Experimental data analysis of wave attenuation in mangroves

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Abstract. The ability of mangrove forest to absorb wave energy was reported in several tsunami events. However, characteristics of mangrove trees that can often withstand the impact of tsunamis, as well as their ability to absorb wave energy, are still an interesting area of research. Based on the experiments conducted in a wave flume at Balai Penelitian dan Pengembangan Pantai, Buleleng, Bali, the effectiveness of mangrove swamps in reducing wave energy was studied. In the wave flume, paddles were put in motion in order to produce monochromatic wave influx. These waves propagate into the domain, then passing through mangrove forest, and further up till the wave was reflected back by the right hard wall boundary. In this article, the Mansard-Funke 3-point method was implemented to decompose the recorded wave signal into incident and reflection waves. Furthermore, the reflection and transmission coefficients were calculated. From sensitivity analysis of experimental data using various water depth and wave period, we found that in a 3 meter length of mangrove, the wave energy was dissipated up to 64%.

1. Introduction
Nowadays, the impact of climate change affected by global warming is increasingly severe. Sea level rises which will cause erosion, and the worst even small islands are threatened with drowning [1]. Some efforts have been done to prevent this phenomena, such as constructing the hard engineering structure along coastal area. Unfortunately, this kind of construction is very costly, beside that such construction may also damage natural ecosystems of animals or plants living on the coastal area.

One alternative to protect coastal areas is by constructing breakwater using soft engineering approach. Mangroves are the living natural vegetation of coastal area. Several field studies [2] reported the role of mangrove forest that might replace the hard engineering structures in reducing the amplitude of the wave. Also mangrove forest play an important role in shoreline protection. From the ecological side, they also can save the natural ecosystem around the coastal area. However, from engineering aspect, the role of mangroves as breakwater still needs further study. Several parameters like the length of mangrove swamp, as well as mangrove density, water depth, and also the frequency of incoming wave clearly affect the amount of wave energy dissipated in mangrove. In recent years, many researchers have conducted experimental
studies on wave attenuation by mangroves, see for instance [3], [4] and [5]. Such an experiment was conducted in a wave flume at Balai Penelitian dan Pengembangan Pantai, Buleleng, Bali, Indonesia, see [6]. Having a set of experimental data, one still need to conduct wave spectra analysis in order to separate the reflected wave and from the recorded wave signal. Then determine the reflected and transmitted coefficients, and that is the goal of this paper.

Here, we adopt the method of Mansard and Funke, 1980 [7]. Essentially, this method requires wave signal that are recorded from three different wave probes along the wave flume, and decomposing the measured spectra into incident and reflected spectra. Compare to the previous 2 point method, this 3 point method is preferable it has a wider frequency range of application, moreover the method is less sensitive to noise and probe spacing. For the sake of clarity, here we give a short resume of the Mansard-Funke method.

2. Mansard-Funke Method
In separating the incident and reflected wave spectra, Mansard-Funke method need the recorded data of wave signals from three different locations as the input. Actually the recorded wave signal consists of a superposition several wave components i.e. incident wave, reflected wave, as well as noises. Let recorded data of wave signal in a probe denotes by following expressions:

\[ \eta(x,t) = \sum_{k=1}^{N} C_{lk} \exp\left(-\frac{2\pi kt}{T} + 2\pi \frac{X_{l}}{L_{k}} + \theta_{k}\right) + \sum_{k=1}^{N} C_{rk} \exp\left(-\frac{2\pi kt}{T} + 2\pi \frac{X_{r}}{L_{k}} + \theta_{k} + \phi_{k}\right) + \Omega_{1}(t) \]

where \( C_{lk} \) is incident wave components, \( C_{rk} \) is reflected wave components, \( T \) is wave period, \( L_{k} \) is wave length of frequency \( k/T \), \( X_{l} \) is the distance from the wave source to the probe, \( X_{r} \) is the distance from wave source to the probe after passing the reflecting structure, \( \theta_{k} \) is some arbitrary phase related to space and time origin, \( \phi_{k} \) is phase change due to reflecting structure, and \( \Omega_{1}(t) \) is cumulative effect of all corrupting signals at probe. The procedure of Mansard-Funke method started by using Fourier Transform to extract wave information of wave signals into wave spectra. Fourier Transform of (1), yields

\[ B_k = Z_{I,k} + Z_{R,k} + Z_{N,k} \]

where

\[ Z_{I,k} = C_{I,k} \exp \left( \frac{2\pi \cdot X_{I}}{L_{k}} + i \cdot \theta_{k} \right) \]
\[ Z_{R,k} = C_{R,k} \exp \left( \frac{2\pi \cdot X_{R}}{L_{k}} + i \cdot (\theta_{k} + \phi_{k}) \right) \]
\[ Z_{N,k} = Y_{k} \exp i \cdot \rho_{k} \]

Since Mansard-Funke method use three different probes along the wave flume, then we will obtain three linear equation. By applying least square method we minimize the noise as the cumulative effect of corrupting signals \( (Z_{N,k}) \). Then, by solving the three linear equation, we will obtain the separated wave spectra; i.e. incident spectra \( (Z_{I,k}) \) and reflected spectra \( (Z_{R,k}) \).

3. Wave dissipation in mangroves
The experiments were conducted in a wave flume of laboratory experiments at Balai Penelitian dan Pengembangan Pantai, Buleleng, Bali. Our study of wave attenuation in mangrove is conducted here by analyzing experimental data.
3.1. Experimental set up
The sketch of experimental set up shown in Figure 1(a), in which bottom topography consist of constant water depth \((d_0)\), followed by three segments of mangrove with the length of each mangrove segment is uniform \((L_M)\), and depth of water emerged the mangrove \((d_M)\). In this experiments, on the left side of the wave flume, there was a wave maker to produce the incoming wave and on the right of channel there was a hard wall. Wave signals were recorded simultaneously at 7 locations, denotes by \(p_1, p_2, \ldots, p_7\), that were installed along the wave flume.

The wave flume has the following dimension: length \(L = 32.16\) m and width \(W = 1\) m. This quite long and narrow wave flume is suitable for our 1D study of wave attenuation by mangrove. All experiments were performed with the following fixed parameters: \(d_0 = 0.3\) m and total length of mangrove \(3L_M\) with \(L_M = 1\) m. The artificial mangroves that we used in this experiments is shown in Figure 1(b).

For Mansard-Funke algorithm wave signals at three adjacent probes is needed, here we used the recorded wave signals at \(p_1, p_4\) and \(p_7\) which are located at 25.87 m, 26.58 m and 32.01 m from the wave maker respectively. This set of choice should involve at least 1 probe behind the mangrove. The experiments vary wave parameters such as wave amplitude \((h)\) and wave period \((T)\), whereas mangrove parameter: mangrove density \((\rho_M)\). In fact all experiments that we analyze here use \(d_M = 0\) (emerged mangrove) and \(d_M = 0.05\) m (submerged mangrove). Several experiments were conducted in order to test the sensitivity of both wave and mangrove parameters on wave dissipation.

3.2. Sensitivity Analysis
In this section we present some results of our experiments to investigate how wave and mangrove parameters influence the wave spectra. The first experiment was conducted using parameters: \(h = 0.09\) meters, \(T = 2\) seconds, \(\rho_M = 1\) trees/m². As shown in Figure 2(a), the wave spectra of incident and reflected wave are significantly different.
Figure 2. Incident and reflected wave spectra. (a) result of experiment I with $h = 0.09$ meters. (b) result of of experiment II with different wave amplitude $h = 0.15$ meters. (c) result of experiment III with different wave period $T = 1.4$ seconds. (d) result of experiment IV with different mangrove density $\rho_M = 0.25$ trees/m$^2$.

The second experiment result is shown in Figure 2(b). This experiment was conducted using higher incoming wave height than experiment I ($h = 0.15$ meters). Compared with the experiment I, for higher incoming wave height is given higher peak of wave spectra. Besides the higher peak of the wave spectra, in incident wave spectra another peaks that have significant heights appear.

Next, we present the result of experiment III with smaller wave period than experiment I. The result is shown in Figure 2(c). As we can see that the highest peak of wave spectra occur when the wave period is 1.4 seconds. In this result, the peak that appears is not as much as other experiments.

The result of experiment IV is shown in Figure 2(d). This experiment was conducted using smaller mangrove density ($\rho_M = 0.25$ trees/m$^2$) than experiment I. The result is quite the same, although the peak is little higher than experiment I.

From result of some experiment above, the incident and reflected wave spectra are sensitive to wave parameters i.e. incoming wave height and wave period. In fact, the area under the spectra density, is actually represent the total wave energy. Discussion on wave energy dissipation and the results of all experiments will be given in the next section.
3.3. Energy dissipation in mangrove

In this section we discuss about wave energy dissipation. Energy dissipation is calculated by reflected and transmission coefficients. According to [8], the reflected and transmitted coefficients are determined by using the following formulas

\[
C_R = \left( \frac{\int_0^\infty S_R(\omega)d\omega}{\int_0^\infty S_I(\omega)d\omega} \right)^{1/2} \quad \text{and} \quad C_T = \left( \frac{\int_0^\infty S_T(\omega)d\omega}{\int_0^\infty S_I(\omega)d\omega} \right)^{1/2},
\]

where \( S_I(\omega) \), \( S_R(\omega) \) and \( S_T(\omega) \) are the incident wave spectra, reflected wave spectra, and transmitted wave spectra, respectively, \( \omega \) is frequency. The incident and reflected wave spectra are computed by calculating area under the curve (Figure 2) using trapezoidal integration function in MATLAB. Meanwhile, the transmitted wave spectra \( S_T(\omega) \) is obtained from auto-spectra of wave signal behind the mangrove (corresponding to data of \( p_7 \)) and we do the same way (as computing the incident and reflected wave spectra) to compute the transmitted wave spectra. Next, by the principal of energy conservation we got this following expression

\[
\int_0^\infty S_I(\omega)d\omega = \int_0^\infty S_R(\omega)d\omega + \int_0^\infty S_T(\omega)d\omega + \int_0^\infty S_D(\omega)d\omega.
\]

By dividing each terms in (4) by \( \int_0^\infty S_I(\omega)d\omega \). Therefore we obtain the following relations

\[
C_R^2 + C_T^2 + C_D^2 = 1,
\]

in which \( C_D \) is dissipation coefficient. Here \( C_D \) indicates how much energy is dissipated by mangrove. Reflected coefficient \( C_R \) describes the reflectance of mangrove. Transmitted coefficient \( C_T \) describes the transmission rate of wave passes through the mangrove. To discuss further about dissipation mechanism of mangrove, we calculated reflection and transmission coefficient of our experiments by using (3). Next, by adopting (5) we can calculate the amount of dissipated energy (\( C_D \)) for each experiment.

Table 1. Reflected coefficient \( C_R \), transmission coefficient \( C_T \), percentage of dissipated energy by mangrove from all experiments.

| Parameters | Results |
|------------|---------|
| \( \rho_M \) (trees/m²) | \( C_R \) | \( C_T \) | \( C_D(\%) \) |
| 1 | 1.4 | 0.09 | 0 | 0.793 | 0.233 | 56.27 |
| 1 | 1.4 | 0.15 | 0 | 0.765 | 0.261 | 58.92 |
| 1 | 1.4 | 0.09 | 0.05 | 0.719 | 0.362 | 59.37 |
| 1 | 1.4 | 0.15 | 0.05 | 0.677 | 0.354 | 64.55 |
| 1 | 2 | 0.09 | 0 | 0.736 | 0.369 | 56.82 |
| 1 | 2 | 0.15 | 0 | 0.728 | 0.390 | 56.43 |
| 1 | 2 | 0.09 | 0.05 | 0.717 | 0.574 | 39.45 |
| 1 | 2 | 0.15 | 0.05 | 0.745 | 0.632 | 21.46 |
| 0.25 | 1.4 | 0.09 | 0 | 0.784 | 0.271 | 55.84 |
| 0.25 | 1.4 | 0.15 | 0 | 0.767 | 0.296 | 56.90 |
| 0.25 | 1.4 | 0.09 | 0.05 | 0.762 | 0.460 | 45.55 |
| 0.25 | 1.4 | 0.15 | 0.05 | 0.674 | 0.475 | 56.57 |
| 0.25 | 2 | 0.09 | 0 | 0.737 | 0.380 | 55.90 |
| 0.25 | 2 | 0.15 | 0 | 0.731 | 0.439 | 52.15 |
| 0.25 | 2 | 0.09 | 0.05 | 0.721 | 0.663 | 20.12 |
| 0.25 | 2 | 0.15 | 0.05 | 0.723 | 0.711 | 16.93 |
Parameters used in experiments are resumed in Table 1. As shown in table, in general about 16%-64% energy was dissipated by mangrove with the total length of mangrove in all experiments is $3L_M$ ($L_M = 1$ m). The highest energy dissipation (64.55%) occur when the parameters are $h = 0.15$ m, $T = 1.4$ seconds, $\rho_M = 1$ trees/m$^2$ and in submerged condition ($d_M = 0.05$ m). For small period ($T = 1.4$ seconds), the higher incoming wave height tend to increase the dissipation of wave energy. This result is inversely proportional to high period ($T = 2$ seconds), the higher incoming wave height tend to decrease the dissipation of wave energy. For the influence of water depth in mangrove ($d_M$), for small period when the mangroves in emerged condition ($d_M = 0$) the dissipated energy is getting higher as the incoming wave height increases. Meanwhile, for high period when the mangroves in submerged condition ($d_M = 0.05$ m) the dissipated energy is getting smaller as the incoming wave height increases. In real situation, the mangroves will effectively dissipate wave energy at the lowest tide.

4. Conclusion
Mansard-Funke method was successfully applied to separate the transmitted and reflected wave spectra in a wave flume experiments with mangrove. Spectral analysis has been used to measure wave energy dissipation due to mangrove forest in the wave flume experiment. The incident and reflected wave spectra are sensitive to wave parameters i.e. incoming wave height and wave period. Mangrove forest with following specification: length 3 m, density 0.25 trees/m$^2$ and 1 trees/m$^2$ used in the experiment can dissipate 16%-64% the energy of incident wave.

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