Analytic Tsunami Model for Physics-Based Impact Risk Assessment

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Contributors

- Engineering risk model development
  - Donovan Mathias
  - Paul Register
- Simulation results
  - Darrel Robertson
  - Marsha Berger
  - Mike Aftosmis
  - Randall LeVeque
Overview

• Motivation for engineering model
• Baseline Ward-based model and our application/adaptation/implementation
• Baseline model seemed to be overly pessimistic compared to initial simulations
• Compare components of the model predictions/assumptions with simulation results to see where adjustments/scaling may improve predictions
  • Energy coupling for splash and airburst
  • Bathymetry: shoaling amplification & shelf effects
  • Inundation
Engineering Model Overview

• Based on formulations from Chesley & Ward 2006, Ward & Asphaug 2000
• Estimates run-in distance as a function of cavity depth ($D_c$), cavity diameter ($d_c$), distance ($r$) from impact point, ocean depth ($d_o$) at impact point:
  • $X_{max} = 2.2796 \times 10^{-3} \times (d_o^{1/10}) \times (d_c^{1/2}) \times (D_c^{2/5}) \times (1+2r/d_c)^{-2\psi/5}$
  • $\psi = 0.5 + 0.575 \times \exp(-0.0175 \times d_c/d_o)$
• Cavity depth and diameter estimated based on impactor energy and tsunami energy fraction $\varepsilon$ of 15% of impactor energy
  • $D_c = R_{I}^{3/4} \left[ 8 \varepsilon \rho_I v^2 / (9 g \rho_{water}) \right]^{1/4}$; $d_c = 3D_c$;
• Intermediate relations for deep-water wave height and shoaled run-up wave height, velocity, and period
• Assumes:
  • Water impact
  • Cavity diameter/depth ratio = 3
  • ~15% impact energy goes into tsunami
  • All water deposited onto cavity lip (no water ejected)
Cavity Comparison

- Baseline engineering model assumes much wider initial cavities than ALE3D simulations generate
- Depth compares reasonably well
- Cavity ratio ~1.5 for 90 mt and ~2 for 250 mt case
Near-field Wave Comparisons

- Baseline engineering model over-predicts near-field waves by a factor of ~2-3 compared to ALE3D simulations
- Decay rates compare reasonably
• Initiating baseline model with simulation cavity dimensions/ratio improves comparison somewhat, but still generates larger near-field waves
Energy Scaling Comparisons for Impact Cases

- Scaling tsunami energy fraction down from 15% to 1.5% of impact energy gives good comparisons with hydrocode waves out to ~10km
- Decay rates and wave heights reasonable
Energy Coupling for Airbursts

- Performed similar energy scaling comparisons using Marsha Berger’s GeoClaw simulations of airburst-generated waves
  - 100 mt and 250 mt airburst at 10 km altitude
  - Initiated using Cart3D spherical burst simulations by Michael Aftosmis
  - Shallow-water 2D radially symmetric
  - 3 km deep, flat-bottom ocean
  - Ran out to ~70 km from impact
Energy Scaling Comparisons for Airburst Cases

- Reducing energy coupling to on the order of 1-5e-5 gives reasonable comparisons
- Leading pressure-driven wave is initially larger and decays more rapidly over first 20km
Bathymetry & Shoaling Effects

• Baseline engineering model does not account for effects of potential variations in bathymetry between impact and shore.

• Randall LeVeque provided simulations of waves propagating over a simplified bathymetry variations for comparison
  • 1D radially symmetric model
  • Shallow-water wave equations
  • Initiated with a 3 km x 1 km cavity

• Bathymetry Variations:
  • Beach slopes: 0.02, 0.1
  • Shelf widths: 0-60 km
  • Shelf depth 100m
  • Shelf slope 20km wide
  • Ocean depth 3km

*Image credit: R. LeVeque
Shoaling Comparison

- **Engineering model**
  - Shoaling factor amplifies deep-water wave to obtain shoaled wave heights at a given depth
  - Final run-up taken as wave height shoaled to the point where the depth = wave height
  - Final run-up estimates are independent of intermediate bathymetry
  - Shoaling effect increases wave height/slow decay compared to unshoaled wave
  - Decays faster in deep-water than

- **Simulations**
  - Unshoaled wave heights taken from 200km impact distance cases over flat ocean before shelf
  - Wave decay slows going up over the shelf slope, but then wave decays much more rapidly as it propagates over the shallow shelf distance
Run-up & Run-in Comparisons for Bathymetry Variations

- Baseline engineering model estimates of final run-up/run-in are within reasonable range of simulation results if you ignore the intermediate differences in decay rates and shelf effects.
Shelf Protection vs Shoaling Amplification

- Eng model’s run-up shoaling amplification is pessimistic compared to 1D sims over bathymetry.
- For no shelf, Ward amplification is within the range for shallow/steep beach sims.
- For 10km shelf is comparable to steep beach, but about twice that for shallow.
- For shelves >= 30 km, Ward amp factor is ~1.5x that of steep beach sims and 2.5x that of shallow beach sims.

<table>
<thead>
<tr>
<th>Shelf width (km)</th>
<th>0</th>
<th>10</th>
<th>30</th>
<th>40</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steep beach</td>
<td>0.6</td>
<td>1.0</td>
<td>1.4</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Shallow beach</td>
<td>1.7</td>
<td>2.0</td>
<td>2.4</td>
<td>2.4</td>
<td>2.7</td>
</tr>
</tbody>
</table>
Long Beach Case

- 90 mt water impact off the coast of Long Beach

Impact location:
- Coordinates: 33.451, -118.25
- Depth: 800m
- Offshore dist: 29.4 km
- Shelf width:
  - (kind of a peculiar case, not very deep, right on bottom of shelf)

- Compared with Marsha’s GeoClaw sim
  - 3D shallow-water simulation
  - Initiated from Darrel’s 90 mt splash case
Near-Shore Wave Height Comparisons

• Compared max waveheights at simulation gauge locations with engineering model waves computed at those distances and relative depths.
Long Beach Case

- Engineering model with energy fraction scaled to 1.5% overpredicts shoaled waves near the shore compared to simulation
  - 2-8x larger than near-shore simulation gauge heights
  - Similar to what we observed in the 1D ideal bathymetry comparisons

![Ward vs GeoClaw Max Gauge Heights](image-url)
Energy Scaling to Gauge Wave Heights

- Scaling initial energy fraction down further to 0.1% matches near-shore gauges, but under-predicts waves further offshore
  - (However this is only one, fairly unusual comparison case – would need other comparisons to determine whether a simple energy scaling could reasonably be used to account for shelf protection factors in shoaling)
Summary

- Reducing initial energy coupling from 15% to 1.5% for water impacts provides better wave height predictions compared to simulations.
- Energy coupling fraction needs to be reduced down to $\varnothing e^{-5}$ to represent air-burst generated waves.
- Baseline model over-predicts shoaling amplification and final near-shore wave heights in cases with continental shelf protection.
- Using scaled engineering model run-up estimates with local topography provides bounding, pessimistic inundation.
- Forward work:
  - Additional simulation comparisons for broader range of cases.
  - Investigate implementation of a shelf-protection factor to better match shoaled wave heights near shore.
  - Refine modeling assumptions on how far inland a given run-up wave height is able to flood.

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