The Science and Engineering of an Operational Tsunami Forecasting System – One Component of a Comprehensive Program to Reduce the Impact of Another Indian Ocean Mega-disaster

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Pacific Marine Environmental Laboratory
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Argonne National Laboratory Seminar
6 April 2005
Argonne, Illinois
Fatalities

Center of Excellence in Disaster Management and Humanitarian Assistance

Emergency Report: January 8, 2005

Damage Estimated to be $13.6B
26 Dec 2004 Sumatra Mega-disaster (Titov MOST Model)

QuickTime™ and a Sorenson Video 3 decompressor are needed to see this picture.
Impacts

Sri Lanka & Phuket, Thailand

Kho Kah, Thailand
QuickTime™ and a Video decompressor are needed to see this picture.
Worst tsunami destruction was not videotaped.

Digital Globe Quickbird Satellite Photos
Tsunami Effects in Banda Aceh

Credit: Dr. Jose Borrero
USC, USA
Slide Not Available
QuickTime™ and a Photo decompressor are needed to see this picture.
Max Tsunami Height
TSUNAMIS … Inevitable, and “Born of Fire”
Definition

A tsunami is a series of long water waves generated when water is displaced by an impulsive geophysical event.

Sources: Earthquakes, Landslides, Volcanoes, Meteors, …
Subduction Zone Earthquake Cycle

1. **Interseismic Period:**
   - 10's - 100's of years between earthquakes

2. **Coseismic Period:**
   - A few minutes of Earthquake Rupture

(Courtesy, Geological Survey of Canada)
Ten Destructive Tsunamis Since 1990
Killed More than 4,000

- February 17, 1996
  - Irian Jaya
  - Maximum Wave: 7.7M
  - Fatalities: 161

- October 9, 1995
  - Jalisco, Mexico
  - Maximum Wave: 11M
  - Fatalities: 1

- November 15, 1994
  - Mindoro Island, Philippines
  - Maximum Wave: 7M
  - Fatalities: 49

- December 12, 1992
  - Flores Island
  - Maximum Wave: 26M
  - Fatalities: 1,000

- January 1, 1996
  - Sulawesi Island
  - Maximum Wave: 3.4M
  - Fatalities: 9

- July 12, 1993
  - Okushiri, Japan
  - Maximum Wave: 31M
  - Fatalities: 239

- September 2, 1992
  - Nicaragua
  - Maximum Wave: 10M
  - Fatalities: 170

- July 21, 1998
  - Papua New Guinea
  - Maximum Wave: 15M
  - Fatalities: 2,200

- February 21, 1996
  - North Coast of Peru
  - Maximum Wave: 5M
  - Fatalities: 12
Northwest Tsunami Hazards

“Local” Sources (Warning ~ 5-30 minutes)

1. Cascadia Subduction Zone
   • M ~ 9
   • Centuries recurrence times

2. Puget Sound Faults
   • M ~ 7.6
   • Millenia recurrence times

“Distant” Sources (Warning ~ 1-4 hours)

3. Alaska-Aleutian Subduction Zone
   • M ~ 8 +
   • Decades recurrence times
Cascadia Subduction Zone
### Tsunami Statistics by Ocean

- **1900 - Present**
- **Significant tsunamis defined as**
  - High Validity Index
  - $>1$ m height

<table>
<thead>
<tr>
<th>Ocean</th>
<th>Significant Tsunamis</th>
<th>All Tsunamis</th>
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<tbody>
<tr>
<td>Pacific</td>
<td>210 (88%)</td>
<td>604 (88%)</td>
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<tr>
<td>Indian</td>
<td>8 (3%)</td>
<td>32 (5%)</td>
</tr>
<tr>
<td>Atlantic</td>
<td>21 (9%)</td>
<td>51 (7%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>239 (100%)</strong></td>
<td><strong>687 (100%)</strong></td>
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</table>

Analysis by Paul Whitmore, West Coast and Alaska Tsunami Warning Center
Data from NOAA/National Geophysical Data Center Historical Tsunami Database
### N. Caribbean Eq/Tsu Events

*Grindley, et al., EOS, 3/22/05.*

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>M</th>
<th>Tsu Ht (m)</th>
<th>Deaths: Eq + Tsu (?)</th>
<th>Deaths: Eq</th>
<th>Deaths: Tsu</th>
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<tbody>
<tr>
<td>1692</td>
<td>Port Royal, Jamaica</td>
<td></td>
<td></td>
<td>2000</td>
<td></td>
<td></td>
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<tr>
<td>1780</td>
<td>S. Coast Jamaica</td>
<td>3</td>
<td>3.1 - 5</td>
<td>100’s</td>
<td></td>
<td>10 ?</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Hurr.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1842</td>
<td>Hispaniola</td>
<td></td>
<td>7.3</td>
<td>6</td>
<td>156</td>
<td>116</td>
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<tr>
<td>1867</td>
<td>Puerto Rico</td>
<td>7.5</td>
<td>2.4 - 12.1</td>
<td></td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>1918</td>
<td>Hispaniola-Puerto Rico</td>
<td>7.3</td>
<td>6</td>
<td></td>
<td>116</td>
<td>40</td>
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<tr>
<td>1946</td>
<td>N.E. Coast, Dom. Rep.</td>
<td>8.1</td>
<td></td>
<td></td>
<td>1800</td>
<td></td>
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</table>

**Map and Diagram:**

- Caribbean Plate
- Tsunami Generating Event
- Predicted GPS vector
- Observed GPS vector
- Northern Caribbean Sea
- Yucatan Straits
- Panama Platform
- Transpressional deformation
- Oblique collision
- Oceanic subduction
- Transtension
- Strike-slip
28 March 2005 Sumatra 8.7
Earthquake risk from co-seismic stress

Following the massive loss of life caused by the Sumatra-Andaman earthquake in Indonesia and its tsunami, the possibility of a triggered earthquake on the contiguous Sunda trench subduction zone is a real concern. We have calculated the distributions of co-seismic stress on this zone, as well as on the neighbouring, vertical strike-slip Sumatra fault, and find an increase in stress on both structures that significantly boosts the already considerable earthquake hazard posed by them. In particular, the increased potential for a large subduction-zone event in this region, with the concomitant risk of another tsunami, makes the need for tsunami warning systems in the Indian Ocean all the more urgent.

Inspection of the aftershock distribution and evidence from recent inversions reveal that the Sumatra–Andaman earthquake of 26 December 2004 ruptured almost 0.25 million square kilometres of the Indian plate/Burma microplate subduction zone (Fig. 1), generating a tsunami. The current death toll is in the region of 306,000.

Subduction zone earthquakes are often coupled: in the Nankai trough subduction zone to the southeast of Japan, for example, five of the seven large earthquakes on the Nankaido segment in the past 1,500 or so years were accompanied by similar events on the contiguous Nan’mao/Todai segment within five years, and three of those occurred in the same year1. This observation is entirely consistent with stress interaction, which has been shown to explain the space–time juxtaposition of large earthquakes2. The destructive 1999 Izmit earthquake (magnitude 7.4) southeast of Istanbul, for example, was triggered by stress increases of less than 2 bars that were due to earlier local events3, in turn, this triggered the Duzce earthquake (magnitude 7.1) which occurred three months later4.

Previous work on the palaeoseismology of the Sunda trench has indicated that this area may already be advanced in the seismogenic cycle5. The northern section of the Sumatra fault has not experienced any large earthquakes for at least the past 100 years either.

Waveform–inversion studies reveal a strongly heterogeneous slip distribution for the Sumatra–Andaman earthquake, with maximum displacements being of the order of 20 m and the majority of the slip being concentrated on the southernmost 500 km or so of the rupture2. We used this slip distribution to calculate the stress perturbation tensor, which was then resolved on the structures of interest. Results show a stress increase of up to 5 bars in the 50 km of the Sunda trench next to the rupture zone, but they also show a strong positive loading of up to 9 bars for about 380 km on the Sumatra fault near the city of Banda Aceh (Fig. 2).

The results indicate that although a subduction-zone event in the Sunda trench has been made more likely by the Sumatra-Andaman earthquake at present the increase in stress is localized on the north of this segment. The effect might be expected to spread further south in the months ahead.

28 March 2005

Wave Amplitude (CENTIMETERS)
At least 1000 people killed, 300 injured and 300 buildings destroyed on Nias; 100 people killed, many injured and several buildings damaged on Simeulue; 200 people killed in Kepulauan Banyak; 3 people killed, 40 injured and some damage in the Meulaboh area, Sumatra. A 3-meter tsunami damaged the port and airport on Simeulue. Tsunami runup heights as high as 2 meters were observed on the west coast of Nias and 1 meter at Singkil and Meulaboh, Sumatra. Felt (VI) at Banda Aceh and (V) at Medan. At least 10 people were killed during evacuation of the coast of Sri Lanka. Felt (IV) along the west coast of Malaysia; (IV) at Bangkok and (III) at Phuket, Thailand; (III) at Singapore; (III) at Male, Maldives. The quake was also felt in the Andaman and Nicobar Islands, India and in Sri Lanka. Tsunami wave heights (peak to trough) recorded from selected tide stations: about 40 cm on Panjang, Indonesia; about 25 cm at Colombo, Sri Lanka; 40 cm on Hanimadu, 18 cm at Male and 10 cm at Gan, Maldives. Initial observations indicate about 1 meter of subsidence on the coast of Kepulauan Banyak as well as 1 meter of uplift on the coast of Simeulue. Seiches were observed on ponds in West Bengal, India.
**20050328 Sumatra Summary Maps**

Gusong Bay, Simeulue Island

West Sumatra International Tsunami Survey Team will arrive at Nias at approximately 2300 31 March UTC

12 foot tsunami wave reported at Gusong Bay, Simeulue Island by Brian Willy (resident)

3 tsunami waves reported at Gusong Bay, Simeulue Island
Gusong Bay, Simeule - Uplift. New Beach
Subsidence of Sarangbaung, Indonesia

Sarangbaung subsided 1.65 meters during the 28 March 2005 earthquake. Etienne Kingsley (USGS contractor) and Gegar Prasetya (Tsunami Research Center/Coastal Dynamic Research Center - BPPT) are standing at the high tide line prior to the 28 March earthquake. Subsidence is fairly consistent around the island. The 28 March earthquake produced a 1 meter tsunami that inundated ~200 m inland.
Displacement
U.S. National Tsunami Hazard Mitigation Program

Reduce the Impact of Tsunamis on U.S. Coastal Communities

State Agencies
Alaska  California  Hawaii  Oregon  Washington

Federal Agencies
• National Oceanic and Atmospheric Admin.
• U.S. Geological Survey
• Federal Emergency Management Agency

Frank González, NOAA TIME Center, PMEL, Seattle, WA
Goal

Reduce Fatalities through:

- **Hazard Assessment**
  - Historical and pre-historic studies
  - “What if” modeling studies
- **Education, Training, Mitigation**
  - Brochures, signs, etc.
  - Community workshops, meetings
- **Tsunami Warning System**
  - Tsunami Forecasting System
    - Real-time Measurements
    - Forecast Modeling
Hazard Assessment
Seattle Fault Tsunami, ~900 A.D.

QuickTime™ and a Sorenson Video 3 decompressor are needed to see this picture.
• **Education, Training, Mitigation**

**Entering A TsunamiReady Community**

*IN CASE OF EARTHQUAKE, GO TO HIGH GROUND OR INLAND*
Rockaway Beach Evacuation Map

LEGEND

- **Yellow**: Evacuation Zone
- **Red Arrow**: Evacuation Route
- **Red Flag**: School
- **Red Truck**: Fire Station
- **Blue Building**: Police Station
- **Red Circle**: City Hall
- **Red Star**: Assembly Area
• Tsunami Warning System

TWS = Seismic + Tide Gage Nets

Problems:
• Seismometers do not measure tsunamis
• Tide Gages IN community, NOT BETWEEN source and community
Short-term Inundation Forecasting for Tsunamis

By Combining
Real-time Tsunami & Seismic Data + Model Simulations Database

For Site-specific Forecasts
**BPR** measures small changes in pressure at the seafloor. Data sent acoustically to surface buoy, then via satellite to the Warning Centers.

**Normal transmissions:** Hourly reporting of 15 minute data to confirm system readiness.

**Two Event Modes:**
- **Automatic:** Triggered by seismic or tsunami wave
- **Request:** Warning Center triggers data stream
Deep Ocean Assessment and Reporting of Tsunamis

Tsunami Warning Centers
- Trigger Mode
- Request Mode

- West Coast / Alaska Tsunami Warning Center
- NOAA/PMEL
- Pacific Tsunami Warning Center
JASON-1 Altimeter Comparison with Tsunami Model

NOAA

Laboratory for Satellite Altimetry:

Remko Scharroo
Walter H. F. Smith

Pac. Mar. Env. Lab.
Vasily Titov
Tsunami Forecasting

Measurement Requirements

1. Measurement type - tsunami amplitude over time for input into forecast models
2. Measurement accuracy - 0.5 cm
3. Measurement sample rate – 1 min or less
4. Measurement processing – within 2 min
5. Measurement availability – within 5 minutes to assimilate into forecast models
How many tsunameters are needed?

- At least 3 measurements on main beam
- 9000 km ~ length of Pacific tsunamigenic zones
- Number of tsunameters
  ~ 15 for 45-min TT
  ~ 25 for 30-min TT
  ~ 50 for 15-min TT
- More required for M < 8
DART Deployments in AASZ - October 1999
Operational Tsunami Forecasting

• Essential to Improve Warning Speed and Reliability

• Vast Ocean Areas with No Tsunami Measurements

• Must Integrate Real-time Measurement and Modeling
  - Measurement: NOAA DART Network
  - Modeling: NOAA Tsunami Forecast Model
Operational Tsunami Forecasting

- **Must Integrate Real-time Measurement and Modeling**
  - **Measurement:** NOAA DART Network
  - **Modeling:** NOAA Tsunami Forecast Model

- **Real-time Methodologies**
  - **Inversion:** Force Model to Match Real-time Data
  - **Interpolation:** Model Values for Areas with No Data
  - **Forecast:** Real-time Inundation Simulations

- **International Modeling Network**
  Transfer, Maintain, and Improve Tsunami Forecast Models
International Modeling Network

Transfer, Maintain, and Improve Tsunami Forecast Models

Network Nodes Share: Models, R&D Tools, Databases, …
Example of Tsunami Forecast: 17 Nov 2003

Q: How would you interpret these data?
Example of Tsunami Forecast:  17 Nov 2003

Q: How would you interpret these data?

A: Operational Forecast Model
1. Pre-computed Nested Grid Database of Offshore Values

2. Provides Initial Conditions for Real-time Inundation Simulation (~10 Minutes)

- Hilo Tide Gage
Result: “Blind” Tsunami Forecast at Hilo

November 17, 2003 Rat Is. tsunami at Hilo

hours after earthquake (06:43:07 UTC, November 17, 2003)
Summary

- **Sumatra mega-disaster a global wake-up call**
- **Tsunamis are inevitable**
- **U.S. accelerating Tsunami Preparedness efforts**
  - Assessment
  - Education, Outreach
  - Tsunami Forecasting and Warning System
Thanks ...