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ENGINEERING PRACTICE FOR ICE FORCE DESIGN IN DENMARK

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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:

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

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

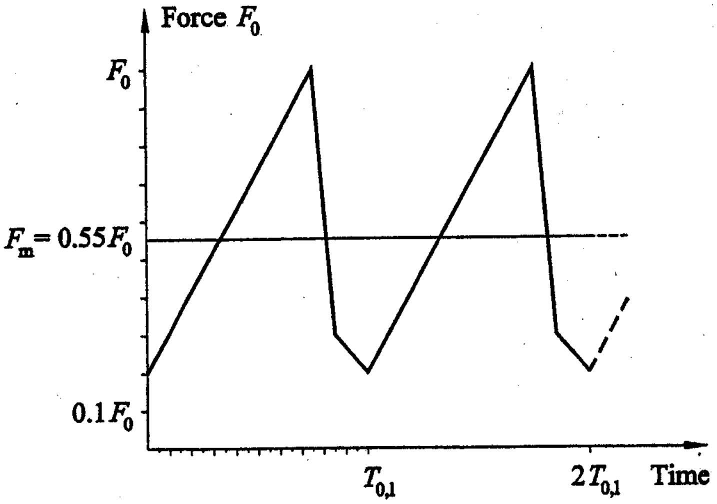

Fig. 4 Specified loading for a structure with ice cone.

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

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

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.

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