 116
Ringhals	+ 145	+ 95	0	- 65	- 120
Göteborg/Torshamnen	+ 150	+ 100	0	- 70	- 120
Smögen (1911-1983)	+ 148	+ 94	0	- 69	- 112
Kungsvik	+ 150	+ 100	0	- 70	- 120

The water level variations are caused by air pressure, wind and tides. The air pressure acts directly by pressing down the water surface at the passage of high pressures and lifting the surface at low pressure. The correlation is not perfect as the low pressures pass too fast for the water surface to reach equilibrium. Air pressure differences causes the winds and when the wind blows persistently over an area of the sea it gives rise to wind set-up at downwind coasts and currents. Especially in the Southern Baltic, the Sound and the Danish waters the water levels depend on wind. The tide is very small in Swedish waters compared to other effects. North of Göteborg on the border to Norway the maximum tidal range is 40 cm. In the Baltic tides are of no practical importance.



## 5 Currents

In Svensk Lots Part A (Sjöfartsverket, 1992) there is a well written summary of the hydrography of Swedish waters. Hydrography concerns salinity, water balance, currents and waves. Here we will only refer information about currents and give a table of normally occurring currents.

The sea currents are driven by complicated action of various processes. In Swedish waters the most important processes are

- a) the wind,
- b) horizontal density differences,
- c) the slope of the water surface and
- d) air pressure variations.

During periods with ice covers the wind cannot act directly on the water but acts on the ice instead forcing the ice to drift.

**Table 6.** Current speed in knots (Sjöfartsverket, 1992)  
(1 knot = 0.5 m/s)

Area	a) Normal	b) Maximal
<b>Gulf of Bothnia</b>	0.2 – 0.3	1.2
<b>Kvarken</b>	0.4 – 0.5	2.0
<b>Sea of Bothnia</b>	0.2 – 0.3	1.2
<b>Sea of Åland</b>	0.4 – 0.5	2.0
<b>Baltic Sea</b>	0.2 – 0.3	1.2
<b>The Sound</b>	0.5 – 1.5	5.0
<b>Kattegat</b>	0.4 – 0.7	4.0
<b>Skagerrak</b>	0.5 – 1.0	4.0

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