TSUNAMI RESONANCE IN THE BAY OF CONCEPCION, CHILE

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Abstract: Natural oscillation modes of the Bay of Concepcion are determined by means of Empirical Orthogonal Functions. Simulations of the 2010 and 1960 tsunamis were performed using 4 nested grids of 120, 30, 6 and 1" arc resolution with the NEOWAVE model. In addition, a spectral analysis of tsunami waveforms at both the continental shelf and inside the Bay of Concepcion was performed, and the results were contrasted with natural oscillation periods. The results showed that the natural oscillation period of the first, second and third modes of the Bay were found to be 95, 37 and 32 min. It was found that large tsunami amplifications at the southern shore of the Bay of Concepcion were due to tsunami resonance and coupling between the shelf resonance and bay oscillations. Large inundations heights during 2010 tsunami were caused by the tsunami exciting the fundamental oscillation mode of the Bay. The relative low inundation during the 1960 tsunami was due to the tsunami exciting the higher frequency.

Keywords: tsunami resonance, Bay of Concepción, shelf resonance, fundamental mode, 2010 tsunami, 1960 tsunami.

INTRODUCTION

Chile is one of the most earthquake prone countries in the world and the last significant earthquake in Central Chile took place in February 2010. The magnitude 8.8 earthquake also generated a destructive tsunami which caused large inundation along major coastal settlements. Moreover, historical records show that the Bay of Concepción has been affected by several tsunamis in the last 500 years; for example the tsunamis of 1570, 1657, 1751 and 1835, which were generated in the same tsunami source area as the 2010 tsunami, resulted in large inundations in Penco (former Concepción) and Talcahuano. In a similar manner, the 1730 tsunami, generated in front of Valparaiso, also caused severe damage to Penco. However, the tsunami generated by the magnitude 9.5 earthquake in 1960 did not cause severe damage. In fact, the reported tsunami inundation height was half of the inundation observed during the 2010 tsunami. It could be thought that the southern location of the tsunami source and the northward orientation of the bay are the main reasons behind this. However, the Bay of Coliumo (Dichato) experienced large inundation height, similar to the 2010 event (Takahashi, 1961), despite a similar orientation to the Bay of Concepción. Other relevant coastal behavior is the 2011 Japan Tsunami, which arrived at Central Chile on March 12th. The tidal gauge at Talcahuano recorded the tsunami inside the Bay of Concepción, with a maximum amplitude of 2m. This event also generated a maximum tsunami height of 4m in Dichato (Aranguiz and Shibayama, 2013). The tsunami resonance in the Bay of Concepcion could be investigated based on such information, since large tsunamis wave heights inside the bay (Fritz et al, 2011, Mikami et al, 2011, Yamazaki and Cheung, 2011) could be due to local amplification.

The present paper analyzes tsunami resonance inside the Bay of Concepción. The natural oscillation modes of the Bay of Concepción are computed by means of empirical orthogonal functions and the amplification of two past events, namely the 1960 and 2010 tsunamis, are analyzed by means of tsunami numerical modeling.

STUDY AREA

The Bay of Concepcion is a semi-enclosed basin 11km in width and 14km in length. The maximum water depth at the entrance is 40m. Farreras (1978) estimated the natural periods of the bay by means of empirical expressions and assuming a rectangular basin (L=14.6km and W=11.7km) with a mean water depth of 25m. The periods were computed to be 15, 27 and 111min. If the varying water depth is considered, and the same values of length and width are used, mathematical formulations given by Rabinovich (2009) give values of the natural periods as 13, 21 and 64 min. None of the previous computation considered the island at the entrance of the Bay.

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NATURAL OSCILLATION MODES

In this subsection, the natural oscillation modes of the Bay of Concepcion will be computed by means of Empirical Orthogonal Functions (EOF) as proposed in the work of Tolkova and Power (2011). We use a numerical domain excluding the continental shelf and generating the initial free surface deformations within the semi-enclosed basin only. Figure 1-a shows the Bay of Concepcion and the location of the 6 scenarios. The initial deformation was in the shape of a round Gaussian hump, as proposed by Tolkova and Power, (2011), i.e. $\eta = ae^{-r^2/2\sigma^2}$ with a =1 m, $\sigma = 5$ km. An example of the initial condition is given Figure 1-b. The six scenarios were simulated with TUNAMI model for 10hours, and a resolution of 3 arcsec was used. The time series of the six events were concatenated skipping the first 30min of elapsed time, thus the time series do not include the more energetic traveling wave.

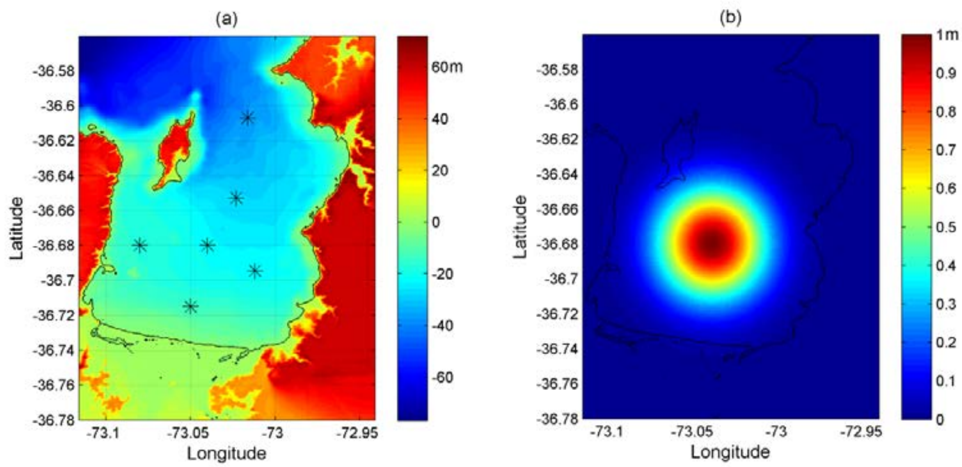

Figure 1. Application of the EOFs method to the Bay of Concepcion. (a) The Bay of Concepcion area, where the asterisks show the origin of 6 events used to derive the EOFs. (b) Example of an initial sea surface perturbation inside the Bay.

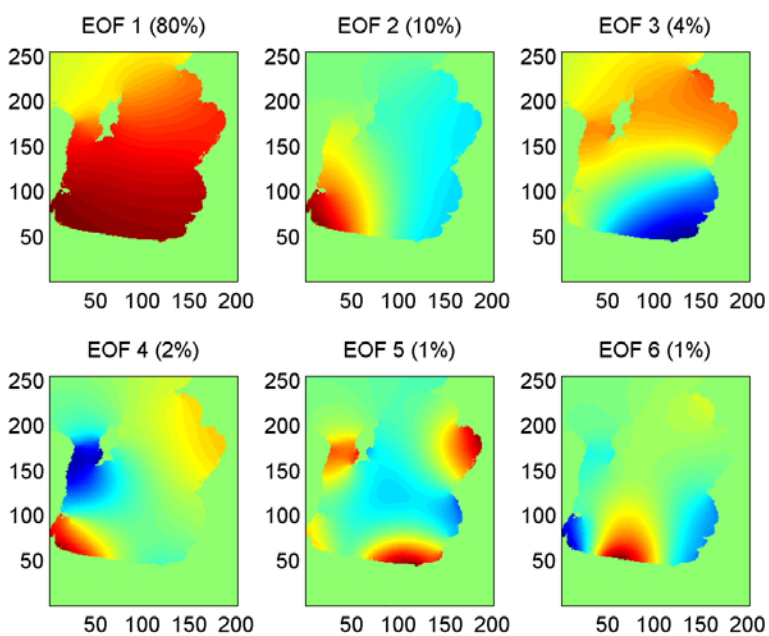

Figure 2. First to sixth EOFs of concatenated timeseries (a=1m σ=5 km). Percentages of total 6-event variance explained by each EOF are shown in the plot.

Figure 2 show the set of 6 EOF. It can be observed that 80% of the total variance corresponds to the fundamental oscillation mode. In addition, the first and second modes involve 90% of the total variance. The period of the first along-the-bay-mode was computed to be T=95 min. However, the first EOF also contains a minor mixture of other modes with longer periodic components (T=120 and 160 min). The period of this first mode is higher than the value computed by means of formulations given by Rabinovich (2009), but smaller than values computed by Farreras (1978). The second EOF is dominated by a mode with a period T=37 min, which is an across-the-bay mode. The third, fourth, fifth and sixth modes have periods of T=32, 25, 18, and 21 min, respectively.

NUMERICAL SIMULATION OF PAST TSUNAMIS

The present study utilizes the dispersive wave model NEOWAVE (Non-hydrostatic Evolution of Ocean WAVEs) for tsunami numerical analysis (Yamazaki et al., 2009, 2011). The computation covers 10 hours of elapsed time with output time intervals of 1min. Four levels of nested grids were setup to model the tsunami from generation to the study area. Grid 1 represents the southeast Pacific Ocean at 2-arcmin (~3,600m) to cover the tsunami generation. Two different sizes of Grid 1 were defined according to the scenario. The first one covers latitudes from 12° S to 41°S. The other grid is defined in order to analyze tsunamis from southern Chile, such as the 1960 tsunami, covering latitudes 32°S to 48°S. Both grids are shown in Figure 3. A common Gauge 1 is defined at the entrance of the Bay of Concepcion. Grid 2 at 30-arcsec (~900m) and grid 3 at 6-arcsec (~180m) describe the wave transformation over the continental shelf and slope along the Chilean coast as well as the Gulf of Arauco. Grid 4 at 1-arcsec (~30m) is used to model inundation and tide gauges at the Bay of Concepción. Grids 2, 3 and 4 are the same for modeling all the selected scenarios, and are shown in Figure 4. The location of gauge 1 can also be appreciated in Figure 4. Grids 1 and 2 were generated from GEBCO 08, and grids 3 and 4 were built from nautical charts and different topography sources. The topography of the higher resolution grids the Bay of Concepcion and the Eastern shore of the Gulf of Arauco were obtained from LIDAR data with 2.5m resolution.

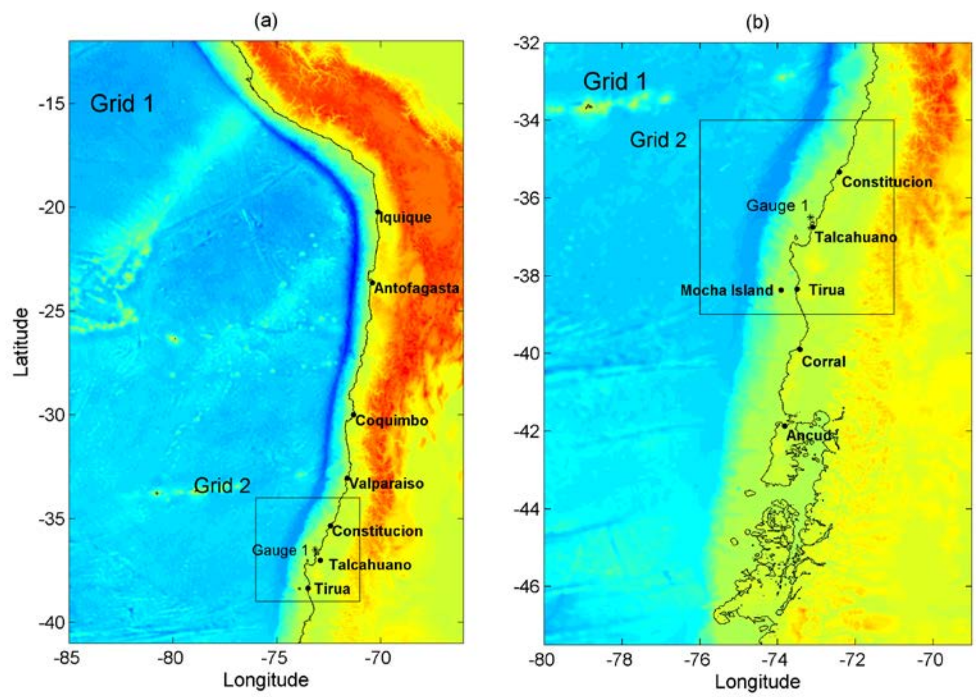

Figure 3. Level 1 grids used in the numerical simulations. (a) Grid 1 used in simulation of both 2010 and 1877 events. (b) Grid 1 used for 1960 event. The tide gauge are indicated with asterisks in each grid.

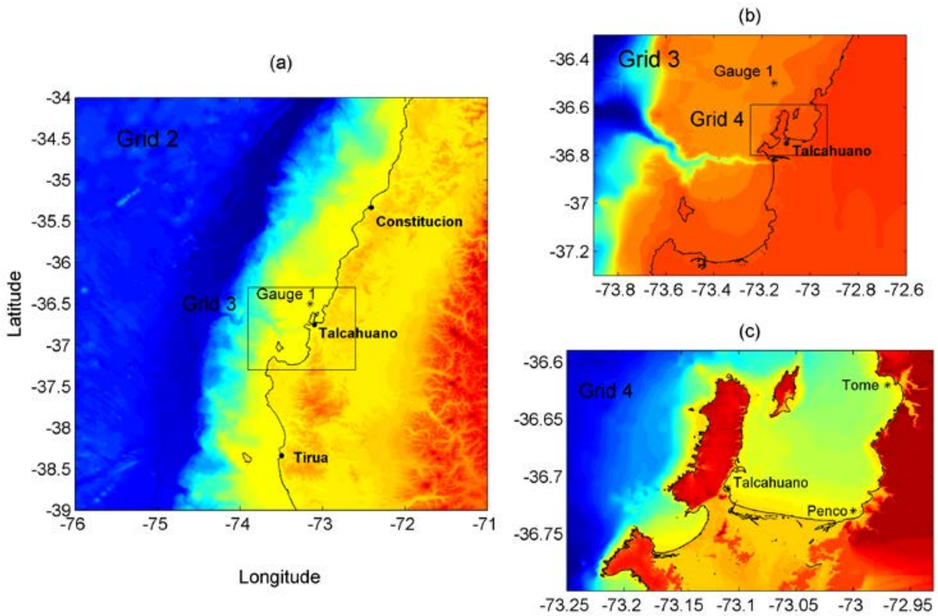

Figure 4. Common grid used in the numerical simulations. (a) Grid 2 with the locations of tide gauges 3, 5, 6 and. 9. (b) Grid 3 with the location of tide gauge 6 at the entrance of the Bay of Concepcion. (c) Grid 4, the tide gauges at Tome, Penco and Talcahuano

The initial condition of the 1960 tsunami was built from the 5-segment model proposed by Aránguiz (2013), which is based on the FFM given by Barrientos and Ward (1990), but it considered the main event only. The tsunami initial condition for the 2010 Chile used the USGS Finite Fault Model (Hayes, 2010). This fault model estimated the fault parameters and rupture sequence over a 540km by 200km region with 180 subfaults of 30km by 20km each. The initial sea surface deformation was built by means of superposition of the 180 subfaults, and each fault is calculated using the Okada (1985) formulation (See Figure 5).

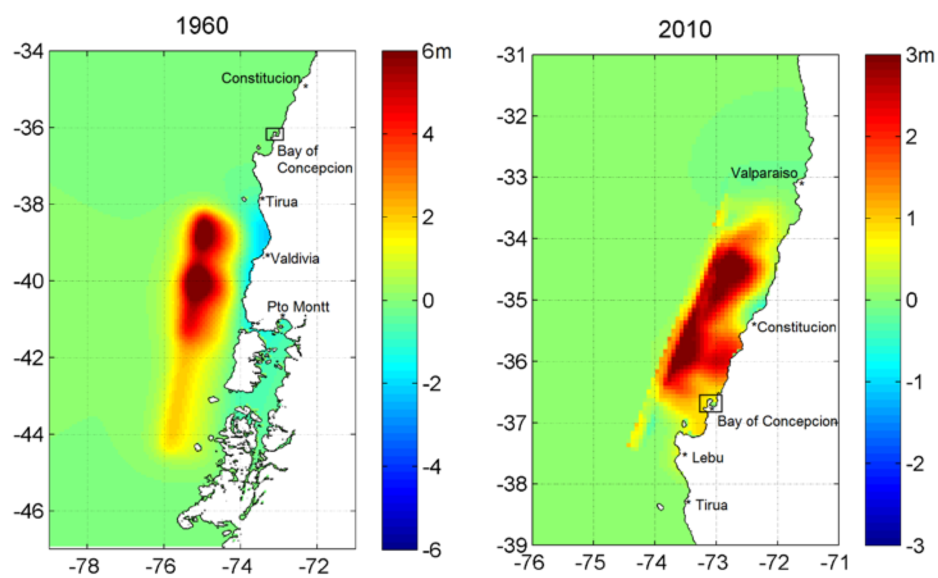

Figure 5. Tsunami initial condition for the 1960 and 2010 tsunamis.

Figure 6 shows the tsunami waveforms and spectral amplitudes at Gauges 1 (Continental Shelf) and Talcahuano for both scenarios, the 1960 and 2010 tsunamis. For the case of the 1960 tsunami, it can be seen that Gauge 1 has two main periodic components at the continental shelf (blue line), one at around a period of 70 min, and a large bandwidth from 100 to 180 min centered at around 130-140 min. In a similar manner, the 2010 tsunami appears to have two important periodic components at the continental shelf, one at around 90 min and another one at around 130 min. These results are in good agreement with the resonant modes computed by Yamazaki and Cheung (2011), who identified resonant modes from 35 to 129 min with bandwidths centered at 73, 93 and 129 min, which coincide approximately with the spectral energy peaks identified now. Therefore, different tsunami scenarios could excite different oscillations modes of the continental shelf. From the tide gauge at Talcahuano (red line), it is possible to observe that the spectral energy is significantly amplified inside the Bay. In the case of 1960 tsunami, a large bandwidth between 80 and 180 min centered at around the component 90-110 min is identified. In addition, a short periodic component around 30 min is also amplified inside the Bay, and can reach a spectral amplitude comparable with the first resonant component at 90-100 min, despite the spectral amplitude outside the Bay not being significantly larger. In a similar manner, the 2010 tsunami shows to have significant amplification inside the bay. Both resonant components at 90 and 130 min are amplified, though the maximum amplitude takes place for a periodic component at around 90 min. If natural oscillation modes of the Bay are contrasted with energy spectra computed from each scenario, it is possible to conclude that the large tsunami amplification inside the Bay was due to excitation of natural oscillation modes. The results of 2010 tsunami showed to have significant amplification at a period around 90 min with a large bandwidth, which coincides with the computed fundamental mode of the Bay (95 min), and thus coupling between bay oscillations and large-scale shelf resonance is generated. On the contrary, the 1960 tsunami excited more the second and third oscillation modes rather than the fundamental mode. It is also possible to see that the superposition of the first to the third normal modes would generate large amplitudes at Talcahuano and Penco (See Figure 2). Therefore, large tsunami amplitudes reported at Penco and Talcahuano during past tsunami events (Soloviev and Go, 1975) can be explained not only due to coupling between shelf resonance and bay oscillations, but also due to the internal normal modes of the Bay itself.

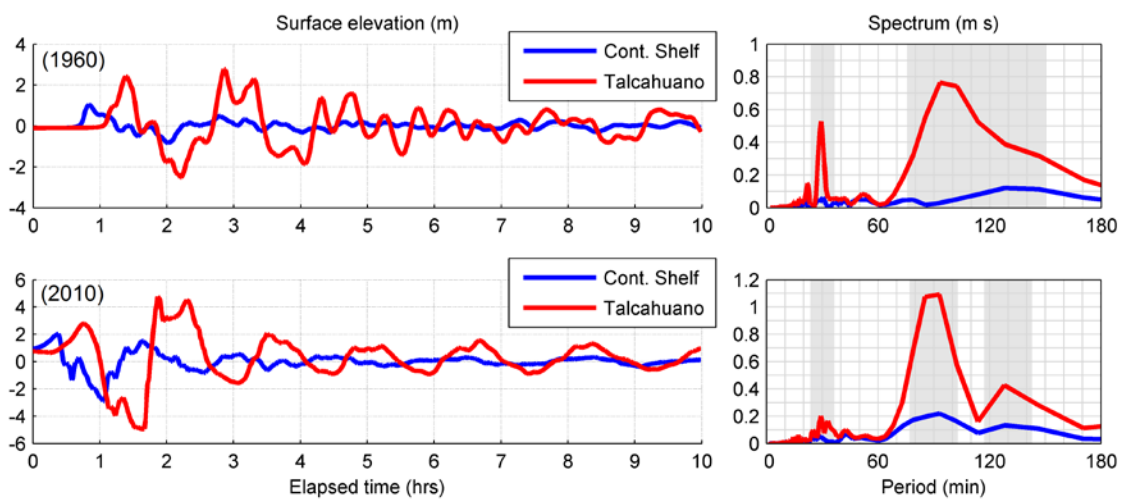

Figure 6. Tsunami waveforms and energy spectra for 1960 and 2010 tsunamis

CONCLUSIONS

The natural oscillation modes of the Bay of Concepcion were estimated by means of the Empirical Orthogonal Functions. The fundamental period of the Bay was computed to be 95min, which is smaller than previous calculations based on theoretical expressions. The main reason for such a difference is the influence of the continental shelf as well as the presence of the island at the bay mouth on the oscillation modes, which is not considered in the theoretical expressions.

From numerical simulations of the 2010 tsunami, it was observed that the amplitude spectra was significantly magnified at Talcahuano, and the maximum amplitude took place for a periodic component at around 90 min, which is almost the same as the one obtained at the continental shelf. For the case of 1960 tsunami, it is observed that the spectral bandwidth of between 100 and 180 min periods was amplified in a similar proportion as in the case of 2010 tsunami. However, the short periodic component around 36 min was amplified in a greater manner at Talcahuano, despite the spectral amplitude outside the Bay not being significantly larger. Therefore, the computed 1960 tsunami showed to have more important resonant components at 36 and 130 min than at 90 min, as the previous case.

ACKNOWLEDGEMENTS

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