The 11.03.2011 Tohoku Earthquake, Japan

- questions raised, lessons learned
Epicentre of the 11 March 2011 earthquake off Sendai (Great Tohoku Earthquake – Great East Japan earthquake)
Prefectures affected

- Iwate
- Miyagi
- Fukushima

Key:
- 20km Nuclear Evacuation Zone
- Tsunami Affected Areas
- Epicenter of Aftershocks
- Prefecture Boundaries

International Environment and Disaster Management
Graduate School of Global Environmental Studies
Kyoto University
Earthquakes in the Japan region, Magnitude > 6.0, since 1900
Some great historical earthquake disasters in Japan

<table>
<thead>
<tr>
<th>Year</th>
<th>Magnitude</th>
<th>Name, fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1293</td>
<td>7.5</td>
<td>Kamakura, &gt; 23000</td>
</tr>
<tr>
<td>1703</td>
<td>8.0</td>
<td>Genroku earthquake, &gt; 100000</td>
</tr>
<tr>
<td>1707</td>
<td>8.6</td>
<td>Hoei, &gt; 5000</td>
</tr>
<tr>
<td>1854</td>
<td>8.4</td>
<td>Tokai, &gt; 2000</td>
</tr>
<tr>
<td>1891</td>
<td>8.3</td>
<td>Mino-Owari, &gt; 7000</td>
</tr>
<tr>
<td>1897</td>
<td>8.5</td>
<td>Sanriku, &gt; 27000</td>
</tr>
<tr>
<td>1923</td>
<td>8.3</td>
<td>Kanto, &gt; 100000</td>
</tr>
<tr>
<td>1927</td>
<td>7.6</td>
<td>Kita-Tango, &gt; 3000</td>
</tr>
<tr>
<td>1933</td>
<td>8.4</td>
<td>Sanriku, &gt; 3000</td>
</tr>
<tr>
<td>1943</td>
<td>7.2</td>
<td>Tottori, &gt; 1000</td>
</tr>
<tr>
<td>1946</td>
<td>8.1</td>
<td>Nankaido, &gt; 1000</td>
</tr>
<tr>
<td>1948</td>
<td>8.2</td>
<td>Fukui, &gt; 3500</td>
</tr>
<tr>
<td>1995</td>
<td>6.8</td>
<td>Hanshin (Kobe), &gt; 6000</td>
</tr>
</tbody>
</table>
Globally, this is the 4th largest earthquake since 1900.

Great (M > 8) Earthquakes Since 1900

- Ecuador 1906
- Alaska 1964
- Russia 1952
- Alaska 1965
- Chile 1960
- Sumatra 2004
- Japan 2011
- Chile 2010
Damage in the Great Kanto earthquake and fires, Tokyo, 01/09/1923
Earthquake epicentres during the last 20 years

The colours of the dots correspond to different depths. The pattern is certainly not a random one.
Why and How do earthquakes happen?
The way that the outlines of the continents fit together suggests that they were once united in a single super-continent – PANGAEA. This occurred about 200 million years ago. Before this time, the (same) land mass was broken up into a different set of continents.
GLOBAL PLATE TECTONICS
Tectonic Plate Velocities from GPS measurements
This earthquake was the result of thrust faulting along or near the convergent plate boundary where the Pacific Plate subducts beneath Japan.

This map also shows the rate and direction of motion of the Pacific Plate with respect to the Eurasian Plate near the Japan Trench. The rate of convergence at this plate boundary is about 83 mm/yr (8 cm/year). This is a fairly high convergence rate and this subduction zone is very seismically active.
subduction zone earthquake
The Japan subduction zone
Earthquake depths mark out the subduction zone.
What is an earthquake fault?

In the region of a plate boundary, parts of the earth’s lithosphere are constantly pushed to move against each other. Because the earth’s rocks are not smooth, the blocks on each side of the fault may remain “locked”, but the motion of the plates will still build up strain on either side. When this strain becomes too large, the fault ruptures.
Reverse fault (thrust)
Reverse fault (thrust)

Compression (shortening)
Earthquake of Kobe, Japan
17 January 1995, M=7.2

horizontal and vertical displacement
The magnitude of an earthquake depends on the area of the fault that ruptures, as well as on the distance moved.
coastal subsidence
offshore uplift creates tsunami

Sendai 5m
1m Trench

EuroAsian Plate 20m
tensional aftershocks in Pacific plate

Mantle

Pacific Plate
9 m each century

9 m each century

Credit: Roger Bilham
Japan 11/03/2011

- Fault length 450 km
- Fault width 150 km
- Rupture velocity 2.0 km/s
- Rupture time 150 sec
- Maximum slip 18 m
- Magnitude Mw 9.0
- Depth of hypocentre 24 km

Three fault segments ruptured at once!

Credit: Earthquake Research Institute, University of Tokyo
Aftershock sequence

- More than 1000 aftershocks, more than 60 being greater than 6.0
- Aftershocks may continue for years, getting smaller in time
- The aftershocks occur within the rupture area

Credit: Roger Bilham
**HOW BIG ARE EARTHQUAKE FAULTS?**

**Red Box: Sumatra 2004**
- M: 9.3
- Length: 1500 km
- Width: 200 km
- Max movement: 30m

**Green Box: Japan 2011**
- M: 9.0
- Length: 450 km
- Width: 150 km
- Max movement: 18m

**Yellow Box: Fucino 1915**
- M: 7.0
- Length: 28 km
- Width: 15 km
- Max movement: 1m
• The *surface* energy released in the earthquake was about 5000 nuclear bombs
• The *total* energy released was about 200,000 times larger
• The shift in the land masses caused a change in the earth’s rate of rotation by a 1.8 microseconds and shifted the earth’s axis by a few cm.
• The main island of Honshu had been compressed by about 4m for hundreds of years, and has now “expanded” again
Japan GPS network records changes in geographical coordinates.
Seismogram of the M8.9 Japan earthquake 11/03/2011 recorded at Malta – such a large earthquake causes the whole planet to vibrate for several hours

Chart represents 24 hour activity

Surface waves
The moment magnitude scale is designed to give an accurate characterization of the true size of an earthquake, but be tied to the original description of magnitude that was developed by Charles Richter. Moment magnitude accounts for earthquake size by looking at all the energy released.

It is striking that only 6 earthquakes over the last 106 years account for over half of the energy released during that time.
Earthquake classification

Earthquake magnitude

Figures seek to measure energy released in an earthquake

- 3.0: Minor
- 4.0: Light
- 5.0: Moderate
- 6.0: Strong
- 7.0: Major
- 8.0: Great

- 6.3: New Zealand 2011
- 7.0: Haiti 2010
- 7.9: China 2008
- 9.3: Sumatra 2004

BBC Science and Environment
Earthquake Damage
Soil liquifaction – a loss of shear strength of soils when subjected to cyclic loading, as in earthquakes.

Nigata (Japan), 1964

In Japan, strong liquifaction effects were observed around Tokyo, mostly on reclaimed land.

Izmit (Turkey), 1999
Effects of building resonance

Mexico City 1985
Inadequate building codes

Izmit (Turchia), 1999
Shaking intensity scales were developed to standardize the measurements and ease comparison of different earthquakes. The Modified-Mercalli Intensity scale is a twelve-stage scale, numbered from I to XII. The lower numbers represent imperceptible shaking levels, XII represents total destruction. A value of IV indicates a level of shaking that is felt by most people.

### Modified Mercalli Intensity

<table>
<thead>
<tr>
<th>Modified Mercalli Intensity</th>
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</thead>
<tbody>
<tr>
<td>X</td>
</tr>
<tr>
<td>IX</td>
</tr>
<tr>
<td>VIII</td>
</tr>
<tr>
<td>VII</td>
</tr>
<tr>
<td>VI</td>
</tr>
<tr>
<td>V</td>
</tr>
<tr>
<td>IV</td>
</tr>
<tr>
<td>III</td>
</tr>
<tr>
<td>I</td>
</tr>
</tbody>
</table>

**Perceived Shaking**

- Extreme
- Violent
- Severe
- Very Strong
- Strong
- Moderate
- Light
- Weak
- Not Felt

Image courtesy of the US Geological Survey

USGS Estimated shaking Intensity from M 9.0 Earthquake
The JMA (Japan Meteorological Association) Intensity scale goes from 1 to 7
The Japan earthquake produced ground accelerations greater than 2g at certain places – even near Tokyo!
Damage Assessment in Japan Earthquake

- Human Life: > 22,000 dead + missing

- Infrastructure:
  - About USD183 billion in economic losses
  - Most damage done by tsunami
  - 6 seaports with major damage and Sendai airport extensively damaged
  - huge impact on international trade (about USD3.4 billion of trade loss per day)
  - 1232 roads damaged
  - 4000 schools damaged or destroyed
  - Many regional train lines suspended
  - Approx 25% of power loss in Tokyo district
  - About 1.4 million households without running water
TSUNAMI
An underwater earthquake causes a break in the sea floor that pushes up the water column. This generates a wave of very long wavelength, travelling at hundreds of km per hour. As the water gets shallower, the wave slows down and the amplitude increases sharply.

In the Japan earthquake, the sea bed was shifted upwards by 5 – 8m.
Where are tsunamis likely to be generated?
Chile earthquake 1960

- Magnitude 9.5, the largest seismic event ever observed
- Tsunami wave up to 70m high!
- The waves travelled for 17000km,
  - from south Chile to Japan,
  - where 200 persons died.
Projected travel times for the arrival of the tsunami waves across the Pacific.

Nearby the earthquake there are only minutes to evacuate. However, in many other regions there is advance warning.

A tsunami map shows projected travel times for the Pacific Ocean. This map indicates forecasted times only, not that a wave traveling those distances has actually been observed. NOAA
This tsunami propagation forecast model shows the forecast maximum tsunami wave height (in cm). Ocean floor bathymetry affects the wave height because a tsunami moves the seawater all the way to the floor of the ocean.

This led to a Pacific wide tsunami warning being issued.
- The maximum tsunami height in Japan was 11.8m, arriving at 15:31 JST.
- The earthquake origin time was 14:46 JST, and the tsunami warning was issued by JMA at 14:49 JST.
- In Fukushima, the tsunami arrived within 30min.
Cities affected by the tsunami

<table>
<thead>
<tr>
<th>Name of Prefecture</th>
<th>Total number of cities</th>
<th>Cities Affected by tsunami</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iwate Prefecture</td>
<td>35</td>
<td>14</td>
</tr>
<tr>
<td>Miyagi Prefecture</td>
<td>36</td>
<td>17</td>
</tr>
<tr>
<td>Fukushima Prefecture</td>
<td>58</td>
<td>12</td>
</tr>
<tr>
<td>Ibaraki Prefecture</td>
<td>45</td>
<td>11</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>174</strong></td>
<td><strong>54</strong></td>
</tr>
</tbody>
</table>

Source: Collected from the various agency of Japan Government

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*Figure 4a. Map of local authorities affected by Tsunami (analyzed by IEDM, Kyoto University).*
Historical Tsunamis in Japan

- 1896: Sanriku >30m
- 1933: Sanriku 25m
- 1993: Okushiri island 30m

The Fukushima nuclear plant was protected by a 5m tsunami barrier. The 11m high wave flooded the plant’s generators and electrical systems, disabling the cooling mechanism.
Prediction vs Preparedness
• Are earthquakes predictable?
• Do earthquakes give any signs before they happen?
• Is there such a thing as an “earthquake cycle”?
• Should we listen to people who “foresee” earthquakes?
• What are seismologists doing about it?
• What should governments be doing about it?
• What about tsunamis?
Seismic gap theory

Seismic Gap Theory: Over the long term, all parts of the fault must have an average of the same rate of slip. A large seismic gap somewhere along the fault usually indicates that a large event is expected there, raising the level of risk in that area.

It is tempting to base predictions on this theory, but the earth’s “clock” is not always regular!
Repeat Earthquakes - the Parkfield experiment

• It was observed that along a section of the San Andreas fault in California, magnitude 6 earthquakes had struck the town of Parkfield about every 22 years.

• Seismologists announced that the next Parkfield earthquake would strike within four years of 1988 – “Parkfield time window”

• The area was comprehensively monitored by instruments.

• The earthquake came in 2004 – 16 years late!
Earthquake Precursors

• Physical changes in the rock
• Changes in slope and elevation
• Gas emissions
• Changes in electric/magnetic fields
• Changes in water levels
• Increased seismic activity
• Accelerating strain release rates
• ......................................
Haicheng, China, 1975

• “successful” prediction based mainly on increase of seismic activity – foreshocks. Lives were saved when people moved out of houses.
• But how do we know they are foreshocks?
• Some earthquakes have foreshocks, many don’t
• One year after Haicheng, a mag 7.5 quake struck Tangshan, killing about 250000 people
• The Tangshan earthquake had no precursors, no foreshocks – it was totally unforeseen.
The TOKAI earthquakes – Can the next one be predicted?

<table>
<thead>
<tr>
<th>Date</th>
<th>Magnitude</th>
<th>Event</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 26, 684</td>
<td>8.3</td>
<td>Hakuho earthquake</td>
<td>unknown</td>
</tr>
<tr>
<td>August 22, 887</td>
<td>8.5</td>
<td>Ninna earthquake</td>
<td>unknown</td>
</tr>
<tr>
<td>December 11, 1096</td>
<td>8.4</td>
<td>Kowa earthquake</td>
<td>unknown</td>
</tr>
<tr>
<td>July 26, 1361</td>
<td>8.5</td>
<td>Shohei earthquake</td>
<td>unknown</td>
</tr>
<tr>
<td>September 11, 1498</td>
<td>8.4</td>
<td>Meio earthquake</td>
<td>40,000</td>
</tr>
<tr>
<td>February 3, 1605</td>
<td>7.9</td>
<td>Keicho earthquake</td>
<td>2,300</td>
</tr>
<tr>
<td>October 28, 1707</td>
<td>8.4</td>
<td>Hiei earthquake</td>
<td>20,000</td>
</tr>
<tr>
<td>December 23, 1854</td>
<td>8.4</td>
<td>Ansei-Tokai earthquake</td>
<td>3,000</td>
</tr>
</tbody>
</table>
• In 1978 – Large-Scale Earthquake Countermeasures Act

• Law requires 24/7 monitoring of earthquake precursor activity to predict the “Tokai” earthquake
Japan Seismograph Network

Total: about 4,100

- JMA (600)
- Municipalities (2,850)
- NIED (667)
Earthquakes that have caused 10 or more fatalities since 1979 that have occurred outside the highest risk areas

*Nature*, volume 472

National Hazard Map of Japan

Government-designated probability of ground motion of seismic intensity of level ‘6-lower’ or higher (on a 7-maximum intensity scale) in the 30-year period starting in January 2010
• The major quest remains that of identifying short-term precursors that will reliably and consistently signify that a major earthquake is imminent.

• Major research question: Can we identify the trigger that causes multiple segments to rupture together and cause a megaquake?
Earthquake Early Warning

To announce estimated seismic intensity and arrival time before the strong motion arrival

Travel Time of Seismic Waves (sec)

S wave (Strong motion) arrival at Point A

S wave (about 4km/sec)

P wave (about 7km/sec)

Time available for taking action

EEW

Quick determination of hypocenter and magnitude

(a) P wave detection at the seismic station

(b) S wave (Strong motion) arrival at Point A

Prompt Analysis

Issuance

(Time available for taking action)
Probabilistic Seismic Hazard Assessment (PSHA) uses the past seismicity history of a region to calculate the probability that a certain level of ground shaking will occur, say over the next 30 years. This must then lead to an appropriate building code and the appropriate level of preparedness.

Deterministic Seismic Hazard Assessment considers a likely earthquake scenario and mathematically models the effects it is expected to produce in the region around it, taking into consideration the type of surface geology at different sites etc.
• Making buildings resistant to earthquake ground shaking remains the best (and only?) defence against earthquake disasters.
• Japan - revised building codes and strict enforcement after Kobe 1995
Tsunami Warning System
Core of the warning system is the monitoring of large offshore earthquakes and their potential of generating a tsunami.
What we need for Tsunami Warning

Components of tsunami warning system

- Network of seismographs
- Real time data transmission
- Real time data processing system
- Criteria for Tsunami grade
- Communication facility to disseminate Tsunami Warning
- Network of tide gauge to monitor tsunami

Generation of Tsunami

Occurrence of Earthquake

Detection of Seismic Wave

Determination of Magnitude and Hypocenter

Evaluation of Tsunami

Issuance of Tsunami Warning

Issuance of Tsunami Information

Re-evaluation of Tsunami

Credit: M. Yamamoto
## Categories of tsunami forecast

<table>
<thead>
<tr>
<th>Tsunami Forecast</th>
<th>Value of Tsunami Height to be issued</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tsunami Warning</strong></td>
<td><strong>Major Tsunami</strong></td>
</tr>
<tr>
<td></td>
<td>&quot;3m&quot;, &quot;4m&quot;, &quot;6m&quot;, &quot;8m&quot;, &quot;over 10m&quot;</td>
</tr>
<tr>
<td></td>
<td><strong>Tsunami</strong></td>
</tr>
<tr>
<td></td>
<td>&quot;1m&quot;, &quot;2m&quot;</td>
</tr>
<tr>
<td><strong>Tsunami Advisory</strong></td>
<td><strong>Tsunami Attention</strong></td>
</tr>
<tr>
<td></td>
<td>&quot;0.5m&quot;</td>
</tr>
</tbody>
</table>
Global Network of TWS

Credit: M. Yamamoto
Seismic Network for Tsunami Warning

Credit: M. Yamamoto
DART (Deep-ocean Assessment and Reporting of Tsunamis) – system of buoys for tracking the wave in the ocean and transmitting data.
Tsunami Estimation by JMA

1. Earthquake
2. Estimation of Focal Mechanism by CMT Analysis
3. Database Search
4. Re-evaluation of Tsunami Amplitude
5. Upgrade or Cancellation of Tsunami Warning

Credit: M. Yamamoto
• Problem: Tsunami hazards are on a very long time scale – can less developed countries finance and sustain the system in good operating condition for several decades until the next event??

• eg Indonesia, Caribbean ??
Central Tokyo

Lessons learned:
1. In Tokyo, where ground accelerations were very high, no buildings were seriously damaged – this was a major success of earthquake engineering. **Good buildings save lives**
2. A major meltdown of Fukushima has so far been averted – successful after-crisis response
3. Subduction zone earthquake potential is not to be underestimated!
4. Implications for other world areas – NW US, Mediterranean, Pacific.
5. TWS’s save lives but need to be maintained
Thank you
Tsunami Warning System

• Pacific Tsunami Warning System established after 1964 Alaska earthquake tsunami that killed more than 120 people.
• National Oceanic and atmospheric Administration (NOAA)
• Pacific Tsunami Warning Centre Hawaii
• Core of the warning system is the monitoring of large offshore earthquakes and their potential of generating a tsunami.
• Coastlines right next to the quake usually do not have enough warning time, but farther coastlines can be warned in time.
Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North Eastern Atlantic, the Mediterranean and connected Seas (ICG/NEAMTWS)