DANSK VANDBYGNINGSTEKNISK SELSKAB

DANISH SOCIETY OF HYDRAULIC ENGINEERING

v/ Helge Gravesen, Carl Bro Anlæg a/s, Granskoven 8, 2600 Glostrup
Tlf. +45 43 48 63 28, Fax +45 43 63 65 67, email hlganl@carlbro.dk

14.05.2002
HlG

Seminar on
Ice loads to marine structures in the Baltic Sea area

Time: Monday 3 June 2002, 14.30 – 18.00 hrs
Language: English
Bygning 116, Auditorum 82, Building 116, DTU, 2800 Lyngby

The main contents in the programme allows that the members of our society will get the opportunity to get an updated overview on design for ice loads been presented by one of the leading ice experts professor Mauri Määttänen, Helsinki University of Technology

14.30-15.15	Present design practice in Denmark. Experiences from recent ice model tests with wind turbine foundations by Helge Gravesen, Carl Bro and DTU
15.15-16.00	Experiences from field measurements of ice loads to light towers, professor Mauri Määttänen, HUT
16.00-16.15	Coffee break
16.15-17.00	Interpretation of results from ice model tests, professor Mauri Määttänen, HUT
17.00-17.45	Status of ice load estimate for wind turbine foundations in Baltic Sea area, professor Mauri Määttänen, HUT
18.00-19.30	Dinner Building 101
19.30-21.00	DVS Generalforsamling

Best regards
Helge Gravesen
chairman of DVS

Selected articles on ice loads will be available to the attendants

RESEARCH MEMO FOR DESIGN BASIS FOR ICE FORCES AT THE MIDDELGRUNDEN

Non-authorised translation by Rambøll, January 2000

1. INTRODUCTION

On behalf of SEAS, Helge Gravesen of Carl Bro has initiated a research of ice forces concerning preparation of design basis for the project regarding wind turbines at the Middelgrunden.

The research group consists of:

Helge Gravesen, Carl Bro A/S
Carsten Sørensen, RAMBØLL
N.-E. Ottesen Hansen, LIC Engineering A/S.

The research memo has been prepared within a limited time based upon the research group's existing knowledge on the basis of a draft from Carl Bro at an initial meeting 26 August 1999. The memo contains both comments and recommendations. The memo is primarily based upon a draft prepared by N.-E. Ottesen Hansen. Supplements and corrections are incorporated by Helge Gravesen, partly on the basis of comments from Carsten Sørensen and partly on the basis of a union meeting held 15 September 1999 at the premises of Carl Bro with participation of the research group and the following:

Lars Jørgensen and Per Vølund, SEAS
Sten Frandsen and Morten Lybech Thøgersen, Risø
René Zorn, DHI
Jørgen Pinholt, Elsamprojekt
Simon Green and Claus Gormsen, Niras
Torben Arnbjerg Nielsen, RAMBØLL
Jeppe Blak Nielsen, Carl Bro.

To the largest possible extent general demands to wind turbines in inner Danish waters have been worded.

2. SYMBOLS

U_{is} velocity of the ice floes (m/s)
τ shear tension on ice floe from air or water (pa)
c_D drag coefficient on ice floe (= 0,004 and 0,006 for air and water, respectively) (-)
ρ density of water and air, respectively (kg/m^3)/auxiliary parameter for ice load evaluation
V water velocity 1 m below water surface or wind velocity at a height of 10 m (m/s)
c_u compressive strength of the ice (pa)
σ_f bending strength og the ice (pa)
t thickness of the ice (m)
K_{max} the total of the 24-hour mean of the frost period (<0°C)
ρ_{is} density of the ice (900 kg/m^3)
Y_{is} bulk density of the ice (8.84 kN/m^3)
γ_w bulk density of the water (=ρ_wg) (N/m^3)
g acceleration due to gravity (9.81 m/m^2)
E elasticity module of the ice (2 GPa)
μ friction coefficient (-)
F ice load (N)
k dimensionless factor on the ice load depending on the D/t ratio
D diameter of the structure at the attack height of the ice, respectively the diameter of the conic structure at the water level line (m)
D_T diameter at the top of the conic structure (m)
α the angle with horizontal on the conic structure (°)
f_n the eigenfrequency of the structure (s^{-1})
L length of fissures in the ice (m)
ν Poisson's ratio (-)
$\sigma_{c,lokal}$ local ice load (pa) on small area A_{lokal}
A_{lokal} small area on the structure exposed to local ice load (m^2)
f_{is} the frequency of the ice load (s^{-1})

3. DIMENSIONING FACTORS

In connection with the establishment of a wind farm a design basis will be prepared for ice loads.

The wind turbines are expected to have foundations with either vertical sides or being issued with a cone (directed upwards or downwards). Design basis shall comprise all these types. Ice load is not defined for structures dominated by fatigue loads.

In the design basis rules are to be specified for the following:

- The strength of the ice
- The friction between ice and turbine foundation
- The static load on the turbine foundation from ice floes
- The dynamic load on the turbine foundation from ice floes
- The load from icing up.

4. ICE FLOES

Ice loads on a structure result from the ice bumping against the structure or by the ice being pressed against the structure as a result of influence from current and wind. Thus there is an upper limit for the amount of ice loads, which may arise in the Øresund depending on forces of nature and the geography. The upper limit for the influences depend on:

a) The kinetic energy of the ice floes
b) Current and wind in the area
c) The size of the ice floes

The limit for the ice forces are evaluated by:

1. Maximum size of ice floe 2 × 2 km

2. Maximum current velocities and distributions of current velocities determinated for the area. It is assumed that the current line at the Drogden course is approx. twice the size of the current over the Middelgrunden. In connection with bid U_{is} = 1.0 m/s is estimated, since no correlation with wind is assumed

3. Wind and current load on ice floes are calculated on the basis of the formula:

   $\tau = 0.5\ c_D\ \rho\ V^2$
   where c_D = 0.004 and 0.006 for air and water, respectively
   ρ = density of water and air, respectively
   V = water velocity 1 m below the water surface or wind velocity at a height of 10 m, respectively.

The ice floes are assumed to have a shape so that the force initially is transferred to one wind turbine. As the ice floe is broken by a wind turbine, this will eventually come into contact with others.

As the basis for the above it may be noted that floes with a diameter of 500-2000 m and a thickness of up to 50 cm were observed in the waters opposite the Prøvestenen on a few days during the winter 1995/96. During the winter 1996/97 ice floes with a diameter of up to 20 m and a thickness of up to 5 cm were observed. SOK (1996 and 1997).

5. THE STRENGTH AND THE THICKNESS OF THE ICE

In the Øresundskonsortiet's Contract No. 2, Dredging & Reclamation, the following dimensioning ice thickness is stated in Design Requirement:

Recurrence period	5 years	10 years	50 years
t(m)	0.33	0.42	0.57

It is suggested to use the same basis for the Middelgrunden.

In the Elsam Project EFP-96 report about wind turbine foundations at sea the following strength parameters for the ice at a 50 years' ice situation at Rødsand are stated:

Compressive strength of the ice, σ_u	1.65 MpPa
Bending strength of the ice, σ_f	0.36 Mpa

It is suggested to use values for ice parameters approx. corresponding to those used by the Øresundskonsortiet for foundations for wind turbines situated at the Belts or further down towards the Baltic Sea, as these values are the newest for the area:

Return period	5 years	10 years	50 years	100 years	10,000 years
K_{max} (-°C 24 hours)	170	245	410	480	960
σ_u (Mpa)	1.0	1.5	1.9	2.0	2.6
σ_f (Mpa)	0.25	0.39	0.50	0.53	0.69
t (m)	0.33	0.42	0.57	0.63	0.91

where
σ_u = the thickness of the ice
σ_f = the bending strength of the ice
t = thickness of the ice = $0.032\ (0.9\ K_{max} - 50)^{0.5}$
K_{max} = the total of the 24 hours mean degree in the frost period (<0°C)

Other ice parameters:

Density of the ice, ρ_{is}	900 kg/m^3
Unit weight, Y_{is}	8.84 kN/m^3
Elasticity module, E	2 GPa
Friction coefficient between ice and ice is estimated to, μ	0.1

The 10,000 years' situation is included in case the ice load is treated as an accident load (without partial coefficients) and not as a natural load with characteristic parameters and appurtenant partial coefficients.

6. STATIC ICE LOADS

6.1 Structure with vertical sides

For determination of the ice load (crushing) on the wind turbines the application formulas stated in DS 410 for vertical structures are suggested. Structures are assumed to have vertical sides, the angle of which is less than 20°.

$$F = k\sigma_u Dt \qquad (6.2)$$

F : Horizontal ice force
k : Dimensionless factor depending on the D/t ratio
σ_u : The compressive strength of the ice
D : Diameter of the structure at the attack height of the ice
t : Thickness of the ice

$k = 1 + 3/(1 + D/t)$ for wind turbine foundations (with $D/t < 9$).

The above-mentioned formula originates from Tryde (1983).

6.2 Conic structures

For determination of the ice force (upbending ice, incl. share from crushing and ride-up) on the wind turbines the Ralston's formula for conic structures is used (API, Bul. 2N, 1995).

For an upward structure, see figure 1, the following formulas are used:

$$F_H = [A_1\sigma f t^2 + A_2\rho_w g\ t\ D^2 + A_3\rho_w g\ t\ (D^2-D_T^2)]A_4 \qquad (6.2)$$

$$F_v = B_1F_H\ 0\ B_2\rho_w g\ t\ (D^2-D_T^2) \qquad (6.3)$$

F_H : Horizontal force on the conic structure
F_V : Vertical force on the conic structure
$\gamma_w=\rho_w g$: Unit weight of water
μ : Friction coefficient between ice and structure
σ_f : Bending strength of the ice
t : Thickness of the ice
D : Diameter of the conic structure in the water level line
D_T : Diameter at the top of the conic structure
α : Angle with horizontal on the conic structure

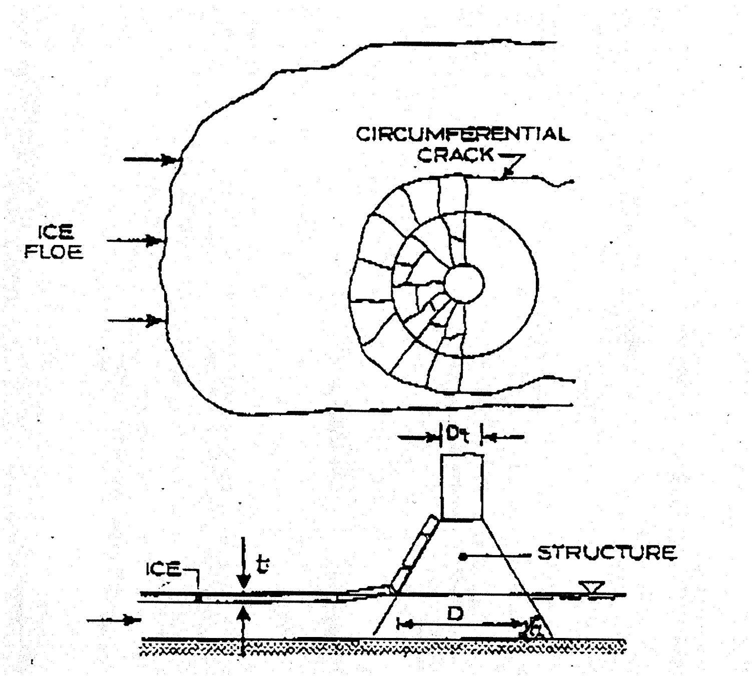


Figure 1. Ice floes pushed towards conic (upward) structure

The dimensionless coefficients, A_1, A_2, A_3, A_4, B_1, and B_2 are found from the figures in Enclosure 1. Often it will be more practical to use an auxiliary parameter ρ defined as a solution to the equation, cf. Thunbo Christensen (1988)

$$\rho - \ln(\rho) + 0.0830\ (2\rho + 1)\ (\rho - 1)^2\ (\gamma_w D^2/\sigma_f t) \qquad (6.4)$$

Thus, A_1 and A_2 may be found analytically as

$$A_1 = (1 + 2.711\rho\ \ln(\rho))/(3(\rho - 1)) \qquad (6.5)$$

$$A_2 = 0.075\ (\rho^2 + \rho - 2) \qquad (6.6)$$

The correlation between ρ and $(\gamma_w D^2/\sigma_f t)$ is also shown on a figure in Enclosure 1.

If the conic structure is very steep ($\alpha > 70°$) the formulas (6.3) and (6.4) may be applied.

For a <u>downward conic structure</u> the formulas (6.3) and (6.4) may be applied with the correction that A_2, A_3, and B_2, read for an upward conic structure, are all multiplied by 1/9.

An attack point for the ice force is assumed between water level and 0.8 × ice thickness below the water level for a vertical construction. For an upward cone an attack point is estimated at the water level. For a downward cone an attack point 0.8 × ice thickness below the water level is estimated.

7. DYNAMIC LOADS

7.1 Vertical walls

It is suggested to use the method from LIC Engineering (1997).

By ice drift both dynamic and static influences arise. The natural vibrations of the structure will influence the breaking frequency of the ice, especially for structures with vertical sides, so that it is tuned to the eigenfrequency (lock-in). This means that the structure is influenced to vibrations in its eigenfrequency forms.

A conservative method for analysis of these vibrations is as follows.

The criterion for tuning is (cf. Singh et al (1990)):

$$U_{is}/t\ f_n > 0.3 \qquad (7.1)$$

U_{is}	:	The velocity of the ice floe
t	:	The thickness of the ice
f_n	:	The eigenfrequency of the structure

The load is applied as a serrate profile, see figure 2, where the maximum value is the static, horizontal ice load. After crushing of the ice the load is reduced to 20% of the maximum load. The load is applied with a frequency corresponding to the eigenfrequency of the structure. All eigenfrequencies fulfilling the tuning criterion shall be gone over.

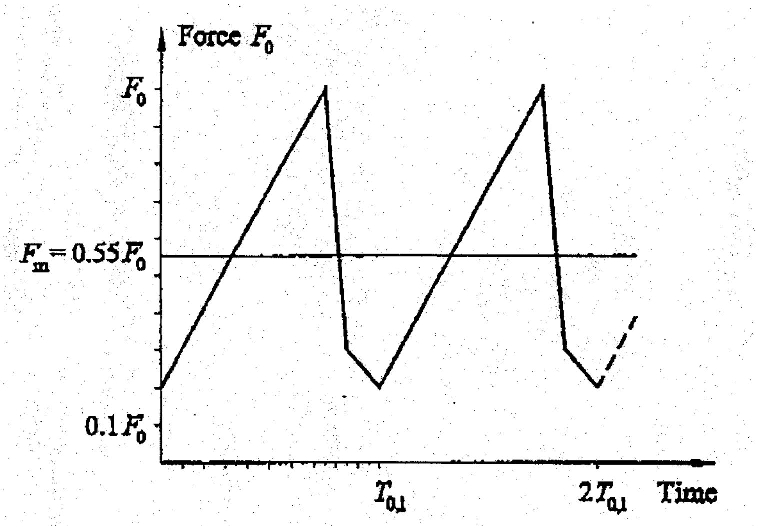


Figure 2. Serrate load profile

All subduing contributions in the structure are taken into account. Generalized contributions to be anticipated. Extra subduing as a consequence of the upfolding of the ice floes may be included if documentation therefore is available.

7.2 Conic structures

For conic structures the breaking frequency of the ice shall be calculated independent of the natural vibration of the structure. For all structures still applies that the frequency of the ice load must not be close to the eigenfrequency of the structure / that the eigenfrequency of the structure must be minimum 20% outside the load frequency area for breaking ice.

The frequency from the ice load, f_{is}, may be determined as

$$f_{is} = U_{is}/L \tag{7.2}$$

where
U_{is} is the velocity of the ice floe
L is the length of fissures in the ice

L is determined as

$$L = \rho\ D/2 \tag{7.3}$$

where
D is the diameter of the cone at the water surface
ρ is determined from Enclosure 1, where ρ is given as function of $(Y_w D^2/\sigma_f t)$
σ_f = the bending strength of the ice
t = the thickness of the ice

The force is applied from the same assumed simplified model as shown in Figure 2 despite the breaking mechanism differs totally for conic structures compared to vertical structures.

The question regarding what is the best estimation for the length of the fissures and whether this changes from static to dynamic load case has been the subject of quite of few discussions.

Thunbo Christensen (1989) states

$$L = (0.5\ E\ t^3/(12\gamma_w(1-v^2)))^{0.25} \tag{7.4}$$

This is also stated by Clough & Vinson (199x). In Tsinker (1991) Blanchet et al (1989) are quoted for the fact that the block typically is 4-5 times t.

Izumiyama et al (1991) quotes Tatinclaux (1986) for the following expression:

$$L/t = 0.26 – 0.54\ (\sigma_t/\gamma_w t)^{0.5} \tag{7.5}$$

The fact that the velocity of the ice floe is included in the calculation expression for the length of the fissures is missing.

Carsten Sørensen has used a previous model for wedge-shaped structures (Sørensen, 1978), in which the velocity of the ice floe is included, for comparison of Ralston's (static) calculation with a wedge of approximately the same geometry, see Enclosure 2. It appears from the example that the dynamic calculation gives fissure lengths of 40% of Ralston's static calculation corresponding to a frequency of ice bumps of approx. 0.13 Hz.

It must be concluded that relatively wide limit of frequencies be assumed in order to give a safe design.

8. LOAD ON THE FOUNDATION FROM FROZEN ICE

In case the ice freezes on to the *foundation* a change of the water level will cause a vertical force on the pile.

The adhesion strength by shear breach for sea ice may be estimated to $\tau_0 < 0.1$ Mpa for structures of wood, steel, or concrete. The values correspond to an upper limit for the load.

Adhesion will appear only during quiet periods with neap tide.

It should be investigated whether the surrounding ice is able to absorb the force arisen in bending.

Values may be found in the literature Nakazawa et al (1994), Terashime et al (1999), and Tsinker (1991).

9. FRICTION ICE/WIND TURBINE FOUNDATION

The decisive factor for the friction between ice and wind turbines is the marine fouling on the wind turbines. A heavy fouling consisting of acorn barnacles and mussels increases the friction while a soft fouling consisting of plants does not increase the water resistance of the structure.

There will be sparse fouling of acorn barnacles below the ripple zone (lowest water level plus wave amplitude). Regarding ice forces the roughness from acorn barnacles is thus not taken into account. This means that normal roughness for concrete or steel will be used in the area where the ice attacks.

The value for friction coefficients is presented in for instance Nakazava et al, 1994.

By investigation of bridge piers and some of our own structures the hard marine fouling – acorn barnacles and mussels – appear below the ripple zone at low water. Some individuals may occur at the border but they will not contribute to a rough surface.

Besides, the few individuals that have settled at the water line are expected to be scoured off during building-up of an ice cover.

The following friction coefficients are used by calculation of ice forces.

Static: steel/ice: 0.2
concrete/ice: 0.3

Dynamic: steel/ice: 0.1
steel/concrete: 0.2

Marine fouling may be ignored.

The friction coefficients may be reduced if special covers are used, for which friction coefficients are given. The covers shall be of a nature so that at least they can be kept intact during an entire hard winter.

10. LOCAL ICE PRESSURE

The expression recommended by Thunbo Christensen et al (1995) is used:

$\sigma_{c,lokal} = \sigma_c(5t^2/A_{lokal} + 1)^{0.5}$

assuming that $\sigma_{c,lokal} < 20$ Mpa

At the same time the maximum load must be exceeded.

11. RAISING OF ICE

For a situation with a recurrence period of 50 years dimensioning for raising of ice to a minimum of level +7 m shall be used. Partial coefficient with earth pressure at rest from a large-grained mass with specific gravity 6 kN/m^3 should not be included.

12. ICING UP OF TURBINE TOWER

Norwegian standards state the following two load cases for icing up corresponding to 56° N latitude:

– spray from waves ice thickness max. 80 mm
– rain/snow ice thickness max. 10 mm

It is estimated that icing up is not a critical load case.

13. LITERATURE

Tryde, P. (1983): "Ice technique, the physical and mechanical properties of the sea ice. Ice forces on structures" (in Danish). Notes from 1983.

Nakazava, N., T. Terashima and H. Saeki, 1994: Ice Material Surface Interaction in Ice Friction and Ice-Adfreeze Bonding. Proceedings of the Fourth (1994) International Offshore and Polar Engineering Conference, Osaka, Japan, April 10-15, 1994.

Terashina, T., T. Kawai, A. Furya, K. Narita, N. Usani and H. Saeki, 1999: Experimental Study on Adfreeze Bound Strength between Ice and Pile Structures, Proceedings of the Ninth (1999) International Offshore and Polar Engineering Conference, Brest, France, May 40 – June 4, 1999.

SOK's Ice and navigation conditions in the Danish waters in winter 1995/96 and 1996/97, respectively (in Danish).

API (1995): "Recommended practice for planning, designing, and constructing structures and pipelines for arctic conditions", Bul. 2N, ed. 1995.

LIC Engineering (1997): "Mono-Pile Foundation. Wind turbine foundations at sea" (in Danish), EFP-96, J.nr. 1363/96-0006. Final report from 1997.

Thunbo Christensen (1988): "Calculation of Optimal Dimensionless Coefficients for Ralston's Plastic Limit Analysis Approach to Determination of Sheet Ice Loads on Conical Structures". Progress Report 66, ISVA, DTU, 1988.

Thunbo Christensen (1989): "Determination of extreme ice forces. Notes from a short course at University of Salford, with corrections from 1995.

Thunbo Christensen, F., Bruun, P. and sackinger, W.M. (1995): "Ice loading and pileup against vertical and inclined sea walls". ASCE task committee on inclined and vertical wall structures.

Ralston, T.D. (1977): "Ice force design considerations for conical offshore structures". Proc. 4th int. conf. on Port and Ocean Engng. under Arctic Conditions (POAC-77, vol. 2, pp. 13-31, Luleå, Sweden.

Ralston, T.D. (1979): "Plastic limit analyses of sheet ice load on conical structures". Physics and mechanics of ice. IUTAM symposium, Copenhagen, 1979.

Singh, S.K., Timeo, G.W., Frederking, R.M.W., and Jordan, L.J. (1990): "Test of ice crushing on a flexible structure". 9th Int. Conf. on Offshore Mechanics and Arctic Engng. Vol IV, pp. 89-94.

Clough & Vinson (199x): "Ice forces on fixed conical structures".

Tsinker (1995): "Marine structures engineering: Specialized applications". Chapman & Hall.

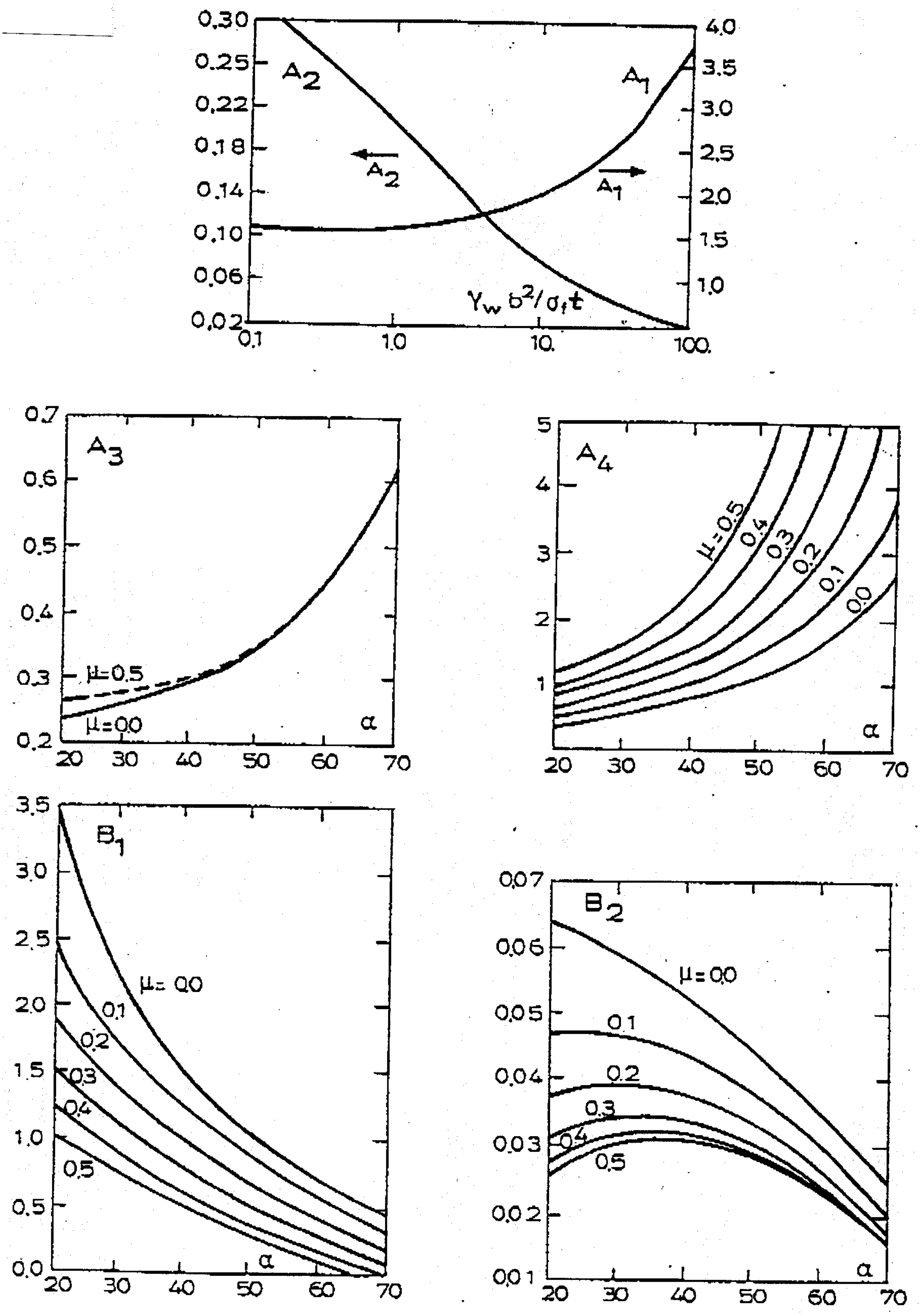
Blanchet, D., Churcher, A., Fitzpatrick, J., and Barda-Blanchet (1989): "An analysis of observed failure mechanics for laboratory first-year and multi-uear ice". In special report 89-5 by IAHR, edited by G.W. Timco.

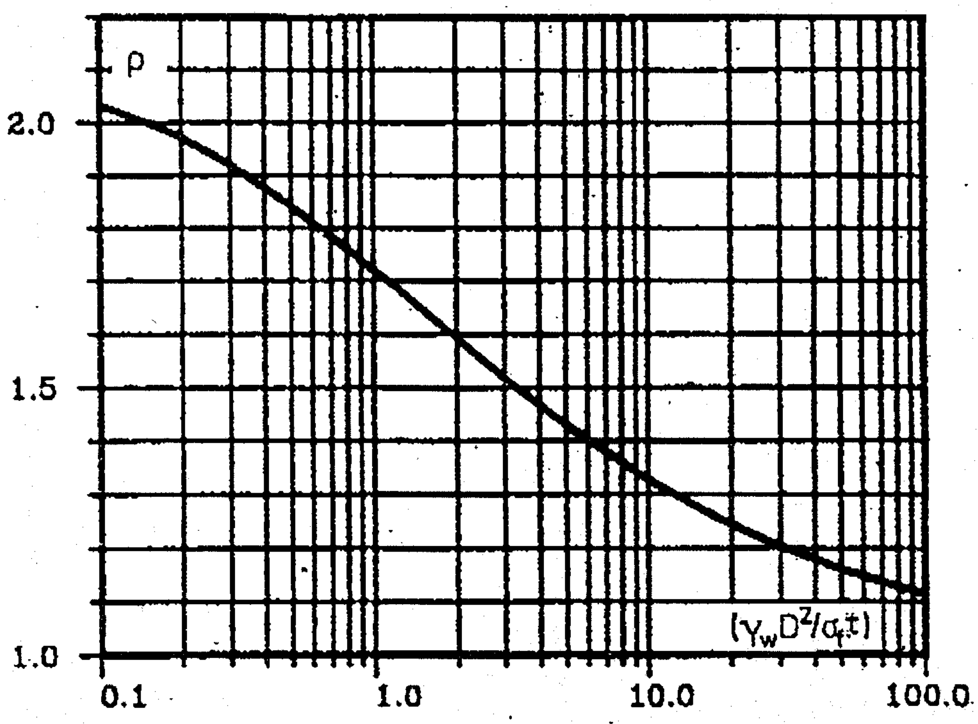
Izumiyama, K., Kitagawa, H., Koyama, K., and Uto, S. (1991): "On the interaction between a conical structure and ice sheet". Proc. 11th int. conf. on Ports and Ocean Engng. under Arctic Cond., St. John's, Canada.

Tatinclaux (1986): Ice floe distribution in the wake of a simple wedge". Proc. OMAE'86, vol. 4.

Sørensen, C. (1978): Interaction between floating ice sheets and sloping structures. Series Paper 19, ISVA. DTU.

ENCLOSURE 1


0.30
0.25
0.22
0.18
0.14
0.10
0.06
0.02
A2
A1
4.0
3.5
3.0
2.5
2.0
1.5
1.0
$\gamma_w b^2/\sigma_f t$
0.1
1.0
10.
100.
0.7
0.6
0.5
0.4
0.3
0.2
A3
μ=0.5
μ=0.0
α
20 30 40 50 60 70
5
4
3
2
1
A4
μ=0.5
0.4
0.3
0.2
0.1
0.0
α
20 30 40 50 60 70
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
B1
μ= 0.0
0.1
0.2
0.3
0.4
0.5
α
20 30 40 50 60 70
0.07
0.06
0.05
0.04
0.03
0.02
0.01
B2
μ=0.0
0.1
0.2
0.3
0.4
0.5
α
20 30 40 50 60 70


ρ
2.0
1.5
1.0
0.1
1.0
10.0
100.0
$(\gamma_w D^2/\sigma_f t)$

ENCLOSURE 2

Comparison of sundry formula expressions

A. CALCULATION ASSUMPTIONS

Structure with leaning front – Cone, cone angle = 45°, diameter = 8 m, tower diameter = 2 m.

Ice parameters: r_o = 1250 kN, r_f = 500 kN, h = 0.64m, velocity of floe u = 1 m/sec, friction factor = 0.2, crushing contact factor k = 0.7.

B. CALCULATION RESULTS

Load case	Horizontal ice movement				Vertical ice movement
Component	horizontal ice load (kN)	vertical ice load (kN)	ice breach, length (m)	ice bump frequency (Hz)	vertical ice load (kN)
method					
ref. 1	750	-680	7.9	0.13	
ref. 2	640	-520	3.1	0.32	

Paper POAC No. 135

ENGINEERING PRACTICE FOR ICE FORCE DESIGN IN DENMARK

N.-E. Ottesen Hansen[1], Director, Ph.D. and Helge Gravesen, Chief Consultant[2]
1) LICengineering A/S, Copenhagen, Denmark
2) Carl Bro A/S, Copenhagen, Denmark

ABSTRACT

Ice loading on structures in the inner Danish seas and in the Danish straits is decisive loads for the structures such as lighthouses or wind turbines. To reduce the loading ice-cones are used. This, however, increases wave loading. Optimum shapes can be reached by analysis. Both loads are dynamic with a considerable dynamic amplification. The dynamic amplification is decisive for the response. For the constricted Danish waters it is shown that there is an upper limit for ice forces due to limitations in fetch. Examples of design and trends are presented.

INTRODUCTION

The Kingdom of Denmark comprises the areas of Denmark proper, the Faroe Islands, and Greenland. The three areas are very different when coming to ice forces on civil structures. Denmark proper typically has its straits and seas ice covered every 4 years on a long term average basis. Design ice thicknesses vary between 0.6m-0.9m, whereas Greenland experiences both polar ice and very large icebergs. The Faroe Islands situated in the Mid Atlantic has deep water and no ice cover in winter.

There is no uniform Code of Practice for Ice loads for the country. For Denmark proper 2 (two) pages are devoted to the subject in the Danish Standard 410 “Code of Practice for Loads for the Design of Structures”, 1998 edition.

This part of the Code of Practice is old and primitive. It has not been revised for many years and only used for small and simple structures. For important structures where the ice-loads may be decisive such as bridges, lighthouses or offshore wind turbines special design bases for ice loads have been prepared. For example a uniform design basis for the offshore wind farms are under preparation at the moment because there is a considerable wave loading too in the Danish seas which means that optimising for one type of loading may increase for other type of loading. This development has resulted in a demand for more accurate ice forcing predictions.

The present paper will describe the solution and developments peculiar to the Danish Waters. Further, the Greenland waters will be briefly considered.

THE WATERS OF DENMARK PROPER

Denmark Proper is the bottleneck between the Baltic Sea and the North Sea. In the south it is dominated by the Danish Straits and in the north by the inner Danish sea - the Kattegat. The straits and the seas are rather shallow in large areas (few metres) whereas the deeper parts in the more open areas are 20m-30m. There are narrow channels or areas with up to 60m water depth.

The water exchange is mainly driven by the passing low pressure systems. They have a typical period of one week. This leads to current velocities in the order 0.5 m/s – 1 m/s. In some narrows these currents are even higher. Tidal range is small and only accounts for a small part of the water exchange. This produces a typical estuarine system with saltwater wedges and density front with occasional upwelling. This means that the salinity varies between salinity of the Western Baltic of 8-9 ppt and that of the North Sea of 30 ppt.

The North Sea never freezes due to the depth, higher salinity and higher temperature, neither do the Central and Western Baltic freeze in even the coldest winters in spite of the brackish water. The reason is the relatively large water depth. A cold winter is not sufficient to cool down the water column such that ice can be formed.

On the other hand, the inner Danish Seas and the Danish Straits freeze in cold winters due to the shallow water even though the salinity areas may be rather high. The freezing begins in the most shallow and most brackish of the bights and inlets. From there it spreads to the more open areas. It is simply a matter of cooling down the water column.

Due to the exchange flows back and forth the ice is broken up into floes. The largest observed floes have been 2 km by 2 km. It is the kinetic energy of these floes which decides the development of the response of the ice loading.

THE DANISH CODE OF PRACTICE

The Danish Standard DS 410 “Code of Practice for Loads for the Design of Structures 1998 ed. comprises two pages of physical parameters etc. for the Danish Sea Ice Forces. These two pages were drafted in 1970 and have been quoted in all later editions. The ice parameters are due to Tryde, 1983.

The Danish Code of Practice published by the Danish Engineering Association (1982), prescribes ice loads in a relatively simple way. In short, horizontal loads from pack ice are found from:

(1) $F = k\sigma_u dh$

in which σ_u is the crushing strength, h the thickness of the ice, d the width of the structure, and k is an aspect ratio factor. The aspect ratio factor is given as:

$$(2) \quad \begin{array}{lll} k = 1+3/(1+d/h) & \text{for} & d/h \leq 9 \\ k = 1.75\text{-}0.05\, d/h & \text{for } 9 \leq d/h \leq 15 & \\ k = 1.00 & \text{for } 15 \leq d/h & \end{array}$$

The recommended values of strength and thickness are 1.25 MPa and 0.6 metres respectively, corresponding to an exceedance probability of 0.02 per year. The resulting load is considered a live load.

This simple standard has several shortcomings, the lack of a size effects being the most conspicuous.

Another shortcoming it is well known from lighthouse that the ice loads are dynamical and have a tendency to lock in with the eigenfrequency of the structure.

A final shortcoming was the use of the ice force as normal live load with a probability of occurrence of 0.02 per year. Investigating the extreme load distributions corresponding to longer return periods and adjusting the safety factors accordingly it turned out that applying the ice loads in the Accidental Limit State i.e. with probabilities of the order 10^{-4} per year actually decides the design. Hence, a better extreme statistics for ice forces was needed..

THE BRIDGES CROSSING THE STRAITS

The shortcomings in the Danish Code of Practice described above were recognised in connection with the construction of the strait crossings the late 1980'ties and 90'ties.

The following improvements were made in the procedure for determining ice forces:

- A systematic long term statistic for the ice strength was made by including the more than 100 yrs record for the accumulated freezing degree days (Celcius).

- Systematic model testing with ice loads on bridge piers.

- Model testing with ice loads on elastic mounted bridge piers to determine lock-in between ice break-up and response of bridge.

For the ice strength this resulted in the values of Table 1.

Table 1 Design values for ice loads, K, is the accumulated freezing degree days, σ_u the crushing strength of the ice, σ_f the flexural strength and t the ice thickness, Gravesen 2001.

Return Period	5 yr.	10 yr.	50 yr.	100 yr.	10.000 yr.
K_{max} ($-^{0}C$ day)	170	245	410	480	960
σ_u (Mpa)	1.0	1.5	1.9	2.0	2.6
σ_f (Mpa)	0.25	0.39	0.50	0.53	0.69
t (m)	0.33	0.42	0.57	0.63	0.91

The above table is the latest revision compared with earlier published values for instance, Christensen et al, 1989. The value of the ice breaking strength reflects the spread salinity and temperature conditions in the Danish waters.

The ice loading on the bridge piers were determined by model tests comprising both rigid and elastically mounted models. They gave information on the steady state loading, dynamic loading and the response to dynamic loading including the lock-in phenomena. Results of these tests are published in for instance Christensen et al 1989 and Christensen and Klinting 1982.

In general the decisive design force level on the bridge piers were not decided by the ice but by the impact loads from stray ships. Only bridge piers far away from the navigations routes were decided by ice loads.

Due to this no efforts were made to reduce the ice forces on the piers. The bridge piers were constructed with vertical sides.

It was found that the maximum forces were caused by buckling of the ice due to the vertical sides and to the large width of the bridge piers (actually the bridge pier comprised two wall shaped columns). The force had a distinct steady state component and a distinct dynamic component. The latter could lock in to the eigenfrequency of the foundation resulting in a growing response for each cycle.

The highest forces would come from drifting ice floes, which due to the limitations in current velocity did not have an infinite energy. Due to the many bridge piers an ice flow would be quickly stopped when encountering the bridge. Hence, there is a limit to the dynamic growth of the response. This was an important discovery. The principle is described later in the paper.

LIGHT TOWERS

To mark the international shipping routes through the Danish Straits long rows of light towers are used. Some ships unfortunately have a tendency to ram these light towers from time to time. The old lighthouse design has a concrete caisson foundation. Ships hitting this caisson will be damaged. Some ships have actually sunk in recent years because their hull was ripped open when encountering these concrete caissons. The risk for oil spill or chemical spill in the narrow seas is thus large due to this type of structure.

This has led to another design where the foundation of the lighthouse comprises a shear link which would yield during a ship impact without rupturing the hull of the ship, whereas it should sustain normal ice loading without yielding. This has put an increased demand on the accuracy of predicting ice forces and especially on reducing them. An example of such a structure is shown in Fig. 1. It shows the light tower W-26 in the Great Belt in 18 m of water depth. The ice cone reduces the ice loads but increases the wave loads instead. The light tower under water is a truss structure.

Fig. 1 Light tower W-26 with ice-cone. Access ladder expected to be sheared off in heavy ice.

The ice cone can be used with advantage because the tidal ranges in the inner Danish Seas are very small. Large water level differences will come with storms. But they are not associated with thick ice cover. This means that the force always can be expected to act on the cone. The ice loading has been determined by Ralstons formula, API 1995. The loading, however, has been divided in a steady state component and a dynamic component, Fig. 4. The dynamic actually decides the design.

OFFSHORE WIND TURBINES

Denmark has a very ambitious plan for the establishing of offshore wind farms in order to increase renewable power production. The plan is to install 160 MW per year the next 25 years such that the total power generation by this source will reach 4000 MW in year 2030, Olsen, 2001.

Two offshore wind farms already exist for small wind turbines in the 0.5 MW class for each turbine. In these wind farms the ice loading is dominant. It is reduced by application of ice-cones, Fig. 2.

Fig. 2 Offshore wind farm with 0.5 MW wind turbine furnished with ice cones. Tunoe Knob Denmark.

This technology has been developed steadily such that the typical offshore wind turbine now has grown to 2 MW. This is a far larger wind turbine than the 0.5 MW. The increased size has resulted in the use of the inverse ice cones, Fig. 3.

The ice loading is reduced with the inverse cones but due to the open seas the wave loading is increased compared with a turbine without cone.

Since both these forces lead to dynamical amplifications of the foundation response it is of interest to optimise the cone such that the response becomes as small as possible in order to obtain the most economical structure.

A committee established by the Danish Energy Agency (under the Danish Ministry of Environment and Energy) has issued a draft for a Recommendation Approval for Offshore Wind Turbines, 4. draft January 2001, where ice loading receives a similar detailing as the API RP 2N

Fig. 3 Offshore wind farm with 2.0 MW wind turbines with inverse ice cones. Middelgrunden, Copenhagen, Denmark.

of 1995, but with the following detail special for the Danish application:

- Simultaneously wind, ice and current situations are defined.
- The response of the foundations are dynamical in nature. Forcing and damping ratios are defined.
- The response of the foundation is limited by current velocity and ice flow size.

Together with definitions on ice flow break-up length and current velocities the response of the foundation can be found.

Due to the limited fetch and the limited current velocities the Recommended Practice for Wind Turbine defines an upper limit for loading on structures by the following statement:

Ice forces on a structure occur by ice floes ramming into the structure or by ice being pressed up against the structure due to the action of current and wind. Hence, there is an upper limit for how large ice forces can be generated in a strait or inner sea. The upper limit for the forces depends on

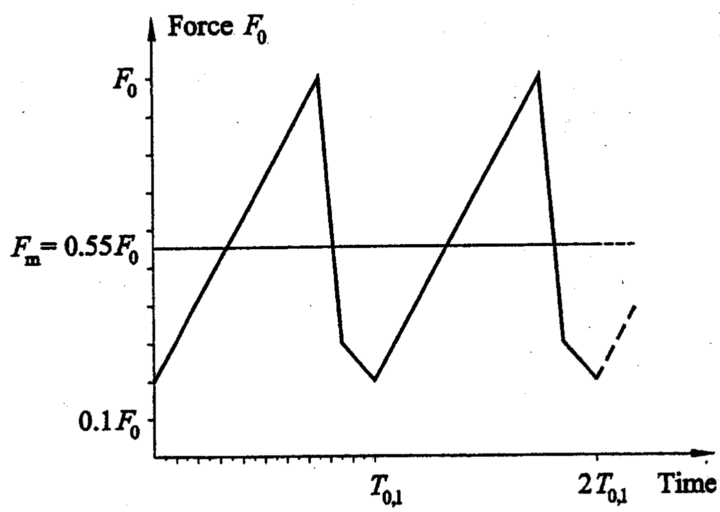


Fig. 4 Specified loading for a structure with ice cone.

1. The greatest ice floe is 2 km x 2 km.
2. The maximum currents and maximum current distributions for the area.

For the Danish seas the current and wind shall be assumed uncorrelated. The ice floes shall be assumed having a form such that the forces initially are transferred to one wind turbine (or one bridge pier). During the impact the ice flow will come into contact with more and more foundations, eventually bringing the ice flow to a stop.

Wind and current forces on ice floes are calculated by the formula

(3) $$\tau = \frac{1}{2} C_D \rho V^2$$

in which
C_D = 0,004 and 0,006 for wind and current respectively.
ρ = mass of air and water, respectively
V = Velocity of water 1 m underneath the water surface or wind velocity in a height of 10 m.

GREENLAND

The ice loads critical to offshore structures in the waters of Greenland are due to impact from icebergs, pack ice and permanent ice cover.

Icebergs are produced from glaciers along the coasts of Greenland. The large icebergs are produced along the entire length of the east coast and in some locations along the west.

West Greenland is the habited part of the island. The ice cover here consists of first year ice. It normally reaches its maximum extent at the end of March, where the ice covers nearly all Davis Strait and the Baffin Bay. In late summer both areas are ice free. Typical iceberg sizes and ice-thickness are presented in Table 2.

Table 2 Iceberg size West Coast of Greenland. Probability for collision per months.

Location of W. Coast	Water depth m	Max. Iceberg mill. tonnes	Probability of collision pr. month	Max. ice cover m
65^0	90	3	0.05	0.5
67^0	200	15	0.06	1.0

Due to the extreme conditions a Code of Practice for Offshore Structures has not yet been established for the Greenland area.

RESEARCH REQUIREMENTS

Research concerning ice loading has been virtually dormant since the construction of the Great Strait Crossings. The establishing of the large scale wind farms, however, has triggered plans for new research. The following research priorities have been established.

- Lock-in phenomena between ice and foundation with and without ice cones.
- Formation of ice ridges in offshore wind farms with many wind turbines due to back and forward drifting of the ice.

- Forces due to the formation of one year ice ridges.
- Effect of shallow water.

REFERENCES

American Petroleum Institute, 1995: Recommended Practice for Planning, Designing and Constructing Structures and Pipelines for Arctic Conditions. API Recommend Practice 2N, Second Edition, December 1, 1995.

Christensen, F.T., N.-E. Ottesen Hansen, Karl-Ulrich Evers, Søren Spangenberg and Leif J. Vincentsen, 1989: Design of the Great Belt Western Bridge for Ice Forces. Proceeding of the 8th (1989) International Conference on Offshore Mechanics and Arctic Engineering, The Hague, The Netherlands, March 19-33, 1989.

Christensen, F.T. N.-E. Ottesen Hansen, S. Spangenberg, and L.J. Vincentsen, 1989: Dynamic Iceloads on the Great Belt Western Bridge. POAC, International Conference on Port and Ocean Engineering under Arctic Conditions.

Christensen, F.T. and P. Klinting, 1992: Ice Loads on Vertical Bridge Pier at two different Model Scales. Journal of Cold Regions Engineering, Vol. 6, No. 3. September 1982.

Danish Engineering Association, 1982: Rules for Safety of Structures (in Danish). Danish Standard DS 409, 1. ed. June 1982. Publication NP-157-N from the "Normstyrelse". Teknisk Forlag.

Danish Engineering Association, 1983: Code of Practice for Pile-Supported Offshore Steel Structures, Danish Standard DS 449. Publication NP-166-T from the "Normstyrelse" English edition Nov. 1984.

Danish Energy Agency Working Group, 2001: Recommendation for Approval of Offshore Wind Turbines. 4th edition. Danish Energy Agency, January 2001.

Danish Standard, 1998: Load on Structures. 4th Ed. Published by Danish Standard.

Gravesen, H., 2001: Decisive Loads on Rigid Offshore Wind Turbine Foundations. Danish Society of Hydraulic Engineering. Seminar on Offshore Wind Turbine Foundations, 17 January 2001, Technical University of Denmark.

Olsen, F, 2001: Wind Power in Denmark. Danish Society of Hydraulic Engineering. Symposium on Offshore Wind Turbine Foundation, 17 January 2001, Technical University of Denmark.

Tryde, P. 1983: Ice Engineering. The Physical and Mechanical Properties of Sea Ice. Ice Forces on Structures. Lecture Notes 1983, ISVA, Technical University of Denmark.

Ice in Surface Waters, Shen (ed.) © 1999 Balkema, Rotterdam, ISBN 90 5410 971 8

Numerical model for ice-induced vibration load lock-in and synchronization

M. P. Määttänen
Helsinki University of Technology, Espoo, Finland

ABSTRACT: Ice loads at different locations in a wide structure or in different legs in a multilegged structure develop independently. A numerical model should be able to predict such synchronization and lock-in phenomena as observed in full scale. An earlier numerical integration program for calculating ice-induced self-excited vibration response is extended to accept 3-dimensional geometry and multi-point ice loading. Numerical integration is used for limit cycle response analysis. The results indicate that the developed model is capable to predict both saw tooth like ice force histories, as well as synchronized resonant type frequency lock-in to the lowest natural modes of the structure, depending on ice velocities. The change of ice thickness or velocity may change the lock-in to a different mode. Multilegged or wide structures with independent zones exhibit more likely lock-in vibrations with symmetric than asymmetric natural modes. At too low or high ice velocity, no lock-in with natural modes will take place.

1 INTRODUCTION

Ice failure by crushing against a vertical offshore structure induces non-stationary loads. Even in the case of a narrow single pile structure there are always random variations in the total ice load. In a multilegged structure or a wide structure ice failure is occurring non-simultaneously at different locations. The most severe loading case is while ice failure synchronizes at all locations, and especially if the failure repeats at the period of a natural vibration mode.

Ice velocity is the governing parameter in the character of ice load history. At very low ice velocities, e.g. thermal expansion, ice behavior is ductile and ice-structure interaction resembles viscous flow. Ice load is pseudo stationary. With increasing velocity interaction time becomes too short for ice stresses to be relaxed and bounded by creep. Ice load and stresses, as well as structural deflection build up until ice compressive strength level is reached. As ice fails the load level drops suddenly, and the deflection of the structure springs back. Often the spring-back stroke exceeds the zero state causing a gap between the ice edge and the structure. Thereafter the advancing ice edge makes contact to the structure and a new load cycle starts. This produces a saw tooth like ice force or displacement history. At higher velocities the response history will gradually change, displacement history approaches a sinusoidal one. The frequency of ice failures depends on the ice velocity. A resonant state occurs if the frequency co-insides the frequency of a natural mode of the structure. At still higher ice velocities conditions for the resonance are lost. Ice failure turns into totally brittle and ice load fluctuations random.

Scale model tests (Määttänen 1983) have indicated that a natural mode frequency controls ice failure frequencies at a wide velocity range. Hence a lock-in to the natural mode frequency takes place. Then in a multilegged or wide structure independent ice failures at different locations are likely to synchronize. This is due to vibration velocity of a natural mode is superimposing to the ice velocity which promotes coherent ice failures at different locations.

A numerical model to simulate dynamic ice-structure interaction and ice-induced vibrations should be able to predict different velocity dependent ice failure patterns, frequency lock-in, and synchronization. Both Sodhi (1988) and Määttänen (1988) give a review of different ice-structure interaction models. Thereafter further models have emerged that also observe multi-point ice load excitation (Kärnä 1992 and 1997, Kajaste-Rudnitski 1996). However, no results have been presented on predicted structural response or lock-in synchronization.

In this paper a self-excited ice induced vibration model is presented. It is based on ice crushing strength dependence on loading rate. The model is an extension of a single point excitation model that has been used to predict ice-induced vibrations in Finnish steel lighthouses (Määttänen 1978). The extension was started after encouraging results of an independent comparison (Muhonen 1996) on the performance of some ice-structure interaction numerical simulation models (Määttänen 1978, Riska et al. 1993, Sodhi 1994). The theory behind the model is briefly described. The model is applied both to a multi-legged and a wide structure to demonstrate the simulation capabilities for varying ice thickness and velocity cases.

2 NUMERICAL MODEL

The structure is discretized by using Finite Element Method. Ice interaction is observed as a nodal load in those nodes that are under ice action. Ice load is simply ice crushing strength times the area that is controlled by the node in question. The crushing strength is dependent both on contact normal velocity and contact area.

$$\sigma_c = \sigma_c(v - \dot{u})\sqrt{\frac{A_0}{A}} \qquad (1)$$

Ice crushing strength against a wide structure is reduced according to the area dependence as defined by Sanderson (1988). Relative velocity at a contact node is ice velocity v minus nodal displacement velocity $\dot{u}$. Crushing strength dependence on relative velocity is based on the stress rate as defined by Blenkarn (1970)

$$\dot{\sigma} = (v - \dot{u})\frac{8\sigma_0}{\pi d} \qquad (2)$$

Here σ_0 is reference strength, now 2 MPa is used, and d the diameter of the structure. Equation 2 was originally intended for narrow structures and is not directly applicable for wide structures. However, if non-simultaneous ice failure at different zones along the width of the structure is assumed a realistic value for d can be used. There is no good advice what is the width of an independent zone. E.g. a value of one or two times the ice thickness can be chosen. The effect of width d in the denominator is to scale velocity range. Thus ice velocity dependence comparisons can be made regardless of the correct width. In the following applications the real leg diameter is used for the multilegged structure and d=1 m for the wide structure.

Based on the measurement data by Peyton as presented by Blenkarn (1970), and combining Equation 1, ice crushing strength vs. stress rate, was approximated by using a fourth degree polynomial,

$$\sigma_c = (2.00 + 7.80\dot{\sigma} - 18.57\dot{\sigma}^2 + 13.00\dot{\sigma}^3 - 2.91\dot{\sigma}^4)\sqrt{\frac{A_0}{A}}\ MPa \qquad (3)$$

in which $\dot{\sigma}$ is given in MPa/s and the reference area A_0=1 m^2. The polynomial part covers ice failure mode transition from ductile to brittle. At higher strain rates ice failure is brittle and strength is assumed to be constant, (Fig. 1). In reality there are always random variations in ice strength, now especially at the decreasing part. Hence the whole curve should be interpreted as a deterministic average presentation on ice crushing strength.

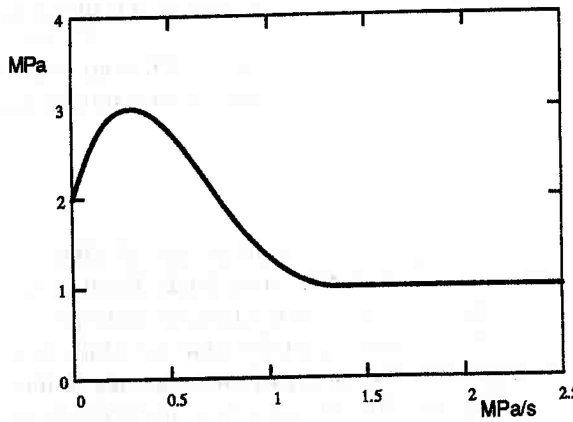


Figure 1. Ice crushing strength vs. stress rate.

Implementing ice crushing strength by Equation 2 and 3 into nodal loads in the dynamic equations of motion for the whole structure yields

$$[k]\{u\} + [d]\{\dot{u}\} + [m]\{\ddot{u}\} = \{F(v,\{\dot{u}\})\} = \{F_0\} + [\phi]\{\dot{u}\} \qquad (4)$$

where [k], [d], and [m] are the stiffness, damping and mass matrices of the structure, $\{u\}$, $\{\dot{u}\}$, and $\{\ddot{u}\}$ are the nodal displacement, velocity and acceleration vectors. $\{F_0\}$ is the constant part of the load vector representing ice strength at the nominal stress rate corresponding to ice velocity v. Matrix $[\phi]$ has nonzero terms only at its diagonal corresponding to ice action nodes and resulting from the structural response velocity according to Equation 2 and 3. Each ice action node has its own ice load, which is independent from others. The coupling plays role only through the combined effect of all nodal loads to displacement response.

In initial state the structure is at rest with no vibrations. As both $\{\dot{u}\}=\{\ddot{u}\}=\{0\}$ only static displacements are caused by the loads $\{F_0\}$. In order to have vibrations the ice-structure system has to be dynamically unstable. Mathematically the autonomous equation system 4 has then roots that have positive real part and make deviations from the equilibrium to grow with time. This means that if there are any disturbances they tend to grow dynamically and develop into vibrations or into an aperiodic divergence. Considering the shape of the controlling curve, (Fig. 1), it is evident that disturbances will not grow without bounds but the vibrations have to develop into stable limit cycles. The reason is that energy is being pumped into the structure only at the decreasing part of Figure 1. Then with increasing vibration amplitudes increasing structural damping will eventually dissipate all the energy that is fed into system during each vibration cycle.

The Equation 4 is highly nonlinear both due to the shape of ice crushing strength curve and the possibility of contact loss between the ice edge and the structure. The response history of the structure can be solved by numerical integration. In order to get stable limit cycles as soon as possible, it is advantageous to use the static displacement of the average ice load as an initial condition. Another way to reduce CPU-time is to use principal mode presentation. Usually only a small number of the lowest modes are needed to model global structural vibration state. If ice velocity is such that the initial state will not fall into the decreasing part of the crushing strength curve, a sufficiently large disturbance is needed to make the structure to vibrate, and allowing conditions for limit cycles either to develop or all vibrations to decay.

The limit cycle ice-induced vibration program for steel lighthouse design from 70's (Määttänen 1978) was extended from one-dimensional beam elements for general 3-D structures. The structure can be modeled by any FEM code. The needed output is natural modes and frequencies for the limit cycle program input. Number of ice action nodes can be freely chosen, and nodal ice loads can have components to all coordinate directions. Each nodal load is calculated independently according to Equation 4.

3 APPLICATION STRUCTURES

3.1 Three-legged jacket platform.

Figure 2 presents the FEM-model of a generic three-legged jacket platform that is intended to operate in moderate first-year ice conditions. Water depth is 19 m and jacket legs go deep into sea bottom. Soil support is simply modeled by pinning the legs at -24 m depth. The diameter of jacket legs at waterline is 1.2 m. The structure is symmetric, each cross section forms an equilateral triangle. At the waterline the distance of legs is 10.2 m. The deck at +13 m level is hexagonal and has a mass of 300 Mg. The structural model includes only primary structures; all secondary structures are omitted.

The first 16 natural modes are given in Table 1. Global modes that are most important in ice-structure interaction in global y-direction (from left to right) are presented in Figure 2. Due to structural symmetry many frequencies are repeated. The first and second bending modes are at 1.31 and 3.24 Hz, and twist modes at 1.44 and 3.70 Hz respectively. The structure is relatively flexible, especially in relation to ice load action at the waterline. The deck mass is a significant factor in the dynamic response of the structure.

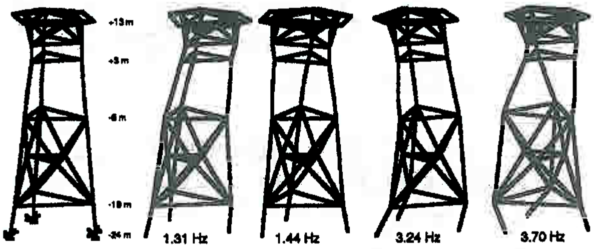


Figure 2. Three legged jacket platform and natural modes.

3.2 Wide structure.

The wide application structure is a fictive caisson retained island intended to withstand multi-year ice loads in 20 m water depth, (Fig. 3). The retaining ring is made of steel. Side height is 8 m above sea level. The deck rests freely on top of the ring. The planview is octagonal with longest sides 64 m at the waterline and total width 90 m. The base is 112 m wide and supported on soil. For vibration analysis soil support stiffness including core sand is simply observed by linear spring elements at foundation nodes. Total horizontal spring coefficient is 29 GN/m. The total mass of the structure including core sand and added soil and water mass is 510 Gg. The foundation springs, ring cross section rigidity and total mass were adjusted to give natural frequencies roughly at the same range as what has been measured on an actual caisson retained islands (Hewitt 1994 and Jeffries and Wright 1988).

The first 16 natural frequencies are given in table 1. The most important modes from the ice-structure interaction point of view are plotted in Figure 3. Even though the structure as a whole is very stiff against ice action, there are many low natural modes that contribute to deformations at ice action points. If the deck would have been fixed on the caisson ring to carry through loads, natural frequencies would have been higher, and many of the modes in Figure 3 totally different.

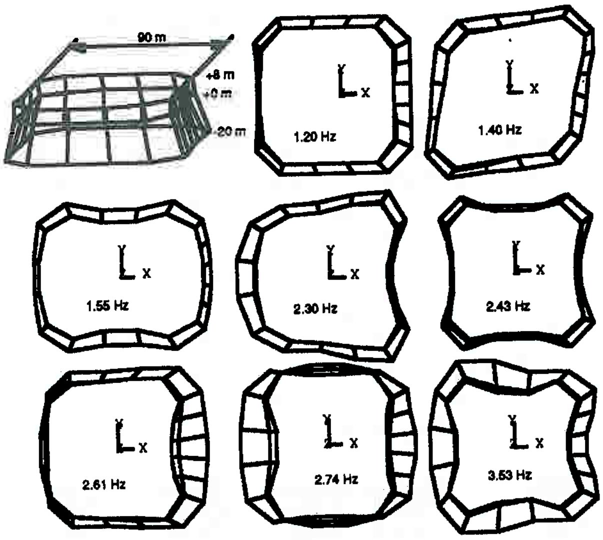


Figure 3. CRI natural modes.

Table 1. Lowest natural frequencies (Hz) of the application structures

Mode	CRI	3-leg
1	1.19	1.31
2	1.20	1.31
3	1.31	1.44
4	1.40	3.24
5	1.55	3.24
6	2.28	3.70
7	2.30	6.76
8	2.43	6.76
9	2.61	8.76
10	2.70	10.6
11	2.74	10.6
12	3.32	10.7
13	3.44	11.1
14	3.52	11.1
15	3.53	11.4
16	3.58	11.4

4 NUMERICAL SIMULATION RESULTS

4.1 Three-legged jacket platform.

Self-excited ice-structure interaction numerical simulation indicates that the 3-legged jacket platform in Figure 2 is highly sensitive for ice-induced vibrations. It would have needed overcritical structural damping to prevent ice-induced vibrations. Resonant lock-in type vibrations, synchronized at each leg, emerge at every practical ice thickness value. Limit cycles develop fast; at ice action point usually during the first cycle, (Fig. 4.a). On the other hand the deck mass takes several cycles before steady limit cycles are stabilized.

At very low ice velocities corresponding the nominal stress rate in the ductile range, left from the ice strength maximum in Figure 1, or at high velocities in the brittle range, no self-excited vibrations develop. If ice velocity makes the nominal stress rate just right from the ice strength maximum, the limit cycles predict saw tooth like structural response at the waterline, (Fig. 4.b). The frequency of repeating ice failures is well below the lowest natural frequency. With increasing velocity at certain point the first natural mode frequency starts to control the crushing frequency regardless of ice velocity, (Fig. 4.c). The lock-in can persist until a higher mode starts to control and makes a lock-in to another frequency, (Fig. 4.d). At velocity range in between, there exist limit cycles that combine both natural modes, (Fig. 4.e). Partly this a result of inertia loads from the deck mass.

If ice is thin, higher modes are likely to control the crushing frequency. E.g. in the case of a 0.1 – 0.2 m thick ice 11.1 Hz frequency is dominating and with 0.3 – 0.6 m thick ice 9.9 Hz respectively. With 0.7 m thick ice it is possible to have steady limit cycles at 6.84, 3.06 or 1.31 Hz frequency depending on ice velocity or whether all the three legs are under ice action. On contrary with thick ice, ice velocity directly controls the crushing frequency. Assuming an unrealistic high ice thickness of 2 m, steady saw tooth like limit cycles can be predicted from 0.27 Hz to about 1 Hz with increasing ice velocity. Thereafter the first mode at 1.31 Hz causes a lock-in to occur. Again at the brittle range no lock-in vibrations occur.

The displacement amplitudes of limit cycle vibrations were not simply related to ice velocity. The reason was the jump from one mode to another, and intermittent combination modes, that prevented distinct velocity dependence to show up.

It was not possible to make the jacket structure in Figure 2 to exhibit asymmetric ice-induced vibrations. Even if the initial state of deformation was that of a pure twist mode, and ice loads were acting only at two legs to allow 180 degree phase shift in excitation, the limit cycle lock-in response soon developed into a symmetric one controlled by the first mode. However, in another jacket platform with different mass and stiffness properties, steady state lock-in twist mode limit cycles could be predicted.

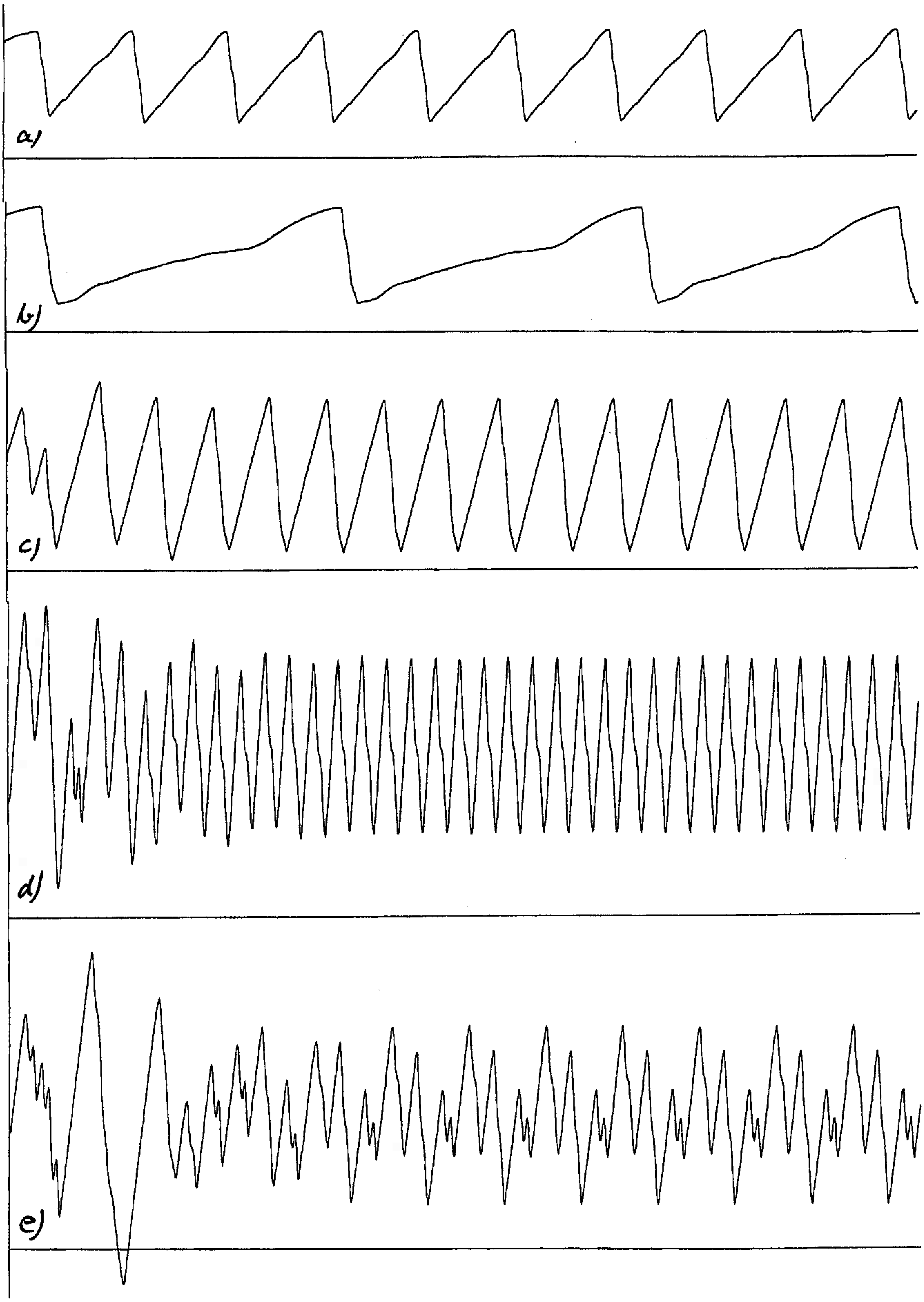


Figure 4. 3-legged platform waterline node displacement history vs. time from 0 - 16 s at different ice velocity ratio r. h is ice thickness, f limit cycle frequency and d is maximum displacement at ice action point. a) h = 1.0 m, r = 0.5, f = 0.78 Hz, d = 69 mm, b) h = 2 m, r = 0.5, f = 0.27 Hz, d = 135 mm, c) h = 1m, r = 1.0, f = 1.31 Hz, d = 76 mm, d) h = 1 m, r = 1.7, f = 3.06 Hz, d = 63 mm, e) h = 1 m, r = 1.4, d = 79 mm.

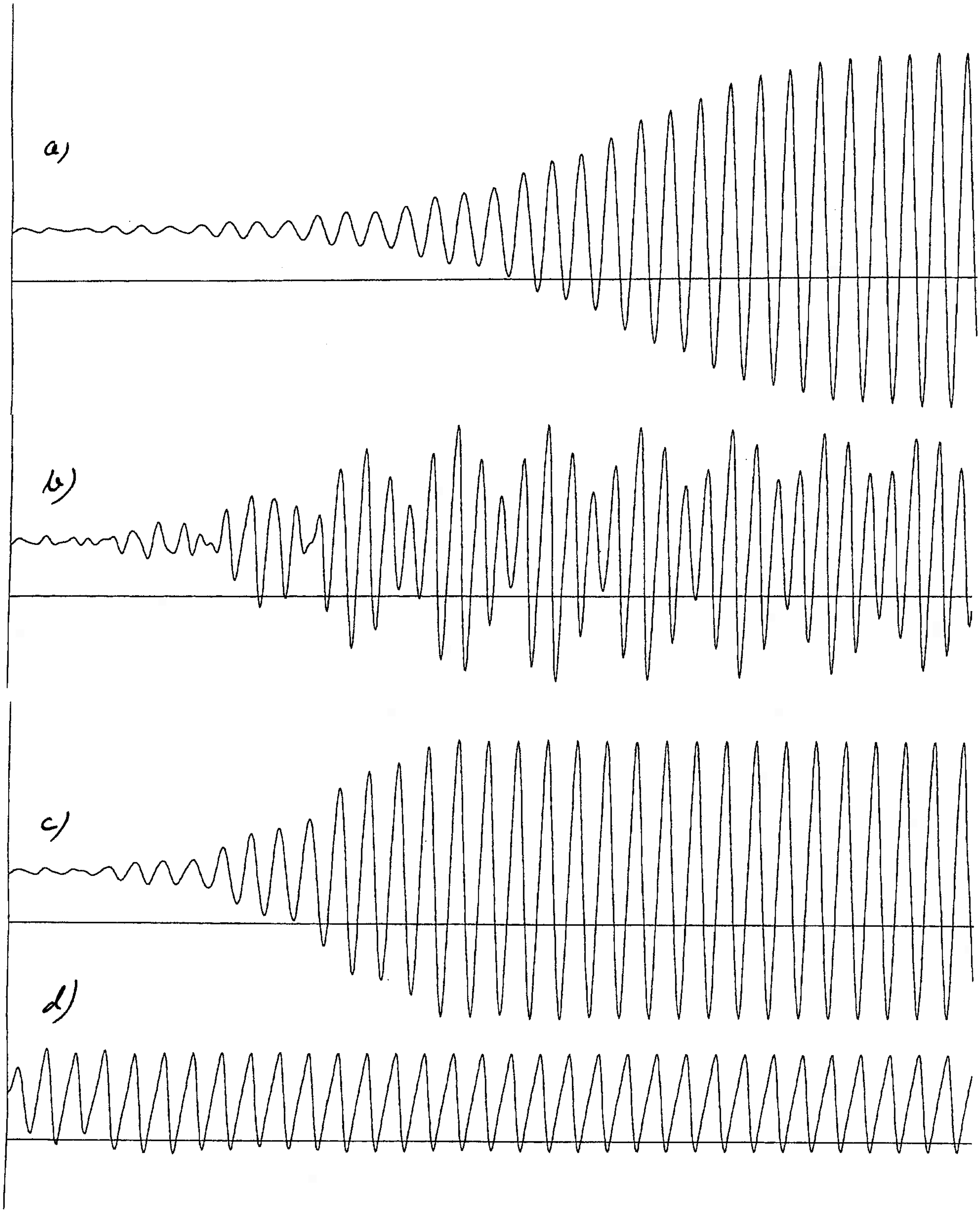


Figure 5. CRI center node displacement history vs. time from 0 - 32.5 s at different ice thickness h. f is limit cycle frequency and d is maximum displacement at ice action point. a) h = 0.5 m, f = 1.21 Hz, d = 20 mm, b) h = 2 m, ice action only at the center part, f = 1.54 Hz, d = 22 mm, c) h = 1m, f = 1.18 Hz, d = 26 mm, d) h = 16 m, f = 1.25 Hz, d = 49 mm.

4.2 Wide structure.

The wide caisson retained island was stiff and not very sensitive to exhibit ice-induced vibrations. By increasing structural damping it was possible to prevent resonant lock-in type ice-induced vibrations totally. In most cases it took many cycles before limit cycle amplitudes started to increase and a steady state to develop, (Fig. 5.a). Always the first mode at 1.2 Hz was the dominant one, and ice loads were synchronized at each ice action node. It was not possible to simulate such saw tooth like response history as was common with narrow structures. Also response, that would be a combination of different modes, (Fig. 5.b), was unlikely. Steady state limit cycles were practically always controlled by the first natural mode frequency at 1.21 Hz regardless of ice thickness. Only small variations at 1.18 and 1.25 Hz appeared, (Fig. 5.c – d).

With increasing velocity the crushing frequency was generally constant, close to the first natural frequency. The limit cycle displacement amplitude, on the other hand, has almost a linear dependence on velocity, (Fig. 6). The non-dimensional velocity is scaled in relation to the center part of the decreasing range in Figure 1. Value 0.5 corresponds to the peak value and 2.0 the beginning of the brittle range.

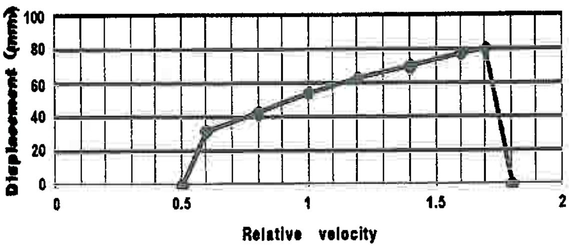


Figure 6. Limit cycle amplitude vs. velocity

It was not possible to make the caisson-retained island to have steady limit cycles at asymmetric modes. With symmetric modes it was easier to have lock-in vibrations if ice loads were only at the center part of the sidewall. This is to be expected when compared to the shape of natural modes. The nodes close to corner experience smaller displacement amplitudes and hence their interaction velocity differs from that of center part nodes. Thus corner nodes are in a sense out of phase of the center part and disturb the development of steady state limit cycles. It would be interesting to know if there is any indication of this kind of behavior during Molikpaq full-scale measurements.

5 CONCLUSIONS

A model based on self-excitation for predicting ice-induced vibrations in general offshore structures is presented. Dynamic equations of the motion are solved by numerical integration by utilizing the principal modes of the structure.

The model is capable to predict both saw-tooth like response at low ice velocity and resonant type of lock-in vibrations manifesting ice load synchronized at each ice action node at intermediate ice velocities. At very low or high velocity range no ice-induced vibrations are predicted. All these phenomena have been encountered in in-field measurements.

A 3-legged jacket platform appears to be very sensitive for ice-induced vibrations. Resonant lock-in will occur at different natural modes depending on ice velocity or thickness.

A caisson-retained island was not sensitive for ice-induced vibrations. The first mode was dominating the crushing frequency. With increasing ice velocity resonant steady state limit cycle amplitudes were increasing monotonically until self-excitation mechanism stopped after ice failure turned into totally brittle.

Both application structures were not able to maintain steady limit cycles at asymmetric natural modes.

The developed model can be used to analyze qualitatively how likely offshore structures are to experience severe ice-induced vibrations. Quantitative results for wide structures need better data on the size effect of ice crushing strength dependence on stress or strain rate.

REFERENCES

Blenkarn K. A. (1970): Measurement and analysis of ice forces on Cook Inlet structures. Proc. 2nd Offshore Technology Conference, Houston, TX, OTC 1261, Vol. II, pp. 365-378.

Eranti E. (1992): Dynamic ice structure interaction. Theory and applications. Technical Research Center of Finland, VTT publications No. 90, Espoo, Finland. 81p.

Hewitt K. (1994): Molikpaq ice interactions: Predicted and actual performance. Proc. IAHR Ice Symposium 1994. Trondheim, Norway.

Jeffries M., and Wright W. (1988): Dynamic response of "Molikpaq" to ice-structure interaction. Proc. OMAE-88, Vol. IV, pp. 201-220. ASME. Houston, USA.

Kajaste-Rudnitski J. (1996): On dynamics of ice-structure interaction. Technical Research Center of Finland, VTT publications No. 257. 104 p + Apps. Espoo, Finland

Kärnä T. (1992): A procedure for dynamic soil-structure-ice interaction. Proc. ISOPE 1992, Vol. II, pp 764-771. International Society of Offshore and Polar Engineers, San Francisco.

Kärnä T. (1997): A layered flaking model for ice load determination. Proc. 6th Finnish Mechanics Days, pp. 85-101. University of Oulu, Finland.

Muhonen A. (1996): Evaluation of three ice-interaction models. Helsinki University of Technology. Espoo, Finland. Licenciates's thesis. 90 p.

Määttänen M. (1978): On conditions for the rise of self-excited ice-induced autonomous oscillations in slender marine structures. Finnish-Swedish Winter Navigation Board, Finland, Research Report 25, 98 p.

Määttänen M. (1983): Dynamic ice structure interaction during continuous crushing. U. S Army Cold Regions Research and Engineering Laboratory, Hanover, NH, USA 03755, CRREL Report 83-5, 53 p.

Määttänen M. (1988): Ice-induced vibration of structures – Self-excitation. Proc. IAHR Ice Symposium 1988, Vol. II, pp. 658-665. Sapporo, Japan.

Matlock H., Dawkins W. and Panak J.(1969): A model for the prediction of ice structure interaction. Journal of Engineering Mechanics, ASCE, EM4:1083-1092.

Ranta M. and Räty R. (1983): On analytical solution of ice-induced vibrations in a marine pile structure. Proc. POAC-83, Vol. II, pp. 901-908. Helsinki, Finland

Riska K., Baarman L., and Muhonen A. (1993): Modeling of ice induced vibration of slender offshore structures. Helsinki University of technology, Arctic Offshore Research Centre, Memorandum M-172. Otaniemi, Finland. 33 p.

Sanderson T. (1988): Ice Mechanics – Risks to Offshore Structures. Graham and Trotman Ltd, London.

Sodhi D. (1994): A theoretical model for ice-structure interaction. Proc. OMAE-94, Vol. IV, pp.29-34. ASME, New York.

Sodhi D. (1988): Ice-induced vibration of structures. Proc. IAHR Ice Symposium 1988, Vol. II, pp. 625-657. Sapporo, Japan.

Vershinin S, and Iliady A. (1990): A new approach to dynamic ice-flexible structure interaction analysis. Proc IAHR Ice Symposium, Vol. III, pp. 73-80. Helsinki University of technology, Espoo, Finland.

Xu J. and Wang L. (1988): Ice force oscillator model and its numerical solutions. Proc. OMAE-88, Vol IV, pp. 171-176. , Houston, TX, USA.

OWEMES '97
(Offshore Wind Energy in Mediterranean and other European Seas)

OFFSHORE WIND TURBINE FOUNDATIONS IN ICE INFESTED WATERS

*Erkki Haapanen, MScTech **Mauri Määttänen, D.Tech,
***Pekka Koskinen, MScTech

* Engineering Office Erkki Haapanen Ky, A Limited Partnership Company
** Helsinki University of Technical - Faculty of Mechanical Engineering
***Technical Research Center of Finland - Manufacturing Technology - Maritime Technology

FINLAND

ABSTRACT

The northern coast of the Gulf of Bothnia has a great potential of wind resources and shallow waters. The majority of the wind turbines in Finland are located ashore along the coast line of the Gulf of Bothnia. The useful area is narrow making the offshore area very promising for wind energy. There are potential offshore sites for major wind parks in many locations along the 300 km coast line.

The real challenge is to develop a technology for wind turbine foundations to withstand high loads caused by up to 1.3 m thick ice during the winter time. The behaviour of ice has to be thoroughly understood. The maximum lateral ice load level can reach to an order of ten MN when high winds drive ice against the foundation structures. The larger the solid ice field the larger are the loads. Pressure ridges, which are causing a lot of trouble for marine operations, are not considered to be a major problem for wind turbines in shallow waters (max 7 m deep), because of a deep keel which will stop the ice well before the wind turbines. Ice may also cause uplift loads during water level changes. This force can reach a magnitude of one MN depending of the dimensions. The most dramatic case is caused by ice blocks piling up against the tower and foundations. This pile-up can reach a height of ten meters or even higher and cause damages to the tower structures. Thermal ice expansion can also induce lateral loads on the foundation structures.

The paper describes ice properties, ice action against structures, and presents different options for solving ice related problems in wind turbine foundations with some recommendations on how to avoid hazardous situations.

KEYWORDS

Offshore, Wind Park, Ice, Wind Energy, Foundation, Load

Introduction

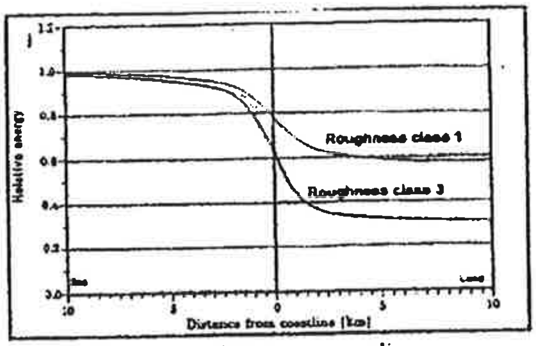


Figure 1. Wind speed across a coast line

The highest wind speeds are found in open sea areas. Figure 1 shows the wind speed change across the coast line. Wind turbines work best in open sea areas where the flow is less turbulent and the wind energy highest. Hundreds of turbines can easily be built offshore. The increase in wind speed will compensate for the higher cost of construction. The large size of modern wind turbines has brought us to a point, where the ice and rough sea can be challenged. We know from maritime winter navigation experience how to build offshore lighthouses and aids-to-navigation on an open sea even if the ice thickness is more than one metre and the sea is deeper than 10 metres. The wind society can now start to use ice infested sea areas for energy production. The technical Research Center of Finland has started a development program in which a prototype wind turbine foundation will be built in the waters of the Gulf of Bothnia.

This paper describes what can be expected from moving thick ice, presents ice load scenaria, and advises how to select a location for an offshore wind park. A practical problem in design is the uncertainty in estimating the ice loads and ice behaviour. Before a decision about the wind park site, the local environment should always be checked and discussions held with local seamen, fishermen and people who have lived years dealing with the ice and know it by heart. In the Gulf of Bothnia there are lots of excellent places for wind parks where the ice loads can be limited to a reasonable level and the production of clean energy is feasible.

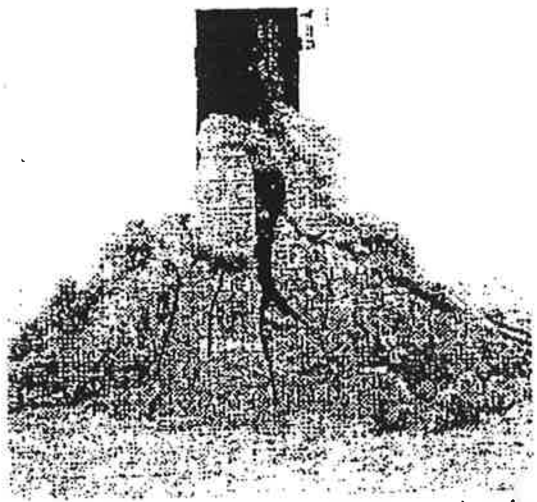


Figure 2. Slow ice movement and failure against the Kemi-1 lighthouse with a test cone

The ice load cases and their order of importance

Offshore structures will be influenced and stressed in many different ways by the ice around them. In the Gulf of Bothnia at the open sea, outside the fast ice zone, the level ice thickness is typically below 80 cm. However, the ice fields are heavily ridged. The pressure ridges are typically 4 to 6 m thick. However, an above water sail of a ridge can be more than 2 m high and an underwater keel more than 10 m deep. The ridged ice fields are often moving due to winds and currents causing high loads on offshore structures. Thus the areas, where heavy ridging occur, are not economically possible locations for wind turbines.

At the coastal region ice is moving only in autumn before the land fast zone is formed. Thus, the thickness of the moving ice is significantly lower than at the open sea area. When a strong wind drives a large ice floe, it may move at a speed up to 1.3 % of the wind speed. When such a floe meets a wind turbine foundation, it will either be stopped or broken by the structure. In the coastal area the level ice thickness may grow more than one metre thick. Temperature changes in the fast ice field will either expand or shrink the ice cover. The foundations at the coastal region have to be designed to withstand the loads due to relatively thin moving ice and thermal expansion of the thick fast ice.

In the Gulf of Bothnia the water level will rise due to storm surges from the south. The water level rise in

Kokkola can be about 1 metre and in Kemi up to 2 metres. After the storm surge, or during northerly winds the water level sinks. In winter the ice cover will reduce these maximum water level changes. When the rising water level lifts the ice, it causes uplift loads on the foundation.

Moving ice.

Shear forces created by the wind will push the ice. The driving force F [kN] is depending on the wind kinetic energy and on the surface roughness of the floe. /7/

(1a) $$\boxed{F = A * \mu * q_k}$$

in which

(1b) $$\boxed{q_k = v_k^2/1600}$$

A = the area of the ice float, m²
μ = friction factor.
= 0 0010 for smooth ice
= 0.0015 for snowy ice;
= 0.0020 ... 0,005 for rough and pack ice
q_k = wind kinetic pressure, KPa
v_k = wind speed, m/s

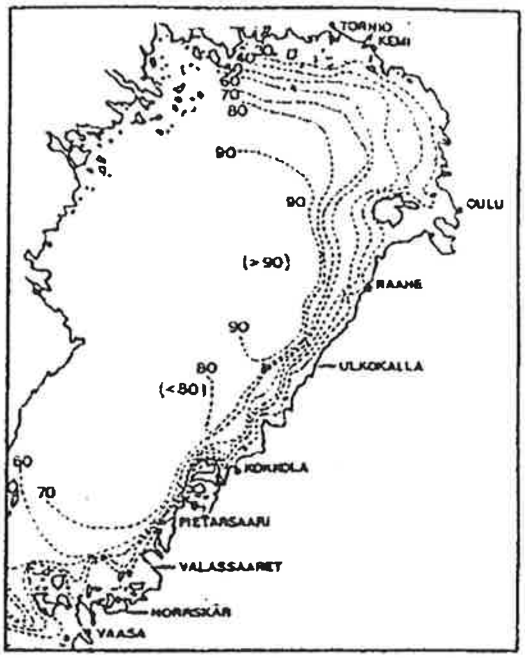


Figure 3. Moving ice thickness on the Gulf of Bothnia. Note the 0,3 m zone nearest to the coast line /10/

We can see from this formula that if the area of a floe is large enough, the force will be extremely high. In designing the maximum area in this formula should be chosen. In the Gulf of Bothnia the floe may easily be 30 x 30 km² and a 20 m/s wind will create a shear load of 0.5 ... 1.0 Pa on the surface and up to 900 MN to the whole floe. In a storm the wind speed may reach 35 m/s for few hours. It is evident that such a driving force is too large for any wind turbine foundation to resist. Practically there are two options, either the ice or the structure has to break.

Near the coastline the ice thickness in a landfast ice zone may reach 1.3 metres while further offshore in the actively moving ice zone an 0.8 m ice thickness is frequent. The structures to break such a thickness have to be extremely strong and heavy. This is an obvious threat to the economy of a wind turbine structure. The site for wind turbines should be chosen in the landfast ice zone so that there are natural or man made objects to prevent too large moving floes to hit the structures. From a long experience we know that in many locations there is a few kilometre-wide zone along the coast, where only thin ice, less than 0.30 m thick, can move at the beginning of the winter before getting thicker and stabilizing, (Figure 3). In these areas the thicker ice can also move during spring, but then its strength has already detoriated. The landfast ice zone is a natural choice for wind generator foundations as maximum ice forces will

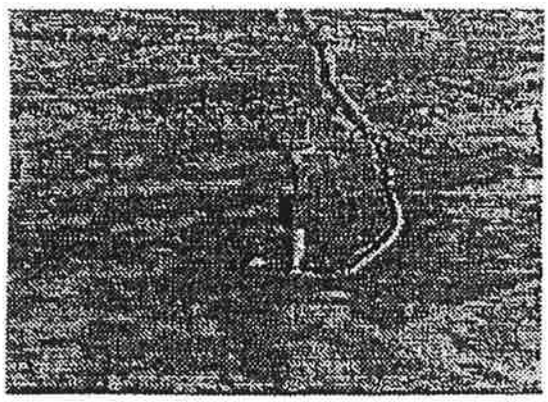


Figure 4. Wind driven ice movement at the active ice zone, Kemi-2 Lighthouse

there be limited due to the limitation of the moving ice thickness.

Forces and means to break moving ice

Ice properties will vary with time due to environmental conditions. The salt content of the water, time history of the temperature, snow coverage and consistency of ice will affect ice strength and ductility. We have to look at different load cases and then be sure that the structures are built for those requirements.

Solid ice in the autumn is the strongest and most ductile but not yet very thick. The strength in compression at a high loading rate would reach up to 10 MPa, or even higher with small test pieces. Ice strenght decreases with decreasing loading rate, and with increasing size. Thin ice cover may buckle and fail by bending before the normal stress reaches the compressive strenght limit along all the contact area. The wind friction on smooth level ice is very low and causes low pushing force. When snow covers the ice, the friction increases with the height of the snow dunes.

At the coldest time in winter, the ice has normally experienced a few temperature fluctuations which bring with thermal cracking and make the ice not homogenous any more. There may be some ridges, cracks, long leads, and other discontinuities in the ice field. Weathered cold, moving ice breaks easier than virgin autumn ice. Compressive strength is still high, but during interaction with a structure the average pressure against the whole contact area falls below 3 MPa. Later in spring when the temperature is close to the melting point the compressive strength goes down to 1.5 MPa and later to 1.0 MPa, when the ice has weakened through melting. And if the ice is moving very slowly as in the case of a thermal expansion, the compressive strength falls below 0.5 MPa and the behaviour of the ice is ductile. All these stress values are subject to arguments and may vary depending on the winter.

When ice is pushing a structure, it is compressed and possibly bent due to the eccentric or inclined contact area. Highly stressed ice will break and due to the brittle nature of the ice, the cracking will continue. Cracked pieces will be forced away, to bypass the foundation, above or below the ice cover depending on the surrounding conditions and the slope of the contact area. The ultimate load depends on the ice properties, dimensions and the geometrical shape of the obstacle.

The crushing load will be dynamic and fluctuate either

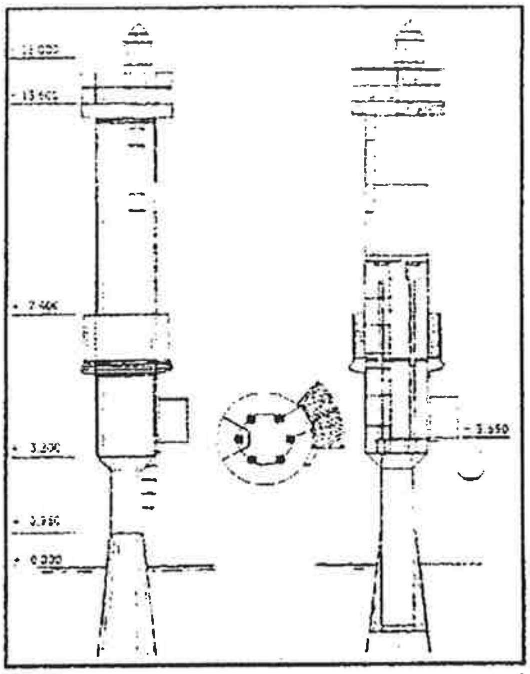


Figure 5. Principle of isolation of dynamic loads of a lighthouse. System allows lateral movement of the upper part of the tower.

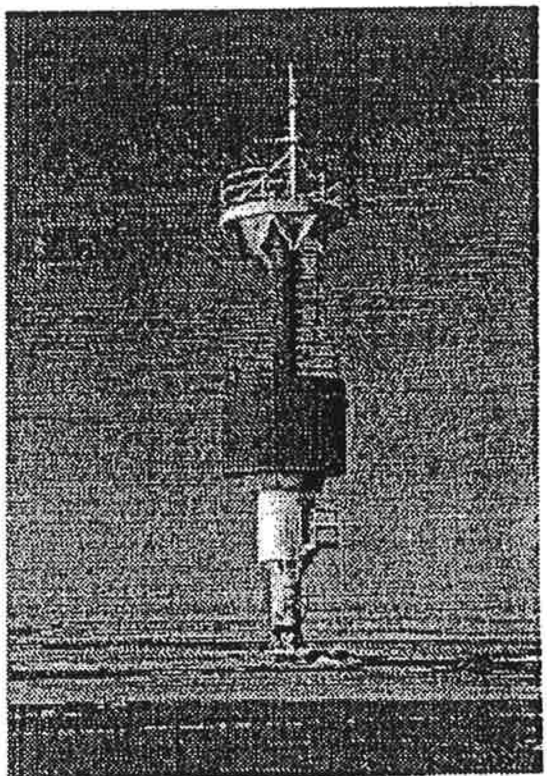


Figure 6. Vibration isolated Kemi-2 Lighthouse. Wind generator on the top has been running smoothly since construction in 1981

randomly between near zero and a certain maximum, or there is a dominant frequency depending on the ice thickness, speed, and structural response. Load amplitude also has random fluctuations. The thicker the ice, the higher the forces. Eigenfrequencies of the structure may control the ice failure frequency resulting in resonant vibrations. This situation is very dangerous for a wind turbine with a nacelle weight at the top of a narrow long tower. The foundations have to be designed in such a way that there is no chance for a resonant loading, or that the tower itself has vibration isolation to prevent oscillations and high dynamic loads. In Finnish offshore steel light houses the superstructure has been installed on top of a vibration isolation section. This concept has been proven in the field for more than twenty years in practice (Figures 5 and 6).

The initial crushing strength of ice is high if the structural shape does not stimulate bending or initiate crack propagation. To avoid extreme loads we could enhance the breaking of the ice before it reaches the wind turbine, or prevent the ice from moving by locking it in place. This is the normal situation in the landfast ice zone near the coast line, where there are natural blocks like rocks and islands to prevent ice from moving. Islands and skerries will also limit the maximum size of a floe, and prevent all but only thin ice movements. Figure 3 shows a landfast ice zone, approx. 3 - 5 km wide, in the coastal area of the Gulf of Bothnia. Here thick ice is locked by natural stoppers. By knowing the local geography and long term ice behaviour, we can approximate the maximum size and pushing force of moving floes and use this information when designing foundations.

Loads to a vertical, cylindrical foundation, when the ice starts to move or is moving.

In literature the formula for the maximum static force due to ice crushing against a vertical structure is /5/ /7/:

(2)

$$\boxed{P_1 = k_1 * k_2 * k_3 * b * h * \sigma_{ip}}$$

where k_1 = shape factor for the structure
= 0.9 for round shape
= 1.0 for rectangular shape

k_2 = ice to structure contact factor
= 1.0 when an adfrozen floe starts moving
= 1.5 when a thick ice collar has adfrozen to the structure
= 0.5 when ice is cracking continuosly

k_3 = shape ratio factor

(3)

$$\boxed{k_3 = (1 + 5 * h/b)^{0.5}}$$

b = width of the structure (at a level ½h down from the ice upper surface)
h = ice thickness
σ_{ip} = compressive strength of ice
= 3.0 MPa for intact ice moving by the wind or current at the coldest time of winter
= 2.5 MPa for intact ice moving very slowly e.g. by thermal expansion or shrinking at the coldest time of winter
= 1.5 MPa for intact ice moving in the spring and the temperature is close to melting point
= 1.0 MPa for partially weakened melting ice moving at a temperature close to melting point

This formula suggests that the worst situation is at the very moment, when a thick ice collar, adfrozen to the structure, starts to crush. Here the ice compressive strength may be σ_{ip} = 3.0 MPa and the contact factor k_2 = 1.5. However, as the ice movement starts, the loading rate is so low that the loading rate dependent ice strength is also low resulting in loads less than in the case of faster moving ice with a lower contact factor but higher strength. Hence it is the combination of all factors that has to be considered. Measurements have proven that the initial ice failure with good contact induces the highest loads, and thereafter, the load decreases suddenly close to zero and rises again to a new maximum, which is a lot less than the initial one because of the reduced contact factor k_2.

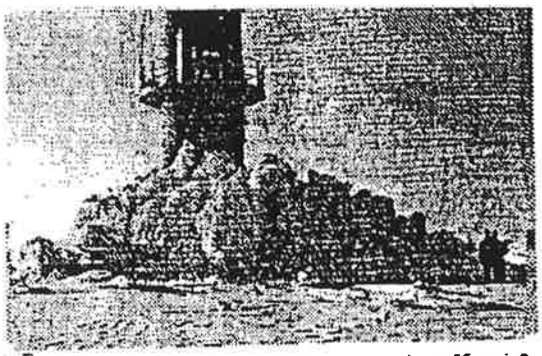


Figure 7. Ice failure and pile-up against Kemi-2 cone at active ice zone.

Loads to a conical foundation

As moving ice hits a conical foundation, both horisontal and vertical loads will develop. An ice sheet breaks easier by bending than by crushing. This makes bending failure dominant, even though crushing and shearing modes are present simultaneously to some extent. In addition the mode of ice failure depends on the shape and size of the structure. It also depends on ice properties, ice velocity and the friction between the structure and ice. In a loading cycle local crushing and shearing will occur initially, smoothening a large enough contact area, making higher ice loads possible. Increasing vertical forces first cause radial cracks and later a circumferential crack, which yields to the final bending failure. Thereafter, a new cycle can start. The ice load is at its maximum just before the formation of the circumferential crack. Clearing mechanisms involve pushing broken ice pieces upwards and aside of the structure. Figures 2 and 7.

The cone ice force calculations are based on loads needed to break the ice in the bending mode, to raise broken pieces up, and to bypass the structure. An upper bound plastic limit analysis solution can be calculated by Ralston's model. Later more refined FEM-analysis and full-scale measurements have indicated that Ralstons's model in general overpredicts maximum loads. The procedure for cone ice load calculations is too demanding to be presented here. see References /5/ and /6/.

Dynamic load

Ice failure against a structure is mostly dynamic causing dynamic load fluctuations. In dynamic ice structure interaction energy from the moving ice is being transferred and stored as elastic and kinetic energy in the structure. A dynamic crushing load P_D may have a random frequency between 0.5 Hz and 10 Hz. A resonant state may develop while an eigenmode of the structure controls the ice crushing frequency. The theoretical explanations for dynamic ice-structure interaction are based on forced or self-excited vibration models. Resulting ice force history can be solved with numerical integration of dynamic equations of motion.

In practise, however, the dynamic ice load is simply assumed to be a fraction of the static level ice load Eq.2, e.g. 50 %. If this load amplitude is applied at the frequencies of lowest eigenmodes of the structure, a conservative design against dynamic ice action is achieved. Another case is the hit of an ice edge which causes dynamic amplification of the superstructure displacements.

When ice is cracking by bending, the frequency varies from 0 to 1 Hz. The amplitude of the load varies between zero and P_D. the Conical shape of the foundations has a great importance in lowering the dynamic stresses.

Pressure ridges and ice pile-up

Pressure ridges are formed, when ice is compressed, buckled and crushed together. The pressure will lift up the crushed area. Some of the crushed ice blocks go under the water forming a keel,which typically has the depth 10 and width 30 times the height of the parent ice sheet. Pressure ridge formation takes place in the active ice zone beyond the landfast ice zone. It is not recommended to install wind generators in such areas.

Ice pile-up frequently occurs in shallow waters, or when moving ice hits the shore or the wind turbine foundations. This can occur also in the landfast ice zone before the ice thickness has grown over 0.4 m. Local loads against the structure are not too high but the threat is in the height of the pile-up, up to 14 m high formations have been recorded. The access door to the wind turbine may be blocked. Removable ladders may be required to enter the tower. The ice blocks may damage all protruding obstacles like a landing stage from the tower and foundation. The lower end of the tower must be strong enough to withstand these impacts. The impact is caused by single ice blocks sliding down and hitting against the foundation. The pressure load is low and the situation looks much worse than it really is. In the wind park area the the formation of pile-ups should be initiated on top of natural or artificial hindrances, well before the wind generators.

Rising water level makes the ice force to lift the foundations

High winds induce water level changes also during winter time even though the sea is ice covered. As ice is normally adfrozen to the foundation or tower, it results in the vertical uplift loads on structures. The surface properties of the contact area determine the maximum force. Wind turbine foundations are usually heavy enough to resist this force. The vertical load can be estimated by a formula

(7)

$$\boxed{V = \tau * A}$$

where A = adhesion or contact area, m^2
τ = adhesion strength (e.g. at - 10°C τ = 0.1 MPa for plastics and up to 1 MPa for concrete)

How to select a proper site for offshore wind park

The wind park location should be in the landfast ice zone in a shallow place, surrounded by some islands, reef or skerries to prevent large floes from pushing the wind turbine foundations. This will limit the maximum moving ice thickness below 0.4 metres which correspondingly limits ice loads against the foundations. If some stones or rocks are seen above the water level, they are excellent stoppers and ice breakers. Shallow water depth in front of a wind park induces ice pile up preventing further ice movement closer to the coastline. However, there should be a waterway to the site for building the foundation and transporting the material.

Summary

An offshore wind park in ice infested waters is a challenge. Moving ice exerts severe loads against the foundations and ice pile-up can reach to the propeller blades or prevent access to the tower.

By choosing the wind park site inside the landfast ice zone significantly reduces the thickness of moving ice, resulting ice forces, and other adverse ice actions. By proper foundation design the ice failure mode can be controlled, which on its behalf further reduces ice loads.

Thorough knowledge of the ice dynamics history in the proposed site is essential in finding optimum solutions, which limit ice loads to a reasonable level and make offshore wind parks not only technically but also economically feasible. Large coastal areas even in ice infested waters can thus be utilized to produce wind energy efficiently

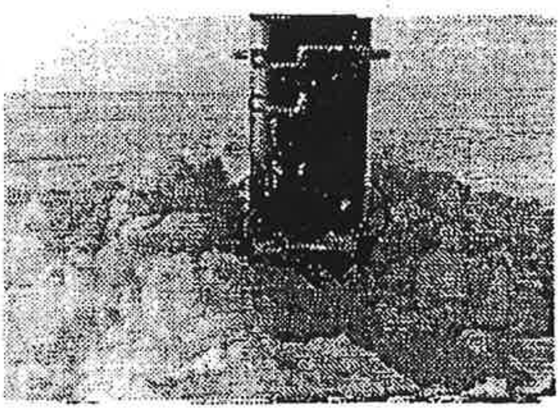


Figure 8. Slow ice movement and failure against a lighthouse at landfast zone in Kokkola

References:

1. Cammaert & Muggeridge: Ice Interaction with Offshore Structures, van Nostrand Rheinhold 1988, New York.

2. IAHR working group on "Ice Forces on Structures" State of Art Reports, 1980, 1984, 1986, 1988 and 1992.

3. Michel B: Mechanics of Ice, Les Presses de L'Universite Laval, Quebec 1978.

4. Määttänen M.: Ice Forces and constructions. Bi-lateral symposium on Ice Engineering The Chinese Hydraulic Engineering Society, The Finnish National Committee on Large Dam. Proceedings report 1989. Beijing

5. Määttänen M.: Design Recommendations for Ice Effects on Aids-to-Navigation. IALA Technical Committeee to study the Effect of Ice on Lighthouses. International Association for Lighthouse Authorities. Paris 1984

6. Ralston T. (1977):Ice Force Design Considerations for Conical Offshore Structures. POAC 1977, Memorial University of Newfoundland, St.John's, Newfoundland, Canada, Vol II, pp. 741-752.

7. RIL: Rakenteiden kuormitusmääräykset. (Finish Regulations for Structural Loads)

8. Sanderson T: Ice Mechanics, Risk to Offshore Structures, Graham & Trottman, Lontoo 1988.

9. YIT Ltd. The Vibration Isolated Lighthouse, Brochure

10. Palosuo E., et Al.: Formation, thickness and stability of fast ice along the Finnish coast. Institute of Marine research. Helsinki 1982.