Remarkable dependence between tsunami size in Japan and the Chilean parent earthquake’s magnitude

Matias Carvajal* (1), Alejandra Gubler (2)
(1) Escuela de Ciencias del Mar, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile
(2) Departamento de Obras Civiles, Universidad Técnica Federico Santa María, Valparaíso, Chile

*Contact e-mail: matias.carvajal.ramirez@gmail.com

Abstract. The far-field tsunami heights expected in Japan are highly dependent on the parent earthquake’s moment magnitudes that are sourced in Chile. A simple linear regression analysis was performed to find a relationship between Chilean earthquake’s size and the maximum tsunami heights expected in Japan, at the opposite side of the Pacific Ocean. The data set comprise the moment magnitudes ($M_w$) of the Chilean inter-plate earthquakes ($M_w > 8$) of 1960, 1985, 1995, 2010 and 2014, and their tsunamis recorded by tide gauges in the Japanese coast. The maximum tsunami heights were measured in de-tided marigrams. A radiation factor was introduced to remove this effect on the far-field tsunami data. This factor is obtained by comparing the maximum tsunami amplitudes predicted in Japan by synthetic earthquakes of equal magnitude located along the Chilean coast. Preliminary results show a remarkable high dependence on the maximum tsunami heights expected in Japan with the parent earthquake’s size sourced in Chile. The results of this study provide quantitative basis for two different purposes: to infer Chilean pre-instrumental earthquake magnitudes whose tsunamis were recorded by tide gauges in Japan and for increasing the reliability of the Japanese far-field tsunami warning system.

Keywords: Far-field tsunamis, tsunami radiation pattern, relation between earthquake and tsunami size, Japanese marigrams, trans-pacific tsunami modeling

1 Introduction

Several studies have presented empirical relations between earthquake magnitude and far-field tsunami size (e.g. Abe, 1979). The maximum tsunami height, defined as the maximum crest-to-trough vertical distance in a marigram, has been commonly suggested to be representative of the tsunami size (Abe, 1979; Abe, 1981; Suppasri et al, 2013). Because far-field tsunami heights are strongly affected by the wave’s radiation pattern, which depends upon the source location and fault’s properties (especially the fault’s strike), the relations have incorporated empirical correction terms as follow:

$$M = a \log(H) + b$$

Where $M$ is the earthquake’s magnitude, $H$ is the maximum tsunami height, and $a$ and $b$ are constants that depend upon the source region and the tsunami observation point.

Abe (1979) presented an empirical relation between large earthquakes sourced in the Chile-Peru region and the maximum tsunami heights expected in the Japanese coast. Nevertheless, the calibration was made with the data available at the time: this is the moment magnitude and tsunami data for the 1960 south central Chile earthquake ($M_w 9.5$) and the 1966 ($M_w 8.1$) and 1974 ($M_w 8.1$) Peru earthquakes. Moreover, the big latitudinal and fault’s strike differences between these events, yield to large differences in tsunami radiation patterns. Thus, the nature of the data involves significant errors. To minimize these errors, the analysis requires a more accurate statistical analysis. This is achieved by considering more and higher quality data, and a refined zonification of the tsunami sources.

In this paper, we exploit the old and robust Japanese tide gauge network, which widely recorded five instrumental Chilean earthquakes ($M_w > 8$), to improve the relationship between earthquake size, sourced in Chile, and the maximum tsunami heights expected in Japan.

2 Methodology

Following the 1960 event, at least four major earthquakes struck the Chilean territory, whose tsunamis were extensively recorded by tide gauges along the Japanese coast. The earthquakes occurred in different segments of the Chilean margin: in north (1995, $M_w 8.1$; 2014, $M_w 8.1$), central (1985, 8.0 $M_w$) and south-central (2010, 8.8 $M_w$) Chile (Fig. 1b). The quantity and quality of the tide gauge records together with the instrumental magnitudes of the parent earthquakes, provides the opportunity to find a more precise relation between Chilean earthquake size and maximum tsunami heights expected in Japan.

To achieve this, we first collected and analyzed Japanese tide gauge tsunami records linked to the Chilean earthquakes mentioned above. Secondly, we
established six tsunami source regions and assigned to each one a radiation factor. Finally, we performed a simple linear regression analysis between the Chilean earthquake’s moment magnitudes and the maximum tsunami heights recorded in Japan, corrected by its respective radiation factor.

2.1 Collection and analysis of tsunami data

The tsunami data is obtained from various sources. For the 1960 tsunami, we scanned and digitized the marigrams from The Committee for Field Investigation of the Chilean Tsunami of 1960 (1961). For the 1985 and 1995 events, we used the maximum tsunami heights, measured in marigrams, published by Watanabe (1998). The 2010 and 2014 tsunami digital marigrams were provided by the Intergovernmental Oceanographic Commission (www.ioc-sealevelmonitoring.org).

We determined the maximum tsunami height in each de-tided marigram. We first approximate the dominant tidal components and then removed them from the original records. Finally, the maximum tsunami heights in each record were determined from the zero up-crossing technique.

2.2 Tsunami radiation factor

A radiation factor ($R_f$) was introduced to remove this effect on the far-field tsunami data (Benmenahem & Roseman, 1972; Kajiura, 1970). This factor is obtained by comparing the maximum tsunami amplitudes predicted in Japan by synthetic earthquakes of equal magnitude (9.0 $M_w$) located in different segments of the Chilean margin (Fig. 1b).

We established six tsunami source regions of equal size: zones A, B, C, D, E and F, as shown in Figure 1b. We named these zones “Chilean tsunamigenic rupture zones”. For each zone we computed tsunami propagation across the Pacific Ocean to Japan. The tsunamis were produced by synthetic earthquakes of 600 km long and 150 km wide inter-plate ruptures, involving 12 m of uniform slip. We adopted local dip and strike angles, according to the global model of subduction zones SLAB 1.0 (Hayes et al., 2012). The slip angle was fixed at 90°, assuming a purely dip-slip faulting. The initial condition for the tsunami computation is provided by crustal deformation, which is computed by Okada’s (1985) equations. This assumes that sea surface and sea floor deformations are the same. The tsunami propagation is computed using a finite-difference method on actual bathymetry. We use the well-validated numerical model COMCOT, which solves the linear and non-linear shallow water equations (Wang, 2009). However, here we use the linear approximation as we limit our simulations to depths greater than 50 m (Shuto, 1991).

The maximum tsunami amplitudes, predicted by each rupture zone, were computed along an imaginary line located offshore Japan. We made this line to be the surface projection of the 500 m depth contour, to avoid possible non-linear components associated to topobathymetric features (Fig. 1c). The radiation factor for each rupture zone corresponds to the maximum positive amplitudes, averaged along this imaginary line and normalized over the maximum average obtained. Thus, the Chilean tsunamigenic rupture zone with the most tsunami radiation towards Japan is assigned a radiation factor of 1.

Figure 1. Chilean tsunamigenic rupture zones (b) and imaginary line (500 m depth contour surface projection) where maximum far-field tsunami amplitudes are computed (e). Rupture areas of the 1960 (Barrientos & Ward, 1990), 1985 (Comte et al., 1986), 1995 (Pritchard et al., 2002), 2010 (Moreno et al., 2012) and 2014 (Gusman et al., 2015) earthquakes are shown in b.

2.3 Simple linear regression

The linear fit between the Chilean earthquake magnitudes and their recorded tsunamis in Japan, was performed using the following expression:

$$M_{W_1} = \alpha \cdot \log (H_i/R_F) + \beta$$

Where $M_{W_1}$ corresponds to the moment magnitude of earthquake $i$, $H_i/R_F$ is the average of the maximum tsunami heights measured in the Japanese marigrams for event $i$, corrected by the associated radiation factor ($R_F$), and $\alpha$ and $\beta$ are the slope and intercept for the best linear fit, respectively.
3 Preliminary results

3.1 Tsunami radiation patterns of the Chilean tsunamigenic rupture zones

The maximum tsunami amplitudes predicted along the imaginary line depend upon the tsunami source. In general, tsunamis sourced in southern Chile have a higher radiation towards Japan than those sourced in the north. The F zone has the highest radiation, while the C zone, associated to north central Chile, has the lowest (Fig. 2; Fig. 3a). The low value of the C zone is discussed in section 4.

Figure 2. Tsunami radiation patterns, in the Pacific Ocean, predicted by synthetic earthquakes sourced in each Chilean tsunamigenic rupture zone. The lower case letters on the upper corners indicate the zones defined in section 2.2 and in Figure 1b.

3.2 Relation between Chilean earthquake magnitude and tsunami heights in Japan

Preliminary results show a high dependence ($r^2 = 0.995$) of the maximum tsunami heights expected in Japan, corrected by the radiation factor, with the parent earthquake’s moment magnitude (Fig. 3b).

4 Conclusions and implications

We exploit the old and robust Japanese tide gauge network to find a relationship between the maximum tsunami heights in Japan and the parent earthquake’s magnitude sourced in Chile. Tsunami heights were corrected by a radiation factor, which depends upon the region and the geophysical properties of the tsunami source. The linear regression shows a high correlation, with a coefficient of determination of $r^2 = 0.995$.

The remarkable linear dependence provides the opportunity to infer Chilean pre-instrumental earthquake magnitudes whose tsunamis were recorded by tide gauges in Japan, such as the 1906 (C-D zone) and 1922 (B-C zone) earthquakes. Because Japanese tide gauges recorded, in average, maximum heights of 24 and 49 cm, respectively, their magnitudes are estimated at $M_W 7.9$ and $8.6$. However, these estimates may be biased, because the method is sensitive to uncommon source depth. This parameter is especially important in the Chilean subduction zone, because unlike others, a significant portion of the seismogenic zone lies beneath the coast. This characteristic yields to a trade-off between coastal and water column uplift. For example, deeper ruptures produce more coastal uplifts and a minor tsunami than shallower ruptures. This is probably the case for the 1906 earthquake, where notable coastal uplifts and a little tsunami were reported (Lomnitz, 1970), suggesting a greater magnitude than the estimated here.

Similarly, this is possibly the main reason for the low radiation factor obtained for the Chilean tsunamigenic rupture zone C (Fig. 3a). This zone exhibits the shortest distance between the trench and the coastline, so that a greater portion of the energy released by the synthetic earthquake is transferred to land deformation and less to tsunami generation.

From a different point of view, the results of this study can be used as an additional tool for increasing the reliability of the Japanese far-field tsunami warning system. Because moment magnitudes are determined very quickly after the earthquake, the maximum tsunami heights expected in Japan can be easily predicted several hours before its impact on the Japanese coast.
References


