2D FEM-DEM modeling of ice-inclined structure interaction

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The ice-structure interaction problem and ice rubble

Figures adapted from the book by T.J.O. Sanderson (1988)

Ice rubble pile at the shoreline of the Gulf of Bothnia (16th Apr 2017, J.R.)
The tool for modeling the ice-structure interaction

• Numerical 2D FEM-DEM model
  – Developed, verified, and validated by the Aalto ice mechanics research group (long-term work)

• Model features (schematic description)
  – Beam finite elements for elasticity
  – Cohesive crack model for describing the ice failure
  – Discrete elements to account for the geometry, contacts, and fluid effects (buoyancy and drag)

• Large-scale response of the system is determined by the mentioned small scale features

The plastic limit parameter limits the normal contact force
The Coulomb friction model limits the tangential contact force
Studied case: Ice-inclined structure interaction

(a) \[ v = 0.05 \text{ m/s} \] \[ g \]

(b) \[ \alpha = 70^\circ \]

(c) \[ L = 0 \text{ m} \] \[ \text{Ice sheet} \]

(d) \[ L = 50 \text{ m} \] \[ \text{Ice rubble} \]

(e) \[ L = 100 \text{ m} \]

(f) \[ L = 200 \text{ m} \]

(g) \[ L = 250 \text{ m} \]
Animation
Typical Force Record and Peak Load Observation

The amount of pushed ice

Global peak load

\[
\begin{align*}
h &= 1.25 \text{ m} \\
\sigma_p &= 2 \text{ MPa}
\end{align*}
\]
Sensitivity to Initial Conditions

- The model is deterministic but very sensitive to initial conditions.
- Repeated simulations with only slightly different initial conditions yielded different load outputs.
- This sensitivity was used to produce large number of independent and identically distributed load observations.
Sensitivity to Initial Conditions

- Naturally, also ice floe arrangements were different in initial condition perturbed simulations.
# Simulation Sets

<table>
<thead>
<tr>
<th>Set</th>
<th>$h$ [m]</th>
<th>$\sigma_p$ [MPa]</th>
<th>$\nu_0$ varied</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.5</td>
<td>1</td>
<td>yes</td>
</tr>
<tr>
<td>S2</td>
<td>0.5</td>
<td>2</td>
<td>yes</td>
</tr>
<tr>
<td>S3</td>
<td>0.875</td>
<td>1</td>
<td>yes</td>
</tr>
<tr>
<td>S4</td>
<td>0.875</td>
<td>2</td>
<td>yes</td>
</tr>
<tr>
<td>S5</td>
<td>1.25</td>
<td>1</td>
<td>yes</td>
</tr>
<tr>
<td>S6</td>
<td>1.25</td>
<td>2</td>
<td>yes</td>
</tr>
<tr>
<td>S7</td>
<td>1.25</td>
<td>$\mathcal{U}(1, 2)$</td>
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</tr>
<tr>
<td>S8</td>
<td>1.25</td>
<td>8</td>
<td>yes</td>
</tr>
</tbody>
</table>

- 50 repetitions in each set
- 400 simulations in total

Non-homogeneous ice

Plastic limit varied
discrete element-wise

\[ \sigma_p = \min(\sigma_p^a, \sigma_p^b) \]
Failure Process Statistics

- Ice load histories were not stationary
- Statistics were calculated using concurrent load observations from repeated simulations
  - Mean, standard deviation, and maximum statistics increased throughout the process with increasing $L$
  - Coefficient of variation (STD/MEAN) decreased with increasing $L$
- Also, concurrent maximums increased with increasing number of simulations ($n$)
Peak Ice Load Statistics

- A dimensionless buckling load factor $\Lambda$ was used to normalize the peak load data
- In general, the Gumbel distribution (EVD type 1) fitted well on the data
- The large scatter in normalized data mainly stem from the complex ice-structure interaction process (ice sheets were homogeneous)
- According to the used normalization, the peak loads are strongly dependent on the ice thickness

$$F^p \propto h^{3/2}$$

$$\Lambda = \frac{F^p}{\sqrt{kEI}}$$
Parameter Effects

- In the data, the effect of the ice thickness was strong
- Plastic limit parameter affects peak loads as well but this effect is minor
Summary

- In the study, full-scale "experiments" were conducted by using numerical simulations
- Large number of simulations provided data for studying statistics and mechanics of ice loads
  - A benefit of simulations is that all ice properties are known exactly (full control on the system)
- In general, data showed large scatter
- Despite of the large scatter, some relationships between ice loads and the used model parameters (ice parameters) were found
  - Peak loads were strongly dependent on the ice thickness
  - Peak loads were observed to depend on the compressive strength as well but this effect was relatively weak
Publications

• Ranta, Polojärvi
  - Limit mechanisms on peak ice loads: Local ice crushing
    Submitted to Marine Structures.

• Ranta, Polojärvi, Tuhkuri
  - Limit mechanisms on peak ice load: Ice buckling
    2018 in Cold Regions Science and Technology.
  - Ice loads on inclined marine structures – Virtual experiments on ice failure process evolution.
    2018 in Marine Structures.
  - Scatter and error esimates on ice loads – Results from virtual experiments.
    2018 in Cold Regions Science and Technology.
  - The statistical analysis of peak ice loads in a simulated ice-structure interaction process.
    2017 in Cold Regions Science and Technology.