April 1\textsuperscript{st}, 2007 Solomon Islands Tsunami

(Wei et. al., 2015)

Comparison of model and observations of tsunami wave amplitude at deep-ocean tsunameters and Honiara tide station for the 1 April 2007 Solomon tsunami

Computed maximum wave amplitude of the 1 April 2007 Solomon tsunami and tectonic settings in the South Pacific.
Index

• Introduction on hydro-acoustic waves generated by submarine earthquakes

• Development of a depth-integrated model for the simulation of hydro-acoustic waves:
  ✓ For Rigid Bottom (MSEWC)
  ✓ For Porous Bottom (MSEDWC)

• Applications:
  ✓ Historical Mediterranean Sea events (365 AD Crete and 1693 Catania)
  ✓ Haida Gwaii 2012 Western Canada
  ✓ Tohoku-oki 2011 Japan

• Conclusions

• Future Works
Motivations:

Improve Tsunami Early Warning System

- Systems based on seismic measurements
- Tsunami measurements are essential to increase the reliability of the system
- Can we use precursors of tsunami?

Hydro-acoustic waves (pressure waves in weakly compressible fluid)
- Travel at 1500 m/s
- Contain information on the tsunamigenic source
- Need of numerical modelling (3D models are computationally expensive)

This research aims at developing numerical models applicable on an oceanic scale

Tsunami early warning system based on real-time measurement of hydro-acoustic waves, 2014, Procedia Engineering. doi:10.1016/j.proeng.2014.02.035
Simplified earthquake

The movement of the bottom generates pressure waves and surface waves (tsunamis)

In the next slide results of computations related to this simple layout are shown
t = 1 s

Surface waves (exaggerated)

Acoustic waves

Tsunami front

Acoustic wave front

30 km

70 km
Hydro-acoustic wave

\[ \zeta_0 = 1 \text{ m} \]
\[ \tau = 1 \text{ s} \]
\[ b = 15 \text{ km} \]
\[ x = 200 \text{ km} \]
\[ h = 1.5 \text{ km} \]

earthquake

Tsunami

Tsunami precursors

\[ f^{(n)} = (2n-1) \frac{c}{4h}; \quad n = 1, 2, 3, \ldots \]
Depth Effect

Frequency spectra of hydroacoustic waves on the shelf

Frequency spectra of hydroacoustic waves on the ocean bottom

\[ \tau = 10 \text{ s}, \ z_0 = 10 \text{ m}, \ b = 40 \text{ km} \]

\[ h = 1 \text{ km} \]

\[ h = 5 \text{ km} \]
Change in Normal Peak Frequencies

\[ f^{(n)} = \left(2n - 1\right) \frac{c}{4h}; \quad n = 1, 2, 3, \ldots \]

### Single Sedimentary Layer:

\[
\tan \left[ \frac{2\pi \gamma_1^{(n)}h}{c} \right] \tan \left[ \frac{2\pi \gamma_2^{(n)}a^{(1)}}{c_s^{(1)}} \right] = \frac{\rho_s^{(1)}c_s^{(1)}}{\rho c}
\]

### Two Sedimentary Layers:

\[
\begin{align*}
\rho_s^{(2)}c_s^{(2)} - \sqrt{\rho_s^{(1)}c_s^{(1)}} & = \frac{2\pi \gamma_1^{(n)}h}{c} \tan \left[ \frac{2\pi \gamma_2^{(n)}a^{(2)}}{c_s^{(2)}} \right] \\
\quad \text{and} \quad \rho_s^{(1)}c_s^{(1)} + \rho_s^{(2)}c_s^{(2)} & = \frac{2\pi \gamma_1^{(n)}h}{c} \tan \left[ \frac{2\pi \gamma_2^{(n)}a^{(1)}}{c_s^{(1)}} \right]
\end{align*}
\]

### Table

<table>
<thead>
<tr>
<th>Layer</th>
<th>Density (kg/m³)</th>
<th>Sound Celerity (m/s)</th>
<th>Layer Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1028</td>
<td>1500</td>
<td>2200</td>
</tr>
<tr>
<td>Sediment (i = 1)</td>
<td>1850</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>Sediment (i = 2)</td>
<td>2200</td>
<td>2500</td>
<td>1000</td>
</tr>
</tbody>
</table>

### Parameters

- Water Density: 1028 kg/m³
- Sound Celerity: 1500 m/s
- Layer Thickness: 2200 m

### Figures

- **(a)** Zero Sedimentary Layer, i=0
- **(b)** Normal Peak Frequencies, f
- **(c)** One Sedimentary Layer, i=1
- **(d)** Normal Peak Frequencies, f
- **(e)** Two Sedimentary Layers, i=2
- **(f)** Normal Peak Frequencies, f
Role of underlying Sedimentary Layer

(a) One layer compressible water model (blue) and a coupled model of compressible water & inviscid compressible sediment (black), $= 0$.

(b) $f^{(n)}$ Cut off frequency for 1 Layer

(c) One layer compressible water model with partial reflecti$\mu$on bottom boundary condition (blue) and a coupled model of compressible water & viscous compressible sediment, $\mu = 2 \times 10^8 \text{ Pa s}$ (black).

(d) $\gamma^{(n)}$ Cut off frequency for 2 Layers

Partially Reflecting BC

$$\Phi_z = \frac{1}{c K_r + 1} \Phi_t$$

$$K_r = \frac{\rho_s c_p - \rho c}{\rho_s c_p + \rho c} \text{ Reflection Coef.}$$

$h = 2200 \text{ m} \quad \rho = 1000 \text{ kg} / \text{ m}^3$

$a = 1000 \text{ m} \quad \rho_s = 1850 \text{ kg} / \text{ m}^3$

$c = 1500 \text{ m} / \text{ s} \quad \tau = 2 \text{ s}$

$c_s = 2000 \text{ m} / \text{ s} \quad \mu = 0$

$b = 112 \text{ km} \quad \mu_s = 2 \times 10^8 \text{ Pa s}$

**Governing Equation**

\[ \Phi_{tt} - c^2 \nabla^2 \Phi = 0 \; ; \; \quad -h + \eta_2(x, y, t) \leq z \leq \eta_1(x, y, t) \]

\[ Q_{tt} - c_s^2 \nabla^2 Q - 2 \nu_s (\nabla^2 Q)_t = 0 \; ; \; \quad -h_s \leq z \leq -h + \eta_2(x, y, t) \]
Previous Results for Rigid Bottom

Rigid Bottom

\[ \psi_{n,tt} \left( \frac{C_n}{c^2} + \frac{1}{g} \right) - \nabla \cdot (C_n \nabla \psi_n) + \left( \frac{\omega^2}{g} - \beta_n^2 C_n \right) \psi_n = \frac{h_{n,t}}{\cosh^2(\beta_n h)} \]

Mild-slope equation weakly compressible fluid (MSEWC)

\[ C_n = \frac{2 \beta_n h + \sinh(2 \beta_n h)}{4 \beta_n \cosh^2(\beta_n h)} \]

\[ \omega^2 = g \beta_n \tanh(\beta_n h) \]

Boundary Conditions

Free Surface and bottom BC

- \( \Phi_{tt} + g \Phi_z = 0; \quad z = 0 \)
- \( Q_z + \nabla_h h_s \cdot \nabla_h Q + h_{s,t} = 0; \quad z = -h_s \)

Interface BC

- \( (R - 1) g \eta_2 = \Phi_t - R Q_t \quad z = -h \)
- \( W_w = W_s = (-h + \eta_2)_t \)

Interface Equilibrium

- \( R = \frac{\rho_s}{\rho} \)

\[ \Phi(x, y, z, t) = \sum_{n=0}^{\infty} \Phi_n(x, y, z, t) = \sum_{n=0}^{\infty} \psi_n(x, y, t) M_n(z) \]

\[ Q(x, y, z, t) = \sum_{n=0}^{\infty} Q_n(x, y, z, t) = \sum_{n=0}^{\infty} \psi_n(x, y, t) N_n(z) \]
Depth Integrated Model Derivation

Orthogonality

\[ I^m + RII^m = 0 \]

\[ I^m = \int_{-h}^{0} M_m L(\Phi) \, dz \]

\[ I_{mn} = \int_{-h}^{0} M_m(z) M_n(z) \, dz \]

\[ K_{mn} = \int_{-h_s}^{0} N_m(z) N_n(z) \, dz \]

\[ \Pi^m = \int_{-h_s}^{0} N_m L(Q) \, dz \]

\[ I^m = \sum_{n=0}^{\infty} \left\{ \nabla_h \left[ I_{mn} \nabla_h \psi_n \right] - \left( \frac{I_{mn}}{c_s^2} + \frac{1}{g} \right) \psi_{n,t} \right\}_{,t} - J_{mn} \psi_n \]

\[ I_{mn} = \sum_{n=0}^{\infty} \left\{ \nabla_h \left[ K_{mn} \nabla_h \psi_n \right] - \left( \frac{K_{mn}}{c_s^2} \right) \psi_{n,t} \right\}_{,t} - L_{mn} \psi_n - 2c \frac{\omega}{c_s^2} K_{mn} \psi_{n,t} \]

\[ \Pi_{mn} = \sum_{n=0}^{\infty} \left\{ \nabla_h \left[ K_{mn} \nabla_h \psi_n \right] - \left( \frac{K_{mn}}{c_s^2} \right) \psi_{n,t} \right\}_{,t} - L_{mn} \psi_n - 2c \frac{\omega}{c_s^2} K_{mn} \psi_{n,t} \]
Mild-slope equation Dispersive weakly compressible fluid

\[
\begin{align*}
\left(I_2^m \psi_{m,t}\right)_t - \nabla_h \cdot \left(I_1^m \nabla_h \psi_m\right) + \left(\omega^2 I_2^m - k_m^2 I_1^m\right) \psi_m + 2 R \varepsilon \frac{\omega}{c_s^2} K_n \psi_{m,t} &= D_1^m h_t + D_2^m h_{s,t} \\
\end{align*}
\]

(MSEDWC)

\[
\begin{align*}
I_1^m &= I_{mm} + R K_{mm} \\
I_2^m &= \frac{I_{mm}}{c^2} + R \frac{K_{mm}}{c_s^2} + \frac{1}{g} \\
D_1^m &= - \left[M_m - R N_m\right](-h) \\
D_1^m &= - \left[R N_m\right](-h) \\
\end{align*}
\]

\[
\begin{align*}
M_n &= \frac{\left(1 - \lambda_n T_n\right) \cosh(\beta_{w,n}(h + z)) + \left(\lambda_n - T_n\right) \sinh(\beta_{w,n}(h + z))}{\left(1 - \lambda_n T_n\right) \cosh(\beta_{w,n}h) + \left(\lambda_n - T_n\right) \sinh(\beta_{w,n}h)} \\
N_n &= \frac{\left(\lambda_n - T_n\right) \cosh(\beta_{s,n}(h_s + z))}{\alpha_n \sinh(\beta_{s,n}a)\left[\left(1 - \lambda_n T_n\right) \cosh(\beta_{w,n}h) + \left(\lambda_n - T_n\right) \sinh(\beta_{w,n}h)\right]} \\
\end{align*}
\]

Dispersion relation

\[ P_1 = P_2 \]
\[ \Phi_{1,z} = \Phi_{2,z} \]

at Interface

\[ \lambda_n^2 \left( R + \alpha_n T_n \hat{T}_n \right) - \lambda_n R \left( T_n + \alpha_n \hat{T}_n \right) + (R - 1) \alpha_n T_n \hat{T}_n = 0 \]

\[ \beta_{w,n}^2 = k_n^2 - \frac{\omega^2}{c^2} \quad \alpha_n = \frac{\beta_{s,n}}{\beta_{w,n}} \quad T_n = \tanh(\beta_{w,n} h) \]
\[ \beta_{s,n}^2 = k_n^2 - \frac{\omega^2}{c_s^2} \quad \lambda_n = \frac{\omega^2}{g \beta_{w,n}} \quad \hat{T}_n = \tanh(\beta_{s,n} a) \quad R = \frac{\rho_s}{\rho} \]

\[ \beta \text{ is the Separation constant} \]

\[ n = 0, \quad \beta \text{ is real} \quad \text{Gravity mode} \]
\[ n \geq 1, \quad \beta \text{ is complex} \quad \text{Hydro-acoustic modes} \]

\[ \left\{ \begin{array}{ll}
\text{if } k_n^2 > \frac{\omega^2}{c^2} \\
\text{progressive mode}
\end{array} \right. \]
\[ \left\{ \begin{array}{ll}
\text{if } k_n^2 < \frac{\omega^2}{c_s^2} \\
\text{Evanescent mode}
\end{array} \right. \]

\[ \rho \quad \text{Water density} \]
\[ \rho_s \quad \text{Sediment density} \]
Model validation
For constant depth

Inviscid Sediment

Viscous Sediment

\[
\begin{align*}
    h &= 2200 \text{ m} & \rho &= 1000 \text{ kg/m}^3 \\
    a &= 1000 \text{ m} & \rho_s &= 1850 \text{ kg/m}^3 \\
    c &= 1500 \text{ m/s} & \tau &= 2 \text{ s} \\
    c_s &= 2000 \text{ m/s} & \mu &= 0 \\
    b &= 112 \text{ km} & \mu_s &= 2 \times 10^8 \text{ Pa s}
\end{align*}
\]
Model validation for Varying Bottom

Results for FSE time series at 150 km from tsunamigenic source from 3D (blue) and 2D models (black).

(b,c) Results for impermeable sea bottom and (d,e) for coupled model.
Large Scale Applications

Tohoku Oki 2011

Haida Gwaii 2012

365 AD Crete & 1693 Catania
Multidisciplinary deep water observatories

- The Catania Test Site (CTS), 25 km offshore the East coast of Sicily, water depth 2 km → \( f^{(1)} = 0.2 \text{ Hz} \)
- The Capo Passero (CP) observatory, 100 km offshore the coast, water depth 3.5 km → \( f^{(1)} = 0.1 \text{ Hz} \)
- Both observatories are connected to shore through submarine electro-optical cables and equipped with hydrophones

Long term observations in the open ocean – from seafloor to sea surface

EMSO (European Multidisciplinary Seafloor and Water Column Observatory) is a large-scale European Research Infrastructure (RI). It is a European network of fixed point, deep sea observatories with the basic scientific objective of real-time, long-term monitoring of environmental processes related to the interaction between the geosphere, biosphere, and hydrosphere.

http://www.emso-eu.org/
Bathymetry, Mediterranean Sea

A Depth-Integrated Equation For Large Scale Modeling Of Tsunami In Weakly Compressible Fluid, International Conference of Coastal Engineering ICCE, Seoul, June. 2014.
DOI: http://dx.doi.org/10.9753/icce.v34.currents.9
365 AD and 1693 Scenario (Historical events)

Sea Bottom Displacement
Snapshots of the free surface ($\eta$) hydroacoustic perturbation (a) and gravity wave (b) given by the AD 365 earthquake. $t = 0$ refers to the time of occurrence of the earthquake.
Snapshots of the free surface ($\eta$) hydroacoustic perturbation (a) and gravity wave (b) given by the 1693 Catania earthquake. $t = 0$ refers to the time of occurrence of the earthquake.
Haida Gwaii 2012 Event (Canada)

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<table>
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<tbody>
<tr>
<td><strong>6.28 s</strong></td>
<td></td>
</tr>
<tr>
<td><strong>2.3 km/h</strong></td>
<td></td>
</tr>
</tbody>
</table>
Bathymetry data of the west Canadian and USA coast (ETOPO1 data).

\[ \zeta_t = \frac{\zeta_0}{2} \left[ 1 - \cos \left( \frac{2\pi (t - t_0)}{\tau} \right) \right] H(t - t_0) - H(t - t_0 - \tau) \]

\[ t_0 = \frac{r}{V_r} \]
Tsunami Wave (Haida Gwaii, 2012)

Revolution of Long Gravitational Tsunami Waves

Pressure time series as measured by the NEPTUNE observatories and DARTs (Measurements in gray and model results in red)
DOI: 10.1002/2014JC010385
Tohoku-Oki 2011 (Japan)

Steel structure collision with Concrete Building

293 tons!
Numerical Domain and Source

Bathymetry and numerical domain with placement of DART and JAMSTEC Observatories

Hydro-acoustic Wave Generation During the Tohoku-oki 2011 Earthquake, Coastal Structures and Solutions to Coastal Disasters joint conference, Boston, Massachusetts, USA, September 9-11, 2015
Snapshots of the free surface ($\eta$) gravity wave perturbation given by Tohoku-Oki 2011 earthquake and submarine mass failure resulted from Zero mode of MSEDWC. $t = 0$ refers to time of occurrence of event.
Conclusions

• We have derived a hyperbolic mild-slope equation for hydro-acoustic waves in weakly compressible fluids for rigid and porous bottoms (MSEWC & MSEDWC).
• The model equation has been validated by comparing with a three-dimensional solver of the governing equations
• First simulations on a real, large scale bathymetry
• Suggestion on where to locate the submarine observatories (hydrophones) for the early detection: not in shallow waters!
Future Work

- Apply the model for Landslide events
- More Real Case Applications
- Considering lower layer being a viscoelastic medium
- Considering the variation of sound speed in water column
- Analysis of collected time series of hydrophone/BP
- Investigation of trapped waves in SOFAR channel
- Using HPC for improvement of model performance
- Using LBM and SPH for compressible fluid modelling
- Study of Mode transition due to depth effect

!!!
JOURNAL PAPERS


Talks


• Abdolali, A, A review of oscillating wave surge converters. Numerical modeling of flap gate farm: from Venice lagoon defense to resonating wave energy production, (talk), School of Civil and Environmental Engineering (CEE), Cornell University, Ithaca, USA, October 9, 2014.

• Abdolali, A, Hydro-acoustic Wave Detection for Tsunami Early Warning System (TEWS), (talk), Center for Applied Coastal Research (CACR), Department of Civil and Environmental Engineering, University of Delaware, Newark, USA, March 10, 2015.

• Abdolali, A, Numerical Modeling of Hydro-acoustic waves In Weakly Compressible Fluid for Tsunami Early Warning System (TEWS), (talk), Department of Ocean Engineering, University of Rhode Island (URI), Narragansett, RI 02882, USA, April 9, 2015.
• Abdolali, A., Cecioni, C., Bellotti, G. And Sammarco, P., 2014, A Depth-Integrated Equation For Large Scale Modeling Of Tsunami In Weakly Compressible Fluid, Coastal Engineering Proceedings, ASCE, 1(34), currents.9. doi: http://dx.doi.org/10.9753/icce.v34.6p


• Abdolali, A., Kirby, J.T., Bellotti, G., Grilli, S., Harris, J.C., 2015, Hydro-acoustic Wave Generation During the Tohoku-oki 2011 Earthquake, Coastal Structures and Solutions to Coastal Disasters joint conference, Boston, Massachusetts, USA, September 9-11, 2015


• Abdolali, A. and Kirby, J.T., 2015, Propagation of low frequency hydro-acoustic waves over a finite barrier, 2nd Young Coastal Scientist and Engineers Conference-North America. 27-29 July, 2015, Newark, DE, USA (Submitted)
Thanks for your attention!