Lessons from the 2011 Tohoku tsunami and tsunami mitigation in Japan

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## About IRIDeS

<table>
<thead>
<tr>
<th>Disaster</th>
<th>Disaster Institute established in Major National University</th>
</tr>
</thead>
<tbody>
<tr>
<td>1923 Great Kanto Earthquake</td>
<td>The University of Tokyo Earthquake Research Institute (1925-)</td>
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<tr>
<td>1950 Typhoon Jane</td>
<td>Kyoto University Disaster Prevention Research Institute (1951-)</td>
</tr>
<tr>
<td>2011 GEJE and Tsunami</td>
<td>Tohoku University International Research Institute of Disaster Science (2012-)</td>
</tr>
</tbody>
</table>

• Overturning the Japanese character meaning disaster 「災」 = reconstruction and sustainable and resilient societies
• Purple is the color of the Tohoku University
• The Iris is the symbol of “hope” and “dignity”

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IRIDeS

- Human and social response
- Hazard and risk evaluation
- Endowed research
- Regional and urban reconstruction
- Disaster science
- Disaster medical science
- Disaster information management and public collaboration
About tsunami engineering

Large spatial scale: Country/region
- Tsunami trace database (Japan)
- Evaluation of historical tsunami magnitude
- The 2011 disaster archive
- Tsunami numerical simulation (TUNAMI) + HPCI, Two-Layer
- Damage/loss estimation (Human, buildings, boat) (IES)+(OBASAN)

Big data
- Countermeasure for Nankai tsunami
- Application of lessons
- Disaster education, system and tool development

Disaster education/enlightenment (Schools/residents)

Ecosystem (i.e., coastal forest) for DRR

Small spatial scale: Individual/group
- Tsunami deposit excavation
- Sediment transport/topographic change simulation

Natural science

Risk cognition/risk communication
- Evacuation behavior (Disaster period)
- Evacuation framework (Normal period)

Human/social science

Tsunami warning/tsunami observation information
- Hazard map (Element/composition)
- Damage/risk map (Element/composition)
- Disaster evacuation information
Size of event – casualties and economic loss

Source: Dr. Stephen Platt, Cambridge Architectural Research (CAR)
## Size of disaster

\[
\text{size} = (\text{deaths} + \text{missing}) \times (\text{loss} / \text{GDP})
\]

<table>
<thead>
<tr>
<th>Disaster</th>
<th>Deaths</th>
<th>Missing</th>
<th>Loss US$bn</th>
<th>GDP US$bn</th>
<th>Size of disaster</th>
</tr>
</thead>
<tbody>
<tr>
<td>China, Wenchuan 2008</td>
<td>87,587</td>
<td>130</td>
<td>9,240</td>
<td>1,232</td>
<td></td>
</tr>
<tr>
<td>Japan, Tohoku 2011</td>
<td>20,350</td>
<td>210</td>
<td>4,919</td>
<td>869</td>
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<td>Pakistan, Kashmir 2005</td>
<td>87,000</td>
<td>2.3</td>
<td>232</td>
<td>863</td>
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<td>Iran, Bam 2003</td>
<td>30,000</td>
<td>1.5</td>
<td>368</td>
<td>122</td>
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<tr>
<td>Chile, Maule 2010</td>
<td>547</td>
<td>30</td>
<td>277</td>
<td>59</td>
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<tr>
<td>New Zealand, Christchurch 2011</td>
<td>181</td>
<td>15</td>
<td>186</td>
<td>15</td>
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<tr>
<td>Thailand, Indian Ocean 2004</td>
<td>8,212</td>
<td>0.4</td>
<td>387</td>
<td>8</td>
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<tr>
<td>Italy, L’Aquila 2009</td>
<td>308</td>
<td>11.6</td>
<td>2,149</td>
<td>2</td>
<td></td>
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<tr>
<td>Turkey, Van 2011</td>
<td>601</td>
<td>1</td>
<td>819</td>
<td>1</td>
<td></td>
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<tr>
<td>USA Northridge 1994</td>
<td>72</td>
<td>41.8</td>
<td>16,768</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Source: Dr. Stephen Platt, Cambridge Architectural Research (CAR)
Economy

Sources: Japan – OECD; Turkey – IMF; Chile – Banco Central de Chile

Source: Dr. Stephen Platt, Cambridge Architectural Research (CAR)
Money
(totat financial assistance from government, insurance and international aid)

Rebuild Cost US$ bn

Source: Dr. Stephen Platt, Cambridge Architectural Research (CAR)
**Planning strategy**

**Japan**

Focus on Protection strategies

Two main protection strategies: Strategy A, moving homes to higher ground, used along the Rias Coast. Strategy B, providing barriers and concentrating housing on raised platforms, is being adopted in Sendai.

**Turkey**

Little planning for new housing

Within 15 months, 10,000 new apartments were built in Van and 5,000 in Erçiș by the government housing agency, TOKİ. But little urban planning, in town centres or new housing estates.

**Chile**

Comprehensive master planning

Moving buildings back from the beach and estuary and planting trees. Canalising the river. Creating a defensive esplanade. Building tsunami resistant housing and signing evacuation routes.

Source: Dr. Stephen Platt, Cambridge Architectural Research (CAR)
Local economic recovery: Situation after four years

Total population and aged population

Completion in percent (%)

Source: Yomiuri newspaper (11 Mar 2015)
Local economic recovery: Situation after four years

Source: Asahi newspaper (11 Mar 2015)
Local economic recovery: Situation after four years

Recovery of damaged farmland

- Miyagi = 74%
- Fukushima = 23%
- Iwate = 60%

Population decline

- Miyagi
- Fukushima
- Iwate

Labor shortage

- Ofunato
- Ishinomaki
- Sendai
- Soma-Futaba

No. of business who came back because of the recovery campaign

Source: Nikkei newspaper (11 Mar 2015)
Underestimation of the earthquake magnitude. Sugawara et al. (2001) estimated magnitude of 8.3-8.6 and 2-3 km inundation distance.

869 Jogan tsunami

Record of May 26, 869

Source: ‘Nihon Sandai-Jitsuroku’
(One of Six Official Chronologies of Ancient Japan)
Imperial Household Agency

http://www.kunaicho.go.jp/e-okotoba/02/address/koen-h24az-mizuforum6th.html
1611 Keicho-Sariku tsunami

Villages in Edo period (1603-1868) were located outside inundation area of the 2011 tsunami
Sanriku tsunamis and Miyagi Sea tsunamis

- **Onagawa**
  - 1896 M8.5
  - 2011 Great East Japan M9.0

- **Miyagi Oki**
  - 1933 M8.1
  - 2011 M9.0

- **Fukushima**
  - 2011 Great East Japan M9.0

- **Hibiase**
  - 1896 Meiji M8.2
  - 1978 M7.4

- **Miyagi Sea earthquake**
  - 1790 M7.3
  - 1830 M7.4
  - 1870 M7.4
  - 1910 M7.4
  - 1936 M7.4
  - 1990 M7.4

- **Maximum tsunami height (m)**
  - 2011 Heisei
  - 1896 Meiji
  - 1933 Showa
  - 1611 Keicho
Tsunami warning systems in Japan

Assumed faults around Japan (100,000 cases)

Numerical simulation results stored in database

Seismic Network

Sea Level Network

1983 tsunami arrived 7 min 100 casualties
1993 tsunami arrived < 5 min 230 casualties
# Tsunami warnings during the 2011 tsunami

<table>
<thead>
<tr>
<th>Local</th>
<th>Event</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:46</td>
<td>Earthquake</td>
<td></td>
</tr>
<tr>
<td>14:49</td>
<td>Mjma = 7.9 Major</td>
<td>Tsunami Warning -</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Iwate, Miyagi and Fukushima</td>
</tr>
<tr>
<td>14:50</td>
<td></td>
<td>Tsunami Information -</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Iwate: 3m, Miyagi: 6m, Fukushima: 3m, etc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Only up to M8.0 in the database</td>
</tr>
<tr>
<td>15:10</td>
<td>GPS buoys &gt; 3m</td>
<td></td>
</tr>
<tr>
<td>15:14</td>
<td></td>
<td>Tsunami Warnings/Advisories extended</td>
</tr>
<tr>
<td>15:14</td>
<td></td>
<td>Tsunami Information -</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Iwate: 6m, Miyagi: over 10m, Fukushima: 6m, etc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tsunami hit the nearest coast</td>
</tr>
<tr>
<td>15:21</td>
<td>Tide gauges at Kamaishi (Iwate) &gt; 4.1m (scale out)</td>
<td></td>
</tr>
<tr>
<td>15:30</td>
<td></td>
<td>Tsunami Warning extended</td>
</tr>
<tr>
<td>15:31</td>
<td></td>
<td>Tsunami Information -</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Iwate, Miyagi, Fukushima: over 10m, etc.</td>
</tr>
<tr>
<td>16:00</td>
<td>Mjma = 8.4</td>
<td></td>
</tr>
<tr>
<td>17:30</td>
<td>Mw = 8.8</td>
<td></td>
</tr>
<tr>
<td>13th May</td>
<td>Mw = 9.0</td>
<td></td>
</tr>
</tbody>
</table>

Observed tsunami waveforms

http://www.pari.go.jp/info/tohoku-eq/
Earthquake generation mechanism and seafloor deformation

- Uplift
- Subsidence

Japan trench

- 1896 Meiji Sanriku (Tsunami earthquake)
- 1896 Jogan tsunami (Typical interplate)
- 1933 Showa Sanriku (Outer-rise)
2011 Tohoku earthquake

Deep region

Interplate earthquake

20xx Nankai earthquake

Shallow region

Tsunami earthquake

Source: NHK
The 2011 tsunami: Large different in tsunami hazard map

Red: 2011 tsunami inundation area
Blue: Predicted inundation area
Stochastic tsunami hazard map

If we use the hazard curve data, we can estimate tsunami inundation area.

- Inundation are with return period of 200 years
- Inundation are with return period of 600 years
- Inundation are with return period of 1200 years

The 2011 GEJE inundation area

(Reference): The Ministry of Land, Infrastructure, Transport and Tourism

An example of inundation map for Soma-city in Japan

Tsunami inundation areas can be captured not by deterministic map but stochastic map.
Lessons : Unosumai Elementary and Junior high schools

Miracle of Kamaishi…Awareness for expected event

- All nearly 3,000 students survived

Three principles
- First, don't put too much faith in outdated assumptions. “In other words, don't trust hazard maps.
- The second rule of thumb is for people to make their best efforts to deal with the situation. They urged the teachers to keep moving higher, adding that the older kids also remembered to help the younger ones.
- And finally, to take the initiative in any evacuation.

http://mnj.gov-online.go.jp/kamaishi.html

http://insite.typepad.jp/a/6a0120a6885bf1970b01543336c30e970c-320wi

http://www.chunichi.co.jp/article/earthquake/sonae/20120312/images/PK2012031202100063_size0.jpg
Questionnaire survey related to tsunami evacuation (1)

By Cabinet Office, Fire Agency and Japan Meteorological Agency

- Total answers: 870 (Iwate = 391, Miyagi = 385 and Fukushima = 94), period: During July 2011
- A: Soon evacuated (57%), B: Evacuated after some actions (31%), C: Tsunami came during doing some actions (11%) and D: Did not evacuated (they were already in high ground) (1%)

- [A+B] Main reasons for starting evacuation: large shaking (48%), were asked to evacuate by family or surrounding people (20%) and surrounding people start their evacuation (15%)
  → Less amount of calling out for evacuation

- [B+C] Why they did not evacuate as soon as possible: Went back home (22%), looking for family or picking up family (21%), tsunami did not come in the past (11%) and did not think about tsunami coming (9%)
  → Have to reduce the amount of people going back home or seeking family

Condition of evacuation shelter
- C has the highest ratio of people who were inside the inundation area (38%)
- A and B are both mostly evacuated to designated evacuation shelters but C is large on the highest floor of the same building

Evacuation method
- In general, about 57% of people evacuated using car.
- Reason for using car: Not enough time without using car (34%), wanted to evacuate together with family (32%), far from safe place (20%)
- About 34% of them were trapped in the serious traffic.
- In general, limit distance for evacuation by walking was about 500 m and by car was 2 km.

Tsunami hazard map
- Number of people who had seen tsunami hazard map or had hazard map in their house was less than 20%
Questionnaire survey related to tsunami evacuation (2)

By Weathernews
- Target area: Hokkaido, Aomori, Iwate, Miyagi, Fukushima, Ibaraki and Chiba
- Total answers: 5,296 (3,298 from survivors and 1,998 related to people who were casualty)

1) Time from earthquake generation to starting evacuation
   - Survivor = 19 min and casualty = 21 min

2) Reason for starting evacuation
   - Major tsunami warning or tsunami warning and only 28 % of the survivors soon evacuated

3) Evacuation condition
   - Reason for not evacuated was they believe they were safe and 20% of victim could not evacuated

4) Selected evacuation place
   - 75% of survivor could evacuated to safe place while 75% of victim could not
   - 40% could not evacuate to high ground and 50% evacuated to non-designated evacuation place

5) Why they could not evacuate from the tsunami
   - 18% of victim was because they were obstructe during their evacuation

6) Evacuated elevation from tsunami
   - Approximately 2.9th floor for survivor and 1.7th floor for victim

7) Moving from evacuation place
   - 60% of victim moved to tsunami inundation zone again

8) Reason for moving from evacuation place
   - Looking for their family was the main reason
Tsunami countermeasures in Japan

- **1896 Meiji-Sanriku tsunami**: by individual
  Moving high ground
- **1933 Showa-Sanriku tsunami**: by country and prefecture
  Moving high ground + Seawall in some areas
- **1960 Chile tsunami**: Structural measures
  Seawalls, breakwaters and tsunami gates
- **1993 Okushiri tsunami**: Structural measures, town planning and combination with soft measures
- **2011 Great East Japan tsunami**: Prevention → Reduction
Tsunami countermeasure system

Breakwater: Kamaishi

Water gate: Fudai

Seawall: Taro

Control forest: Rikuzenakata

Highland residence: Toni-hongo
Reconstruction plan of Miyagi prefecture

- Period: 10 years (Goal: 2020)

- Restoration
  2011-2013
  (3 years)

- Reconstruction
  2014-2017
  (4 years)

- Development
  2018-2020
  (3 years)

- Miyagi’s Recovery

- Prefectural citizens
  - Groups
  - NPO, etc.
  - Prefectural government
  - University
  - City
  - Local municipalities
  - NPO

- National government
  - Relocation to high ground, separation of business and residence
  - Assemble and recognize fishing ports, branding of marine processed products, “sixth industry”
  - Tourism promotion that draws on the nature of the Sanriku area
  - Promoting the maintenance of Sanriku expressway

- Senhōmaeki/Matsushima area
  - Relocation to high ground, separation of business and residence
  - Multiple barriers
  - Assemble and integrate fishing ports, assemble and advance industries
  - Tourism promotion that makes use of Matsushima and Oslika peninsula

- National government
  - Multiple barriers
  - Advancing logistics function by utilizing airport and ports, and advancing business location to Miyagi
  - Agricultural land accumulation, “sixth industry”
  - Maintenance of national public park and disaster prevention green space
  - Promoting the maintenance of Shonan Expressway

The world’s largest breakwater

Kamaishi breakwaters
@ sea depth = 63 m

http://livedoor.blogimg.jp/shyougaitisekkeisi2581/imgs/4/a/4aab1165.jpg
http://f.hatena.ne.jp/images/fotolife/k/kimkaz/20110401/20110401220511.jpg
Level 1 & Level 2 tsunami

**Level 1:**
High frequency (30-200 years) but small to moderate tsunami. Community should be mostly protected by coastal defense structures. Height of coastal structures were decided by past Level 1 tsunami events.

**Level 2:**
Low frequency (200-1,000 years) but very high tsunami. Forget about properties but secure evacuation routes for safe evacuation. Coastal structures should be strong enough even in case of the overtopping.

New height of seawalls in Miyagi prefecture

After 2011

Before 2011

2011 tsunami
Sendai city plan: land use management

The 2011 tsunami

Increase road level = 6 m

http://www.city.sendai.jp/fukko/1198749_2757.html
Reduction effect from control forest
Building damage: Overturned building in Onagawa town
Building fragility and tsunami damage
Example from Ishinomaki city

Inundation depth = 4 m
Condition before March 2011

Tokai-Tonankai-Nankai earthquake

Earthquake possibility in Japan

http://www.jishin.go.jp/main/chousa/07_yosokuchizu/img/f1-3-2.jpg

New estimated tsunami height (M9 earthquake) VS historical tsunami data

http://www.bousai.go.jp/jishin/chubou/nankai_trough/15/kisya_5.pdf
Advance technology of earthquake and tsunami observation

DONET (Dense Oceanfloor Network System for Earthquakes and Tsunamis) is a unique development program of submarine cabled real-time seafloor observatory network. This program has aimed to establish the technologies of large scale real-time seafloor research and surveillance infrastructure for earthquake, geodetic and tsunami observation and analysis. The first phase of this program has been carried out since 2006 with the purpose to monitor the hypocentral region close to Nankai trough and the installation of observational equipment on 20 stations at Kumanonada has been completed in 2011. The second phase (DONET2) has also started to cover a wider region in 2010. Totally 29 observatories are planned to be installed at offshore Kii peninsula for DONET2 and 2 additionally at Kumanonada for DONET.


New tsunami warning classification

<table>
<thead>
<tr>
<th>Tsunami warning and watch</th>
<th>Previous system (8 levels)</th>
<th>Present system (5 levels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Announce tsunami height</td>
<td>Number</td>
<td>Message</td>
</tr>
<tr>
<td>Warning</td>
<td>&gt; 10 m</td>
<td>&gt; 10 m</td>
</tr>
<tr>
<td>Major tsunami</td>
<td>8 m, 6 m</td>
<td>10 m</td>
</tr>
<tr>
<td></td>
<td>4 m, 3 m</td>
<td>5 m</td>
</tr>
<tr>
<td>Tsunami</td>
<td>2 m, 1 m</td>
<td>3 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advisory Tsunami advisory</td>
<td>0.5 m</td>
<td>1 m</td>
</tr>
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<td></td>
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</tbody>
</table>

Source: JMA
<table>
<thead>
<tr>
<th>Year</th>
<th>No. of Participants</th>
</tr>
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<tbody>
<tr>
<td>1977</td>
<td>800</td>
</tr>
<tr>
<td>1979</td>
<td>1200</td>
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<tr>
<td>1981</td>
<td>1400</td>
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<td>1983</td>
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<td>2003</td>
<td>1200</td>
</tr>
<tr>
<td>2005</td>
<td>1400</td>
</tr>
</tbody>
</table>
Preservation of buildings and other facilities destroyed by the tsunami

Several memorial in rocks, stones, shrines and temples before the 2011 event…

But…no preservation of damaged structures after the 2004 event
After tsunami in 1933

Toni Hongo village: Highland residence

After tsunami in 1960

http://d.hatena.ne.jp/meiji-kenchikushi/19530101/
Tsunami evacuation problems in Thailand

<table>
<thead>
<tr>
<th>V (%)</th>
<th>E (μ) (min)</th>
<th>F (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30</td>
<td>23%</td>
</tr>
<tr>
<td>0</td>
<td>60</td>
<td>26%</td>
</tr>
<tr>
<td>0</td>
<td>90</td>
<td>30%</td>
</tr>
<tr>
<td>0</td>
<td>120</td>
<td>34%</td>
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<td>25</td>
<td>30</td>
<td>9%</td>
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<td>25</td>
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<td>100</td>
<td>60</td>
<td>11%</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
<td>15%</td>
</tr>
<tr>
<td>100</td>
<td>120</td>
<td>22%</td>
</tr>
</tbody>
</table>

“V” is the percentage of population using vehicles for evacuation. Either as driver or passenger. It is assumed that each car has four passengers.

“E” is the mean of the distribution (μ) used to construct the evacuation start time curve.

“F” is the Fatality ratio.

11 April 2012

One way along shoreline
One way from inland

Patong beach
Incorporation with: Southern Meteorological Department (West Coast), TMD
DamageEstimateApp: Pilot version for Kesennuma city

[Image of the app interface showing different steps and results]

Estimated damage level:
- Level 5
- Described as destructive damage to walls (i.e., more than half of wall density) and several columns (i.e., bend or destroyed).
- Condition: It lost its functionality (i.e., system collapse). It is non-repairable or consumes great cost of retrofitting.

Collapse probability:
- 90.42%

Collapse probability with debris impact:
- 95% (if velocity is 19.0 m/s) 75% (if velocity is 16.5 m/s) 50% (if velocity is 7.0 m/s)

[References: 1 is based on Li and Sham et al. (2019); 2 is based on Masekawa & Suhara (2013); 3 & 4 is based on Chen et al. (2016).]
World Tsunami Day (5 November)

- The World Tsunami Day proposal materialized after the third U.N. World Conference on Disaster Reduction in Sendai in March.
- Japan hopes to play a leading role in the international community in the field of disaster reduction after the March 2011 earthquake and tsunami devastated the Tohoku region.
- Japan designated Nov. 5 as Tsunami Disaster Prevention Day under a law on measures to deal with tsunami after the March 2011 disasters.
- The day was chosen in honor of a villager, Mr. Hamaguchi, in the region currently known as Wakayama Prefecture who saved the lives of many by evacuating them in anticipation of a massive tsunami spurred by the Ansei Nankai earthquake of Nov. 5, 1854.
- Inamura no Hi in your language from ADRC website