MODELING TSUNAMI FLOODING OF HIKO, HAWAII

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ABSTRACT

The interaction of tsunami waves with Hilo Bay and harbor is being numerically modeled for specific historical events. The modeling is performed using the SWAN code which solves the nonlinear long wave equations.

The 1964, 1960 and 1964 tsunamis are being studied. The tsunami generation and propagation to the Hawaiian Islands were modeled using a 20 minute grid for the North Pacific or for the entire Pacific Ocean. The wave arriving in the region of the Hawaiian Islands was then modeled using a 5 minute grid to follow the wave to the mouth of Hilo Bay. The wave arriving at the mouth of Hilo Bay was then modeled using a 100 meter grid of Hilo Bay, harbor and town. Each grid had a friction coefficient to describe the local roughness (trees, grass, buildings, coral, etc.). The models gave approximately the observed maximum areas of flooding.

The observed levels of flooding at individual locations was not well described by the 100 meter grid, so a 10 meter grid of Hilo was developed to resolve the flooding at individual locations and around large buildings.

The high resolution 10 meter grid of Hilo was used to model the flooding around Hilo Theater by the 1960 tsunami wave. The Hilo Theater was located near the shore, in flat and unobstructed terrain 2.7 meters above sea level. The tsunami flooded level reached 9.5 meters at the seaward side and 6.7 meters at the rear of the Hilo Theater. The third bore-like wave arriving at the harbor entrance in the 100 meter grid model was used as the tsunami source for the high resolution study of flooding around Hilo Theater.

The maximum level of flooding observed at Hilo Theater was reproduced by the high resolution numerical model.

THE NUMERICAL MODEL

The tsunami waves and their interaction with the study site topography were numerically modeled using the SWAN code which solves the shallow water long wave equations. It is described in detail in the monograph Numerical Modeling of Water Waves by Mader (1988).

The long wave equations solved by the SWAN code are

\[ \frac{\partial U_x}{\partial t} + U_x \frac{\partial U_x}{\partial x} + U_y \frac{\partial U_x}{\partial y} + g \frac{\partial a}{\partial x} = F U_x + F^x - \frac{U_x(U_x^2 + U_y^2)^{1/2}}{C^2(D + H - R)} \]

\[ \frac{\partial U_y}{\partial t} + U_x \frac{\partial U_y}{\partial x} + U_y \frac{\partial U_y}{\partial y} + g \frac{\partial a}{\partial y} = F U_y + F^y - \frac{U_y(U_x^2 + U_y^2)^{1/2}}{C^2(D + H - R)} \]
\[
\frac{\partial H}{\partial t} + \frac{\partial (D + H - R) U_x}{\partial x} + \frac{\partial (D + H - R) U_y}{\partial y} - \frac{\partial R}{\partial t} = 0,
\]

where

- \( U_x \) = velocity in \( x \) direction (i index)
- \( U_y \) = velocity in \( y \) direction (j index)
- \( g \) = gravitational acceleration
- \( t \) = time
- \( H \) = wave height above mean water level
- \( R \) = bottom motion
- \( F \) = Coriolis parameter
- \( C \) = coefficient of DeChzy for bottom stress
- \( F_{wind}, F_{bar} \) = forcing functions of wind stress and barometric pressure
- \( D \) = depth.

As described in the monograph, the SWAN code has been used to study the interaction of tsunami waves with continental slopes, shelves, bays and harbors such as Hilo harbor.

The SWAN code has been used to study the interaction of tsunami waves with continental slopes and shelves, as described in Mader (1974). Comparison with two-dimensional Navier-Stokes calculations of the same problems showed similar results, except for short wavelength tsunami.

The SWAN code was used to model the effects of tides on the Musi-Upan estuaries, South Sumatra, Indonesia, by Hadi (1985). The computed tide and water discharge were in good agreement with experimental data.

The SWAN code was used to model the large waves that were observed to occur inside Waianae harbor under high surf conditions in Mader and Lukas, (1985). These waves have broken moorings of boats and moved boats up the boat-loading ramps into the parking lot. The numerical model was able to reproduce actual wave measurements. The SWAN code was used to evaluate various proposals for decreasing the amplitude of the waves inside the harbor. From the calculated results, it was determined that a significant decrease of the waves inside the harbor could be achieved by decreasing the harbor entrance depth. Engineering companies used these results to support their recommendations for improving the design of the harbor.

The effect of the shape of a harbor cut through a reef on mitigating waves from the deep ocean was studied using the SWAN code in Mader, et al. (1986). A significant amount of the wave energy was dissipated over the reef regardless of the design of the harbor. The reef decreased the wave height by a factor of 3. The wave height at the shore can be further decreased by another factor of 2 by a V-shaped or parabolic bottom shape.

Other examples of applications of the SWAN code are presented in Mader and Lukas (1984). They include the wave motion resulting from tsunami waves interacting with a circular and triangular island surrounded by a 1/15 continental slope and from surface deformations near the island. The effects of a surface deformation in the Sea of Japan similar to that of the May 1983 tsunami was modeled. The interaction of a tsunami wave with Hilo Bay was described.
The SWAN code was used to model the effect of wind and tsunami waves on Mauna Lani Bay, Oahu as described in the State Department of Transportation draft (1998). The calculated wave behavior at any location in the bay was a function of complicated and time varying wave reflections and interactions.

The SWAN code was used to model the interaction of waves with a site near the Mauna Lani Resort on the South Kohala Coast on the Island of Hawaii in Mader (1990a). The calculated results agreed with the results obtained using the procedures developed and applied for flood insurance purposes by the U.S. Army Corps of Engineers and the recent JIMAR study at the University of Hawaii of tsunami evacuation zones for the site.

The 1987-88 Alaskan Bight tsunamis were modeled in Gonzalez, et al. (1990) using the SWAN code. The deep sea pressure gauge measurements for those tsunamis could be described using realistic source models for the tsunamis.

A numerical study of effect of the shallow water approximation on tsunami flooding was performed in Mader (1990b). Calculations using the full Navier-Stokes model were compared to SWAN code calculations.

The 1946 and 1960 tsunamis were caused by Alaskan earthquakes and the 1960 tsunami by an earthquake in Chile. The 1946 and 1960 tsunamis resulted in extensive flooding of Hilo while the 1964 tsunami caused limited flooding.

The tsunami generation and propagation to the Hawaiian Islands were modeled using a 20 minute grid for the North Pacific or for the entire Pacific Ocean (Mader and Curtis, 1981). The wave arriving in the region of the Hawaiian Islands was then modeled using a 5 minute grid to follow the wave to the mouth of Hilo Bay. The wave arriving at the mouth of Hilo Bay was then modeled using a 100 meter grid of Hilo Bay, harbor and town. Each grid had a friction coefficient to describe the local roughness (trees, grass, buildings, coral, etc.). The use of computational grids of different grid sizes over different geographical domains to model tsunami is similar to that reported by Kowalik and Whitmore (1981).

The models gave approximately the observed maximum areas of flooding. The large amount of flooding from the 7.6 magnitude 1946 Alaskan earthquake and small amount of flooding from the 8.5 magnitude 1964 Alaskan earthquake were reproduced by the numerical models. This demonstrated the large effect of wave directionality and the necessity of modeling the entire process of tsunami generation, propagation and flooding for each event.

The observed levels of flooding at individual locations was not well described by the 100 meter grid, so a 10 meter grid of Hilo was developed to resolve the flooding at individual locations and around large buildings.

APPLICATION OF THE NUMERICAL MODEL TO INUNDATION OF HILO THEATER

The high resolution 10 meter grid of Hilo was used to model the flooding around Hilo Theater by the 1960 tsunami wave. The Hilo Theater was located near the shore, in flat and unobstructed terrain 2.7 meters above sea level. The tsunami flooded level reached 8.5 meters at the seaward side and 6.7 meters at the rear of the Hilo Theater. A photograph of the Hilo Theater after the May 1960 tsunami is shown in Figure 1.
Figure 1. The Hilo Theater after the 1960 tsunami. The solid water water line is 26 to 22 feet above sea level. The building is located 9 feet above sea level. The inset shows the location of the theater relative to the shore line. The photograph is taken from the parking lot on the west side of the building. Note the four men standing on the right side of the photograph.

The grid was 240 by 240 cells of 10 meters on a side. The time step was 0.2 second. The theater building was described by 3 by 6 cells with a height of 11.9 meters. The third wave was a bore-like wave inside the harbor entrance 3 meter high from the North-West. The initial water level was 1 meter lower than the normal sea level to approximate the second wave recession that occurred before the third wave arrived. The wave had a period of 1500 seconds with the first rise occurring in 60 seconds to approximate the bore-like wave.

The surface level of the water, land and theater building is shown at various times in Figure 2. The contour interval is one meter. The building is 11.5 meters high.

The height of the water at locations near the harbor entrance and near the building as a function of time are shown in Figure 3. The front of the theater building (Location 5) was flooded to the 8.5 meter level and the rear of the building (Location 6) to the 8.0 meter level. The rear of the building was calculated to flood to a higher level than observed.

The inundation of the town of Hilo is shown in Figure 4. The inundation continues after the maximum flooding of the theater occurs. The maximum level of inundation calculated is similar to that observed from the 1960 tsunami.

The maximum levels of flooding observed at Hilo Theater was reproduced by the high resolution numerical model using a realistic description for the 1960 tsunami wave.
Figure 2. The surface level of the water, land and theater building is shown at various times. The contour interval is one meter. The building is 11.9 meters high. The initial water surface is 1 meter below normal sea level to approximate the second wave withdrawal.
Figure 3. The height of the water at locations near the harbor entrance and near the building as a function of time are shown. Location 1 is in the ocean near the harbor entrance, Locations 5 and 6 are on the front and back of the side of the theater as shown in Figure 1.
REFERENCES


