A Story about the GPS-Aided Tsunami Early-detection System

Y. Tony Song

Content:
1. Tsunami history & tragedies
2. Tsunami mystery
3. New detection technologies
4. Early warning systems
5. Tsunami hazard mitigation
The first recorded, the Aegean Sea tsunami in 426 B.C. by Greek historian Thucydides (460 – 400 B.C.), who linked the flood to an earthquake.
Figure 1. The Red Sea parted, allowing Moses and the Israelites to escape the pursuing soldiers of the Pharaoh (by permission of Pictures Now! Powered by Wood River Media, Inc., 1998, Wood River Media, June 1998; http://www.lycos.com/picturethis RELIGION/JUDAISM/HISTORY/bible_stories/crossing_the_red_sea/310521.html). The picture suggests a tsunami with high nonlinear distortion, what is now called a soliton of
**Real Tsunamis & Tragedies**

2004: Indian Ocean tsunami death ~230,000
2006: Java tsunami death ~730
2007: Solomon tsunami death ~54
2011: Japan tsunami ~1,900
Real Tsunamis & Tragedies

2011 Japan tsunami

https://youtu.be/FB6A3n8EblE

http://www.godtube.com/watch/?v=9C2MEJNU
How high the tsunami can go?

A car on the roof of a building in Phakarang Cape, Khao Lak
State of Hawaii’s estimation: an evacuation from a tsunami alarm would have cost the state $58.2 million in economic losses (Eddie Bernard, 1996).

Since 1982, tsunami warnings based on earthquake magnitude have produced false alarms 16 out of 16 in Pacific (U.S. Government Accountability Office, GAO-06-519).

Panic evacuation killed ~100 in March 2005
Tsunami Formation Mystery

- Tsunami speed: 800 km/hour (jet plane speed)
- Wave length: ~ 200 km
- Wave height: 20 cm ~ 10 m+
- Reaches shore: 20~30 minutes after an earthquake

\[ c = \sqrt{gh} \]
Because no observation, lab experiment was the only choice.


**Vertical uplift was the only force in the experiment!**
Long-held Tsunami Theory

“Seafloor uplift is the main cause of tsunamis”

Pond & Pichard (1983)
Introductory Dynamical Oceanography:
“Earthquakes that involve a significant vertical motion are more effective in generating tsunamis than those that primarily horizontal motion.”

Tanioka & Satake (1996): “We ignore the horizontal motion of water due to movement of slope, because ...(Iwasaki 82).”

\[ \Delta \eta = U + E \cdot h_x + N \cdot h_y \]
Unfortunately,
1. Earthquake magnitude is not a good indicator of a resulting tsunami;
2. DART buoys measure tsunamis when a wave arrives at a station.
Recent Tsunamis

Tsunami occurs quite often—the most devastating disaster

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Magnitude</th>
<th>Early Warning?</th>
<th>Fatality</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 Dec 2004</td>
<td>Sumatra</td>
<td>9.2</td>
<td>No warning</td>
<td>Tsunami death ~230,000</td>
</tr>
<tr>
<td>28 Mar 2005</td>
<td>Nias Island</td>
<td>8.7</td>
<td>Panic evacuation</td>
<td>Evacuation killed ~100</td>
</tr>
<tr>
<td>19 July 2005</td>
<td>North California</td>
<td>7.7</td>
<td>False alarm</td>
<td>No tsunami</td>
</tr>
<tr>
<td>27 Jan 2006</td>
<td>Benda Sea</td>
<td>7.6</td>
<td>No warning</td>
<td>No tsunami</td>
</tr>
<tr>
<td>3 May 2006</td>
<td>Tonga</td>
<td>8.0</td>
<td>Panic warning</td>
<td>No tsunami</td>
</tr>
<tr>
<td>19 July 2006</td>
<td>South Java</td>
<td>7.7</td>
<td>No warning</td>
<td>No tsunami</td>
</tr>
<tr>
<td>15 Nov 2006</td>
<td>Kuril Islands</td>
<td>8.3</td>
<td>False alarm/alert</td>
<td>No tsunami</td>
</tr>
<tr>
<td>13 Jan 2007</td>
<td>Kuril Islands</td>
<td>8.1</td>
<td>False alarm/alert</td>
<td>Tsunami death ~730 Small tsunami</td>
</tr>
<tr>
<td>1 Apr 2007</td>
<td>Solomon Island</td>
<td>8.0</td>
<td>Alert</td>
<td>Tsunami death ~54</td>
</tr>
<tr>
<td>15 Aug 2007</td>
<td>Central Peru</td>
<td>8.0</td>
<td>Alert</td>
<td>No tsunami</td>
</tr>
<tr>
<td>12 Sep 2007</td>
<td>South Sumatra</td>
<td>8.4</td>
<td>Alert</td>
<td>No tsunami</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27 Feb 2010</td>
<td>Chile</td>
<td>8.8</td>
<td>Basin-wide Warning</td>
<td>Casualty? (relative small)</td>
</tr>
<tr>
<td>25 Oct 2010</td>
<td>Sumatra</td>
<td>7.7</td>
<td>No warning</td>
<td>Tsunami death ~100</td>
</tr>
<tr>
<td>11 Mar 2011</td>
<td>Tohoku-Oki, Japan</td>
<td>9.0</td>
<td>Basin-wide Warning</td>
<td>Tsunami death ~19,000</td>
</tr>
</tbody>
</table>
NASA Earth Science Missions
Global Measurements
1. Evidence from satellites

Vertical uplift was not the only cause of the 2004 tsunami (Song & Han 2006), rejected

Song, Y.T. and S.-C. Han (2011)
2. New Tsunami Theory

Song et al., Horizontal impulses of faulting continental slopes dictate tsunami genesis, *Ocean Modell.* (2008).

1: Lateral motions of continental slopes ALSO transfer energy (KE) into the ocean.

   (a) No energy transferred
   (b) No energy transferred
   (c) Potential energy transferred
   (d) Kinetic energy transferred

2: Tsunamis source energy: $E_T = PE + KE$

Theoretical formulation proposed.
Zhang Heng (張衡, 78 – 139 A.D.) was an astronomer, mathematician, and poet of the Eastern Han Dynasty in ancient China. He invented the first seismograph in 132 A.D.

“Refusing to accept superstitious explanation of the earthquakes, Zhang made heroic observations of earthquakes and invented the ‘Didong Yi’ to detect earthquake from distance”

Horizontal pendulum seismograph invented by English seismologist John Milne in 1880.

Caltech Prof. Charles Richter invented the Richter’s scale of earthquake in 1935.
A New Tsunami Detection Approach

Song, Y.T., Detecting tsunami genesis and scales directly from coastal GPS stations, GRL, 34, (2007).

Tony Song, April 2010
# Tsunami Scale

- Earthquakes—Richter’s scale (magnitude)
- Hurricanes—Simpson’s scale (category)
- Tsunamis can be scaled (based on $\sqrt{E_T} \sim$ tsunami height):

$$S_T \equiv \log_{10} E_T - 10$$

<table>
<thead>
<tr>
<th>Earthquake Magnitude</th>
<th>Tsunami Energy ($E_T$)</th>
<th>Tsunami Scale ($S_T$)</th>
<th>Basin-wide Warning?</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 Sumatra ($M_w$ 9.2)</td>
<td>6.0e+15 J</td>
<td>5.8</td>
<td>&gt;&gt; 5 Yes</td>
</tr>
<tr>
<td>1964 Alaska ($M_w$ 9.2)</td>
<td>8.2e+15 J</td>
<td>5.9</td>
<td>&gt;&gt; 5 Yes</td>
</tr>
<tr>
<td>2005 Nias Island ($M_w$ 8.7)</td>
<td>2.8e+14 J</td>
<td>4.4</td>
<td>&lt;&lt; 5</td>
</tr>
<tr>
<td>2009 Samoa ($M_w$ 8.0)</td>
<td>3.5e+14 J</td>
<td>4.5</td>
<td>&lt;&lt; 5</td>
</tr>
<tr>
<td>2010 Chile ($M_w$ 8.8)</td>
<td>6.5e+14 J</td>
<td>4.8</td>
<td>&lt;&lt; 5</td>
</tr>
<tr>
<td>2011 Tohoku-Oki ($M_w$ 9.0)</td>
<td>3.0e+15 J</td>
<td>5.5</td>
<td>&gt;&gt; 5 Yes</td>
</tr>
</tbody>
</table>

Tony Song, June 2011
Real-Time Test 1: 2010 Chile M8.8 Earthquake Demonstrates GPS method

(a): NASA's Global Differential GPS (GDGPS) measures the Chile M8.8 earthquake displacement in real time at Santiago.

(b): JPL team predicts a moderate sized tsunami using the real-time GPS and the Song tsunami generation model.

(c): NASA/CNES satellites Jason-1 and Jason-2 confirm the tsunami amplitude of the GPS-based model prediction.

Next steps: Strengthen real time GDGPS network, automate models.

Tony Song, Yoaz Bar-Sever, et al /JPL
Challenges in Transferring Research to Operation

Tony Song, Jan 2012
If GPS had been used in the 2011 Japanese Tsunami
3. JPL/OSU Tsunami Experiments

Large wave flume (104 m)  
Multidirectional wave basin (48.8 m)
During my experiment, the 2011 Japan tsunami occurred.

The 2011 Tohoku data are the guidance in our experiments.

Data:
- Coastal GPS [GeoNet Japan]
- GPS–acoustic array [Sato et al.]
- Seafloor survey [Fujiwara et al.]
- Pressure–acoustic gauge [Ito et al.]
- Seismic reflection [Tsuji et al.]
Experimental Results

Summary:

(a) With a fixed stoke distance (PE), kinetic energy (KE) increases with speed.

Simple non-dimensional parameter does not explain reality (e.g., Tohoku & Sumatra).

(b) Normalized parameters explain the reality and confirm that the horizontal motions of faulting slope is the key force of tsunami.
NASA Team at Tsunami Warning Center
Overview
Real-time tests on a prototype GATEW system

Tsunami Warning Centers

Gworm Geodetic Data Processing Flow Diagram
Phase 1
V6.8 February 7, 2017

Y. Tony Song, Yoaz Bar-Sever, Zhen Liu, Robert Khachikyan, Kejie Chen
Time needed for earthquake source inversion: (right) using GPS data only, and (right) using GPS and seismic data, for all Mw\(>7.0\) earthquakes (color dots on the map) since 1990.  

(Chen et al., in prep)
Tsunami Education & Mitigation

Recognize Tsunami Warning Signs!
FEEL the ground shaking?
SEE an unusual disappearance of water?
HEAR a roar from the ocean?
RUN to higher ground!

https://www.youtube.com/watch?v=UzR0Rt3i4kc&feature=youtu.be
Tsunami Resistant Buildings

Many buildings along the Hilo, Hawai’i coast are built on pilings with the intention of withstanding flooding and tsunamis. Photo by: Eric Muehling
Mitigation & Preparedness

BE TSUNAMI SMART

When at the beach, if you:
1 FEEL STRONG SHAKING
2 HEAR A STRANGE NOISE FROM THE SEA
3 SEE THE WATER WITHDRAW AN UNUSUAL DISTANCE FROM THE SHORE

RUN!

www.weready.org