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High Resolution Analysis of the 1960 Chilean Tsunami at Crescent City, California

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Abstract: Crescent City, California is particularly vulnerable to tsunamis (Uslu et al., 2007). Since 1938, 24 tsunamis have been recorded and three have caused significant damage, most recently in November 2006. The largest and most deadly of these, the tsunami generated by the 1964 Alaskan earthquake, was discussed in detail by Dengler and Magoon (2005) at the previous Solutions conference. This paper discusses a 'new' source of data for assessing the risk to Crescent City, i.e. digitized high-speed gauge records from the second most damaging tsunami that followed the May 22, 1960 Chilean earthquake. These newly digitized records will allow spectral and statistical analyses so that the evolution of spectral characteristics with time can be studied and questions of tsunami resonance and the partitioning of the energy into wave types can be better understood.

Introduction

On May 22, 1960, the Great Chilean Earthquake produced a tsunami that was measurable as far away as Japan and the west coast of the US. At Crescent City, California the signal was recorded not only on the U.S. Coast and Geodetic Survey tide gage, but also on two high-speed water level recorders that had been installed to study harbor seiche or surge.

Crescent City Harbor (Figure 1) is located about 17 miles (27 km) south of the California/Oregon border in the lee of Battery Point. The Outer Breakwater extends south-easterly from the point for about 1.5 km, facing the bay, which has a crescent shaped sandy beach along the south shore. The commercial fishing harbor is protected by an Inner Breakwater which extends from Whaler Island. Figure 1 reflects the harbor structures during the 1960 tsunami; subsequently the structure labeled Dutton's Dock was replaced and realigned and the inner breakwater extended 400 feet (122m).

In order to study long period harbor oscillations, the US Army Corps of Engineers had installed two Stevens type A-35 water level recorders which operated at a chart paper speed of one yard per hour during the 1960 tsunami. This chart speed provided for a relatively high resolution signal. One recorder was located at Dutton's Dock near the Crescent City Outer Breakwater and the other at Citizen's Dock in the protected inner harbor (Figure 1).

Figure 1: Crescent City Harbor in 1960 showing surge gage locations at Dutton's and Citizen's Dock

The recorders were float activated and used a stilling well fourteen inches (36 cm) in diameter with a three inch (7.6 cm) circular opening on one side of the pipe well and a variable triangular slot on the other side (See Figure 2). After the news of the

earthquake in Chile, the triangular slots were fully opened in order to provide an unattenuated signal during the arrival of the tsunami.

Figure 2: Crescent City Harbor surge monitoring gage details

Data Recording and Initial Observations

The recorders had been turned on several days before the first tsunami arrival on May 23, 1960 and continued to run until June 15, 1960, providing a detailed and continuous record of the tsunami at the harbor. The data from each recorder are contained on thirty-five 24-yard scrolls.

According to Magoon (1962), the first disturbance clearly associated with the tsunami was recorded (Citizen's dock) May 23, 1960 at 0220 Pacific Standard Time (PST), when the water level started to drop faster than would have been normally expected due to tidal action alone. The maximum recorded water level occurred at 1110 PST (or nearly nine hours after the initial disturbance was observed) when a height estimated at +12.5 feet (3.8m) Mean Lower Low Water (MLLW) was reached. The predicted astronomical tide at the time was 5.1 feet (1.5m) MLLW.

Note that it is not uncommon at Crescent City to see the largest disturbance occur well after the first arrival of the tsunami. The 1964 Alaskan and 2006 Kuril events also behaved this way. Please see papers by Barberopoulou et al. (2008) and Uslu et al. (2008) in these same Proceedings.

At the time of maximum water elevations, the period of the disturbance was about 20 minutes. The maximum sustained rate of change of water level was about one foot (0.3m) per minute for almost 10 minutes. The lowest water level reached was estimated to be -3.8 feet (-1.1m) at 0508 PST. The predicted tide at the time was +3.1 feet (0.95m) MLLW. Long period water level fluctuations were recorded until 28 May, but the heights had decreased to less than one foot (0.3m) by the third day.

Figure 3 shows an early plot produced from the record at Citizen's and Dutton's docks during the time of maximum water levels (Magoon, 1962).

Figure 3: Maximum water levels (Ft, MLLW) recorded at Crescent City during the 1960 tsunami (time = PST): Citizen's Dock dashed line; Dutton's Dock solid line (Magoon, 1962)

As shown on Figure 3, the wave form at Dutton's dock (solid line) contains a number of shorter period waves, with periods of from two to three minutes not present at Citizen's dock (dashed line). The tsunami apparently excited the harbor basin to cause oscillations in one or more nodes in the outer harbor or in such a manner that there was a node at Citizen's Dock. As the periods of these apparently locally induced waves are not harmonically related, it is assumed that these waves represent oscillations in the outer portion of the harbor only. These short term (2-4 minutes)

variations between the two gauges were about one foot. The wave form at Citizen's Dock was more regular than that at Dutton's Dock, and the higher water levels accompanied this regular wave.

In attempting to understand the reason for the large amplitude and unusually long duration of tsunami signals at Crescent City compared to nearby coastal sites, investigators have considered a number of factors, including resonance with the offshore shelf features. Keulegan et al. (1969), in analyzing these 1960 readings, noted that "predominate periods of 80.0, 33.0, 22.0, and 18.0 minutes are clearly defined in all cases and can be accepted with confidence. These predominate periods are in good agreement with periods computed by consideration of the oscillations of the Crescent City area from the offshore area to the beach". Conclusions such these can be revisited using the recently scanned and digitized form of the 1960 recordings.

Scanning and Digitizing

A Contex FSS 4300 scanner was used to scan the rolls using various settings to enhance the trace and fade the background grid. After scanning, the images were digitized using a Matlab based program for use with seismic data (Bromirski and Chuang, 2003). The program was modified specifically to accommodate differences between the seismic and water level data types, including the much larger aspect ratio of the scrolls.

The tsunami records were digitized at 1-sample per second allowing the wind-generated gravity wave signal as well as the tsunami and other harbor waves to be captured. A scanned segment from one of the Citizen's Dock scrolls is shown in Figure 4a, with the digitized data for approximately the same time period shown in Figure 4b.

Preliminary spectral analysis shows the local gravity wave spectral variability in addition to apparently tidally-modulated signals (potentially either harbor or coastal edge wave related) at 100 s period, a higher harmonic at 50 s and the tsunami at longer periods. We anticipate that analysis of the temporal variability of the spectral levels both during and preceding the tsunami at Citizen's and Dutton's Docks will enhance the understanding of tsunami effects at Crescent City.

Figure 5 captures a longer time series of the first tsunami signals generated by the Chilean earthquake of May 22, 1960. For comparison, Figure 5 also includes the predicted astronomical tide obtained from the NOAA Tides and Currents Website: <http://tidesandcurrents.noaa.gov/> for station 9419750. The tide predictions were retrieved in intervals of 6 minutes. Maximum excursions of the tsunami signal from the predicted tide average about 3-4 feet (1m +/-). These high amplitude tsunami water level fluctuations persist for more than six hours, and will be studied in great detail when the digitized record is complete. The water level transfer function used in Figure 5 still needs some adjustment. The transfer function will be re-estimated

when more of the data are digitized, using the digitized record and the Crescent City tide gauge data.

Figure 4: (a) Segment of the scan from the May 22-23, 1960 scroll taken at Citizen's Dock in Crescent City. Scale markings and times (0400 and 0420) in PST appear on the chart record. (b) Digitized data corresponding to the approximate times of the scan in (a). Note that short period ocean gravity wave displacements are captured in the digitized data and can be identified in the scan of the chart recording.

Figure 5: Digitized water level data from Citizen's Dock compared with predicted tide levels.

Conclusions

The 1960 tsunami was fortuitously recorded on two analog Stevens type A-35 water level recorders that had been temporarily located in Crescent City Harbor by the US Army Corps of Engineers as part of a harbor seiche monitoring effort. The recorders were located across the harbor from each other, one on Citizen's Dock and the other near the Crescent City waterfront on Dutton's Dock about 1 kilometer away and were set for a relatively high resolution with a speed of one yard per hour.

These high resolution records are now being digitized, providing detailed time series from the second most damaging tsunami to impact Crescent City. The 1960 tsunami

signal appears to persist on both water level recorders for at least five days after the initial arrival, suggesting that the tsunami energy may have generated other wave types, such as edge waves (Munk et al. 1956).

The digitization of the water level data will allow spectral and statistical analyses so that the evolution of spectral characteristics with time can be observed and questions of tsunami resonance and the partitioning of the energy into wave types can be examined.

Time and frequency domain studies will help determine the return to background, marking the end of the tsunami influence. Understanding and forecasting event duration continues to be important as unexpected durations have caught local officials off guard as recently as the 2006 tsunami. In addition, it is anticipated that the digitized records will provide a source of data for various studies, not limited to those mentioned or to the tsunami itself.

We anticipate completing the complicated and tedious data scanning and digitization processes over the next several months, after which time the original analog data scrolls will be available through the San Francisco District of the US Army Corps of Engineers. The digitized data are scheduled for public release after our initial analysis is complete sometime in 2009.

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