Surges along the Honolulu coast from the 2011 Tohoku tsunami

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[1] The 2011 Tohoku earthquake of Mw 9.0 generated a massive tsunami that devastated communities along the northeastern Japan coasts and damaged coastal infrastructure across the Pacific. A nearshore observatory in Honolulu recorded clear signals of the surface elevation and flow velocity at 12 m water depth, where adjacent harbors and marinas experienced persistent hazardous surges. The measurements allow validation of numerical model results, which in turn reveal complex oscillation and flow patterns due to resonance over the insular shelf and reef system. The computed wave amplitude and flow speed increase from 0.4 m and 0.1 m/s at the 100-m depth contour to 1.6 m at the shore and 3.5 m/s near an entrance to Honolulu Harbor. Although resonance of the tsunami along the Hawaiian Islands produced the strongest surface signal at 42 min period, standing waves with periods 16 min or shorter, which are able to form nodes on the reefs, are the main driving force of the nearshore currents. Citation: Yamazaki, Y., K. F. Cheung, G. Pawlak, and T. Lay (2012), Surges along the Honolulu coast from the 2011 Tohoku tsunami, Geophys. Res. Lett., 39, L09604, doi:10.1029/2012GL051624.

1. Introduction

[2] The Tohoku earthquake of Mw 9.0 ruptured the subduction zone megathrust fault offshore of northeastern Honshu on March 11, 2011, generating strong shaking across the region and a devastating near-field tsunami with 39.75 m of runup [Mori et al., 2011]. Figure 1a shows the locations of the epicenter and coastal and deep-ocean buoys that recorded the tsunami. The 1.75 m amplitude registered at DART 21418, nearest to Tohoku, triggered warnings across the Pacific. The waves reached Hawaii at 3:00 am local time, 7 hours after the earthquake, and caused localized damage across the state. The insular slope and shelf complex depicted in Figures 1b and 1c is prone to trapping of tsunami energy [Bricker et al., 2007; Munger and Cheung, 2008]. The Pacific Tsunami Warning Center maintained the warning for Hawaii until 7:31 am, when the wave amplitude had reduced to less than 1 m at tide gauges around the islands. The advisory remained in effect until 11:26 a.m., when wave amplitude fell below 0.5 m.

[3] Honolulu Harbor and adjacent marinas, despite location in sheltered basins dredged from the reefs as shown in Figure 1d, experienced strong currents and oscillations. The tsunami damaged dock facilities and destroyed over 200 small boats in Keehi Lagoon Marina. The hazardous surges continued through the morning with amplitudes of 3 ft (~1 m), flow speeds of ~3–4 knots, and a period of 45 min observed at the nearby University of Hawaii Marine Center. The US Coast Guard deployed a vessel at the entrance of Keehi Lagoon to prevent evacuated boaters from returning prematurely. The observed surges diminished to less than 1 ft (~0.3 m) amplitude and ~1–2 knots speed with a period of 15 min in the evening. The persistent surges and the change of the oscillation period from 45 to 15 min are indicative of resonance at regional and coastal scales. In addition, the shallow reef system along the Honolulu coast might play a role in the localized impacts as observed on Tutuila during the 2009 Samoa tsunami event [Roebel et al., 2010b].

[4] The Kilo Nalu Observatory of the University of Hawaii provides real-time measurements of ocean conditions on the Honolulu coast for scientific research and environmental monitoring [Pawlak et al., 2009]. An upward-looking RDI 1200kHz Sentinel ADCP and a pressure gauge at 12 m depth (21.288°N, 157.865°W) atop a fringing reef recorded clear signals of the flow velocity and surface elevation associated with the 2011 Tohoku tsunami suitable for model validation. Yamazaki et al. [2011b] examined the source faulting distribution and seafloor deformation through modeling of the near-field tsunami. The present study extends the modeling work to include the North Pacific with a focus on the surge conditions on the Honolulu coast. The extensive DART measurements across the Pacific and high-quality nearshore data at Kilo Nalu allow validation of the modeled tsunami at the basin and coastal scales. The validated data enables a careful examination of the behavior and impact of the tsunami on harbors and marinas along the Honolulu coast.

2. Modeling and Validation

[5] Extensive seismic networks, geodetic instruments, and water-level stations provided unprecedented datasets of the 2011 Tohoku earthquake and tsunami for scientific research. We utilize NEOWAVE (Non-hydrostatic Evolution of Ocean Wave) to model the tsunami from its generation by earthquake rupture to the surge conditions along the Honolulu coast. The staggered finite difference model builds on the nonlinear shallow-water equations with a vertical velocity term to account for weakly-dispersive waves and a momentum conservation scheme to describe bores or hydraulic jumps [Yamazaki et al., 2009, 2011a]. Figures 1a–1d show the four levels of two-way nested grids used to capture physical processes with increasing resolution toward Honolulu. The level-1 grid models propagation of the tsunami across the North Pacific at 2-arcmin (~4000 m) resolution, while the level-2 and 3 grids describe its transformation around the Hawaiian Islands and Oahu at 24 and 3 arcsec (~720 and
The level-4 grid, which covers the Honolulu coast at 0.3 arcsec (≈9 m), provides adequate resolution of the reefs, channels, and coastlines for computation of the surge conditions. The digital elevation model includes ETOPO1, multibeam, and LiDAR data at 1 arcmin (≈1800 m), 50 m, and 3 m resolution, respectively.

Figure 1e shows a slip distribution inferred from finite-fault inversion of the seismic P waves and forward modeling of the near-field tsunami records at GPS and wave buoys along northeast Japan coasts [Yamazaki et al., 2011b]. The model comprises 20 × 20 km² subfaults with strike and dip angles of 192° and 12° and utilizes the epicenter (38.107°N, 142.916°E) and origin time 14:46:18.14 UTC from Zhao et al. [2011]. The rupture lasted for 150 sec with 70% of its energy released in the first 100 sec. The 62-m slip obtained near the trench is consistent with findings from geodetic records [e.g., Ito et al., 2011; Simons et al., 2011].

Implementation of the finite-fault solution in the planar fault model of Okada [1985] provides the time history of seafloor deformation. The vertical velocity term in NEOWAVE facilitates modeling of tsunami generation and transfer of kinetic energy from the seafloor deformation. Figure 1f shows a distinct pattern of uplift on the continental margin and subsidence on the shelf. The sensitivity analysis of Yamazaki et al. [2011b] indicates that the large vertical seafloor displacement along the trench is responsible for the 6 m wave amplitude recorded at two GPS buoys off the Tohoku coast. This input condition to NEOWAVE is thus compatible with seismic data from around the world as well as recorded geodetic and tsunami data along the Japan coasts.

The computation covers 20 hours of elapsed time with time steps of 1 to 0.05 s from the level-1 to 4 grids and output intervals of 1 min at the DART buoys and 10 sec at the level-4 grid. Figure 2 compares the recorded and...
Figure 2. Comparison of recorded (black lines) and computed (red lines) data at DART buoys.
computed surface elevations at 16 DART buoys in the North Pacific. The datasets on the left, which correspond to buoys west of the dateline, show typical tsunami signals in the open ocean. The buoy signals east of the dateline on the right reflect influences from adjacent coasts. NEOWAVE reproduces the amplitude and phase reasonably well, but shows additional short-period components superposed on the initial wave at DART 21413 and 52402 due to poorly constrained slip in the southern part of the finite-fault model. The agreement improves at the buoys east of the dateline because the subtleties of the rupture have less effect on the far-field tsunami. The computed time series, however, have been shifted between 2 to 6 min due to underestimation of travel time. The lag time is comparable to results from nonlinear shallow-water and Boussinesq models [e.g., Tanioka, 2001; Yamazaki et al., 2006; Grilli et al., 2012]. NEOWAVE captures the full range of frequency content recorded by the DART buoys. The initial tsunami waves have a dominant period between 35 and 60 min followed by short period waves resulting from rupture details and dispersion. The signals between 100 to 200 min are due to large-scale standing edge waves along the Pacific margin coasts as observed during the 2010 Chile tsunami [Yamazaki and Cheung, 2011].

DART 51407 recorded the tsunami off the insular shelves of the Hawaiian Islands at 4,700 m water depth. The dominant and persistent component at 42 min corresponds to regional standing waves along the island chain [Munger and Cheung, 2008]. The shorter waves with decreasing amplitude and period over time are likely due to higher harmonics released from local refraction-diffraction of the initial waves and subsequent arrival of dispersive waves generated during propagation. The short-period waves shoal over the insular slope and increase in amplitude relative to the 42-min component at the Honolulu tide gauge and Kilo Nalu as shown in Figure 3. The computed surface elevation gives very good agreement with the measurements. The Honolulu tide gauge recorded waves with 9 min or longer periods in the harbor, while Kilo Nalu recorded additional signals between 3 to 8 min periods on the open coast. The wave components between 4 to 16 min periods have greater contributions to the current at Kilo Nalu despite having much weaker surface signals in comparison to the 42-min component. The depth-averaged currents from the ADCP and NEOWAVE agree reasonably well, but the short-period components show discrepancy over time due to difficulties in fully capturing far-field dispersive waves across the Pacific with the 2-arcmin level-1 grid.

3. Nearshore Surges

Resonance oscillation plays an important role in nearshore tsunami characteristics and provides an explanation for the observed and recorded surge conditions on the Honolulu coast. Spectral analysis of the computed surface elevation over the level-4 grid and collation of the complex amplitude define the oscillation as a function of period. The results show resonance oscillations with periods as short as 3 min in the channels and basins. Figure 4 provides the amplitude and phase plots of four oscillation modes between 9 and 42 min that have well-defined nodes at harbor entrances and high spectral energy as indicated in Figure 3. The results show a mix of standing and partial standing waves with zero and near-zero nodal lines, where the phase varies rapidly across by 180°. The surface elevation and velocity have a 90° phase difference typical of standing waves in which the strongest horizontal flows occur at the surface elevation nodes and the water is nearly stagnant at the antinodes.

The first two modes at 42 and 16 min period, which match the observations at Honolulu Harbor, are related to the regional standing waves along the Hawaiian Islands as
The body of water from Oahu to Molokai is an antinode of the 42-min oscillation that results in gentle flood and ebb flows over the insular shelf fronting Honolulu despite its large amplitude. At the 16 min period, a complex system of standing waves develops in this body of water with one antinode spanning the entire Honolulu coast. The shorter period waves excite resonance oscillations in the coastal waters. Local amplification occurs over the shallow reefs in front of Keehi Lagoon and Waikiki, while well-defined nodes develop at the entrances of Ala Wai Boat Harbor and Honolulu Harbor (see Figure 1d for a location map). The oscillation in Honolulu Harbor extends into most of Keehi Lagoon with the same phase and then transitions to standing and partial standing waves to the north and south, respectively. The oscillations in these basins of varying size are coupled with the flows over the shelf and reef system with a 180° phase shift.

[11] The 11 and 9-min oscillation modes are dominant on the Honolulu coast with a narrow insular shelf. The 11-min mode comprises primarily standing waves over the shelf coupled with local resonance and amplification at the shore. The shorter period introduces a second node inside Honolulu Harbor, where an antinode extends into Keehi Lagoon just outside the west entrance. This antinode shows an abrupt 180° phase shift to the south but a gradual phase transition of 180° indicative of a progressive wave across the shallow marina to the north. A partial standing wave develops over the reef fronting Waikiki, while Kewalo Basin is excited by the shelf oscillation. At 9 min period, the standing waves are confined to the nearshore reef system inside the 20-m depth contour. The resonance at Honolulu Harbor still has sufficient energy with the node shifted inward from the east entrance and a new node at the west entrance. This new node couples the harbor oscillation with the standing wave in Keehi Lagoon Marina. A nodal line develops in front of Waikiki and the two adjacent basins indicative of coupled oscillations with the flow over the outer reefs. The formation of nodes in harbors and marinas provide an explanation for the strong currents observed during the tsunami event.

Figure 4. Resonance modes along Honolulu coast. The grey lines indicate the 20 and 100-m contours.
The maximum surface elevation and flow speed in Figure 5 are less than 0.4 m and 0.1 m/s outside the designated 100-m depth contour, where vessels take refuge during a tsunami, and increase to 0.5 m and 0.3 m/s at 20 m depth, which is the extent of the fringing reefs. The 46-min mode, which has a large amplitude and bandwidth, dominates the surface elevation. Oscillation modes 16 min or shorter are able to develop standing waves over the shelf and reef complex. Constructive and destructive inference of their antinodes with the 42-min mode produces asymmetric oscillations with maximum and minimum surface elevations of 1.5 m and −1.8 m at the coast. The computed minimum surface elevation of −1.2 m agrees with the recorded drawdown near Aloha Tower from the Harbor Traffic Control Log. The minimum surface elevation is discontinuous along the reef edge to the south of Kekahi Lagoon due to phase lags between the receding flows over the reef flat and slope as observed in the laboratory experiments of Roeber et al. [2010a]. The nodes and shoals define the nearshore flow pattern with speed reaching 2.4 and 3.3 m/s at the west and east entrance channels of Honolulu Harbor.

The model results provide a consistent explanation for the observations. Although the maximum flow speed of 1.3 m/s in Kekahi Lagoon Marina is not high, the drawdown of close to 1 m together with the receding flow is sufficient to pull boats from the moorings and damage dock facilities. The Honolulu tide gauge did not record signals of 9 min or shorter because of migration of the node from the entrance to the gauge location. Kilo Nalu, atop a narrow reef, where antinodes are developed for the short-period oscillations, recorded clear signals of the tsunami for periods 3 min or longer. The current at the site is relatively weak compared to other locations with wider reefs and includes secondary flows generated by ingress and egress through the adjacent channels. Despite the complexity of the local flow and basin-wide propagation, NEOWAVE and the seismic source parameters from Yamazaki et al. [2011b] reproduce the Honolulu tide gauge and Kilo Nalu data. Since resonance oscillation modes are independent of the excitation, recorded signals at Kilo Nalu show similar spectral components for the 2006 Kuril and 2010 Chile tsunamis [Yamazaki et al., 2012]. The model results are useful for emergency management agencies and harbor administration for planning of tsunami hazard mitigation in Hawaii.

4. Conclusions

The 2011 Tohoku tsunami caused persistent oscillations and hazardous currents in coastal waters around Hawaii. The dispersive-wave model NEOWAVE utilizes a finite fault solution to recreate the tsunami from its generation by earthquake rupture to the surge conditions at the Honolulu coast for a detailed investigation. In addition to prior validation with buoy data along the Japan coasts, open-ocean measurements from DART buoys validate the modeled tsunami across the North Pacific. The tsunami varies significantly across the ocean due to dispersion, rupture subtleties, and land masses. The Honolulu tide gauge and Kilo Nalu Observatory, which recorded additional shelf and reef processes, provide the most pertinent dataset to confirm the computed surface elevation and current for application in Hawaii.

Spectral analysis of the computed surface elevation reveals energetic standing waves between 9 to 42 min periods at the Honolulu coast. The 42-min oscillation dominates the surface elevation with its large amplitude and bandwidth, but only produces gentle flood and ebb flows over the insular shelf. Standing waves with period 16 min or shorter are able to form a series of nodes and antinodes over the reefs that results in strong currents and large drawdown responsible for the damage in harbors and marinas. Since the shelf oscillations have low damping, their coupling with the
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