Severity of Tsunami Events – Statistical Analysis and Classification

O. Ebadi, H. J. Caldera, M. Salari, L. Wang
M. Ghaffari, S. C. Wirasinghe

CRHNet Symposium
Calgary
November, 2015
Tsunami:

- The Japanese word for “large harbor wave” series of large water waves produced by a sudden vertical displacement of water
- Capable of triggering thousands of deaths, injuries and property damage
- Tsunami causes:
  - Earthquake
  - Volcano
  - Landslide
  - Nuclear explosion
  - Impact of objects from outer space
    (meteorites, asteroids, comets)
• Period in the range of 10 minutes to 4 hours

• Wavelength in excess of 500 km

• May reach a maximum vertical height onshore above sea level, called a run-up height, of 40 meters

• Earliest written records of tsunamis are
  • Syria in 2000 B.C
  • Greece 1610 B.C
Primary Impacts of Tsunami

The 2004 Indian Ocean earthquake

- The deadliest natural disasters in the past 100 years
- Approximately 230,210 people (including 168,000 in Indonesia alone), the deadliest tsunami
- Moment magnitude of 9.1–9.3
- Caused by the third largest earthquake in recorded history

The Pacific coast of Japan, March 2011

- Moment magnitude of 9.0 magnitude
- 33 feet (10 m) high
- 18,550 people killed/missing
- The highest tsunami reached a total height of 40.5 metres (133 ft)
Secondary Impacts of Tsunami

The Pacific coast of Japan, March 2011

- More than 80 fires
- Flames and smoke rise from a petroleum refining plant next to a heating power station in Shiogama, about 220km north of Tokyo, 13 March, 2011

Fukushima Daiichi nuclear disaster

- The largest nuclear disaster since the Chernobyl disaster of 1986
- The second disaster (after Chernobyl) to be given the Level 7 event classification of the International Nuclear Event Scale

Should Canada be Concerned about Tsunamis?

- 21 records of tsunamis in Canada since 1774 (According to NOAA)
- 330 deaths because of the tsunamis
- Underwater earthquake off the coast of Alaska -> most likely cause on Canada’s Pacific Coast
- Cascadia megathrust earthquake
  - No prediction when the next one will strike
  - In the next 50 years, 12% probability of occurrence
- Pacific Northwest coast is not heavily populated
  - Cascadia quake and tsunami is not expected to be as deadly as the Sumatra quake
- In east coast, landslide can result in tsunami
Tsunami Parameters

- **Maximum water height**: The maximum water height above sea level in meters

If the type of measurement of the runup was a:
- Tide Gauge - half of the maximum height (minus the normal tide) of a tsunami wave recorded at the coast by a tide gauge.
- Deep Ocean Gauge - half of the maximum height (minus the normal tide) of a tsunami wave recorded in the open ocean by a seafloor bottom pressure recording system.
- Runup Height - the maximum elevation the wave reaches at the maximum inundation.

- **The total number of runups**: Displaying the runup locations associated with a particular tsunami event

- **Tsunami intensity**: Defined by Soloviev and Go (1974) as

\[ I = \log_2(2^{0.5} \cdot h), \text{ where } "h" \text{ is the maximum runup height of the wave} \]
Importance of Severity Classification

- Tsunami currently measured through
  - Tsunami Intensity, maximum water height, etc.
  - Can these measures represent a tsunami severity?

- Intensity or maximum water height are not highly correlated with severity or impacts of tsunami

- Provide
  - An overall picture about the severity of tsunami
  - A set of criteria used to make comparisons and to rank tsunamis
    - Easier to recognize an event occurrence and manage the associated data

- Benefit to
  - Emergency responders, disaster managers, disaster compensation and insurance policies (insurance managers and estimators), national/regional local governments, NGO’s, local relief agencies, media outlets, researchers, reporters, general public, etc.
  - Information management and processing and research community
Severity Classification: Different Scales

- Gad-el-Hak M (2008b): The art and science of large-scale disasters
  The ranges proposed for casualties and the area affected appear to be arbitrary

<table>
<thead>
<tr>
<th>Scope</th>
<th>Disaster</th>
<th>Casualties (persons)</th>
<th>Area Affected (Km2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Small</td>
<td>$C &lt; 10$</td>
<td>$A &lt; 1$</td>
</tr>
<tr>
<td>II</td>
<td>Medium</td>
<td>$10 \leq C &lt; 100$</td>
<td>$1 \leq A &lt; 10$</td>
</tr>
<tr>
<td>III</td>
<td>Large</td>
<td>$100 \leq C &lt; 1,000$</td>
<td>$10 \leq A &lt; 100$</td>
</tr>
<tr>
<td>IV</td>
<td>Enormous</td>
<td>$1,000 \leq C &lt; 10,000$</td>
<td>$100 \leq A &lt; 1,000$</td>
</tr>
<tr>
<td>V</td>
<td>Gargantuan</td>
<td>$10,000 \leq C$</td>
<td>$1,000 \leq A$</td>
</tr>
</tbody>
</table>

- Wirasinghe et. al (2013): Preliminary Analysis and Classification of Natural Disasters Fatality Based Disaster Scale with seven levels: Emergency to Calamity
  Scale for classification of the severity of the natural disasters including: earthquake, flash flood, flood, forest fire, landslide, cyclone, lightning, tornado, meteoroid strike, tsunami, volcano eruption.
# Severity Classification for Natural disasters

## Fatality Based Disaster Scale

<table>
<thead>
<tr>
<th>Type</th>
<th>Fatality Range</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency</td>
<td>$1 \leq F &lt; 10$</td>
<td>A small landslide that kills one person</td>
</tr>
<tr>
<td>Disaster Type 1</td>
<td>$10 \leq F &lt; 100$</td>
<td>Edmonton tornado, Canada -1987 that killed 27 people</td>
</tr>
<tr>
<td>Disaster Type 2</td>
<td>$100 \leq F &lt; 1,000$</td>
<td>Thailand flood-2011 that resulted in a total of 815 deaths</td>
</tr>
<tr>
<td>Catastrophe Type 1</td>
<td>$1,000 \leq F &lt; 10,000$</td>
<td>Hurricane Katrina-2005, U.S.A that killed 1833 people</td>
</tr>
<tr>
<td>Catastrophe Type 2</td>
<td>$10,000 \leq F &lt; 100,000$</td>
<td>Tohoku earthquake and tsunami-2011, Japan that killed 15882 people</td>
</tr>
<tr>
<td>Calamity Type 1</td>
<td>$100,000 \leq F &lt; 1M$</td>
<td>Haiti earthquake 2010 killed 316,000 people</td>
</tr>
<tr>
<td>Calamity Type 2</td>
<td>$1M \leq F &lt; 10M$</td>
<td>China floods-1931 death toll $&gt; 2,500,000$</td>
</tr>
<tr>
<td>Cataclysm Type 1</td>
<td>$10M \leq F &lt; 100M$</td>
<td>Black death pandemic in 1346 to 1353</td>
</tr>
<tr>
<td>Cataclysm Type 2</td>
<td>$100M \leq F &lt; 1B$</td>
<td>Super Volcano (e.g. Yellowstone): Estimated deaths $&lt; 1B$</td>
</tr>
</tbody>
</table>

- Meteor strike (diameter $> 1.5$ Km) - estimated deaths $< 1.5 \times 10^9$
- Pandemic (Avian influenza) – estimated deaths $< 2.8B$

Source: Caldera & Wirasinghe (2014)
Objective of the Study

Offering a severity classification approach considering tsunami fatalities
NOAA Database

U.S. National Oceanic and Atmospheric Administration (NOAA) database includes:

- 2520 historical tsunami events between 2000 B.C.E. and 2015 C.E
- Date, location (name, latitude and longitude) and tsunami parameters (maximum water height, number of runups and intensity) for each event
- Tsunami impacts (death, injuries, damage, house destroyed and house damaged)
# Fatality Analysis

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td></td>
<td>232</td>
</tr>
<tr>
<td>Valid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missing</td>
<td></td>
<td>2289</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>4035</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td>73.5</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td></td>
<td>25230</td>
</tr>
<tr>
<td>Skewness</td>
<td></td>
<td>10.155</td>
</tr>
<tr>
<td>Minimum</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td>300000</td>
</tr>
</tbody>
</table>
Studying the tail is our mainly interest
The lower the AD, the better the fitted distribution
Best fitted distribution is Log-Normal probability distribution function

\[ f(x) = \frac{\exp\left(-\frac{1}{2} \left(\frac{\ln x - \mu}{\sigma}\right)^2\right)}{x\sigma\sqrt{2\pi}} \]

\( \sigma = 2.95, \mu = 4.43 \)
- Increase in the number of fatalities might relate to the following parameters:
  - Tsunami Intensity
  - The maximum water height
  - The number of run ups

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Earthquake Magnitude</th>
<th>Maximum Water Height</th>
<th>Run-ups</th>
<th>Intensity</th>
<th>Death</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake Magnitude</td>
<td>1</td>
<td>0.145</td>
<td>0.157</td>
<td>0.117</td>
<td>0.183</td>
</tr>
<tr>
<td>Maximum Water Height</td>
<td>1</td>
<td></td>
<td>.075</td>
<td><strong>0.283</strong></td>
<td><strong>0.068</strong></td>
</tr>
<tr>
<td>Run-ups</td>
<td></td>
<td>1</td>
<td>.098</td>
<td>.160</td>
<td></td>
</tr>
<tr>
<td>Intensity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.248</td>
</tr>
<tr>
<td>Death</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
Extreme Fatality Analysis

Study the tail of the Log-Normal probability distribution function

Extremes events:

- Very low probable events
- Located on the tail of PDF

Models of Extreme Values:

1. Block Maxima
   - Artificial blocks
2. R\textsuperscript{th} order statistic
   - Artificial block selection
     - Record-based: Few records between 2000 BC and 362 AC => R\textsuperscript{th} order
     - Location-based: Considerable amount of event for 1\textsuperscript{st} order => Block Maxima
   - PDF => Gumbel or Frechet or Weibull
3. Extremes exceed a high threshold
   - PDF => Exponential or Pareto or Beta
Extreme Value Analysis : Block Maxima

- Blocks based on location (country)
- Choosing highest fatality record in each block

39 Countries

\[ f(x) = \frac{\alpha}{\beta} \left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left(-\left(\frac{x}{\beta}\right)^\alpha\right) \quad \alpha=0.39227, \beta=2324.1 \]
Extreme Value Analysis: $R^{th}$ Order Statistic

- Different combination of block lengths (150, 200 & 300)
- $R$ values (1, 2, 3, 4, 5 and 6) were $R$ number of highest fatality records in each block
- Combine three tests according to different weights
  - Anderson-Darling:
    - More emphasis to the tails (extremes)
    - Higher weights between 0.9 and 0.4
  - Smirnov-Kolmogorov
  - Chi Square

- Best extreme value distribution
- The lowest value for all 3 tests
- Block = 150 event & $R=2$
Extreme Value Analysis: 2nd Order Statistic

\[ f(x) = \frac{\alpha}{\beta} \left(\frac{\beta}{x - \gamma}\right)^{\alpha+1} \exp\left(-\left(\frac{\beta}{x - \gamma}\right)^\alpha\right) \]

\[ \alpha = 0.7 \]
\[ \beta = 1828.4 \]
\[ \gamma = -0.9 \]
### Extreme Value Analysis: 2nd Order Cont.

<table>
<thead>
<tr>
<th>Country</th>
<th>No. extreme records</th>
<th>Total frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>11</td>
<td>352</td>
</tr>
<tr>
<td>Indonasia</td>
<td>9</td>
<td>242</td>
</tr>
<tr>
<td>Chile</td>
<td>3</td>
<td>158</td>
</tr>
<tr>
<td>India</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>Taiwan</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>Portugal</td>
<td>1</td>
<td>35</td>
</tr>
<tr>
<td>Greece</td>
<td>1</td>
<td>164</td>
</tr>
<tr>
<td>Philippines</td>
<td>1</td>
<td>91</td>
</tr>
<tr>
<td>Ecuador</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Italy</td>
<td>2</td>
<td>154</td>
</tr>
<tr>
<td>Pakistan</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Russia</td>
<td>1</td>
<td>92</td>
</tr>
<tr>
<td>PAPUANEWGUINEA</td>
<td>1</td>
<td>69</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>34</strong></td>
<td><strong>1405</strong></td>
</tr>
</tbody>
</table>

- Extreme records belong to only 13 countries out of 39
- Ignores the **extreme records in 66%** of tsunami-prone countries (e.g. China with 10000 deaths, Peru with 5000 deaths, UK with 2000 deaths)

2nd Order statistic is biased toward location.
Extreme Value Analysis: Threshold method

- Mean residual life (MRL) plot, by representing the points

\[
(\sum_{i=1}^{n_\mu} (x(i) - \mu)/n_\mu) \mu < x_{\text{max}}
\]

where

- \( n_\mu \) : number of observations exceeding \( \mu \)
- \( x_{\text{max}} \) : the maximum observation in the data set

- Threshold the value

- Plot is approximately linear in \( \mu \)
- Representation of confidence intervals can help to the determination of this point.
Extreme Value Analysis: Threshold method

- Too high threshold
  - Only few values will be used
  - Large variance for the estimated parameters

- Too low threshold
  - Biased parameters estimation

Threshold should be selected balancing between biasness and Variance
- An increasing liner tendency between 2000 and 5000 approximately threshold value was chosen as 2000.
- It considers 44 data out of 232

Full MRL plot

Expand the first half of MRL plot
Extreme Value Analysis: Threshold method

$f(x) = \frac{\alpha \beta^\alpha}{x^{\alpha+1}}$

$\alpha = 0.94$

$\beta = 2000$
## Comparison of Extreme Value Distributions

<table>
<thead>
<tr>
<th>Method</th>
<th>PDF</th>
<th>MSE</th>
<th>MAE</th>
<th>MAPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block maxima (Location-based)</td>
<td>Weibull</td>
<td>0.001</td>
<td>0.034</td>
<td>0.091</td>
</tr>
<tr>
<td>R&lt;sup&gt;th&lt;/sup&gt; order (Record-based)</td>
<td>Frechet</td>
<td>0.016</td>
<td>0.113</td>
<td>0.402</td>
</tr>
<tr>
<td>Threshold</td>
<td>Pareto</td>
<td>0.012</td>
<td>0.09</td>
<td>0.376</td>
</tr>
</tbody>
</table>

### Error measurement indices

- Mean square error (MSE),
- Mean absolute error (MAE),
- Mean absolute percentage error (MAPE)

- **Weibull, Frechet & Pareto**
  - Very close values for MSE
  - Significantly different values for MAE and MAPE among the methods

- Weibull has lowest MSE, MAE & MAPE

- Close approximate probabilities of actual data
Comparison Cont.

Block Maxima:
• Advantages:
  • **Approximate probabilities closest to actual extremes**
  • Better representation of full range of extremes (common to \( R^{th} \) order)
• Disadvantages:
  • Artificial block and procedure (common)
  • Some extreme neglected (common)

\( R^{th} \) order:
• Advantages:
  • Can be used to determine the return period in structural design
• Disadvantages:
  • **Biased to location**
    • Extreme records belong to only 13 out of 39 countries
    • Ignores the extreme records in 66% of tsunami-prone countries (e.g. China with 10000 deaths, Peru with 5000 deaths, UK with 2000 deaths)
• Disadvantages:
  • Lack of data between 2000 BC and 362 AC
  • \( R^{th} \) order selection procedure

Threshold method:
• Advantages:
  • **Consider all extreme more than 2000 fatalities**
  • No artificial blocks
• Disadvantages:
  • Ignores many extreme events fatality less than 2000
  • Threshold selection procedure
# Tsunami Severity Classification

<table>
<thead>
<tr>
<th>Type</th>
<th>Fatality Range</th>
<th>Probability (%)</th>
<th>Historical tsunami probability %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Weibull (Block maxima)</td>
<td>Frechet (2nd order)</td>
</tr>
<tr>
<td>Emergency</td>
<td>$1 \leq F &lt; 10$</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Disaster Type 1</td>
<td>$10 \leq F &lt; 100$</td>
<td>14</td>
<td>0.05</td>
</tr>
<tr>
<td>Disaster Type 2</td>
<td>$100 \leq F &lt; 1000$</td>
<td>26</td>
<td>22</td>
</tr>
<tr>
<td>Catastrophe Type 1</td>
<td>$1000 \leq F &lt; 10000$</td>
<td>32</td>
<td>52</td>
</tr>
<tr>
<td>Catastrophe Type 2</td>
<td>$10000 \leq F &lt; 0.1M$</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Calamity Type 1</td>
<td>$0.1M \leq F &lt; 1M$</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Calamity Type 2</td>
<td>$1M \leq F &lt; 10M$</td>
<td>0.002</td>
<td>0.97</td>
</tr>
<tr>
<td>Cataclysm Type 1 or higher</td>
<td>$10M \leq F$</td>
<td>0.198</td>
<td>0.25</td>
</tr>
</tbody>
</table>

*2000 < F < 10000

- There is 32% of chance, the most severe tsunami in a particular country will be Catastrophe Type 1
- There is 52% chance, the most severe tsunami affected location from next 150 tsunami affected locations will be Catastrophe Type 1
- There is 78% of chance, the most extreme tsunami affected location will be Catastrophe Type 1
Conclusions & Keynotes

- New severity classification for tsunami

<table>
<thead>
<tr>
<th>Type</th>
<th>Fatality Range</th>
<th>Estimated probability %</th>
<th>Tsunami Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency</td>
<td>$1 \leq F &lt; 10$</td>
<td>11</td>
<td>Haiti, 2010, 7 deaths</td>
</tr>
<tr>
<td>Disaster Type 1</td>
<td>$10 \leq F &lt; 100$</td>
<td>14</td>
<td>Mexico, 1932, 75 deaths</td>
</tr>
<tr>
<td>Disaster Type 2</td>
<td>$100 \leq F &lt; 1000$</td>
<td>26</td>
<td>Indonesia, 2006, 802 deaths</td>
</tr>
<tr>
<td>Catastrophe Type 1</td>
<td>$1000 \leq F &lt; 10000$</td>
<td>32</td>
<td>Philippines, 1976, 4376 deaths</td>
</tr>
<tr>
<td>Catastrophe Type 2</td>
<td>$10000 \leq F &lt; 100000$</td>
<td>16</td>
<td>Japan, 2011, 17007 deaths</td>
</tr>
<tr>
<td>Calamity Type 1</td>
<td>$100000 \leq F &lt; 1M$</td>
<td>1</td>
<td>India, 1737, 300000 deaths</td>
</tr>
<tr>
<td>Calamity Type 2</td>
<td>$1M \leq F &lt; 10M$</td>
<td>0.002</td>
<td>No historical records</td>
</tr>
<tr>
<td>Cataclysm Type 1 or higher</td>
<td>1</td>
<td>0.198</td>
<td></td>
</tr>
</tbody>
</table>

- It will provide
  - An overall picture about the severity of tsunami
  - A set of criteria used to make comparisons and to rank tsunamis
    - Easier to recognize an event occurrence and manage the associated data
Conclusions & Keynotes

- Facilitates the comparison among various degrees of disasters and obtaining a sense of scale
  - Disaster managers to identify the hazard potential, responding to the event properly, and allocating resources for mitigation measures
  - Provide timely assistant from emergency responders, international & local relief agencies, national/regional/local governments, NGO’s, media outlets, reporters, volunteer communities, general public

- Easier to recognize an event occurrence and manage the associated data
  - Information management and processing and research community
Thank you