Ship waves in Tallinn Bay: Experimental and numerical study

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Outline of talk

Background and motivation

Basic properties of ship generated waves

Equations for the numerical model

Ship waves in the Tallinn Bay area

Summary
The Baltic Sea and Tallinn Bay
Wash waves from high speed vessels

HSC SuperSeaCat IV
Service Speed:
38 knots (∼ 20 m/s)
Dimensions:
Length: 100.30 m
Width: 17.10 m
Draught: 2.60 m

- Waves from high speed vessels:
  - Long wave lengths and wave periods.
  - Large wave energy.
  - Qualitatively different from waves generated by conventional ships.
- Potentially dangerous for people on the shore or in small boats.
- May damage structures at the shore or moored vessels.
- May increase erosion and disturb marine habitats.
Parameters for ship wave generation

▶ Length Froude number: \( F_L = \frac{U}{\sqrt{gL_w}} \)
  ▶ High speed vessels: \( F_L > 0.4 \)
  ▶ Maximum wave resistance (hump speed): \( 0.4 < F_L < 0.6 \)
▶ Depth Froude number: \( F_h = \frac{U}{\sqrt{gh}} \)
  ▶ Maximum wave resistance: \( F_h \approx 1 \)
▶ Yang\(^1\): Wave resistance amplification when \( h/L_w < 0.4 \)
  ▶ For \( F_h \approx 1 \) and \( h/L_w \approx 0.2 \): \( R_h/R_{\infty} \approx 3 \)

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Wave resistance of a parabolic strut. Comparison between theory and experiment.
Ship wave patterns

- **Subcritical:** $F_h < 0.6$
- **Critical:** $F_h \approx 1$
- **Supercritical:** $F_h > 1.2 - 1.4$
Ship wave patterns

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Kelvin angle

\[ F_h < 1 : \quad F_h^2 = \frac{\tanh(kh)}{2kh} \left[ 3 - \frac{2kh}{\sinh(2kh)} \right] \]

\[ \sin \alpha = \frac{1+2kh \sinh^{-1}(2kh)}{3-2kh \sinh^{-1}(2kh)} \]

\[ F_h > 1 : \quad F_h = \frac{1}{\sin \alpha} \]
Formulate equations in terms of depth averaged velocity \( \bar{u} \), where \( \nabla_H = (\partial/\partial x, \partial/\partial y) \).

Continuity equation:

\[
\frac{\partial \eta}{\partial t} + \nabla_H \cdot [(h + \eta)\bar{u}] = 0
\]

Momentum equation:

\[
\frac{\partial \bar{u}}{\partial t} + (\bar{u} \cdot \nabla_H)\bar{u} = -\nabla_H \eta - \nabla_H \rho_a + \frac{1}{3} h^2 \nabla_H \nabla_H \cdot \left( \frac{\partial \bar{u}}{\partial t} \right)
\]

Higher order formulations:

- Include higher order \( \nabla_H h \) terms for stronger depth variation.
- Include dispersive terms with higher order nonlinear correction terms.
Waves generated by a pressure disturbance

Waves generated by a moving pressure disturbance.

- Simple to implement.
- Realistic ship wake patterns except near the wave source.
The COULWAVE model

Homepage: http://isec.nacse.org/models

- 2-D depth integrated model, with multiple vertical layers.
- Fully nonlinear equations: \( \epsilon = O(1) \)
- Accurate representation of linear dispersion for \( \lambda \geq 2h \).
- Originally discretized with finite differences, recent development of finite volume version.
- 4th order predictor-corrector method for time integration.
- Sponge layers used at open boundaries.
- Wave runup enabled by linear extrapolation through the wet-dry boundary at the coast.
- Wave breaking enabled through an eddy viscosity model.

Pressure disturbance is not included in the standard COULWAVE model.
Field work at Aegna Island, Summer 2008
Ship tracks and Froude numbers
Wave measurements at Aegna
Echo sounder: Mobile Log_aLevel (General Acoustics GMBH)

Range: 6 m
Resolution 1 mm
Sample rate: up to 5 Hz
Frequency: 80 kHz
Measurements of wave height and runup

- Scatter diagram: Maximum wave height vs. maximum wave runup.
- Large amplification of small waves ($> \times 2$).
- Small amplification of large waves, due to breaking.
- Nordic and SuperSeaCat produce a wide wave spectrum.
- Difficult to control wave runup by limiting wave height in the sea.
Measurements for a single event

- Wave record (blue), wave height (red), and runup height (black).
- Dashed line: Hunt (1959) - low amplitude sea swell.
- Black squares: 5 largest waves from the first wave group.
Simulated results

Track 1: June 29 - 2008

Track 2: July 5 - 2008

<table>
<thead>
<tr>
<th></th>
<th>Western half-angle</th>
<th>Eastern half-angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track 1</td>
<td>21°</td>
<td>30°</td>
</tr>
<tr>
<td>Track 2</td>
<td>22°</td>
<td>26°</td>
</tr>
</tbody>
</table>
Comparison between measurements and simulations

- Main features of the leading wave group is represented in the simulations.
- Significant errors in the trailing wave train.
- Wave periods are slightly larger in the simulations than in the measurements.
- Wave amplitudes are generally not well represented in the simulations.

<table>
<thead>
<tr>
<th></th>
<th>June 29 - 2008</th>
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<th>July 5 - 2008</th>
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<tbody>
<tr>
<td></td>
<td>Period</td>
<td>Amplitude</td>
<td>Period</td>
<td>Amplitude</td>
</tr>
<tr>
<td>Measurements</td>
<td>10.6 s</td>
<td>0.45 m</td>
<td>8.8 s</td>
<td>0.20 m</td>
</tr>
<tr>
<td>Simulations</td>
<td>10.8 s</td>
<td>0.46 m</td>
<td>9.2 s</td>
<td>0.27 m</td>
</tr>
</tbody>
</table>
Max Wave amplitude distribution in Tallinn Bay

- Large spatial variability in maximum wave amplitude.
- Significant differences in max amplitude distribution between tracks 1 and 2.
Summary

- Long waves generated by high speed vessels are a recent addition to the typical wave specter in coastal areas. They pose a potential safety and environmental hazard.
- The long wave part of the ship wash is well described by the Boussinesq equations.
- Wake waves from ships may be significantly influenced by the local topography. Numerical simulations may help to locate areas of intense wave action, which can be useful in wave forecasting and in the planning of field studies.
- Comparison between simulations and measurements show qualitative similarities, but quantitative results are not accurate.
Thank you for your attention!