MODELING THE MITIGATION EFFECTS OF COASTAL FOREST ON TSUNAMI

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by

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		Unit
α	relative vegetation height with respect to the water depth	-
A_0	projected area of trees under water surface	m^2
A_V (A)	horizontal coverage area of vegetation stands (cylinder pile)	m^2
β	decay number	m^{-1}
C_D	drag coefficient	-
C_M	inertia coefficient	-
d	water depth below the mean sea level	m
D_C	diameter of canopy	m
D_R	diameter of each root	m
D_T	diameter of trunk	m
D_V (D)	diameter of vegetation stands (cylinder pile)	m
ε_V	time averaged rate of energy dissipation	$Nm^{-1}s^{-1}$
F	hydraulic resistance force	N
F_D	drag force	N
F_M	inertia force	N
F_V	total hydraulic resistance forces by vegetation	N
F_x	momentum loss due to bottom friction	m^2s^{-2}
g	gravitational acceleration	ms^{-2}
H	total water depth	m
H_{th}	preassigned threshold value for total water depth	m
H_C	height of canopy part	m
H_R	height of root part	m

H_T	height of trunk part	m
H_V	height of vegetation stands (cylinder pile)	m
k	wave number	m^{-1}
KC	Keulegan-Carpenter number	-
L	wavelength	m
Le	effective length scale of vegetation	m
n	Manning's roughness coefficient	$sm^{-1/3}$
n'	averaged Manning's roughness coefficient	$sm^{-1/3}$
n_0	bottom roughness coefficient without vegetation	$sm^{-1/3}$
η	free surface displacement from the mean sea level	m
η_0	initial offshore wave height	m
η_{formax}	maximum run-up height with forest	m
η_{max}	maximum run-up height without forest	m
N_R	number of roots per tree	-
N_T	number of trees	-
N_V	number of vegetation stands	-
ρ	water density	kgm^{-3}
P_C	canopy porosity	-
r_η	reduction ratio of run-up height	-
R	run-up height	m
R_f	linear friction coefficient	s^{-1}
Re	Reynolds number	-
S	spacing between cylinders	m
t	time	s
Δt	time step	s

τ_b	bottom shear stress	$kgm^{-1}s^{-2}$
T	wave period	s
u	depth-averaged horizontal velocity in x-direction	ms^{-1}
U	horizontal discharged flux in x-direction	m^2s^{-1}
μ	kinematic viscosity of water	m^2s^{-1}
v_0	initial velocity	ms^{-1}
V	control volume	m^3
V_0	vegetation occupancy volume	m^3
W	forest width	m
x	distance	m
$\ddot{x}$	half distance	m
x_0	location at the toe of the slope	m
x_s	location where the maximum amplitude of the incoming wave is measured	m
$\Delta x, \Delta y$	spatial step / length in x and y-direction of control volume	m
γ	friction coefficient	-
λ	coefficient of upwind scheme	-
θ	slope angle	deg.
σ	wave frequency	s^{-1}

LIST OF ABBREVIATIONS

BIEM	Boundary Integral Equation Model
CN	Crank-Nicolson
DBH	Stem Diameter at Breast Height
DMCR	Department of Marine and Coastal Resources
EERI	Earthquake Engineering Research Institute
FDPM	Forestry Department Peninsular Malaysia
FRIM	Forest Research Institute of Malaysia
GAP	Gap Analysis Program LA: Louisiana, MS: Mississippi
IUCN	International Union for Conservation of Nature
JMA	Japanese Meteorological Agency
LDN	Leading Depression N-wave
MSL	Mean Sea Level
NAHRIM	National Hydraulic Research Institute of Malaysia
NGOs	Non-governmental Organizations
NLCD	National Land Cover Dataset
NOAA	National Oceanic and Atmospheric Administration
NRE	Ministry of Natural Resources and Environment
NSWE	Nonlinear Shallow Water Equations
NTHMP	National Tsunami Hazard Mitigation Program
OAR-PMEL-135	Office of Oceanic and Atmospheric Research – Pacific Marine Environmental Laboratory – 135
SWAN	Simulating Waves Nearshore
TEPCO	Tokyo Electric Power Company
TUNA-RP	Tsunami-tracking Utilities and Application – Run-Up

UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey

PEMODELAN KESAN MITIGASI HUTAN PESISIRAN PANTAI TERHADAP TSUNAMI

ABSTRAK

Seperti yang telah kita pelajari dalam kejadian tsunami mega Andaman pada 26 Dis 2004 yang mengorbankan lebih daripada 200,000 nyawa di seluruh dunia, tsunami merupakan satu bencana alam dahsyat yang boleh menimbulkan impak yang teruk termasuk kehilangan nyawa manusia dan kemusnahan harta benda. Oleh demikian, penting untuk Malaysia bersiap sedia untuk mengambil tindakan balasan yang sewajarnya untuk mempertahankan persisiran pantai dari ancaman tsunami yang mungkin berlaku pada masa hadapan. Struktur-struktur pantai biasanya dibina untuk mengurangkan gelombang tsunami. Namun begitu, struktur sedemikian memerlukan kos pembinaan yang tinggi dan secara ketaranya mereka boleh mengurangkan nilai estetik serta menyebabkan masalah alam sekitar. Oleh itu, hutan pantai semula jadi merupakan jenis formasi pantai pilihan yang dapat menawarkan tahap perlindungan tertentu terhadap gelombang tsunami dengan menyebarkan tenaga gelombang. Diberkati dengan kelimpahan hutan bakau pesisiran pantai, Malaysia berpotensi memanfaatkan hutan bakau berkenaan untuk mitigasi bencana tsunami. Untuk mengukur keberkesanan hutan pesisiran pantai dalam mengurangkan gelombang tsunami, satu model dalaman 2-D, TUNA-RP telah dipertingkatkan prestasinya dan digunakan dalam tesis ini. TUNA-RP telah disahkan terlebih dahulu dengan ujian piawaian yang dicadangkan oleh Pentadbiran Lautan dan Atmosfera Kebangsaan (NOAA) untuk memastikan kebolehpercayaan dan ketepatan ramalan evolusi gelombang tsunami. Kesan pengurangan gelombang dalam pelbagai keadaan hutan kemudian disiasat dengan

menggunakan pekali kekasaran Manning untuk membayangkan rintangan hidraulik yang diberikan oleh pelbagai jenis liputan tumbuhan. Kajian simulasi tersebut mencadangkan bahawa tahap pengurangan ketinggian gelombang berubah secara ketaranya, bergantung pada lebar hutan, jenis hutan serta kala gelombang. Perwakilan hutan pesisiran pantai yang lebih realistik boleh dicapai dengan menggunakan persamaan Morison untuk memodel daya rintangan hidraulik yang dikenakan oleh tumbuhan. Model ini yang dipertingkatkan prestasinya dengan persamaan Morison digunakan untuk menilai kesan hutan bakau di Pantai Acheh dalam meredam gelombang tsunami Lautan Hindi 2004. Kajian simulasi ini mencadangkan bahawa rintangan hidraulik hutan bakau di Pantai Acheh berjulat antara 0.1 dan 0.12 $sm^{-1/3}$. Hasil kajian ini dapat memberikan kefahaman yang bernilai mengenai keberkesanan dan batasan hutan pesisiran pantai yang akan berguna untuk program-program pemeliharaan dan pemuliharaan hutan di Malaysia.

MODELING THE MITIGATION EFFECTS OF COASTAL FOREST ON TSUNAMI

ABSTRACT

As we have learned from the 26 Dec 2004 mega Andaman tsunami that killed more than 200,000 lives worldwide, tsunami is a devastating natural disaster that can cause severe impacts including immense loss of human lives and extensive destruction of properties. It is therefore important for Malaysia to be prepared with appropriate countermeasures to defend our coasts from impending future tsunamis. Coastal structures are commonly used to mitigate tsunami waves; however, they are costly to build and they can substantially diminish aesthetic value and may cause environmental problems. Hence, natural coastal greenbelts are the preferred type of coastal formations that could offer some degree of protection against tsunami waves by dissipating the wave energy. Blessed by an abundance of coastal mangrove forest, Malaysia can potentially engage these coastal mangrove forests for tsunami mitigation. To quantify the effectiveness of coastal forests in mitigating tsunami waves, an in-house 2-D model TUNA-RP is enhanced and used in this thesis. TUNA-RP is first validated against standardized benchmarks recommended by the National Oceanic and Atmospheric Administration (NOAA) for the purpose of ensuring reliable and accurate predictions of tsunami wave evolution. The wave attenuation effect of various forest conditions is then investigated by using Manning's roughness coefficient to mimic the hydraulic resistance presented by different vegetation covers. The simulation study suggests that the degree of wave height reduction varies significantly depending on forest width, forest type as well as wave period. A more realistic representation of coastal forest may be achieved by using the Morison's Equation to model the hydraulic resistance forces exerted by vegetation. This enhanced model with Morison's Equation is then used to assess the wave attenuation effect of mangrove forest at Pantai Acheh for the 2004 Indian Ocean tsunami. The simulation study suggests that the hydraulic resistance provided by the mangrove forest in Pantai Acheh ranges from 0.1 to 0.12 $sm^{-1/3}$. The finding of the study provides valuable insights on the effectiveness and limitations of coastal forests which is useful for forest rehabilitation and restoration programmes in Malaysia.

CHAPTER 1

INTRODUCTION

1.1 Introduction to Tsunami

Tsunamis are generated by the sudden uplift or subsidence of seafloor when there is an underwater earthquake, submarine landslide or volcanic explosion. Seafloor displacement will trigger a series of water waves that travel outwards in all directions from the disturbance source. In reality, tsunami waves propagate across the deep ocean with the speed of several hundred kilometers per hour and with wave height of less than a meter. Therefore, they can reach the coastlines within a relatively short time. As a tsunami wave propagates over shallow areas of the continental shelf, the leading edge of the wave slows down due to the reduction in depth while the trailing edge is still moving rapidly. Subsequent reduction in wavelength is compensated by gradually increasing the wave amplitude. Upon reaching the coast, tsunami waves can be amplified by a factor of 2 or more depending on the coastal topography, nearshore bathymetry and tsunami intensity (Shuto, 1991). Moreover, they may travel several kilometres inland across low-lying coastal areas which result in destruction of property as well as loss of life.

As witnessed in December 26, 2004, an undersea megathrust earthquake off the coast of Sumatra, Indonesia triggered a devastating tsunami that killed more than 200,000 people, making it one of the deadliest natural disasters in recorded history (Andy, 2014). The resulting tsunami devastated many coastal areas of Asian countries bordering the Indian Ocean. Affected countries include Indonesia, Sri Lanka, India, Thailand and Malaysia. The large and destructive tsunami waves reached run-up heights of up to 30 m and travelled as far as 4 km inland in Sumatra (Saatcioglu et al., 2005). Although it is impossible to prevent the occurrence of natural disasters including tsunami but it is possible to minimize or mitigate their harmful effects. Tsunami early warning system should be implemented as an integral part of the disaster preparedness system. It allows the detection of tsunamigenic earthquakes and provides immediate early warning to countries that are likely to be affected by the approaching tsunami. Information of tsunami arrival time and wave height can be predicted well using computer-based models so that people may be able to evacuate in time (Wei et al., 2003; Joseph, 2011).

A tsunami's travel time varies from minutes to a few hours, depending on the distance from the tsunami source to the coastal location (National Tsunami Hazard Mitigation Program (NTHMP), 2011). For a far-field tsunami, the tsunami early warning system can provide effective warning and information to the affected coastal communities. On the other hand, a locally generated tsunami may reach nearby shores in just a few minutes, resulting in insufficient time to assess the potential severity of tsunami before the waves inundate the coast. The Great East Japan Earthquake with moment magnitude, M_w of 9.0, also known as the Tohoku Earthquake, struck the northeastern coast of Japan on March 11, 2011 (United States Geological Survey (USGS), 2011). The Japanese Meteorological Agency (JMA) issued a timely tsunami warning around 3 minutes after the earthquake and continually updated it based on the offshore tsunami observations. The tsunami waves traveled at jetliner speeds of about 700 km/hr and reached the Japanese mainland within 20-30 minutes, leaving too little time for evacuations

(Shaw and Takeuchi, 2012). Nearly 16,000 deaths were reported and hundreds of thousands of people were rendered homeless temporarily. Hence, there is an increased awareness of the importance of risk mitigation measures that may help reducing coastal vulnerability to both local and distant tsunamis. Additionally, early warning system will be more effective in reducing loss of life and property if it is incorporated into an integrated framework of coastal zone management.

1.2 Coastal Defenses for Tsunami Mitigation

Various mitigation measures have been implemented to minimize tsunami damage caused on shore, particularly in tsunami-prone countries such as Japan (United Nations Educational, Scientific and Cultural Organization (UNESCO), 2009). A common measure is to have physical barriers protecting the coast against tsunami waves. This coastal defense means is generally classified into two categories: artificial and natural methods. Artificial methods refer to construction of seawalls, breakwaters and floodgates while natural methods refer to plantation of coastal forests, sand dune vegetation and coral reefs. A combination of artificial and natural mitigation measure is sometimes necessary to provide a more efficient and environmentally acceptable coastal protection system.

1.2.1 Artificial Methods

The most common structures erected for tsunami mitigation are seawalls, breakwaters and floodgates. Seawalls are constructed along the coast to reflect the incident wave energy back towards the sea, as shown in Figure 1.1(a). These walls are usually composed of stone or concrete blocks and placed at an elevation above the mean high water mark. Recently, the Japanese government has embarked on a

10-year reconstruction project costing about $255 billion, which includes the construction of seawalls along the Tohoku's Pacific coast to protect the country against high waves, typhoons or even tsunamis. Breakwaters are another sea defense structures that are usually placed 100-600 m offshore in relatively shallow water. Consider the example shown in Figure 1.1(b), a 1,960 m long breakwater was constructed at the mouth of Kamaishi bay in order to protect the densely populated Kamaishi city from tsunamis as well as from other significant wave action (Mimura et al., 2011). The narrow entrance between the breakwater arms restricts the inflow of tsunami waves into the bay. Breakwaters generally use the mass of the caisson or concrete armour units to dissipate the wave energy, leading to sediment deposition and accretion in the lee of the breakwaters. In addition, floodgates can be installed at the river mouths to regulate water flow. In Fudai, the 15.5 m high floodgates were built to prevent the inland penetration of a tsunami (see Figure 1.2). They successfully protected most of the Fudai villages despite being overflowed by the 2011 Tohoku tsunami (Federica, 2014). However, more than 70 volunteer firefighters lost their lives while attempting to close the floodgates in affected areas. Consequently, the Japanese government has decided to introduce a remote control system for all the floodgates on major rivers flowing into the Pacific Ocean.

However, the effectiveness of these mitigation strategies has been questioned as tsunamis may exceed the design specifications of prevention measures. For instance, the 1993 Hokkaido Nansei-Oki tsunami overwhelmed the 4.5 m high seawalls erected on the coast of Okushiri Island, Japan (Shuto and Fujima, 2009). Over 185 people were killed with property losses estimated at $600 million. The

2011 Tohoku tsunami initiated an automatic shutdown of the operating reactors at the Fukushima Daiichi Nuclear Power Station. The 13 m high tsunami waves overtopped the plant’s seawall, which was only 10 m high, and destroyed the emergency diesel generators used to cool the reactors. The insufficient cooling eventually resulted in the partial meltdown of reactor core and uncontrolled release of radioactive material into the environment. On August 2013, the Tokyo Electric Power Company (TEPCO) reported that at least 300 tons of highly radioactive water continued leaking into the Pacific Ocean every day. Furthermore, strong currents associated with tsunami runup and drawdown can cause severe erosion and scour, leading to undermining of the structural foundation, instability of embankment slope and even liquefaction failure. Figure 1.3(a) shows the formation of a large scour hole behind the collapsed seawall near the river mouth of Abukuma in Japan (Towhata et al., 2012). Waste tires and other resilient cushioning materials can be placed along the landward side of the seawall to provide scour protection (Hazarika et al., 2016), as displayed by Figure 1.3(b).

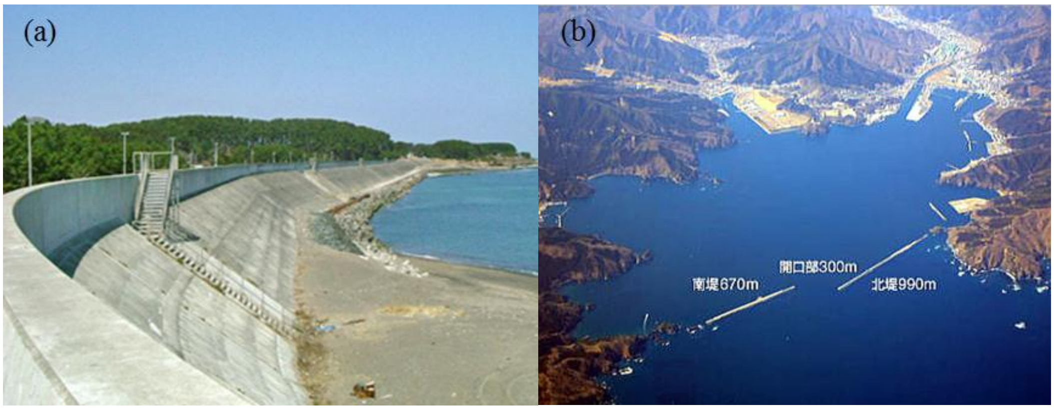

Figure 1.1: Artificial mitigation measures: (a) seawall and (b) tsunami breakwater in Kamaishi city, Iwate Prefecture (Mimura et al., 2011).

Figure 1.2: The floodgates that protected Fudai village despite being overtopped (Federica, 2014).

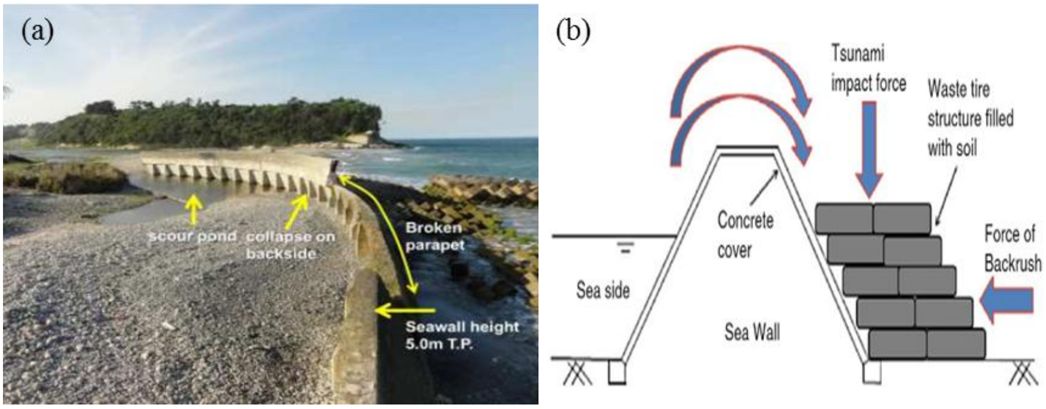

Figure 1.3: (a) Damage on seawalls near the Kidogawa River mouth, Naraha Town (Towhata et al., 2012). (b) New concept of protecting the seawall by using waste tires (Hazarika et al., 2016).

1.2.2 Natural Methods

The construction of hard physical defenses could substantially decrease the aesthetic value of the beautiful coasts despite their high construction and maintenance costs. Utilization of natural coastal defense system for tsunami mitigation appears to be a more viable and sustainable option. Planting appropriate tree species along the coastlines will assist in land stabilization and dissipation of wave energy. When tsunami waves encounter vegetation structures, they will undergo energy loss through hydrodynamic drag and generation of local turbulence, leading to smaller overwash rates and reduced flood inundation extents. Due to the wave attenuation function, the reduction in flow velocity will enhance sediment deposition and subsequently protect the bed from erosion. There are a number of scientific studies supporting the vegetation bio-shield concept with field observation and laboratory experimental data (Danielsen et al., 2005; Kar and Kar, 2005; Kathiresan and Rajendran, 2005). For example, during the 2004 Indian Ocean tsunami, plants such as mangroves and coconut palms provided certain degree of protection to the affected countries by functioning as wave energy absorbers (Peterson, 2008). Figure 1.4(a) shows a coastal mangrove forest with their extensive root systems that are able to withstand the tsunami forces to some extent. A combination of sand dune and vegetation shown in Figure 1.4(b) is strongly recommended to act as the first line of protection against wave attack. At Yala and Bundala National Parks in Sri Lanka, it was observed that vegetated sand dunes completely stopped the impending tsunami waves, with most structural damage occurring at places where the dunes were broken by river flows (United Nations Environment Programme (UNEP), 2005).

Coral reefs act as natural submerged breakwaters, protecting adjacent land from erosion, storm surges and tsunamis, as shown in Figure 1.4(c). They are present in a narrow fringe along the shore, ranging from a few hundred meters to over a kilometer in length. Coral reefs help in dissipating wave energy, mainly by breaking waves at the reef's seaward edge and through bottom friction as the waves move across the reefs. In Sri Lanka, the illegal coral mining resulted in a number of gaps between the reefs which led to flow amplification and increased vulnerability of coastal zones (Fernando et al., 2005). However, Adger et al. (2005) pointed out that the presence of coral reefs in Banda Aceh, Indonesia did not have a significant effect on tsunami wave amplitude reduction as the waves were simply too high. Nevertheless, additional studies are required to access the protective capacity of reefs against large scale tsunamis. Figure 1.5 illustrates some concept regarding the spatial zonation of coastal vegetation, from seagrass beds to terrestrial forests (Prasetya, 2006).

Figure 1.4: Natural mitigation measures: (a) coastal forests, (b) vegetated sand dunes and (c) coral reefs (Amit, 2010; Spalding et al., 2014; James, 2015).

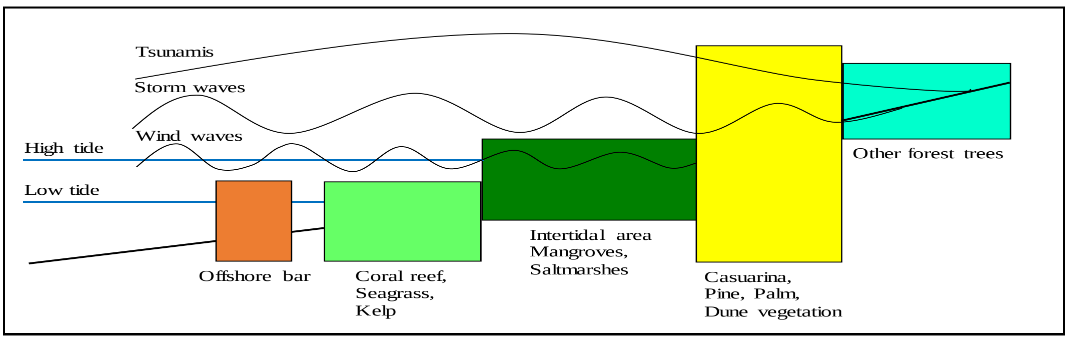

Figure 1.5: Spatial zonation of coastal vegetation (Prasetya, 2006).

1.3 Coastal Forests

Malaysia's coastline is dominated by mangrove forests which play a protective role in reducing the adverse impact of tsunamis. With extensive exposed roots and stems, coastal forests particularly mangroves are capable of reducing tsunami impacts by attenuating the destructive energy of waves passing through them (Mazda et al., 1997). Reduced damage was reported in the areas of dense mangrove forests at Kuala Sala, Kedah compared to the unprotected coastal areas which were severely eroded during the Indian Ocean tsunami incident (NAHRIM, 2006). By taking advantage of the strategic geographic location and abundance of natural resources, the Malaysian Government has taken various integrated measures to develop tsunami preparedness including the establishment of "Special National Task Force Committee on Planting of Mangrove and Other Suitable Species in Coastal Areas".

Over the past few decades, various modelling and mathematical studies were carried out to understand the role of mangroves and other types of coastal forests in attenuating tsunami wave energy (Mazda et al., 1997; Massel et al., 1999; Harada and Immamura, 2000; Hirashi and Harada, 2003). Danielsen et al. (2005) pointed out that the deterioration and clearing of vegetation along the coastline will increase coastal vulnerability to storm surge and flooding. The effectiveness of coastal forest in mitigating tsunami waves depends on the forest properties such as tree species, forest density, forest width, local bathymetrical and geographical features as well as the wave conditions. However, the function of coastal forest in reducing force of tsunamis is not adequately quantified yet.

In order to utilize coastal forests as an effective countermeasure against tsunami disasters, understanding the physical processes in vegetation fields is important for practical modeling. Therefore, this research is intended to serve as an investigation of wave dissipation over vegetation fields to assess the effectiveness of coastal forest in tsunami mitigation. One of the important aspects from this research is about the investigation on how to incorporate the effect of wave attenuation into an in-house tsunami numerical simulation model named Tsunami-tracking Utilities and Application – Run-Up (TUNA-RP). Modeling analysis will enable us to quantify the hydrodynamic flow resistance induced by coastal forests and thereby predicting the typical levels of wave attenuation. The resistance and limitation associated with several controlling forest parameters will be examined for effective coastal management planning.

1.4 Objectives of Thesis

The objectives of this thesis are as follows:

a) To enhance the capability of the in-house tsunami run-up model TUNA by simulating the presence of a coastal forest.
b) To investigate the tsunami waves mitigation effect of coastal forest via TUNA model simulations.
c) To identify the key characteristics of coastal forest that determine the magnitude of tsunami mitigation.

1.5 Scope and Organization of Thesis

This thesis begins in Chapter 1 with an introduction to tsunami and mitigation measures used to protect both human lives and property from tsunamis. Coastal forest serves as a cost-effective and environmentally-friendly option for coastal protection. For optimal planning of natural coastal systems and their maintenance, the effects of coastal forest on tsunami flow reduction need to be quantitatively elucidated, which is the primary focus of this thesis.

Chapter 2 describes the protective functions of coastal forests against tsunami hazards during the occurrence of a tsunami event. The status and distribution of mangrove forests in Malaysia are reviewed, followed by the mangrove rehabilitation efforts taken by government agencies. This chapter also provides a review of related literature on the risk reduction performance of coastal forests based on the field investigations and laboratory experiments. A review is conducted on the modelling approaches used to describe the wave energy dissipation due to flow resistance provided by vegetation.

Chapter 3 describes an in-house tsunami numerical model named TUNA-RP (Koh et al., 2009; Teh et al., 2009) used to simulate tsunami wave propagation and run-up. In this chapter, we will discuss model evaluation with several benchmark tests, along with the existing analytical and empirical formulae to ensure the reliability of TUNA-RP in predicting the coastal protection effect of tsunami.

In Chapter 4, the Manning's friction term in the nonlinear shallow water model is used to imitate the hydraulic resistance provided by coastal forest. Simulations of tsunami wave passing through coastal forests are performed by characterizing the coastal forests with the Manning's friction term. The simulation results are corroborated with known analytical solution. Then, sensitivity analyses are performed to investigate the relation between wave attenuation and vegetation characteristics.

In Chapter 5, the effects of coastal forest in reducing wave heights and velocities are simulated by the incorporation of the Morison's Equation to model the hydraulic resistance forces exerted by vegetation. The tree parameterization approach using a simple group of cylinders is adopted for coastal vegetation species such as mangroves to facilitate its incorporation into the model framework of TUNA-RP. As a measure of resistance to flow, the drag coefficient formulations are investigated. The enhanced two dimensional simulation model TUNA-RP is then used to assess the wave attenuation by mangroves at Pantai Acheh during the 2004 Indian Ocean tsunami.

The closing Chapter 6 concludes the achievement of the research and gives some recommendations for further research.

CHAPTER 2

LITERATURE REVIEW

2.1 Protective Role of Coastal Forests

Coastal greenbelts have been receiving increasing attention as an environmental-friendly and cost-effective defence measure against tsunamis. Shuto (1987) investigated the role of coastal forests based on the Japan's historical record of tsunamis. Coastal forests serve as an effective natural buffer against tsunami waves by reducing the inundation water depth and flow velocity. Coastal forests play their role in obstructing timbers, boats and other floating debris from washing inland which may cause much damage to the coast. Coastal forests also provide a live-saving means by catching people who have been carried away by tsunami and enabling them to land on tree branches.

Recent tsunami events provide some opportunities for researchers to collect field-based evidences on the protective role of coastal greenbelts in reducing tsunami impacts, particularly in the case of 2004 Indian Ocean tsunami. Coastal areas with dense mangrove forests and other shelterbelt plantations reported to have substantially lower human casualties and lesser infrastructure damage than those areas where forest ecosystems had been severely degraded or converted to other land uses (UNEP, 2005; NAHRIM, 2006). Since the 1998 Papua New Guinea tsunami, many researchers started to investigate the effects of coastal vegetation on tsunami mitigation by using field investigations, laboratory experiments and numerical simulations (Hamzah et al., 1999; Harada and Imamura, 2000; Hiraishi and Harada, 2003). Investigations on wave dissipation in vegetation were more intensified after the occurrence of 2004 Indian Ocean tsunami for preparedness and mitigation of future tsunami damage (Danielsen et al. 2005; Harada and Immamura, 2005; Kathiresan and Rajendran, 2005).

Currently coastal forest is considered as a comprehensive strategy to mitigate the destructive force of tsunami waves. This technique is particularly appropriate for developing countries because it involves relatively lesser capital investment than more sophisticated coastal physical defence measures such as artificial structures. Recognizing the crucial role of coastal forests, many government authorities, donor agencies and non-governmental organizations (NGOs) have invested in planting vegetation belt along coastal areas as a natural bio-shield against tsunamis and other natural disasters (Feagin et al., 2010). In Aceh, the Board of Rehabilitation and Reconstruction of the Ministry of Forestry has planted over 10,000 ha of mangrove forest in areas affected by the 2004 Indian Ocean tsunami. In Phang Nga, Thailand, the Department of Marine and Coastal Resources (DMCR) and local residents worked together to rehabilitate more than 200 ha of mangroves damaged by the tsunami (Paphavasit et al., 2007). DMCR also planted 3,000 seedlings of *Casuarina equisetifolia*, *Cocos nucifera*, *Pandanus odoratissimus* and *Barringtonia asiatica*.

2.2 Mangrove Forest in Malaysia

Located in the world's tropical belt, Malaysia is blessed with abundant mangrove forests covering an area of approximately 575,000 ha (Asian Development Bank, 2014). Although it represents about 2 % of the total land area of Malaysia, the Malaysian mangrove is reported as the third largest mangrove forest in the Asia-

Pacific region after Indonesia and Australia. Figure 2.1 depicts the distribution of mangroves along the coastline of Malaysia, with 60% located in Sabah, 23% in Sarawak and the remaining 17% in Peninsular Malaysia (Hamdan et al., 2012). In Sarawak, mangroves can be found along the coastlines and estuaries of the Sarawak River, Trusan River and Rajang Delta, while in Sabah, they are found mainly on its east coast facing the Sulawesi and Sulu Seas. In Peninsular Malaysia, mangrove forests are well developed on the relatively sheltered west coast in the states of Kedah, Perak, Selangor and Johor. Seas are calmer on the west coast due to the protection afforded by Sumatera whereas the east coast is entirely exposed to the South China Sea that has larger and more energetic waves.

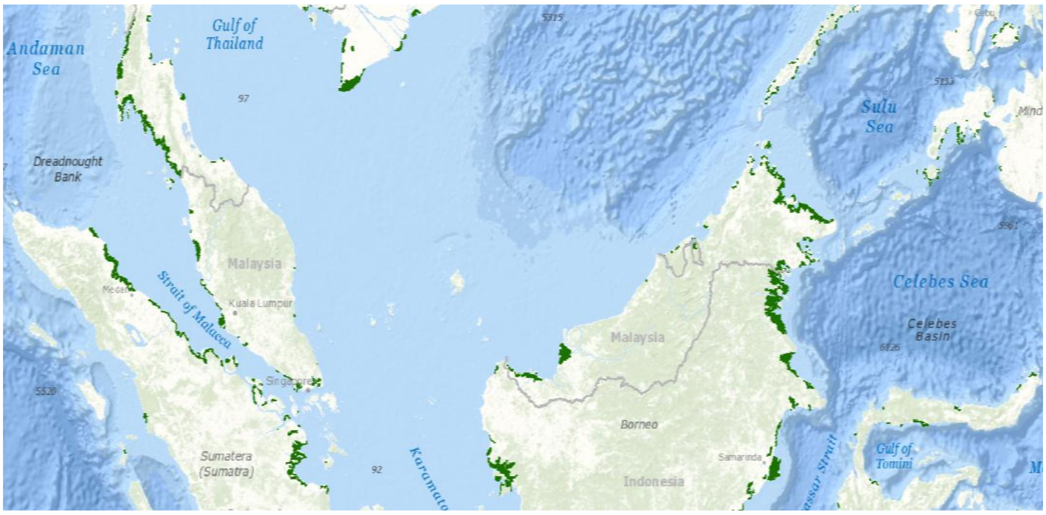

Figure 2.1: Distribution of mangroves (in green) in Malaysia (Hamdan et al., 2012).

Mangrove trees reduce wave energy by obstructing the waves with their dense network of roots and trunks. They play a crucial role in buffering coastlines against storm surges and tsunamis through wave attenuation. Reduced water flows enhance deposition of sediment, resulting in sediment accretion rather than erosion (Blasco et al., 1996). Mangrove forests annually sequester large amount of carbon dioxide from the atmosphere. Under anaerobic conditions, the rate of decomposition of organic plant material is much lower and the carbon present in the plant material will remain intact rather than being broken down and released back to the atmosphere. Hence, they are highly capable of storing carbon in their soils for long periods of time. In addition, mangroves help to maintain the water quality by removing organic and inorganic nutrients from the water column. They lower nitrate and phosphorus concentrations in contaminated water through denitrification and soil-nutrient burial and therefore inhibiting coastal eutrophication (Ewel et al., 1998). Mangroves also provide ideal breeding grounds for fish, birds and other wildlife.

Mangrove forests have drawn more attention by the Malaysian Government when they have been credited with mitigating the tsunami waves during the 2004 Indian Ocean tsunami (Kathiresan and Rajendran 2005; NAHRIM, 2006). All state governments were given the instruction to rehabilitate and restore the degraded forest areas with the hope to provide some mitigation in future tsunami events. Subsequently, the Federal Government allocated RM40 million under the Ninth Malaysian Plan (2006-2010) for the restoration of mangroves and other coastal vegetation. On 7 February 2005, the Ministry of Natural Resources and Environment (NRE) established the “Special National Task Force Committee of Planting Mangrove and Other Suitable Species in Coastal Areas” to monitor the progress and implementation of tree planting programmes throughout the coastal region in the country. Two technical committees were formed to assist the National Task Force committee, namely the Planning and Implementation Technical Committee which is headed by the Director General of the Forestry

Department Peninsular Malaysia (FDPM) and the Research and Development Technical Committee which is headed by the Director General of Forest Research Institute of Malaysia (FRIM). The Research and Development Technical Committee aims to conduct research on coastal stabilization techniques, particularly in highly eroded areas with strong wave actions. Improved planting techniques are needed to ensure that the planted mangroves serve their role in holding the ground instead of being uprooted and washed away. Larger plants with more extensive root systems provide a greater shore protection.

2.3 Effectiveness of Coastal Forests

However, there is a debate regarding the effectiveness of coastal vegetation in mitigating tsunami waves. An analysis of pre- and post-tsunami satellite imagery of Tamil Nadu, India indicated that mangrove forests provided protection from tsunami damage (Danielsen et al., 2005; Kathiresan and Rajendran, 2005) although this study had been criticized for not accounting for the distance from shore (Dahdouh-Guebas et al., 2006; Kerr and Baird, 2007). A reanalysis of the data by Kerr et al. (2006) proved that there is no relationship between human mortality and the extent of forests fronting coastal hamlets. According to Chatenoux and Peduzzi (2007), the areas covered by mangrove forests were only slightly affected by tsunami just because the forest communities were located on the sheltered coasts. They suggested that the intensity of tsunami waves was mainly determined by the distance from the tsunami source and near-shore coastal bathymetry.

Shuto (1987) stated that if the wave heights exceed 4 m, the coastal trees might be snapped or uprooted, creating floating tree debris that could enhance tsunami damage to the local coastal communities. The 2010 Mentawai tsunami and 2011 Tohoku tsunami have revealed evidence of the inability of coastal forest to withstand the impact of extreme tsunami (Borrero et al., 2010; Suppasri et al., 2011). The 2010 Mentawai tsunami produced significant wave heights in excess of 10 m in the Mentawai Island of Indonesia and almost all trees in the front lines suffered heavy damage. In the 2011 Tohoku tsunami, coastal forests were wiped out by 20-m high tsunamis and this caused the Rikuzentakata city to be devastated. Only a single pine tree survived the tsunami attack, out of 70000 mature trees whose trunks were completely broken at 1-2 m height above the ground (Earthquake Engineering Research Institute (EERI), 2011). Consequently, an assessment of forest vulnerability is essential to avoid making generalizations and creating a false sense of security that bio-shields will be able to protect against coastal hazards (Wolanski, 2007; Yanagisawa et al., 2009).

Despite these contradictory opinions, it may be concluded that coastal forests could provide effective protection against tsunamis up to a certain magnitude. The level of protection is determined by the forest characteristics such as tree species, tree age, forest density, forest width, local bathymetrical and geographical features as well as the wave conditions. Over the past few decades, many field measurements and laboratory scale experiments have been carried out to investigate the effectiveness of coastal vegetation in mitigating tsunami waves (Mazda et al., 1997; Tanaka et al., 2007; Yanagisawa et al., 2009; Bao, 2011).

Based on the field investigations carried out after the 1998 Papua New Guinea tsunami and 2004 Indian Ocean tsunami, *Casuarina equisetifolia* performed remarkably as absorbers of energy from violent waves. Dengler and Preuss (2003) pointed out that *Casuarina* trees presented relatively higher resistance than palm trees during the 1998 Papua New Guinea tsunami. In Sri Lanka and Thailand, older *Casuarina* plantations withstood the 2004 Indian Ocean tsunami but they were not able to provide good protection (Tanaka et al., 2007). Field measurements also revealed that only frontal *Casuarina* strips were attacked when tsunami run-up heights ranged from 0.7 to 6.5 m and the inundation distance varied from 31 to 862 m (Mascarenhas and Jayakumar, 2008). On the other hand, *Pandanus odoratissimus*, one of the beach sand vegetation was found to be effective in mitigating tsunami damage due to its mangrove-like stilt roots and dense foliage (Tanaka et al., 2007). However, they were only able to withstand a tsunami of less than 5 m wave height. Further, increasing forest width would significantly reduce the water flow velocity and tsunami force (Tanimoto et al., 2007). A mixed forest of *P. odoratissimus* and *C. equisetifolia* demonstrated strong ability to reduce the damage behind the vegetation cover (Tanaka et al., 2007). The vertically dense structure of *Pandanus* forest reduced the flow effectively whereas the strong and high *Casuarina* trees trapped floating debris and reduced the water flow velocity in the upper space of forest.

In Tamil Nadu, India, Mascarenhas and Jayakumar (2008) reported that roads perpendicular to the coast in a coastal forest served as pathways for tsunami waves to travel inland during the 2004 Indian Ocean tsunami. As shown in Figure 2.2, the presence of forest gaps could intensify the force of tsunami waves by channeling them into the narrow constrictions (Tanaka, 2009; Thuy et al., 2009). Thuy et al. (2009) found that the maximum velocity at the gap exit was 1.7 times in comparison with the case of no vegetation belt. It is unrealistic to consider a coastal forest without frequent breaks in the barrier and thus, careful planning is needed to ensure that the designed coastal greenbelt would reduce the associated disadvantages of the open gaps. The flow velocity in the gap could be reduced by staggering the gap or inclining the gap direction away from the direction of the tsunami current (Tanaka, 2009). Additionally, Samarakoon et al. (2013) proposed establishment of *P. odoratissimus* in front of the existing *C. equisetifolia* forest to minimize the amplification of tsunami force through the open gaps.

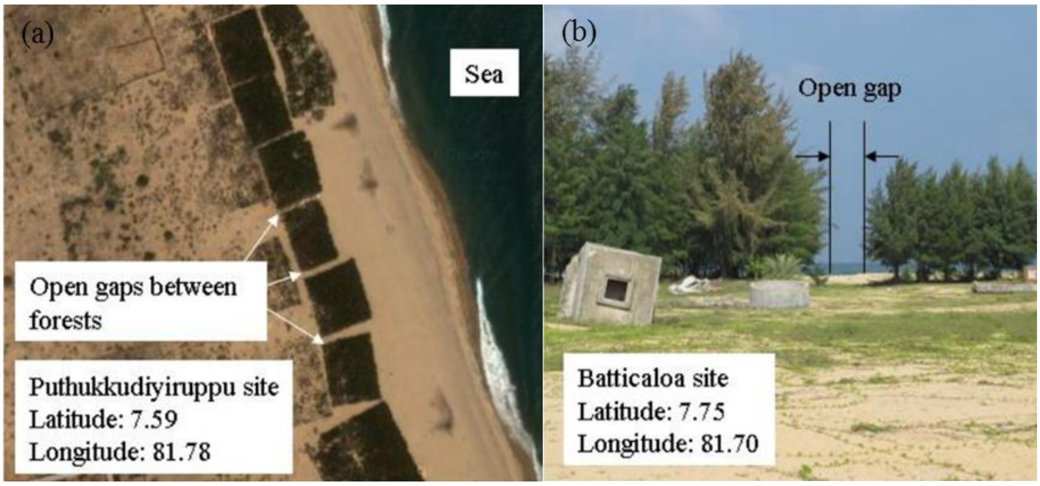

Figure 2.2: Examples of open gaps in coastal vegetation
(Tanaka, 2009; Thuy et al., 2009).

Harada et al. (2002) carried out a hydraulic experiment in order to understand the tsunami reduction effect of the coastal permeable structures. The study concluded that mangroves could be as effective as concrete seawall structures for reducing tsunami damage behind the forests. In India, a dense mangrove forest of *Rhizophora* sp. and *Avicennia* sp. contributed to low tsunami damage in most of