ICE MECHANICS: SOME ACCEPTS OF ICE MODELLING AND CASE STUDIES

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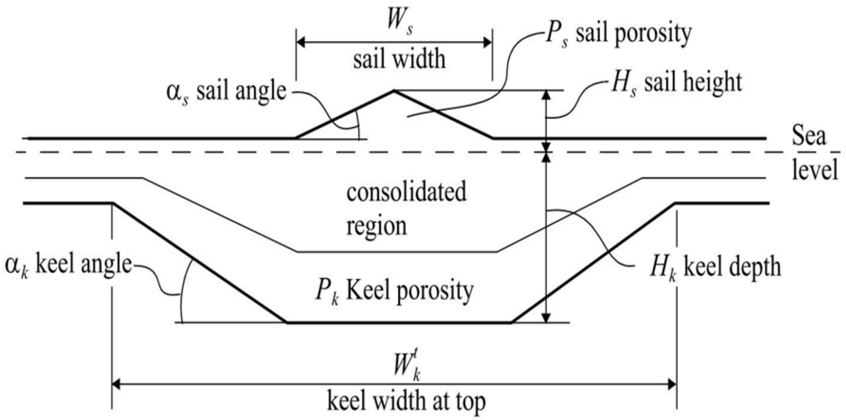
Introduction

- Ice mechanics is the study of properties of ice features and create phenomenological and physical models ty predict the realist behaviour of such ice features.
- Abundant natural resources give raise to unique opportunities to arctic and northern sea areas. Presence of ice creates new threat to offshore and onshore structures. Sea ice features such as icebergs and ridges are common in this area.
- Due to decline in the average extent of sea ice, new shipping routes are opening across the arctic and sub-arctic areas.
- Knowledge of the load levels due to ice structure interaction is required to exploit these opportunities fully. Therefore, experimental and numerical investigations on are proposed.
- Design of offshore structures in Arctic waters is strongly depended on accurate and representative estimates of local and global ice loads.

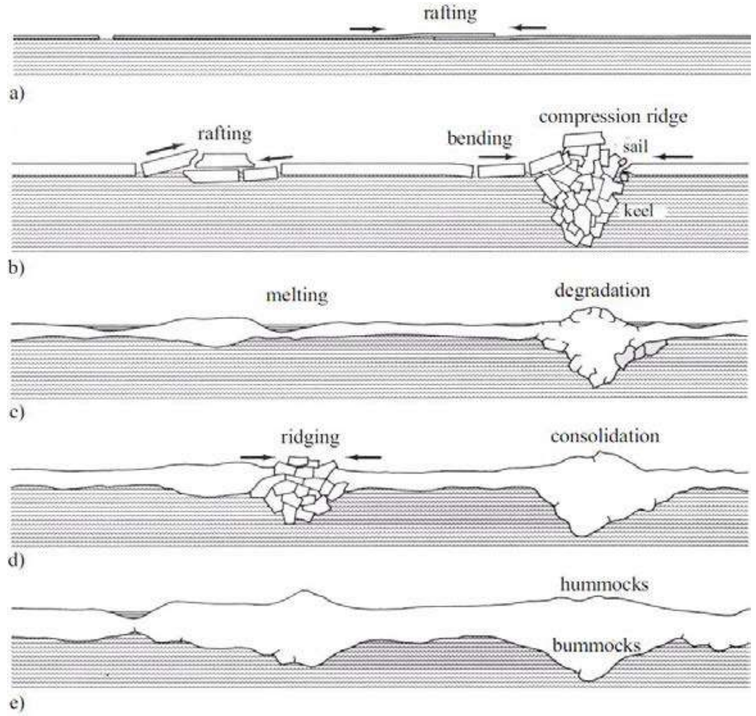
Sea ice ridges

The major ice loads come from the sea ice ridges which are common in arctic and sub-arctic areas and ice ridges are made of ice rubble. (*if icebergs are not present !*)

- Driving forces in formation of ridges
  - Wind
  - Currents
- Formation of Ridges
  - Compression
  - Shear
- Types of ridges
  - Multi year
  - First year



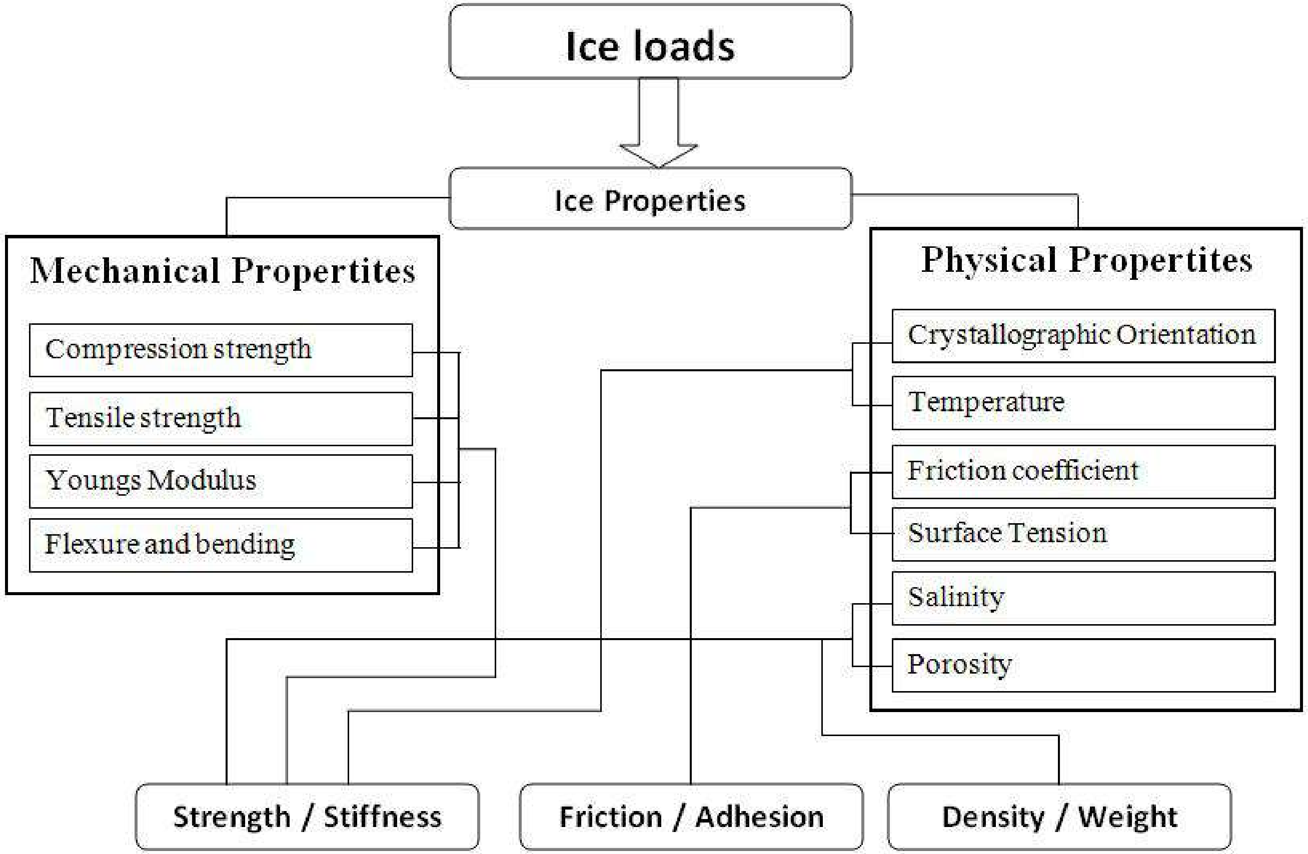
Ref: Timco, G.W.,Burden,R.P., An analysis of the shapes of sea ice ridges



Ref: Sanderson, T.J.: Ice Mechanics-risk to offshore structures

Ice properties

- Sea ice properties dependency flowchart



Ref: Gudmestad et al. (2007), Engineering aspects related to Arctic offshore developments

Ice structure interaction

- Physical parameters used to describe interaction scenarios

Level ice	ice thickness
	drift speed
Rafted ice	total thickness
	extent of rafted ice areas
	drift speed
	mean floe thickness
	floe edge thickness
	floe drift orientation relative to the structure
	floe speed
Multi-year ridges	ridge spacing or frequency
	ridge orientation
	ridge length
	maximum ridge sail height
	maximum ridge keel draft
	ridge keel geometry

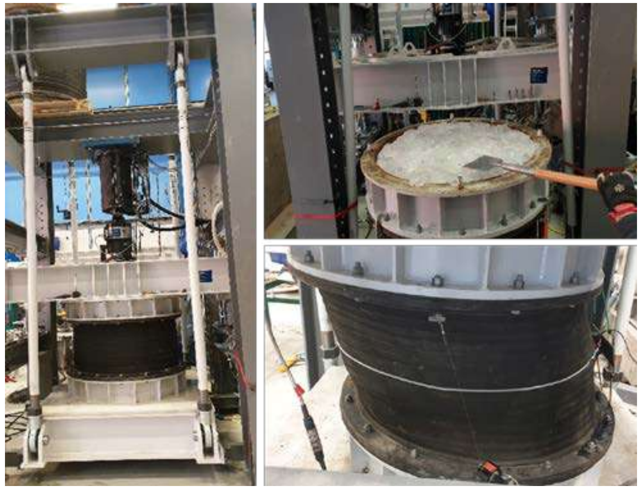
First-year ridges	surrounding level ice thickness
	thickness of the consolidated layer
	extent consolidated layer thicknesses
	ridge length
	maximum keel draft
	drift speed
Icebergs	waterline length
	waterline width perpendicular to length
	maximum height above waterline
	maximum draft
	depth of first contact with structure
	mass
	local shape
	drift orientation
	drift speed

Ref: Sanderson, T.J.: Ice Mechanics-risk to offshore structures

Experimental Techniques

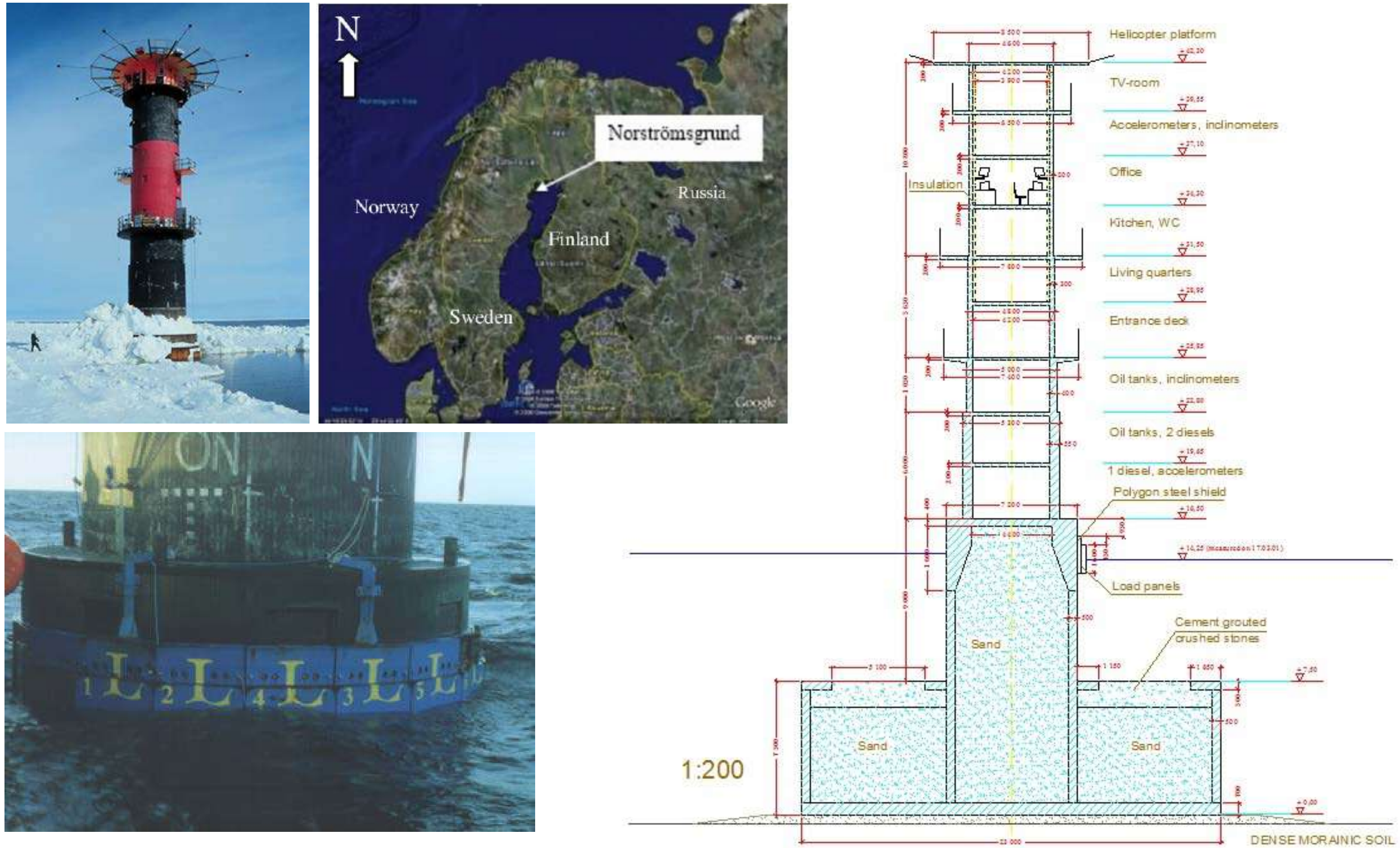
Pull-up test

Ref: Patil et al., (2021)



Large-scale simple shear test

Ref: Patil et al., (2021)



Ice-structure interaction load events on Norströmsgrund lighthouse

Ref: Patil and Sand, (2019)

Material Modelling (I)

The material model describes the physical properties of given material under certain stress state. The most popular material model comes from soil mechanics e.g. Mohr-Coulomb.

$$\tau_{\max} = \sigma_n \tan \phi + c$$

Advantages

- Simplicity and less no. of variables needed to validate
- The model gives a straight forward connection between the shear strength and the material parameters .Thus, this model is useful in simpler computation models like limit load calculations.

Disadvantages

- Assumptions of linear relationship between shear and normal stresses may be contested
- Compression failure can not be simulated

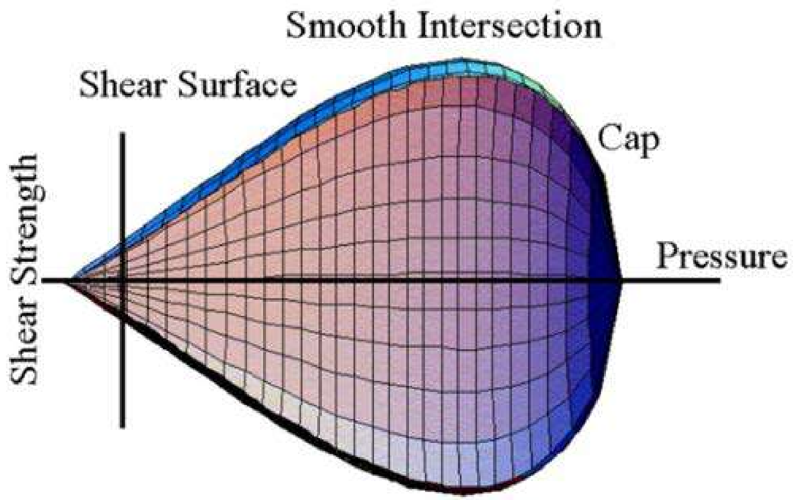
Material Modelling (II)

Continues **S**urface **C**ap **M**odel (CSCM)

- Proposed by Sandler et al. (1976) and further developed by Schwer and Murray (1994)
- CSCM has calibration and validation in LS-Dyna for concrete
- Smooth interaction of “cap” and shear failure surface
- Damage formulation implemented

Material model parameters can be divided into

- Strength Parameters
- Shear Surface Parameters
- Cap Hardening Laws
- Damage Parameters



Ref: Murray et al. (2007)
Ref: Schwer and Murray (1994)

Hill’s failure criterion for anisotropic ice

- Elasto-plastic/Continuum Damage Mechanics formulation based on Hills yield criterion to model the compressive behaviour of ice.

Effective stress expressed by damage D:

$$\bar{\boldsymbol{\sigma}} = (1 - D)\boldsymbol{\sigma}$$

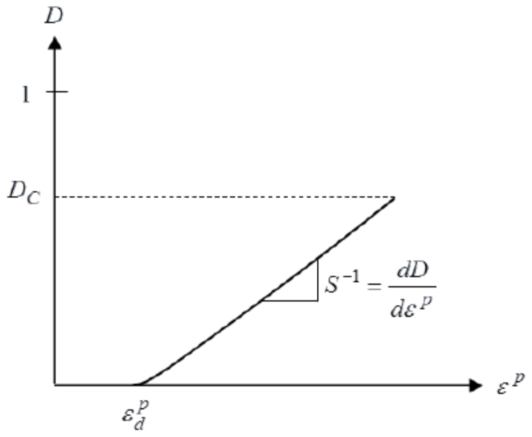
Yield function:

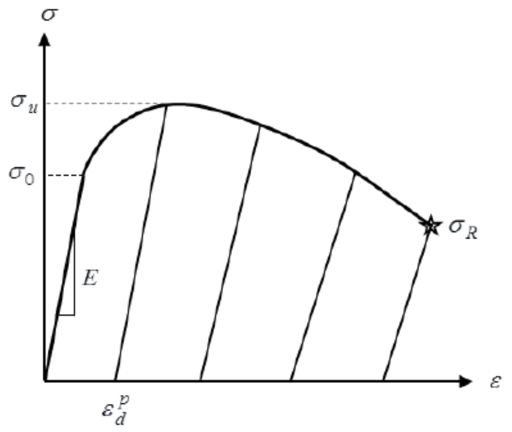
$$f(\boldsymbol{\sigma}, R, D) = \sqrt{\bar{\sigma}_{eff}} - \left(\sigma_0 + R\right) = 0$$

Effective stress based on Hill’s criterion:

$$\bar{\sigma}_{eff} = F\left(\bar{\sigma}_y - \bar{\sigma}_z\right)^2 + G\left(\bar{\sigma}_z - \bar{\sigma}_x\right)^2 + H\left(\bar{\sigma}_x - \sigma_y\right)^2 + 2L\bar{\tau}_{yz}{}^2 + 2M\bar{\tau}_{zx}{}^2 + 2N\bar{\tau}_{xy}{}^2$$

Damage as function of effective plastic strain:





Calibration of Hill’s criterion

Effective stress - Hill’s criterion:

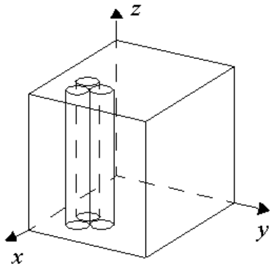
$$\bar{\sigma}_{eff} = F\left(\bar{\sigma}_y - \bar{\sigma}_z\right)^2 + G(\bar{\sigma}_z - \bar{\sigma}_x)^2 + H\left(\bar{\sigma}_x - \sigma_y\right)^2 + 2L\bar{\tau}_{yz}{}^2 + 2M\bar{\tau}_{zx}{}^2 + 2N\bar{\tau}_{xy}{}^2$$

Transversally isotropic material, independent material parameters reduces to 3 :

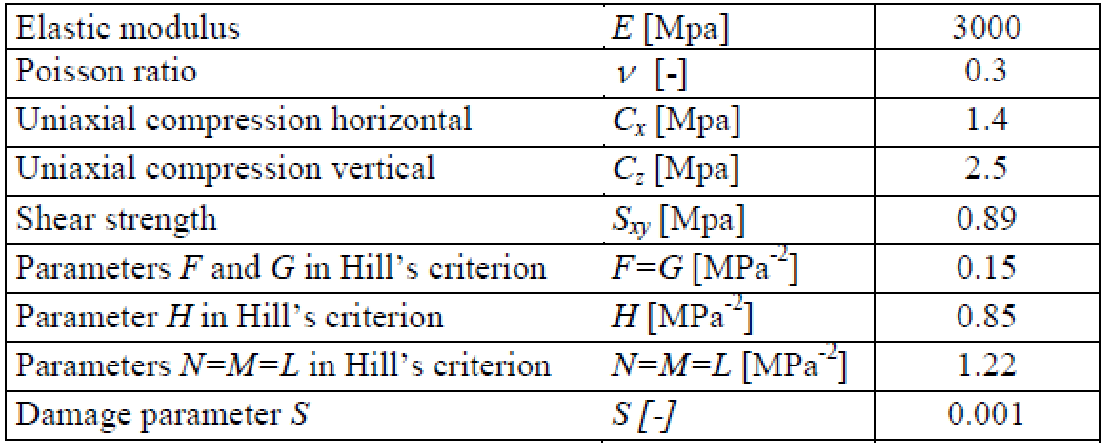
$$F = G = \frac{1}{2C_z^2}$$

$$H = \frac{1}{C_x^2} - \frac{1}{2C_z^2}$$

$$N = M = L = \frac{1}{2S_{xy}^2}$$



Properties of Hills criterion:



Elastic modulus	E [Mpa]	3000
Poisson ratio	ν [-]	0.3
Uniaxial compression horizontal	C_x [Mpa]	1.4
Uniaxial compression vertical	C_z [Mpa]	2.5
Shear strength	S_{xy} [Mpa]	0.89
Parameters *F* and *G* in Hill’s criterion	F=G [MPa^{-2}]	0.15
Parameter *H* in Hill’s criterion	H [MPa^{-2}]	0.85
Parameters *N*=*M*=*L* in Hill’s criterion	N=M=L [MPa^{-2}]	1.22
Damage parameter *S*	S [-]	0.001

- Hill’s orthotropic failure surface contains only quadratic terms in stresses.
- Tensile strength of ice is overestimated significantly.
- A tensile cut-off criterion is added, by using a cohesive zone element model, to simulate the brittle behaviour of ice subjected to tensile stresses.

Nonlinear finite element analysis of ice-structure interaction

Key ingredients:

- **Constitutive modelling of level ice**
  - An elasto-plastic/Continuum Damage Mechanics formulation based on Hills yield criterion to model the compressive behaviour of ice.
  - Combined with a Cohesive Zone Element formulation for modelling the tensile- and shear behaviour to account for fracture of ice.
- **Hydrostatic, buoyancy forces and gravity of ice blocks**
  - A spring-dashpot model to account for buoyancy and drag acting on ice sheet/ice blocks during ice-structure interaction.
- **Contact kinematics**
  - A Coulomb friction model is employed, and the sticking force limit is a function of the friction coefficient and the contact forces normal to the interacting surfaces.

Highlights - *Simplified methods for ice structure interaction forces*

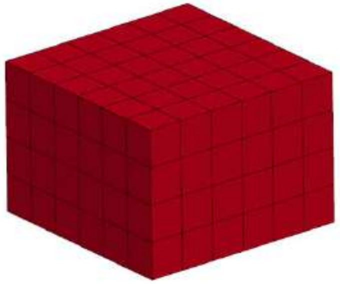
Strain rate dependent model:

- Application of the equivalent strain rate approach to indentation is nothing new.
- A new viscosity function for estimating the compressive strength of ice is introduced.
- Uniaxial compressive strength is taken as an ice regime parameter in different sea areas:
- Takes account of effects of strain rate, temperature, salinity, density and porosity on the compressive strength.
- Calibrated to predict compressive strength of :
  - Brackish ice (Bay of Bothnia)
  - Sea ice (Beaufort Sea)
- Full-scale data from measurements of ice forces on Norströmsgrund lighthouse in the Baltic Sea, and Molikpaq in the Canadian Beaufort Sea has been utilized for calibration of the proposed model.
- Comparisons have shown that the strain rate dependent model is capable of predicting reasonable results for level ice crushing loads on vertical structures.

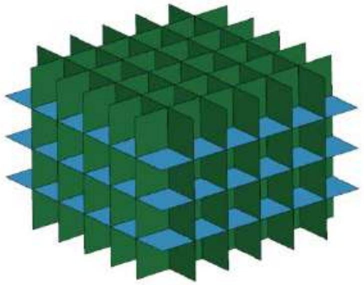
Cohesive Element formulation (CEM)

- Elastic behavior under compression
- Nonlinear spring elements
- Cohesive elements deleted when separation $\delta=\delta_f$ in Mode I, Mode II or mixed mode failure.

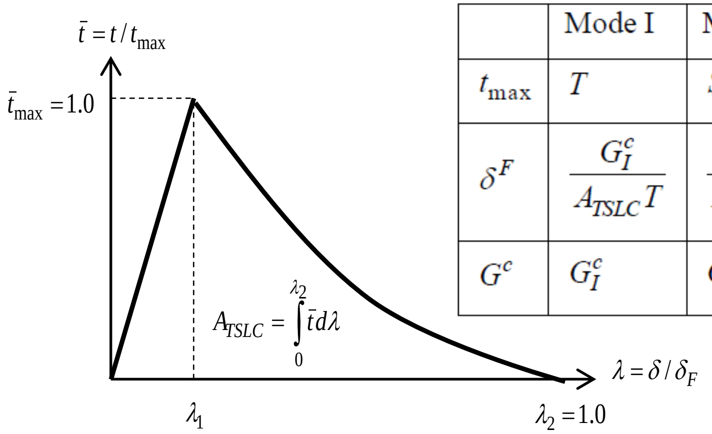
Bulk elements



Cohesive elements
at inter-element faces



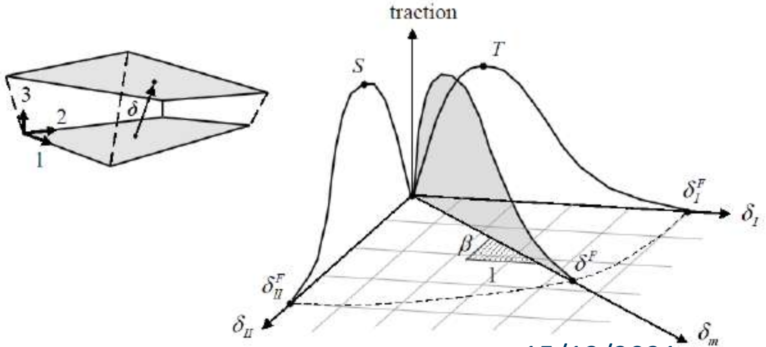
Normalized traction-separation curve:



	Mode I	Mode II
$t_{\max}$	T	S
δ^F	$\frac{G_I^c}{A_{TSLC} T}$	$\frac{G_{II}^c}{A_{TSLC} S}$
G^c	G_I^c	G_{II}^c

Interpolation mixed mode failure:

- Mode I (tension)
- Mode II (shear)



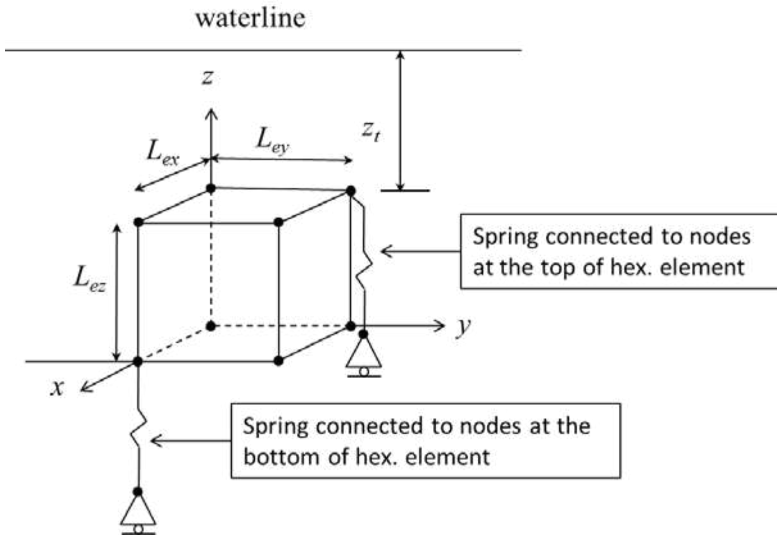
Buoyancy drag forces acting on ice blocks

- Buoyancy is modelled by using a spring-dashpot model.
- Springs are attached to all 8 nodes on hexahedral elements.
- Drag force is introduced by adding damping to the spring behaviour.

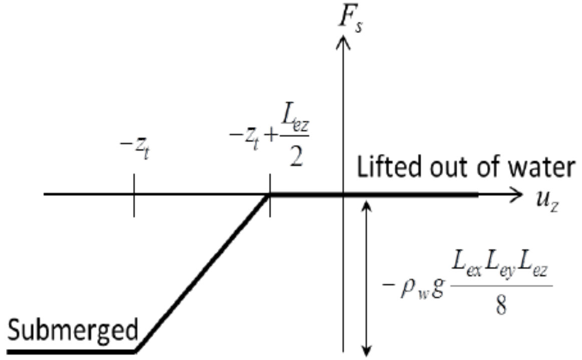
$$F_s^D = \frac{1}{2}\rho_w {v_z}^2 C_D \frac{Ae}{8}$$

- The water density is ρ_w
- v_z is the velocity of the node on hexahedral elements.
- Cd is the drag coefficient (1.05 for cubes)
- Effective area $A_e = L_{ex} L_{ey}$

Spring-dashpot model for hexahedral elements

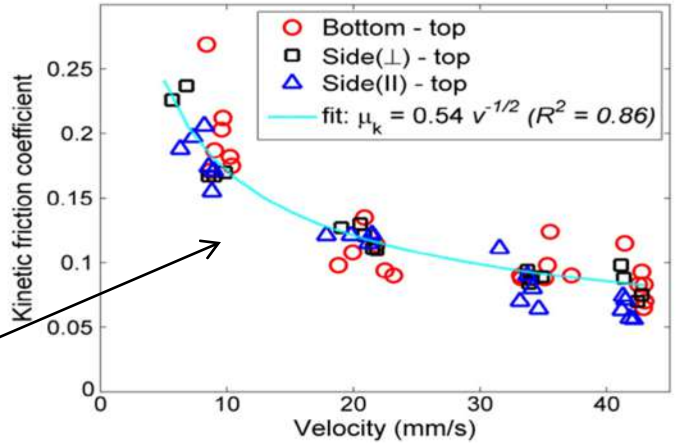


Force vs. displacement diagram for springs



Contact kinematics and friction

- Sukhorukov and Løset (2013) studied the friction of sea ice on sea ice
- The presence of sea water in the sliding interface had very little effect on the static and kinetic friction coefficients.
- Equation proposed by Sukhorukov and Løset (2013) :



$$\mu_D = \frac{0.54}{\sqrt{|v_{rel}|}}$$

LS-Dyna friction law:

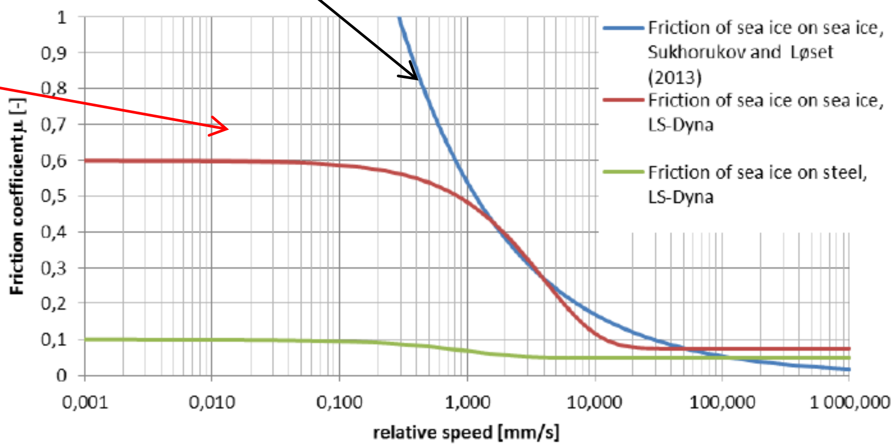
$$\mu = \mu_D + (\mu_S - \mu_D)\exp(-D_C|v_{rel}|)$$

Sea ice to sea ice friction:

- dynamic friction μ_D=0.075
- static friction μ_S =0.6
- decay coefficient D_C=0.25.

For ice on steel,

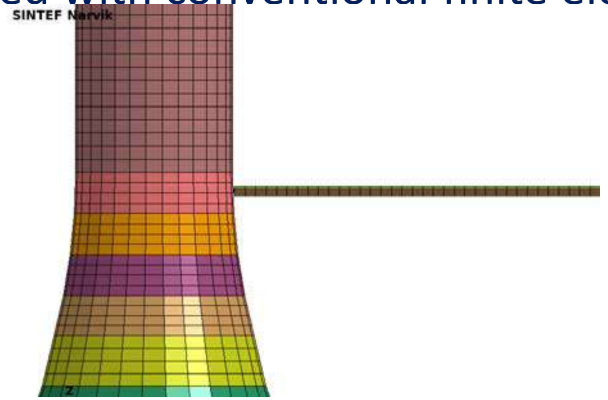
- dynamic friction μ_D=0.05
- static friction μ_S =0.1
- decay coefficient D_C=1.0.



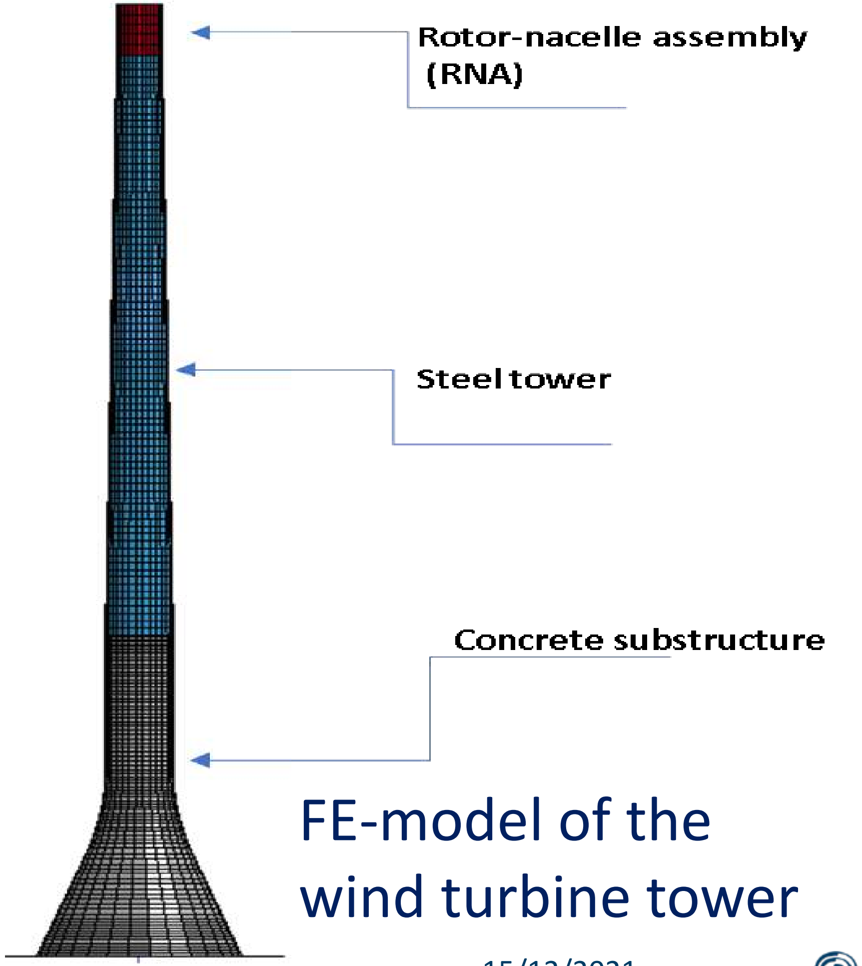
Case Study (I)

Numerical simulation of level ice loads and responses of an offshore wind turbine

- Data for Rotor-nacelle assembly (RNA) and the steel tower are based on the LW 8 MW reference wind Desmond Et al. (2016).
- The steel tower acts as a support structure for the RNA and concrete substructure, designed by Kvaerner.
- The Wind turbine tower geometry as well as the level ice was modelled with conventional finite elements.

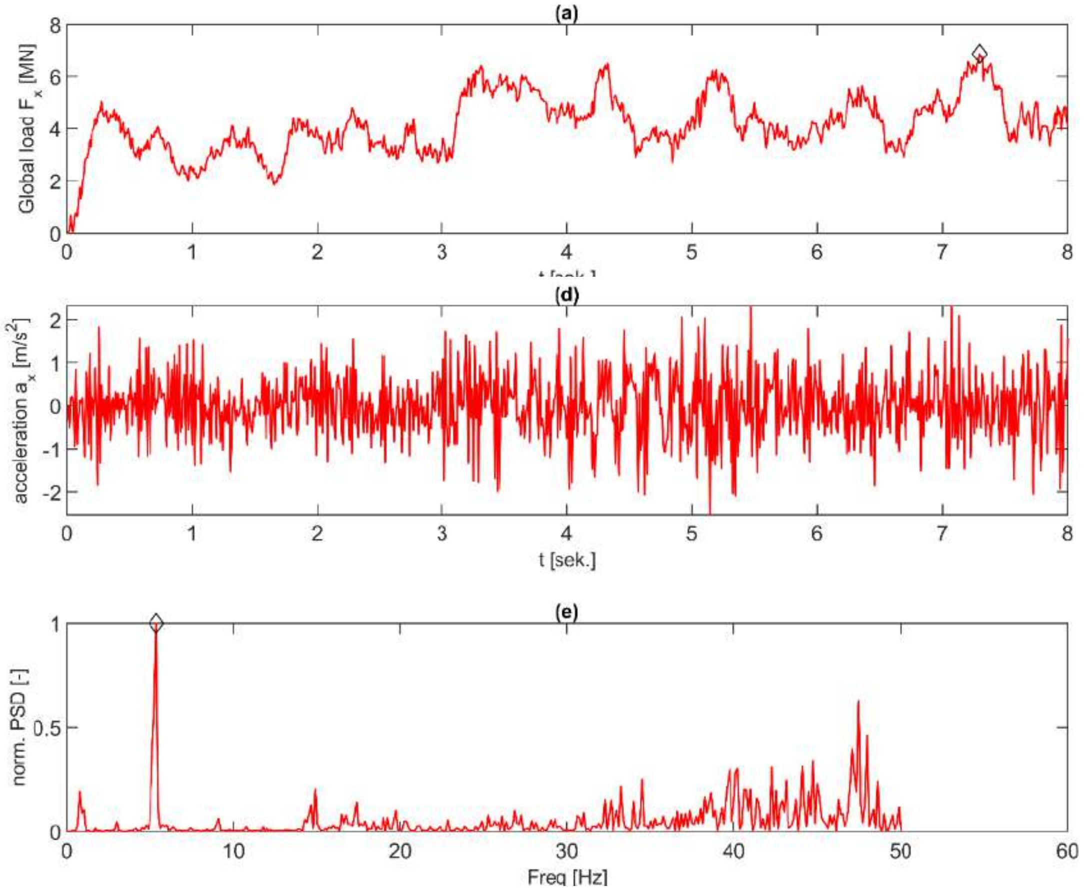


3D FEM model of wind turbine and ice sheet

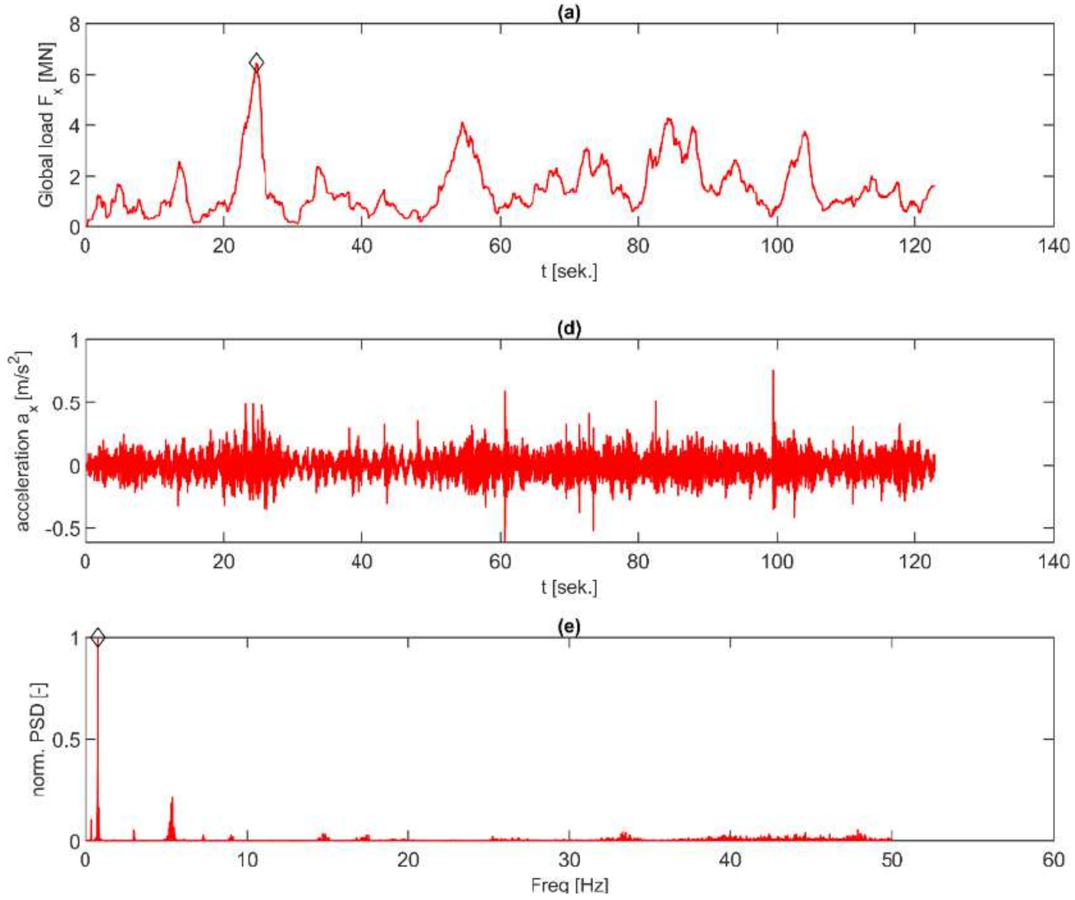


FE-model of the wind turbine tower

Results



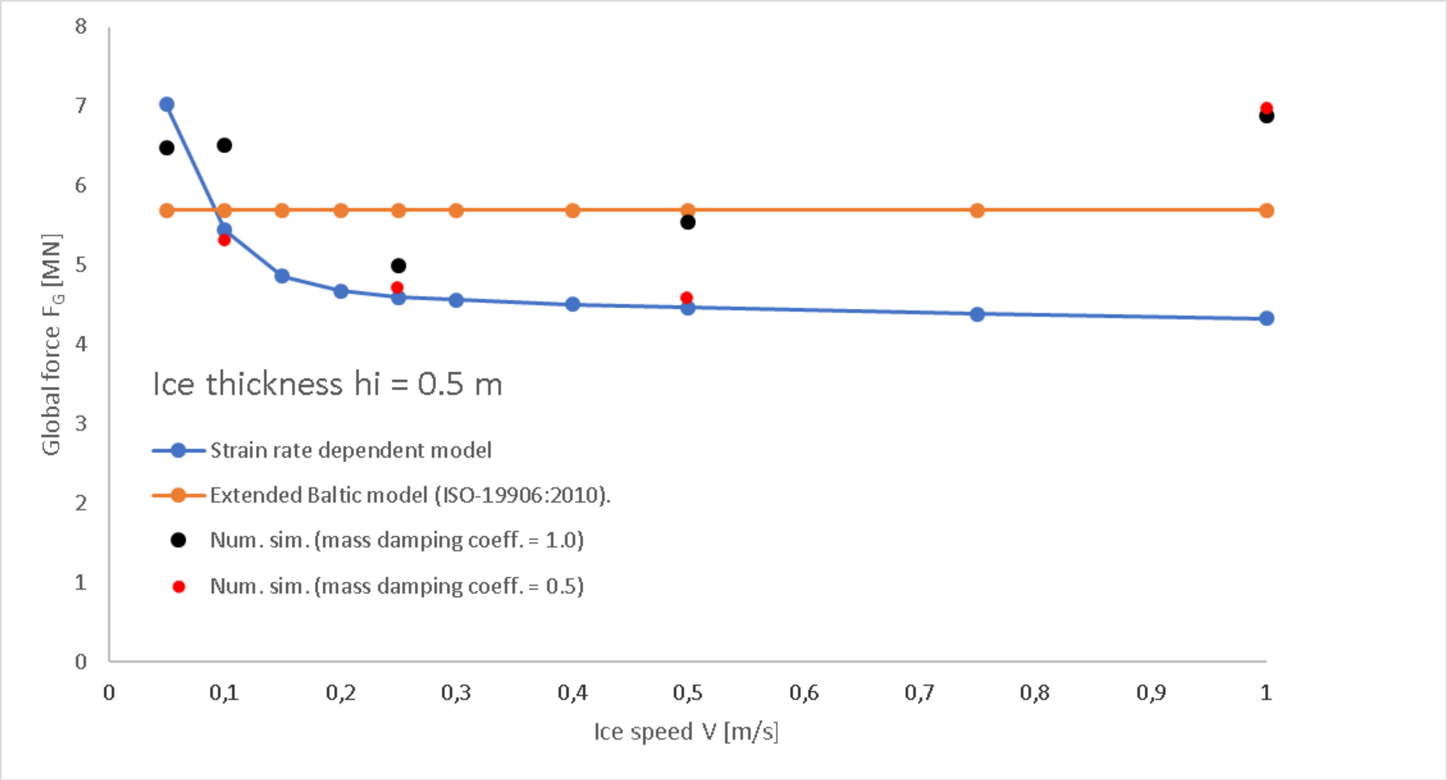
For ice speed 1.0 m/s



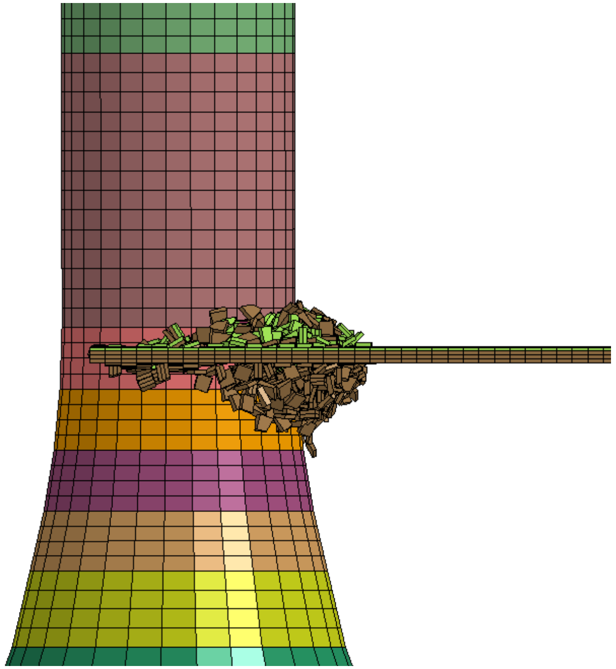
For ice speed 0.05 m/s

Global Ice loads

- Numerical model is capable of simulating effects of ice speed on global ice load and take account for ice-induced vibration.
- Strain rate dependent model and Extended Baltic model are valid for ice speeds lower than 0.5 m/s.



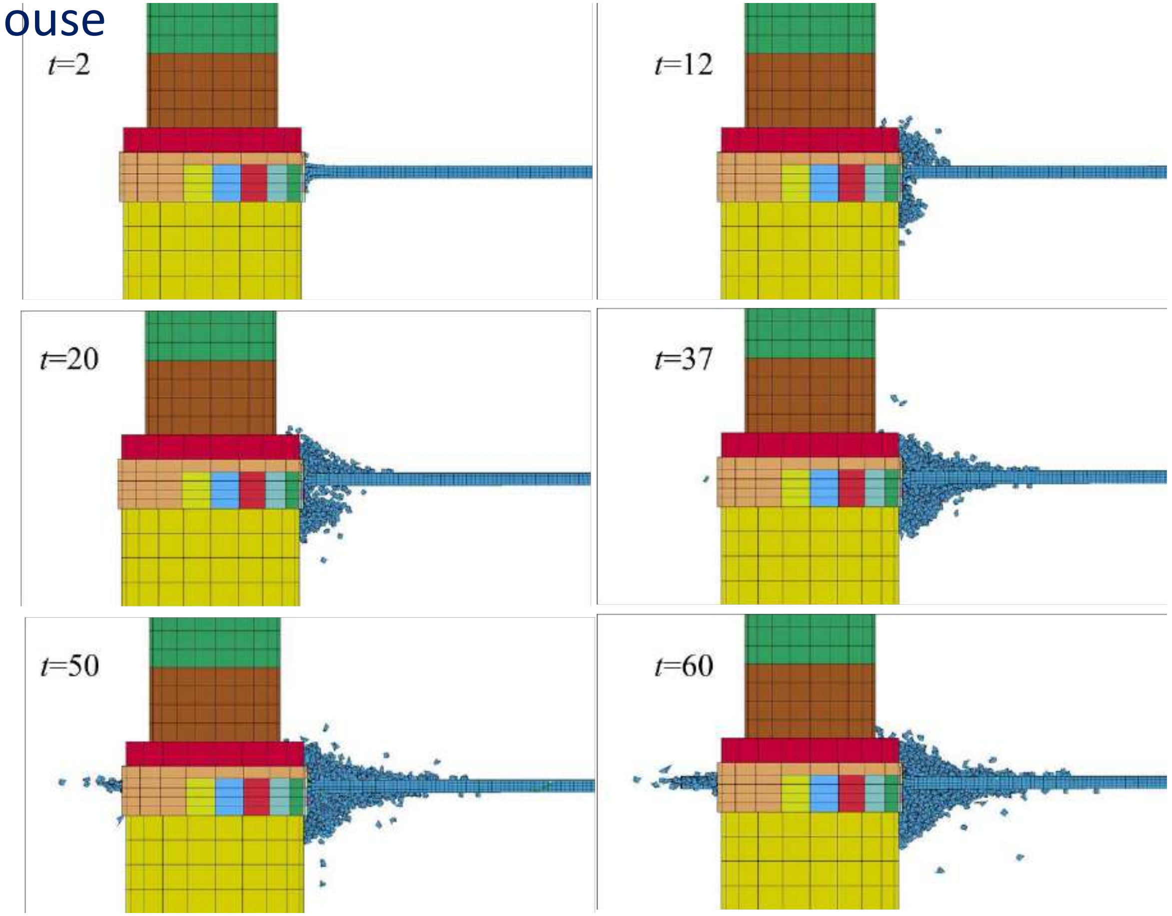
Ice rubble build up

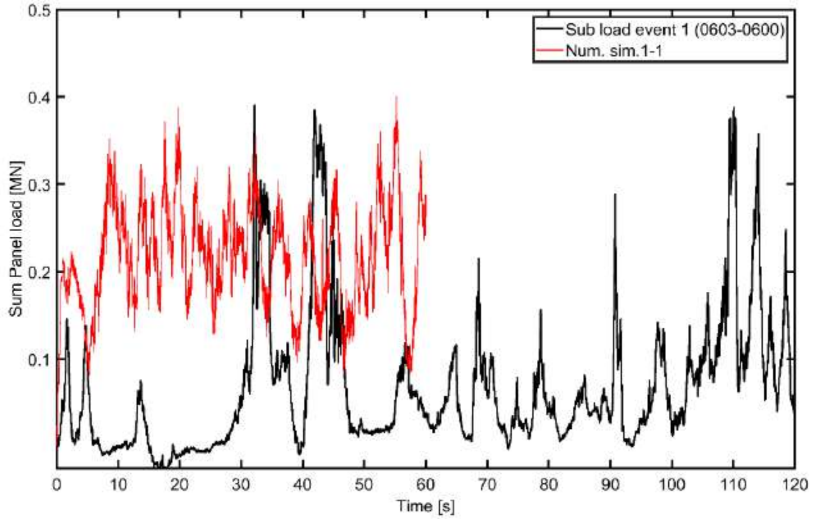


Case Study (II)

Interaction of <u>Ice rubble field </u>with Norströmsgrund lighthouse

- Load event From STRICE 2002 project database
  Cohesive element method (CEM)
- Mohr-Coulomb (MAT 173) as Bulk Element and Cohesive General (MAT 159) implemented
- Damping of structure included
- Buoyancy and friction included





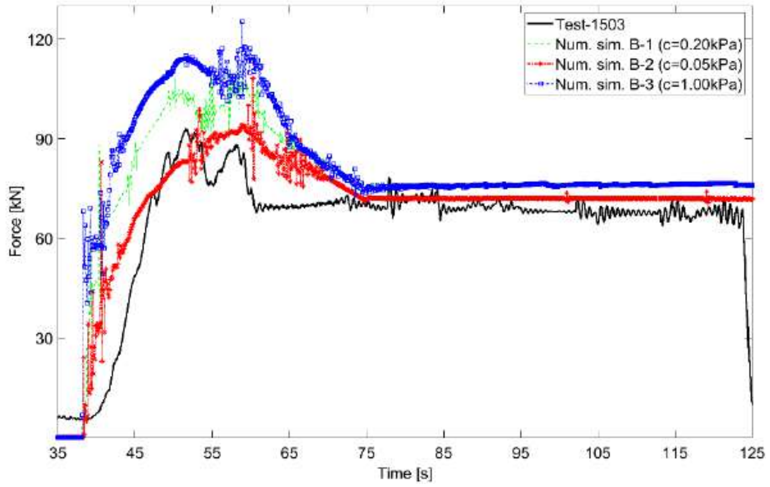
Ref: Patil et al., (2015)

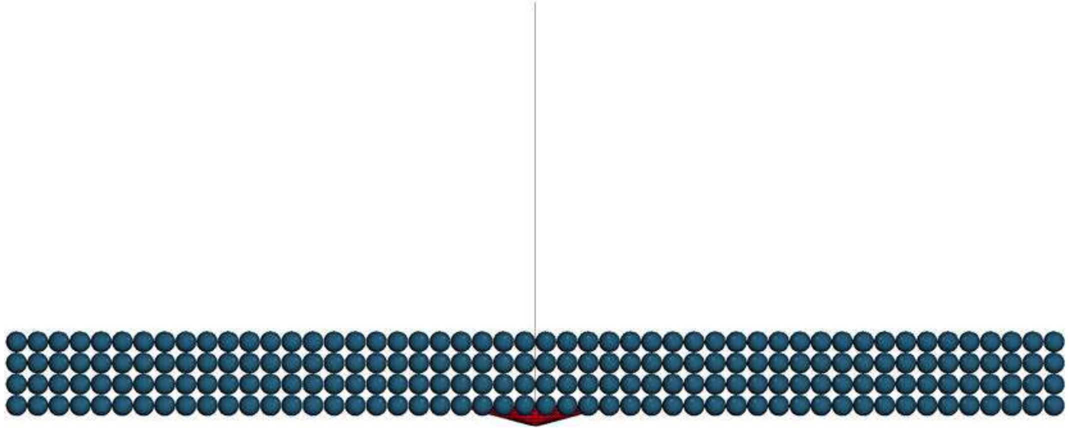
Case Study (III)

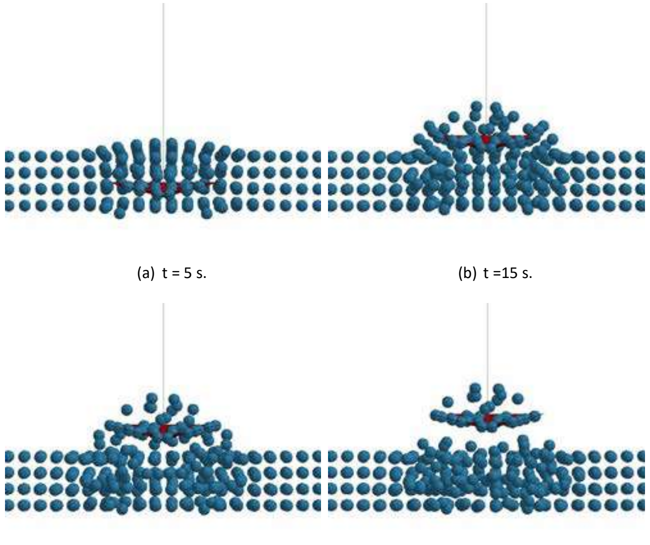
Pull-up test

Smoothed **P**article **H**ydrodynamics

- Smoothed particle hydrodynamics (SPH) is a mesh free Lagrangian method developed by Lucy (1977) , Gingold and Monaghan (1977).
- The method was developed to avoid the limitations of mesh distortion issues in large deformation problems in finite element method. The main difference between finite element methods and SPH is absence of a grid.
- CSCM used as brash ice material model
- Spring dash pot model to simulate buoyancy and drag
- Parametric study







(a) t = 5 s.

(b) t =15 s.

(c) t =25 s.

(d) t = 40 s.

Ref: Patil et al., (2021)

Conclusions and Remarks

The main findings of this study are:

- Simplified method using strain rate deepened model, with spring dah system top simulate buoyancy and drag, has been successfully implemented to simulate in structure interaction.
- Ice-structure interaction scenarios may be simulated by the proposed cohesive element formulation and realistic magnitudes of ice loads can be simulated for ice in continuous crushing for a wide range of ice speeds.
- Effect of buoyancy in ice-structure simulations is important in order to achieve a realistic representation of up-riding and submergence of failed ice.
- The proposed spring-dashpot model for modelling buoyancy reduces simulation times significantly compared to fluid-structure interaction algorithms.
- The ad-hoc scaling factor used in pull-up test and ice rubble field structure interaction, gives satisfactory results. Although further investigation is needed.
- Wide verity of experiments are needed to calibrate material model for level ice and ice rubble. Although some assumptions and simplifications can used to reduce the nos. of parameters.

Conclusions and Remarks

- Ice rubble is highly complex material, laboratory and in-situ testing is needed. High quality experiments are also needed to validate and verify numerical models.
- In-situ or field testing is costly and highly depended on natural variable such as weather. In-situ testing offers realistic boundary conditions but requires special attentions to interpret the results.
- Laboratory testing may be less expensive but based on assumptions and simplifications of process may over or under estimate the measured parameter. Hence, careful attention is needed.
- Finding suitable material model parameters is difficult and complex activity. Material models parameters can be reduced with some assumptions and simplifications.
- Scaling factor based on porosity

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