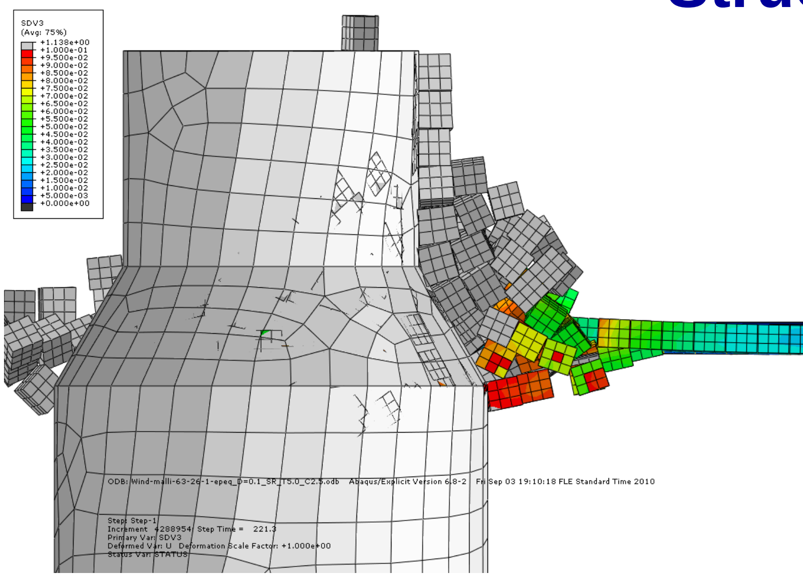
Business from technology

Structural performance of offshore wind turbine in ice-covered waters



Winterwind 2014

11th of February, 2014
Sundsvall, Sweden

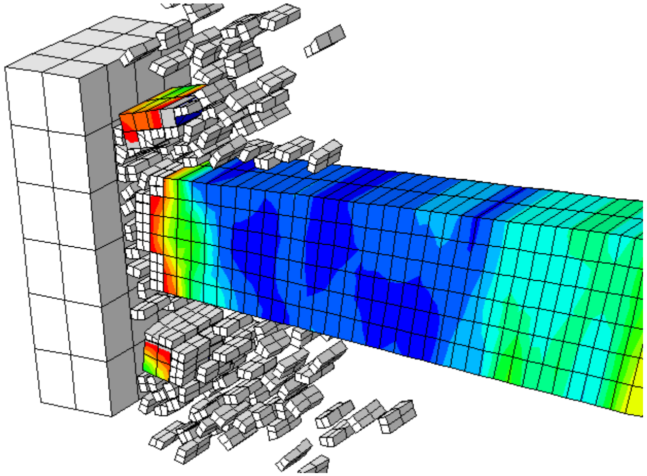
Maria Tikanmäki, Jaakko Heinonen, Vilho Jussila & Juha Kurkela
VTT Technical Research Centre of Finland

Content

- Motivation
- Sea ice conditions
- Ice loads
- Ice-interaction of offshore wind turbine
- Conclusions

Basic research of ice

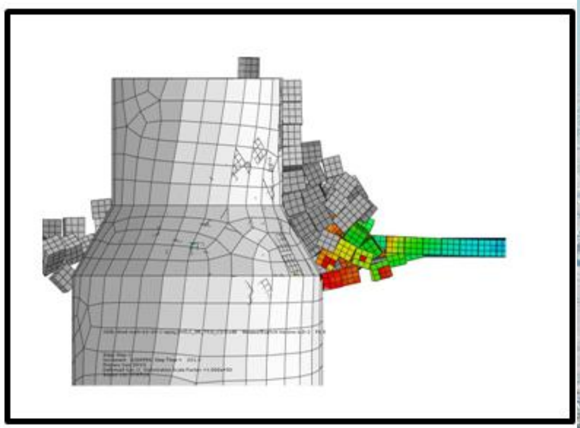
- Icing on structures
- Ice adhesion
- Friction of ice
- Ice mechanics
  - Mechanical properties of ice
  - Failure of ice

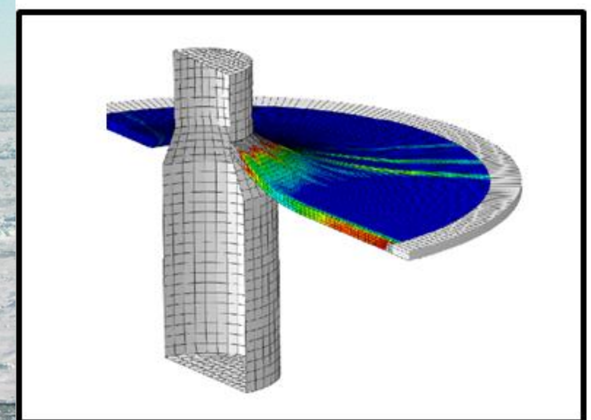


Simulation, Kuutti & Kolari (2012):

Motivation of Ice Research

- Ice loads introduces the most significant uncertainty for structural design in arctic/sub-arctic regions
  - Safety factors are high resulting in structures, that are not cost-effective





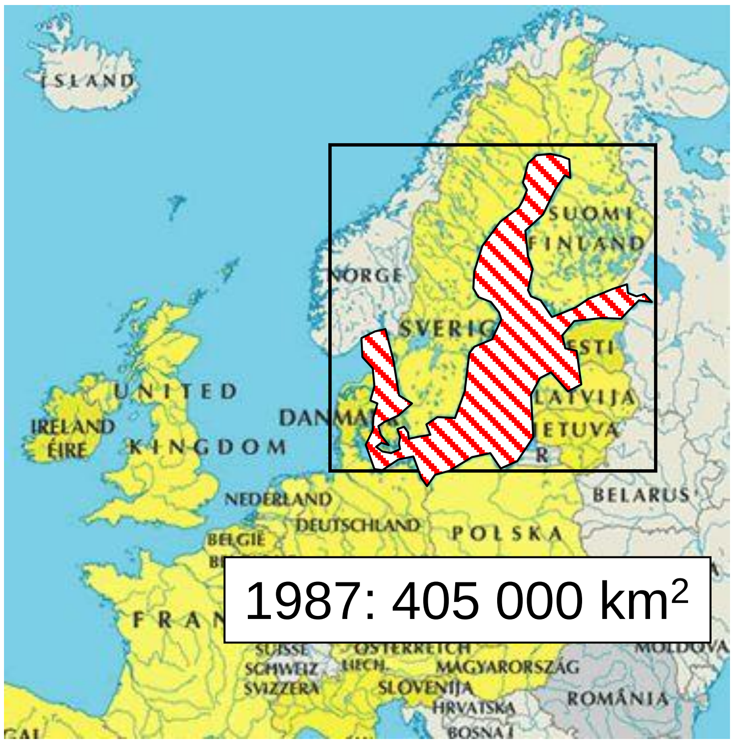
Main challenges in ice-covered sea areas

- Understanding of the local ice conditions
  - Ice features, ice concentration, thickness, ice drift, ridges etc.
- Understanding of the environmental loads: wind, wave and ice
- Structural performance in ice-interaction
  - Structural design: shape, dimensions, dynamic behaviour
  - Understanding of ice failure mechanisms: ice crushing, bending, buckling, stopping etc., ridge interaction,
- To determine the maximum forces on offshore structures due to ice-interaction, one needs to understand how ice fails

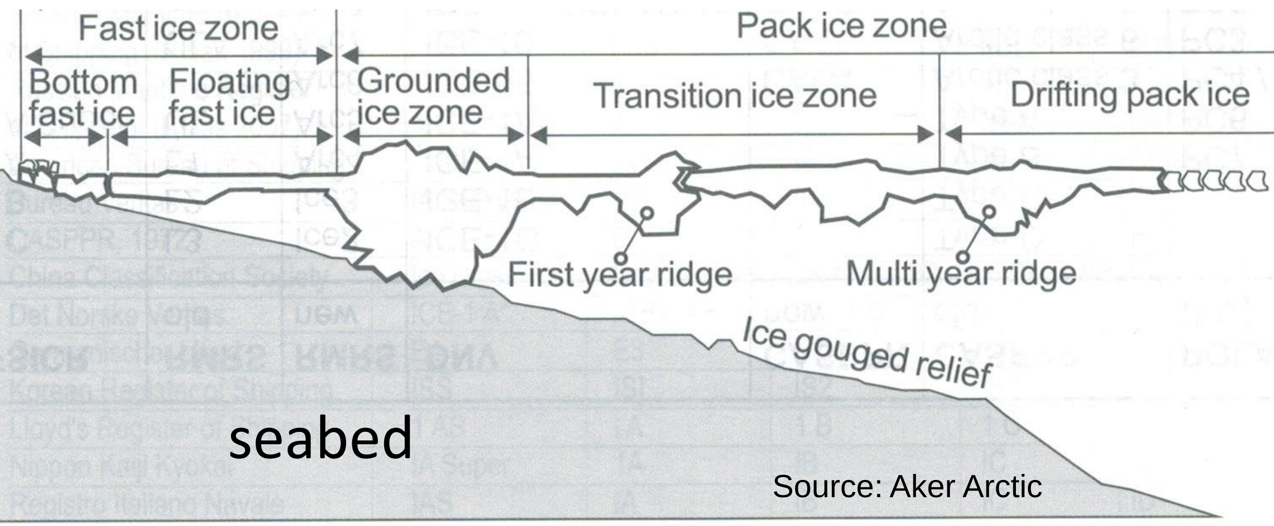
ICE CONDITIONS

Ice coverage – examples

Level ice conditions 1987 & 1989



Sea ice features

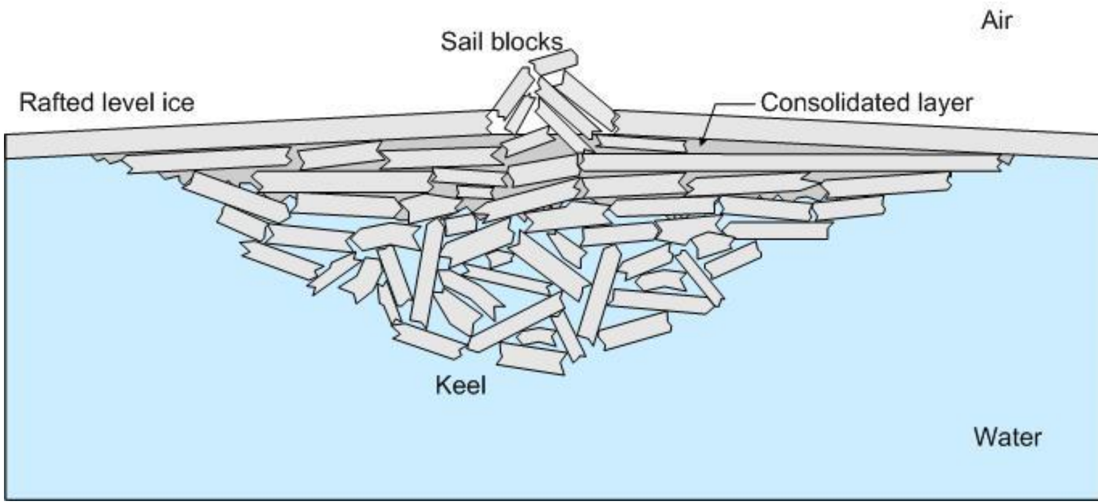


Source: Aker Arctic

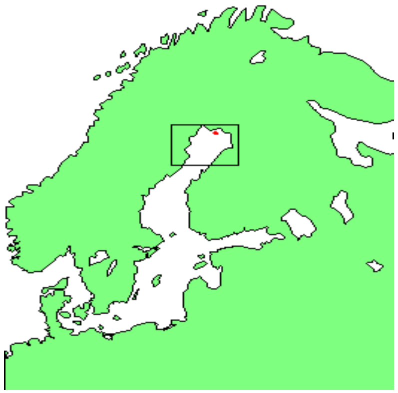
© Kari Kolari

Ice ridges

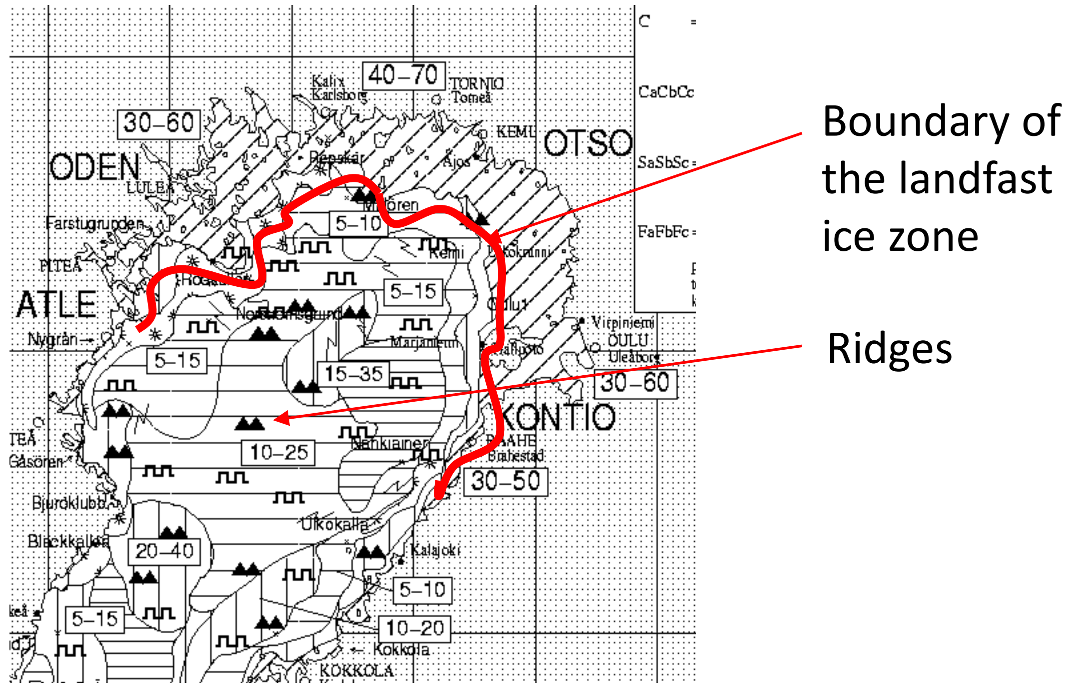
- Ridges are common ice features in the northern seas
- They are moving due to wind and sea currents causing remarkable loads to offshore structures during ice interaction
- Ice ridges in the Baltic Sea:
  - Sail height up to 2 m
  - Keel depth usually less than 10 m



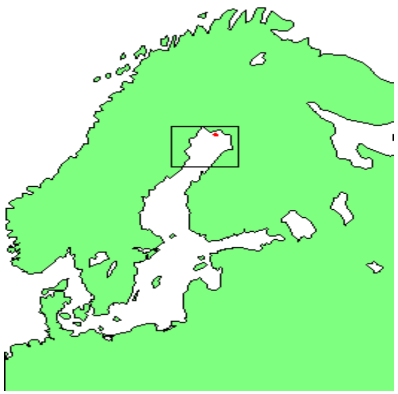
Local ice conditions in Gulf of Bothnia

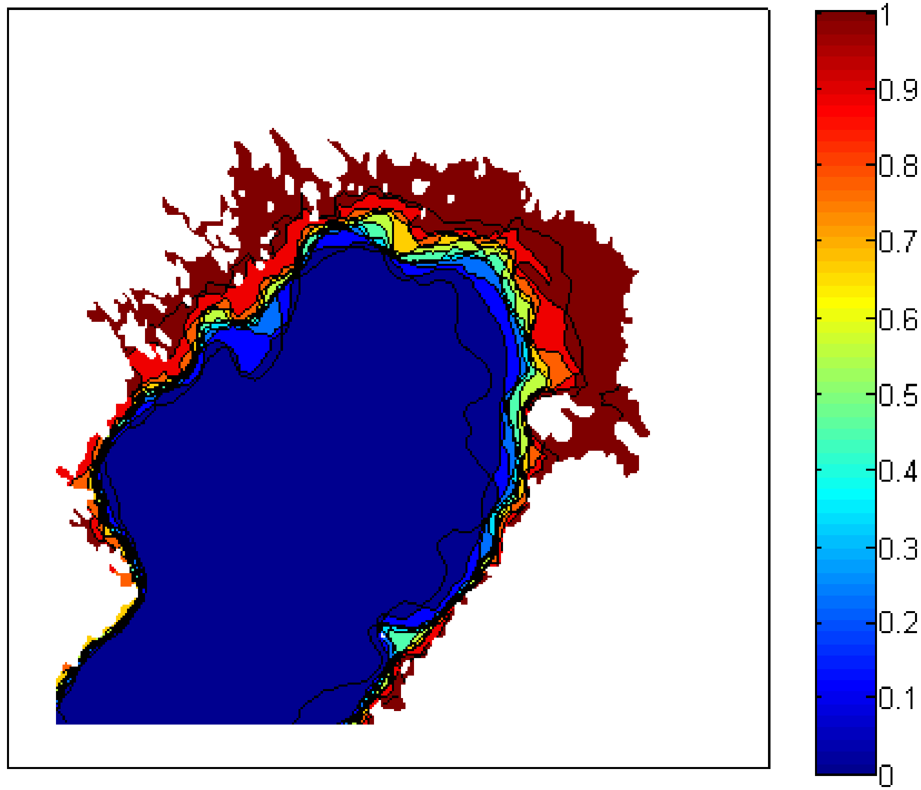


The analysis of the ice conditions is made based on the daily ice charts from the Finnish Meteorological Institute (FMI) and Swedish Meteorological and Hydrological Institute (SMHI)

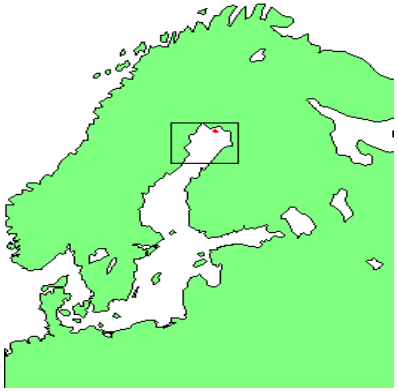


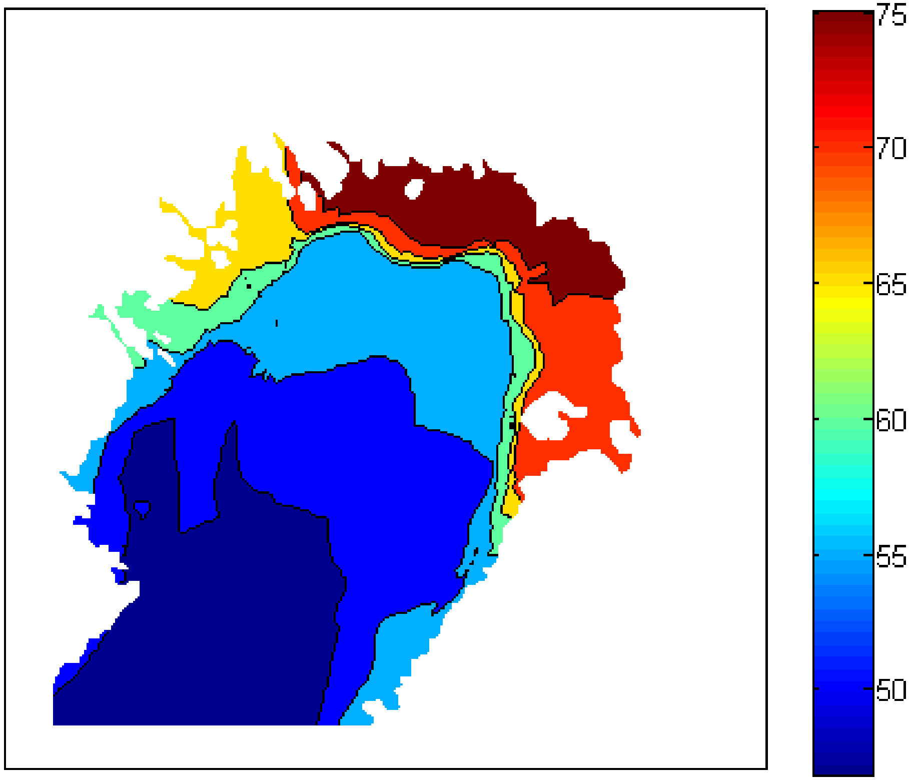
Wide landfast-ice region and shallow coastal region





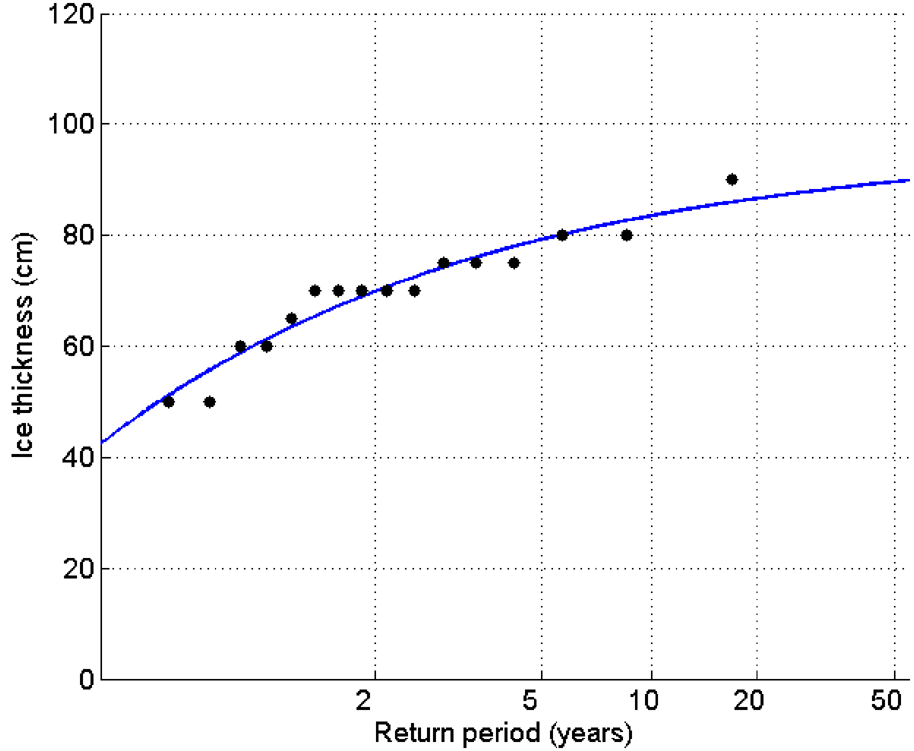
Frequency of the existence of the landfast ice in the Bay of Bothnia during the years 1994 and 1996 – 2011 at the day of the maximum ice extent in the Baltic Sea.



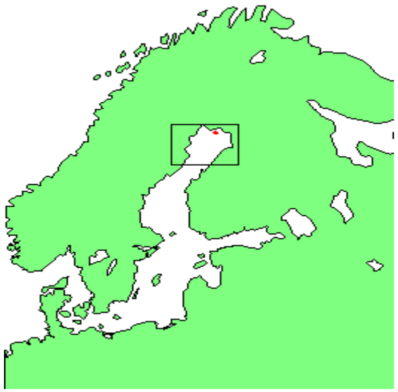


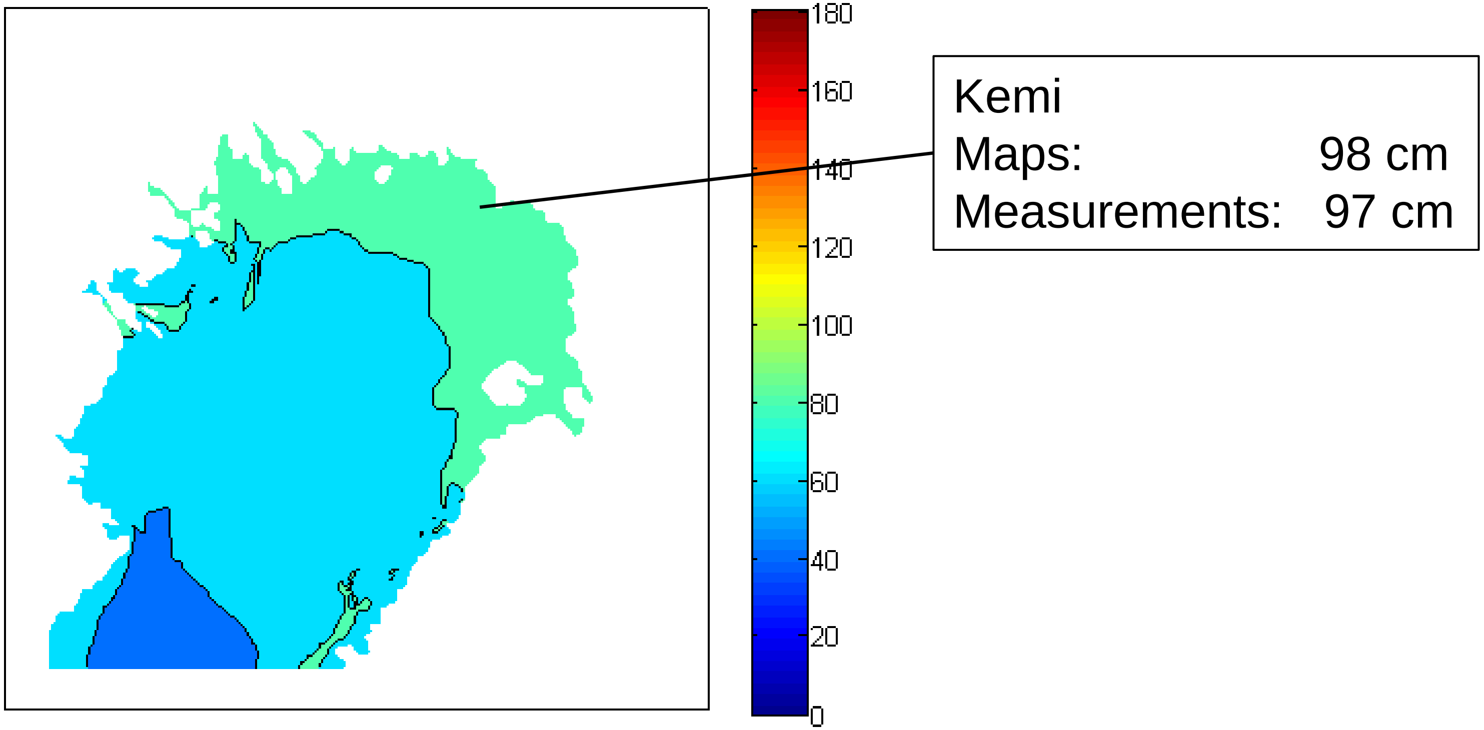
Typical yearly maximum ice thickness (cm) in the Bay of Bothnia calculated by averaging the ice thicknesses from the years 1996 - 2011.

Analysis of maximum ice thickness

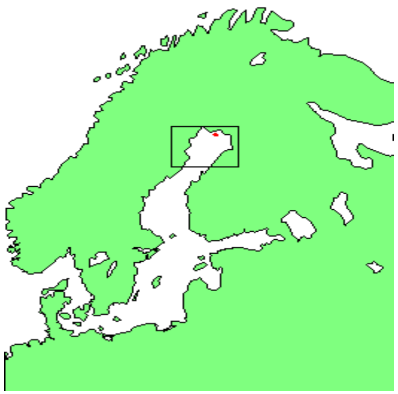


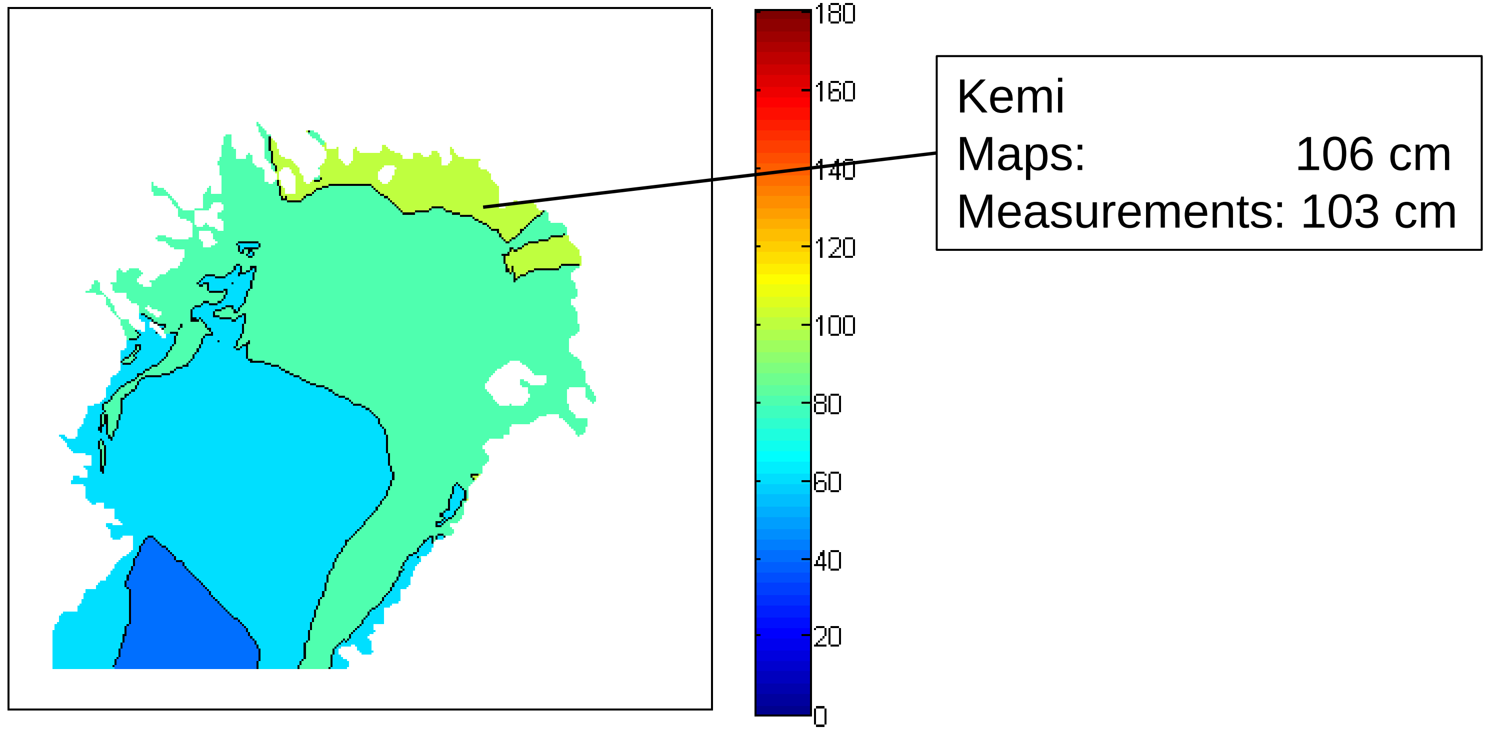
The new objective extreme value analysis method developed in VTT is applied to the maximum ice thicknesses





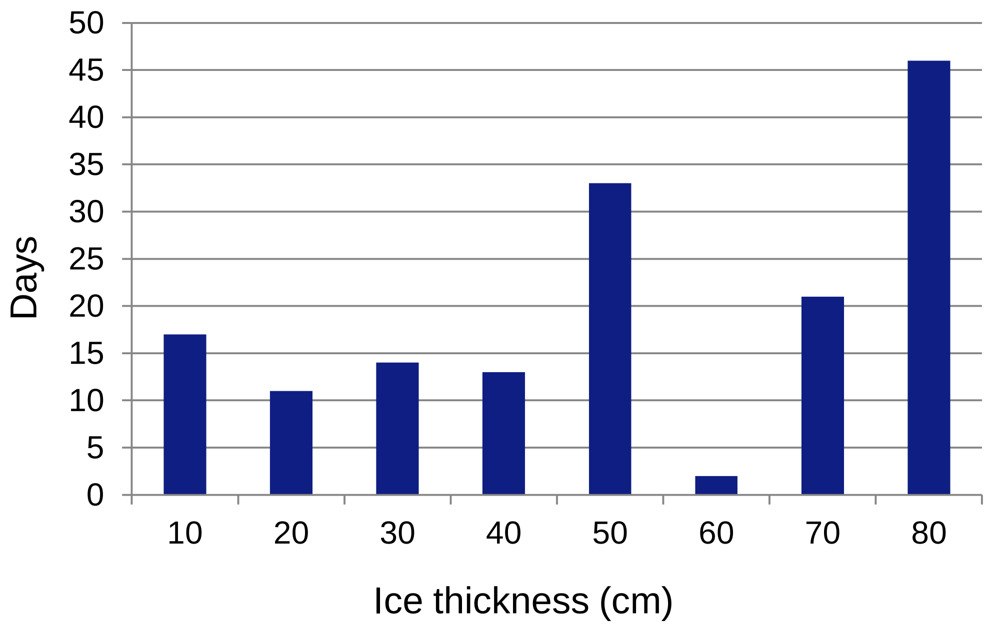
Maximum ice thickness (cm) occurring once in 20 years in the Bay of Bothnia.





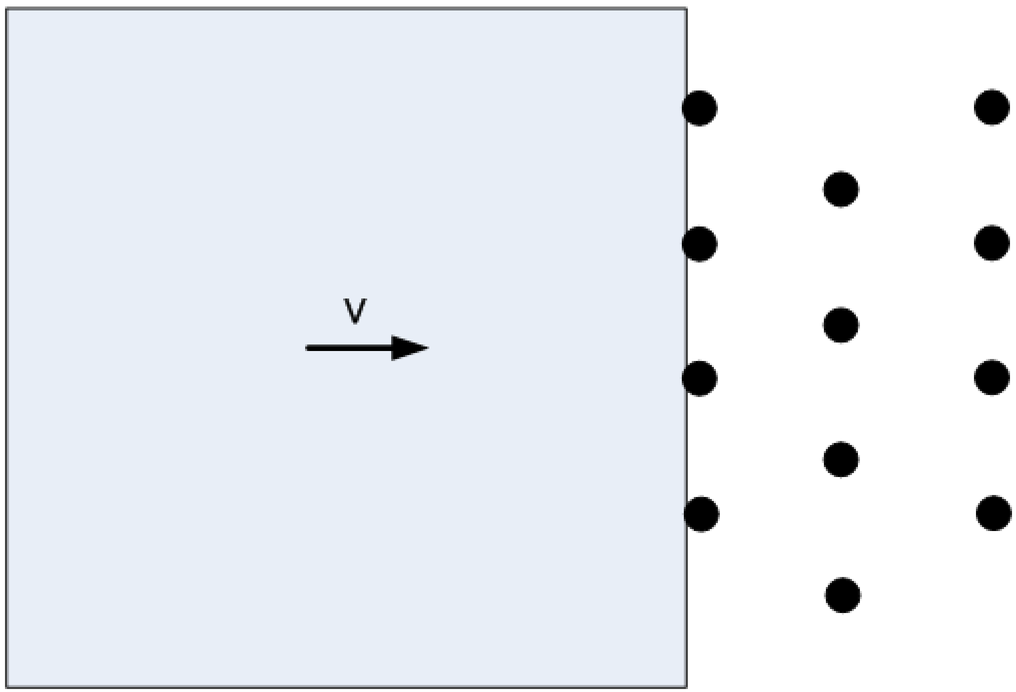
Maximum ice thickness (cm) occurring once in 50 years in the Bay of Bothnia.

Ice days in Kemi at 2006 (maximum)

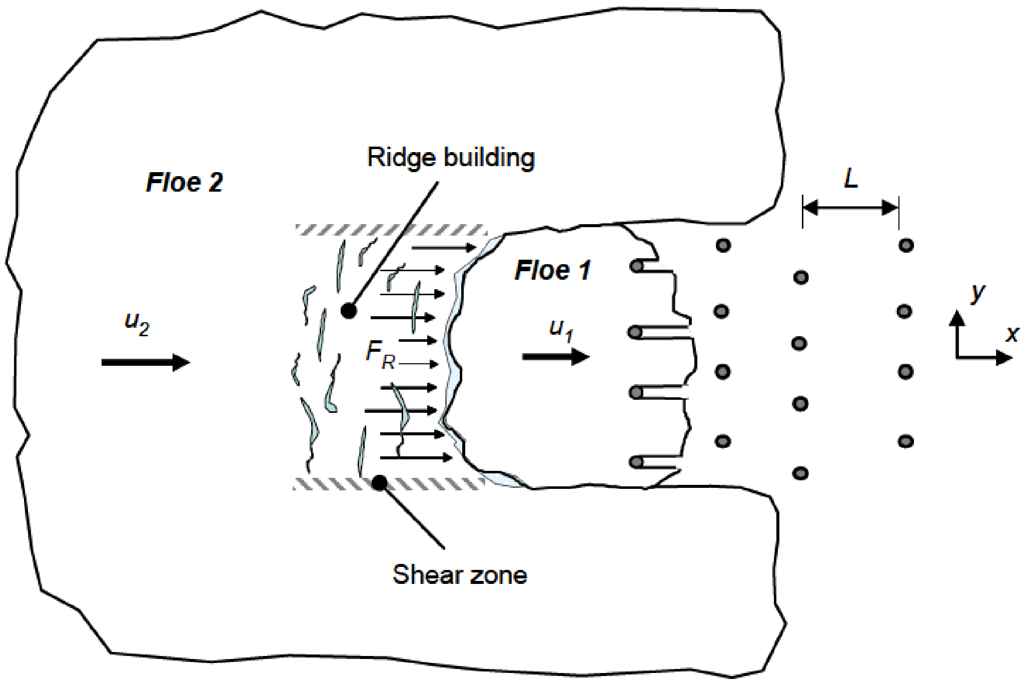


- Based on maximum ice thickness information
- Maximum thickness 80 cm (76 cm)

Does the wind power plant make ice floe to stop?



Ridge building caused by wind power plant



From Kärnä et al. (IAHR, 2010) with slight modifications

$$M_1\ddot{u}_1 = F_{a1} + F_{w1} + F_R - F_{ice}$$

$$M_2\ddot{u}_2 = F_{a2} + F_{w2} - F_R$$

Wind drag:

$$F_{aj} = \rho_a c_a v_{a,10}^2 A_j$$

Water current drag:

$$F_{wj} = \rho_w c_w A_j |v_w - \dot{u}_j| (v_w - \dot{u}_j)$$

Limit ridge building force:

$$F_R = \left(Rh^{1.25} D_y^{-0.54}\right) D_y \cdot 10^6$$

ICE LOADS

Characteristics of sea ice loading

- Moving Sea-Ice Floe
  - Ice floe velocity, up to 1.2 m/s
- Driving Forces:
  - Wind
  - Sea current
  - Tidewater

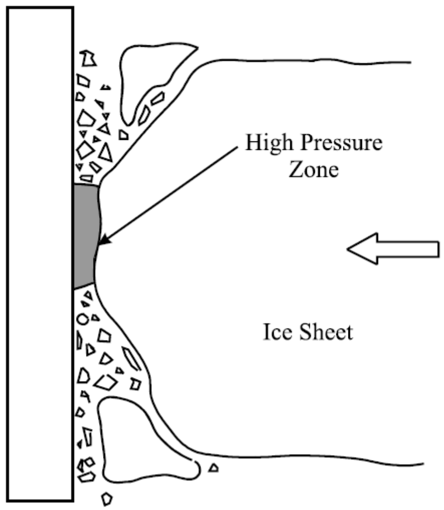
- Ice load depends on
  - Floe thickness
  - Ice drift speed
  - Shape of the structure
  - Failure mode of ice
  - Crystal structure of ice
  - Flexibility of the structure at ice level
  - Etc.

Ice loads – analyses methods

- Engineering methods based on standards
  - ISO 19906, IEC 61400-3 etc.
- Numerical simulation of ice-structure interaction based on ice mechanics
  - Understanding of ice failure process
  - Gives opportunity to investigate
    - How the ice loads develop
    - How the shape of the structure influences to the failure mode of ice
    - How the shape of the structure should be optimized to minimize the loads and vibration
- Model scale studies in ice tank
- Full-scale measurements

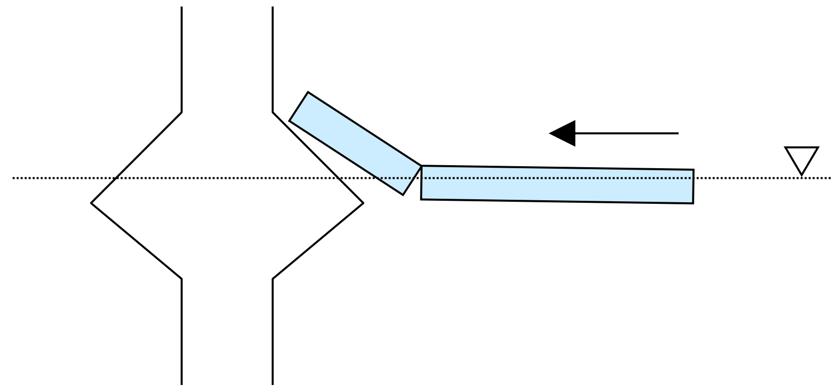
Failure Mode – Shape of Structure

Crushing failure



Vertical structure
cylinder

Bending failure



Conical structure
downwards / upwards

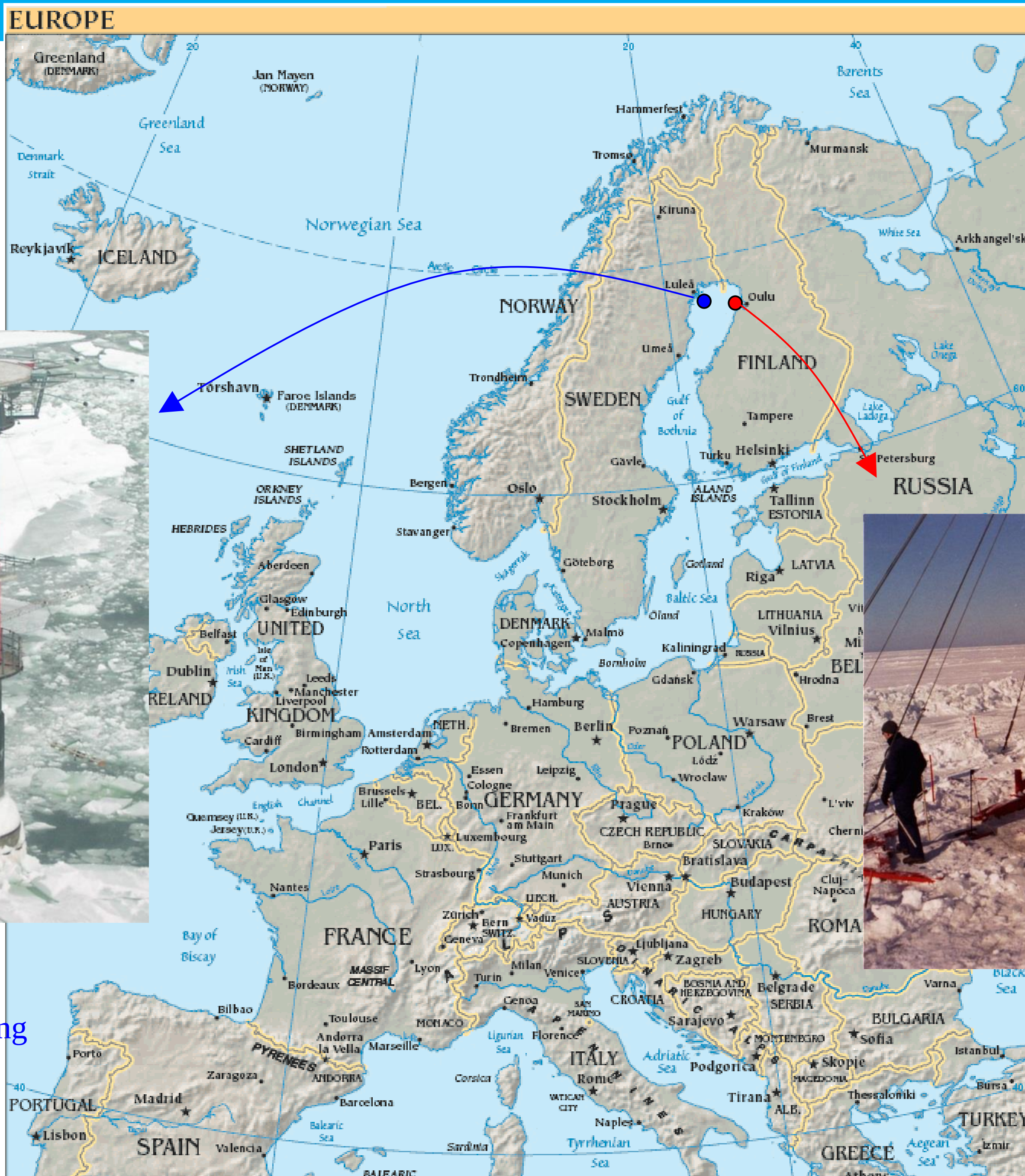
- Ice Breaking Cones
    - Crushing => Bending failure
    - Smaller Ice-force
    - Reduce vibrations

Previous Public Projects

- LOLEIF (1997-2000), EU
- STRICE (2001-2003), EU
- NEST (2001-2003), EU
- STANDICE (2004-2008), EU

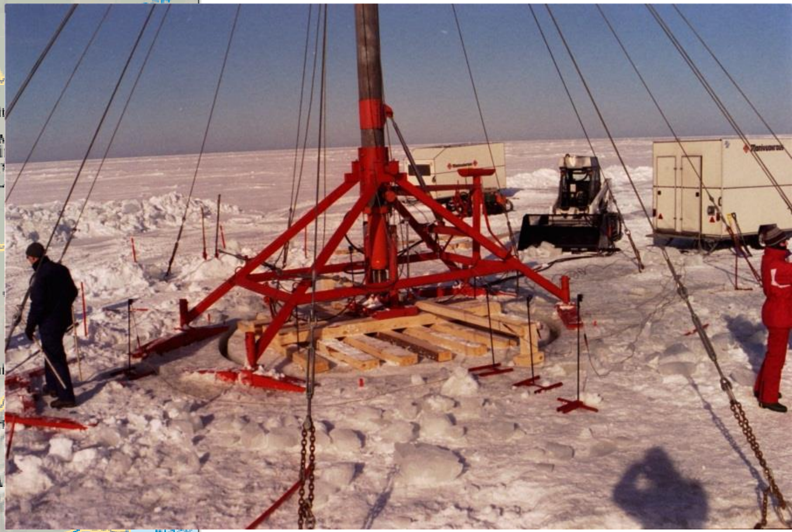
  ISO 19906 Arctic Structures
- VIBRA at HSVA 2002 (Large Scale Facilities)
- ARKI (1999-2003), Tekes (Domestic)

Industrial contract projects



Norströmsgrund lighthouse

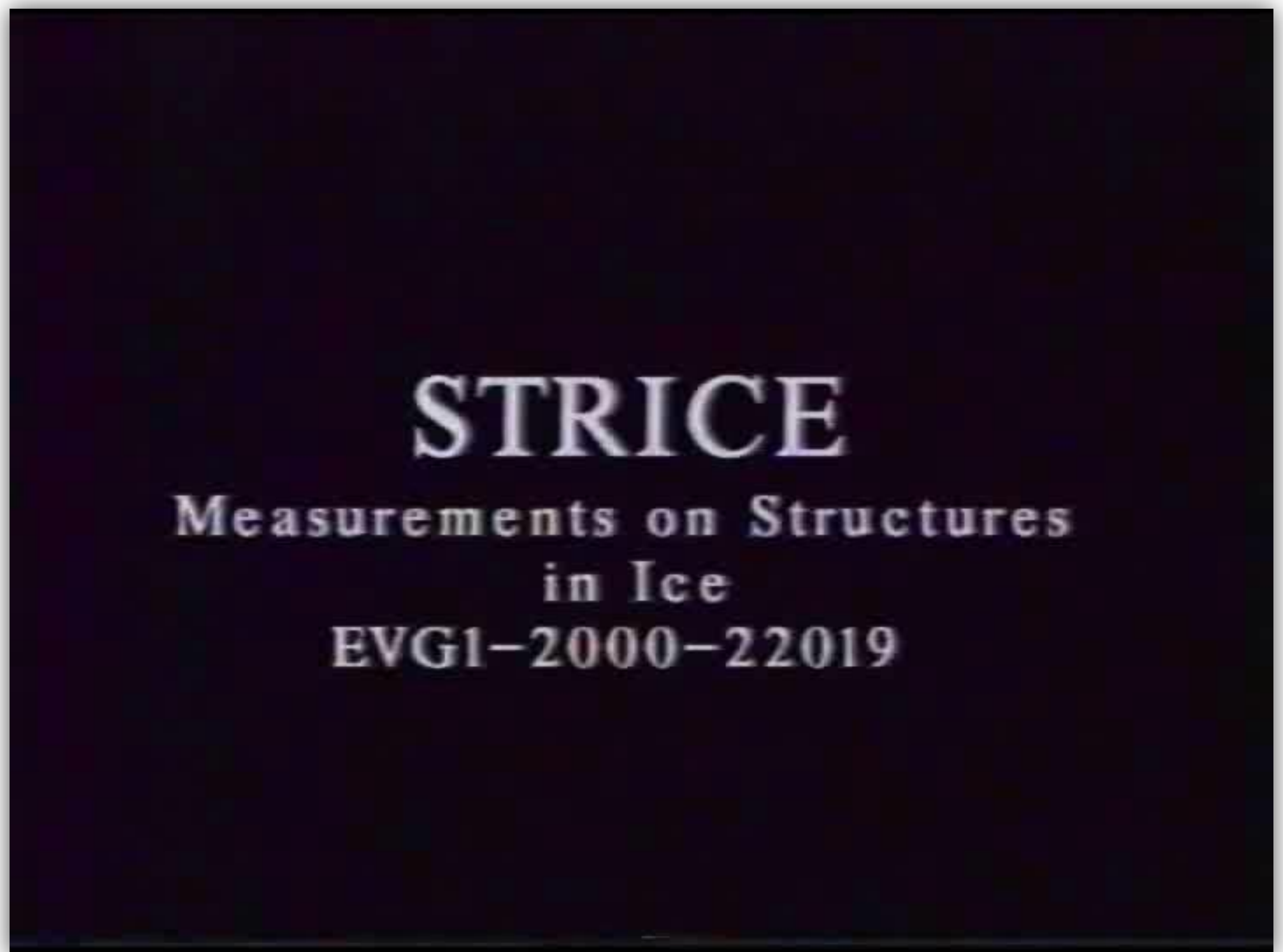
Ice force monitoring



Hailuoto

Ridge keel loading tests

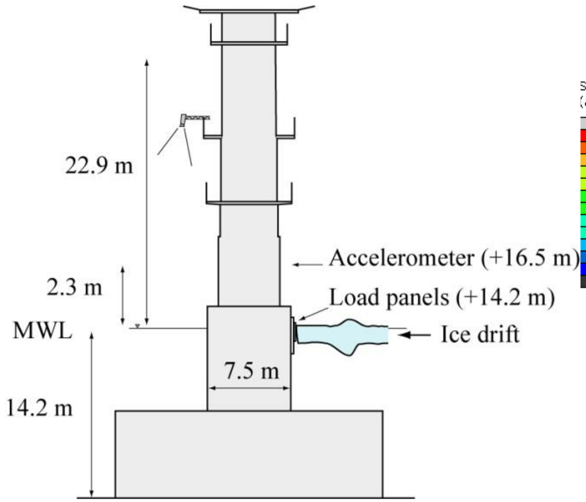
Norströmsgrund lighthouse – ice load measurements



Video

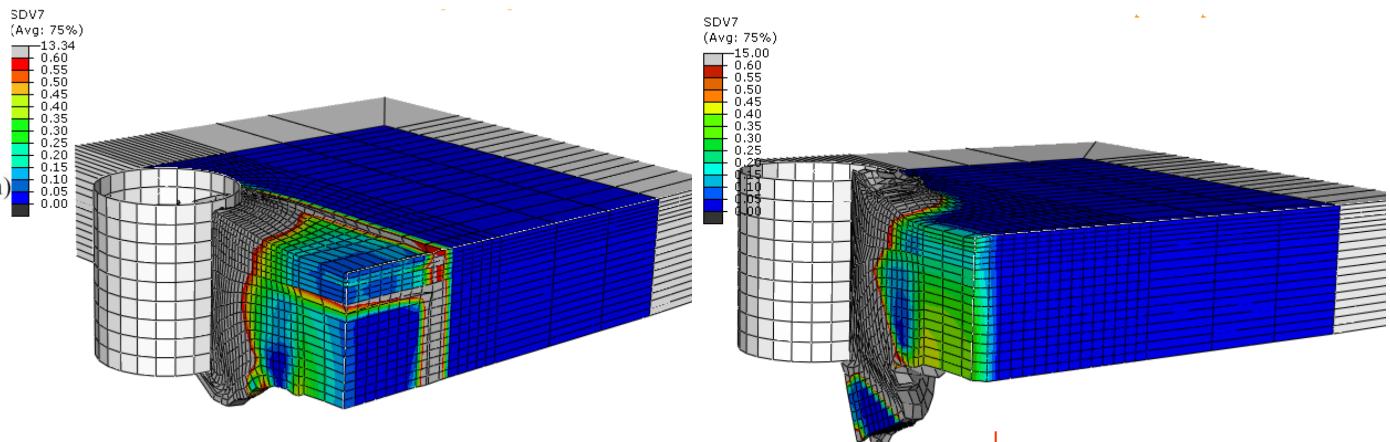
- 21.2.2003
- Ice thickness ~ 50 cm

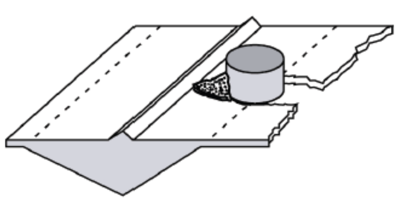
Ridge-structure interaction simulation



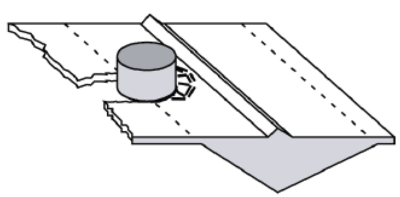
Norströmsgrund lighthouse

Variation of the strength of consolidated layer

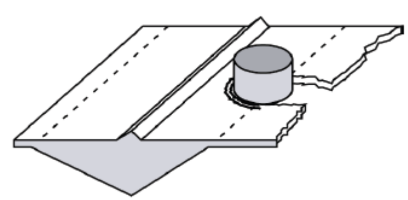




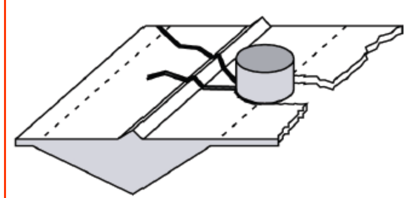
1) failure on a rubble wedge



2) bending failure



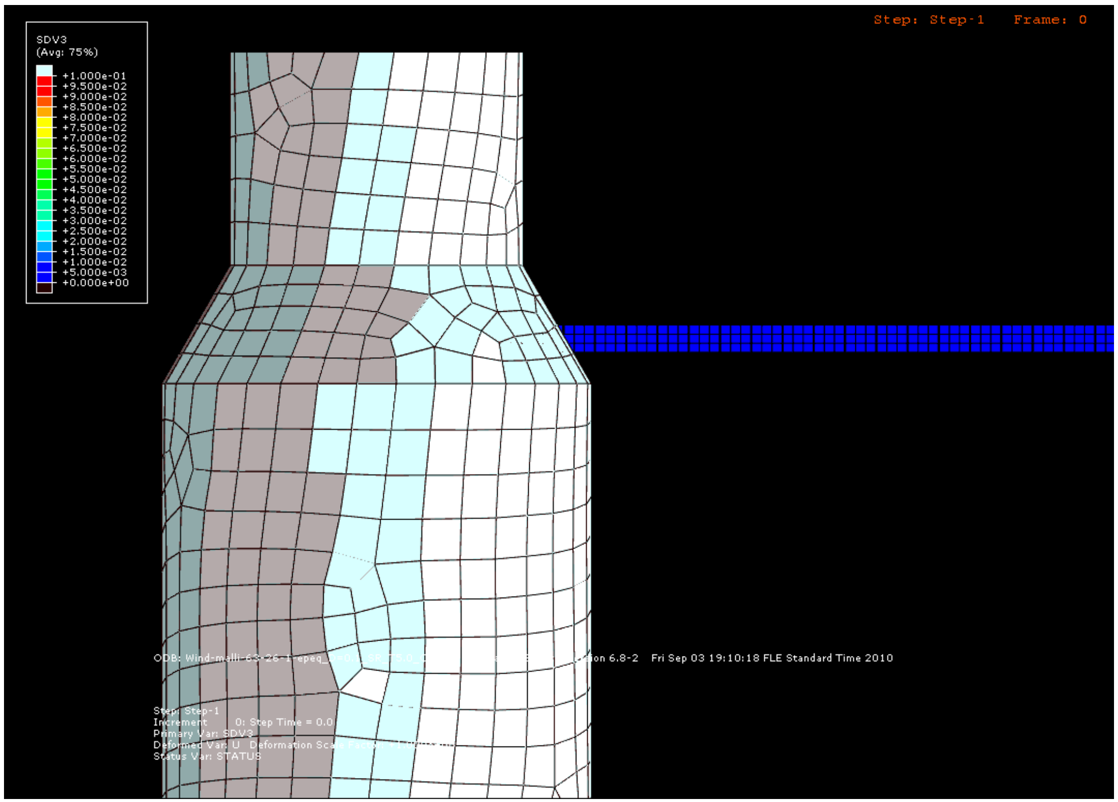
3) crushing.

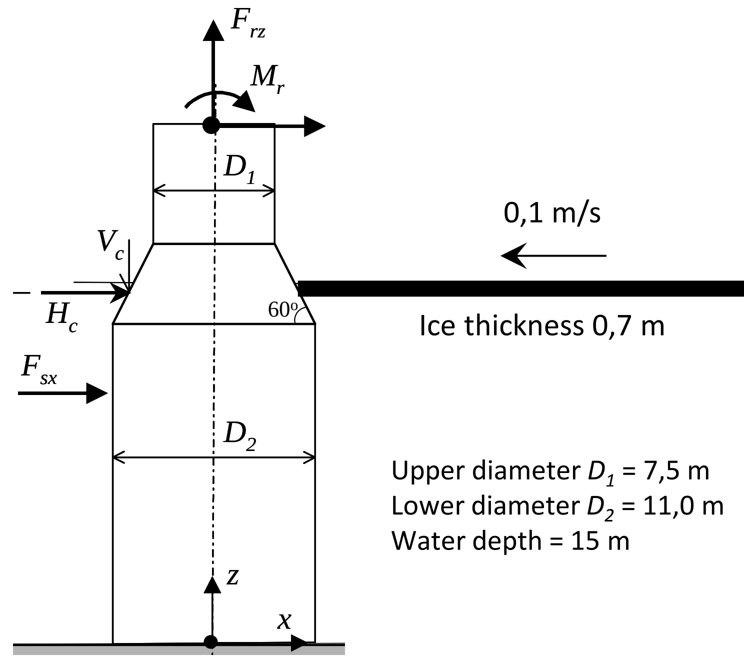


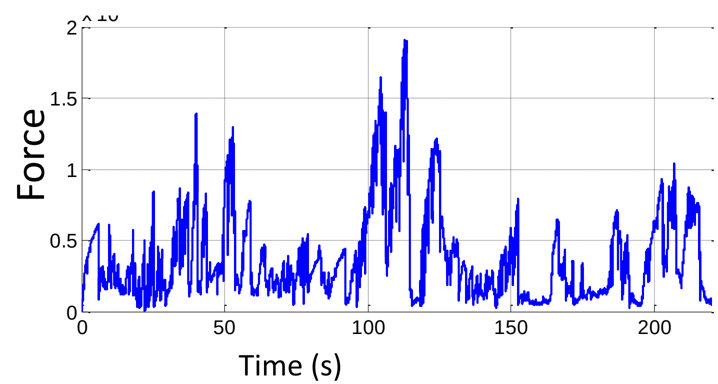
4) splitting

Bjerkås (2006)

Ice-structure interaction simulation



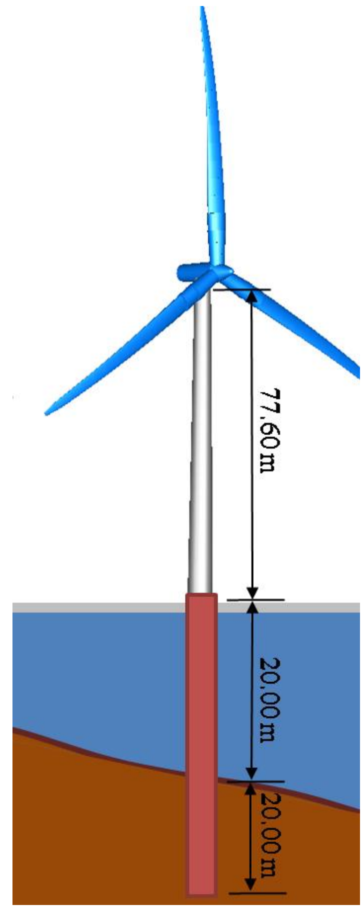




ICE-INTERACTION OF OWT

Introduction of ice loads in overall simulation of offshore wind turbines

- Structural model for dynamic analysis including
  - GOAL: all essential parts and loads within one tool
- Simulation of ice-structure interaction
  - Ice induced vibrations
  - Fatigue loads
- Feasibility studies of structural concepts
- Optimization of offshore foundations
  - Less conservative safety factors
  - Cost effective



Advanced models and analysis tools

Vertical structures:

- PSSII - a dynamic analysis program for soil-structure-ice interaction
- Määttänen – Blenkarn ice load model

Conical structures:

- Dynamic ice load model based on Ralston's equations

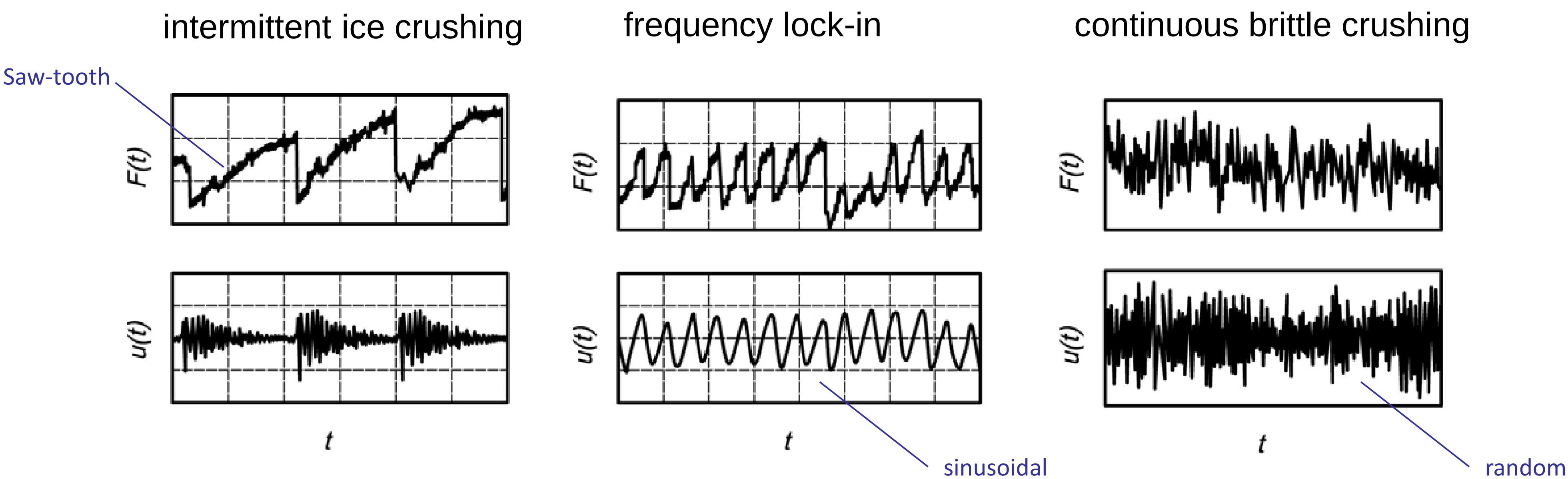
FEM based simulation tools:

- Ice failure models for ABAQUS Standard and Explicit

Simulation platform development:

- Collaboration with Fraunhofer IWES (Bremerhaven) and HSVA Ice Model Basin (Hamburg)

Time-varying ice-interaction processes

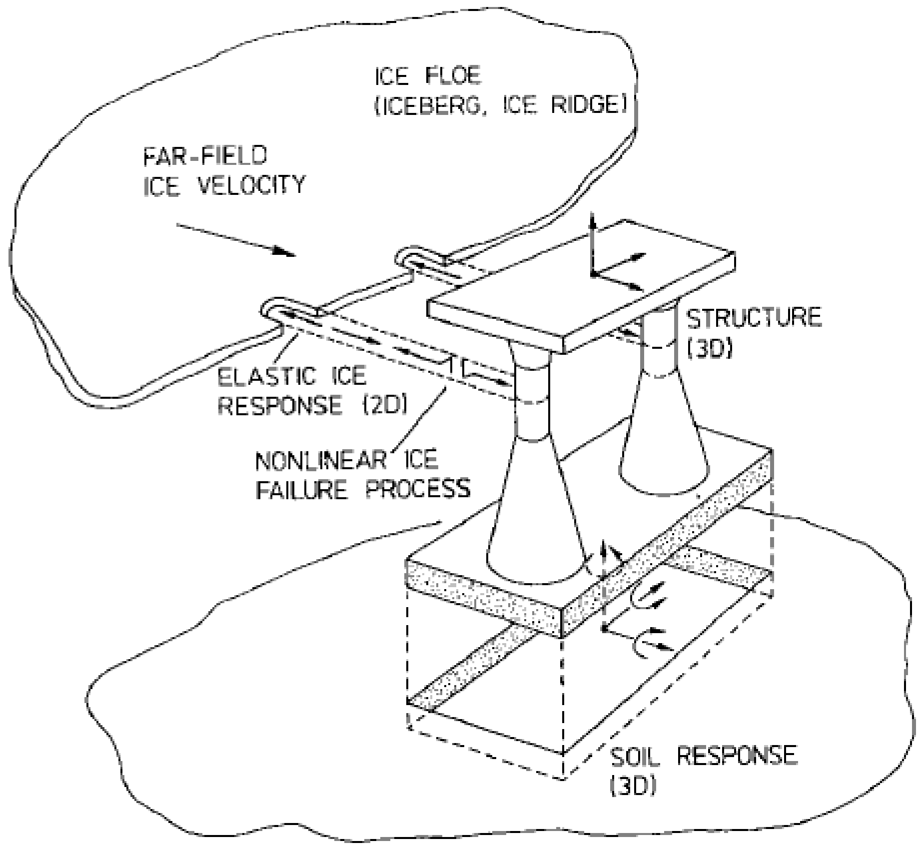


t time
F ice action
u structure displacement at ice level

Reference: ISO/DIS 19906

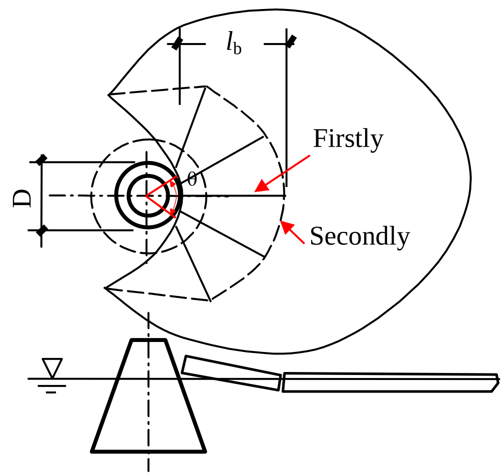
PSSII – dynamic ice load model for vertical structures

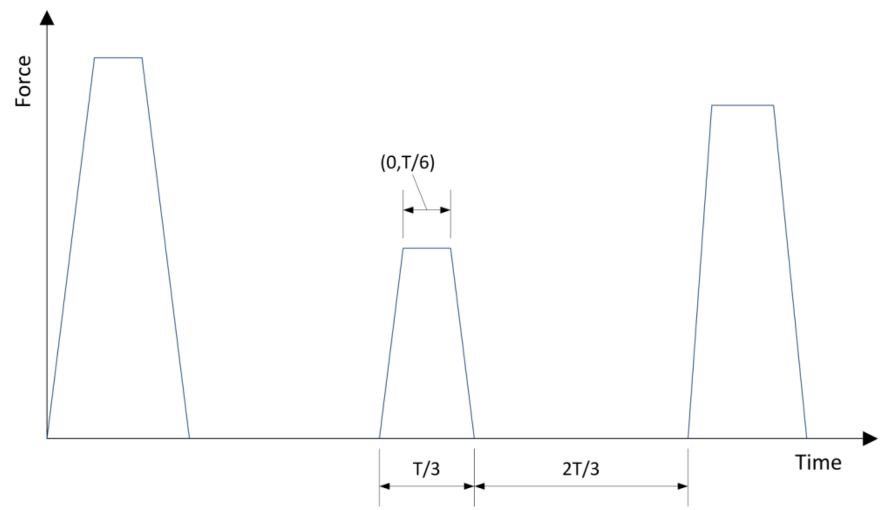
- PSSII is a dynamic analysis program for soil-structure-ice interaction
- Development has started at the beginning of 90's by Tuomo Kärnä at VTT
- Main input parameters
  - Dynamic model of OWT
  - Ice thickness
  - Ice drift velocity
  - Crushing pressure of ice
- The model outputs are
  - Ice loads
  - Dynamic response of the structure



The dynamic ice load model for a conical substructure

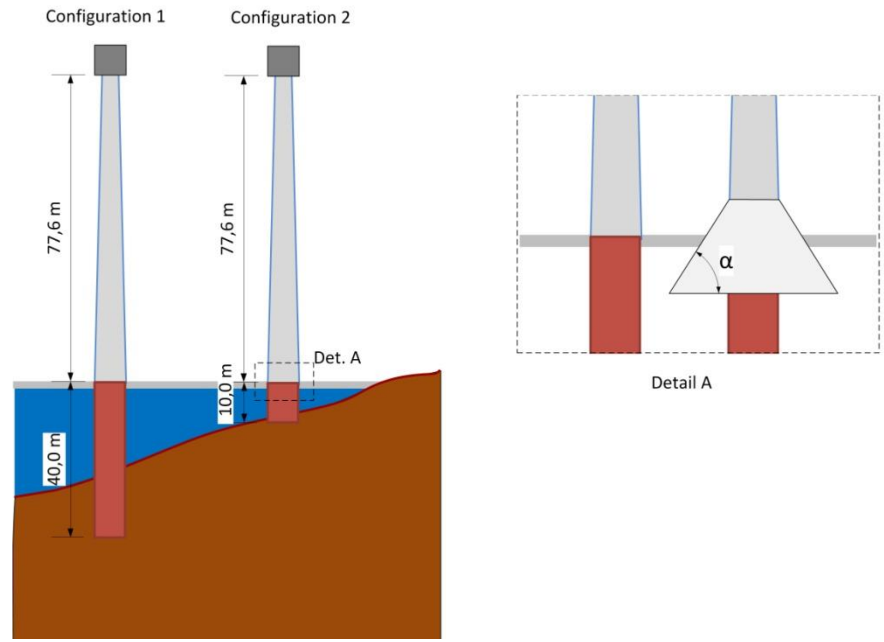
- Based on ice forces on a conical structure defined by Ralston
- The ice force is assumed to be normally distributed
- Breaking length of an ice block is normally distributed and defines the time interval between load peaks
- Main input parameters
  - Geometric model of OWT
  - Ice thickness
  - Ice drift velocity
  - Bending strength of ice
- The model output is the dynamic ice load





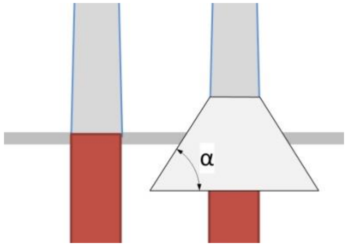
Case studies of ice induced vibration

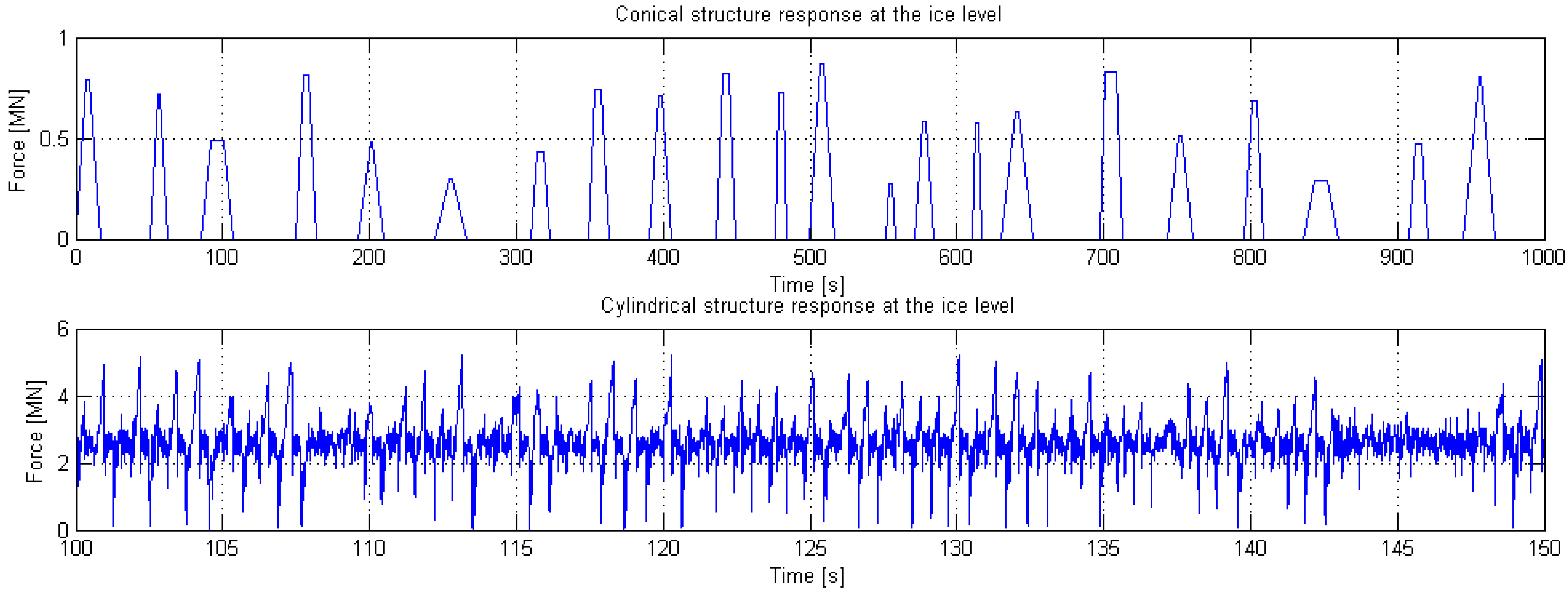
- Conceptual studies of different shapes of the substructure at the water level
  - Conical – ice fails by bending
  - Cylindrical – ice fails by crushing
- Conical substructure reduces vibration amplitude and load magnitude in the ice-structure interaction
- Structural performance in ice interaction at different water depths



Jussila, V., Heinonen, J., 2012. Comparison of Ice-induced Vibrations on a Conical and a Cylindrical Offshore Wind Turbine Substructure. Proceedings of 21st IAHR International Symposium on Ice.

Dynamic ice loads of a conical and a cylindrical structure





Conclusions

- Large capacity for offshore wind energy in cold climate regions
- Design of offshore wind energy in cold regions needs understanding of
  - Ice conditions in site
  - Ice actions
- Sea ice actions usually dominates the structural loads and the design of OWT
- Ice loads and ice-induced vibrations should be determined by combining information from
  - Full-scale experiments
  - Small-scale experiments
  - Numerical simulations

VTT provides solutions for offshore wind energy

- Site-specified environmental conditions:
  - prevailing sea ice conditions: thickness and drift, identification of different ice features
  - stochastic analysis of expected conditions in selected recurrence periods
- Structural performance of offshore wind turbine in ice-covered waters
  - Dynamic ice loads on structures
  - Ice load due to different ice features: level ice, ridges, etc.
  - Ice interaction with different types of substructure: monopile, conical shapes, jackets, etc.
- Structural concepts and materials for offshore wind turbines in ice covered sea areas
- Ice accretion analysis and prevention of ice on structures

VTT creates business from technology