Shelf resonance and impact of near-field tsunami generated by the 2010 Chile earthquake

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[1] The 2010 Chile earthquake of Mw 8.8 generated a destructive tsunami in the near field that resulted in warnings across the Pacific. Numerical modeling shows trapping and amplification of the energy over the continental shelf and slope. A spectral analysis of the computed surface elevation reveals resonance oscillations with periods up to 129 min along the central Chile coast. The temporal and spectral data provides an explanation for the long-period waves recorded by DART buoys and the prolonged wave activities and belated impacts reported by residents and survey teams. The present study of the 2010 Chile tsunami together with those of the 2006 Kuril and 2009 Samoa tsunamis has directly associated shelf resonance with impacts on insular and continental coasts and provided a tool to identify at-risk localities in tsunami hazard assessment. Citation: Yamazaki, Y., and K. F. Cheung (2011), Shelf resonance and impact of near-field tsunami generated by the 2010 Chile earthquake, Geophys. Res. Lett., 38, L12605, doi:10.1029/2011GL047508.

1. Introduction

[2] An Mw 8.8 earthquake ruptured a 550-km fault along the Peru-Chile Trench on February 27, 2010 at 3:34 am local time (6:34 UTC). Figure 1a shows the epicenter and rupture area as well as the locations of four DART buoys in the eastern Pacific that recorded distinct signals of the resulting tsunami. The most severe impacts occurred along the coastline from San Antonio to Tiriua with the floodwater reaching 29 m elevation and at least 521 deaths. An intriguing aspect of the 172 sec event (–2000-m) ETOP01 data. The level–1 grid describes propagation of the tsunami across the eastern Pacific at 2 arcmin (~4000 m) resolution, while the level–2 grid resolves the seafloor deformation and near-field tsunami at 0.5 arcmin (~1000 m).

[3] An inspection of Figure 1a reveals a wide continental shelf in front of the central Chile coast hardest hit by the tsunami. This coastline happened to be within the rupture zone and obviously sustained the most severe impact, but the prolonged, near-field tsunami waves from multiple directions must be a result of the local bathymetry. Munger and Cheung [2008] and Roeber et al. [2010] reported resonance of the 2006 Kuril and 2009 Samoa tsunamis over the insular shelves and slopes of Hawaii and American Samoa that caused prolonged oscillations of the coastal waters. While the continental margin is distinct from volcanic insular settings, the observed wave activities and survey findings of the 2010 Chile tsunami corroborate the characteristics of large-scale resonance triggered tsunamis. The recently developed dispersive wave model of Yamazaki et al. [2009, 2011] allows reconstruction of the near-field tsunami to understand the behaviors and impacts of resonance on continental coasts.

2. Modeling and Validation

[4] NEOWAVE (Non-hydrostatic Evolution of Ocean WAVEs) is a staggered finite difference model, which 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 flow discontinuities such as bores or hydraulic jumps [Yamazaki et al., 2009, 2011]. The vertical velocity term also facilitates modeling of tsunami generation and transfer of kinetic energy from time histories of seafloor deformation for accurate description of the near-field wave conditions. Figure 1a shows two levels of nested grids derived from the 1-arcmin (~2000-m) ETOP01 data. The level–1 grid describes propagation of the tsunami across the eastern Pacific at 2 arcmin (~4000 m) resolution, while the level–2 grid resolves the seafloor deformation and near-field tsunami at 0.5 arcmin (~1000 m).

[5] USGS analyzed the 2010 Chile earthquake using the finite fault algorithm of Ji et al. [2002] and estimated the fault parameters and rupture sequence over a 540 km by 200 km region with 180 subfaults of 30 km by 20 km each (G. Hayes, http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010tfan/finite_fault.php, 2010). The 172–sec event released most of its energy in 90 sec. The individual subfaults have an average rise time of 15 sec and an average slip of 4.2 m. The parameters at each subfault allow computation of the seafloor deformation through the planar fault model of Okada [1985]. Superposition of the deformation from the subfaults according to their rupture initiation time and rise time as well as an assumed linear slip motion reconstructs the time history of the seafloor vertical displacement and velocity for input to NEOWAVE. Figure 1b shows the slip distribution over the rupture area and the permanent vertical displacement of the seafloor. The deformation has a distinct pattern of subsidence on the continent and uplift on the seafloor with a maximum value of 4.2 m west of Pichilemu.

[6] The computation covers 15 hours of elapse time with the level–1 and 2 time steps of 1 and 0.5 sec and output intervals of 1 min. Figure 2a shows two snapshots from the Animation S1 in the auxiliary material that illustrates the time...
history of the tsunami event.\(^1\) Constitución, which was adjacent to the epicenter, was hardest hit by the initial wave. The tsunami propagates away from the rupture in radial directions with a prominent initial wave over a 30° arc. The continental slope refracts and traps the radiated energy initially as progressive edge waves on the shelf. Reflection between headlands and continental shelf boundaries produces a number of standing and partial standing wave systems along the coast. The trapped waves oscillate at the natural periods of the shelf and slope and emit long-period waves into the open ocean for several hours. The phases of the standing wave systems aligned near Talcahuano 3 hours after the earthquake. Scattering of the main tsunami waves and the leaked trapped waves around the many islets in the southeastern Pacific generates the distinct short-period waves with a circular pattern.

\[^1\] Auxiliary materials are available in the HTML. doi:10.1029/2011GL047508.

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Figure 1. Model setting and data. (a) Nested computational grids, location of DART buoys, and rupture area. (b) Slip distribution and vertical seafloor displacement. Red circle indicates the epicenter and black rectangular boxes denote the rupture area and subfaults.

[7] The surface elevation time series and amplitude spectra in Figure 2b quantify the tsunami behaviors across the eastern Pacific. The computed data at 20-m depth near Valparaiso, Constitución, and Tolten shows sustained oscillations of varying characteristics along the coast. The initial wave is not necessarily the largest as supported by tide gauge data (http://nctr.pmel.noaa.gov/chile20100227/chile20100227-valparaiso.html), but a direct comparison cannot be made due to the low-resolution computation. The computed and recorded data at DART 32412, 51406, and 43412 shows a prominent initial wave followed by leaked trapped waves from different parts of the continental margin and scattered waves around islands. The signals at DART 32411 are unique because the buoy was located off the main energy arc without the distinct initial wave observed at other buoys. Its location immediately north of the Galápagos islands also results in modulation of the signals through refraction and diffraction over the steep insular slope [Chandrasekera and Cheung, 1997, 2001]. The computed results at all four DART buoys
reproduce the dominant processes and show good agreement of the amplitude, phase, and frequency content with the measurements, thereby validating the modeled tsunami for an in-depth analysis of the resonance.

3. Shelf Resonance

Spectral analysis of the computed surface elevation and collation of the complex amplitude over the level-2 grid define the surface motion along the central Chile coast as a function of period. Figures 3 and 4 show the amplitude and phase of eight dominant oscillation modes between 35 and 129 min period selected for their well-defined nodes and antinodes indicative of resonance. The 200-m contour and trench axis indicate the extents of the continental shelf and slope for reference. The amplitude plot shows migration of resonance energy from south to north as the oscillation period decreases with the width of the continental shelf. The oscillations include a mix of standing and partial standing waves as inferred from the phase plot. Standing waves have the same phase within an antinode and an abrupt 180° phase shift to the adjacent antinodes, while partial standing waves show gradual phase variation across the nodes associated with leakage of resonance energy. The selected modes show 180° alternating phases along the coast indicating these are coherent oscillations resulting from shelf resonance.

Figure 2. Propagation of the 2010 Chile tsunami. (a) Snapshots of surface elevation. Triangle indicates Talcahuano and circle-dots indicate Valparaiso, Constitución, and Tolten from north to south. (b) Waveforms and amplitude spectra. Red and black lines denote computed and recorded data.
Figure 3. Amplitude of resonance oscillations along Chile coast. Grey lines indicate the 200-m depth contour and the Peru-Chile trench.
Figure 4. Phase angle of resonance oscillations along Chile coast. Grey lines indicate the 200-m depth contour and the Peru-Chile trench.
The first resonance mode has a large bandwidth centered at 129 min as recorded by the DART buoys. The large-scale standing waves along the shore extend beyond the continental margin with well-defined nodes near Lebu and Pichilemu. The energy is amplified over the shelf in the Gulf of Arauco and the Bay of Concepción and in the embayment at Tolten. The resonance at 93 min, which has a similar large-scale structure as the first mode, shows the fundamental mode of oscillation in the Gulf of Arauco and the Bay of Concepción as well as a system of mode-0 standing edge waves over the shelf at Tolten. The embayment oscillations show a well defined node at the open boundary, while the edge waves have nodes and antinodes along the shore. As the period decreases from 79 to 73 min, the large-scale standing waves shorten and a new node emerges south of Coquimbo. Additional antinodes develop in the shelf oscillation at Tolten and mode-0 standing edge waves become evident over the shelf north of the Gulf of Arauco.

The large-scale standing wave system is in a transitional stage with gradual phase variations at 64 min period. The shelf oscillation diminishes along the Tolten coast and the mode-0 standing edge waves to the north become dominant. As the period decreases, the large-scale standing waves align with the embayments at Los Vilos and Coquimbo causing local amplification over the continental slope in the absence of a shelf. The mode-0 standing edge waves migrate northward and higher-order edge waves with offshore antinodes develop over the wider continental shelf to the south. The large-scale system vanishes at 35 min period, while the mode-0 standing edge waves extend to the narrow shelf north of Valparaíso and produce the 35-min peak of the corresponding amplitude spectrum in Figure 2b. Coherent shelf oscillations exist with periods as short as 22 min, but at low energy levels that do not significantly impact the coastal communities.

The large-scale standing waves along the Chile coast have a 180° phase lag with the standing edge waves over the shelf that in turn show a 180° phase lag with the fundamental oscillations in the Gulf of Arauco and the Bay of Concepción. This indicates coupling between the dynamic systems of vastly different geographic scales and provides an explanation for the long and multiple fundamental periods in a relatively small embayment such as the Bay of Concepción. Although the large-scale standing waves have small amplitude, they extend beyond the continental margin with low dissipation rates and provide a source of energy to sustain the shelf and embayment oscillations. Similar coupling of multi-scale standing wave systems also exists in insular...
environments. Munger and Cheung [2008] reported large-scale standing waves along the Hawaiian Island chain with periods up to 42 min and their coupling with oscillations over the insular shelves, while Roeber et al. [2010] described coupling of standing waves over the fringing reefs, insular shelf, and slope of Tutuila, American Samoa from 3 to 18 min period.

4. Tsunami Impact

[12] The shelf resonance provides an explanation for the observed tsunami waves and the impacts along the central Chile coast. The flow direction of standing edge waves varies from longshore at a node to cross-shore at an antinode. Superposition of the edge waves with different periods results in onshore waves from different directions at different times. Talcahuano Harbor, which is located in the Bay of Concepción, was one of the hardest hit locations. The north facing embayment trapped floodwater moving along the shore from the large-scale standing waves at 129 min period. The fundamental mode of oscillation occurs in the embayment with a well defined node near its opening at 64, 73, 79, and 93 min periods. The embayment oscillation shows an 180° phase lag with the standing edge waves over the continental shelf. Such asymmetric coupling amplifies and sustains the oscillation in the Bay of Concepción. Constructive interference of the resonance modes caused destruction of Talcahuano Harbor and the waterfront district 3 hours after the earthquake.

[13] Figure 5 compares the recorded floodwater elevation and runup with the computed spectral energy, wave amplitude, and peak period. The recorded data, which was compiled from measurements made by Fritz et al. [2011] and Chilean and Japanese survey teams, covers the coastline from Tolten to Valparaiso that experienced severe wave activities during the tsunami. The recorded flood elevation reaches 29 m near Constitución just north of the epicenter and 23.5 m near Tirúa south of the rupture zone. The spectral energy, which primarily lies within the 200-m depth contour, corresponds well to the recorded data. An exception is the coastline from Pichilemu to La Trinchera, where its narrow shelf and proximity to the epicenter resulted in a large initial wave with minor residual oscillations. The coastline from Constitución to Arauco has a wide continental shelf and experienced the most severe impact from both the tsunami and resonance. The long-period oscillation modes have a node between Arauco and Lebu, where the computed spectral energy and amplitude of the surface elevation are low. The recorded data might be attributed to splash-up from the strong longshore flows at prominent headlands. The isolated, large runup values at Tirúa are due to lock-in of nodes and antinodes in the narrow passage between Mocha Island and the headland that results in local amplification and constructive interference of waves and oscillatory currents.

[14] The peak period of the wave spectrum varies along the coastline in accordance with the width of the continental shelf. The coastline south of Pelluhue experiences oscillations of over 68 min period, while the coastline to the north with a narrower continental shelf is dominated by shorter period waves between 17 and 57 min. The prolonged oscillation with a period of 129 min and the gentle nearshore slope in the embayment at Tolten provide an explanation for the low recorded runup and computed wave amplitude despite a high spectral energy level in the region. The resonance oscillations on the continental shelf have far reaching effects across the ocean. DART 32412 recorded distinct energy peaks at 93 and 129 min and DART 51406 recorded the 54 and 129-min resonance periods, respectively at 2400 and 6100 km from the source. Shelf resonance provides an explanation for the long-period signals that typically follow the main tsunami waves as recorded by DART buoys in the far field.

5. Conclusions

[15] The rupture of the 2010 Chile earthquake under a wide continental shelf exacerbated and prolonged the impact of the near-field tsunami. Trapping of the radiated tsunami energy over the continental margin resulted in resonance oscillations between 35 and 129 min period. The standing edge waves generated flows in multiple directions at the coast corroborating eyewitness accounts and survey findings. Coupling of the shelf resonance and the fundamental oscillation mode in the Bay of Concepción resulted in the large unexpected wave that devastated Talcahuano Harbor and the waterfront district more than 3 hours after the earthquake. There are many coastal communities in subduction zones with wide continental shelves around the world that might experience similar near-field tsunami impacts.

[16] The present study of the 2010 Chile tsunami demonstrates the multi-scale resonance along continental coasts. Together with the studies of the 2006 Kuril and 2009 Samoa tsunamis for insular environments, we have confirmed the role of shelf resonance in defining the near-shore wave characteristics and the impact along the coast. The resonance modes, which are largely independent of the tsunami source, allow identification of at-risk communities and infrastructure for planning and mitigation of tsunami hazards. Shelf resonance also represents an important mechanism that defines the frequency contents of the tsunami waves across the ocean. Understanding of this mechanism would allow better interpretation of recorded water-level data for issuance of warnings or advisories during a tsunami event.

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References


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