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Recent Trends in Simulation of Ice-Structure Interaction

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POAC 2019 – TU Delft, June 13, 2019

Outline

1. Ice-structure interaction
2. Simulation methods and approaches
3. Validation
4. Examples of interesting results obtained with DEM
   - Ice rubble & punch-through tests
   - Ice rubble & shear box tests
   - Ice failure against an inclined structure
5. Conclusions

Ice-Structure Interaction

- Complicated
  - Velocity, temperature – brittle vs. ductile ice response
  - Width, shape, inclination, stiffness of the structure – ice failure mode
  - Thickness of the ice – failure mode, aspect ratio
  - 2D / 3D processes – cone is a 3D structure
- How to study such a complicated problem?
  - Full scale – Molikpaq, Norströmsgrund, Kemi I, Confederation Bridge, MSI
  - Laboratory scale – Contact line observations, ridging / rafting tests
  - Analytical models – Korchavin, Popov, ISO19906
  - Simulations – FEM, DEM, PBM
- All the approaches are needed, all have pros and cons.
  Parallel use of different approaches usefull.
  All approaches should be equally and critically assessed.

Ice-Structure Interaction

	Cost	Realism	Control	Level of details in analysis
Full scale tests	☆☆☆☆☆	☆☆☆☆☆	☆	☆☆
Lab scale tests	☆☆☆	☆ … ☆☆☆☆☆	☆☆☆	☆☆☆
Analytical models	☆	☆ … ☆☆☆☆☆	☆☆☆☆☆	☆☆☆☆
Simulations	☆	☆ … ☆☆☆☆☆	☆☆☆☆☆	☆☆☆☆☆

Simulation methods:

- Low cost
- Can be made realistic
- Full control of parameters
- Superior in analysing complicated processes, such as ice-structure interaction

Simulation Methods and Approaches

- Continuum methods
  - FEM, XFEM, ALE
  - Well established
  - Direct simulations of 3D fracture or ice crushing may not be possible – too many elements are needed – need to use phenomenological models.
- Discrete methods
  - DEM, NDEM, Lattice
  - Usage growing fast
  - Can be computationally challenging
- Hybrid methods, Physically-based modeling
  - Analytical or heuristic solutions + a numerical method
  - Computationally effective
  - Need carefull consideration on what is modelled; constraints

Simulation Methods and Approaches

- Peridynamics
  - New, yet to show the benefit to Arctic engineering.
- CFD
  - Growing, very much needed
  - Hydrodynamics in ice problems
  - Ice + waves

Simulation Methods and Approaches

- Computational speed vs. attension on details
- Desing ice load vs. numerical experiments
- Method development vs. research in ice engineering
- Some problems are too complicated to be simulated in detail.

Validation

Nobody believes in simulations – except the one who conducted them.

Everybody believes in experiments – except the one who conducted them.

Validation

- Large scale – ice load, ice resistance
  - Appears attractive
  - Not easy to get reliable full scale data with all the relevant information.
  - Somewhat easier to get lab scale data.
  - Statistical nature of ice load data: What do one or few data points represent?
  - Not all experimental data is reliable.
  - Downscaling only in a statistical sense.
  - Lack of generality: may not apply to another load case.

- Small scale – beam bending, plate bending, fracture length
  - Requires experimental data in small scale – only.
  - Upscales naturally.
  - Ideally leads to emerging properties at a larger scale.

Validation

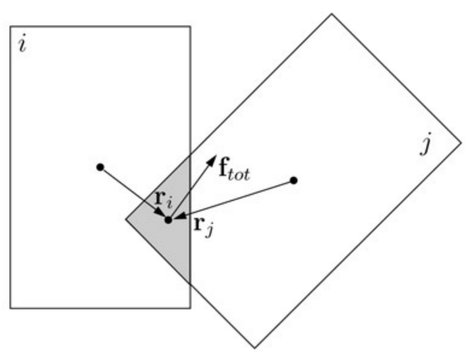
- If you do not believe in simulations, what is it you do not believe in?

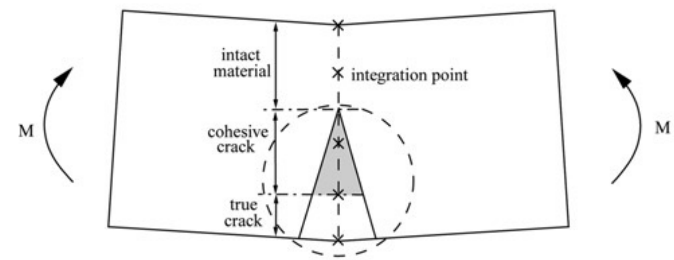
  Consider
  - N elastic spheres on a frictionless surface with rigid boundaries.
  - A DEM to model the contacts of elastic spheres, and of a sphere and a wall.
  - Validation to show that a contact follows the Herzian contact model. This is local scale validation, or micromechanics.
  - It is reasonable to assume that we can model N spheres also; no need to validate the results for N spheres.
- Similar cases in ice-structure interaction
  - Floating and colliding ice floes.
  - Bending of floating beams.
  - Sliding of an ice block against another ice block.

Three DEM Examples

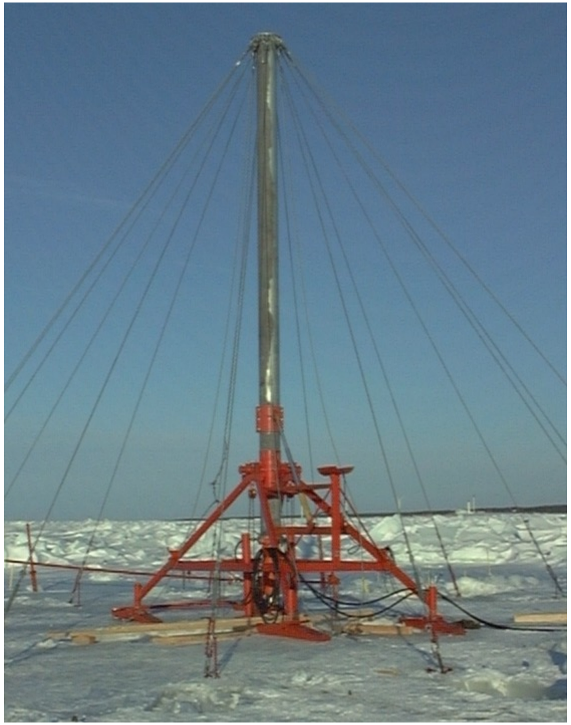
Discrete Element Method

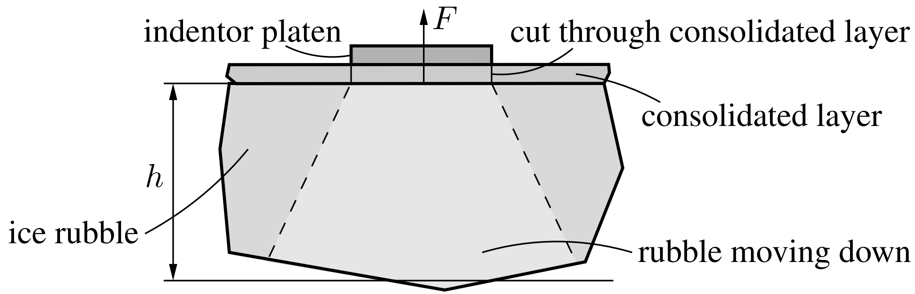
- Newtonian dynamics of a system of discrete particles.
  - Allows finite displacements and rotations
  - Recognises contacts
  - Can model fracture and fragmentation
- FEM-DEM and other variants
- The pioneers
  - Method: Cundall & Strack (1979); Walton (1980)
  - Ice: Hocking, Mustoe & Williams (1985); Hopkins (1992); Løset (1994)

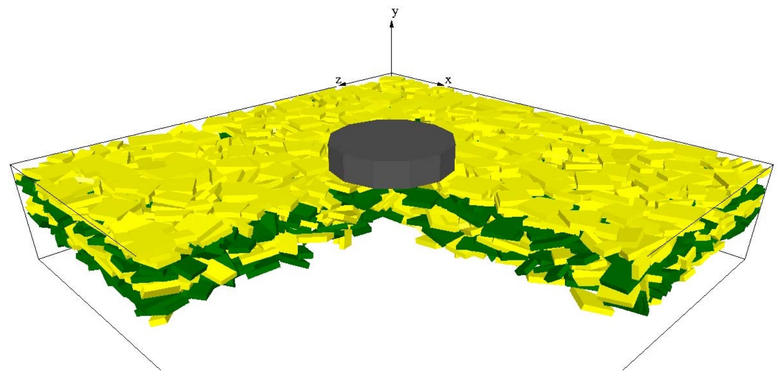




Example 1: Ridge Punch-Through



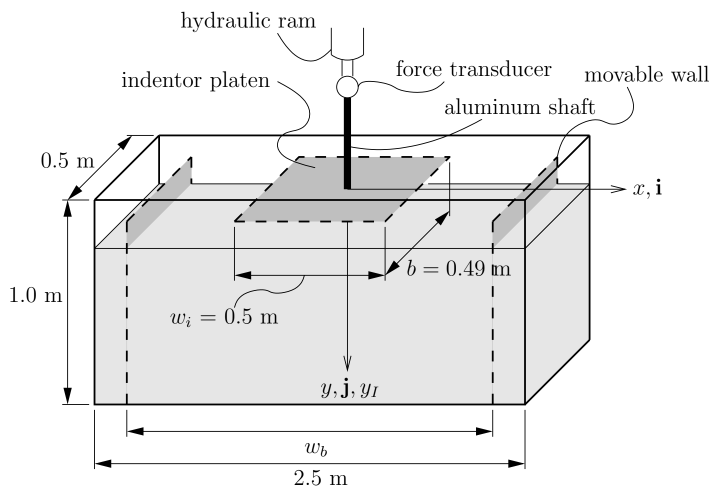


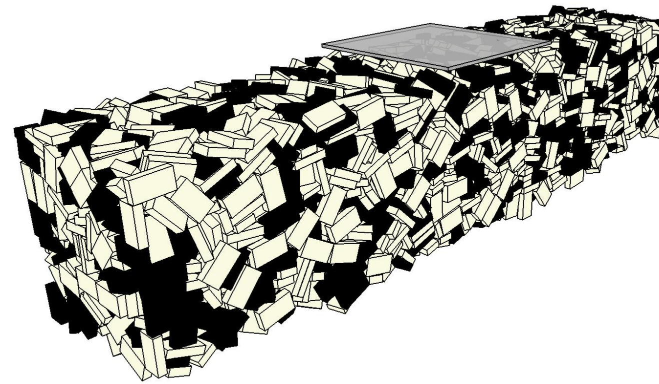


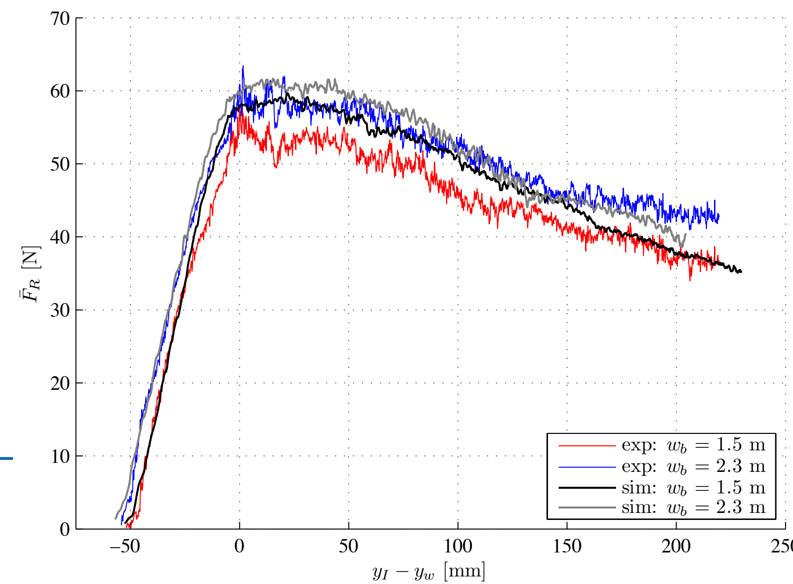
Heinonen & Määttänen 2001; Heinonen, 2004; Polojärvi & Tuhkuri, CRST, 2009

Example 1: Ridge Punch-Through

- Validation through both field and lab experiments.
- In lab: plastic blocks, no cohesion.



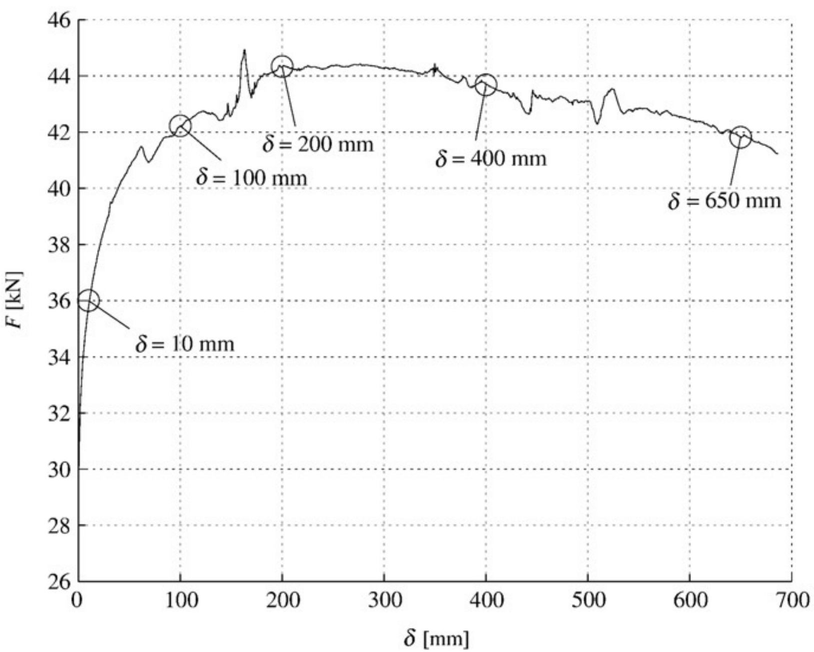


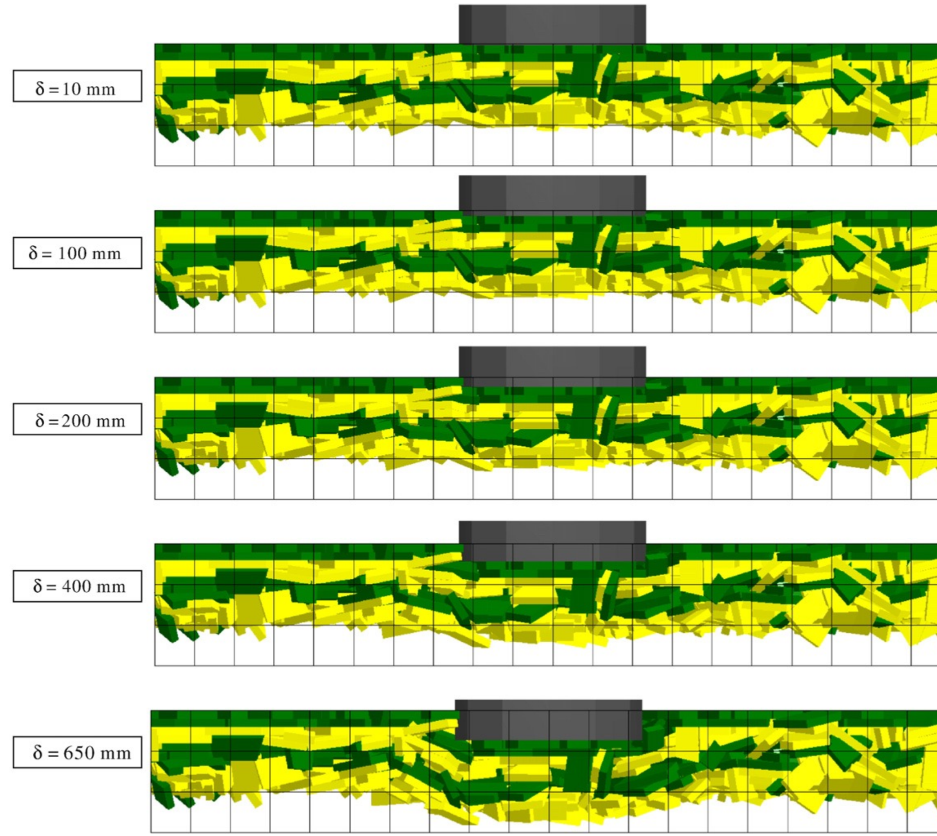


Polojärvi, Tuhkuri & Korkalo, CRST, 2012

Example 1: Ridge Punch-Through

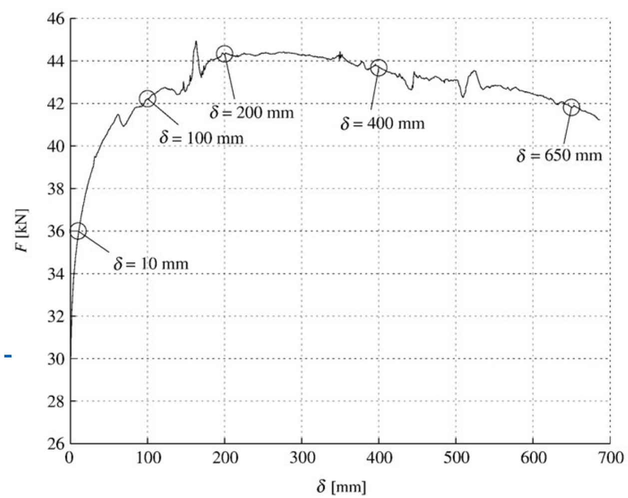
- Force linked to rubble deformation.
- Max force at an early stage.

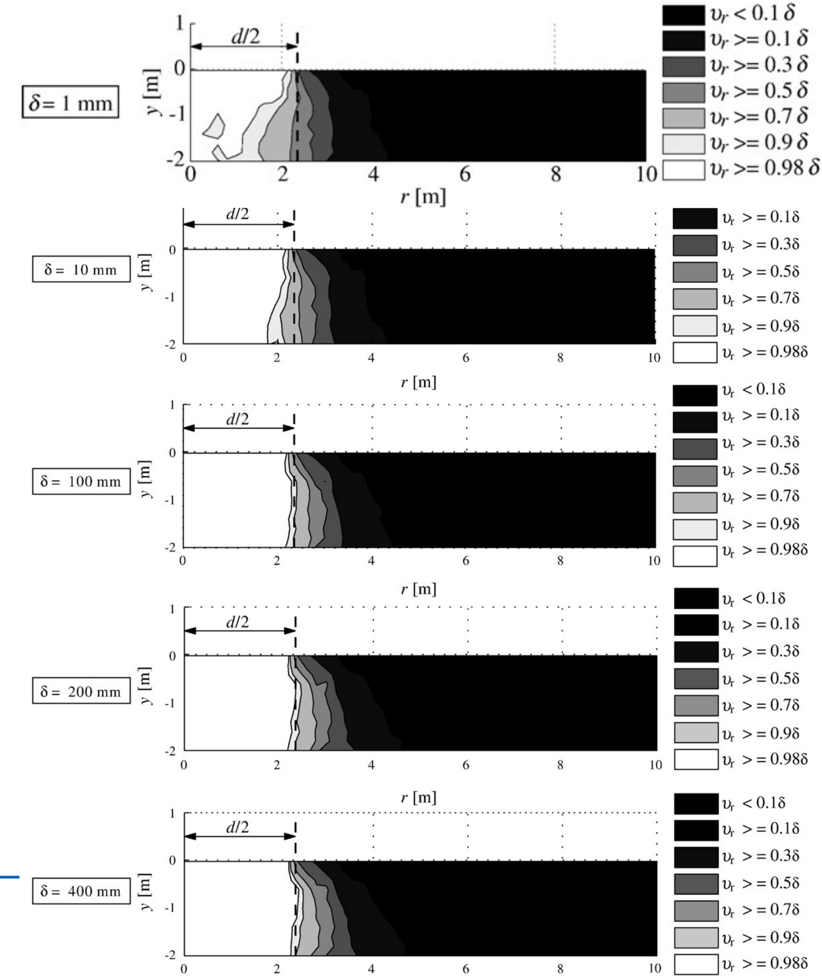




Example 1: Ridge Punch-Through

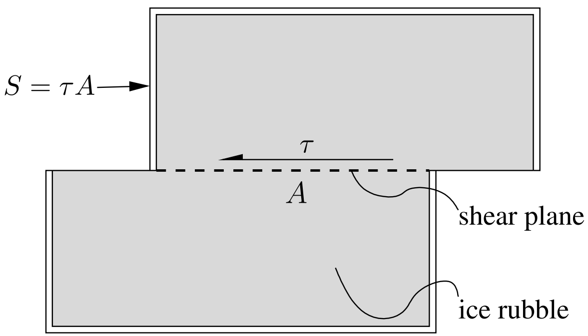
- No unique shear plane.
  Shape of moving ice mass:
  - Initially upward opening cone
  - Then a cylinder
  - Finally a downward opening cone
- Ice-ice friction important
  - Affects the max force
  - Affects the compaction of the rubble

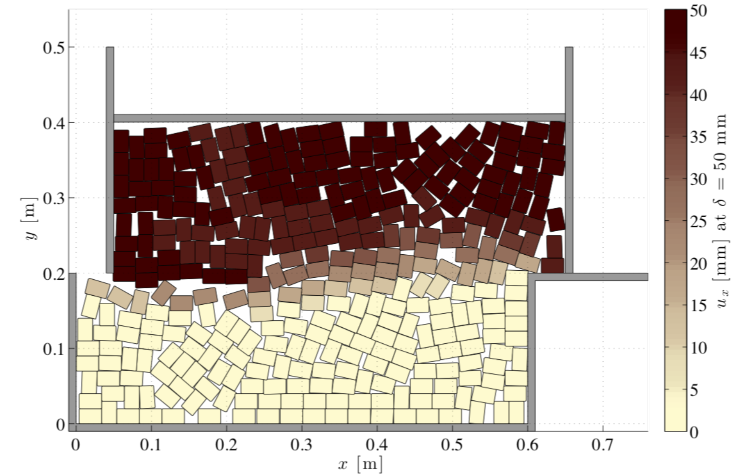


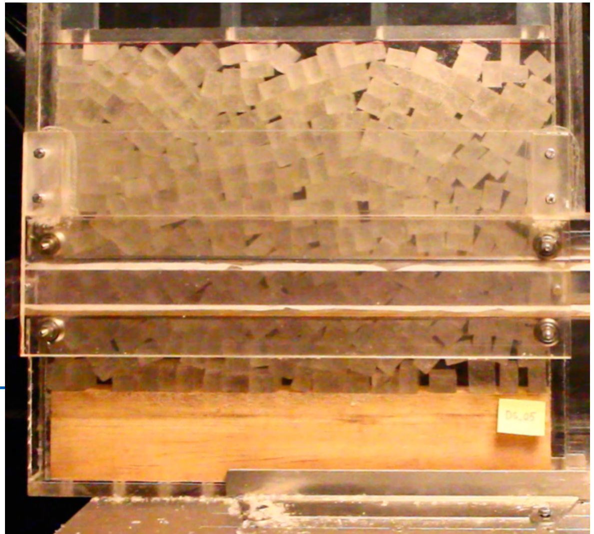


DEM Example 2: Shear Box

- Lab experiments at NTNU.
- DEM simulations at Aalto.







Polojärvi, Tuhkuri & Pustogvar, CRST, 2014

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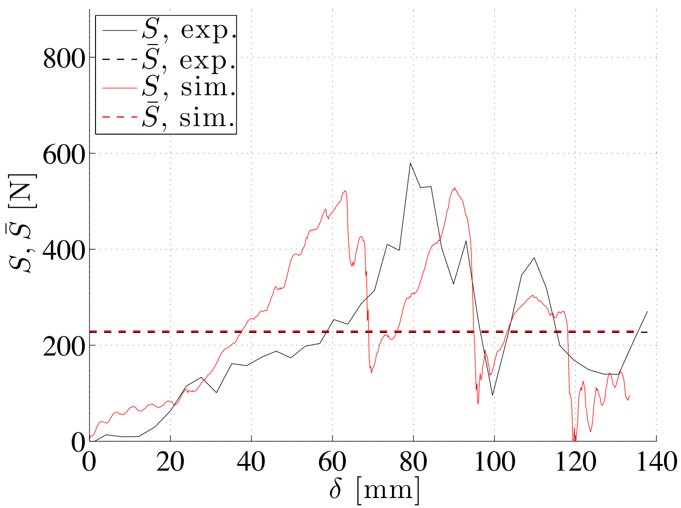
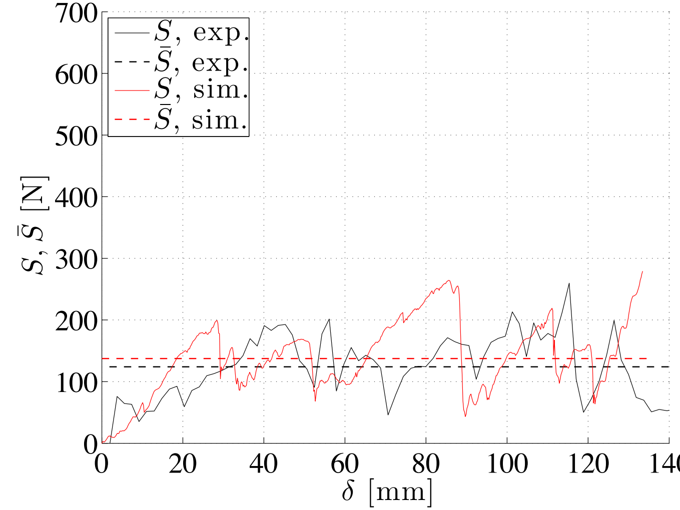
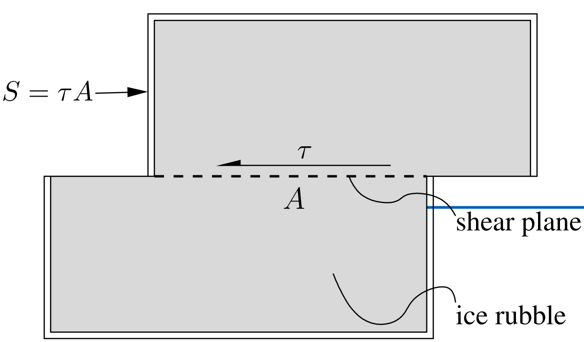
DEM Example 2: Shear Box

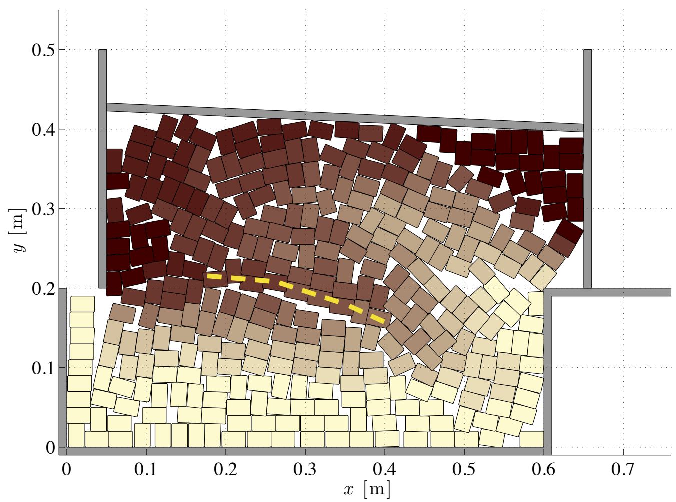


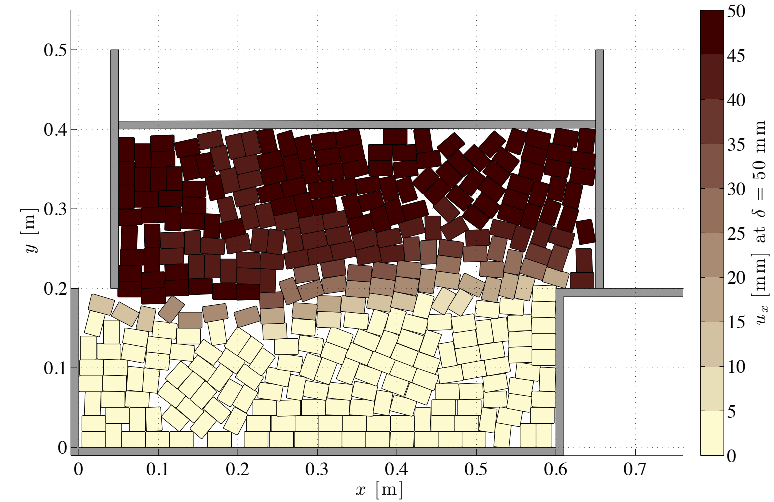


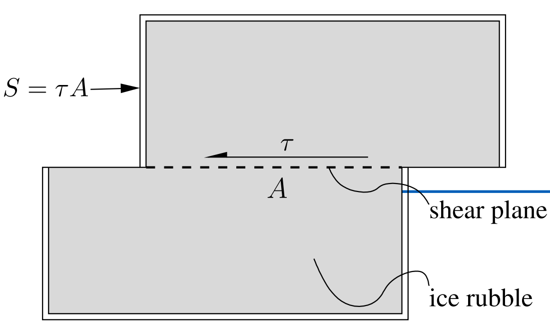


Measured and simulated shear loads.
Left: large blocks. Right: small blocks.

DEM Example 2: Shear Box

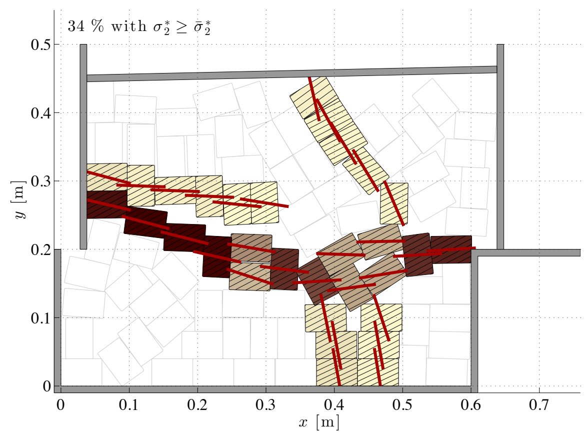


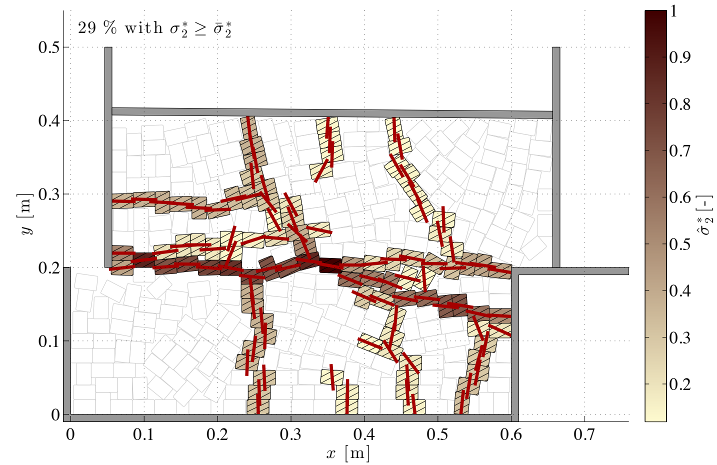




No clear shear plane: difficult to interpret results.

DEM Example 2: Shear Box

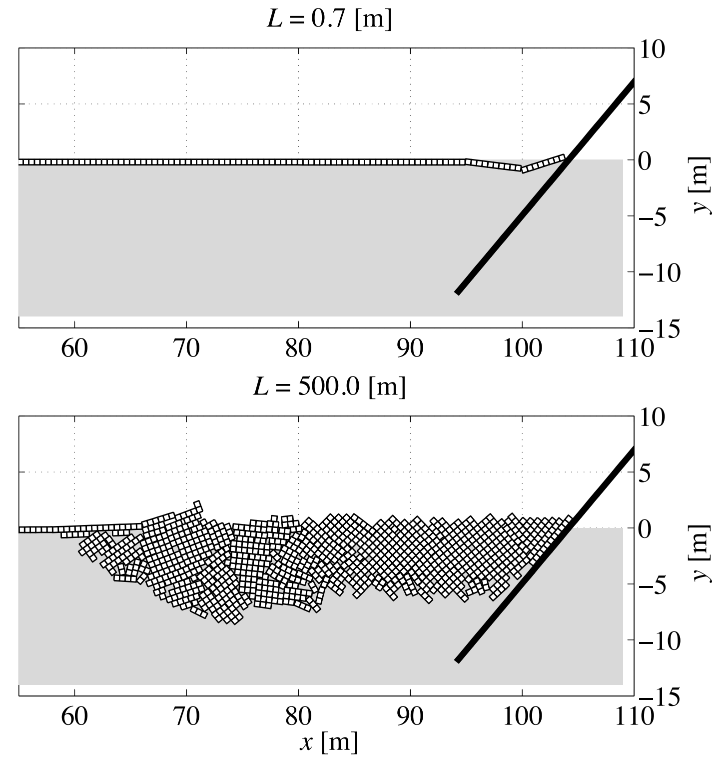


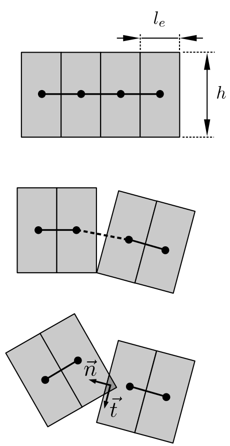


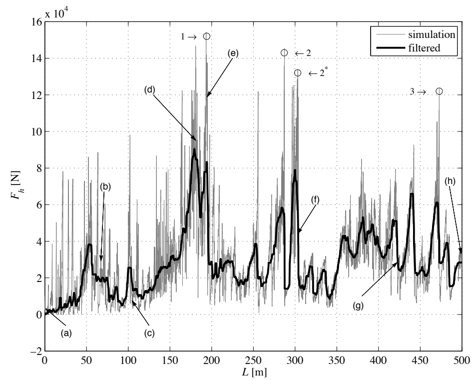
Peak loads due to force chains: What is rubble strength?

DEM Example 3: Rubbling

- To understand ice loads: model ice failure process.
- FEM: joining discrete blocks with Timoshenko beam elements; elasticity, cohesive crack model.
- DEM: contacts, buoyancy, drag







Paavilainen, Tuhkuri & Polojärvi, CRST, 2009, 2011

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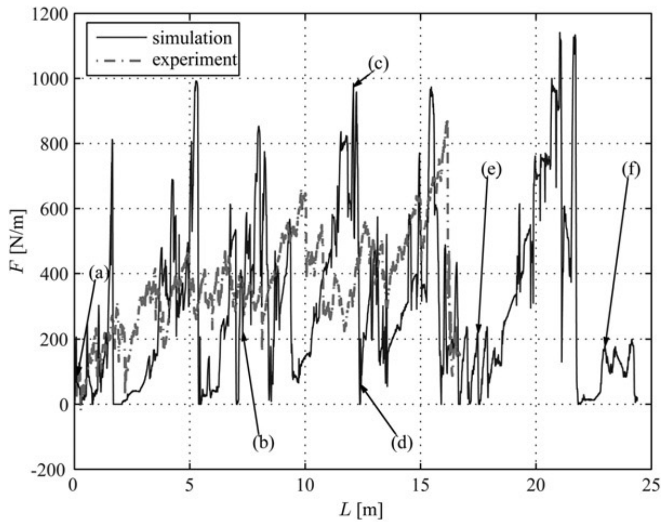
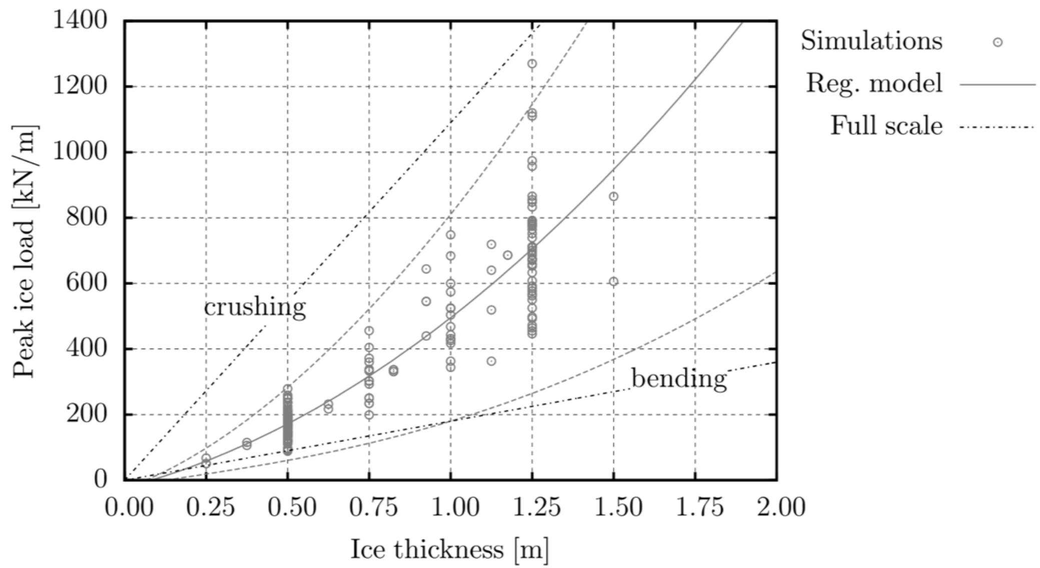
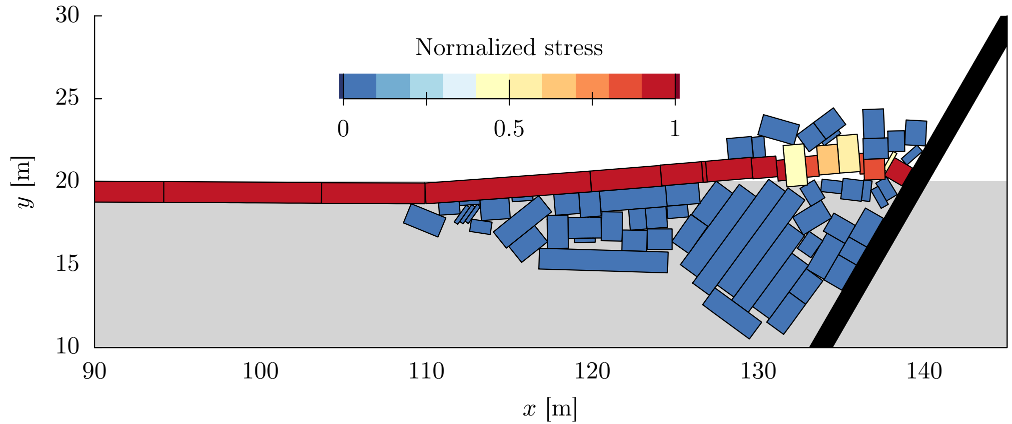
DEM Example 3: Rubbling





Left: DEM with Lab data from Aalto Ice Tank (Saarinen, 2000)
Right: DEM with Field data from Molikpaq (Timco & Johnston, CRST, 2004)

DEM Example 3: Rubbling

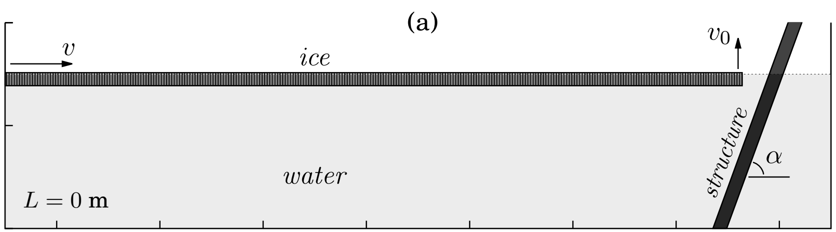


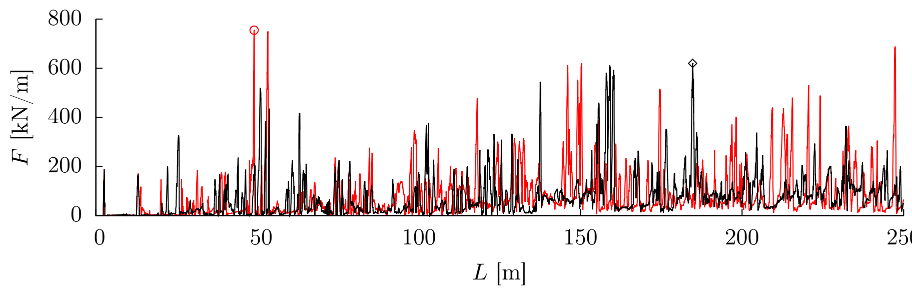
- The ice load is transmitted through force chains.
- The force chains define the max ice load. Load drops are linked with buckling of force chains.
- This observation is not in line with assumtions in ISO19906, where the rubbling load is the sum of different ice action events: $F_H \sim H_B + H_R + H_L + H_T$

Paavilainen & Tuhkuri, CRST, 2013

DEM Example 3: Rubbling

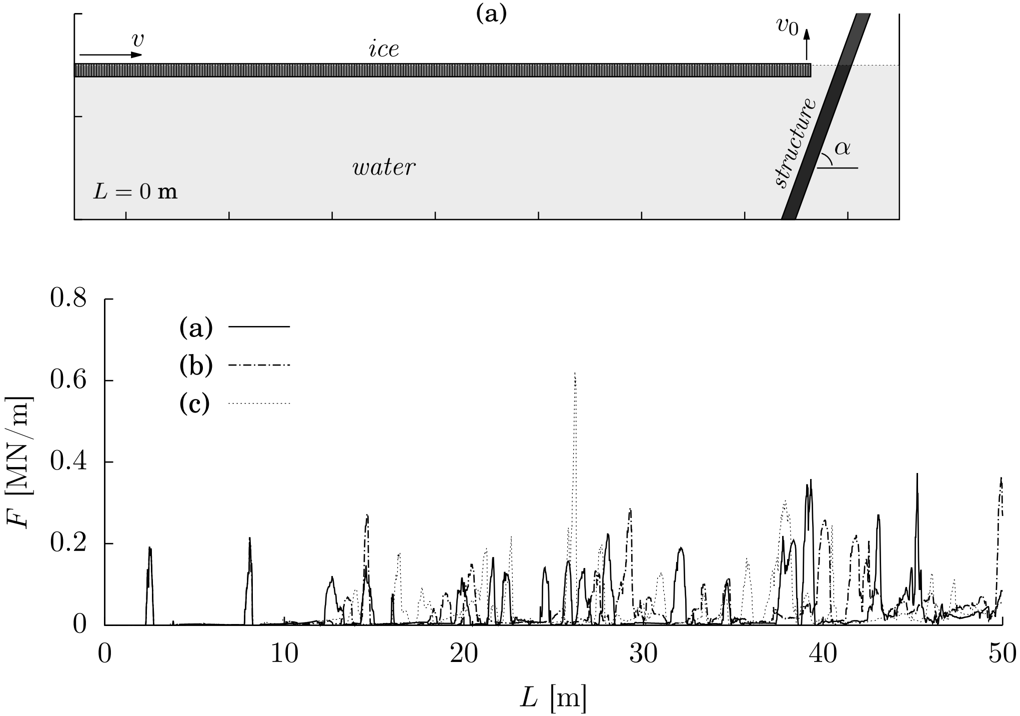
- Simulation is deterministic but sensitive to initial conditions.
  - Possibility to create data
  - Peak load discributions
  - Ice load evolution.
- This sensitivity gives similar load statistics than non-homogenous ice properites.

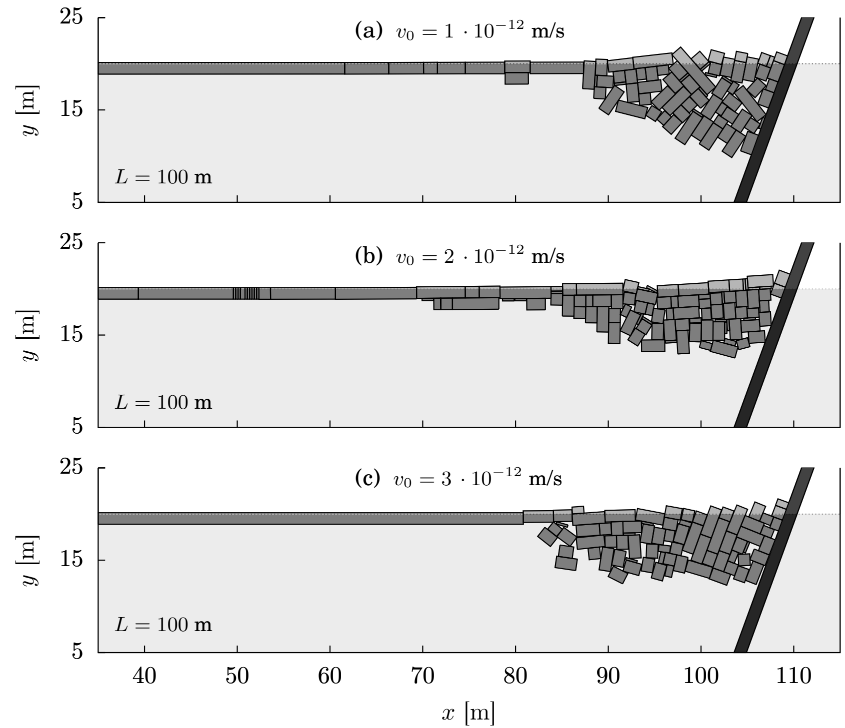




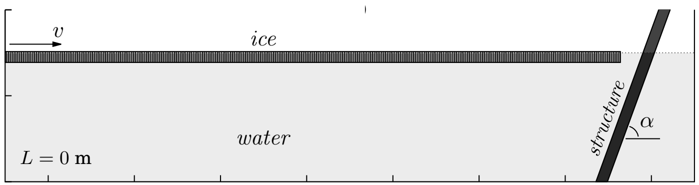
Ranta, Polojärvi & Tuhkuri, CRST, 2016

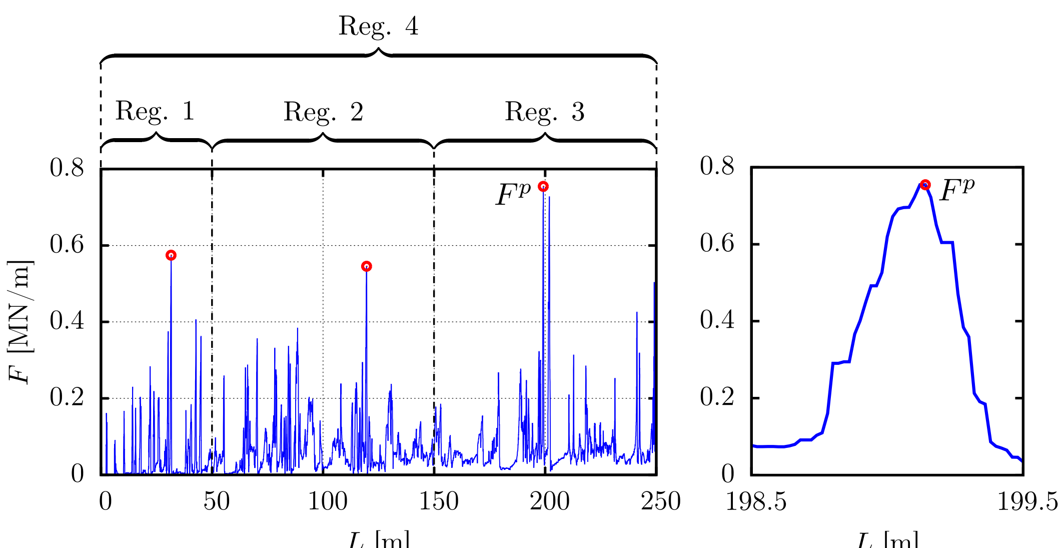
DEM Example 3: Rubbling





DEM Example 3: Rubbling

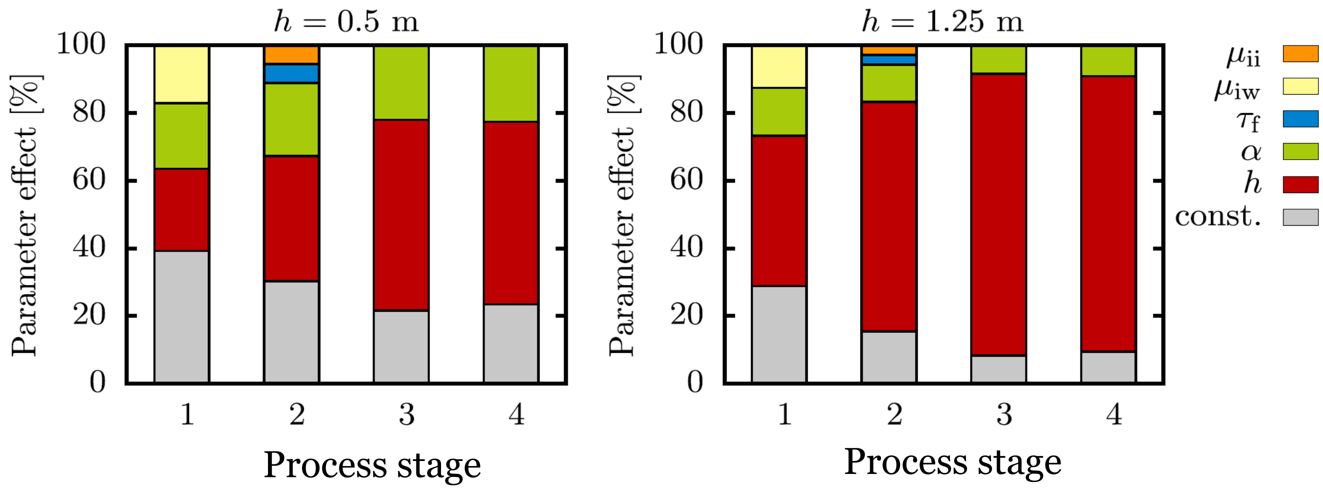




What are the effects of

- ice thickness h, h^2
- inclination angle $\boldsymbol{\alpha}$, $\boldsymbol{\alpha}^2$
- elastic modulus E
- flexural strength $\boldsymbol{\sigma}_f$
- plastic limit $\boldsymbol{\sigma}_p$
- shear strength $\boldsymbol{\tau}$
- ice-ice friction $\boldsymbol{\mu}_{ii}$, $\boldsymbol{\mu}_{ii}^2$
- ice-structure friction $\boldsymbol{\mu}_{is}$, $\boldsymbol{\mu}_{is}^2$

DEM Example 3: Rubbling



Simulations and multivariate regression analysis suggests:

- The ice load can be explained with h and **α** only.
- The importance of parameters changes during the process.

Conclusions

1. Different methods have each their own merits and limitations – Use the right method.
2. Validation is not trivial – The scale at which the validation is conducted is important. Ice load statistics should be taken into account in validation.
3. Novel results have been obtained through simulations: shear planes, force chains, key parameters in rubbling.

Acknowledgements: Arttu Polojärvi, Mark Hopkins, Jani Paavilainen, Janne Ranta, Anna Pustogvar, Knut Høyland.
Academy of Finland, Business Finland, industrial partners, SAMCoT (NTNU, Research Council of Norway, partners)

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