Research Article

Effectiveness of Mangrove Forests in Surface Wave Attenuation: A Review

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Abstract: For once, mangrove forests were surprisingly resistant to the forceful impacts of the Indian Ocean Tsunami of December 2004 which swept away entire villages and caused the deaths of approximately 200,000 people. It was reported that human death and loss of property were significantly reduced in areas of dense mangrove forests in southeastern India. As the importance of mangrove is gaining attention lately, numerous countries have started to replant mangroves for coastal protection. This study discusses the extensive researches that have been conducted to study the role of mangrove forests in wave energy dissipation. These include field measurements, numerical studies and laboratory experiments. The findings illustrate that mangrove species, density, forest width, forest structure, age, water depth and incident wave height are among the factors affecting the performance of mangroves in attenuating waves. Dense forest, larger forest width, bigger trunk diameter and higher wave height resulted in relatively more wave energy dissipation by mangroves.

Keywords: Field observation, laboratory experiment, mangrove, numerical studies, surface wave attenuation

INTRODUCTION

The 2004 Indian Ocean Tsunami has caused economic and ecological impact in thirteen Asian and African countries (Kathiresan and Rajendran, 2005). The western coast of Thailand (Tanaka et al., 2007) and approximately two-thirds of Sri Lanka (Wijetunge, 2005) were severely destroyed on a scale these countries have never encountered before. Vo-Luong and Massel (2008) reported that in the South-East part of India, the human causalities and economic damage were less severe at the places where dense mangrove forests presented. Most of the mangrove forests experienced minimal damage (Alongi, 2008) and only limited to the seaward focus fringe (Dahdouh-Guebas et al., 2005). While in Simeuleu Island in Indonesia where the epicenter of the tsunami was close to the island, however, the death toll on this island was significantly low due to the presence of dense mangroves.

Mangrove forests are capable of reducing the severity of tsunami wave and attenuating the disastrous amount of wave energy associated with it (Mazda et al., 1997a, 1997b; Kathiresan and Rajendran, 2005; Dahdouh-Guebas et al., 2005). The above-ground portion of wetland plants can directly dampen waves through their structural presence and indirectly dampen wave impacts by stabilizing and building up sediment (Gedan et al., 2011). Models of tsunami hydrodynamics indicate that the wave heights and current velocities are reduced when waves propagating through mangrove forests compared to bare land (Hiraishi and Harada, 2003; Teo et al., 2009). Because of their great importance, increasing number of researches have been undertaken to study the behavior of wave propagation through mangrove forests. The mangrove species, density, forest structure, forest width, age, tree size, water depth and incident wave height are among the factors influencing the performance of mangrove forests in wave energy dissipation. However, quantitative effect of each factor is still not fully understood. Investigations on wave dissipation in mangroves were more intensified after the 2004 Indian Ocean Tsunami. Although numerous field, laboratory and numerical studies have been carried out, most of the studies only concentrated on a particular mangrove species or wave condition. This study presents an overall review on the previous researches done and also describes the various factors influencing the performance of mangrove forests in wave attenuation including the mangrove vegetation characteristics and hydraulic conditions.

PREVIOUS RESEARCHES

Field observations: Bao (2011) conducted a study at two coastal mangrove forests in Vietnam which consisted of replanting mangroves and naturally regenerating mangroves. The results showed that the wave height decayed exponentially with the distance...
from mangrove front. A forest structure index expressed as a function of tree height, density, and canopy closure was derived to determine the required mangrove band width for coastal protection. A field study by Yanagisawa et al. (2009) at Pakarang Cape, Thailand revealed that the survival rate of mangroves increased with increasing stem diameter. They found that 72% of Rhizophora trees with stem diameters of 25 cm to 30 cm survived the tsunami impact, whereas only 19% with stem diameters of 15 cm to 20 cm survived. Vo-Luong and Massel (2008) reported that the effect of wave breaking played a more important role on wave attenuation in sparse forest, as observed in Can Gio Mangrove Biosphere Reserve, Vietnam. Quartel et al. (2007) conducted field observation in Red River Delta, Vietnam which consisted of 88.9% Kandelia candel, 7.4% of Sonneratia spp. and 3.7% of Avicennia marina. They found that the wave height reduction by mangroves was 5 to 7.5 times larger than by sandy bed only. Mazda et al. (2006) reported that Sonneratia spp. gave higher reduction rate which was 0.006 m-1 compared to 0.002 m-1 in the Kandelia candel forest. The effect of the drag force on Kandelia candel by the wave was weak compared to those of Brugueira spp. and Rhizophora spp. because Kandelia candel has no pneumatophores (Mazda et al., 1997a). It was also noticeable that the rate of wave reduction decreased with increasing water depth. Massel et al. (1999) also added that as the water level increased, wave energy was transmitted further into the forest, thus causing less attenuation of wave energy. This can be explained by the rapid drop of the ratio of the projected area of obstructions to the total cross-sectional area of flow with increasing water level.

A study was conducted by Mazda et al. (1997a) in Tong King delta, Vietnam which is a mangrove reforestation area comprised of Kandelia candel of different ages. At site where mangrove trees were sufficiently tall, the rate of wave reduction per 100 m was as large as 20%. They further predicted that for 6 years-old trees, wave height can be reduced from 1.0 m to 0.05 m across a 1.5 km mangrove forest width while it will only be reduced to 0.75 m in area without mangroves. Another field study carried out by Mazda et al. (1997b) in a pristine mangrove forest in Coral Creek, Australia and Iriomote Island, Japan. They found that the hydrodynamics in mangrove swamps changed in a wide range with vegetated mangrove species, vegetation density and tidal condition.

Tanaka et al. (2007) in their field survey in Sri Lanka and Andaman coast of Thailand reported that Rhizophora apiculata and Rhizophora mucronata were especially effective in providing protection from tsunami damage due to their complex aerial root structure. Field survey at Parangipettai, India has lead (Kathiresan and Rajendran, 2005) to support that Rhizophora species are more suitable species to mitigate the effect of tsunami than Avicennia species. However, it should be noticed that Rhizophora species generally occurs seaward while Avicennia species exists landward in India which is significantly different from mangrove zonation in Southeast Asia where it is vice-versa.

**Laboratory experiments:** Reimann et al. (2009) tested models of Rhizophora spp. and Casuarina spp. in a wave flume and found that the models with tandem arrangement gave lower wave reduction in comparison to the models with staggered arrangements. Tuyen and Hung (2009) claimed that for same incoming wave heights, the shallower the water the more wave energy will be dissipated. They also suggested that a mangrove forest with the recommended length of about 2 times the wave length in storm condition and above (at least 200 m) can provide 80% wave height reduction approximately. Augustin et al. (2009) studied the effect of plant rigidity on wave attenuation and found that both the rigid and flexible vegetation elements yielded the same friction factors in the laboratory experiments. Furthermore, there was less wave damping for near-emergent vegetation condition compared to emergent condition. Both Reimann et al. (2009) and Augustin et al. (2009) considered the vegetation as cylindrical elements in the experiments. Harada et al. (2002) also conducted a hydraulic experiment but to study the tsunami reduction effect using mangroves, coastal forests, wave dissipating block, rock breakwater and houses. Their experiment revealed that mangroves were as effective as concrete seawall structures for the reduction of tsunami effect on property damage behind the forest.

**Numerical studies:** Suzuki et al. (2011) studied the wave dissipation over a vegetation field by implementing the Mendez and Losada (2004) formulation in SWAN (Simulating Waves Nearshore) model. Similar to Vo-Luong and Massel (2008), the varying water depths, wave-trunk interaction and wave breaking conditions were taken into consideration in the numerical model. The main difference was in their attempt to include the vertical layer schematization in case of layered vegetation such as mangroves. This inclusion enabled the vegetation in a given region to be varied so as to reflect real density variations in the field. There are also similarities between Mendez and Losada (2004) formulation and forest structure index derived by Bao (2011) based on field work which accounted for the vegetation characteristics such as density, tree height and diameter.

Vo-Luong and Massel (2008) investigated about the wave-induced velocities at varying water depths and found that the vertical profiles of horizontal and vertical velocities attenuated very quickly with distance from mangrove front and were negligible be-hind the
mangroves. Yanagisawa et al. (2009) simulated the 2004 Indian Ocean Tsunami and reported that a mangrove forest of Rhizophora spp. with a density of 0.2 trees/m² and stem diameter of 15 cm in a 400 m wide area can reduce the tsunami wave height by 30%. On the other hand, Hiraishi and Harada (2003) simulated the tsunami reduction effect of coastal trees with higher density of 0.3 trees/m² and reported that it would require a reduced forest width of 100 m to give wave height reduction of more than 50%.

Hadi et al. (2003) analyzed two types of mangrove forests, namely Rhizophora and Ceriops forests and found that Rhizophora forest attenuated wave energy most effectively. They also suggested that the resulting rate of wave energy attenuation depended strongly on the density of mangrove forest and on the diameter of mangrove roots and trunks. Their analytical study was based on the model developed by Massel et al. (1999). However, Massel et al. (1999) did not consider the wave breaking in the model. The theoretical prediction model by Massel et al. (1999) served as a rough estimate for attenuation of wind induced waves propagating through mangrove forests due to some limitation of the model.

FACTORS INFLUENCING PERFORMANCE OF MANGROVE

Mangrove vegetation characteristics: A mangrove forest varies from site to site, in terms of its species composition, density, forest width, age distribution, tree sizes and root configuration. Combination of each different vegetation characteristics presents a varying level of resistance to incoming waves, thus affecting the attenuating capability of a mangrove forest is very much dependent on its vegetation characteristics.

- **Species:** The species composition of the mangrove forest is correlated with the its capacity to reduce wave energy (Alongi, 2008; Dahdouh-Guebas et al., 2005; Mazda et al., 1997a, 1997b; Tanaka et al., 2007; Koch et al., 2009). Tanaka et al. (2007) simulated vegetation drag forces and found that, of mangroves (Rhizophora spp. and Avicennia spp.) and other coastal trees (Pandanus odoratissimus, Casuarina equisetifolia, Cocos nucifera and Anacardium occidentale), Rhizophora mangroves and Pandanus odoratissimus were most effective in slowing down water flow and reducing wave heights. This is further supported by Mazda et al. (1997b) that Rhizophora spp. created greater friction to waves. Sanit et al. (1992) and Jayatissa et al. (2002) explained that Rhizophora apiculata-type trees have complex aerial root structures that contributed to higher drag coefficient. This is parallel with the findings by Tanaka et al. (2007) that Rhizophora apiculata and Rhizophora mucronata were especially effective in providing protection from tsunami damage, based on their field observation in Sri Lanka and Andaman coast of Thailand. Therefore a complex of various species would be desirable as different species have different types and sizes of leaves, trunks and roots, hence resulting in different levels of resistance (Tanaka et al., 2007). The forest width required is also closely related to the type of mangrove species. According to Alongi (2008), 100 m of Sonneratia forest can reduce wave energy up to 50%. On the other hand, Othman (1994) reported that 50 m of Avicennia forest is sufficient to reduce waves from 1 m to 0.3 m in Sungai Besar, Malaysia, corresponding to 70% wave height reduction.

- **Density:** Dense mangrove forest attenuates waves more effectively than low density forest (Alongi, 2008; Mazda et al., 1997a, b; Massel et al., 1999). Several studies have related density to the age, size of trees, mangrove species and forest width. The dense mangrove forest presents a much larger drag force to incoming waves as compared to a bare mudflat (Bao, 2011). The greater the friction the wave encounters, the greater the energy that will be dispersed (Lacambra et al., 2008). Mangrove density and complex structure were considered to be important by some authors based on site measurement (Mazda et al., 1997b), direct observation (Othman, 1994; Danielsen et al., 1997a, b; Massel et al., 1999) and mathematical developed models (Massel et al., 1999; Hiraishi and Harada, 2003). Vo-Luong and Massel (2008) in their numerical model, found that the effect of wave breaking played a more important role on wave attenuation in less dense mangrove forest while the effect of wave-trunk interactions dominated in the case of denser mangrove forest. For the high density forest, the wave height reduction rate was higher. Hadi et al. (2003) in their numerical studies also found that the rate of wave energy dissipation was higher for the case of denser mangrove forests.

- **Band width:** Lacambra et al. (2008) stated that the optimum mangrove forest width ranges from 100 m up to 1500 m, depending on the mangrove species, stem density and characteristics of the area. Some Asian countries have outlined the minimum required width for mangrove forests. According to Lacambra et al. (2008), a mangrove belt between 500 m and 1000 m width has been set as a buffer zone in Vietnam along the Mekong delta coastline. In Philippines the buffer zone is 20 m and can reach up to 50 m in the storm prone areas. In Malaysia, the 1950s regulation specified 200 m mangrove buffer zone before any structures protecting agricultural land (Othman, 1994).
Field experiment was conducted by Massel et al. (1999) at Coral Creek in Australia. Normalized energy was calculated and the results showed a decrease in wave energy transmission with distance into the forest. On the other hand, Bao (2011) analyzed wave attenuation in coastal mangrove forests in Vietnam and established a relationship between the required mangrove forest band width and the forest structure index. When the mangrove forest is tall and dense, a narrower forest band width is required for coastal protection.

- **Forest structure:** The magnitude of the energy dissipated depends on the mangrove structures such as the stem configurations, roots and branches diameters as well as submerged part of the vegetation (Alongi, 2008; Massel et al., 1999; Quartel et al., 2007). Vegetation leaves and stems slow water velocity, reduce turbulence and increase deposition of sediments (Redfield, 1972; Christiansen et al., 2000; Bao, 2011). The wave dissipation rates are also contributed by stem stiffness (Bouma et al., 2005; Peralta et al., 2008) and the presence of pneumatophores (Mazda et al., 2006). From their field work in Vietnam, Mazda et al. (2006) found that thick mangrove leaves were capable of dissipating huge amount of wave energy during storms and typhoons. Other field experiment by Quartel et al. (2007) also revealed that the wave-driven, wind-driven and tidal currents reduced due to the dense network of trunks, branches and aboveground roots of the mangroves and this could be seen as an increased bed roughness.

- **Age:** Latief and Hadi (2006) related the age of mangrove, indirectly the size of trees to the mangrove capacity in wave energy dissipation. Age of a mangrove tree implies the size of the tree, the trunk and root diameter as well as stem density (Lacambra et al., 2008). The older and bigger the trees, the higher their resistances to the wave damage (Othman, 1994; Mazda et al., 1997a; Massel et al., 1999; Hadi et al., 2003; Danielsen et al., 2005; Alongi, 2008). Mazda et al. (1997a) conducted a field observation in a mangrove reforestation area (dominated by Kandelia candel) in the Tong King delta, Vietnam and reported that the wave reduction rate was influenced by the mangrove vegetation’s age. In area with 0.5 year-old mangrove, the rate of wave reduction was small because the vegetation was still young and sparse, thus the wave energy loss was caused by bottom friction only. In area where mangrove trees were 5-6 years old, the wave reduction rate was larger, suggesting the better developed mangrove plants imposed higher drag force, therefore resulted in greater wave reduction rate. The wave reduction rate in area with 2-3 years old mangrove lied between mangrove of age 0.5 year and 5-6 years old.

- **Height:** According to Mazda et al. (2006), bottom friction caused by roots and pneumatophores are important at shallow water depth. However, leaves start to play role in attenuating waves at higher water depth. Lacambra et al. (2008) reported that taller trees seem to suffer greater damage from wind, but they also seem to be more resistant to wave energy. Mazda et al. (1997a) further added that the wave reduction was higher with an increase in mangrove vegetation height and density.

**Hydraulic conditions:** Besides the vegetation characteristics, the hydraulic conditions also have their influence on wave attenuation. Among the main factors that affect wave energy dissipation include the water depth and incident wave height.

- **Water depth:** The maximum wave height in shallow water is proportional to the depth of water between the bed surface and sea level (Gedan et al., 2011). Based on a field experiment, Quartel et al. (2007) reported that the resistance due to the un-vegetated sandy bed lowered with increasing water depth, resulted in a lower wave height reduction. While in the presence of mangrove forest, the resistance coefficient increased with increasing water depth, resulted in a higher wave height reduction. This is due to the larger submerged part of mangrove branches and leaves which obstruct the water flow (Quartel et al., 2007).

There is also a correlation between the mangrove species and water depth. Mazda et al. (1997a) demonstrate that in a mangrove forest dominated by Kandelia candel where the trees were sufficiently tall, the wave reduction rate per 100 m was as much as 20%. The wave reduction was large even the water depth increased due to the high density of vegetation distributed throughout the whole water depth. To relate water depth with other mangrove species, another field observation was conducted by Mazda et al. (2006) at the Vinh Quang coast (dominated by Sonneratia spp.) in northern Vietnam. They suggested that at shallow water depth, since the shape of pneumatophores of Sonneratia spp. tapered off upward, the effect of drag force by these roots on the wave reduction decreased with increasing water depth. This resulted in a subsequent decrease in the wave height reduction rate.

- **Incident wave height:** At higher water depth, the wave reduction rate in mangrove area is relatively much dependent on the incident wave height. Mazda et al. (2006) reported that the wave
reduction rate was independent of the incident wave height in the area without mangrove. In the mangrove forest dominated by Sonneratia spp., the wave reduction rate depended in a linear trend with incident wave height when the water level reached the height of the leaves (Mazda et al., 2006). This suggests that the wave reduction was caused by the thickly grown leaves. However, this effect is not significant if the waves do not reach the height of the leaves.

CONCLUSION

Mangrove forests are capable of dissipating wave energy, thus they play an important role in coastal protection. This review study articulated how the wave attenuation capacity of a mangrove forest influenced by various factors including mangrove species, density, forest width, size of tree, water depth and incident wave height. At mangrove site, the wave height decays exponentially with distance from mangrove front. The significant function of mangroves in reducing wave heights and thus serve as natural protection buffer for coastal areas warrants the needs for their preservation and maintenance for a more sustainable future.

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