ICCE 2012; Santander, Spain
July 5, 2012

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FREQUENCY-BASED HARBOR RESPONSE TO INCIDENT TSUNAMI WAVES IN AMERICAN SAMOA

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Contents

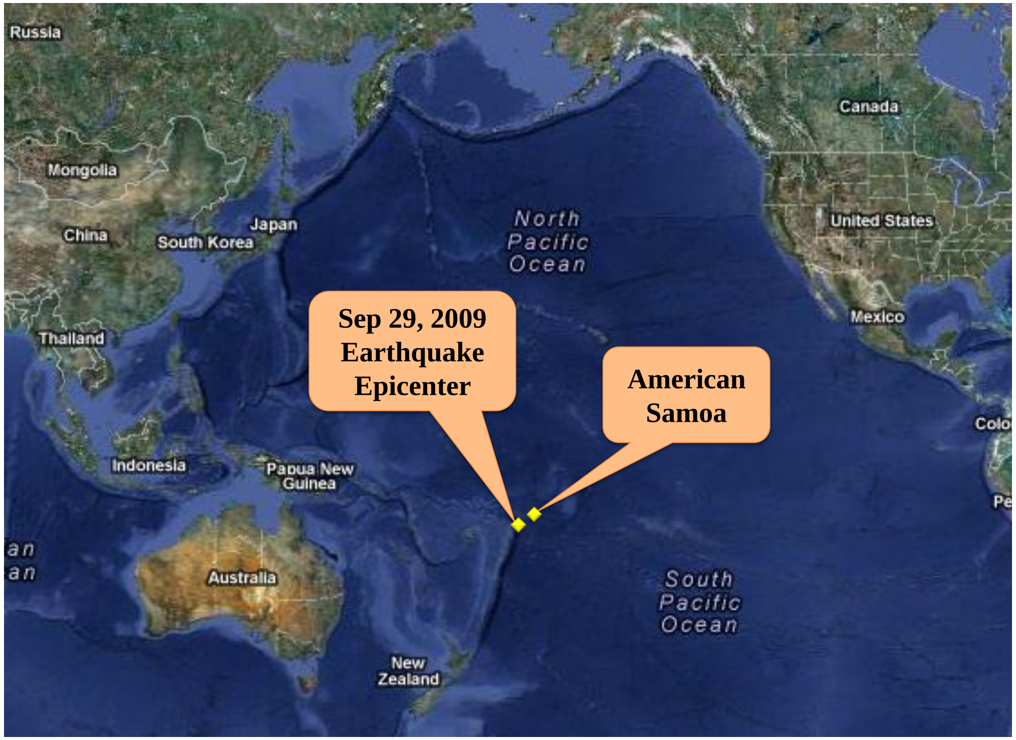
September 29, 2009 Samoa tsunami

Epicenter northern Tonga Trench

- Connecting Australian and Pacific plate
- 200 kilometers away from Samoa
- 14 shakes of magnitude 7.5 or greater since 1990 (USGS)

Earthquake (USGS)

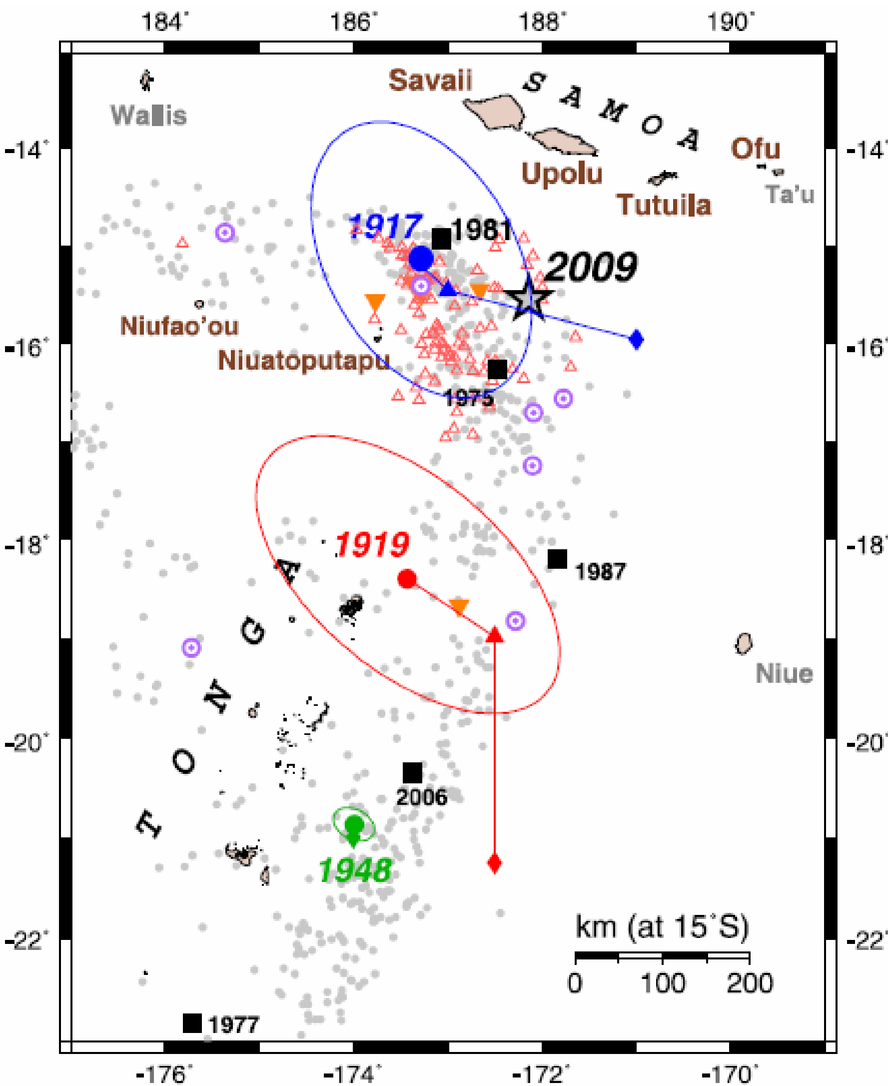
- Magnitude 8.1
- Seismic moment 1.2×10^{28} dyn-cm



Tsunami

- Arrives at American Samoa 20 minutes later
- Hit Samoa archipelago before Pacific Tsunami Warning Center issued an alert

Tsunamigenic Predecessors (Okal et al., 2011)



- Historical tsunami in Samoa region
  - Large earthquake generated tsunamis are shown by circle dots
  - Earthquakes with decimetric tsunamis are shown by square dots
  - Conclusion: only 1917 earthquake caused a destructive tsunami comparable to 2009 event, but lack of ancestral memory due to the 1918 influenza epidemic

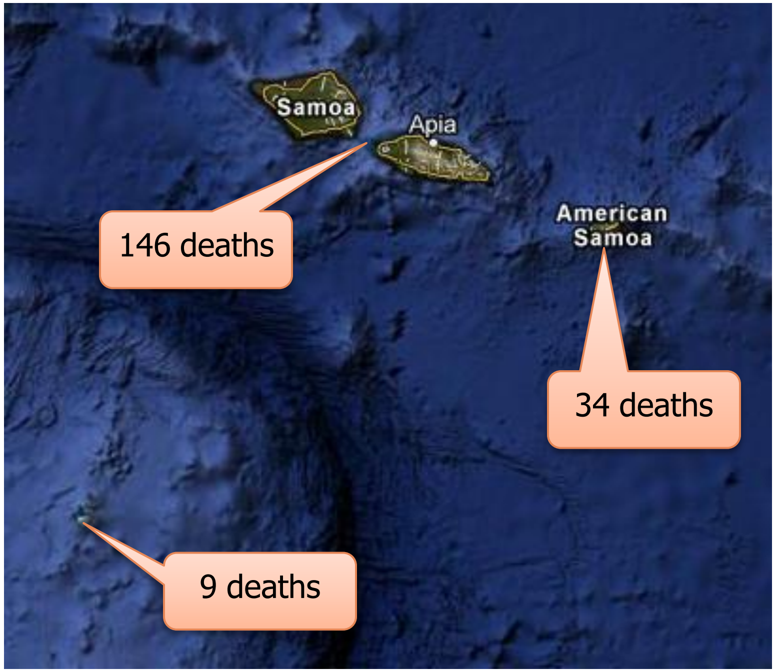
Fatalities and Damages

About $200 million economic loss

189 people killed

Modification of shoreline landscape

First reported tsunami event in Samoa islands



Photos taken by International Tsunami Survey Team in American Samoa (Okal et al., 2010)

Tsunami Measurements

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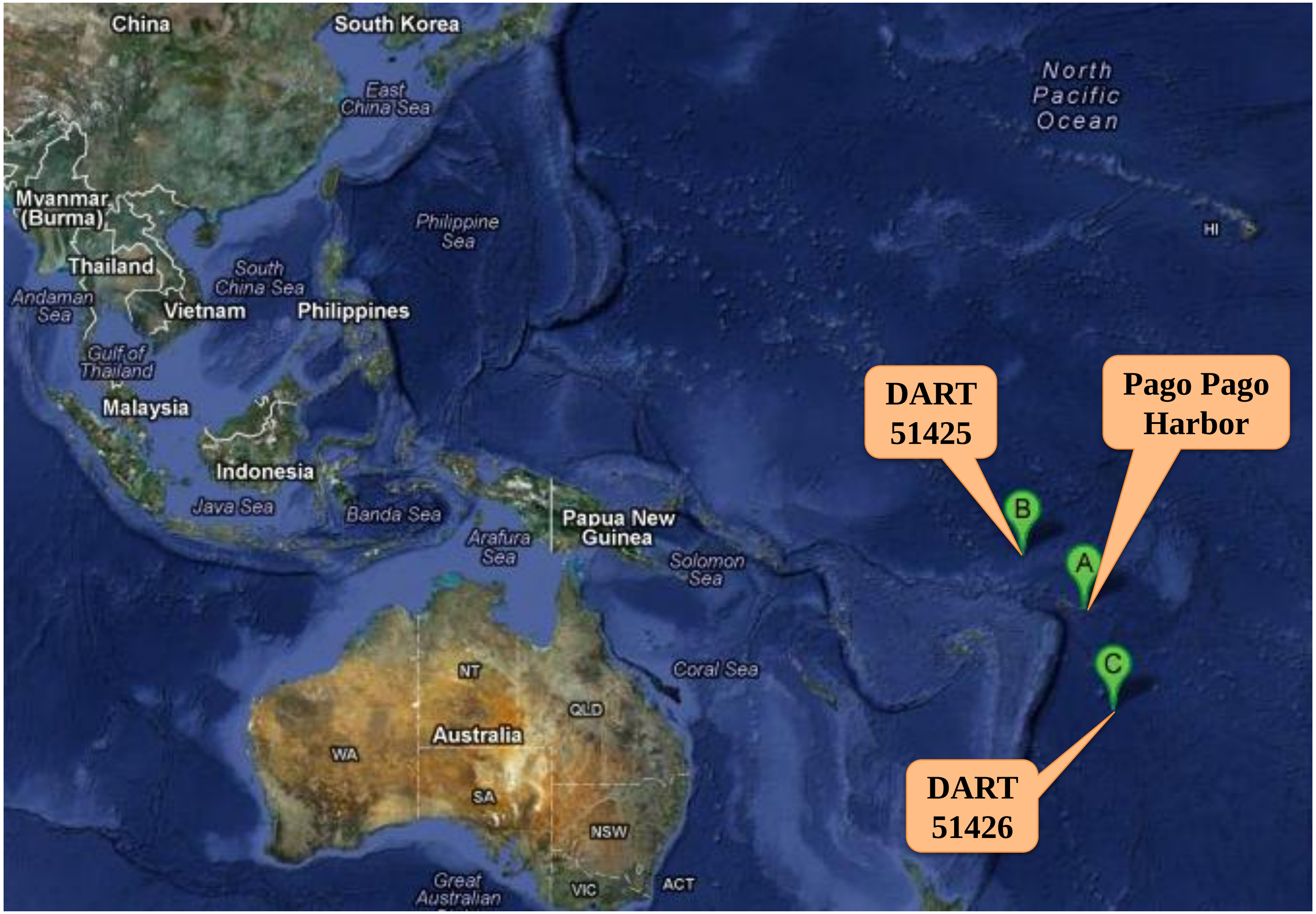

Google satellite map superimposed by locations of Pago Pago Harbor tidal gauge and two buoys

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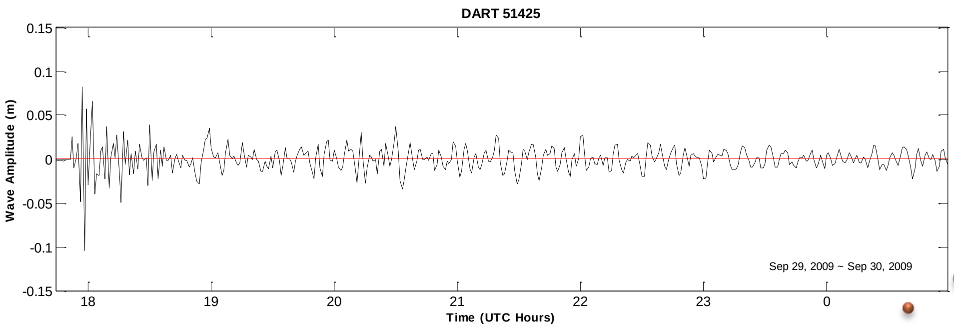
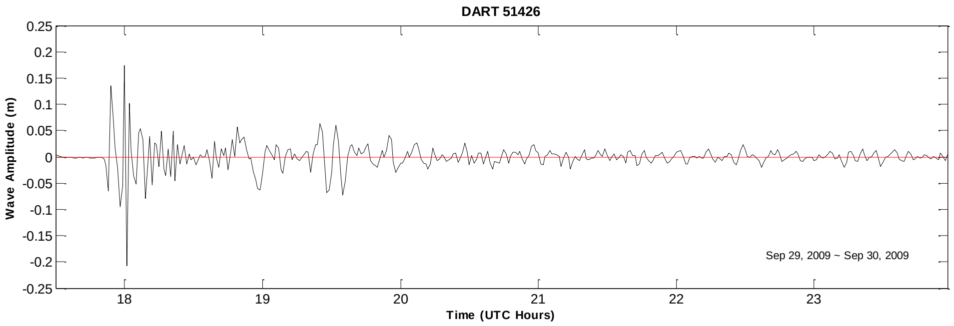
Tsunami Measurements (continued)

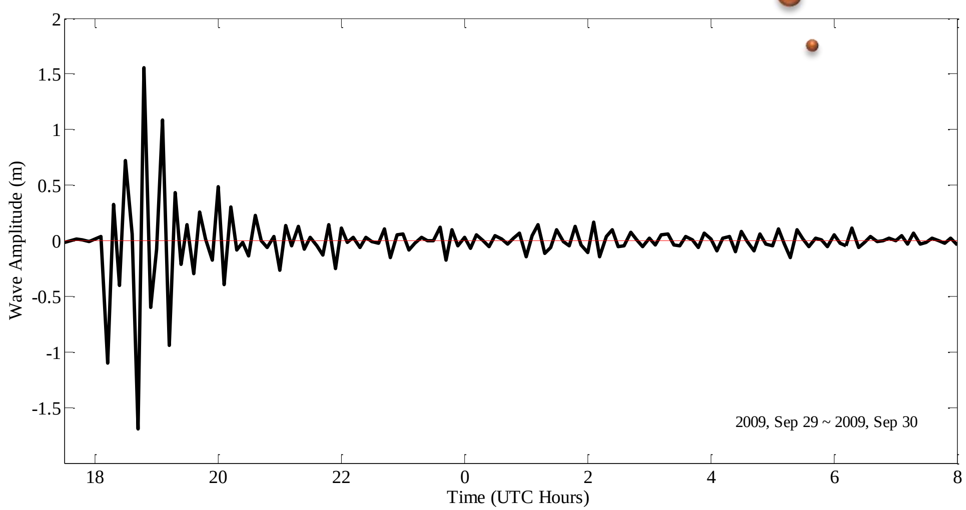




Weak oscillations

Strong oscillations

U.S. NOS Station 1770000



Wave amplitude was greatly magnified when tsunami surges propagated into the harbor

Numerical Model (Lee & Xing, 2010)

- **Mild slope equation (Berkhoff, 1972)**

$$\nabla \cdot \left(C C_g \nabla \phi \right) + \frac{C_g \omega^2}{C} \phi = 0$$

$$\Phi = \mathbb{R} \left\{ \phi(x,y) \frac{\cosh\left[k(z+h) \right]}{\cosh(kh)} \exp(-i\omega t) \right\}$$

$$\eta = -\frac{1}{g} (-i\omega) \phi \exp(-i\omega t)$$

ϕ	C	C_g	ω
Horizontal variation in velocity potential	Wave celerity	Group velocity	Angular frequency
Φ	k	h	η
Velocity potential	Wave number	Water depth	Surface elevation

- **Hybrid model: numerical solution in harbor and inner region; analytical solution in ring-shape, infinite outer area**
- **Solutions in inner and outer region should match at semi-circle connecting boundary**
- **Energy losses due to partial boundary reflection, flow separation at entrance, and bottom friction are also incorporated**

Numerical Model (Lee & Xing, 2010)

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- **Finite element variation**

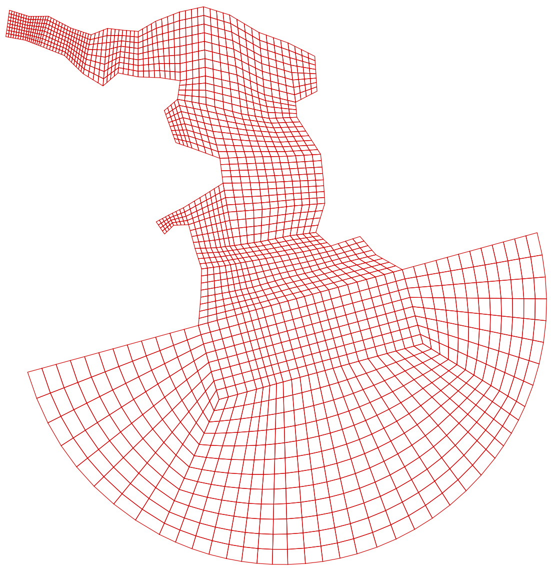
$$\Psi(\phi) = \frac{1}{2}\int_{\Omega} F\left(\phi, \frac{\partial^2 \phi}{\partial x^2}, \frac{\partial^2 \phi}{\partial y^2}\right) dxdy$$

$$\delta\Psi = \lim_{\alpha \to 0} \frac{\Psi(\phi + \alpha\varepsilon) - \Psi(\phi)}{\alpha} = 0$$

- 9 nodal points for each element
- Weighted by shape function
- System of linear equations solved by a matrix algorithm

- **The whole computational domain is discretized into 1,984 elements**

- **Boundary conditions**
  - **Partial reflection at harbor boundary**
  - **Incident waves enter from semi-circle**
  - **Non-reflection at semi-circle**



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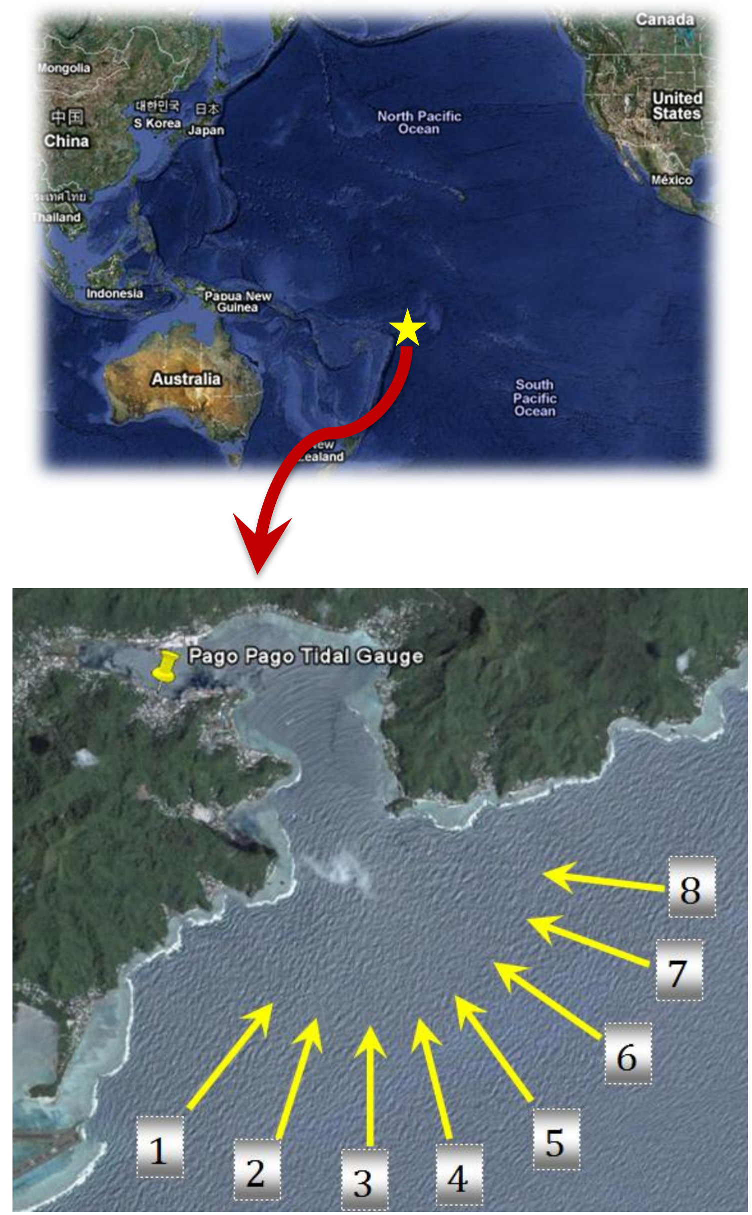
Simulation Results

- **Numerical experiment on Pago Pago Harbor**

- **Interested in amplification factor: responded wave amplitude / incident wave amplitude**
- **Eight different incoming directions**
- **Various wave modes**
- **Use partial reflection at harbor boundary**
- **Variable water depth**



Simulation Results

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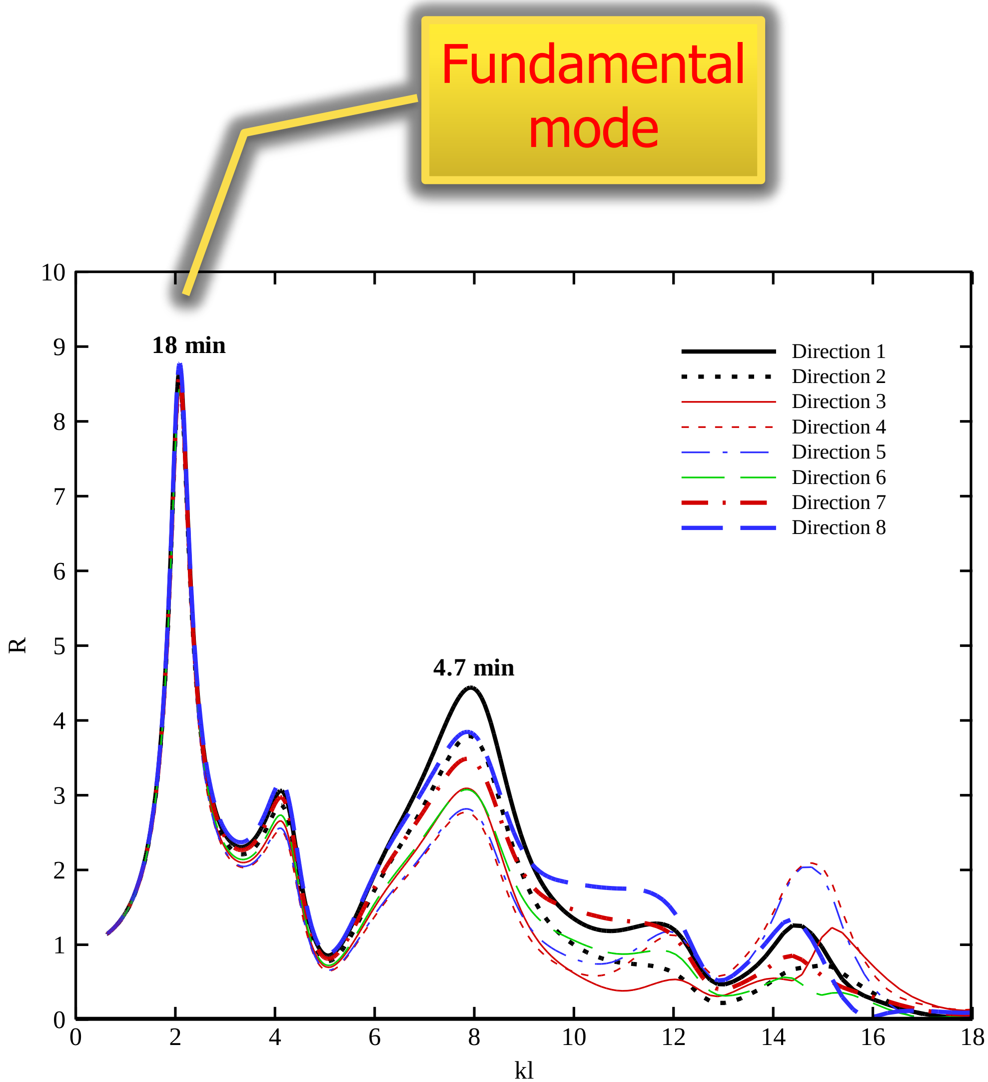

Pago Pago tidal gauge location

➢ Response curves

- **Amplification factor is the largest at 18-min period for all directions**
- **Amplification factor does not vary with different directions at the fundamental mode**
- **Incoming waves with the fundamental mode can be amplified 9 times!**
- **Explains the considerable difference of wave amplitude recorded by tidal gauge and buoys**
- **Secondary mode is 4.7-min period**

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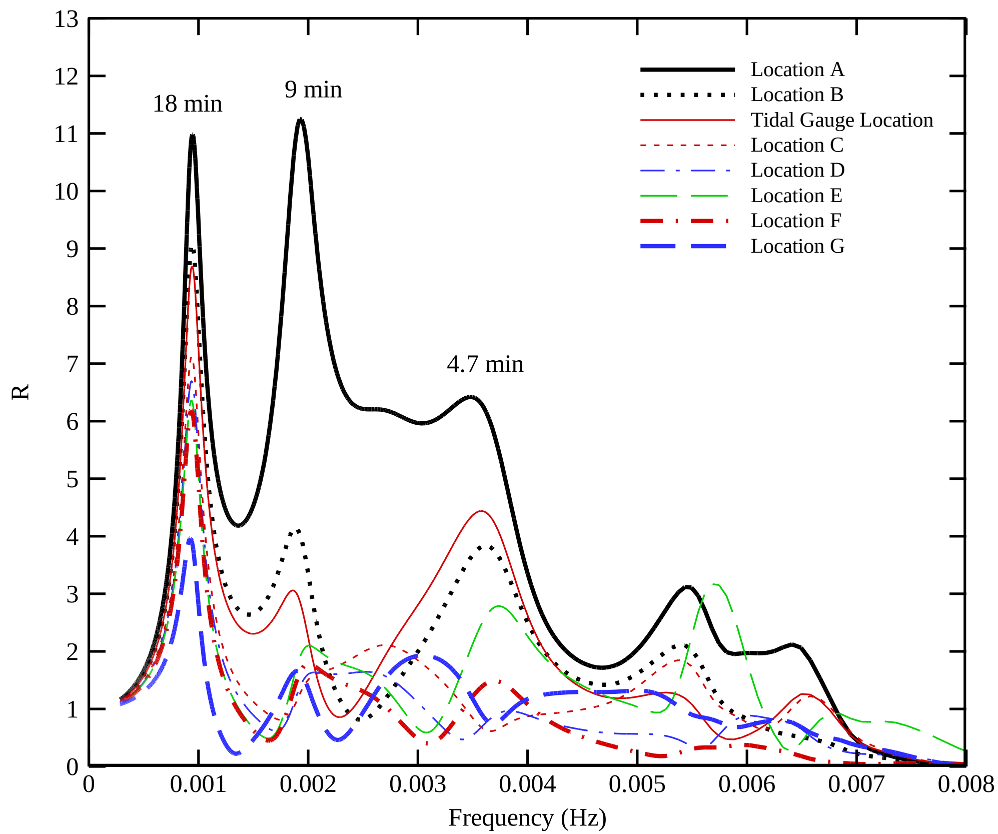
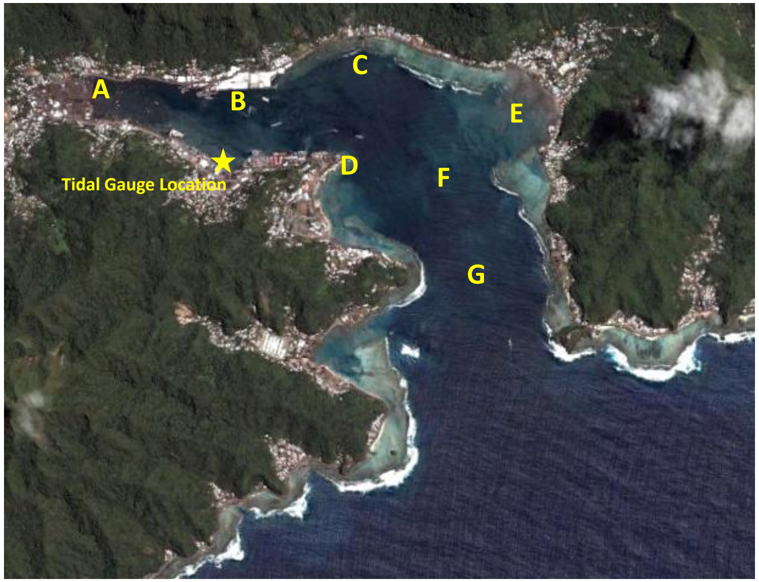
Simulation Results

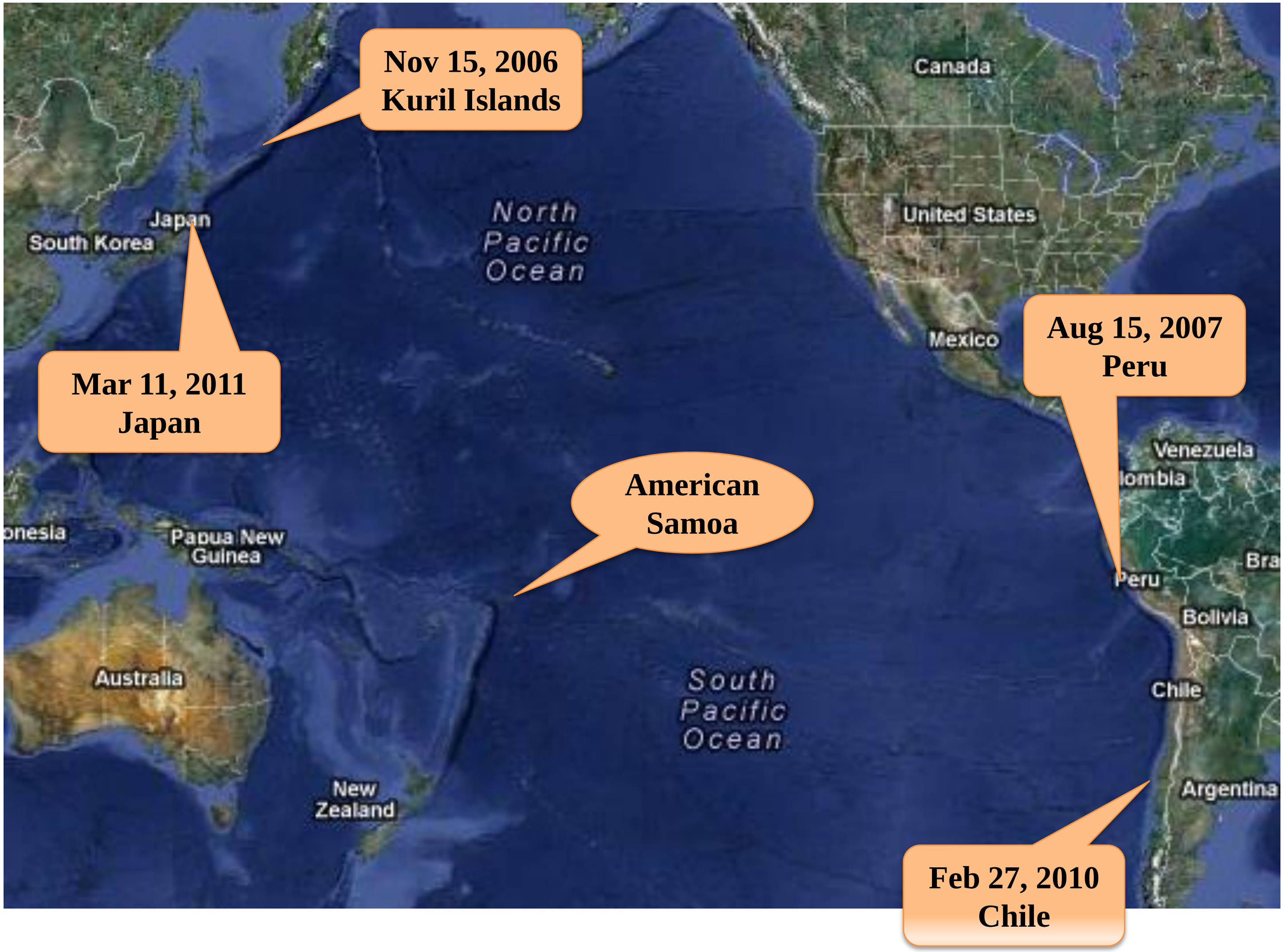


Direction 1



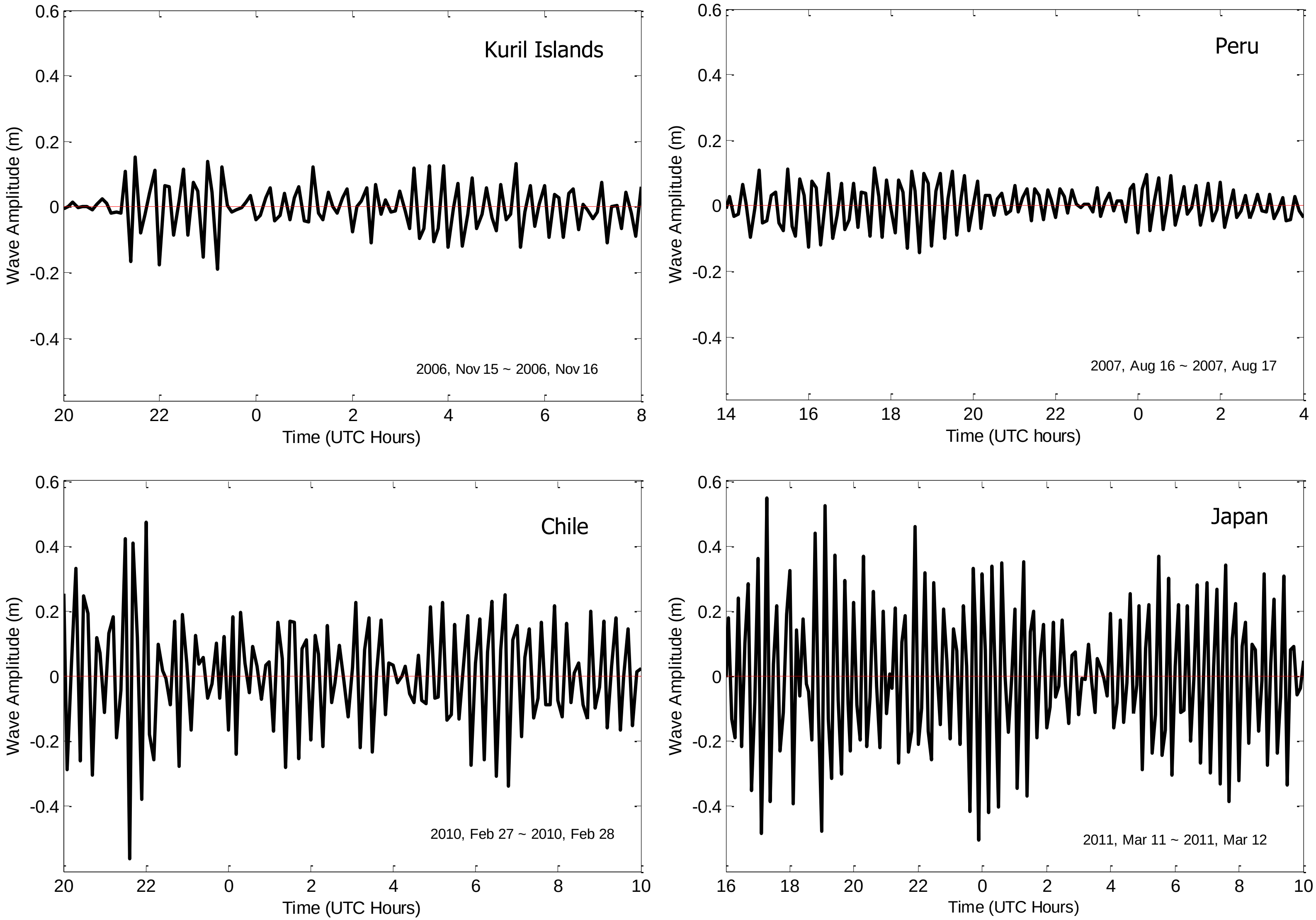
- Response curves
- Amplification factor becomes larger to inside of the harbor at 18-min
- Large amplification factor at the most interior for a wide range of wave modes

Comparison with Tidal Measurements

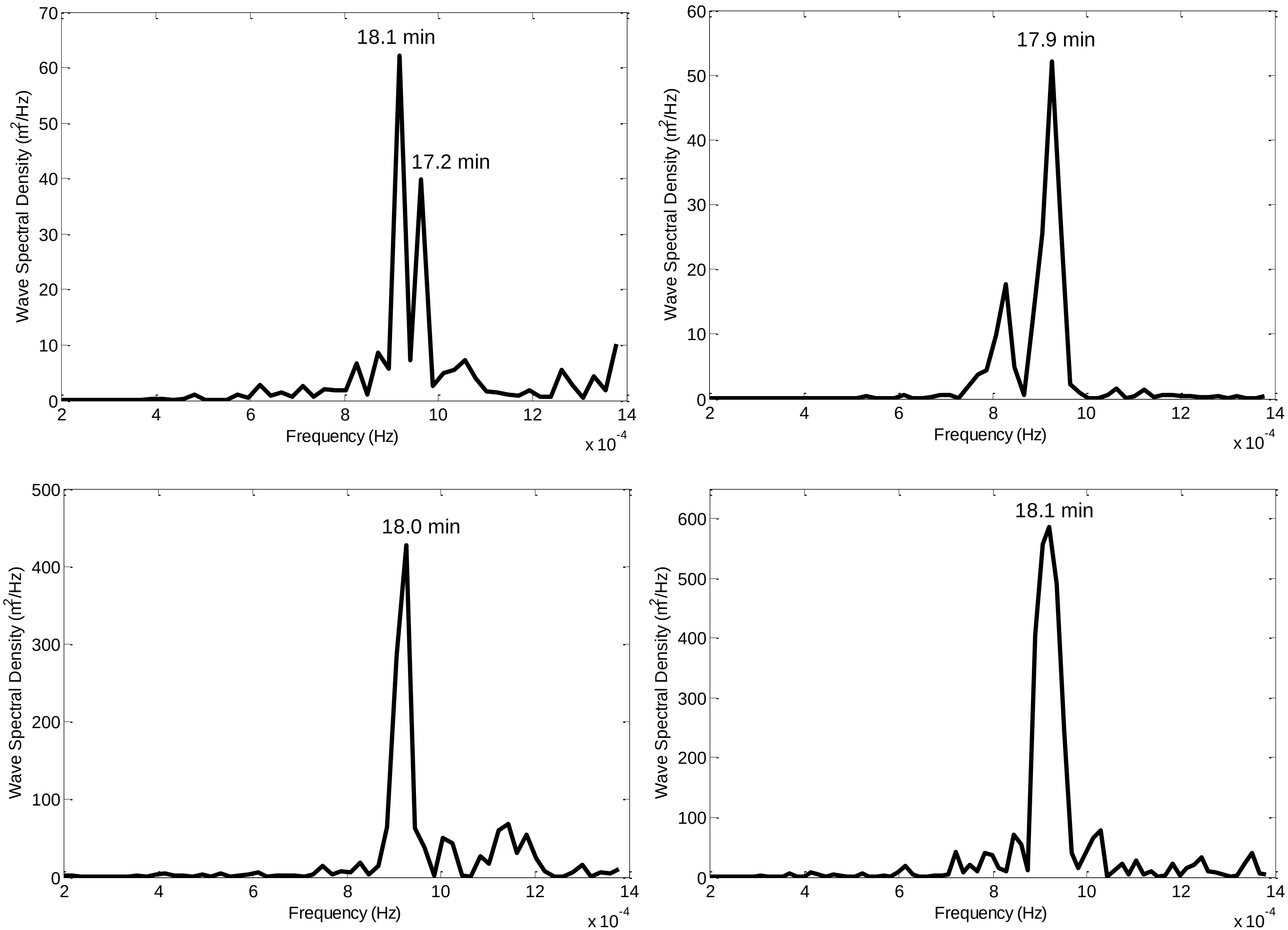


Google satellite map superimposed by the date and location of tsunami events selected for comparison with numerical results

Surface oscillation of Selected Events

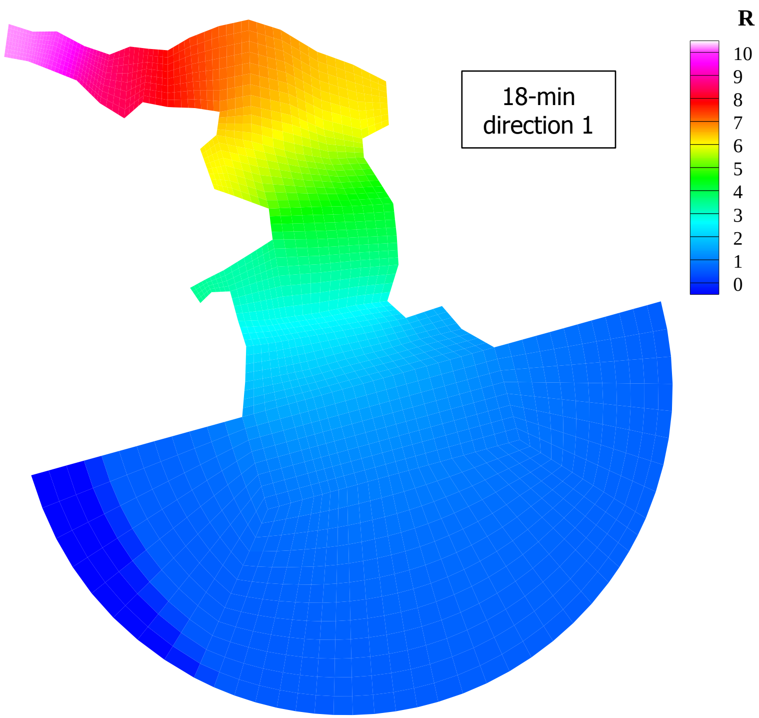


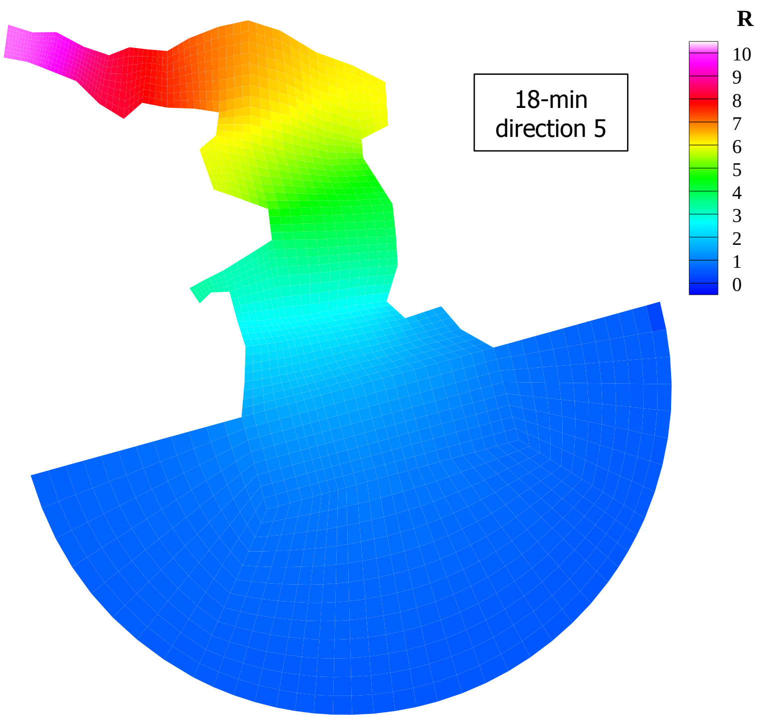
Spectral Density of Selected Events



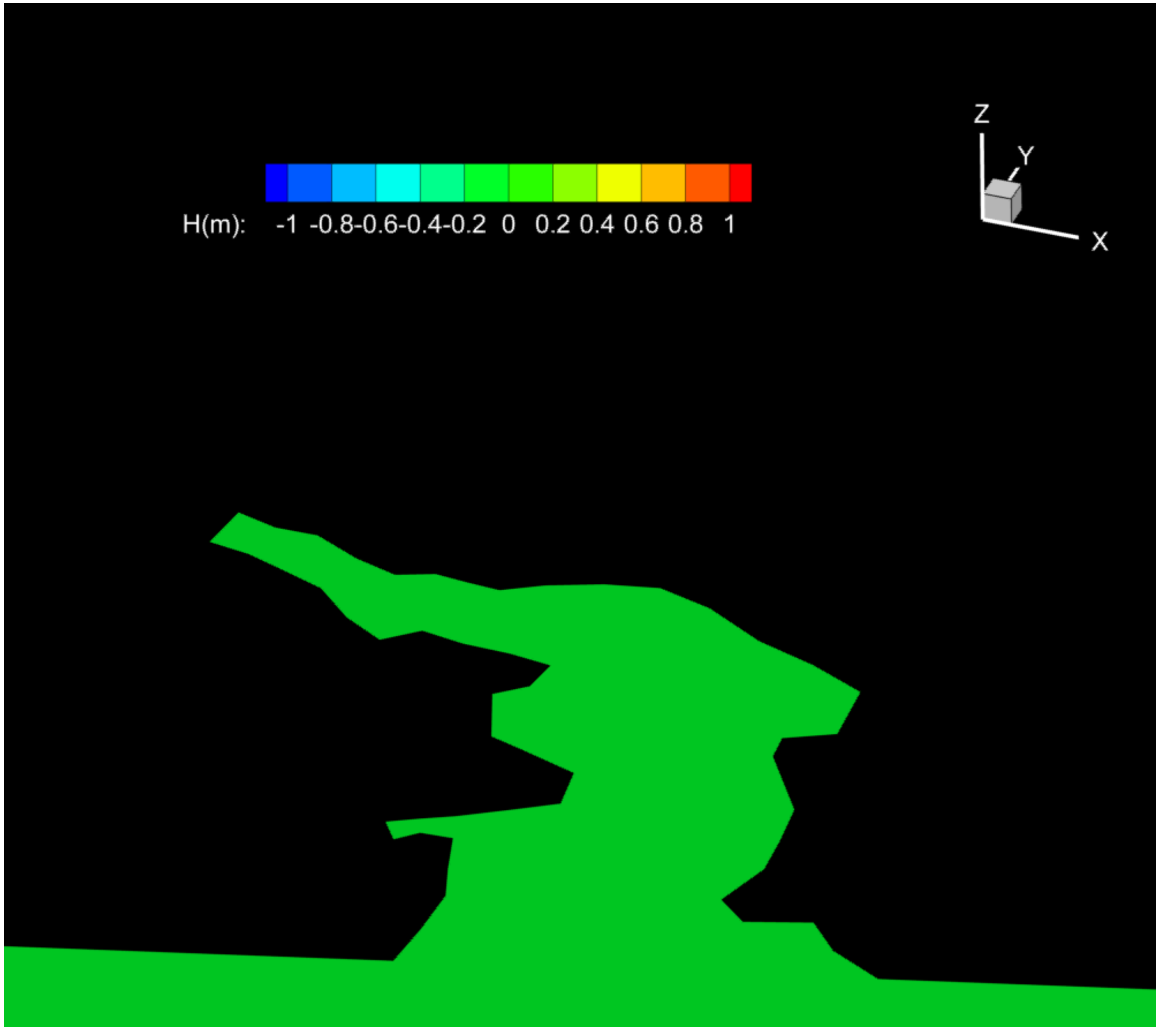
Simulation Results

- **Mode shape**
  - **Distribution of amplification factor inside harbor**
  - **A particular wave mode and incoming direction**
  - **Identical amplification distribution for 18-min wave from different directions**
  - **Maximum wave amplitude occurs at the most interior**



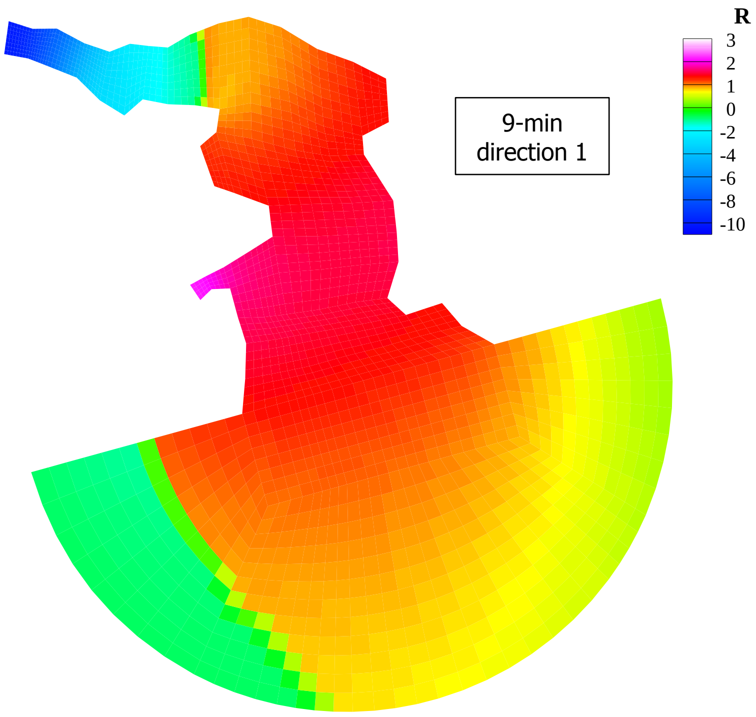


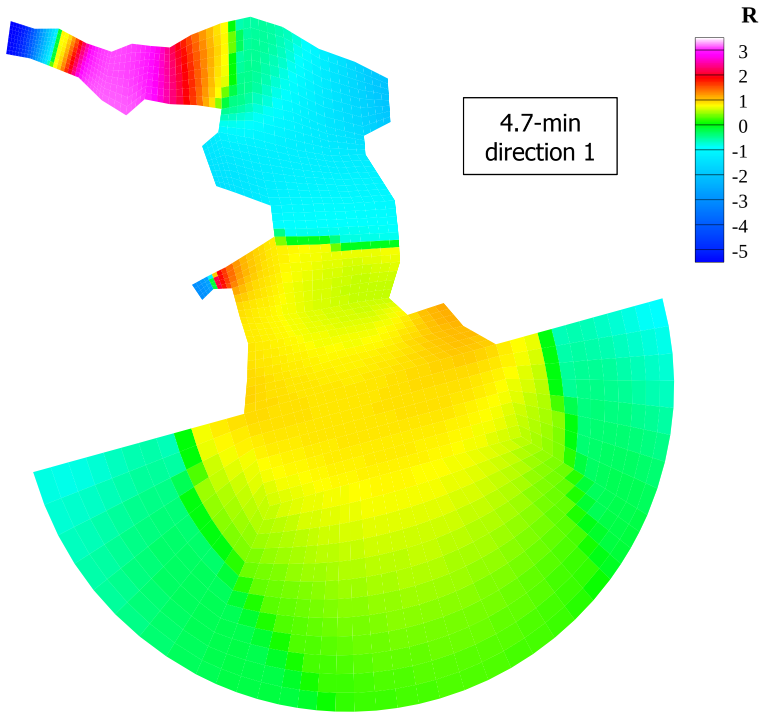
Fundamental mode oscillation



Simulation Results

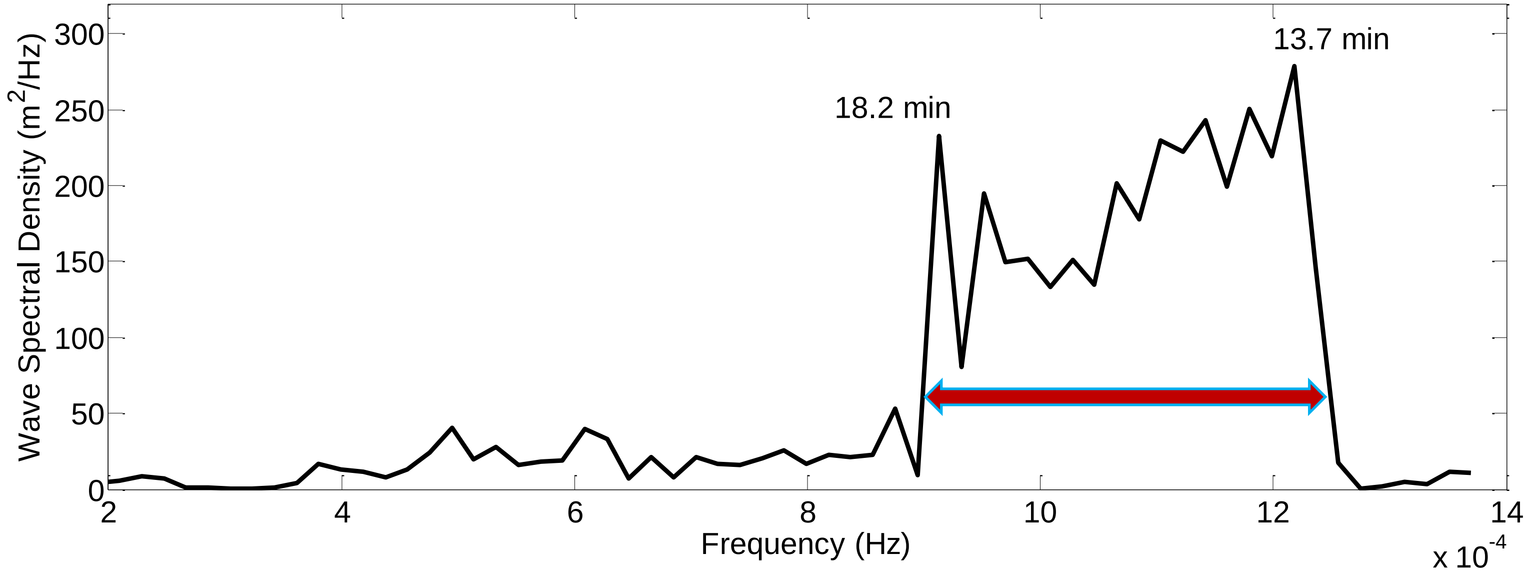
- Greater amplification factor for 18-min wave
- More crests and troughs for 4.7-min wave
- Shorter wave length for 9-min and 4.7-min wave
- Large wave amplitude at semi-enclosed areas





Further Discussion on the Near-field Tsunami

➢ **Spectral density of Samoa event's tidal measurement**



➢ **Significant wave energy on periods other than 18.2 min**

➢ **Hypothetical interpretation**

- **Waves appear at fundamental mode for far-field events**
- **Near-field tsunami**
- **Insufficient distance for the dispersion process**
- **Future researches are required, including tectonic and seismological information, dispersion process from epicenter, response inside harbor**

Conclusion

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Sep 29, 2009 Samoa tsunami

- The largest destructive tsunami ever in Samoa
- Led to numerous fatalities and economic losses
- Tsunami surges magnified inside Pago Pago Harbor

Frequency-based Simulation results

- Response curves: identification of the fundamental mode
- Mode shape: distribution of the amplification factor
- Verified by field measurements: local response of harbor

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Thank you
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Questions ?

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