ABSTRACT

This study aims to analyze the parameters of mangrove vegetation and wave that influence the ability of mangrove forest in dissipating surface wave. Surprisingly, in December 2004, mangrove trees have shown impressing resistant to the forceful impacts of the Indian Ocean Tsunami. It is reported that approximately 200,000 people dead in the countries around the Indian Ocean and scientist observed that the mangrove forests protected villages from the worst destruction. With the urge for mangrove protection and replanting, questions were raised about the degree to which the mangrove forests are able to reduce damages to the property and loss of human life. In recent years, mangroves have been studied extensively but they still remain poorly understood. This research focus on performance of mangrove trees *Rhizophora* spp, of age ten years old. This research comprises of site visits, field measurements as well as laboratory experiments. The site visits were conducted to observe the behaviour of waves propagating through mangrove forests and to obtain the dimensions of mangrove trees, specifically *Rhizophora* spp. The dimension were then scaled down to 1:10 and modelled in the wave flume in laboratory. The parameters tested include forest density, tree arrangement, age, incident wave height and water depth, in a narrow wave flume by using artificial mangrove models. It is found that wave height reduction in the area of 100 m mangroves of age 10 years old was 2.5 times larger than area without mangroves whereas for area with mangrove of age 20 years old is 4 times greater compared to area without mangrove. The difference of wave reduction between tandem and staggered arrangement was less than 3 %, which was not significant. For a 200 m mangrove forest width, a density of 0.11 trees/m^2 is sufficient to reduce wave height over 77 %. Significant wave reduction was shown when water level was within the height of the roots. At this shallow water depth, the higher the wave heights, the more wave reduction occurred. The experimental results were also compatible with the results of field observation at Pantai Teluk Tiga, Perak.

ACKNOWLEDGEMENT

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

For ages, the ability of coastal wetlands to stabilize shorelines and protection to coastal communities has been recognised. According to McIvor et al. (2012), the world's coastal margins are among the most densely populated and intensively used places on Earth. The growth rate of coastal population increased rapidly as is associated infrastructure, industry and agriculture. Coastal area and small island cater for more than one third of the world's population (UNEP, 2006) while more than 10% of people live in a distance within 10m from sea level (McGranahan, Balk, & Anderson, 2007). Coastal land and its population can be at risk from natural hazards such as waves, storms and tsunamis (McIvor et al. 2012). Mazda et al., Magi, Kogo, & Hong (1997a), Mazda et al. (1997b), Ewel et al., (1998), Massel et al., (1999), Siripong et al., (2008), Chong (2005), UNEP-WCMC (2006), Barbier & Heal (2006) and Alongi (2008) claim that the role of mangrove forest for the protection of coastal areas, property, and human life in tropical and subtropical countries by attenuating wave energy from tsunamis and storms as well as holding the substrate in place thus preventing erosion. Surprisingly, in December 2004, mangrove trees have shown impressing resistant to the forceful impacts of the Indian Ocean Tsunami. It is reported that approximately 200,000 people dead in the countries around the Indian Ocean and scientist observed that the mangrove forests protected villages from the worst destruction (Dahdouh-Guebas et al. 2005, Danielsen et al. 2005, Braatz, Fortuna, Broadhead, & leslie, 2007, Cochard et al. 2008).The coastal mangrove forest are capable of mitigating high waves during tsunami and it was reported that human death and loss of property were reduced in areas of dense mangrove forests (Dahdouh-Guebas et al. 2005, Kathiresan & Rajendran, 2005, Havanod, 2005). With the recent urge for mangroves protection and replanting (Barbier, 2006), questions were raised about the degree to which the mangrove forest are able to reduce damages to the property and loss of human life (Hashim & Catherine 2013, Chatenoux & Peduzzi, 2007, Kerr & Baird, 2007, Kerr et al. 2009).

1.2 Problem Statements

1.2.1 Problem Identification

Mangrove forest has the ability in reducing the severity of tsunami and attenuating the disastrous amount of wave energy associated with it (Shuto, 1987, Mazda et al. 1997a, Kandasamy & Narayanansamy, 2005, dahdouh-Guebas et al. 2005). The level of mangrove forest performance in coastal protection has been called into question since the studies on wave dissipation by mangroves are still limited as compared to those on seagrass and salt marshes (Knutson, 1998). The quantitative effects of mangrove species namely *Rhizophora stylosa* (Magi, Mazda, Ikeda, & Kurokawa, 1996) and *Kandelia candel* (Mazda et al. 1997a) on the reduction of sea waves have been shown based on mathematical model. Massel et al. (1999) also discussed the effect of *Rhizophora* spp. on the reduction of sea waves based on mathematical model. However, these results are not applicable to other species as mentioned by Wolenski et al. 2001, each mangrove species has a unique configuration of trunks, prop roots or pneumatophores that work as different drag force and therefore results in a different wave reduction rate of sea waves. In addition, Hadi et al. (2003) claims that the resulting rate of wave energy dissipation relies on the density of mangrove forests and diameter of the roots and trunks. Hence, the role of mangrove forest in dissipating waves depends on various conditions such as mangrove species, densities, vegetation structures, ages, heights as well as various wave conditions. Because of their great importance, mangroves have been studied extensively but they still remain poorly understood. Especially study on wave process with in mangrove forest and the measurements are a few (Vo-Loung & Massel, 2008). Therefore, the study on the influence of mangrove vegetations characteristics in protecting coastal area is needed.

1.2.2 Significant of the Project

Mangrove forest plays an important role in coastal protection. Its importance in reducing the impact of waves is further stressed after the 2004 Indian Ocean Tsunami (Dahdouh-Guebas et al. 2005, Kathiresan & Rajendran, 2005). Economic damage and human casualties were less severe at the places where dense mangrove forests present in the South-East part of India (Vo-Loung & Massel, 2008).

As the awareness of the importance of mangroves has been arising lately, more and more countries are focussing on mangrove replanting for better coastal protection. In order to achieve the optimum energy dissipation by mangroves, it is important to determine the effective combination of mangrove forests characteristics and their arrangement on wave energy dissipation. These informations are highly useful and can be incorporated during mangroves replanting projects in Malaysia.

1.3 Objectives

a) To determine the optimum mangrove age in attenuating the wave height.
b) To determine the optimum buffer zone for coastal protection.
c) To quantify the percentage wave height reduction with various ages, densities, distances from mangrove front, water depths and incident wave heights.

1.4 Scope of Study

This research comprises of field measurements and laboratory experiments involving modelling of mangrove forest. The mangrove species chosen are the common type found in Asian, which is *Rhizophora* spp. The field measurements are conducted to collect the information about the behaviour of waves propagating through mangrove forest. The observations are then modelled in the laboratory. By varying the mangrove species age, density, tree arrangement, incident wave height, wave period and water depth, the optimum vegetation characteristics as well as other external factors are determined. Prior to that, site assessments were conducted to acquire sufficient knowledge about mangroves and its surrounding environment.

1.5 Relevancy of the Project

The role of mangrove forest in coastal protection is gaining attention in recent years and some countries have started to replant mangroves. However, the effectiveness of mangrove forest in dissipating wave energy is still not fully understood and proved. Hence, findings from this study will provide better understanding on the performance of mangrove forests in coastal protection.

1.6 Feasibility of the Project

This research is a fundamental study of performance of mangrove forests in coastal protection. This research is feasible in terms of materials availability and it is within time frame according to the schedule from Gantt Chart. The equipment required for experiments is available in offshore laboratory in Universiti Teknologi PETRONAS. Prior to conducting the experiments, site assessments to mangrove forest were carried out and the technical papers and journals are studied to enhance the knowledge on performance of mangrove forests in coastal protection. This project has the potential to develop into diverse and wider scope for further research but this will require longer duration of study.

CHAPTER 2

LITERATURE REVIEW

2.1 Mangrove performance in dissipating wave energy

Mangroves formed the physical borders for the land-sea relations, that is at the transition zone between earthly and aquatic environments and between coastal areas and the open sea (Moberg and Ronnback 2003, Ismail. et. al. 2012). Mangroves have the capability to reduce the impacts of waves, storm surges and tsunami on coastal infrastructure and property by reducing the incoming wave energy. (Keqi Zhang et al. 2012, Barbier et al. 2008, Cochard et al. 2008). Mangroves are found on many tropical coasts, mostly in locations with low incoming wave energy. However according to McIvor et al. (2012), they can be exposed to much greater wind and swell waves during storms, tsunami, hurricanes, and periods of high waves. When they pass through a larger density of obstructions, waves are dissipated most rapidly. (McIvor et al. 2012). According to Wolanski et al. (2008) mangroves absorb energy from the water, reducing wave height and slowing down the currents.

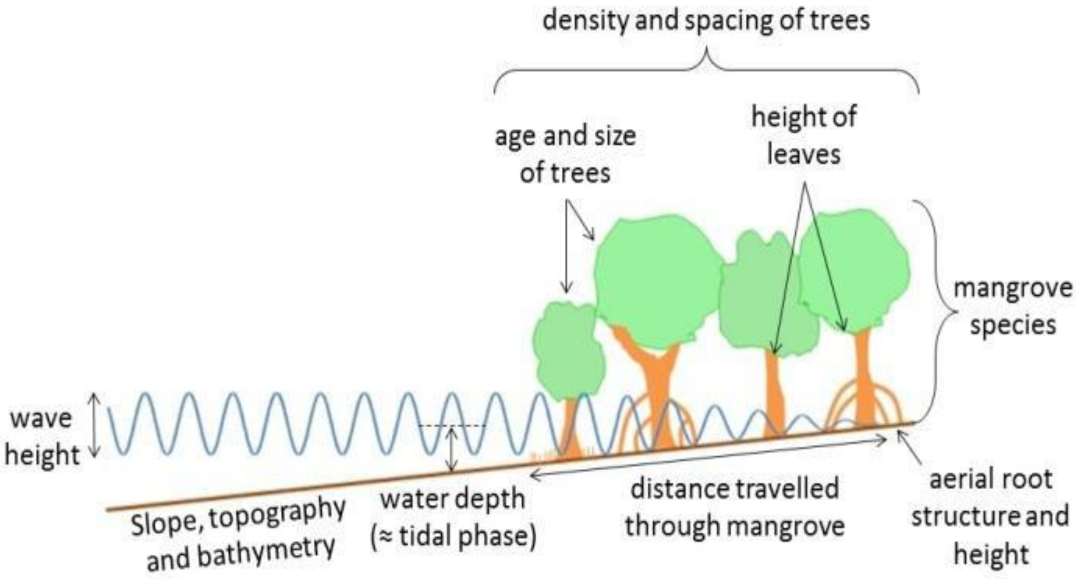


Figure 1: Mangrove forest dissipating wave energy (McIvor et al. 2012).

According to G Prasetya et al. (2006) diminishing of coastal forest such as mangrove has increased its vulnerability to coastal erosion-such as Vietnam (Mazda et al., 1997; Cat et al., 2006), Malaysia (Othman, 1994), Indonesia (Bird and Ongkosongo, 1980; Nurkin, 1994; Tjardana, 1995), Sri Lanka (Samarayanke, 2003), India (Malini and Rao, 2004; Gopinath and Seralathan, 2005) China (Bilan, 1993) and Thailand (Thampanya et al., 2006).

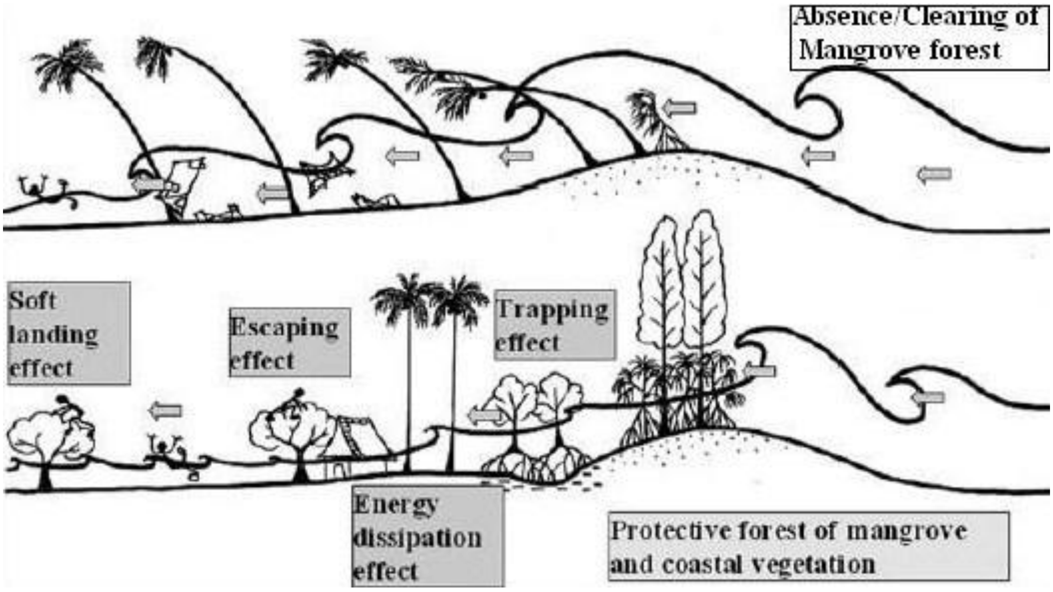


Figure 2: Mangrove forest acts as natural hurdle shielding (Tanaka 2007).

Mangrove forests acts as natural hurdle shielding the life and property of coastal society from storms, high waves and cyclones. The above-ground root system does not only promote sediment to settle and impedes water flow but also inhibits its redeferment (Gilbert & Janssen 1998; R Badola & S.A Hussain., 2005). Stabilization of sediments affords protection to shorelines and associated shore-based activities and can lead to land gains (Spaninks & van Beukering 1997; R Badola & S.A Hussain., 2005). These statements has been strengthened by Gedan, Kirwan, Wolanski, Barbie, & Silliman (2011) that the upper portion of wetland plants that above the ground can directly reduce waves energy through their structural conditions and indirectly reduce wave impacts by stabilizing and building up sediment.

Wave dissipated by mangrove vegetation because it acts as an obstruction for the oscillatory water flow in the waves. As the water flows around the mangrove vegetation it creating drag. It has to change direction and do work against the friction of the mangroves surface. This dissipates some of the energy of the waves, thereby reducing wave height (McIvor et al. 2012).

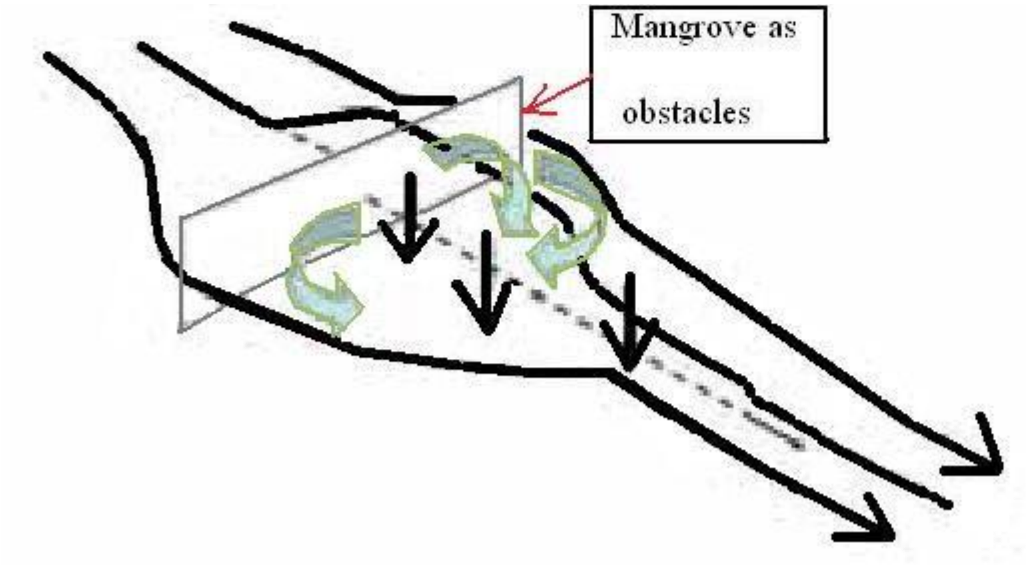


Figure 3: 3-D wake effects of flow around an obstacle if the obstacle is made larger (Wolanski).

The rate of wave height reduction (r) per unit distance in the direction of wave propagation is defined as the reduction in wave height (ΔH) as a proportion of the initial wave height (H) over a distance (Δx) travelled by the wave (Mazda et al. 2006):

$$r = -\frac{\Delta H}{H} \cdot \frac{1}{\Delta x} \qquad \textbf{Eqn. 1}$$

The units of r are /m or m^{-1}. For example, if wave height is reduced by 1% over a distance of 1 m, then r = 0.01 / m. When r is constant, Equation 1 can be solved as:

$$H_x = H_0.e^{(-r\cdot x)} \qquad \textbf{Eqn. 2}$$

Where H_0 is the incident wave height (cm) and Hx is the wave height (cm) after the wave has travelled x metres (Mazda et al. 2006).

A similar equation can be derived from wave theory (Han Winterwerp, pers. comm.):

$$H_x = H_0.e^{k_i \cdot x} \qquad \textbf{Eqn. 3}$$

Where k_i is the imaginary wave number. When this number is negative, the waves are being damped (i.e. they are reducing in height), while if this number is positive, waves are increasing in size. (McIvor et al. 2012).

2.2 Storm surge reduction

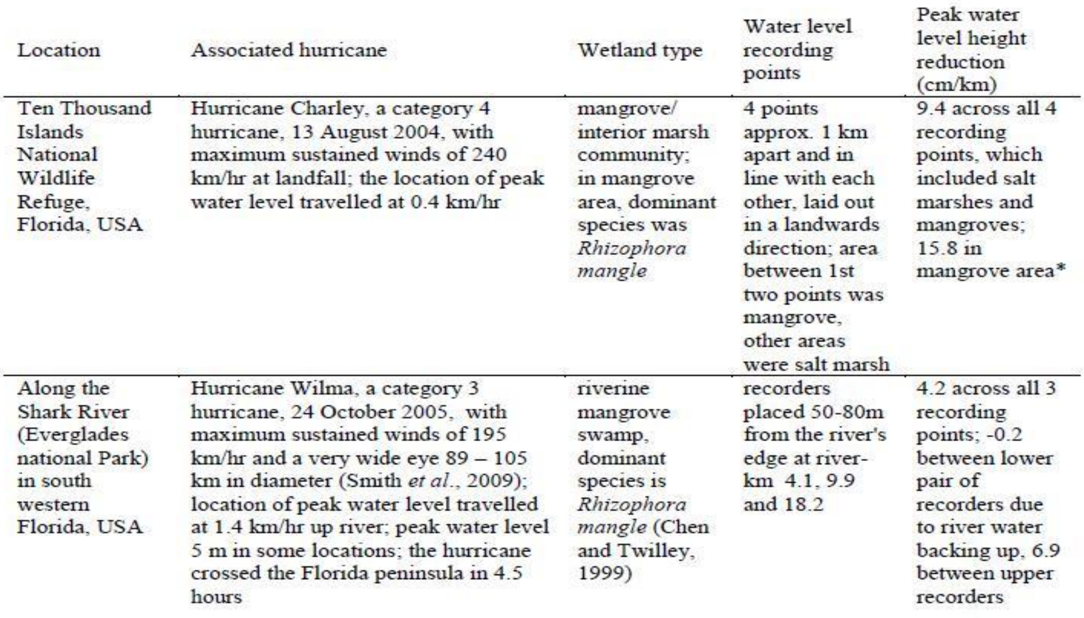
A few studies have been carried out to investigate whether mangroves give significant impacts to reduce damage and loss of life during storm surges. Mangroves have the ability to reduce storm surge water level by slowing the flow of water and reducing surface waves. According to McIvor et al. (2012), measured rates of storm surge reduction through mangrove per kilometre of mangrove width, range from 5 to 50 centimetres water level. Additionally, surface wind waves are expected to be reduced by more than 75% over one kilometre of mangroves.

Although there is sufficient scientific evidence suggesting that mangroves provide protective services from storms, there is a lack of ecological data on how loss of mangroves in specific locations will affect their ability to provide storm protection to neighbouring communities (Barbier et al. 2007).

Mazda et al. (1997a) studied tidal flows, which are relatively similar to storm surge flows, in an area with young *Kandelia candel* trees (less than 7 years old). They found that the tides rose faster at the early stage of the flood tide and fell more slowly at the latter stage of the ebb tide than in a nearby location without mangroves. They attribute this difference to the flow resistance from the mangrove vegetation and the bottom mud. They note that the changes in flow speed were considerably smaller than those seen in mangrove swamps dominated by *Rhizophora* spp. or *Bruguiera* spp., as measured by Wolanski et al. (1992) and their own unpublished data. Unlike *Kandelia candel*, these other species have prop roots or pneumatophores, which are likely to slow water flows more than the trunks of *Kandelia* (Mazda et al., 1997a).

Mazda et al. (1997) demonstrated through field measurements of water levels and current velocities in replanted mangrove stands of different ages (½ year old seedlings, 2-3 year old seedlings and 6 year old seedlings). They found that 6 year old mangrove stand 1.5km wide was effective at reducing 1m high waves at the open sea to 0.05m at the coast. However, the authors note that more research is needed on how dependent wave reduction is on species composition, spacing between trees, water depth, wave period and wave height.

To investigate whether mangroves can reduce the height of peak water levels as storm surges pass through, Krauss et al. (2009) analysed water level measurements in wetland areas during Hurricanes Charley (2004) and Wilma (2005) in Florida (Table below). They used a network of water level recorders that collected water level data at hourly intervals in two different wetland ecosystems containing mangroves and saltmarshes (Table1 below).



Location	Associated hurricane	Wetland type	Water level recording points	Peak water level height reduction (cm/km)
Ten Thousand Islands National Wildlife Refuge, Florida, USA	Hurricane Charley, a category 4 hurricane, 13 August 2004, with maximum sustained winds of 240 km/hr at landfall; the location of peak water level travelled at 0.4 km/hr	mangrove/ interior marsh community; in mangrove area, dominant species was *Rhizophora mangle*	4 points approx. 1 km apart and in line with each other, laid out in a landwards direction; area between 1st two points was mangrove, other areas were salt marsh	9.4 across all 4 recording points, which included salt marshes and mangroves; 15.8 in mangrove area*
Along the Shark River (Everglades national Park) in south western Florida, USA	Hurricane Wilma, a category 3 hurricane, 24 October 2005, with maximum sustained winds of 195 km/hr and a very wide eye 89 – 105 km in diameter (Smith *et al.*, 2009); location of peak water level travelled at 1.4 km/hr up river; peak water level 5 m in some locations; the hurricane crossed the Florida peninsula in 4.5 hours	riverine mangrove swamp, dominant species is *Rhizophora mangle* (Chen and Twilley, 1999)	recorders placed 50-80m from the river's edge at river-km 4.1, 9.9 and 18.2	4.2 across all 3 recording points; -0.2 between lower pair of recorders due to river water backing up, 6.9 between upper recorders

Table 1: Peak water level reduction during storm surges passing through mangrove wetlands in Florida (data from Krauss et al., 2009; McIvor et al. 2012).

As the storm surge from Hurricane Charley passed through the Ten Thousand Islands National Wildlife Refuge (NWR), the peak water level reduction was 9.4 cm/km through an area that included both mangroves and saltmarshes. The following calculations based on data given in Krauss et al. (2009: Figure 2 and p. 145) show how the reduction in peak water level through the mangroves area may have been higher. At the first recording point 2.3 km from Faka Union Bay, the peak water level was 78.6 cm above ground level and 43.6 cm above the expected high tide level; at the second recording point 3.2 km further inland, at the transition between the mangrove and the marsh, the peak water level was 40 cm above ground level and 29.6 cm higher than the water level prior to the arrival of the storm surge. This implies a decrease in peak water level of 14.0 cm (reduction in water level relative to high tide/antecedent water levels) over 0.9 km, equivalent to a reduction in peak water level through mangroves of 15.8 cm/km.

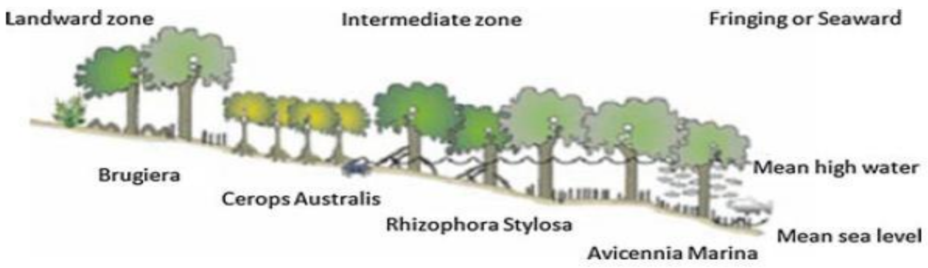
McIvor et al. (2012) said that one limitation of the current numerical models is their inability to include spatial variation in mangrove characteristics, such as mangroves density. It is very likely that the ability of mangroves to reduce peak water levels depends on mangrove characteristics, with sparse, fragmented or channelized areas reducing storm surge water levels less effectively than dense mangrove vegetation. Currently, mangroves are represented in numerical models as an increase in surface roughness, and a single value for the roughness coefficient is used for all mangroves areas (Xu et al., 2010; Zhang et al., 2012). Including mangroves variation would probably improve the prediction of storm surge heights, and would therefore aid in planning the use of mangroves in coastal defence.

2.3 Mangrove vegetation characteristics

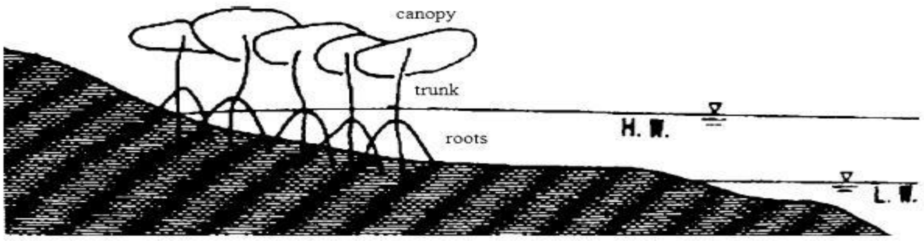
Mangrove forest can attenuate wave energy, as shown by various modelling and mathematical studies (Brinkman et al., 1997, Mazda et al., 1997, 2006, Massel et al., 1999, Quartel et al., 2007) which indicate that the magnitude of the energy absorbed strongly depends on forest density, diameter of stems and roots, forest floor slope, bathymetry, the spectral characteristics (height, period, etc.) of the incident waves, and the tidal stage at which the wave enters the forest. The density of mangroves vegetation and the diameter of aerial roots and stems are expected to affect the ability of mangroves to reduce storm surge water levels (Krauss et al., 2009, Alongi, 2008).

However, few data are yet available to support this assumption. For instance, one model estimates that at high tide in a *Rhizophora*-dominated forest, there is a 50% decline in wave energy by 150 m into the forest (Brinkman et al., 1997). Mazda et al. (2006) similarly found that waves were reduced in energy by 50% within 100 m into *Sonneratia* forests. Mazda et al. (1997) and Tanaka et al. (2007) showed that another important factor is vegetation type, for example, the percentage of forest floor area covered by either prop roots or pneumatophores, as the drag coefficient of these structures is related to the Reynolds number (which differs for each species depending on diameter and aboveground root architecture).

The site condition for mangroves to survive is where the ground lies between the mean sea level and the mean high water level. The typical water level during low water (LW) and high water (HW) are as shown below. The vertical configuration of the mangroves restricts water flow due to drag forces and viscous forces and is expected to dissipate more tsunami wave energy. Both the forces depend on the tidal level because of the vertical profile of mangroves. The zonation and the tidal level of the mangroves are also shown in figures below.



Hypothetical schematization of a mangrove forest (Burger 2005)



Fringe forest (Cintron and Novelli 1984)

Figure 4: Hypothetical schematization of a mangrove forest (Burger 2005).

Figure 5: Fringe forest (Cintron and Novelli 1984).

The energy of a tsunami could also be greatly reduced because of the substantial resistance provided by the underground roots. With low water depths, the aerial roots system causes the largest part of the wave attenuation. According to Burger (2005), mangrove canopies start to grow from around the high water level upwards. Hence, at higher water depths, trunks and canopies play a more significant role.

2.3.1 Mangrove Species

Rhizophora Spp

Rhizophora spp. has stilt roots, which form a network above the substrate. These stilt roots present considerable resistance to the flow of water. Above the stilt roots, the trunks present less of an obstacle to waves, allowing them to pass more easily. This results in high wave attenuation at shallow depths, and then a reduction in wave attenuation as the water becomes deeper and the waves are less affected by the stilt roots.

This pattern was seen by Brinkman et al. (1997) at Cocoa Creek in Australia where *Rhizophora stylosa* is the dominant species over the 180m of mangrove forest nearest to the shore. When the tide was rising and the waves were passing through the prop roots, less than half the peak wave energy was transmitted through the first 80 m of mangrove (water depths 1.25 m at the forest edge and 0.5 m at a point 80 m into the forest). Brinkman et al. note that at these shallow depths, the projected area of obstructions to the flow caused by above-ground roots was only slightly smaller than the total cross-sectional area of the flow, so they would have created significant drag (the projected area is the area of the silhouette of mangrove vegetation as seen from the direction of the on-coming waves). As the water level increased, wave energy was transmitted further into the forest: at high tide, almost 50% of the peak wave energy was transmitted through to a point 80 m into the forest. At these water depths, the ratio of the projected area of obstructions to the total cross-sectional area of flow decreases because the water is now higher than the prop roots, so that the waves experience less drag and there is less wave attenuation.

Figure 6: ***Rhizophora*** **spp**.

Figure 7: ***Brugueira*** **spp.**

Brugueira spp.

Knee roots emerge as a root loop from the underground root system and allow the exchange of gases in oxygen-poor sediments. Each underground horizontally growing root develops several knee roots at regular intervals. Knee roots of an adult *Bruguiera gymnorhiza* for example extend in a radius of approximately 10 meters around the trunk and can reach a height of up to 60 cm. The knee roots of the different *Bruguiera* species differ in size, shape and frequency and can vary depending on the location and growth conditions. While the knee roots of *Bruguiera* spp. are quite dissimilar in structure to the stilt roots of *Rhizophora* spp., they nonetheless dissipate waves in a similar way. Brinkman et al. (1997) found that wave height reduction was greatest at shallow depths; in deeper water, wave heights were reduced less with distance, and more wave energy was transmitted further into the forest on Iriomote Island.

Sonneratia spp.

Sonneratia spp. and *Avicenni*a spp. have characteristic pneumatophores, aerial roots which project out of the substrates and support an air supply to the roots. *Sonneratia* aerial roots have secondary thickening and so are more cone-shaped, reaching over a metre in height in some species. Like the prop roots of *Rhizophora* spp. and the knee roots of *Bruguiera* spp., the pneumatophores of *Sonneratia* act as obstacles to water movement at shallow depths, creating higher wave attenuation at these depths. Mazda et al. (2006) measured wave attenuation in a mangrove forest created by planting *Sonneratia* in northern Vietnam. They found the highest attenuation at shallow depths, and lower wave attenuation as water levels rose, until the water levels reached the height of the branches and leaves. According to Alongi (2008), 100 metres of *Sonneratia* forest can dissipate wave energy up to 50 %.

Figure 8: *Sonneratia* spp.

Figure 9 : *Avicennia* spp.

Avicennia spp.

Avicennia mangroves grow flat root systems; the underground, horizontally growing roots grow away the trunk and develop pencil roots in regular intervals which grow up to 30 cm in height, measured from the soil to the tip of the pencil root. Pencil roots do not have the ability to develop branches and normally have a diameter of 4 to 7 mm. The outer layers of pencil roots contain chlorophyll, pencil roots do have the ability to go through the process of photosynthesis. *Aegialitis rotundifolia* and *Avicennia marina* are found only in areas of high salinity. The other two species of *Avicennia*, namely *A. alba* and *A. officinalis*, show a wider range of salt tolerance. The aerial roots of *Avicennia* are narrow and can reach 20 to 30 cm in height. In 1994, Othman reported that 50 metres of *Avicennia* forest can attenuates waves from 0.3 m to 1m in Sungai Besar, Malaysia. Some species of mangroves may reduce bank erosion more effectively than others; for example, Teas (1980) suggests that black and white mangroves (*Avicennia germinans* and *Laguncularia racemosa*) form denser mats of roots than red mangroves (*Rhizophora mangle*), and are therefore more able to stabilize shorelines.

2.3.4 Density

The density of mangroves vegetation and the diameter of aerial roots and stems are expected to affect the ability of mangroves to reduce storm surge water levels (Krauss et al., 2009; Alongi, 2008). High density forest composed of species with aerial roots and dense canopies are consequently expected to reduce waves and wave set-up more effectively. However, few data are yet available to support this assumption. Wave reduction is expected to be reliant on the density of vegetation (i.e. aerial roots or branches); and the surge water level. When the waves encounter the densest vegetation, the largest rates of wave reduction occur (Quartel et al., 2007; McIvor et al., 2012). These shows that mangrove may have the ability to perform significantly in reducing wave set-up and run-up during storm surges, thereby reducing impacts on local infrastructure. In addition, Bao et al. (2011) explained that the tree with high density and the aboveground roots in a mangrove forest present a much higher drag force to incoming waves than the bare sandy on a mudflat does. Likewise, Mazda et al. (1997) predicted that mangrove forests as wide as 1000 m might be required to reduce wave energy by 90%, but that this was dependent on tree density rather than spatial extent of trees (Massel et al. 1999; figure below).

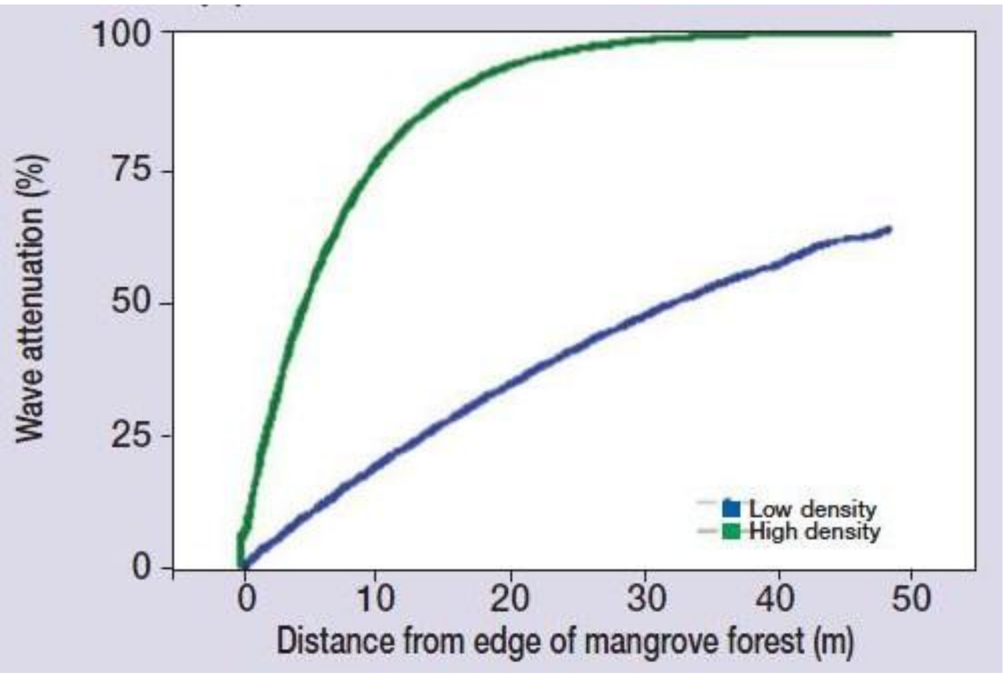


Figure 10: Wave attenuation for different mangrove densities has been modelled (Massel et al. 1999; Barbier et al. 2009).

Komiyama et al., (2008) and Massel et al., (1999) conclude that in very dense mangrove forest, full dissipation of wind and swell waves may occur within 30 m of the edge, while in low-density mangroves, such as those usually found at the edge of mangrove forest, much wider vegetated areas are required to obtain the same results. (Barbier et al., 2009).

Medeiros et al. (2012) proposed that improved representation of mangroves in numerical surge models may well increase the accuracy of estimates of inundation extent and duration. Manning's roughness coefficient would need to vary in a way that realistically reflected the geographical variation in mangrove characteristics in order to include variation in mangrove density or morphology in numerical models such as the CEST model used by Zhang et al. (2012; Section 2.2.2)(McIvor et al., 2012). At present, roughness is estimated from the National Land Cover Dataset (NLCD); land cover types such as grassland, woody wetland, open water and commercial uses are distinguished, and each of these is associated with a range of Manning's coefficient values (McIvor et al., 2012).

Sheng et al. (2012) has proposed an alternative approach to including variation in vegetation in numerical storm surge models. They propose a three-dimensional numerical model of storm surges based on the coupled CH3D-SWAN (Curvilinear-Hydrodyamics 3D – Simulating Waves Nearshore) model (more information about the SWAN model is given in Booij et al.,1999, and Suzuki et al., 2011)(McIvor et al., 2012). Sheng et al. (2012) demonstrate the model by simulating the flow of a surge through vegetation similar to that found in marshes. The model allows them to vary the height, density and width of the vegetation, and they find that increases in height, density and/or width result in a reduction in inundation volume. Their model is yet to be applied to mangroves vegetation.

2.3.5 Mangrove width

Depending on the mangrove species, stem density and area's characteristics, Lacambra et al. (2008) stated that the optimum mangrove forest width ranges from 100 metres to 1500 metres. According to McIvor et al. (2012), athwart a 500 m width of mangrove forest, attenuation rates suggest that wave height would be reduced by 50 to 99%. Das and Vincent (2009) found that villages with wider mangroves between them and the coast had significantly fewer deaths than villages with narrower mangrove belts or no mangroves. They expected that with absence of mangrove there would have been 1.72 additional deaths per village within 10 km of the coast.

Measurements of storm surge reduction rates through coastal wetlands are often excerpted as some number of centimetres of water level reduction per metre of inland distance, usually measured in the direction of travel of the surge (McIvor et al. 2012). However such constant attenuation rates imply a linear reduction in water level with distance into the mangroves. This is rarely true, both because the landscape is usually heterogeneous (i.e. it is usually a mixture of channels, pools and vegetation with a varied topography), and also because the underlying rate of reduction might not be linear even if the environment were homogeneous, as described below. Consequently, such attenuation rates should be regarded with caution. At best they may serve as rules of thumb around which there is usually a high degree of scatter (Resio and Westerink, 2008, Wamsley et al., 2010). Taking this into account, the rate of reduction of surges through mangroves appears to range between 5 and 15 cm/km (observed reduction rates; Krauss et al., 2009) up to 50 cm/km (well-validated numerical models; Zhang et al., 2012).

Zhang et al. (2012) used the simulations of CEST model to explore the effects of different widths of mangroves being present, and they found that surge attenuation through mangroves was non-linear: the largest reduction in peak water levels occurred at the seaward edge of the mangroves, while further inland the water level changed more slowly (figure below). They suggest that this might explain the relatively low rates of peak water level reductions measured by Krauss et al. (2009; described in Section 2.1), whose measurements start some distance into the mangroves; the water level reduction in the most seaward mangroves might have been higher.

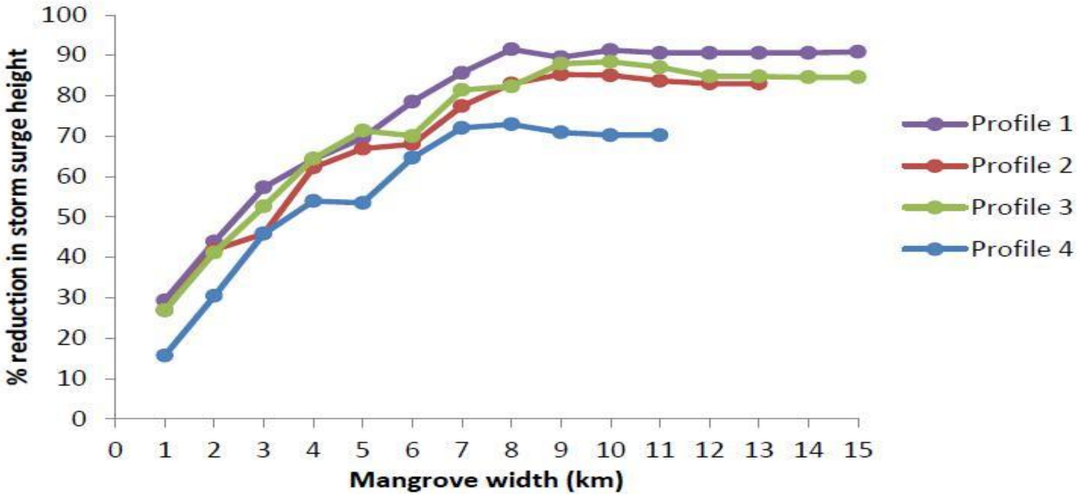


Figure 11: The reduction in storm surge height as the mangrove belt width increases for four different shore profiles (adapted from Zhang et al. 2012).

2.4 Mangrove forest structures

One of the most important factors affecting the rate of wave attenuation is the structure and characteristics of the mangroves vegetation (McIvor et al. 2012). The stem configurations, roots and branches diameters together with the submerged part of the vegetation plays important role in the magnitude of energy dissipation (Catherine et al. 2012; Massel et al. 1999; Quartel et al. 2007; Alongi et al. 2008). Collectively, these parameters determine the nature of obstacles encountered by waves as they pass through the mangrove forest (McIvor et al. 2012). Greater obstacles will result in higher resistance which eventually give significant impact on wave attenuation.

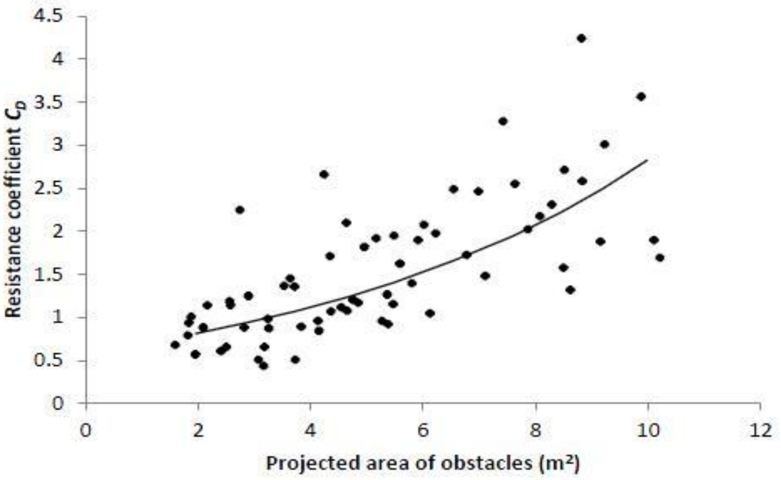


Figure 12: Variation of projected area of obstacles per meter width with the drag coefficient in the mangrove forest to the incoming waves for *Kandelia candel* in the Red River Delta, Vietnam.The smooth line is the exponential trend line. (Quartel et al. 2007).

Mazda et al. (2006) found a similar pattern in *Sonneratia* spp. in Vietnam. At higher tidal levels, when the water levels allowed the waves to pass through the branches and leaves of the trees, wave attenuation increased (McIvor et al. 2012).

As suggested by Mazda et al. (2006), this increase in wave attenuation at higher water depths was due to the thickly spread branches and leaves dissipating the wave energy (McIvor et al. 2012).

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

The role of mangrove forest as a wave energy dissipater depends on various factors such as mangrove species, age, density, trunk and root size, height, root systems as well as external factors such as water depth, incident wave height an etc. Field observations are conducted to investigate the behaviour of waves propagating through mangrove forest as well as to determine the boundary conditions for physical model testing. The data obtained will be modelled in the laboratory.

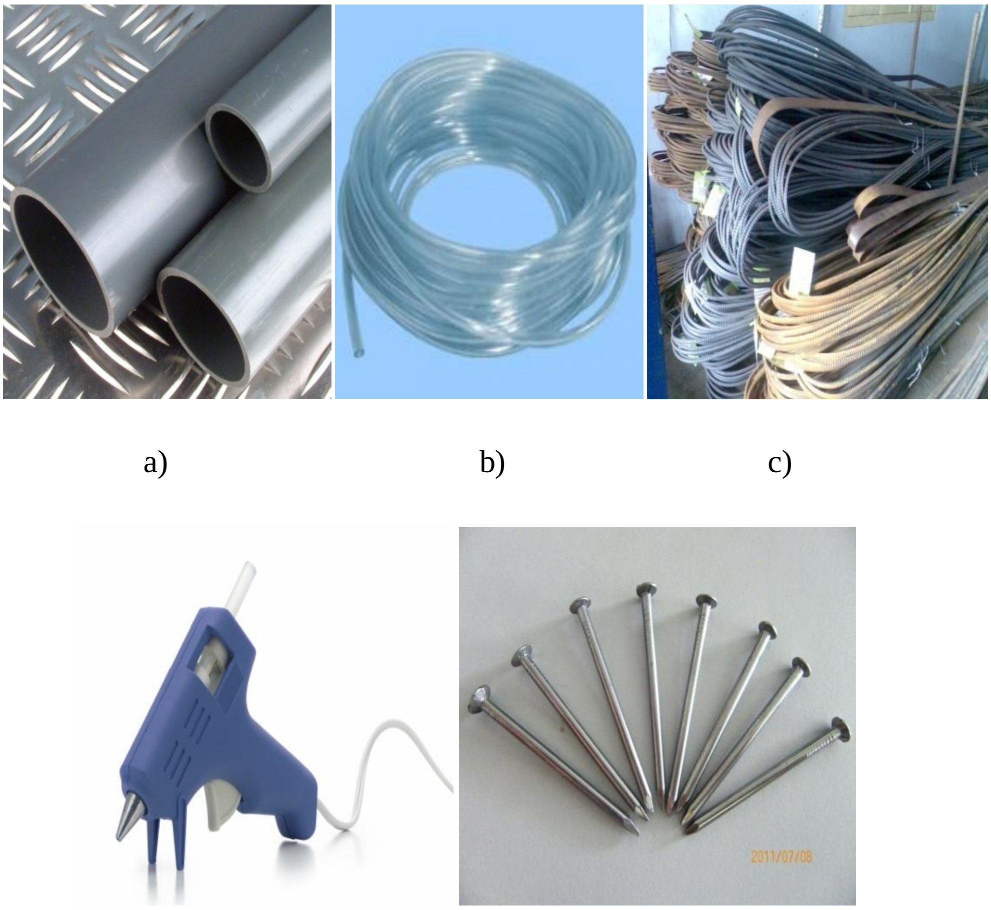
A few series of experiments were conducted. It is initiated by determining the most effective mangrove species out of three species commonly found in Asian, which are *Rhizophora* sp., *Avicennia* sp. and *Bruguiera* sp. The most effective species chosen were further tested with various vegetation parameters such as mangrove age, density, tree arrangement and forest band width while maintaining water depth and wave parameters (incident wave height, wave period etc). Next, the experiments are tested by varying the water depths and incident wave heights while maintaining the vegetation parameters.

3.1.1 Assumptions for modelling works.

Some assumptions were made for the modelling of mangroves in laboratory based on collected data and site observations to simplify the processes. Mangrove models were scaled down to a ratio of 1:10. The dimensions of tree for modelling were obtained through field measurement with the help of a forest ranger in Kuala Sepetang Mangrove Park and Lumut Mangrove Park. Wave period representative of nearshore wind waves range from 1.5 to 2.0 s (Catherine et al., 2012, Augustin et al., 2009), thus a period of 2.0 s is chosen for initial setting. These waves also correspond to the peak period of 8.0 s in the real mangrove field (Tuyen & Hung, 2009). As the slope at real mangrove swamp is generally very gentle, about 1:200 to 1:300, as reported in Catherine's (2013) study (as cited in Tueyen & Hung, 2009), hence the mangrove field is modelled on a flat surface in laboratory. With regard to that, experiments were carried out to investigate the effect of slope on wave height. According to Cathetine et al. (2013), comparing the flat surface and slope of 1:200, it was found that the difference was insignificant. Tuyen & Hung (2009) also stated that JONSWAP (JOin North Sea Wave Project) wave spectrum is suitable for modelling waves coming from the South China Sea; therefore it is adopted in the experiment.

3.1.2 Making of artificial mangrove plants

The main materials for making the mangrove models are Polyvinyl chloride (PVC) pipes, PVC tubing, iron rods, nails and glue.



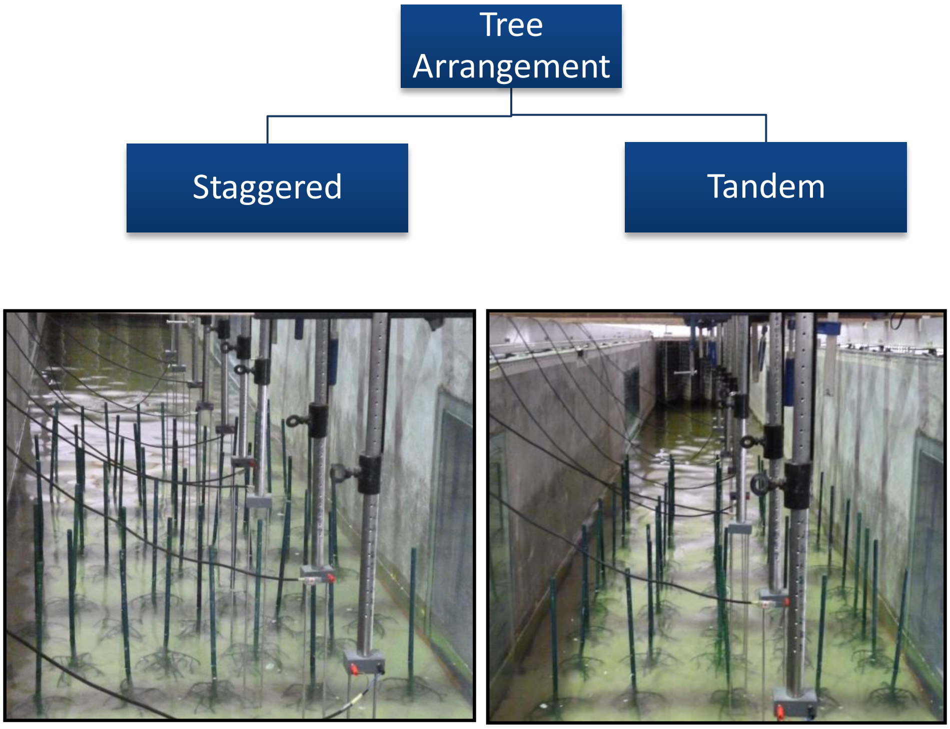
a) b) c)

d) e)

Figure13: a) PVC pipes, b) PVC tubing, c) Iron rod, d) Nail, e) Hot glue gun

3.1.3 Test conditions

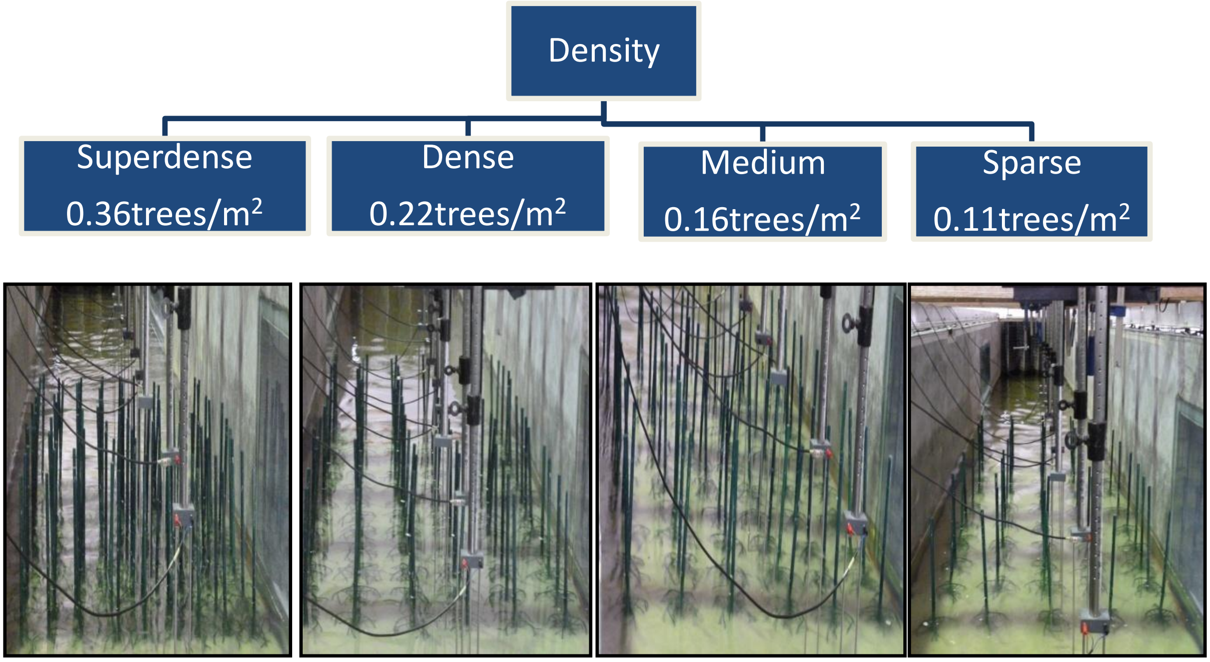
(a) Test for tree arrangements



Water depth = 0.15 m; wave height = 0.05 m; density = 0.11 trees/m²

Figure 14. Test for tree arrangements.

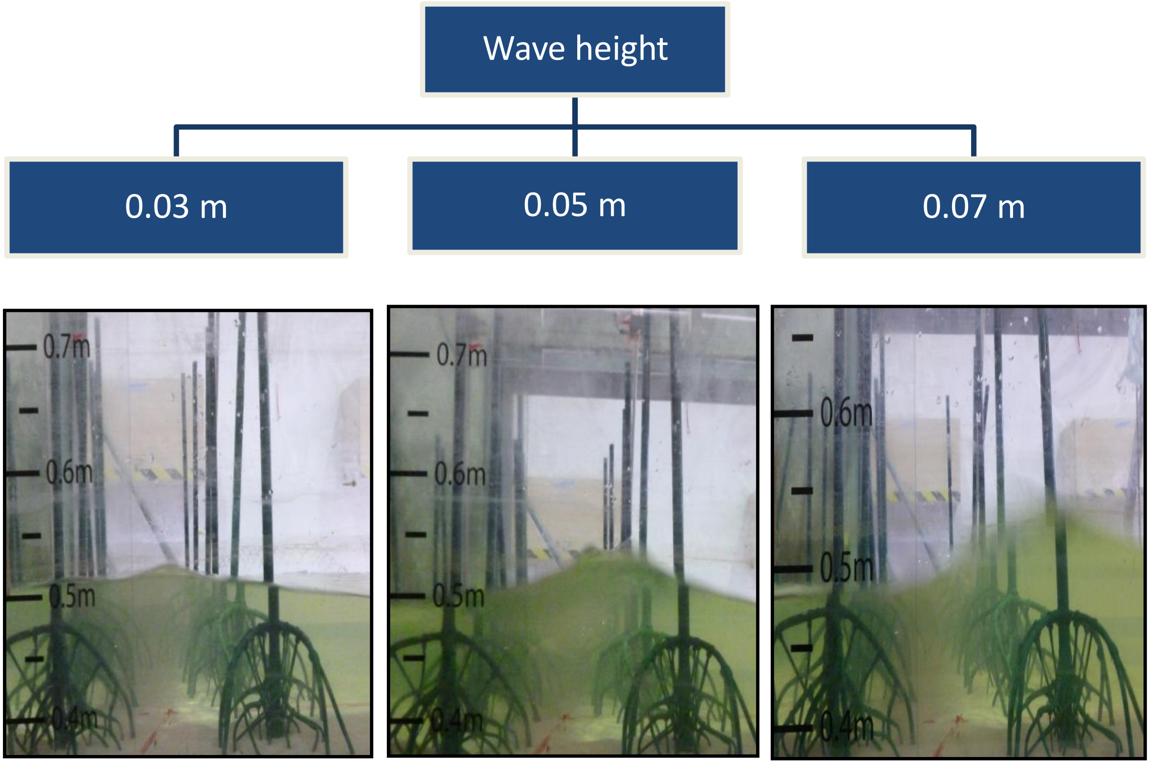
(b) Test for densities



Water depth = 0.15m; wave height = 0.07 m

Figure 15. Test for mangrove densities.

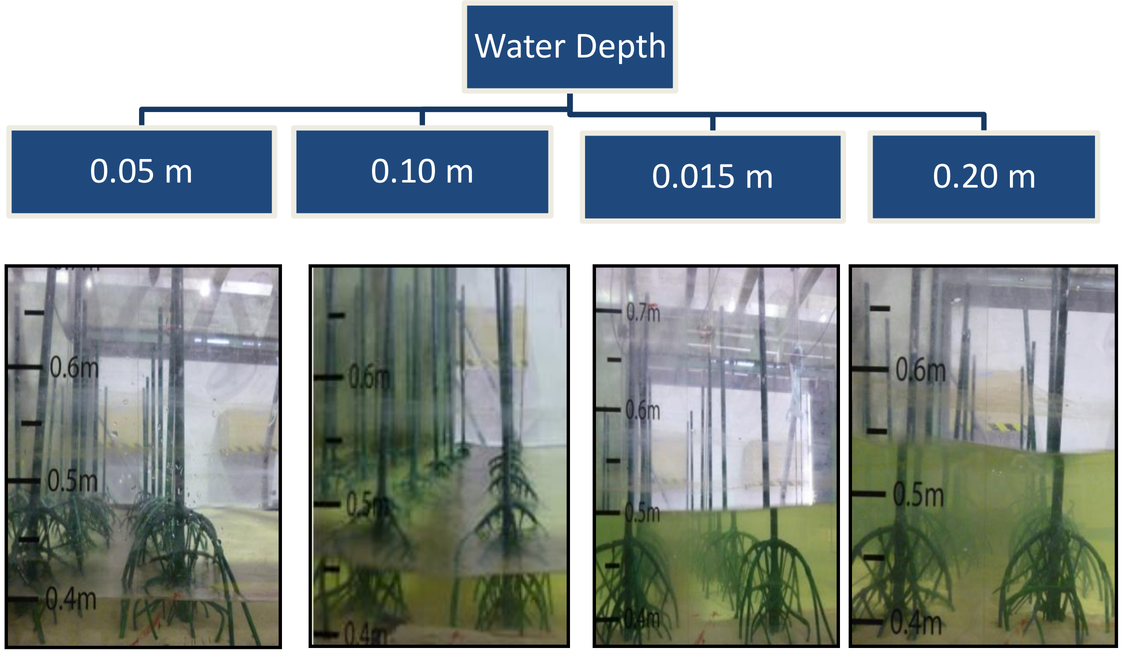
(c) Test for wave heights



Density = medium; water depth = 0.15 m

Figure 16. Test for wave heights.

(d) Test for water depths



Density = medium; water height = 3 cm

Figure 17. Test for water depths.

3.1.4 Experimental Setup

The experiments were conducted in a narrow wave flume in Offshore laboratory of Universiti Teknologi PETRONAS to assess the effect of mangrove age, density, tree arrangement, water depth and incident wave height on wave attenuation. One wave gauge was placed before the slope while 10 wave gauges on the flat platform (Fig. 20). The wave gauge before the slope was placed 4.5 m from the second wave gauge while remaining wave gauges were spaced 0.5 m away from each other on flat platform. In order for the waves to stabilize before reaching the models, the models were placed 1.0 m after the slope. The wave heights before and inside the mangrove field were measured. All test conditions are to be completed at least three times to ensure that they were repeatable and accurate representations of conditions being tested. The narrow wave flume is 23 m long, 1.5 m wide and 1.2 m high.

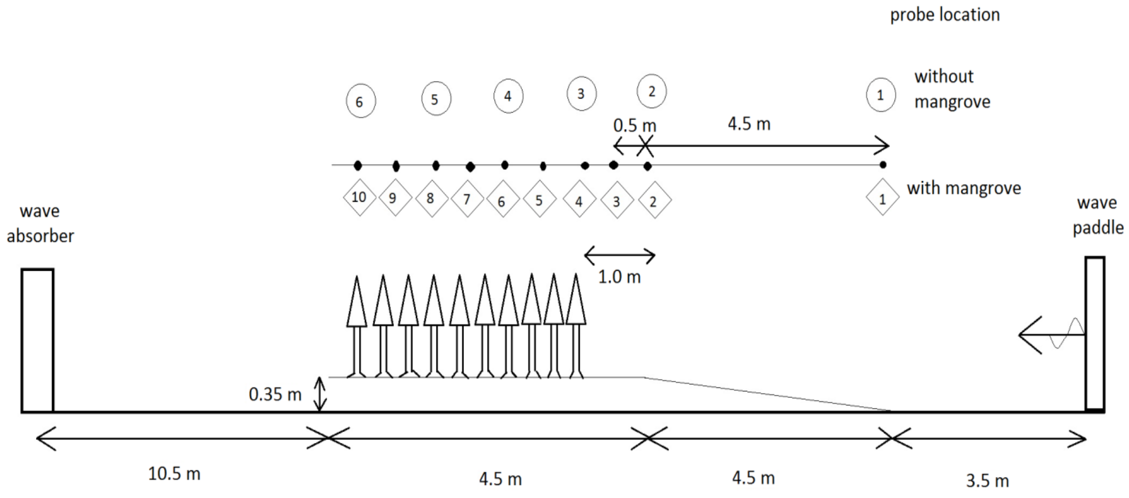


Figure 17. Schematic of narrow wave flume setup.

3.2 Tools & Equipments Required

Tools	Purpose
Wave flume	To model waves propagating through mangrove field
Wave maker	To generate waves
Wave energy absorber	To reduce reflection effects by waves
Artificial mangrove plant	To model the real mangrove tree
Resistance wire probe electric wave gauges(x10)	To measure water surface elevation
Edinburgh Design's Ocean Software	To control the wave maker, collect and analyze incoming data from the waves

Table 2: Tools and equipments required.

3.3 Site Assessments and Field Measurements

Site visits to mangrove forests were conducted to measure the physical characteristics of mangrove trees and to determine the boundary conditions for laboratory experiments. These include the mangrove forest density, bed slope, water depth, wave height and etc. The sites visited are:

1. Kuala Sepetang Mangrove Park
2. Lumut Mangrove Park
3. Tanjong Kepah
4. Pantai Lekir
5. Pantai Teluk Tiga

3.3.1 Kuala Sepetang Mangrove Park

It is the largest mangrove reserve in Malaysia with over 40,000 hectares in size. The mangrove forest stretches for 50 km from Kuala Gula to Pantai Remis along Perak's coastline. At Kuala Sepetang, the Rhizophora trees are planted for charcoal production. The Rhizophora apiculata and Rhizophora mucronata are planted at the spacing of 1.2 m and 1.8 m, respectively.

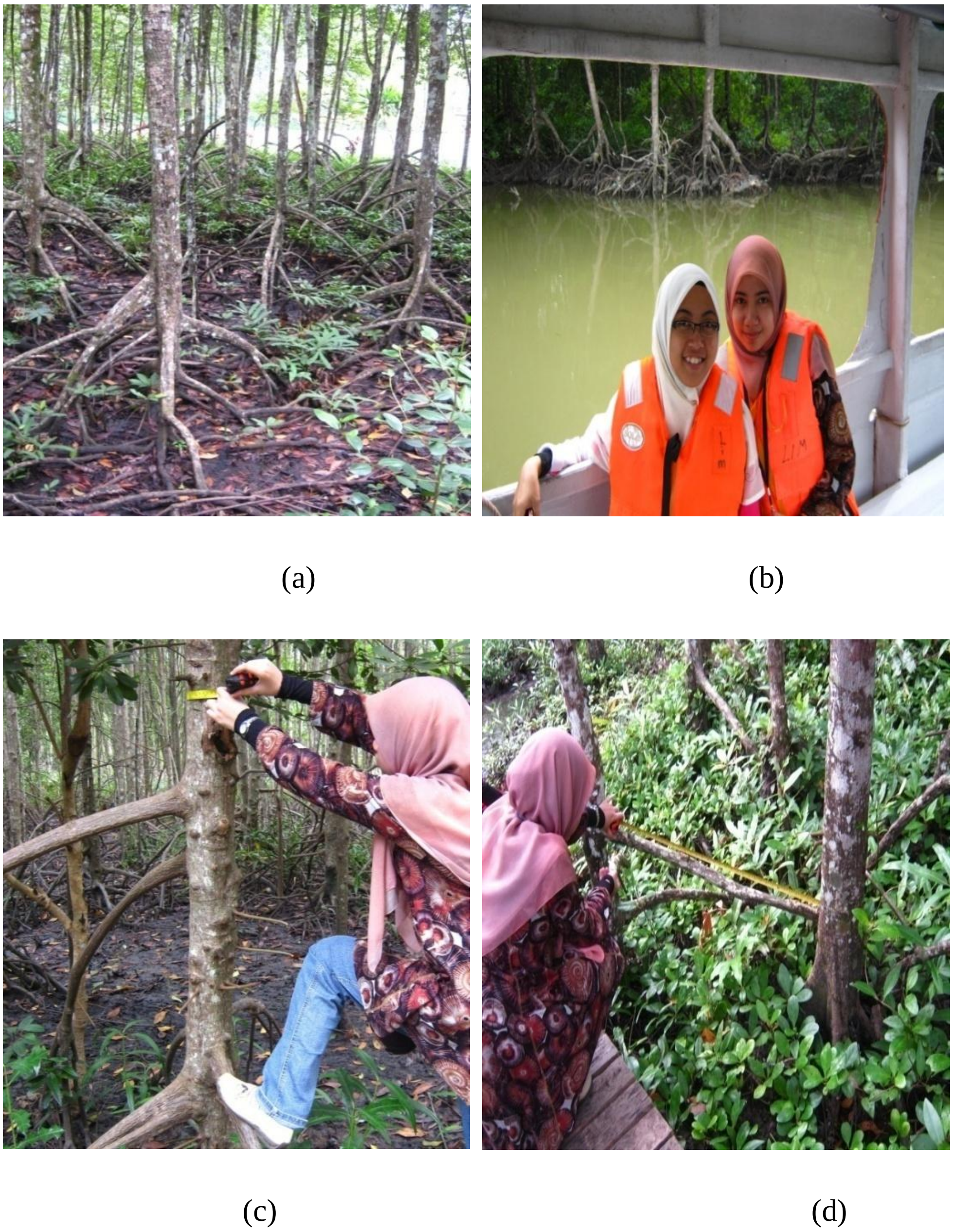
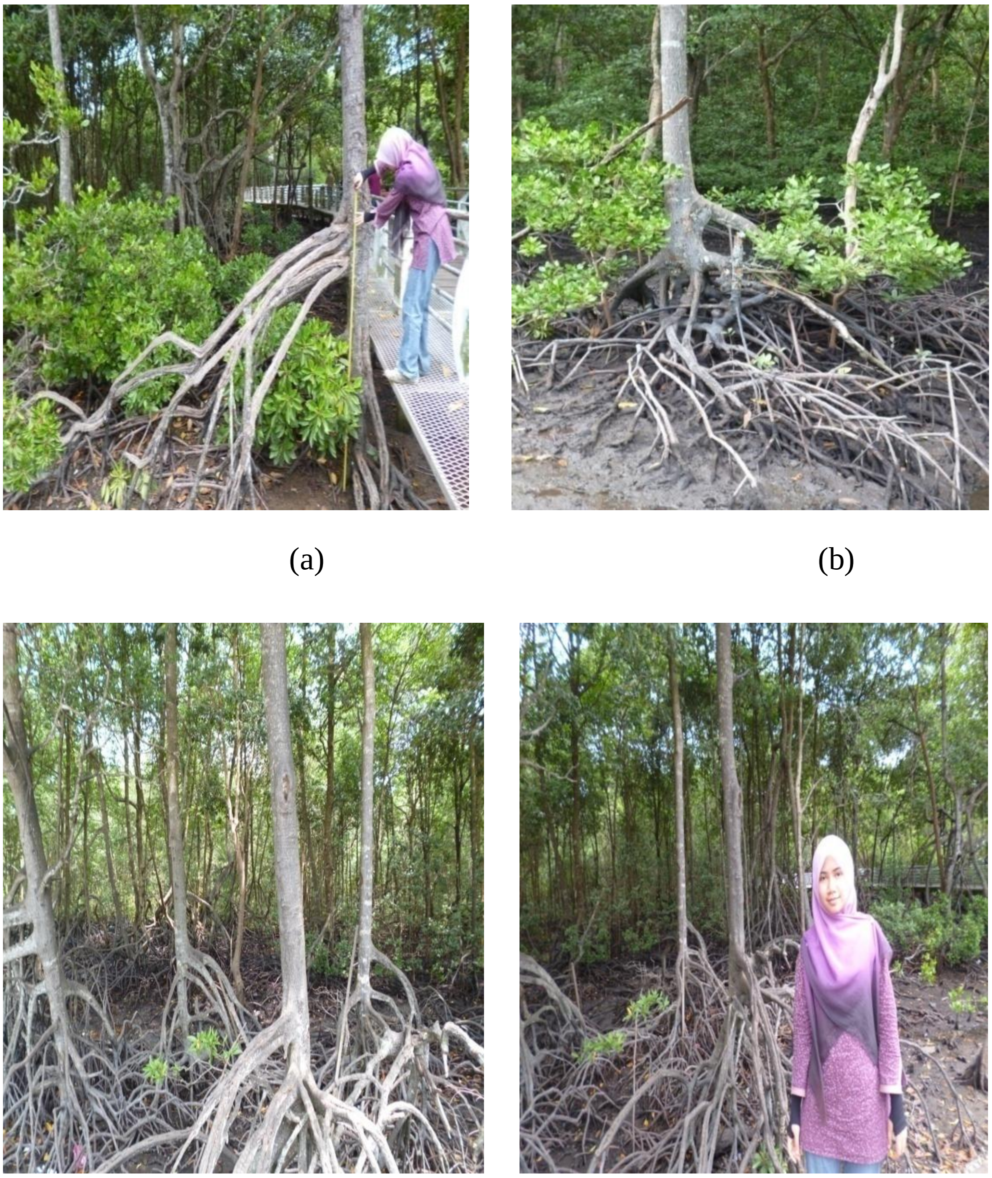


Figure18: a) Mangrove tree of various size, b) Observing the interaction of waves and mangrove forest, c) Measuring the dimensions of mangrove tree, d) Measuring the dimension of mangrove tree.

3.3.2 Lumut Mangrove Park

The Lumut Mangrove Park is dominated by *Rhizophora mucronata* and *Rhizophora apiculata* with minor *Bruguiera gymnorhiza*. The mangrove forest is approximately 100 m wide measured from river bank to the land. The *Rhizophora* trees of various ages can be observed.



(a) (b)

(c) (d)

Figure 19: a) Measuring the dimensions of mangrove tree, b) Observing the structures of mangrove root system, c) Mangrove tree of various size, d) Observing mangrove forest structures.

3.4 Field Observations

3.4.1 Pantai Teluk Tiga

The field observation was conducted at Pantai Teluk Tiga, Perak to measure the wave height reduction across mangrove forest. Pantai Teluk Tiga is located approximately 19 km from Sitiawan while 17.4 km from Bagan Datoh which is previously affected by 2004 Indian Ocean Tsunami (Fig. 21). The site consists of *Rhizophora* plantation of less than 10 years old. The wave heights before and inside mangrove forest were observed during the highest tide of the day.

Figure 20. Location of Pantai Teluk Tiga.

Figure 21. The exposure of Rhizophora roots during low tide.

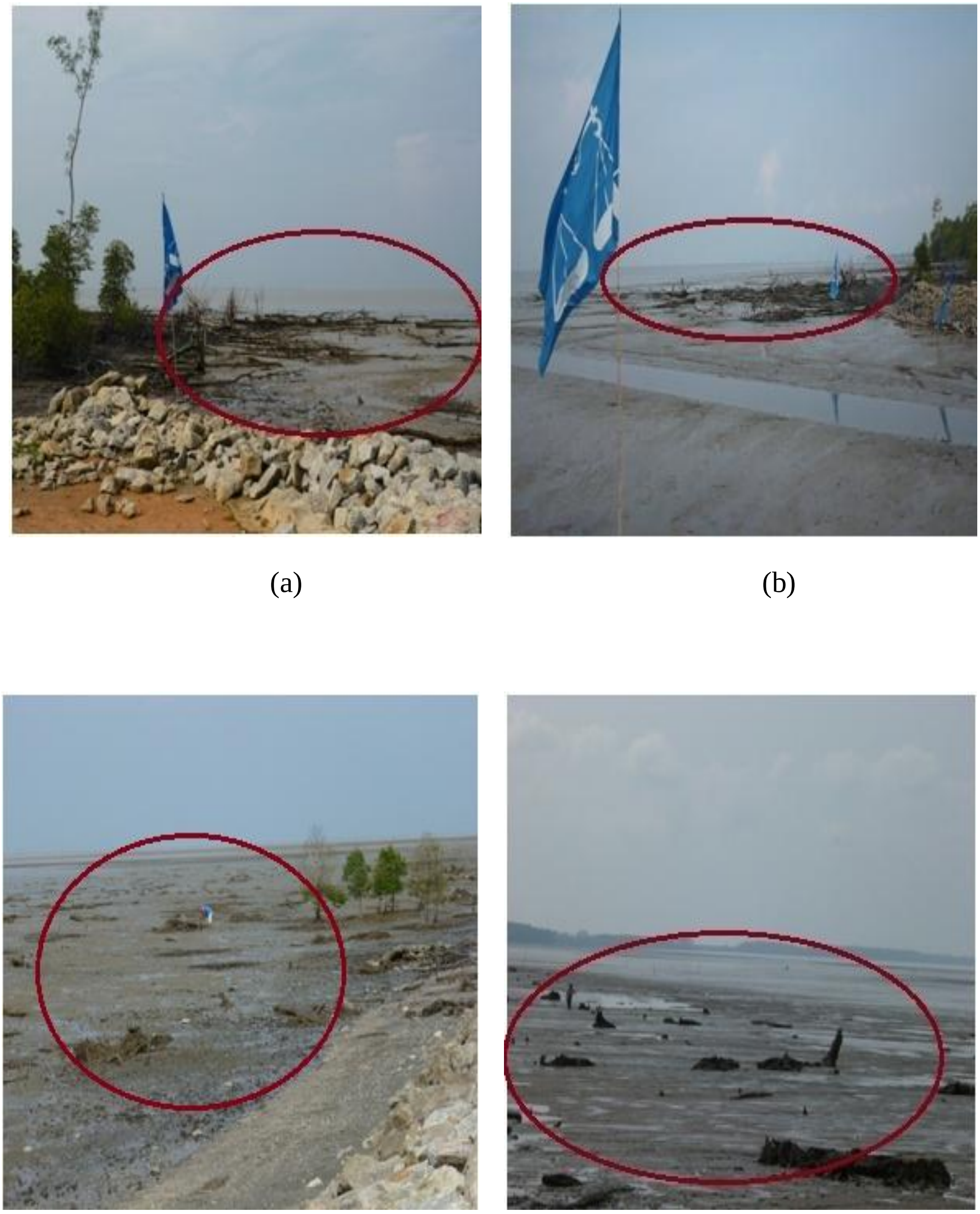
Figure 22. The flooding of Rhizophora roots during high tide.

Figure 23. Measuring wave height in front of Rhizophora forest.

Figure 24. Measuring wave height in Rhizophora forest.

3.4.2 Pantai Lekir

Lekir is one of the main village in Manjung district, Perak, Malaysia.



(a) (b)

(c) (d)

Figure 25: a), b), c), d) Diminishing of mangrove forest due to severe erosion problem.

3.4.3 Tanjung Kepah

Tanjong Kepah is located approximately 11 km from Sitiawan, Perak. The site is directly fronting the sea and *Avicennia* spp. is the dominant species.

(a) (b)

Figure 26: a) , b) Failure of mangroves replanting project.

3.5 Project activities

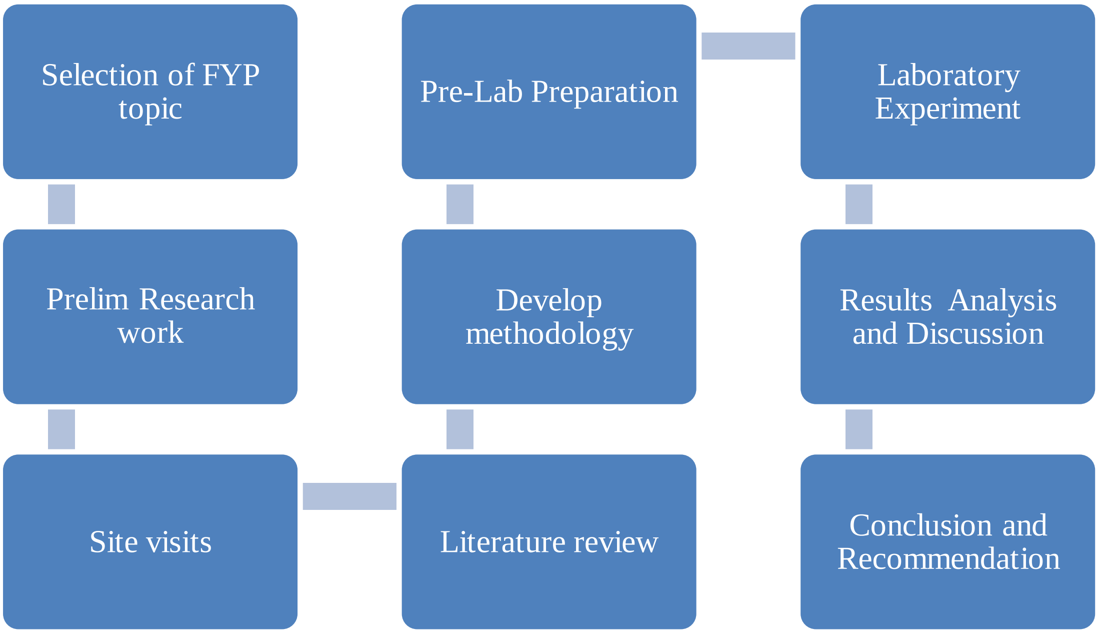


Figure 27: Project Process Flow

3.6 Key milestone

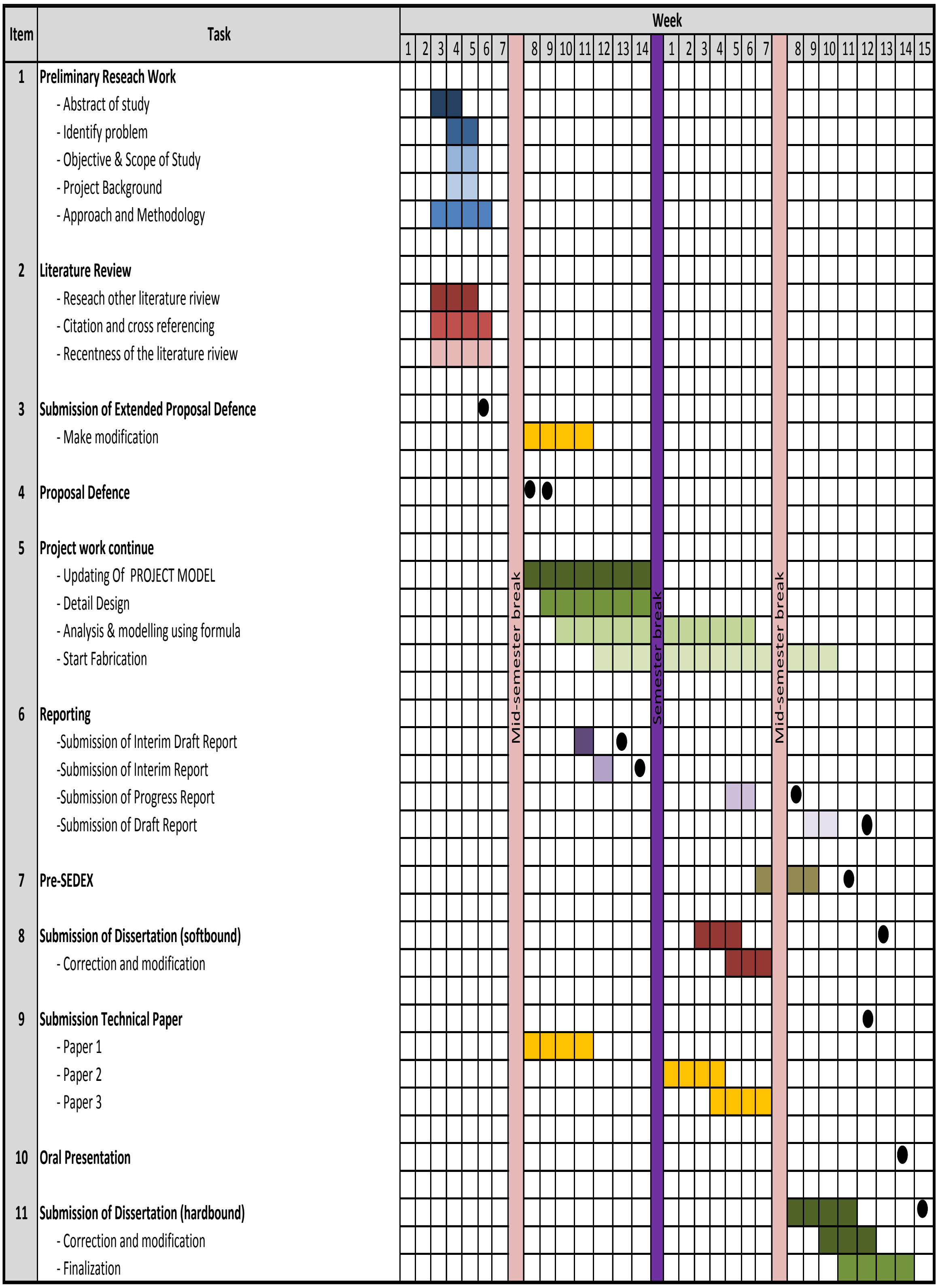
Details	Week
1. Title selection	1
2. Extended proposal submission	6
3. Proposal defence	9
4. Draft report submission	13
5. Interim report submission	14

Table 3: Timelines for FYP I.

Details	Week
1. Project work continues	1 - 7
2. Submission of progress report	8
3. Project work continues	8 - 12
4. Pre-SEDEX	11
5. Submission of draft report	12
6. Submission of dissertation(soft bound)	13
7. Submission of technical paper	13
8. Oral presentation	14
9. Project dissertation (Hard bound)	15

Table 4: Timelines for FYP II.

3.7 Gantt Chart



Item	Task	Week																															
		1	2	3	4	5	6	7	Mid-semester break	8	9	10	11	12	13	14	Semester break	1	2	3	4	5	6	7	Mid-semester break	8	9	10	11	12	13	14	15
1	**Preliminary Reseach Work**																																
	- Abstract of study			■	■																												
	- Identify problem				■	■																											
	- Objective & Scope of Study				■	■																											
	- Project Background				■	■																											
	- Approach and Methodology			■	■	■	■																										
2	**Literature Review**																																
	- Reseach other literature riview			■	■	■																											
	- Citation and cross referencing			■	■	■	■																										
	- Recentness of the literature riview			■	■	■	■																										
3	**Submission of Extended Proposal Defence**						●																										
	- Make modification									■	■	■	■																				
4	**Proposal Defence**									●	●																						
5	**Project work continue**																																
	- Updating Of PROJECT MODEL									■	■	■	■	■	■	■																	
	- Detail Design										■	■	■	■	■	■																	
	- Analysis & modelling using formula											■	■	■	■	■		■	■	■	■	■	■										
	- Start Fabrication												■	■	■	■		■	■	■	■	■	■	■		■	■	■					
6	**Reporting**																																
	-Submission of Interim Draft Report												■		●																		
	-Submission of Interim Report													■		●																	
	-Submission of Progress Report																					■	■			●							
	-Submission of Draft Report																										■	■		●			
7	**Pre-SEDEX**																							■		■	■		●				
8	**Submission of Dissertation (softbound)**																			■	■	■									●		
	- Correction and modification																					■	■	■									
9	**Submission Technical Paper**																													●			
	- Paper 1									■	■	■	■																				
	- Paper 2																	■	■	■	■												
	- Paper 3																				■	■	■	■									
10	**Oral Presentation**																															●	
11	**Submission of Dissertation (hardbound)**																									■	■	■	■				●
	- Correction and modification																											■	■	■			
	- Finalization																												■	■	■	■	

● Suggested milestone by UTP

■ Process

Table 5: Schedule planning for Final Year Project.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Result

The wave heights before and inside mangrove field for varying tree arrangements, forest densities, water depths and incident wave heights have been measured and plotted. The wave reduction rate (*r*) was calculated by using Equation (2):

$$H_x = H_0 . e^{(-r \cdot x)} \qquad \textbf{Eqn. 2}$$

The change in the wave reduction rate (*r*) is considered to be very small throughout the mangrove field. Hence, it can be used to further estimate the total wave reduction across 30 m, 50 m, 100 m and 200 m mangrove forest width (Refer to Appendix 2 for example calculation).

4.1.1 Effect of tree arrangements on wave reduction.

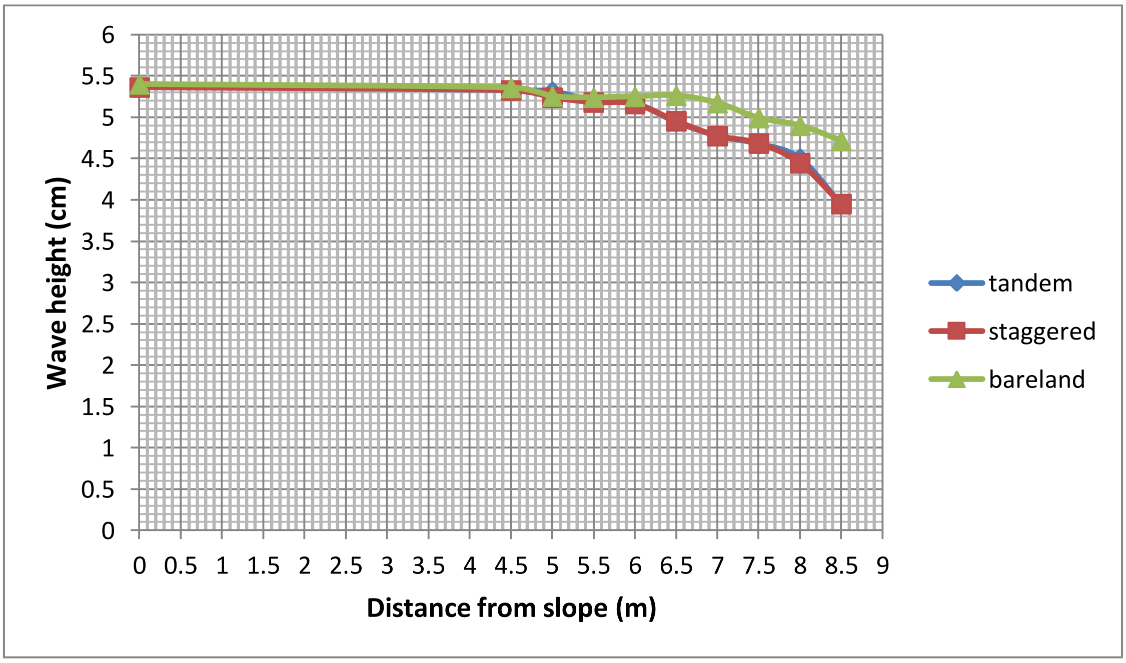


Figure 28. Wave reduction in the area with mangroves and bare land. For area with mangroves, the trees were arranged in tandem and staggered order. The mangrove models were placed from a distance of 5.5 m from slope front.

Table 6. Wave reduction rate in bare land, mangrove forest of tandem and staggered arrangements.

Tree arrangement	Wave reduction rate, r (m^{-1})
Bare land	0.023172
Tandem	0.071534
Staggered	0.076135

Table 7. Estimated total wave reduction (%) for mangrove forest of width 30 m, 50 m and 100 m for different tree arrangements.

Tree arrangement	Total wave reduction for mangrove forest of width		
	30 m	50 m	100 m
Bare land	6.7%	10.9%	20.7%
Tandem	19.3%	30.1%	51.1%
Staggered	20.4%	31.7%	53.3%

4.1.2 Effect of densities on wave reduction.

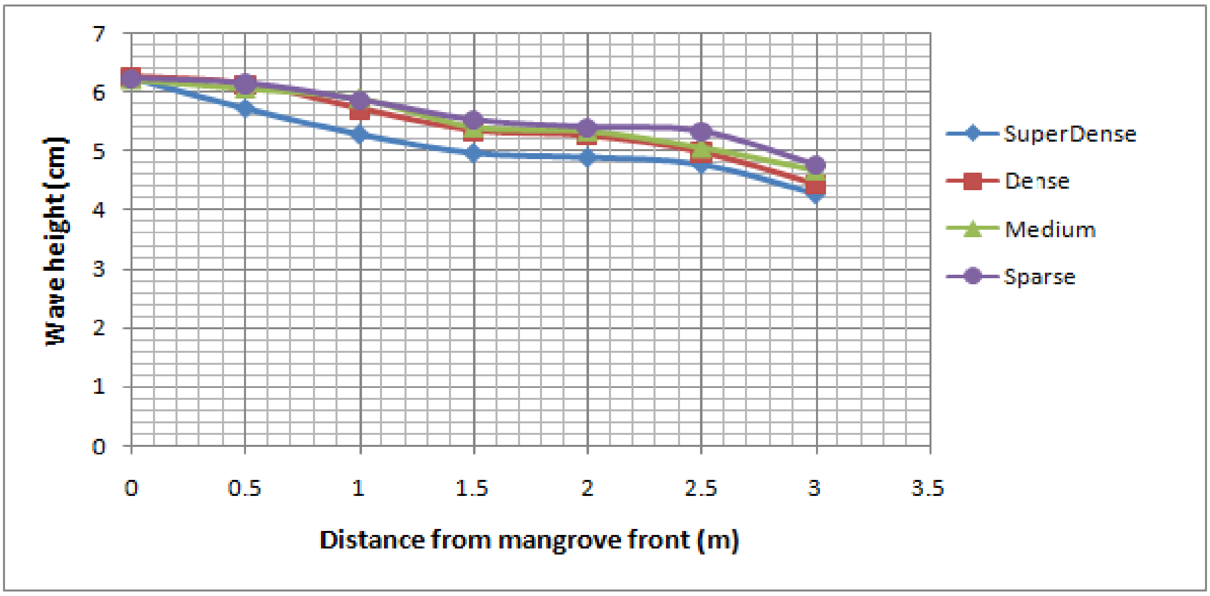


Figure 29. Wave heights with distance into mangrove forest of different densities. The extend of mangrove models for super dense,dense, medium and sparse densities were 3.0 m.

Table 8. Wave reduction rate in mangrove forest of dense, medium and sparse densities.

Density	Wave reduction rate, r (m^{-1})
Super dense	0.12034318
Dense	0.10415342
Medium	0.09844387
Sparse	0.07276273

Table 9. Estimated total wave reduction (%) for mangrove forest of width 50 m, 100 m and 200 m of various densities.

Density	Total wave reduction for mangrove forest of width		
	50 m	100 m	200 m
Super dense (0.36 trees/m²)	45.2 %	69.9 %	91. 0%
Dense (0.22 trees/m²)	40.6 %	64.7 %	87.5%
Medium (0.16 trees/m²)	38. 7 %	62.6 %	86.0%
Sparse (0.11 trees/m²)	30.5 %	51.7 %	76.7%

4.1.3 Effect of wave heights on wave reduction.

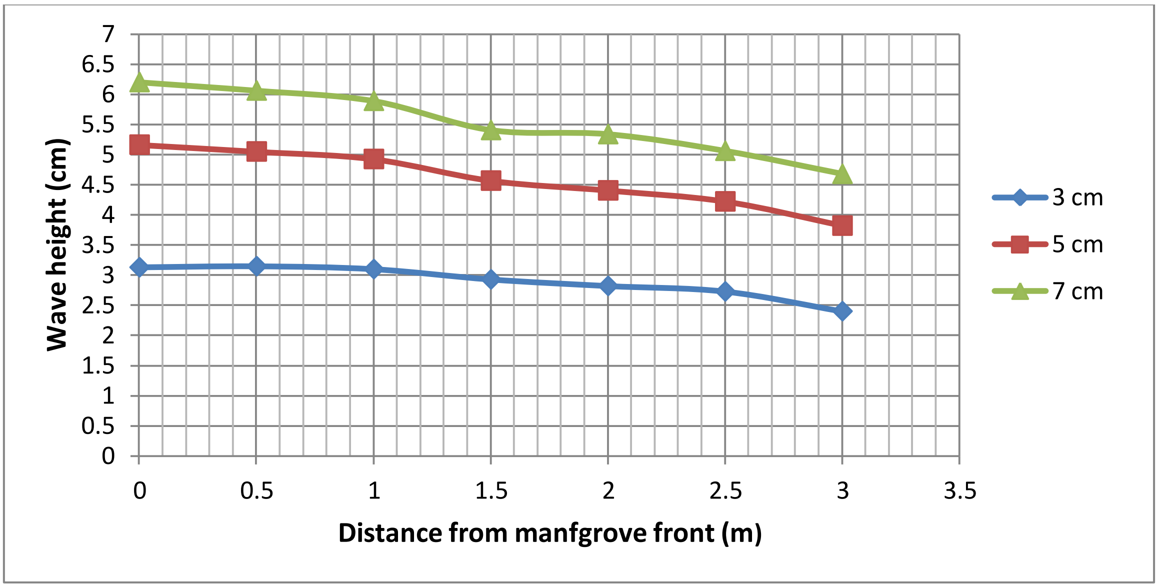


Figure 30. The wave reduction with distance from mangrove front for three different incident wave heights. The mangrove models extended for a length of 3.0 m.

Table 10. Wave reduction rate with respect to various incident wave heights.

Wave height (m)	Wave reduction rate, r (m⁻¹)
0.03	0.040361
0.05	0.072206
0.07	0.073103

Table 11. Estimated total wave reduction (%) for various incident wave heights.

Wave height (m)	Total wave reduction for mangrove forest of width	
	50 m	100 m
0.03	18.3 %	33.2 %
0.05	30.3 %	51.4 %
0.07	30.6 %	51.9 %

4.1.4 Effect of water depths on wave reduction.

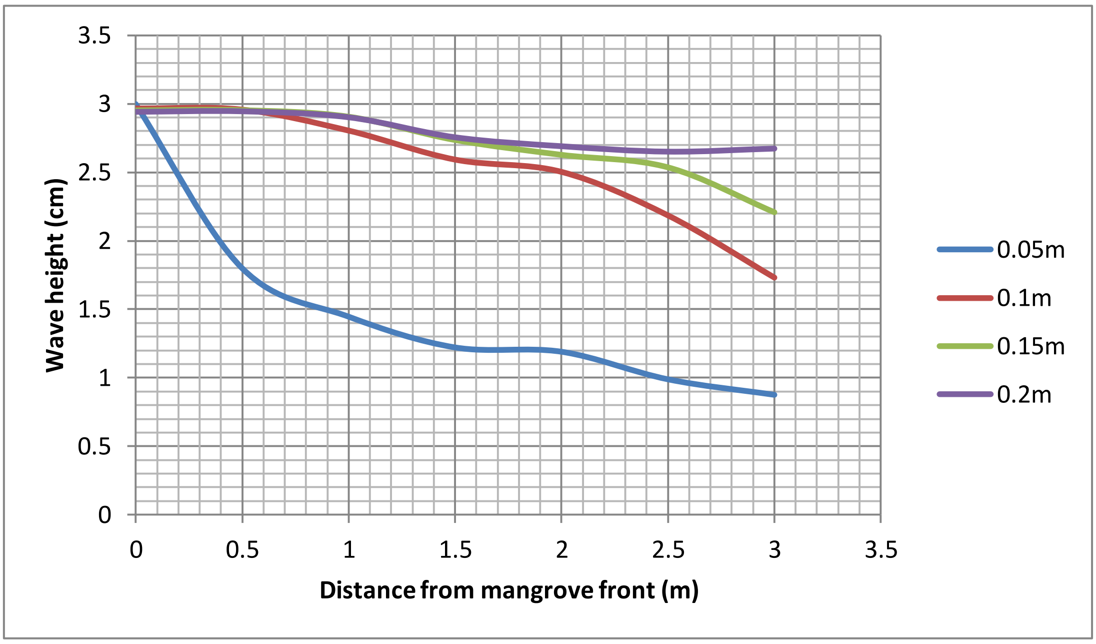


Figure 31. Wave heights with distance from mangrove front for different water depths.

Table 12. Wave reduction rate with respect to different water depths.

Water Depth (m)	Wave reduction rate, r (m^{-1})
0.05	0.410393
0.1	0.179498
0.15	0.096832
0.2	0.035293

Table 13. Estimated total wave reduction (%) for mangrove forest of width 50 m and 100 m of various water depths.

Wave height (m)	Total wave reduction for mangrove forest of width	
	50 m	100 m
0.05	87.2%	98.3%
0.1	59.2%	83.4%
0.15	38.4%	62.0%
0.2	16.2%	29.7%

4.15 Comparison of mangrove performance of age 20 years old and 10 years old on tree arrangement.

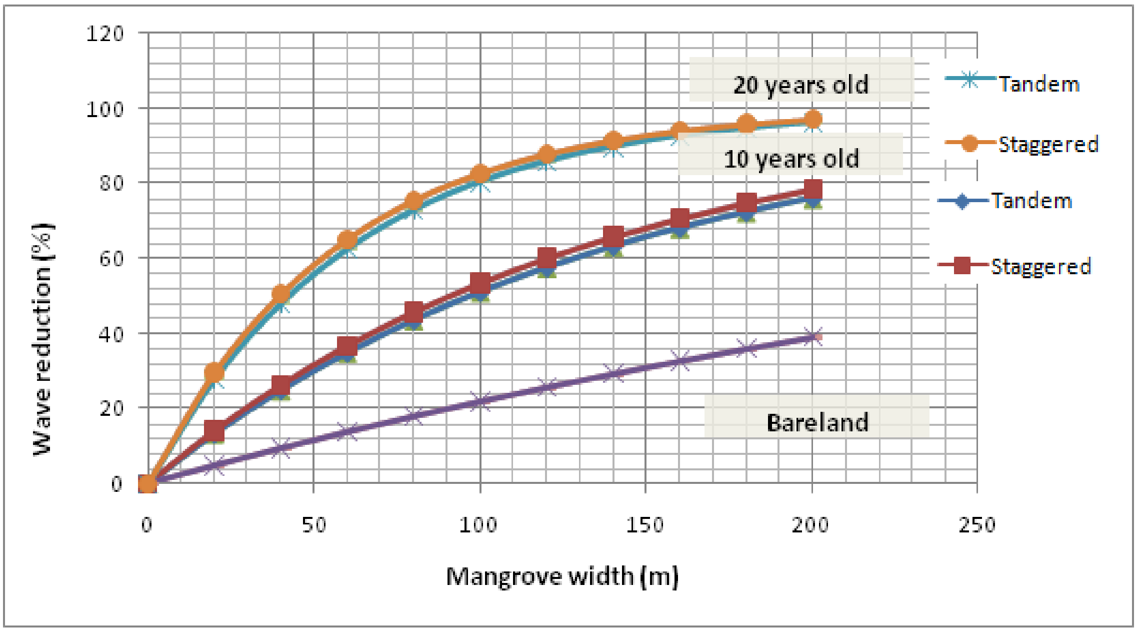


Figure 32. Wave reduction with respect to age group on different tree arrangement

Table 14. Wave reduction rate with respect to age group on different tree arrangement.

Tree arrangement	Wave reduction rate, r (m^{-1}) 20 years	Wave reduction rate, r (m^{-1}) 10 years
Bare land	0.0247	0.037659
Tandem	0.1632	0.071534
Staggered	0.1758	0.076135

Table 15. Comparison of estimated total wave reduction (%) for mangrove forest of age 20 years and 10 years old on tree arrangement.

Tree arrangement	Total wave reduction for mangrove forest of width					
	30 m		50 m		100 m	
	20 years	10 years	20 years	10 years	20 years	10 years
Bare land	7.1%	10.6%	11.6%	17.2%	21.9%	20.7%
Tandem	38.7%	19.3%	55.8%	30.1%	80.4%	51.1%
Staggered	41.0%	20.4%	58.5%	31.7%	82.8%	53.3%

4.16 Comparison of mangrove performance of age 20 years old and 10 years old on tree densities.

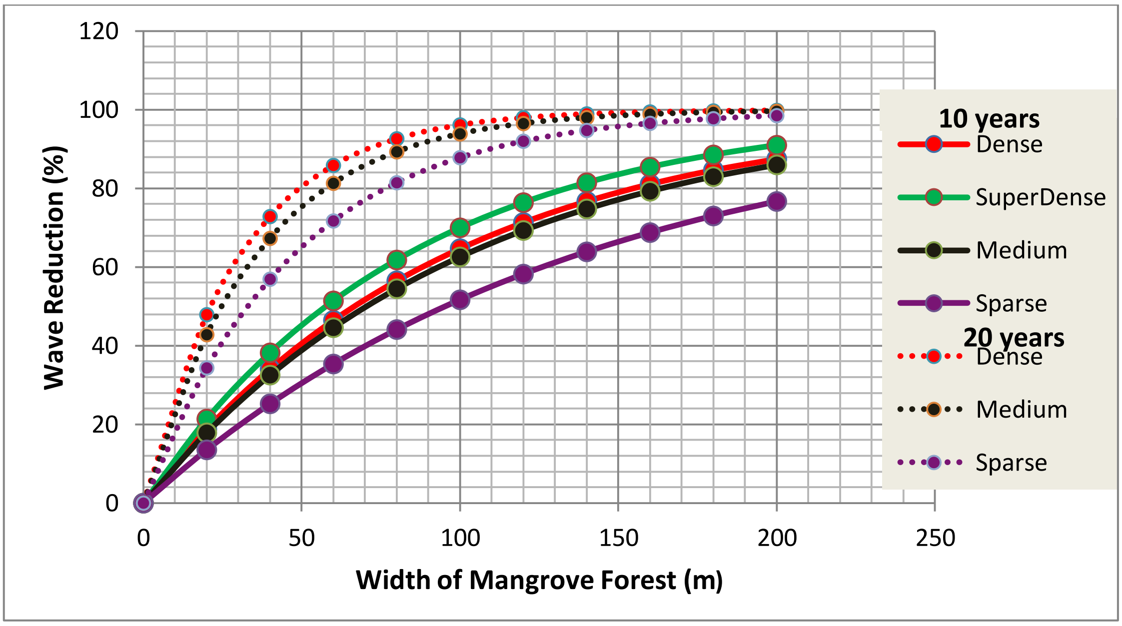


Figure 33. Wave reduction with respect to age group on different forest densities.

Table 16. Wave reduction rate with respect to age group on different forest densities.

Density	Wave reduction rate, r (m^{-1})10 years	Wave reduction rate, r (m^{-1})20 years
Super dense	0.12034318	-
Dense	0.10415342	0.3261
Medium	0.09844387	0.2795
Sparse	0.07276273	0.2106

Table 17. Comparison of estimated total wave reduction (%) for mangrove forest of age 20 years and 10 years old on various densities.

Density	Total wave reduction for mangrove forest of width					
	50 m		100 m		200 m	
	20 years	10 years	20 years	10 years	20 years	10 years
Super dense (0.36 trees/m²)	-	45.2%	-	70.0%	-	91.0%
Dense (0.22 trees/m²)	80.4%	40.6%	96.2%	64.7%	99.9%	87.5%
Medium (0.16 trees/m²)	75.3%	38.9%	93.9%	62.6%	99.6%	86.0%
Sparse (0.11 trees/m²)	65.1%	30.5%	87.8%	51.7%	98.5%	76.7%

4.1.7 Field observation.

Table 18. Field observation at Pantai Teluk Tiga, Perak (consists of Rhizophora trees of less than 10 years old).

Wave height at sea-mangrove fringe	Wave height at 50 m inland	Wave reduction rate, r (m^{-1})
0.3 m	0.1 m	0.021972

4.2 Discussion

The experimental results show that the wave heights decreased when the waves propagated further into the mangrove field (Fig. 28). Whereas in the area without mangroves, there was only a slight reduction in the wave heights. This is because in area without mangroves, the reduction is mainly caused by the bottom friction due to the sandy surface. The wave reduction was significantly higher in area with mangroves due to the additional friction contributed by the trunks and root system. Hashim et al. (2013) through their physical model testings found that wave height reduction by mangrove trees of age 20 years attenuate 80 % (Fig. 32) of total wave reduction for mangrove forest of width 100 m which is four times greater compared to bareland. In year 2007, according to Quartel et al., from their field measurements found that the wave height reduction by a 31.8 m wide mangrove forest dominated by *Kandelia candel* was 5 to 7.5 times larger compared to bare land. Based on the wave reduction rate obtained from the experiments (Table 6), for similar water depth (1.5 m) and mangrove forest width , the wave reduction for bare land was 10.7 % while the reduction was over 19.31 % for area with mangroves, which was about 2 times larger compared to bare land (Table 7). This suggests that resistance exerted by mangroves also depends on the mangrove age since each age has different structures and sizes of trunk and root system. It is further estimated that for a 100 m wide of *Rhizophora* of age 10 years old forest, the wave reduction was over 51.1 % compared to 20.7 % by bare land, about 2.5 times larger. The wave height reduction through mangroves was larger than by bottom friction only, indicating the effectiveness of mangrove forests in surface wave attenuation.

The wave reduction was greater when the mangrove models of age 20 years were arranged in staggered order compared to tandem arrangement by 3 %, Hashim et al. (2013) (Fig. 32) . For the case of staggered arrangement, the waves could not propagate freely through the gaps between mangrove plants as in tandem case, hence more wave energy was dissipated. Subsequently, the difference in total wave reduction for both arrangements for mangroves of age 10 years was also less than 3 %, which is considerably not significant (Table 10). This findings strenghtening the suggestions by Hashim et al. (2013) that the arrangement of mangrove seedlings is not important during mangrove replanting project. This might be due to the structure of *Rhizophora* roots which spread widely and in most case overlap with roots of other trees. As most of the waves were attenuated by the roots, the wave reduction was still considerably high no matter how the trees were arranged, either tandem or staggered order.

Through laboratory testings, it is proven that dense mangrove forest attenuated waves more effectively (Fig. 29). The spacing between mangrove trees was smaller in denser forest, hence imposes higher resistance to the incoming waves due to larger quantity of trunks and roots available per m² area. The density of 0.36 trees/m² represented a spacing of 1.7 m between trees in real mangrove site. In real condition, naturally grown matured forest, the distance between *Rhizophora* trees are seldom be less than 2.0 m because the prop roots spread wide enough that take up lots of space, Hashim et al. (2013) . In Larut Matang, *Rhizophora apiculata* and *Rhizophora mucronata* are planted at the spacing of 1.2 m and 1.8 m, respectively. However, the thinning process will be done at later time to provide enough space for growing. As observed during the site visits to mangrove parks, the spacing of naturally-grown mangrove trees is about 3.0 m, equivalent to 0.11 trees/m² and this density was also being tested in the laboratory. For 100 m wide of 10 years *Rhizophora* forest, the total wave reduction estimated for super dense, dense, medium and sparse forest were 70.0 %, 64.7 %, 62.6 %, and 51.7%, respectively (Table 12). Currently, the Malaysian’s guideline has specified 200 m mangrove buffer zone along the coast for coastal protection. For *Rhizophora* forest of this age and width, it is found that a density of 0.36 trees/m² is required to reduce wave height of 91 %. During replanting project, the seed can be planted at a closer distance with higher density and later thinning process could be carry out. This is because, Rhizophora forest of same width require 20 years to gain more than 98 % total wave reduction.

For *Rhizophora* tree, the root system plays a major part in wave attenuation. The highest wave reduction rate was shown when water depth was 0.05 m, followed by 0.10 m, 0.15 m and lastly 0.20 m (Fig. 31). These water depths represented the normal water depth range in mangrove swamp. Mangrove forests normally grow in intertidal zone which is between Mean Sea Level (MSL) and Mean High Water Spring (MHWS). In Malaysia, the water depth at mangrove swamp can reach up to 1.9 m. When water depth increased, the total area of obstacles per area of water column decreased, Hashim et al. (2013). Hence, this resulted in a decrease of wave reduction. The height of root system of the mangrove models was 11.2 cm. As shown by the experimental results, when the water depth was at greater than 11.2 cm, the wave reduction reduced because the obstruction to the incoming waves was mainly caused by the trunk. When water depth was within root height, the 0.05 m and 0.10 m water depth were estimated to give 98.3 % and 83.4 % wave reduction, respectively, across 100 m wide mangrove forest (Table 13). This suggests that the waves were attenuated more effectively when water level was within the height of the root system.

At Pantai Teluk Tiga, the measurements of the wave heights were taken at sea-mangrove fringe and inside mangrove forest during high tide. The wave height has been reduced from 0.3 m to 0.1 m across a 50 m wide mangrove forest. Based on the wave reduction rate computed (Table 18), it is estimated that a 100 m wide mangrove forest would give 19.7 % wave reduction. For similar water depth and wave height, the wave reduction rate obtained from laboratory experiment was 0. 0.040361 m^{-1}, which will contribute to 33.2 % wave reduction across 100 m wide mangrove forest. The higher wave reduction as shown by laboratory experiment is perhaps due to the older mangrove trees being modelled. When the age of mangroves increases, the trees grow bigger and root system is more developed and denser, imposing higher resistance to incoming waves. Therefore, the 10 years old mangroves as tested in laboratory caused higher wave reduction compared to *Rhizophora* forest of less than 10 years old at real site.

The wave heights tested in the laboratory represented wave heights of 30 cm to 70 cm in reality and these were within the normal wave height range in Malaysia. The wave reduction across 100 m mangrove forest width under 30 cm, 50 cm and 70 cm wave heights were estimated to be 33.2 %, 51.4 % and 51.9%, respectively (Table 11). This shows that the mangrove forest of age 10 years is effective to attenuate more than 33% of all the wave heights within normal range in Malaysia. As compared to the performance of Rhizophora of age 20 years, with the same forest width under 30 cm, 50 cm, and 70 cm wave heights it can attenuate 81.5 %, 90.7 %, and 93.1 % respectively, Hashim et al. (2013) . This suggests that a wider width of mangrove forest of younger age is required to increase the capability of the forest to attenuates wave.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

It is proven that age plays an important role for the mangrove forests in attenuating surface wave. The wave reduction for area with a 100 m width mangroves of age 20 years was 4 times larger than area without mangroves, Hashim et al. (2013). Whereas for 100 m width of mangroves of age 10 years, it can attenuate 2.5 times larger than area without mangroves. In area protected by mangroves, the wave impact on shore is reducing. This is really important to mitigate erosion problem as high waves could wash away the soil, causing higher cost to retreat the coastline. Through the study, the arrangement of the mangrove trees did not reflects significant effect on wave reduction with differences of less than 3 %. For matured age of 20 years,both arrangements generated comparable high waves. This indicates that arrangement of mangrove seedlings is not of great concern during mangrove replanting project. A 10 years mangroves width of 200 m with density of 0.11 trees/m^2 is able to dissipate wave height over 77 %. Whereas for mangrove of same width and age with density of 0.36 trees/m^2, the forest can dissipates wave as high as 91 %. It can be concluded that the performance of Rhizophora of age 10 years old is about half of the Rhizophora of age 20 years old. At Pantai Teluk Tiga, the 0.3 m wave height at sea-mangrove fringe was reduced to 0.1 m across a 50 m forest width of age less than 10 years old. When the age of mangroves increses, the trees grow bigger and the root system changes, more developed and denser, resulting greater resistance to the incoming waves.

5.2 Recommendations

The sizes and structures of mangroves increase with age up to the mature stage of about 20 years old. As larger sizes impose higher resistance to waves, a fully grown mature mangrove tree causes higher wave reduction compared to a young tree, Hashim et al. (2013). It is proven that the younger trees will contribute to lesser wave reduction compared to the older ones. Malaysia has started mangrove re-planting projects since 2005. It is eminent to know the wave attenuation capability of mangroves trees especially few years after re-planting so that we can forecast the performance of each stages of mangrove forests in attenuating surface wave. Since the study on performance of mangroves of about 20 and 10 years old in attenuating surface waves were studied in laboratory, therefore further study on performnace of mangove of younger age and in terms of dissipating current flow can be considered for future research. Besides, extra cares must also be paid when sand is used as bed materials in the wave flume. It has to be leveled after each test. Otherwise, uneven bed surface will be resulted and this will affect the wave height generated.

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APPENDICES

APPENDIX 1

Parameterization of mangrove tree

Left : A Rhizophora trees **Right : An artificial Rhizophora model**

Scale used = 1:10

APPENDIX 2

Calculation of mangrove forest density

Case: Super Dense

Spacing between trees = 0.20 m

Forest width = 1.5 m

Forest length = 1.8 m

Number of trees/models = 60

Density = $\frac{99\ models}{1.5\ m\ x\ 1.85\ \ m}$ = 35.5 models/m^2

Density (real) = $\frac{99\ trees}{15\ m\ x\ 18.5\ m}$ = 0.355 models/m^2

Case: Dense

Spacing between trees = 0.20 m

Forest width = 1.5 m

Forest length = 1.8 m

Number of trees/models = 90

Density = $\frac{90\ models}{1.5\ m\ x\ 2.725\ \ m}$ =22.2 models/m^2

Density (real) = $\frac{90\ trees}{15\ m\ x\ 27.25\ m}$ =0.22 models/m^2

Case: Medium

Spacing between trees = 0.20 m

Forest width = 1.5 m

Forest length = 1.8 m

Number of trees/models = 60

Density = $\frac{72\ models}{1.5\ m\ x\ 3.0\ m}$ = 16 models/m^2

Density (real) = $\frac{60\ trees}{15\ m\ x\ 30\ m}$ = 0.16 models/m^2

Case: Sparse

Spacing between trees = 0.20 m

Forest width = 1.5 m

Forest length = 1.8 m

Number of trees/models = 60

Density = $\frac{50\ models}{1.5\ m\ x\ 1.8\ m}$ = 11 models/m^2

Density (real) = $\frac{50\ trees}{15\ m\ x\ 18\ m}$ = 0.11 models/m^2

APPENDIX 3

Sample calculation for wave reduction

Effect of densities on wave reduction: Dense case

Distance from mangrove front (m)	0	0.5	1.0	1.5	2.0	2.5	3.0
Wave height (cm)	6.270	6.151	5.726	5.354	5.267	4.988	4.446

$H_x = H_o \exp(-rx)$

At $x = 0.5$ m,

$6.151 = 6.270 exp\,(-\ r\,(0.5))$

$r = 0.038014$

At $x = 1.0$ m,

$5.726 = 6.270 exp\,(-\ r\,(1))$

$r = 0.090612$

At $x = 1.5$ m,

$5.354 = 6.270 exp\,(-\ r\,(1.5))$

$r = 0.134522$

At $x = 2.0$ m,

$5.267 = 6.270 exp\,(-\ r\,(2))$

$r = 0.083581$

At $x = 2.5$ m,

$4.988 = 6.270 exp (- r (2.5))$

$r = 0.108763$

At $x = 3.0$ m,

$4.446 = 6.270 exp (- r (3))$

$r = 0.169429$

$$\text{Average } r = \frac{0.038014 + 0.090612 + 0.134522 + 0.083581 + 0.108763 + 0.169429}{6}$$

$$= 0.10415342$$

When $x = 0.5$ m,

$H_x = 6.270 \exp(-0.10415342 \text{ x } 0.5) = 6.003$ cm

When $x = 1.5$ m,

$H_x = 6.270 \exp(-0.10415342 \text{ x } 1.5) = 5.502$ cm

When mangrove forest width = 50 m,

In laboratory scale, $x = 5$ m

$H_x = H_o \exp (-rx)$

$H_x = H_o \exp (-0.10415342 \text{ x } 5)$

$H_x = 0.5941H_o$

Wave reduction = (1 – 0. 5941)*100 = 40.59353%