Tsunami Disaster Mitigation in Asia after the 2004 Indian Ocean and 2011 Tohoku Tsunamis

Kenji Satake

Earthquake Res. Inst. Univ. Tokyo
satake@eri.u-tokyo.ac.jp
Earthquakes with > 1,000 fatalities in last decade

<table>
<thead>
<tr>
<th>Date</th>
<th>Region</th>
<th>M</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011/3/11</td>
<td>Tohoku, Japan</td>
<td>9.0</td>
<td>20,896</td>
</tr>
<tr>
<td>2010/1/12</td>
<td>Haiti</td>
<td>7.0</td>
<td>222,570</td>
</tr>
<tr>
<td>2009/9/30</td>
<td>Padang, Indonesia</td>
<td>7.5</td>
<td>1,117</td>
</tr>
<tr>
<td>2008/5/12</td>
<td>Sichuan, China</td>
<td>7.9</td>
<td>87,587</td>
</tr>
<tr>
<td>2006/5/26</td>
<td>Java (Jogjakarta), Indonesia</td>
<td>6.3</td>
<td>5,749</td>
</tr>
<tr>
<td>2005/10/8</td>
<td>Kashmir, Pakistan</td>
<td>7.6</td>
<td>86,000</td>
</tr>
<tr>
<td>2005/3/28</td>
<td>Sumatra (Nias), Indonesia</td>
<td>8.6</td>
<td>1,313</td>
</tr>
<tr>
<td>2004/12/26</td>
<td>Sumatra (Aceh), Indonesia</td>
<td>9.1</td>
<td>227,898</td>
</tr>
<tr>
<td>2003/12/26</td>
<td>Bam, Iran</td>
<td>6.6</td>
<td>31,000</td>
</tr>
<tr>
<td>2003/5/21</td>
<td>Algeria</td>
<td>6.8</td>
<td>2,266</td>
</tr>
<tr>
<td>2002/3/25</td>
<td>Afghanistan</td>
<td>6.1</td>
<td>1,000</td>
</tr>
<tr>
<td>2001/1/26</td>
<td>Bhuj (Gujarat), India</td>
<td>7.6</td>
<td>20,023</td>
</tr>
</tbody>
</table>

Of these 12 events, 10 occurred in Asia and 4 in Indonesia
Multi-disciplinary Hazard Reduction Program from Earthquakes and Volcanoes in Indonesia

Disaster Risk = Natural Hazard X Society’s Vulnerability

1. Eq. Forecast
2. Volcanic eruption
3. Engineering
4. Social Sciences
5. Education and Awareness
6. Coordination with Governments
Outline

1. March 11 earthquake and tsunami
2. Long-term forecast of earthquake
3. Past tsunamis on Tohoku coasts
4. Observation and analysis of the 2011 tsunami
5. Giant earthquakes in the world
Outline

1. March 11 earthquake and tsunami
2. Long-term forecast of earthquake
3. Past tsunamis on Tohoku coasts
4. Observation and analysis of the 2011 tsunami
5. Giant earthquakes in the world
Plates around Japan

11 March Tohoku Eq.
GPS data and Slip distribution

1998-2000

March 11, 2011

GSI (2010, 2011)
Seafloor displacement

Max observed slip: 24 m horizontal, 3 m vertical

Sato et al. (Science 2011)

Max slip on fault (estimated): > 50 m
Slip Distribution from Seismic Waves

Yoshida et al. (2011)
Seafloor displacement
(cross-section)

Surface displacement

Subsidence  Uplift

W E

Tohoku coast  Japan trench

Fault motion
March 11, 2011 tsunami

Miyako, Iwate pref.

About 30 minutes
After the earthquake

Mainichi Newspaper

Natori, Miyagi pref.

About 1 hour after eq.

AP
Tsunami generation and propagation

2011 off the Pacific coast of Tohoku earthquake 0001 min

Iwate

Miyagi

Fukushima

Water height (m)
Outline

1. March 11 earthquake and tsunami

2. Long-term forecast of earthquake

3. Tsunami warning system

4. Past tsunamis on Tohoku coasts

5. Observation and analysis of the 2011 tsunami

6. Giant earthquakes in the world
GPS data and slip distribution

1998-2000

March 11, 2011

GSI (2010, 2011)
GPS data and past earthquakes

1998-2000

Large earthquakes since 1900

GSI (2010, 2011)

Long-term forecast of earthquakes

Long-term forecast by ERC (2003)
Long-term forecast of earthquakes

Long-term forecast by ERC (2003)
Long-term forecast of earthquakes

Iwate

Miyagi

Fukushima

Long term forecast by ERC (2003)
Seismologists assumed earthquake cycle (~35 years) from past records of two centuries and made forecast (99% in 30 years), but there seems to be a supercycle (~700 years) on top of it.
Outline

1. March 11 earthquake and tsunami
2. Long-term forecast of earthquake
3. Past tsunamis on Tohoku coasts
4. Observation and analysis of the 2011 tsunami
5. Giant earthquakes in the world
1896 Sanriku tsunami

1896 Meiji tsunami: 22,000 casualties (more than 2011 tsunami)

M 7.2, Max tsunami height 38 m
Weak shaking but large tsunami
“Tsunami earthquake”

Width: 50 km, slip: 6m
Near trench axis
The 869 Jogan earthquake

Nihon Sandai Jitsuroku (Chronicle of Japan)
A large earthquake in Mutsu
Panic stricken by violent tremblings
Fallen houses, wide-opened ground fissures
Roaring like thunder heard from the sea
Sea rushed into castle, a few hundred miles
About 1,000 people were killed

Tsunami deposit studies
Sand layer brought by tsunami below volcanic ash (AD915)
distributed ~ 5 km from the coast
The 869 Jogan earthquake

A fault model proposed in 2008

- The 869 deposits
- Possible 869 deposits
- No deposits
Outline

1. March 11 earthquake and tsunami
2. Long-term forecast of earthquake
3. Past tsunamis on Tohoku coasts
4. Observation and analysis of the 2011 tsunami
5. Giant earthquakes in the world
**Tsunami observation**

- **Boqom Pressure Gauge**
  - 70 km offshore
  - 1600 m water depth

- **Boqom Pressure Gauge**
  - 40 km offshore
  - 1000 m water depth

**Map**

- Miyako (Coastal)
- Kamaishi (Coastal)
- Ofunato (Coastal)
- Iwate S (GPS)

**Graphs**

- Water height vs. time after earthquake for Miyako, Kamaishi, Ofunato, and Iwate S.
Slip distribution from tsunami waveforms

Iwate N (GPS)

Miyagi M (GPS)

TM–1

TM–2

Iwate S (GPS)

Fukushima (GPS)

Time (min)

Amplitude (m)

obs
syn

Map showing the slip distribution with various markers and colors indicating different slip magnitudes.
2011 earthquake: 1896 and 869 types
2011 earthquake: 1896 and 869 types

Iwate N (GPS)
Miyagi M (GPS)
Fukushima (GPS)

TM-1
obs
shallow
TM-2

Amplitude (m)

Time (min)
2011 earthquake: 1896 and 869 types

Miyagi-oki
- 869-type
- 1896-type

Fukushima-oki
- 869 type

869 Jogan-type
- 15-20 m slip Miyagi-oki

1896 Sanriku-type
- >40m slip off Miyagi-oki

<10 m slip Fukushima-oki
Outline

1. March 11 earthquake and tsunami
2. Long-term forecast of earthquake
3. Past tsunamis on Tohoku coasts
4. Observation and analysis of the 2011 tsunami
5. Giant earthquakes in the world
Only five M9 earthquakes since 20\textsuperscript{th} century

2004 Sumatra-Andaman earthquake

Andaman-Nicobar Is.
- 1941 M 7.7
- 1881 M 7.9
- 1847 M 7.5
(from historical records)

Sumatra
- 2004 M 9.1
- 2005 M 8.7
- 1861 M 8.5
- 1797 M 8.4
- 1833 M 8.9
(from coral studies)
Paleoseismological Studies since 2004

Map showing the locations of the Andaman (Burma) microplate, Nicobar Islands, Sumatra Islands, and the Inde-Australia plate. The map highlights the 2004 tsunami, the ~AD1400 tsunami, and other historical earthquakes. The text references Aung et al. (2008 J. Earthq. Tsunami) and Jankaew et al. (2008 Nature).
**South-Central Chile**

<table>
<thead>
<tr>
<th>Historical Evidence</th>
<th>1575</th>
<th>1737</th>
<th>1837</th>
<th>1960</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concepción</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imperial</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Villarica</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valdivia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Osorno</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Río Maullín</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isla Guar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ancud</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Castro</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isla Lemu</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>San Rafael</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hawaii</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **1960 source** (subsided area)
- **Giant (M~9.5) earthquakes ~300 yr interval**
  - NOT ~ 130 yr as inferred from historic data

Cisternas et al. (2005 *Nature*)

- **AD1960** tsunami deposit
- **AD1575** tsunami deposit
- **~AD1300** tidal-flat deposit
- **~AD1100** tsunami deposit

**Diagram:**

- 10 cm
- High tsunami
- Low tsunami
- Few or no writings
- Shaking
  - Coastal uplift
  - Coastal subsidence
- Writing w/o evidence
Tsunami recorded in Japan in 1700

Fault length: 1,100 km, slip: 14 m, 
Mo $4.6 \times 10^{22}$ Nm (Mw 9.0)
similar to the 2004 Sumatra-Andaman earthquake
Average recurrence interval: ~500 years

Satake, Wang, Atwater (2003, JGR)
Interval of Giant (M~9) Earthquakes

- Cascadia ~ 500 yrs
- Hokkaido ~ 500 yrs
- Chile ~ 300 yrs
- Indian Ocean Several hundred yrs
Conclusions

1. 2011 Tohoku earthquake was the largest (M~9) in Japan’s history

2. Long-term forecast estimated 99 % probability but M~8 in Miygai-oki

3. Tsunami warning was issued in 3 minutes but the heights were initially underestimated

4. The Tohoku coasts experienced similar tsunamis in the past

5. The 2011 tsunami was a combination of the 1896 and 869 type tsunamis

6. Giant earthquakes (M~9) occur once in several centuries in the world’s subduction zones