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

Ziyi Huang[1] and Jiin-Jen Lee[1]

September 29, 2009 Samoa tsunami attacked Pago Pago Harbor, the major harbor in American Samoa. The original tsunami waves were greatly amplified when they propagated into the harbor, causing extensive inundations and thus fatalities and village damages. A frequency-based numerical model developed by Lee and Xing (2010) was utilized to investigate the mechanism of the amplification. The fundamental resonance mode of the harbor was identified as 18-minutes period based on the average water depth; the computed amplification factor, defined as the ratio of responded wave amplitude to incoming wave amplitude, was quite large on the fundamental mode at the interior of the harbor. Tidal gauge measurements of several other tsunami events in Pacific Ocean verified the simulation results and further corroborated the local response due to the topography and bathymetry of the harbor is responsible for the amplification of incoming waves. An unfounded speculation was discussed to interpret the distinguishing frequency distribution of wave spectral density in the Samoa tsunami event.

Keywords: incident tsunami waves; American Samoa; Pago Pago Harbor; frequency-based model; fundamental resonance mode; local response; mode shape; near-field tsunami

INTRODUCTION AND BACKGROUND

American Samoa, located at the South Pacific Ocean, is vulnerable to tsunamis generated from earthquakes at Tonga Trench only 200 kilometers away. The Tonga Trench, connecting the Australian plate and Pacific plate, has one of the highest levels of seismic activities over the world, with about 14 shakes of magnitude 7.5 or greater since 1900 at this deep groove (USGS 2009). However, no historical tsunami damage and casualty in American Samoa were reported on published materials before 2009 except vague information of June 26, 1917 earthquake (Okal et al. 2011).

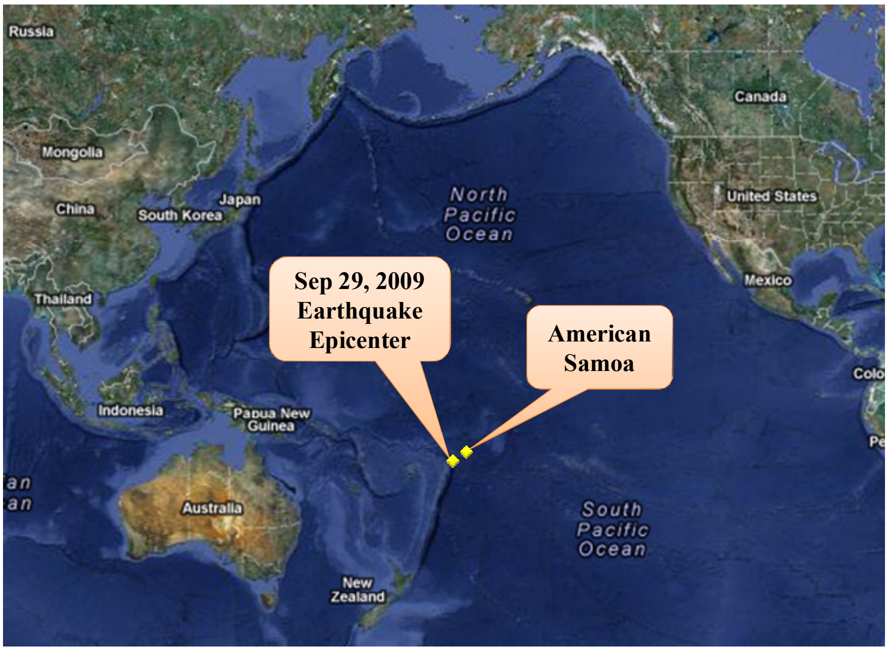

Figure 1. Locations of American Samoa at the South Pacific Ocean and the September 29, 2009 Samoa earthquake epicenter on a Google satellite map.

On September 29, 2009 a magnitude 8.1 earthquake doublet (Beavan et al. 2010; Lay et al. 2010) occurred near the northern end of the 3,000 kilometers long segment of the Australian-Pacific plate boundary. Figure 1 shows the locations of American Samoa and the earthquake epicenter. The earthquake triggered a massive tsunami that arrives at Pago Pago, the major harbor in Tutuila which is

[1] Department of Civil and Environmental Engineering, University of Southern California, 3620 South Vermont Avenue, Los Angeles, CA, 90089, USA

the main island of American Samoa, 20 minutes later. The maximum wave height based on measurements by the Pago Pago tidal gauge (U.S. National Ocean Service Station 1770000), which is a part of U.S. National Water Level Program, was reported to be 3.14 meters. Figure 2 presents the time series of wave amplitude of the tsunami surges.

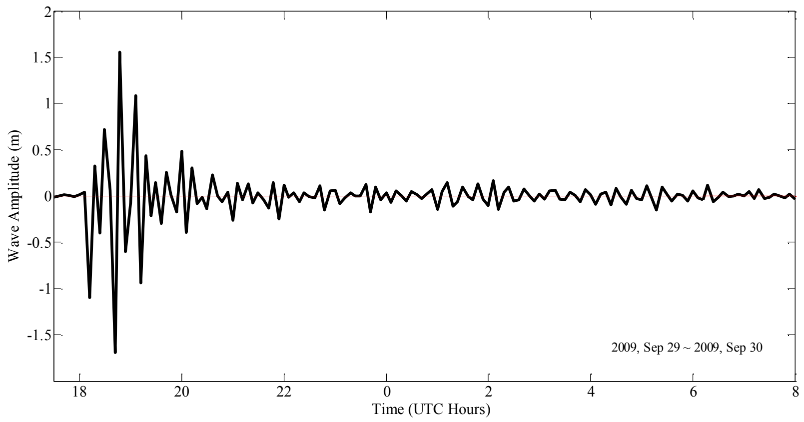

Figure 2. Time series of wave amplitude at the Pago Pago tidal gauge location for September 29, 2009 Samoa tsunami event (recorded by U.S. National Ocean Service Station 1770000).

According to an International Tsunami Survey Team, the flow depth, run-up, and inundation reached 3, 8, and 538 meters, respectively, at the most inside of the harbor (Okal et al. 2010). The tsunami belatedly advised by the Pacific Tsunami Warning Center induced at least 189 fatalities in Samoa Islands Region and 34 deaths at American Samoa, as well as damages of harbor facilities and village infrastructures. The tsunami also modified the deposit and landscape characteristics, and even in-ocean vegetation distribution along the shoreline of the harbor (Richmod et al. 2011).

Two bottom pressure-measuring buoys belonging to U.S. DART (Deep-ocean Assessment and Reporting of Tsunamis) program also recorded the water surface oscillations associated with this tsunami event. The buoy DART 51425 is located at about 800 kilometers NW of Pago Pago Harbor, while the buoy DART 51426 is at about 1,000 kilometers SES of Pago Pago Harbor. The DART records showed the maximum wave height outside Pago Pago Harbor was about only one-tenth of that inside the harbor. Figure 3 illustrates locations of the two buoys and Pago Pago Harbor and Figure 4 shows the surface oscillations of the two buoys.

The purpose of the present study is therefore to explore the response characteristics of Pago Pago Harbor which resulted in the amplification of the incoming tsunami waves. A frequency-based numerical model was constructed to simulate the comprehensive wave transformation processes inside the harbor. The outcome of this numerical model included the identification of the fundamental mode of Pago Pago Harbor and the amplification factor throughout the harbor at various wave modes. The fundamental mode resulted from the numerical study was verified by spectral analyses of tidal gauge measurements of several earthquake-generated tsunami events during 2006 ~ 2010.

NUMERICAL MODEL

We adopted the numerical model developed by Lee and Xing (2010). The model is capable of solving the Mild Slope Equation

$$\nabla \cdot \left(C C_g \nabla \phi \right) + \frac{C_g \omega^2}{C} \phi = 0 \tag{1}$$

originally derived by Berkhoff (1972) over arbitrary-shaped harbors of variable water depth. In the above equation, ϕ is the horizontal variation of the velocity potential which is the dependent variable. C and C_g is the wave celerity and group velocity respectively. ω is the angular wave frequency. The model is a hybrid one such that the solution of the Mild Slope Equation is obtained over the finite inner region and harbor while the Sommerfeld radiation condition is applied at the infinite outer region. Also, solutions of both regions should be matched at the semi-circle connecting boundary. By implementing

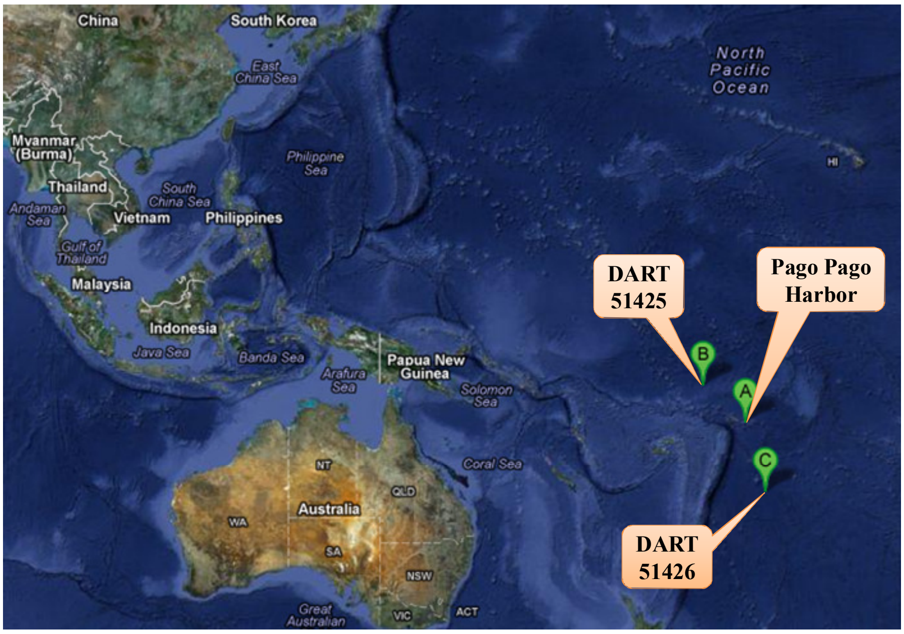

Figure 3. Illustration of locations of two buoys (DART 51425 & DART 51426) and Pago Pago Harbor on a Google satellite map.

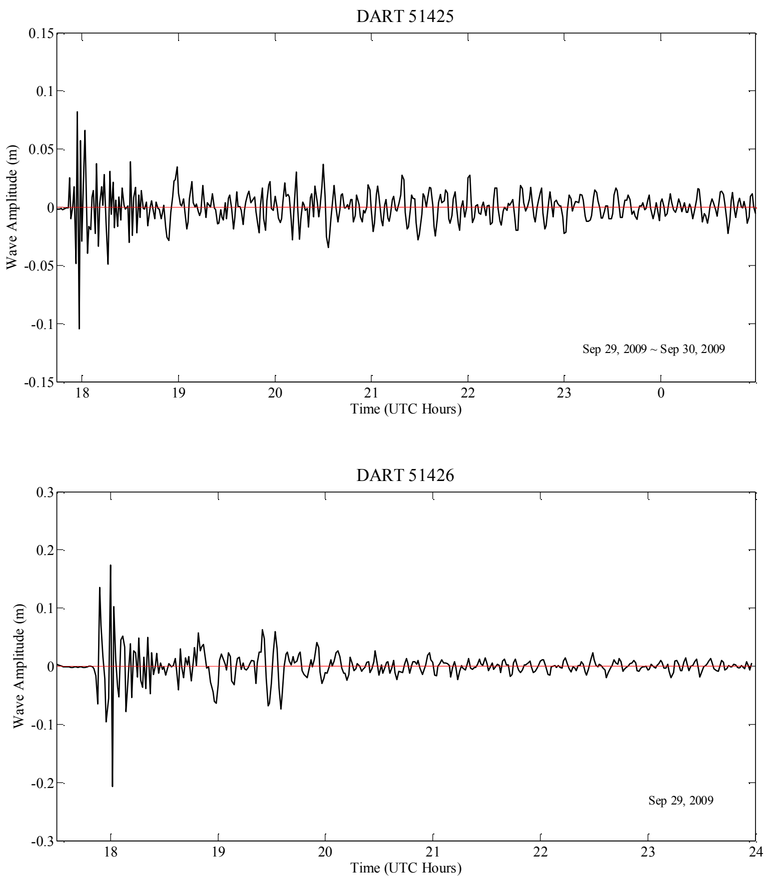

Figure 4. Time series of wave amplitude of two buoys (DART 51425 & DART 51426) for September 29, 2009 Samoa tsunami event.

the Mild Slope Equation, the effects of wave refraction and diffraction can be efficiently described. In addition, energy losses due to the partial reflection from the harbor boundary, wave transmission through breakwaters, flow separation at the harbor entrance, and bottom friction are incorporated into the model.

The finite element method, particularly the variational principle, is used to numerically solve the Mild Slope Equation inside the simulation domain for the Pago Pago Harbor. The whole computational domain is discretized to 1,984 elements, and 9 nodal points are assigned in each element. The discretization of the simulation domain is presented in Figure 5. The mathematical formulation by using the variational principle is written as

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

and

$$\delta\Phi = \lim_{\alpha\to 0}\frac{\Phi(\phi+\alpha\varepsilon)-\Phi(\phi)}{\alpha} = 0. \tag{3}$$

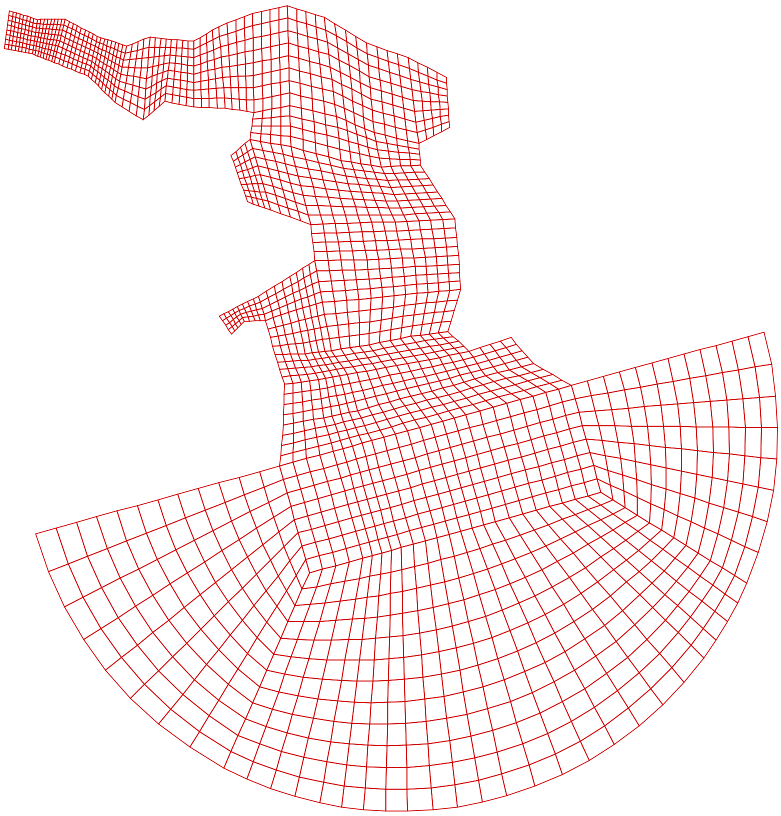

Figure 5. Disretization of the simulation domain for Pago Pago Harbor.

The dependent variable ϕ over each element is specified as the summation of that on 9 nodal points, with weighted by the shape function. Hence, a system of linear equations governing the dependent variable at all nodal points throughout the computational domain can be constructed and solved using suitable matrix algorithms, thereby leading to the solution of the dependent variable on each element.

SIMULATION RESULTS AND COMPARISON WITH FIELD MEASUREMENTS

Utilizing the numerical model, we are able to obtain response curves everywhere inside Pago Pago Harbor for any incoming wave direction. The response curves describe the amplification factor, which is the ratio of the responded wave amplitude to incoming wave amplitude, as a function of the dimensionless wavenumber which is a product of the wavenumber and the characteristic length of Pago Pago Harbor. The amplification factor is denoted by R while the dimensionless wave number is denoted by kl. There were eight incoming wave directions that were analyzed in this study presented in Figure 6.

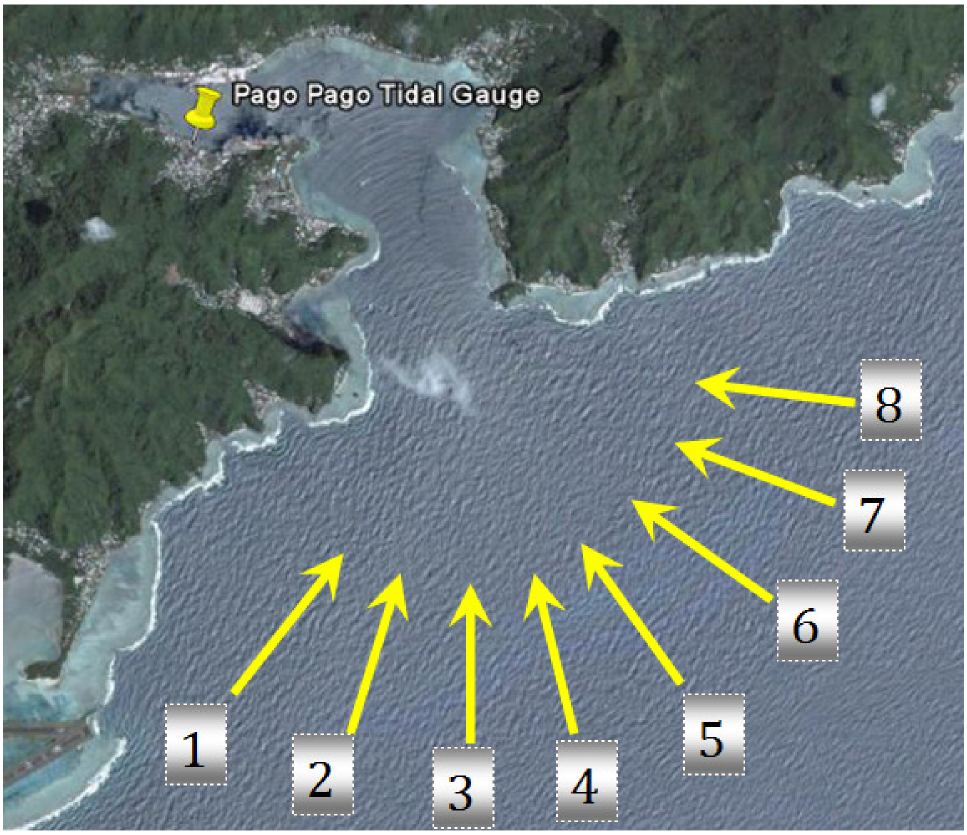

Figure 6. Illustration of eight incoming wave directions in the simulation of Pago Pago Harbor response characteristics. The location of Pago Pago tidal gauge is indicated.

The simulated response curves at the Pago Pago tidal gauge location for eight incoming wave directions are presented in Figure 7. It is very clear that the amplification factor is the largest at the dimensionless wavenumber of 2 for all incoming wave directions. This implies the dominant wave period of Pago Pago Harbor is 18 minutes based on the average water depth. Therefore, 18-minutes period is identified as the fundamental resonance mode of Pago Pago Harbor, as suggested by Roeber et al. (2010). Moreover, the amplification factor associated with the fundamental mode is as large as 9. Hence the considerable difference between the wave amplitude recorded by the Pago Pago tidal gauge and two buoys outside the harbor can be explained. It also can be seen that the amplification factor is the same at the fundamental mode for all incoming wave directions. The other notable resonance mode of the harbor is 4.7 minutes shown by Figure 7. Unlike the fundamental mode, the amplification factor on this mode varies with different directions.

In order to verify the resonance mode of Pago Pago Harbor derived from the numerical model, spectral analyses of tidal gauge measurements of four earthquake-generated tsunami events in Pacific Ocean were performed. The date and earthquake epicenter location of those events are illustrated by Figure 8. The surface oscillation time series after eliminating the average water depth at the Pago Pago tidal gauge location for those events are presented in Figure 9. The corresponding results of spectral analyses are shown in Figure 10. The spectral analyses were implemented through calculating the discrete Fourier transform (DFT) of the time series presented in Figure 9. As such, the wave spectral density, representing the modulus square of the Fourier transform, can be described as a function of frequency. The results of spectral analyses clearly show the dominant period of all four events is very close to 18 minutes, even though the wave amplitude of them is different. Since the smallest time step

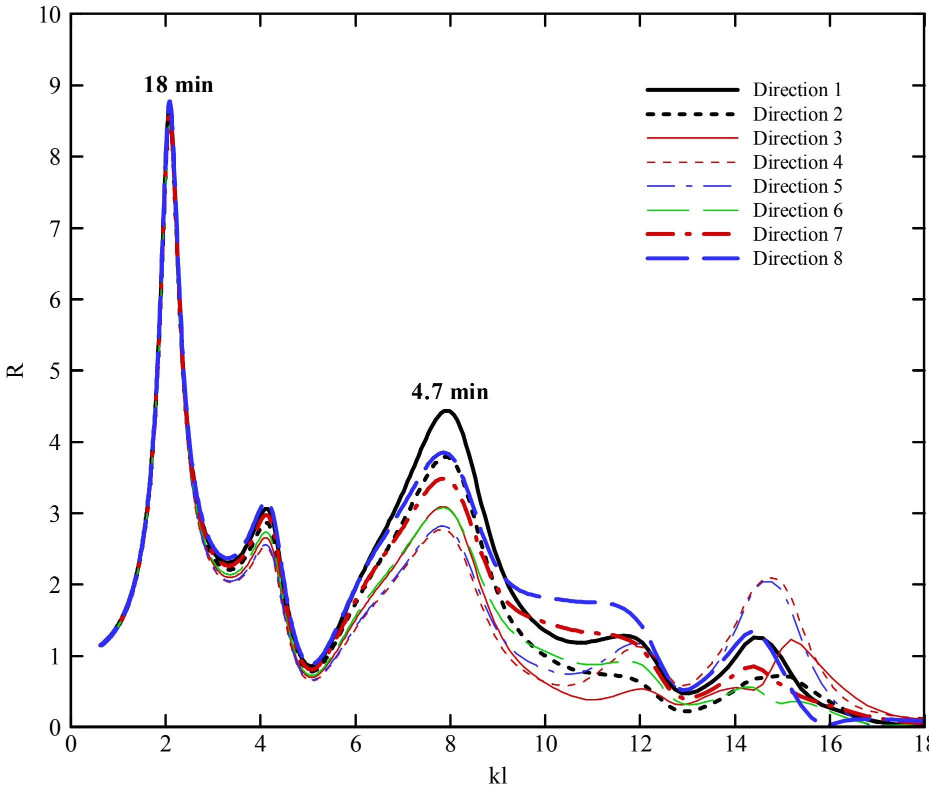

Figure 7. Simulated response curves at the Pago Pago tidal gauge location for eight incoming wave directions. Two wave modes with large amplification factor including the fundamental wave mode are indicated.

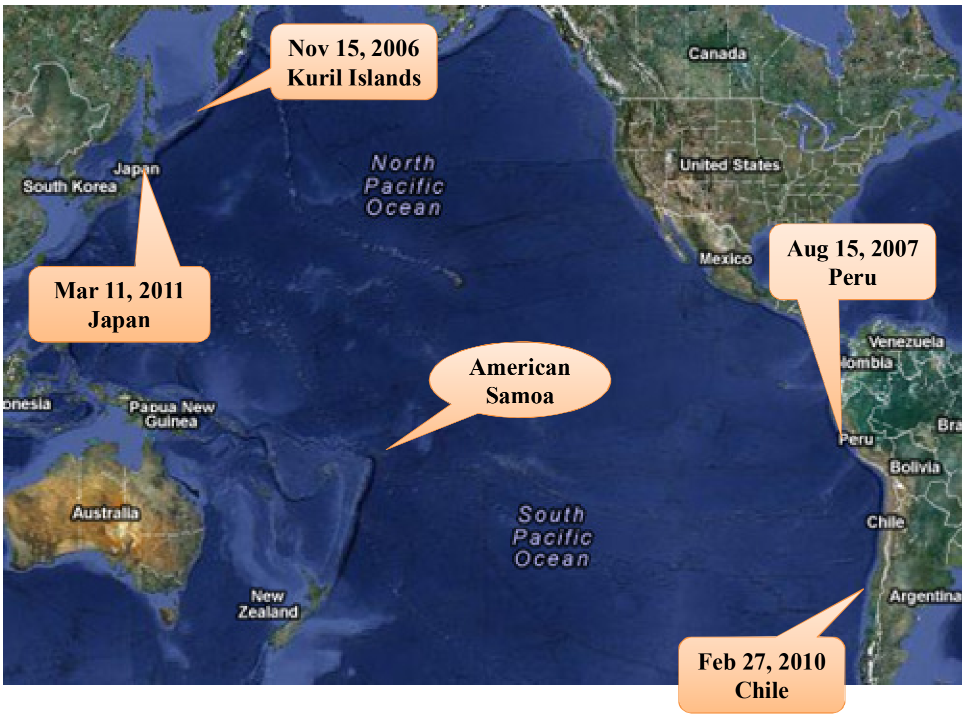

Figure 8. Google satellite map superimposed by the date and earthquake epicenter location of four earthquake-generated tsunami events selected for the comparison with the numerical results. The location of American Samoa is also shown.

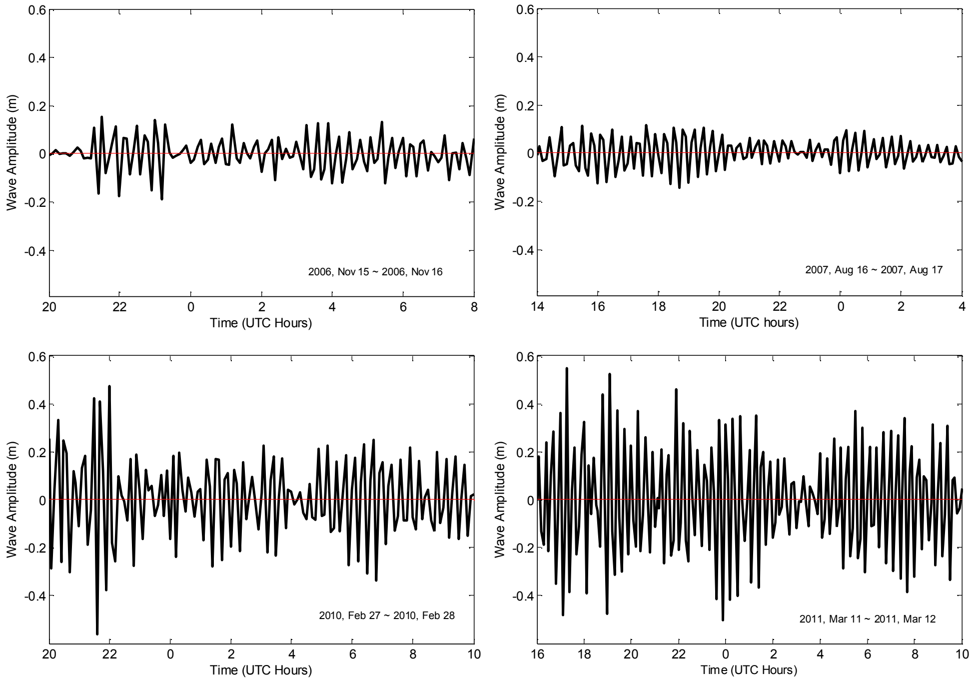

Figure 9. Time series of surface oscillations at the Pago Pago tidal gauge location for the four tsunami events in Pacific Ocean.

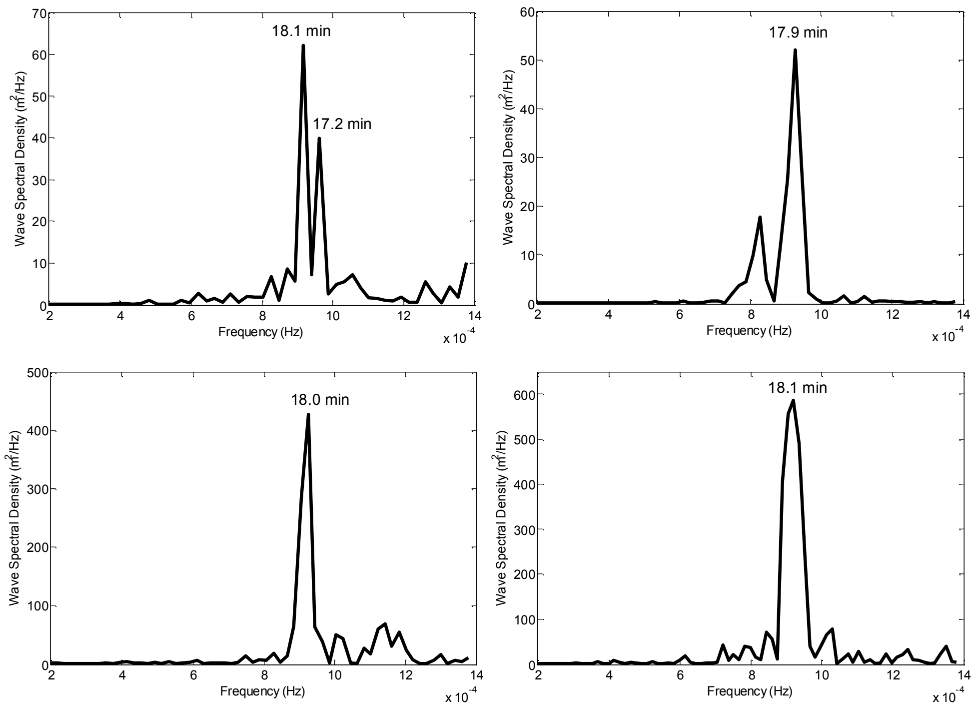

Figure 10. Corresponding spectral analysis results of the time series shown in Figure 9. The dominant wave period(s) for each time series is(are) indicated.

provided by the tidal gauge measurements is 6 minutes, the other mode of 4.7 minutes detected from the numerical model could not be verified.

With the response features at the tidal gauge location of Pago Pago Harbor specified and verified, the next interesting topic is how the amplification factor distributes throughout the harbor. The distribution of the amplification factor inside a harbor is known as mode shape. A particular wave mode and incoming wave direction should be selected so as to obtain the numerical result of a mode shape. Figure 11, Figure 12, and Figure 13 show three examples of the mode shape of Pago Pago Harbor. The mode shape presented in Figure 11 and Figure 12 were resulted from the 18-minutes waves coming from the direction 1 and direction 5, separately. The direction 1 is roughly the incoming direction of September 29, 2009 Samoa tsunami surges. The mode shape presented in Figure 13 was resulted from the 4.7-minutes waves coming from the direction 1. The two mode shapes with 18-minutes waves but different directions are almost identical. Nevertheless, the distribution of the amplification factor is quite different between the 18-minutes and 4.7-minutes wave mode shapes. The maximum wave amplitude is greater for the 18-minutes wave mode shapes, as indicated by the response curves. Also in the 18-minutes wave mode shapes, the amplification factor is nearly at the same sign (positive) over the simulation domain whereas the amplification factor in the 4.7-minutes wave mode shape has both positive and negative values. This indicates that the 4.7-minutes waves result in both wave crests and troughs inside the harbor while the 18-minutes waves, with greater wavelength, lead to only either crest or trough. Yet the amplification factor reaches the maximum absolute value at the most inside of the harbor, in all mode shapes.

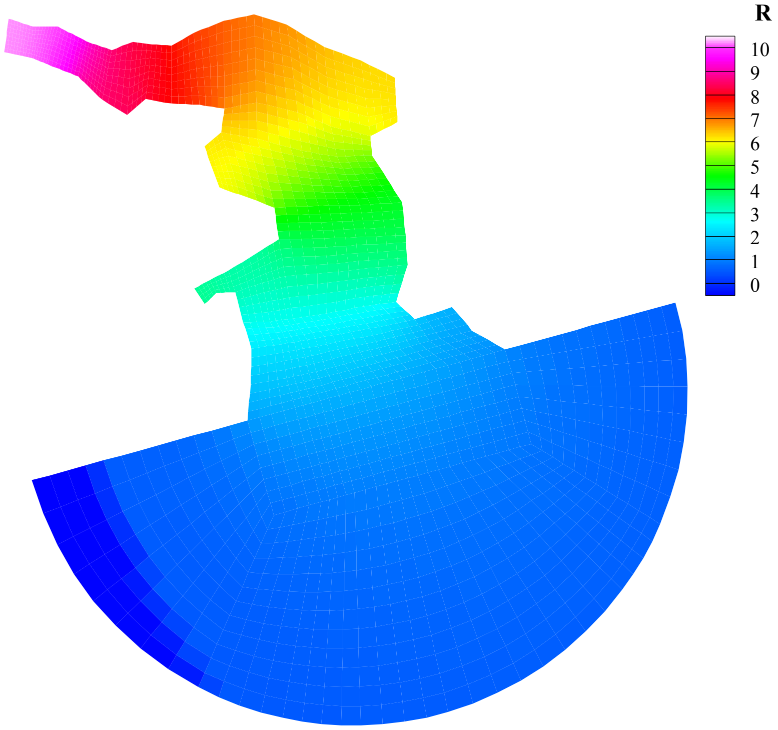

Figure 11. The numerical result of a mode shape of Pago Pago Harbor. The incoming waves have a period of 18 minutes and come from direction 1.

FURTHER DISCUSSION ON THE NEAR-FIELD TSUNAMI

The wave spectral density-frequency plane corresponding to the time series shown by Figure 2 for the September 29, 2009 Samoa tsunami event is presented by Figure 14. Besides the dominant period of 18.2 minutes close to what has been predicted by the numerical model, there is significant wave energy on other periods less than 18.2 minutes. This natural phenomenon is distinct from those tidal gauge measurements in previous tsunami events.

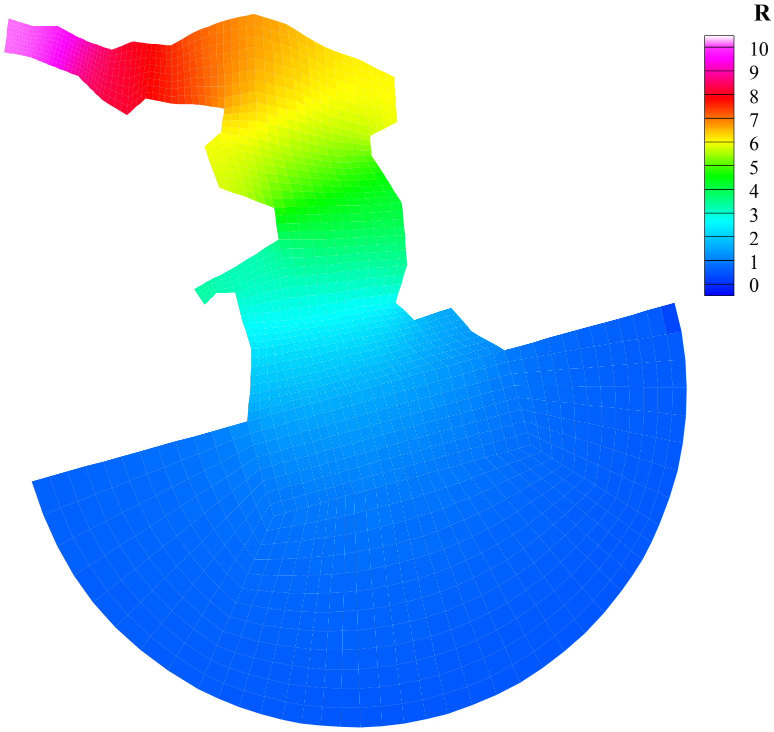

Figure 12. The numerical result of a mode shape of Pago Pago Harbor. The incoming waves have a period of 18 minutes and come from direction 5.

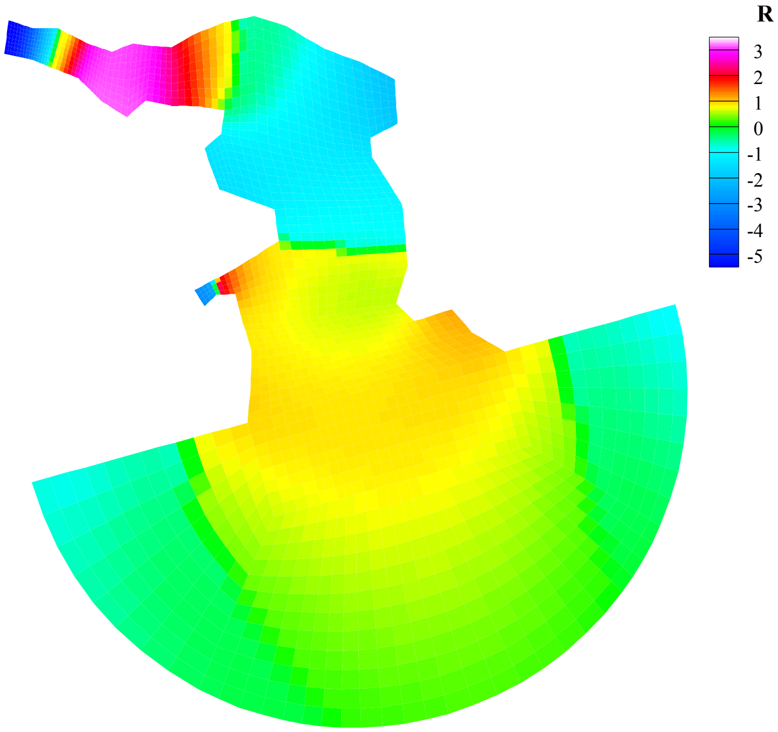

Figure 13. The numerical result of a mode shape of Pago Pago Harbor. The incoming waves have a period of 4.7 minutes and come from direction 1.

Without any virtual research, a speculation was proposed so as to interpret this natural phenomenon. The earthquake epicenter for this event is merely 200 kilometers away from American Samoa. Hence this event can be classified as a near-field tsunami. Those previous events illustrated in Figure 8 are classified as far-field tsunamis, since the origin of the earthquakes are distant from American Samoa. When water surface displacement is caused by the earthquake, the initial hump or dip comprises waves with numerous different modes. When the hump or dip propagates, those waves will disperse due to the difference of phase velocity. The wave dispersion process, however, requires a sufficient distance. Consequently, the tsunami waves in September 29, 2009 Samoa event had not dispersed out when they hit Pago Pago Harbor because of a short propagation distance. Those waves with modes other than 18-minutes period were agitated as "accompanying waves" of the 18-minutes period wave.

Obviously, the validation of above hypothesis requires future researches related to the tectonic and seismological information, complete wave dispersion process from the earthquake epicenter, and finally response process inside the harbor.

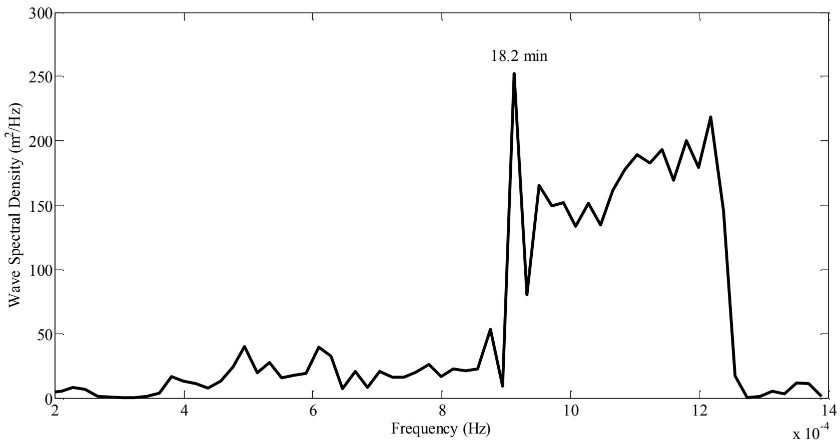

Figure 14. Spectral analysis result of surface oscillation time series at the Pago Pago tidal gauge location in September 29, 2009 Samoa tsunami event.

CONCLUSIONS

This study was motivated by the September 29, 2009 Samoa earthquake-generated tsunami event. In order to have a better understanding on the response characteristics of Pago Pago Harbor that caused the amplification of incoming tsunami waves, a frequency-based numerical model was established. As solving the Mild Slope Equation to describe processes of wave refraction and diffraction, the model also incorporated energy losses induced by the partial boundary reflection, wave transmission through breakwaters, entrance separation, and bottom friction.

The numerical simulation reveals the fundamental resonance mode of Pago Pago Harbor is 18-minutes period. Waves with the fundamental mode will be greatly amplified when they propagate into the harbor. Hence the large difference between the wave amplitude recorded inside and outside the harbor in September 29, 2009 Samoa tsunami event can be explained. This response feature is attributed to the particular topography and bathymetry of Pago Pago Harbor. The harbor responses to waves with other modes are also predictable. Tsunami surges originated from different locations in different events appear at the fundamental mode after the local response of the harbor, as evidenced by tidal gauge measurements. The maximum wave amplitude occurs at the most inside of the harbor for whatever wave mode and direction.

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