Tsunami Theory
Tsunami Casualties

Killer Tsunami in historical times

- **India**
  - 1941
  - 5,000 killed
- **China**
  - 1765
  - 10,000 killed
- **Philippines**
  - 1976
  - 8,000 killed
- **Japan**
  - 1896
  - 27,000 killed
  - 1771
  - 13,000 killed
  - 1707
  - 30,000 killed
  - 1498
  - 26,000 killed
  - 1293
  - 23,000 killed
  - 1782
  - 50,000 killed

- **Lisbon**
  - 1755
  - 60,000 killed?
- **Virgin Is**
  - 1690
  - 3,000 killed
- **Peru**
  - 1746
  - 18,000 killed
- **Chile**
  - 1868
  - 26,000 killed
- **Indonesia**
  - 1917
  - 15,000 killed
  - 1815
  - 10,000 killed
  - 1883
  - 36,000 killed

Based on Bryant 2001 & NOAA

Michael Paine, Australian Spaceguard Survey - updated 24 Jan 05
Tsunamigenic Sources

(after Gusiakov)
Landslide: Lituya Bay, Alaska 1958

About 500 m run-up
A tsunami following an earthquake devastated several villages. Run-up up to 15 meters. More than 2100 casualties.

Dengler & Preuss (2003)
Run-up distribution of Papua New Guinea 1998 and Nicaragua earthquake Tsunami 1992 ($M_w=7.7$)
Asteroid impact tsunami

Gisler et al. (2003) Two and Three Dimensional Simulations of Asteroid Ocean Impacts

1200 processors for several weeks. Up to 200,000,000 computational cells were used, and the total computational time was 1,300,000 cpu-hours
Asteroid impact

Gisler et al. (2003)
Asteroid impact

Initial tsunami height > 1 km!

Gisler et al. (2003)
Earthquake distribution
Plate motions imaged by GPS
Plate tectonics
Continental drift

PERMIAN
225 million years ago

TRIASSIC
200 million years ago

JURASSIC

CRETACEOUS

PRESENT DAY
Mantle convection

- Plates of the Lithosphere
- Convective Currents

- Trench "SLAB PULL"
- Ridge
- Lithosphere
- Trench
- Mantle
- Asthenosphere
- 700 km
- Outer core
- Inner core
Driving forces

Thermal convection

Force balance

$F_{RP}$: Ridge-push force
$F_{DF}$: Mantle-drag force
$F_{SP}$: Slab-pull force
$F_{SD}$: Slab-drag force
$F_{TR}$: Transform-resistance force
$F_{SR}$: Subduction-resistance force
$F_{RP}$: Trench-suction force

Moores and Twiss (1995)
Elements of plate tectonics
Subduction Factory

McCaffrey (2009)
Subduction earthquake tsunami source
Subduction earthquake tsunami source
Subduction earthquake tsunami source
Tectonic setting Sumatra
Tsunami Generation

Coupling at the subduction interface
Tectonic loading

Sudden release
Transfer of potential energy
Tsunami velocity and wave length

\[ V = \sqrt{g \cdot d} \]

\[ \lambda = \lambda_0 \sqrt{\frac{h}{h_0}} \]
Tsunami properties

Linear theory for long waves $\lambda \gg h$

Phase and group velocity  
\[ c = c_g = \sqrt{gh} \]

Energy density (per unit area)  
\[ E = \frac{1}{2} \rho g a^2 \]

Energy flux (per unit length)  
\[ F = Ec_g \]

Constant wave period and energy flux lead to:

\[ \lambda = \lambda_0 \sqrt{\left(\frac{h}{h_0}\right)}, \quad a = a_0 \left(\frac{h_0}{h}\right)^{1/4} \]

Wave length decreases and amplitude increases in shallow water  

Gjevik (2004)
## Tsunami properties table

### Amplification in shallow water

<table>
<thead>
<tr>
<th>$h$ (m)</th>
<th>$a$ (m)</th>
<th>$\lambda$ (km)</th>
<th>$c$ (km/t)</th>
<th>$u$ (km/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000</td>
<td>1</td>
<td>100</td>
<td>713</td>
<td>0.18</td>
</tr>
<tr>
<td>1000</td>
<td>1.4</td>
<td>50</td>
<td>356</td>
<td>0.50</td>
</tr>
<tr>
<td>250</td>
<td>2</td>
<td>25</td>
<td>180</td>
<td>1.4</td>
</tr>
<tr>
<td>100</td>
<td>2.5</td>
<td>16</td>
<td>113</td>
<td>2.8</td>
</tr>
<tr>
<td>50</td>
<td>3.0</td>
<td>11</td>
<td>80</td>
<td>4.8</td>
</tr>
<tr>
<td>20</td>
<td>3.8</td>
<td>7</td>
<td>50</td>
<td>9.4</td>
</tr>
<tr>
<td>10</td>
<td>4.4</td>
<td>5</td>
<td>36</td>
<td>26.8</td>
</tr>
</tbody>
</table>

Gjevik (2004)
Most tsunamis do not result in giant breaking waves. Rather, they come in much like very high and fast tides. Much of the damage inflicted by tsunamis is caused by strong currents and floating debris.
Modelling steps

- Tsunami generation: Initial condition
- Tsunami propagation (nonlinear shallow water)
- Tsunami run-up and coastal inundation (high resolution, Boussinesq equations)
Tsunami is a long wave

Long-wave
\[ V_x \neq f(z) \]
\[ \left( \frac{h}{L} < \frac{1}{20} \right) \]

Short-wave
\[ V_x = f(z) \]
\[ \left( \frac{h}{L} > \frac{1}{2} \right) \]
Numerical schemes

• Finite differences on structured grids
  • *Pro*: easy to implement, robust, simple grids, straightforward parallelization of computation
  • *Contra*: constant resolution, need for nested grids in coastal regions
  • *Examples*: TUNAMI-family, MOST, FUNWAVE

• Finite elements on unstructured grids
  • *Pro*: single computational domain for deep-ocean propagation and inundation
  • *Contra*: time consuming, stability problems, hard to program, complex grids
  • *Examples*: TsunAwi, ANUGA, Uni Bologne
Finite differences on structured grid

\[ \frac{\partial \eta}{\partial t} = \frac{1}{\Delta t} \left[ \eta_{i,j}^{k+1} - \eta_{i,j}^k \right] \]

\[ \frac{\partial M}{\partial x} = \frac{1}{\Delta x} \left[ M_{i+\frac{1}{2},j}^{k+\frac{1}{2}} - M_{i-\frac{1}{2},j}^{k+\frac{1}{2}} \right] \]

\[ \frac{\partial N}{\partial y} = \frac{1}{\Delta y} \left[ N_{i,j+\frac{1}{2}}^{k+\frac{1}{2}} - N_{i,j-\frac{1}{2}}^{k+\frac{1}{2}} \right] \]

Imamura (1996)
Nested grids

Fig. 2 The upper panel shows the nested grids A, B, and C in TUNAMI (grid A: $1,280 \times 1,354$ nodes, $dx = 900$ m; grid B: $297 \times 357$ nodes, $dx = 300$ m; grid C: $289 \times 274$ nodes, $dx = 100$ m).

Harig et al. (2008)
GITEWS Indonesian grid:
> 4 Mio elements with resolution down to 50 m

Harig et al. (2008)
Limits of modelling

General rule also applies here:
Last 10% of model accuracy costs 90% of efforts.

While increasing numerical grid resolution do not
forget about physical resolution of bathymetry used.

Source uncertainty is always there...
Sumatra 2004
Tsunami Animation

tsunami_large_2d
sumatra_3d
Source Modelling
Initial condition

- Tsunami generation: Initial condition
- Tsunami propagation (nonlinear shallow water)
- Tsunami run-up and coastal inundation (high resolution, Boussinesq equations)
- How do we get an appropriate initial condition?
Seismology: Source parameters

GFZ Potsdam - Earthquake Bulletin
Region: Southern Sumatra, Indonesia
Time: 2007-09-12 11:10:25.9 UTC
Magnitude: 8.0
Epicenter: 101.34°E 4.57°S
Depth: 32 km
Status: manually revised

Teleseismic Rupture Tracking University of Potsdam
2009-09-12 11:10 (Mw 8.0, GEOFON) off-coast Java
Figure: Epicentre (star), moment-tensor solution (CMT). Colour lines code area of seismic energy release and time from source time.

GEOFON: Epicenter, Magnitude
Telesismics: Source Extent
Telesismics: Rupture Timing (D. Roessler)

Magnitude saturation? Slip Distribution?

ISNET/ISA Workshop Tehran
12.09.2013 Andreas Hoechner
Magnitude Saturation, Kanamori 1983
Fault Extension

Magnitude is a logarithmic function of moment
Source is not a point source

- $m_b = 7.2$
- $M_s = 8.2$
- $M_w = 9.3$

Hoechner et al. 2008
Source determination

- Present status:
  - Use Epicenter and Magnitude to extract scenarios from database
  - Check with buoys, tide gauges, GPS, if available

- Problems and Requirements:
  - Time-critical: Tsunami can reach coast within 20 minutes
  - Magnitude might be underestimated for large events (was 8.0 for Sumatra instead 9.3)
  - Seismological methods measure acoustic luminosity, rather than total energy release
  - Epicenter is just nucleation point, Centroid not so easy to determine
  - Slip distribution necessary for large events or complex bathymetry
Warning center: Data flow

Sensor-Systeme
- Seismik
- GPS
- Pegel
- Bodendrucksensor
- Boje
- EB Daten

Messungen

Simulation

Lagebeurteilung und Entscheidungsunterstützung

- Lokale Behörden
- Gefährdete Bevölkerung
- Weitere nationale und internationale Empfänger
Warning center: Decision Support System