Spectral Characteristics of Wave Breaking and Dissipation in Combined Tsunami-Swell Wave Conditions

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INTRODUCTION:
Tsunamis are generally treated as singular phenomena, and often their interactions with the surrounding oceanographic or sedimentary environment are not fully studied. There is evidence that their interaction with other phenomena (tides, background vorticity, etc.) can have a measureable effect on the tsunami characteristics. Tsunamis, during the course of transformation, can also generate smaller scale features which themselves can interact with the oceanographic surroundings.

Left: Pictures from Koh Samui Island, Thailand, prior to inundation from the 2004 Indian Ocean tsunami. Copyright: Andrea Graviss

Kaithai and El Safy (2011) conducted laboratory tests which showed that the tsunami (modeled as a solitary wave) broke further offshore with random swell present in the tank than without. Separation of the short and long wave motions via wavelet analysis of Tian et al. (submitted) shows that the steepness of the long wave with the short waves present reaches a maximum further offshore than if the long wave were run in isolation. Building on these findings, a series of laboratory experiments were proposed in which the interactions between tsunamis and other oceanographic features (short swell, bottom sediment) were modeled.

LABORATORY EXPERIMENTS:
Two experiments were run in the Large Wave Flume at the O.H. Hinsdale Laboratory at Oregon State University. Random waves were run along with a solitary wave representing the tsunami) and a series of cnoidal waves (representative of the short waves generated by the tsunami). Resistance wire gages and ultrasonic gages measured the free surface elevations. Velocities were measured with ADVs and acoustic profilers. For the first set of experiments (Feb-Mar 2013), a sediment bed was located in the horizontal portion of the tank, and was exposed to the waves for part of the experiment. Sediment concentrations were measured with OBS and the evolution of the sediment bed was measured with a pencil beam sonar. For the second set (Aug-Sep 2014) no sediment was used, and an uninterrupted concrete slope was used in the tank.

SPECTRAL DISSIPATION:
Our focus for this work will be the second phase of the experiment, as there were more instruments in the very nearshore measuring free surface elevations and velocities. With these measurements, we are able to closely follow the evolution of the waves through the shoaling and breaking zones.

Wave conditions consisted of tsunami, cnoidal wave trains, and tsunamis. These conditions were run in isolation and in tandem (swell-tsunami and swell-cnoidal waves). For the ease of wave interaction with tsunami, multiple random realizations were run in order to overcome any effects of relative phasing between the random swell and the tsunami.

Combined swell-cnoidal waves – spectral signature of breaking and dissipation:
As is evident from the Graviss photos, there is a very strong coherent structure leading the front face of the landfalling tsunami. Work on characterizing the spectral evolution of random breaking waves (e.g. Kaithai et al. 2007 JGR) have shown that the shape of the tail of the free surface elevation spectrum approaches a J^-1 dependency in shallow water, while the frequency dependence of the dissipation rate of J^-3 approaches J^-1. However, Kaithai and El Safy (2010 ICEC) show that this dependency is destroyed in the case of a very narrow banded process such as wave groups. Our interest here, then, is to see what the effect of an underlying coherent wave train is on the dissipation characteristics and spectral signature of random waves.

The instantaneous dissipation in a wave train can be deduced using the adiabatic vorticity mechanism of Zelt (1991 Coastal Engineering):

\[ \dot{e} = -\rho g \nabla (H^2) \]

The rate of dissipation \( \dot{e} \) can be calculated from the dissipation and free surface spectra:

\[ \dot{e} = \frac{\rho g H^3}{12} \int \left( \frac{\omega}{f} \right)^2 \frac{\omega}{f} \text{d}f \]

The rate of dissipation is related to the free surface amplitudes \( A_n \):

\[ \frac{\partial^2 A_n}{\partial t^2} + c_n^2 A_n = - \alpha A_n \]

The power of the frequency dependence for the spectral tails of both the dissipation rate \( \dot{e} \) and free surface spectra \( S_H(f) \) were calculated for both random waves and random waves with cnoidal waves. In situations where the presence of the cnoidal wave impacts the frequency dependence noticeably during shoaling and breaking, the evolution of the frequency dependence with depth is always suppressed.

Random Wave – Tsunami Interaction: Bulk Dissipation Estimates

Standard FFT-based dissipation analysis similar to that done for the cnoidal – random wave combination would not be as revealing for the case of random wave - tsunami interaction, as the highly transient tsunami would not have a strong signature in the spectrum, despite having several random realizations of tsunami-random wave interactions. While we analyze these signals using FFT in order to evaluate the dissipation spectrum in the same manner, we evaluate the overall bulk dissipation over the entire spectrum.

The bulk dissipation can be calculated from estimates of the dissipation rate \( \dot{e} \) as:

\[ \dot{E} = \int \dot{e} df \]

The dissipation rate \( \dot{e} \) is calculated using the instantaneous dissipation of Zelt (1991 Coastal Engineering), as before.

Bulk dissipation estimates for random waves and random wave – tsunami interaction are shown below as a function of depth. For the most part, the trends in the bulk dissipation are quite similar between random waves and random waves – tsunami combinations. To the extent that differences exist, the presence of the tsunami appears to reduce the overall bulk dissipation of the combined random waves – tsunami conditions.

Analysis of Combined Random Wave – Tsunami Interaction With Short-Time Fourier Transforms

In order to uncover more details regarding the spectral signature of dissipation in combined random wave – tsunami conditions, short-time Fourier transforms were used to generate spectrograms of these combined signals. Our future work will entail using information from these spectrograms to quantify the inter-frequency detail of the dissipation in these combined conditions.


Spectrogram of random swell (top row) and combined swell – tsunami (middle) for H=1m, T=6s, and tsunami height = 0.85m. Bottom row is the difference between combined and random spectrograms.

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