Travel time difference between estimated and observed values of the 2011 trans-oceanic Tohoku tsunami

by Latifatul Cholifah

Travel Time Difference between Estimated and Observed Values of the 2011 Trans-Oceanic Tohoku Tsunami

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Abstract – Difference in travel times between estimates from numerically simulated tsunami waves and records from field observations is vital for predicting tsunami arrival times at shorelines hence minimizing disaster risks. In this study, we provide estimated travel times of the 2011 Tohoku tsunami and compare them with observed travel time records provided by NOAA for a number of DART stations. We then find a systematic increase in the calculated travel time difference, termed as travel time delay, with increasing epicentral distance. The linear dependence of travel time delay upon epicentral distance suggests that the trans-oceanic tsunami wave in nature encountered geophysical disturbances, mainly due to the elastic effects of the solid Earth on bottom topography. This source of disturbance contributes to tsunami speed variations, leading to a time delay of up to 17 minutes for the wave to reach the first peak after the origin time of distant observations.

1. INTRODUCTION

The travel time of tsunami wave propagation from a tsunami source to a place where a station is located is one of important tsunami parameters. In the context of hazard mitigation, knowledge of accurate tsunami travel times is required to accurately predict arrival times of a tsunami at shorelines that is useful for minimizing disaster risks. Previous work [2, 3, 4, 6] have confirmed that gigantic, trans-oceanic tsunamis propagating across the Pacific with a travel distance of more than thousands of kilometers away from the epicenter revealed systemic differences in tsunami travel times between simulated and observed waves. The differences were then arguably attributed to tsunami speed variations in nature while advancing over large distances compared with the non-dispersive speed of a tsunami predicted by the long, surface gravity wave approximation, as addressed in [2, 3, 5]. In this study, we extract estimates of travel times from tsunami waveforms discussed in relevant work [6] and compare them with those obtained from field records. In turn, we examine travel time delay in place of the calculated travel time difference in relation to epicentral distance.

Here we provide basic assumptions commonly made for the case of shallow-water, surface gravity waves in numerically modeled tsunamis that include a homogeneous fluid of seawater with no density stratification and flat-bottomed sea floor. Such assumptions lead to the theoretical, non-dispersive speed c of a propagating tsunami as follows

$$c = (gH)^{1/2} \tag{1}$$

where g denotes the gravitational acceleration and H is the ocean depth. For a typical ocean depth of $H \sim 5$ km, the tsunami speed is about 720 km/h. However, as discussed in [2] the propagating speed is limited by a factor originated from loading effects of seafloor deformation on the bottom topography as given by

$$c = (gH)^{1/2}\,(1-\beta)^{1/2} \tag{2}$$

where β is the factor representing such effects that result in the speed reduction relative to (1) by as much as 1%. On the basis of (2), we argue that tsunami speed variations occur while propagating over large distances across the ocean, as also suggested by [3, 5]. These variations in speed lead to apparent tsunami travel time differences between values estimated from numerical simulations and those obtained from direct observations [4, 6].

2. METHODS

For the case of the 2011 Tohoku tsunami examined in this study, we have utilized a number of numerical data providing travel time datasets visually derived from the first peak of simulated tsunami waveforms recorded at various geographical locations of the Deep-ocean Assessment Reports of Tsunamis (DART) stations discussed by [6]. These datasets represent estimates of tsunami travel times, and in comparison with the observed values of travel times taken from either the National Oceanic and Atmospheric Administration (NOAA) or similar stations in [6], the data sets allowed us to calculate travel time differences simply. The differences in travel times were tabulated and classified into three regions of observations, depending upon a particular DART location measured from the source, namely near-field, intermediate-range, and distant measurements. We argue here that the data from near-field measurements were values provided by DART codes positioned less than 3,000 km away from the epicenter. Intermediate observations were then obtained from DART stations located between 3,000 km and 12,000 km, comprising the majority of the field data used in the current study. Monitoring of far-field regions for this case was provided by DART stations located more than 12,000 km away. All the differences were termed as tsunami travel time delay plotted against epicentral distance to see systematic delays, as the wave propagates away from the source to large travel distances across the Pacific. The results are discussed within the context of tsunami speed variations as predicted in (2) by [2] and also addressed by [3, 5], as well as reported by [4, 6] as the apparent travel time delay for distant tsunamis.

3. RESULTS AND DISCUSSIONS

As previously stated, Table 1 describes a total of 13 DART stations located at different geographical positions used in this study, covering three regions of field observations with increasing epicentral distances and providing a list of corresponding estimated and observed travel times. The difference in travel times was then defined as travel time delay, measured in minutes.

Table 1. The data for the 2011 Tohoku event with travel time delay is defined as the travel time difference.

DART Code	Observational Location	Latitude	Longitude	Epicentral Distance (km)	Estimated Travel Time (h)	Observed Travel Time (h)	Travel Time Delay (min)
21413	near-field	30.51° N	152.12° E	1,246	1.29	1.30	0.6
21415	near-field	50.18° N	171.85° E	2,670	3.14	3.18	2.4
52402	intermediate	11.88° N	154.12° E	3,165	3.71	3.76	3.0
52403	intermediate	4.05° N	145.59° E	3,828	4.91	4.97	3.6
46409	intermediate	55.30° N	211.48° E	5,344	6.71	6.78	4.2
52406	intermediate	5.29° S	165.00° E	5,388	6.71	6.80	5.4
51407	intermediate	19.59° N	203.41° E	6,183	7.63	7.74	6.6
51425	intermediate	9.51° S	183.76° E	6,839	8.11	8.23	7.2
46411	intermediate	39.35°N	232.98° E	7,486	9.23	9.35	7.2
43412	intermediate	16.07° N	253.00° E	10,619	13.40	13.59	11.4
51406	intermediate	8.48° S	234.97° E	10,828	13.37	13.59	13.2
32411	far-field	4.99° N	269.16° E	12,741	16.57	16.82	15.0
32412	far-field	17.97° S	273.61° E	14,816	18.90	19.18	16.8

The data listed in Table 1 in particular columns providing distances to which the wave travels from the epicenter and time delays with which the simulated wave is predicted to arrive earlier at larger distances indicate a linear dependence of the delays upon epicentral distances. This is not surprising in that in regions far from the tsunami source the observed speed predicted in (2) is slowed down by ~ 1% from its value derived from the long, surface gravity wave approximation due to topographic variation effects along tsunami propagation. We provide a plot of the linear dependence of the time delay on the travel distance in Figure 1 below.

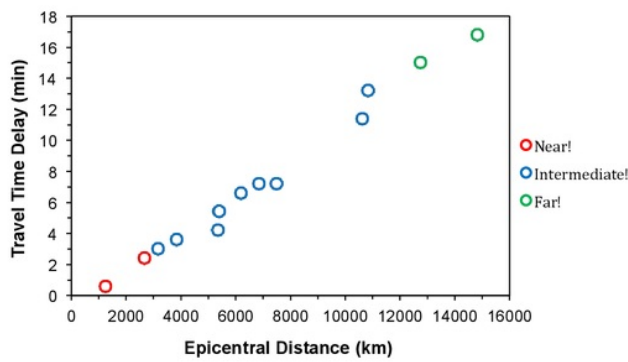

Figure 1. Travel time delay as a function of epicentral distance for the 2011 Tohoku event.

Some interesting features are drawn from careful examinations on the plot. At a near-field region of observation, particularly for travel distances of less than 1,000 km, the time delay is insignificant, meaning that there is no apparent travel time difference between the simulated and observed waves. This is supported by [1] stating that tsunamigenic earthquakes recorded at stations in the radius of less than 1,000 km from the earthquake epicenter are classified into local events. We argue here that this covered travel distance by such events is, to some extent, not much influenced by the geometry of the elastic, solid Earth and hence giving no delayed propagation times. The near-field observations cover a travel distance of up to 3,000 km away from the source and correspondingly take a travel time of up to 4 hours for the trans-oceanic wave with a typical speed of 720 km/h to travel across the ocean with only limited amount of energy loss and with no significant perturbations with respect to changes in its waveforms [4, 5, 6]. For this region, the speed variation is responsible for a slight increase in the time delay of up to 1.0%.

For regions in the range 3,000 – 12,000 km away from the source (intermediate regime – open blue circles in Figure 1), the travel time delay appears in a manner reflecting that the estimated travel times are systematically shortened relative to the observed values. The delays are found to be in the range 3.0 – 15.0 minutes, in good agreement with some of the previous work [4, 6]. As travel distance increases, more geophysical disturbances upon the tsunami wave propagation come into play reducing the speed, relative to (1), to a varying value of 1.3 – 1.6%. This speed reduction is effectively consistent with a maximum value of 1% obtained from numerically predicted speed given in (2) as discussed by [2, 3] and also addressed by [7].

At remote locations where the giant wave travels to a distance of more than 12,000 km away from the source or equivalent to a traveling time of more than 16 hours, a further reduction in speed gives a longer time delay of more than 15.0 minutes, visually seen as two green open circles in Figure 1. However, the longer delays found in these field observations give no significant change in the proportion of speed reduction relatively compared with the wave speeds relevant to the observed travel times. In other words, for the distant measurements as listed in the last two rows of Table 1 a maximum value of the time delay of 16.8 minutes only corresponds to a reduction in the speed of approximately 1.5%, lying in the range of values given in the intermediate regime.

The results for all regions of space for tsunami monitoring considered in this study is a bit surprising in the sense that while the time delay taken up by the computed and observed waves increases the proportion of the reduced speed is relatively fixed with the small reduction only at a value of 1.0 – 1.6%, in good agreement with [2, 3, 7]. It should be noted here that there are at least two logical consequences that can be drawn from these findings. Firstly, it is true to say that tsunami wave speed varies primarily with the external, local parameters, such as bathymetry effects on the topography induced by seafloor deformation [4, 6, 7]. Secondly, the reduction in tsunami speed in correlation with the propagation of a tsunami wave indicates that some amount of energy is lost. The loss of energy needs clarifying regarding calculations of energy dissipation incompressible fluids that go beyond of the present study and therefore this issue is promising for future work.

4. CONCLUSIONS

We have calculated the travel time delay defined here as the difference in travel times between simulations and observations for the 2011 Tohoku, trans-oceanic tsunami. We have divided the Pacific into three zonal divisions, namely near-, intermediate-, and far-field observations at which the time delay is determined. The delay is found to increase linearly with increasing epicentral distance and is then measured to be of up to 17 minutes estimated from the origin time for distant DARTs managed by NOAA. The tsunami speed variation in nature is believed to cause such delays, where the observed speed is reduced by 2% from its value calculated using the shallow-water wave theory. The speed reduction is primarily caused by the Earth elasticity in terms of topographic variations of the ocean.

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