A systematic decrease in tsunami amplitude with epicentral distance

by Tjipto Prastowo

A Systematic Decrease in Tsunami Amplitude with Epicentral Distance

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Abstract – The dynamics of tsunami wave propagation in the open ocean includes discussion on the behavior of tsunami amplitude while propagating over time and distance. In this study, we use data records of sea surface displacement considered as the wave amplitudes of the 2011 Tohoku tsunami monitored by 14 DART buoys at various positions across the Pacific to examine tsunami energy decay in terms of the decrease in the amplitude with increasing epicentral distance. The data reveal the fact that the amplitude decreases sharply in the near-field observation and decreases gradually while covering a travel distance of up to 15,000 km away from the source. This suggests that there are at least two different mechanisms of energy release in near-field and distant tsunamis but the details of the mechanisms go beyond of the present study. The amplitude attenuation is then discussed in the context of dispersive tsunamis with the importance of frequency-dependent speed in the far-field only.

1. INTRODUCTION

The need for a better understanding of the behavior of tsunami wave energy and amplitude with respect to travel time and distance from a particular tsunami source while a tsunami wave propagates in the open ocean is crucial for the development of the reliable tsunami early warning system and hazard assessment [1, 6]. Prediction of water run-up as the giant wave approaches a coastline requires knowledge of accurate tsunami amplitude measured in the ocean. Although previous work [2] has suggested that a large tsunami could travel great distances across the ocean with only limited amount of energy loss, careful examination and analyses of tsunami waveforms from observations and simulations have clearly indicated a systematic decrease in the maximum wave amplitudes of a propagating tsunami with increasing epicentral distance [3, 5, 7].

In the limit of non-dispersive long wave propagation theory, the phase speed of a tsunami is only determined by the external parameter, namely the ocean depth H. For this approximation; the tsunami speed c is given by

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

where g is acceleration due to gravity. Regardless of the Earth's imperfectly spherical surface, g is considered constant across the globe and hence for a relatively constant depth of the open oceans the tsunami generated by a large earthquake moves at a constant speed with no loss of kinetic energy during its propagation, independent of zonal divisions of observation.

However, from records of travel times, the speed given in (1) remains true for only near-field measurements, and it starts to slightly deviate from the predicted value in (1) for adequately distant tsunami observations [3, 5, 7, 8]. It follows that for global trans-oceanic tsunami propagation there may be energy decay due to dispersion effects. Previous studies [6, 8] have addressed these effects and suggested the significance of frequency-dependent speed for dispersive tsunamis, particularly for far-field observations. As wave energy is proportional to the square of wave amplitude, the energy decay of a tsunami wave can be examined in terms of tsunami amplitude decrease while advancing over large distances in the ocean. In this preliminary study, we show the spatial distribution of the decreased amplitude from the 2011 Tohoku event and discuss a functional relationship that is likely possible for the decrease in the observed amplitudes with respect to travel distances measured from the epicenter.

2. METHOD

We have used a major tsunami event, namely the 2011 Tohoku tsunami as a case study reported in this study. The mega-tsunami event was generated by a large earthquake with a magnitude of M_W 8.9 and its hypocenter off the northeastern-coast of Japan that occurred on March 11, 2011, at 5:46 UTC, causing a devastating giant wave initially formed only 5 minutes after the main-shocks. The epicenter of the tsunami was at 38.3º N and 142.4º E.

We have then utilized field data records of vertical sea surface displacement of disturbed seawater monitored by 14 Deep-ocean Assessment Reports of Tsunamis (DART) buoys distributed over various geographical positions around the Pacific rim, from nearby the source at 1,246 km away (DART-21413) to a distance of 14,816 km away from the epicenter (DART-32412). The data records in the form of tsunami waveforms from which tsunami amplitudes were estimated are made freely available at http://www.ngdc.noaa managed by the National Geophysical Data Center (NGDC) as part of the National Oceanic and Atmospheric Administration (NOAA). The observed amplitudes given by all the DART buoys are then plotted against travel distances measured from the source to examine the observed variations in tsunami amplitude with increasing epicentral distance.

3. RESULTS AND DISCUSSIONS

Table 1 below describes a total of 14 DART buoys located at different geographical positions across the Pacific used in this study, covering broad regions of tsunami observations from the nearest position, DART-21413, to the far station, DART-32412. A list of the epicentral distance measured in kilometer away from the tsunami source and its corresponding observed amplitude measured in meter from the sea surface is provided.

Table 1. Fields of observation for the 2011 Tohoku event using DART buoys.

DART Code	Latitude	Longitude	Epicentral Distance (km)	Observed Amplitude (m)
21413	30.51° N	152.12° E	1,246	0.76
21415	50.18° N	171.85° E	2,670	0.25
52405	12.88° N	132.33° E	3,001	0.36
52402	11.88° N	154.12° E	3,165	0.30
52403	4.05° N	145.59° E	3,828	0.28
46409	55.30° N	148.51° W	5,344	0.20
52406	5.29° S	165.00° E	5,388	0.17
51407	19.59° N	156.58° W	6,183	0.16
51425	9.51° S	176.24° W	6,839	0.10
46411	39.35°N	127.02° W	7,486	0.18
43412	16.07° N	107.00° W	10,619	0.13
51406	8.48° S	125.03° W	10,828	0.07
32411	4.99° N	90.84° W	12,741	0.11
32412	17.98° S	86.39° W	14,816	0.04

We here provide a plot of the tsunami amplitude against the epicentral distance measured from the source in Figure 1 below and discuss consequences from the apparent trend in the plot. We focus on providing arguments based on physical grounds that are sensible for the explanation of the decreased trend in the observed amplitudes with increasing epicentral distances.

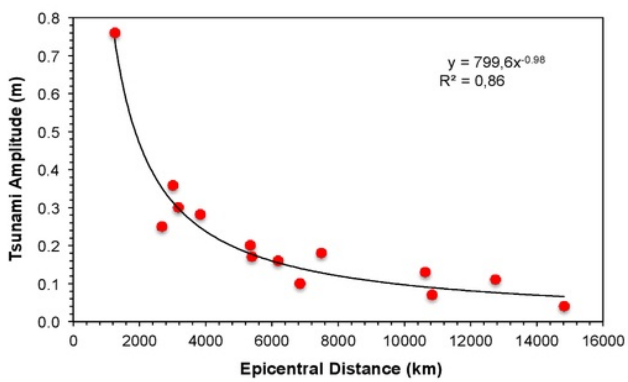

Figure 1. Tsunami amplitude as a function of epicentral distance for the 2011 Tohoku event.

The data points in Figure 1 indicate that there are two possible mechanisms of energy release in the context of mechanical energy conservation during the rapid generation and propagation of a tsunami wave in the ocean. The first mechanism is likely to the extent within a few hours (of about 4 hours) calculated from tsunami origin time. This duration is estimated at the time when sea surface elevation was recorded at 0.76 m by DART-21413 at about 1,250 km away from the source to the time when the mean sea level change was measured to be 0.30 m given by a group of three stations: DART-21415, 52405, 52402, where the average position is about 3,000 km away from the epicenter. This period of time where the energy decay was rapid is considered as the initial stage.

The initial stage of the energy release is arguably linked to mechanical energy available for the tsunami wave generation and is dominated by the gravitational collapse of initial potential energy that is directly converted into kinetic energy during a phase of the tsunami generation. This phase could extend to several hours of propagation and in Figure 1 it takes approximately 4 hours, which is relevant to a travel distance in the near-field observation, from zero points to a distance of approximately 3,000 km away from the source if the tsunami speed is taken to be in the order of 750 km/h.

Following the initial development of the gigantic wave, the second stage occurred during the tsunami passage in the ocean from the time when the propagating wall of seawater reached a quasi-steady state at the upper end of the near-field station (of about 3,000 km away) to more than 14,000 km away from the epicenter, proportional to a total time of approximately 15 hours traveling across the Pacific, spanning over basin-wide. This wider range of observations is named intermediate to distant observations. In this stage, the actual rate of the energy decay and hence the amplitude attenuation is much slower than the previous stage, indicating that there may be the interplay between potential energy change and its corresponding change in kinetic energy. This energy budget, however, is out of the scope of the present study and at present, it is enough to say we leave this challenging issue for future work.

Another interesting argument for the decreased trend in the observed amplitude with travel distance comes from a theoretical point of view. Instead of using the non-dispersive, long surface gravity wave approximation where the speed is predicted in (1), some modelers have used dispersive tsunamis to modeling tsunami propagation. The inclusion of dispersion effects results in different features as these effects play a crucial role in modifying the energy and hence the corresponding amplitude for the distant propagation of global trans-oceanic tsunami [6, 8]. For this approach, the speed of a tsunami wave is written in terms of the dispersion relation as follows,

$$c^2 = g/k \tanh(kH) \tag{2}$$

where $k = 2\pi/\lambda$ and λ represents the wavelength of a tsunami wave. Thus, the speed of a propagating tsunami can be different for various wavelengths of dispersive tsunamis. Equation (2) is, therefore, the general form of (1) in the sense that if kH is extremely less than unity than the shallow-water approximation applies, modifying (2) to be (1). Using the concept of frequency dispersion as a measure of the spread of tsunami energy over time and space along the direction of advancing front owing to different wavelengths, [6] convincingly demonstrated that waveforms developed from simulations had slightly lower amplitudes relatively compared with those obtained from observations in all cases considered. It was found that dispersion effects accumulate in time and space, and thus such effects are less important for near-field observations and become important for distant tsunamis.

While [4] have argued that the tsunami energy density decreased with the vertical length scale, *i.e.*, the depth of the ocean, the results of the present study clearly show that the open-ocean amplitude is likely to be inversely proportional to the epicentral distance, with a proportionality constant that is not yet clearly explained. Further reduction in the tsunami energy includes other external factors, such as the irregularity of bottom topography and shallow coastal shelves, as discussed by [1].

All the above arguments explaining the decay of the energy and hence the observed amplitude in this study have been an increasing issue in recent years for the development of reliable tsunami prediction off and on shores in the context of reducing hazard risks. Tsunami warnings are important not only for people living in local regions within the perimeter of the near-field measurements but also lives in remote areas within the distant observations. This is in line with the findings of some previous work [1, 6, 8], addressing the significance of dispersion effects on limiting the energy propagation particularly for the far-field only. Therefore, enhanced tsunami prediction of arrival times and tsunami heights using accurate simulations by adding factors, such as the frequency content of tsunami sources and the geometry of subsurface structures in the governing equations describing the generation and propagation of a trans-oceanic tsunami is of fundamental importance for the far-field tsunami measurements.

4. CONCLUSIONS

We have examined tsunami wave energy decay in terms of tsunami wave amplitude attenuation with distance measured from the epicenter. The datasets of the observed amplitudes and the corresponding epicentral distance were provided by 14 DARTs operated by NOAA around the Pacific rim that monitor the 2011 Tohoku tsunami from different zonal divisions of observations. The results indicate that the observed amplitude decreases rapidly during the initial stage of the tsunami generation relevant to the near-field and decreases steadily for the rest of the stage reaching the far-field points of measurements. The role of wave dispersion effects owing to the frequency content of the wave is found to be vital particularly for distant tsunami monitoring.

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