Introduction to Basic Mechanisms
Natural Disasters Over the World

**Tsunami, Storm Surge, High Waves (Coastal Erosion), Earthquake, Fire, Flood, Liquefaction, Drought, Landslide, Volcanic Eruption**

Two Basic Approaches

1. **Field Survey + Numerical Simulation + Hydraulic Experiment**
   - create a realistic image of the disaster
   - harmonize the image with local residents

2. **Variety of different disaster scenarios under local conditions**
   It is necessary to:
   - decipher the social context of disasters
   - prepare disaster reduction scenarios
   - work with local government staff and local residents
The Paradigm of Newtonian Mechanics

1. **Derive Equations**
   - Physical phenomena $\rightarrow$ Mathematical equations
   - Time or spatial changes $\rightarrow$ $d/dx$, $d/dt$
   - Differential equations

2. **Solve the Equation Set and Get Solutions**
   1. Linearization
   2. Perturbation; power series $y=a_0+a_1x+a_2x^2+a_3x^3+…$
   3. Numerical solutions

3. **Compare** the solutions with laboratory or field data to **evaluate** accuracies

Examples:
- Tsunami propagation model
- Meteorology based storm surge model
- Turbulence model for structure failure
The Three Basic Conservation Laws in Hydraulics

1. **Mass**
   - Continuity equation

2. **Momentum**
   - Microscopic application of momentum conservation
   - Euler’s equation
   - Inclusion of viscosity to Euler’s equation $\rightarrow$ Navier-Stokes equation

3. **Energy**
   - Gas dynamics: Gas equation of state
   - Dynamic energy conservation for water: Bernoulli’s law (This is not independent from momentum conservation equation)
Basic Mechanisms: Methodology 2

Field Survey + Regional Study

Comparative Study of Regional Preparedness
- From the views of Prediction + Prevention + Correspondence

Survey Results over the World
- Long History and Experiences in Japan
Tsunami Mechanisms
Prediction for Tokyo Bay

Earthquake: Northern Area of Tokyo Bay (M7.3)

70% probability in 30 years

First Step to Tsunami Simulation - Initial Displacement

Genroku Earthquake

<table>
<thead>
<tr>
<th>Date</th>
<th>Place</th>
<th>Magnitude</th>
<th>Tsunami Height (m)</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>1703/12/31</td>
<td>Near Boso peninsula</td>
<td>7.9~8.2</td>
<td>8~20</td>
<td>5230</td>
</tr>
</tbody>
</table>

Conditions for the Genroku Earthquake

<table>
<thead>
<tr>
<th>Position at Center</th>
<th>Length (m)</th>
<th>Width (km)</th>
<th>Strike Φ (°)</th>
<th>Direction θ (°)</th>
<th>Sliding Degree δ (°)</th>
<th>Landslide Dam Height Hd (m)</th>
<th>Dislocation Parameter Dd (m)</th>
<th>Dislocation Parameter Dr (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>139.8N</td>
<td>34.7N</td>
<td>65</td>
<td>70</td>
<td>N45E</td>
<td>N44W</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>34.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Namegaya et al., 2011)
\[ c = \sqrt{gd} \]

- \( c \): tsunami speed \((m/s)\)
- \( g \): gravity acceleration \((m/s^2)\)
- \( d \): water depth \((m)\)

*Tsunami travels from left to right.*

Structured like a solitary wave.
Typical Tsunami Speed

**Deep Ocean**
Water Depth: \( d = 4000 \text{ m} \)

\[
c = \sqrt{gd} = \sqrt{9.8 \times 4000} \approx 200 \text{ m/s} \approx 700 \text{ km/hr}
\]

(Jet Airplane: 900 km/hr)

**Continental Shelf**
Water Depth: \( d = 200 \text{ m} \)

\[
c = \sqrt{gd} = \sqrt{9.8 \times 200} \approx 44 \text{ m/s} \approx 160 \text{ km/hr}
\]

(Rapid Railway: 200 km/hr)

**Tokyo Bay**
Water Depth: \( d = 20 \text{ m} \)

\[
c = \sqrt{gd} = \sqrt{9.8 \times 20} \approx 14 \text{ m/s} \approx 50 \text{ km/hr}
\]

(Car Speed)
Tsunami Transformation

1. Shoaling  
2. Breaking  
3. Reflection and Transmission  
4. Refraction  
5. Diffraction

Plan View

- Shoaling
- Breaking
- Reflection and Transmission
- Refraction
- Diffraction

Side View

- Incident wave
- Jetty
- Shoaling area
- Breaking area
- Reflection
- Refraction
- Diffraction
Green’s Formula

\[ \frac{\eta_2}{\eta_1} = \left( \frac{h_1}{h_2} \right)^{1/4} \left( \frac{b_1}{b_2} \right)^{1/2} \]

\( \eta \): tsunami height (m)
\( h \): water depth (m)
\( b \): width of bay (m)
2. Tsunami Breaking

*Tsunami travels from left to right.
3. Tsunami Reflection and Transmission

*Tsunami travels from left to right.*

Tsunami

Reflection

Transmission

Breakwater
4. Refraction

Snell’s law

\[
\frac{\sin \theta}{c} = \text{constant}
\]

\[
\frac{\sin \theta_1}{c_1} = \frac{\sin \theta_2}{c_2}
\]

\(c\): tsunami velocity

\(c_1 > c_2, \quad \theta_1 > \theta_2\)

Map: Japan Meteorological Agency (1960)
5. Tsunami Diffraction

- Open area
- Protected area
- Breakwater
- Offshore
- Tsunami Rays
- Wave Crests
In the case of the Tohoku Tsunami in 2011:

**Location A:** Central Iwate offshore

**Location B:** Central Miyagi offshore

**Location C:** Fukushima offshore

Map: Image Landsat, Data SIO, NOAA, U.S. NAVY, NGA, GEBCO, Data Japan Hydrographic Association

Storm Surge Mechanisms
Components of a Storm Surge

Typhoon, Cyclone, Hurricane

1. Pressure Surge
2. Wind Induced Set-up
3. Wave (Run-up)
4. Tide

Coast levee or Dike
Evaluation of Pressure Set-Up and Wind Set-Up

**Pressure Set-up**

1 hPa difference ≈ 1 cm surge height

**Wind Set-up**

\[
\frac{\partial \eta}{\partial x} = \frac{\tau_s}{\rho gh}
\]

\(\tau_s\) : Wind Shear Stress

Additional hydrostatic pressure

\(\rho g \frac{\partial \eta}{\partial x} \Delta x\)
Storm Surge Simulation Model

Typhoon Simulation

- TC-Bogus (Hsiao et al., 2010)

Weather Research and Forecasting

- WRF (Skamarock et al., 2008)
  - 1. Wind velocity
  - 2. Atmospheric pressure

Storm Surge Simulation

- Unstructured Grid, Finite Volume Community Ocean Model

- FVCOM (Chen et al., 2003)

- SWAN (Booji et al., 1999)
  - Third-generation wave model for coastal regions

- WXtide (Flater, 1998)

Result of Storm Surge
Weather Research and Forecasting (WRF)

Advanced Research WRF Model (Skamarock et al., 2005)

- Next generation meso scale numerical weather forecast model and data assimilation system.
- Developed by NCAR, NOAA, NCEP and several other organizations.

Governing Equations

1. Momentum conservation equation
2. Mass conservation
3. Geo potential equation
4. Potential temperature conservation
5. Scalar conservation
6. Equation of state
Finite Volume Community Ocean Model (FVCOM)

**FVCOM (Chen et al., 2003)** *(used to calculate water movement)*

- The unstructured meshes adopt themselves to complex coastline
- Finite volume conserve better mass and momentum equations. (Chen et al., 2007)

![Image: Structured (Right) and Unstructured (Left) Grids are applied to coastal complex geometry](image)

**Governing Equations**

1. Momentum conservation equation
2. Mass conservation
3. Potential temperature equation
4. Salinity equation
5. Density equation

Image based on work by Chen et al., 2007
Methodology: WRF

**TC-Bogussing Scheme**

- Using artificial Rankin vortex for initial conditions (Hsiao et al., 2010)

**Surface Pressure (Pa)**

**Without TC-Bogussing**

**With TC-Bogussing**

---

**Rankin Vortex**

\[ \nu = A[z]F[r] \]

\[ F[r] = \frac{v_m}{r_m} r \quad (r \leq r_m) \]

\[ F[r] = \frac{v_m}{r_m^\alpha} r^\alpha \quad (r > r_m) \]

\( \nu \): Wind speed

\( v_m \): Maximum velocity at the Max velocity diameter \( r_m \)

\( \alpha \): Constant \( \alpha = -0.75 \)

\( A[z] \): Scale Factor depending on each typhoon, 0.90 for this case.

(Kurihara et al., 1993; 1995)
Simulating Waves Near Shore (SWAN)

SWAN (Booji et al., 1999) [TU Delft]

- Third-generation wave model for calculating realistic estimates of wave parameters
- Based on the wave action balance equation with sources and sinks

Governing Equations

1. Spectral action balance equation

\[
\frac{\partial}{\partial t} N + \frac{\partial}{\partial x} (c_x N) + \frac{\partial}{\partial y} (c_y N) + \frac{\partial}{\partial \sigma} (c_{\sigma} N) + \frac{\partial}{\partial \theta} (c_{\theta} N) = \frac{S(\sigma, \theta)}{\sigma}
\]

2. Kinematics of a wave train

\[
c_x = c_g \cos \theta + U c_y = c_g \sin \theta + V c_{\sigma} = \frac{\partial}{\partial t} \left( \sqrt{g k \tanh(kh)} - k \cdot U \right)
\]

\[
c_{\theta} = \frac{c_g}{c} \left( \sin \theta \frac{\partial c}{\partial x} - \cos \theta \frac{\partial c}{\partial y} \right) - \left( \sin \theta \frac{\partial}{\partial x} - \cos \theta \frac{\partial}{\partial y} \right) \left( \frac{k}{k} \cdot U \right)
\]

3. Sources in shallow water

\[
S(\sigma, \theta) = S_{in} + S_{ds,w} + S_{ds,br} + S_{ds,b} + S_{nl4} + S_{nl3}
\]

In Equation 3:
- \(S_{in}\) = wave growth by wind
- \(S_{ds,w}\) = wave decay due to white capping
- \(S_{ds,br}\) = depth induced wave breaking
- \(S_{ds,b}\) = bottom friction
- \(S_{nl4}, S_{nl3}\) = non linear transfer of wave energy terms
### Calculation Conditions for WRF (Ver. 3.5)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (PHT)</td>
<td>13/11/05 02:00 ~ 13/11/09 08:00 (102hr)</td>
</tr>
<tr>
<td>No. of Domain</td>
<td>3</td>
</tr>
<tr>
<td>Nesting Method</td>
<td>2 way nesting (mutual influence)</td>
</tr>
<tr>
<td>Projection Method</td>
<td>Mercator Projection</td>
</tr>
<tr>
<td>Horizontal Mesh Number</td>
<td>Domain 1: 16.2km x 16.2km</td>
</tr>
<tr>
<td></td>
<td>Domain 2: 5.4km x 5.4km</td>
</tr>
<tr>
<td></td>
<td>Domain 3: 1.8km x 1.8</td>
</tr>
<tr>
<td>Vertical Air Layers</td>
<td>27</td>
</tr>
<tr>
<td>Time Step</td>
<td>Domain 1: 40s</td>
</tr>
<tr>
<td></td>
<td>Domain 2: 20s</td>
</tr>
<tr>
<td></td>
<td>Domain 3: 10s</td>
</tr>
<tr>
<td>Topography Data</td>
<td>USGS</td>
</tr>
</tbody>
</table>
Using TC-Bogussing, central pressure accuracy estimation is improved.

History of Central Pressure (PHT) Measured Value from Digital Typhoon

**Without TC-Bogussing**
Surface Pressure Distribution (11/8 4:00 PHT)

**With TC-Bogussing**
Surface Pressure Distribution (11/8 4:00 PHT)
Wind distribution is better calculated using TC-Bogussing.

Time History of Maximum Wind Velocity (PHT) Measured values are from Digital Typhoon
# FVCOM Calculation Conditions

<table>
<thead>
<tr>
<th>Calculation Conditions for Ocean Modeling FVCOM</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Topography</td>
<td>ETOPO 1min</td>
</tr>
<tr>
<td>Program for Unstructured Topography</td>
<td>Blue Kenue</td>
</tr>
<tr>
<td>Latitude Range</td>
<td>9.32° - 11.80°</td>
</tr>
<tr>
<td>Longitude Range</td>
<td>124.7° - 126.8°</td>
</tr>
<tr>
<td>Time Step</td>
<td>1s</td>
</tr>
<tr>
<td>Horizontal Resolution</td>
<td>A right triangle with long side 1800m</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>19350</td>
</tr>
<tr>
<td>Number of Cells</td>
<td>38144</td>
</tr>
<tr>
<td>Element Type</td>
<td>T3</td>
</tr>
</tbody>
</table>

Unstructured topography of Leyte Bay (The image is created by the BlueKunue)

Surface Resistance Coefficient: $C_d$

Honda and Mitsuyasu (1980) with a condition that wind speed is constant (Yokota et al., 2011) when the speed is more than 30m/s.

$$
\begin{align*}
(1 - 1.89 \times 10^{-4} \times U_{10}) \times 1.28 \times 10^{-3} & : U_{10} < 8 \\
(1 + 1.078 \times 10^{-3} \times U_{10}) \times 5.81 \times 10^{-4} & : 8 \leq U_{10} < 30 \\
(1 + 1.078 \times 10^{-3} \times 30) \times 5.81 \times 10^{-4} & : U_{10} \geq 30
\end{align*}
$$

$U_{10}$: Wind Speed at 10m elevation (m/s)
Storm Surge Yolanda: Typhoon Yolanda Simulation

Date/Time: 2013-11-05 00:00:00

Animation created using Vapor [www.vapor.ucar.edu]
Storm Surge Simulation

08:00 PST 07th Nov, 2013
Bay Resonance
Introduction to the Local Behavior of a Tsunami

- February 27th, 2010
- Mw 8.8 earthquake
- Large tsunami generated
- Tsunami had diverse effects along the coast:
  - Large run-up measured in the southern shore of the Bay of Concepcion and the Gulf of Arauco.
  - Run-up decreases below 5m in the eastern Gulf of Arauco
  - Seawater surged hundreds of meters into several rivers
  - No inundation recorded at the 2-km wide Biobio river

Source: Aranguiz and Shibayama, 2013
Introduction

Historical records show that the Bay of Concepcion has been affected by several tsunamis:

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 8th 1570</td>
<td>Concepcion</td>
</tr>
<tr>
<td>Mar 15th 1657</td>
<td>Concepcion</td>
</tr>
<tr>
<td>Jul 8th 1730</td>
<td>Valparaiso</td>
</tr>
<tr>
<td>May 24th 1751</td>
<td>Concepcion</td>
</tr>
<tr>
<td>Feb 20th 1835</td>
<td>Concepcion</td>
</tr>
<tr>
<td>Aug 13th 1868</td>
<td>Arica</td>
</tr>
<tr>
<td>May 9th 1877</td>
<td>Iquique</td>
</tr>
<tr>
<td>May 22nd 1960</td>
<td>Valdivia</td>
</tr>
<tr>
<td>Feb 27th 2010</td>
<td>Concepcion</td>
</tr>
</tbody>
</table>

Analysis of Past Earthquake Epicenters

Source: Aranguiz and Shibayama, 2013
Last Tsunamis to Affect the Biobio Region

1877 Iquique tsunami:
- Estimated magnitude 8.8
- Inundation of the low areas in the Bay of Concepcion
- 3m inundation height at Talcahuano

1960 Valdivia Tsunami:
- Magnitude 9.5
- Maximum 25 m run-up in Mocha island
- 2-3m inundation height at Talcahuano
- Low inundation on the eastern shore of the Gulf of Arauco
- Effects of the tsunami reported in Japan

2010 Concepcion Tsunami:
- Magnitude Mw 8.8
- Significant inundation at the Bay of Concepcion
- 6-7m inundation height at Talcahuano
- Low inundation on the eastern shore of the Gulf of Arauco

Numerical Simulation of Last Tsunamis in Talcahuano (1877)

Initial conditions (Okada, 1985)

Tsunami time history in Talcahuano

Source: Aranguiz and Shibayama, 2013
Waveforms and spectral analysis

2010 Tsunami

1877 Tsunami

Source: Aranguiz and Shibayama, 2013
Analysis of Natural Oscillation Modes

The Empirical Orthogonal Function (EOF):

- Space-time data: \[ S(r, t) = \sum_{i=1}^{m} f_i(r)p_i(t) \]
- Covariance Matrix: \[ R = S^T S \]
- Find eigenvalues and corresponding eigenvectors: \[ RC = C\Delta \]
- Initial Perturbation: \[ \eta = ae^{-r^2/2\sigma^2} \]

Fig.1. The depth of the bay

Fig.2. Initial condition of the calculation

Source: Aranguiz and Shibayama, 2013
Natural Oscillation Modes in the Bay

The first EOFs give:

- T1 = 95 min
- T2 = 37 min
- T3 = 32 min

Source: Aranguiz and Shibayama, 2013
Effect of Submarine Canyons on Tsunami Propagation

Results of simulations in the Gulf of Arauco

Bangladesh and Sri Lanka

Source: Aranguiz and Shibayama, 2013
Bangladesh: US Dept of State Geographer, Image Landsat, Data SIO, NOAA, U.S. Navy, NGA, GEBCO Image ©2016 TerraMetrics
Sri Lanka: © 2016 Google, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image Landsat
Calculation of Submarine Canyons Effect on Tsunami Propagation

- Idealized bathymetry
- Length, width and depth of the canyon
- More than 300 simulations were performed using the TUNAMI model
  
  (Tohoku University’s Numerical Analysis Model)

\[
\begin{align*}
\frac{\partial M}{\partial t} + \frac{\partial}{\partial x} \left( \frac{M^2}{D} \right) + \frac{\partial}{\partial y} \left( \frac{MN}{D} \right) + gD \frac{\partial \eta}{\partial x} + \frac{g n^2}{D^{7/3}} M \sqrt{M^2 + N^2} &= 0 \\
\frac{\partial N}{\partial t} + \frac{\partial}{\partial x} \left( \frac{MN}{D} \right) + \frac{\partial}{\partial y} \left( \frac{N^2}{D} \right) + gD \frac{\partial \eta}{\partial y} + \frac{g n^2}{D^{7/3}} N \sqrt{M^2 + N^2} &= 0
\end{align*}
\]
Effect of Submarine Canyons on Tsunami Propagation – Calculation Results

Effect of length, width and depth

Source: Aranguiz and Shibayama, 2013
Longshore Distribution of Tsunami Height to Submarine Canyons

Results show longshore change of tsunami height distribution

Source: Aranguiz and Shibayama, 2013
Conclusion

- Past tsunami behavior in the Biobio region was analyzed.
- The diverse effects of the 2010 Chile tsunami on the Biobio region can now be better explained.
- Important findings are:
  - Large tsunami amplifications caused by oscillation
  - Variations in run-up height are due to the presence of a submarine canyon
Field Measurements
Survey Methodology

1. Check the damage and find appropriate places to estimate the maximum water level or run-up height
2. Measure the ground height from sea level for each survey point
3. Measure the height of marks from ground level

Maximum water level or run-up height
Field Measurements: Measuring the Height from the Shore
Field Measurements: Measuring the Height from the Ground
Measuring Ground Height

\[ 3 = 1 - 2 \]
Measuring Ground Height

\[
\begin{align*}
3 &= 1 - 2 \\
6 &= 3 + 4 - 5
\end{align*}
\]