DESIGN OF A TSUNAMI BARRIER TO THE NORTH OF PENANG ISLAND

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To My Beloved Family

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ABSTRACT

On December 26, 2004 a major earthquake with a magnitude between 9.1 and 9.3 on the Richter scale occurred off the West Coast of Sumatra, Indonesia. This earthquake generated a devastating tsunami. Several countries suffered from the gigantic tsunami, many people died and many more lost their properties. The tsunami struck the West Coast of Peninsular Malaysia and killed 68 people and destroyed many properties. The Island of Penang was one of the places that suffered from the disaster. Fifty seven people died in this area when most of them were enjoying their time on the beach. Many home appliances, several boats and fishing equipments were also destroyed in the area. In order to prevent similar damages from a possible recurring tsunami event, the Steady-State Spectral Wave (STWAVE) model of Surface Water Modelling System (SMS) has been used to design an offshore barrier to dissipate the tsunami wave energy in this study. The December 2004 tsunami was used as a reference case. Nearshore tsunami wave amplitude was obtained from field surveying data conducted on July 9-10, 2005. Whilst, offshore tsunami wave height and direction have been acquired from an output of TUNAMI-N2 program. The model which has been calibrated against field survey data showed good agreement. Several breakwater layouts were simulated in the STWAVE model to derive an optimal configuration which could dissipate the tsunami wave energy before it reaches the Penang Island shoreline. From analysis made, it was found that eleven layouts reduced the tsunami wave heights by more than 70%. After extensive evaluation, breakwater layout number 39 was selected as the optimized layout showing an efficiency at 83%. At this efficiency, a wave height of 1.02 meter would impact the shoreline should a 6.0 m tsunami wave was made to propagate from offshore.

ABSTRAK

Pada tanggal 26 Disember 2004, satu gempa bumi dengan magnitud antara 9.1dan 9.3 pada skala Ritcher telah melanda pantai barat Sumatera, Indonesia. Gempa bumi yang kuat ini telah menyebabkan kejadian tsunami berlaku. Beberapa buah negara telah terkena tempias tsunami yang mana banyak kematian dan kemusnahan harta benda telah direkodkan. Malaysia juga tidak terkecuali daripada kejadian tersebut di mana tsunami telah menyerang pantai barat Semenanjung Malaysia, membunuh sebanyak 68 nyawa dan memusnahkan sebahagian harta benda. Pulau Pinang merupakan di antara negeri yang paling teruk dilanda gempa bumi ini di Malaysia. Lima puluh tujuh orang meninggal dunia semasa kebanyakan mereka sedang menghabiskan masa di kawasan perairan pantai. Bagi menangani kemusnahan yang hampir serupa daripada kemungkinan kejadian tsunami berulang, model komputer STWAVE (Steady-State Spectral Wave) yaug terdapat di dalam pakej SMS (Surface Water Modelling System) telah digunakan untuk merekabentuk struktur airdalam bagi melemahkan tenaga ombak tsunami di dalam kajian ini. Kejadian tsunami pada Disember 2004 digunakan sebagai titik rujukan. Gelombang ombak tsunami dekat pantai telah diperolehi daripada data ukur tapak yang telah dilakukan pada 9-10 Julai 2005. Manakala ketinggian dan arah ombak diperolehi daripada hasil program TUNAMI-N2. Model yang telah dikalibrasi dengan data ukur tapak telah menunjukkan persetujuan yang baik. Beberapa konfigurasi pemecah ombak yang tenggelam telah disimulasi dengan menggunkan model STWAVE untuk menghasilkan konfigurasi optimal yang dapat melemahkan tenaga ombak tsunami sebelum menghampiri pantai di Pulau Pinang. Daripada analisis yang dilakukan, terdapat sebelas pelan pemecah ombak berupaya menghasilkan kecekapan melebihi 70% untuk melemahkan tenaga ombak tsunami. Pelan kedudukan pemecah ombak yang ke 39 telah dikenalpasti sebagai pelan konfigurasi yang sesuai untuk menyumbang sebanyak 83% kecekapan. Pada kecekapan ini, jika ombak tsunami setinggi 6 m di arahkan ke pantai, ketinggian ombak pada 1.02 m akan terhasil di kawasan pantai.

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B	-	Crest width
B_t	-	Toe apron width
C	-	Wave celerity
D_{n50}	-	Nominal diameter of armour rock
d	-	Water depth
E	-	Energy density in a given frequency and direction
g	-	Gravitational acceleration
H	-	Wave height
H_e	-	Water displacement
H_i	-	Incident significant wave height
H_0	-	Wave height at deep water
H_r	-	Wave run-up
$H_{r\ max}$	-	Maximum tsunami run-up
H_s	-	Significant wave height in front of breakwater
H_t	-	Transmitted significant wave height
h	-	Water elevation
h_c	-	Breakwater crest relative to DHW / structure height
h_t	-	Depth of structure toe relative to still water level
J	-	Grid row index
K	-	Wave number
K_t	-	Transmission coefficient
L	-	Wave length
L_0	-	Wave length in deep water
L_c	-	Wave length on the crest
L_h	-	Wave length at the toe

L_{om}	-	Deepwater wave length corresponding to mean wave period
L_{op}	-	Deepwater wave length corresponding to peak wave period
M, M_w	-	Earthquake magnitude
M_p, M_u	-	Overturning moment around the heel
N	-	Total number of armour layer
N_{od}	-	Number of units displaced out of the armour layer
N_s	-	Number of wave
N_s^*	-	Spectral stability number
P	-	Notional permeability
P	-	Wave pressure
R_c	-	Crest freeboard
R_e	-	Effective radius
S	-	Arch length, Relative eroded area
S_m, S_{op}	-	Wave Steepness
T	-	Wave period
T_p	-	Peak period
t	-	Thickness of layers
$\tan \alpha$	-	Seaward slop of structure
U	-	Uplift force
u,v	-	Velocity
W	-	Armour unit weight
x,y	-	Orthogonal horizontal coordinate
α	-	Front slope (seaside)
α_b	-	Back slope (lee)
δ	-	Direction of current relative to a reference frame
ζ, η^*	-	Height of free surface above the still water level
ζ_{op}	-	Breaker parameter
η	-	Wave elevation
ρ_s	-	Mass density of rock
ρ_w	-	Mass density of water
ω	-	Angular frequency

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CHAPTER 1

INTRODUCTION

1.1 Tsunami

Tsunami is a Japanese word which means a "harbour wave". The first character (Tsu) means harbour and the second character (Nami) means wave. It is a series of waves created when a body of water is rapidly displaced. In the past tsunami waves were referred to as tidal waves by the general public and as seismic sea waves by the scientific community. Although a tsunami wave impact upon a coastline is dependent upon the tidal level at the time a tsunami strikes, it cannot be named as tidal wave since tides result from the imbalanced gravitational influences of the moon, sun and earth system.

Tsunami can be generated by many causes such as earthquakes, submarine landslides, volcanic activities, under water explosion and asteroid falls. Tsunami cannot be felt in the open ocean due to its long wave length but as it leaves the deep water and propagates into shallower water near the coast, it undergoes transformations, its speed reduces and its wave height increases. Perhaps this natural disaster cannot be prevented but its result and effects can be reduced through proper planning.

1.2 Tsunami Barriers

Different types of breakwaters, seawalls and even soft structures may provide protection against tsunamis. It may decrease the inundation on land as well as reduce the current velocities and wave magnitude. However, structures may also have undesired effects on other areas (by reflection) or even on the area to be protected, because it may affect the resonant period of bays and harbours so that wave height increases instead of decreases. The energy of a tsunami wave, which is either dissipated on land or reflected when there is no structure, must now be dissipated by the structure (Van der Plas 2007).

Different types of structures which can be used for protection against tsunami waves include:

(a) High-crested structures which have a crest-level that is at least comparable with the height of the tsunami such as:
  - Vertical walls
  - Rubble-mound structures

(b) Low-crested and submerged structures (LCS) such as :
  - Detached breakwater
  - Artificial reefs

(c) Soft structures such as:
- Mangroves
- Sea grasses

1.3 Available Computer Models for Wave Simulation

There are many different types of public domain and commercial software available which can be used for wave modelling such as SWAN and STWAVE model as well as CGWAVE model of the Surface-Water Modelling System (SMS). SWAN is a third-generation wave model which can be used for estimating wave parameters in coastal areas, lakes and estuaries from given wind, bottom and current conditions. It also can be used on any scale relevant for wind-generated surface gravity waves. This model is based on the wave action balance equation with sources and sinks (Delft University of Technology 2008). CGWAVE is a model developed at the University of Maine under a contract for the U.S. Army Corps of Engineers, Waterways Experiment Station. It is a finite-element model that is interfaced to the SMS model for graphics and efficient implementation. This model can be used for estimation of wave fields in harbours, open coastal regions, coastal inlets, around islands and around fixed or floating structures (Demirbilek and Panchang 1998).

STWAVE is a steady-state finite difference model based on the wave action balance equation and it is formulated on a Cartesian grid. STWAVE simulates depth-induced wave refraction and shoaling, current induced refraction and shoaling, depth- and steepness-induced wave breaking, diffraction, wind-wave growth, wave-wave interaction and whitecapping that redistribute and dissipate energy in a growing wave field (Smith et al 2001).

As mentioned in the previous paragraphs there are different types of models which can be used for this research. But owing to availability, only the STWAVE of SMS will be used for this research work.

1.4 Problem Statement

Tsunamis are infrequent high impact events. They are among the most terrifying and complex physical phenomena which can cause a considerable number of fatalities, major damages and significant economic losses.

Horikawa and Shuto (1981) used tsunami damage official records to categorise the disaster caused directly by the tsunami. They summarized this into the following groups:

(a) Death and injury.

(b) House destroyed, partly destroyed, inundated or flooded and burned.

(c) Property damage and loss.

(d) Boats washed away, destroyed and run on the rocks.

(e) Lumber washed away.

(f) Marine installations destroyed.

(g) Disastrous damage of public utilities such as roads, electric power supply installations and water supply installation.

Secondary damages that are indirectly caused by the tsunami can also be divided into four groups:

(a) Burning houses, oil tank and gas stations

(b) Drifting matter such as houses, lumber, boats, drums, automobiles and sea culture nursery rafts

(c) Environmental pollution caused by drifting materials, oil, polluted sea bed and epidemic prevention

(d) Traffic obstruction due to the destruction of roads and railways

On the 26th of December 2004, a tsunami struck the West Coast of Peninsular Malaysia and killed 68 lives, caused injuries to hundreds of people and destroyed many properties and fishing equipment. Pulau Pinang was one of the places which was impacted by this disaster. According to reports from local residents, the tsunami waves hit several times between 1.15 pm and 1.30 pm local time. The maximum height of the breaking wave when it arrived at the beach was reported to be as high as 6 m. In total 615 houses, especially those made of wood were destroyed in Pulau Pinang. Private vehicles were also damaged because of the intrusion of salt water and mud into the vehicles (Komoo and Othman 2006).

Figure 1.1 Tsunami Disaster in Pulau Pinang

Areas that were flooded included residential areas located on the lower altitude along the beach. According to a survey carried out by Komoo and Othman

(2006) all observed areas showed evidence of flooding, such as mud marks on buildings walls or mangrove trees, as well as damage to plants due to inundation. In the coastal area, flood levels reached up to 1.5 m. The flood water which contained mud damaged many agriculture and ornamental plants along the coastline.

To prevent similar damages due to the recurrence of tsunami wave as mentioned above to Pulau Pinang, the present research work will focus on undertaking a computer model investigation to design an offshore structure to dissipate the tsunami wave energy before it reaches the shoreline. In the present work the STWAVE module of SMS will be used due to its availability.

1.5 Objectives of Study

The objectives of this project are:

(a) To determine and design an appropriate layout of an offshore barrier to dissipate the tsunami wave energy along the shoreline to the north of Penang Island.

(b) To execute a computer model in particular the STWAVE module of Surface Water Modelling System (SMS) to evaluate the performance of the optimized structure layout in dissipating the tsunami wave energy.

1.6 Scope of Study

This study is limited to the following scope of work in order to meet the specified objectives:

(a) To collect existing data and information relevant to the Study Area, that is the shoreline to the north of Penang Island.

(b) To design offshore barriers to dissipate the tsunami wave energy at three points namely points 1, 2 and 3 as shown in Figure 1.2.

(c) To evaluate the response of tsunami wave energy around the barrier by running a computer model typically the STWAVE model of SMS.

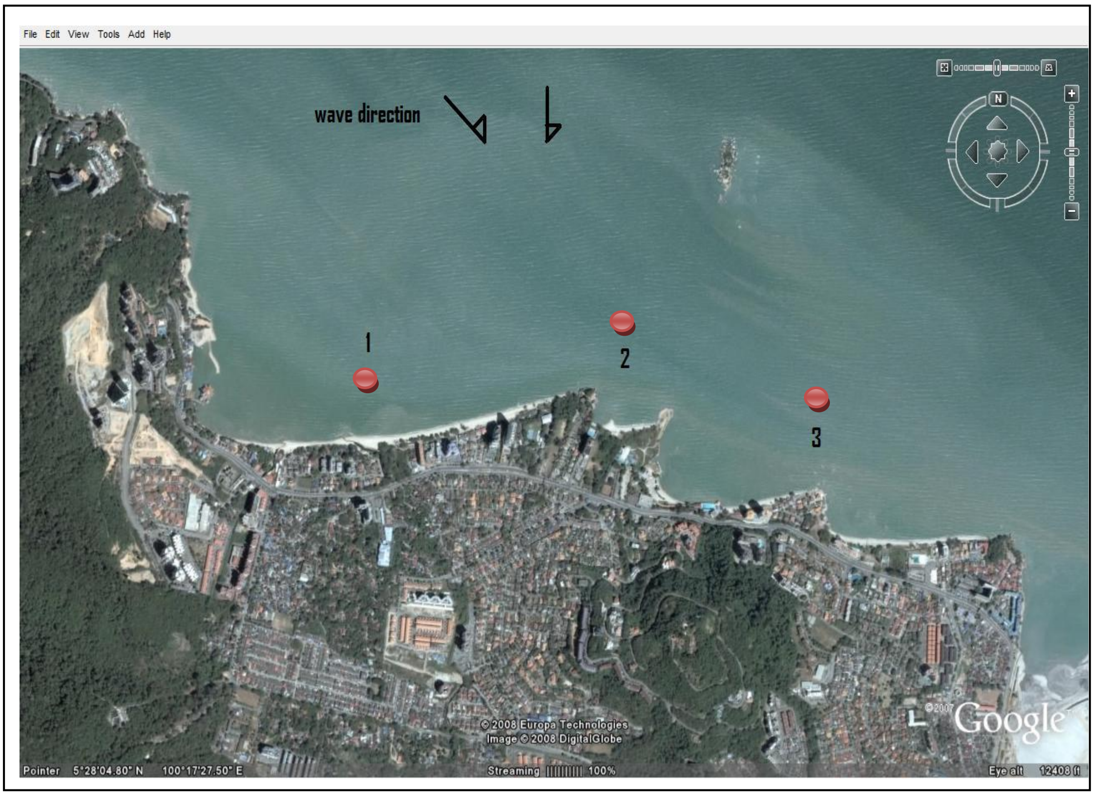


Figure 1.2 Location of the Study Area Showing the Coastline to the North of Penang Island

The three points to be considered in the study area will include:

- Point 1: Point 1 which fronts a wide coastal area which is open and vulnerable to tsunami waves.
- Point 2: There are two headlands near this point from which waves can cause damage to the pocket beach.
- Point 3: This coast accommodates a residential area.

CHAPTER 2

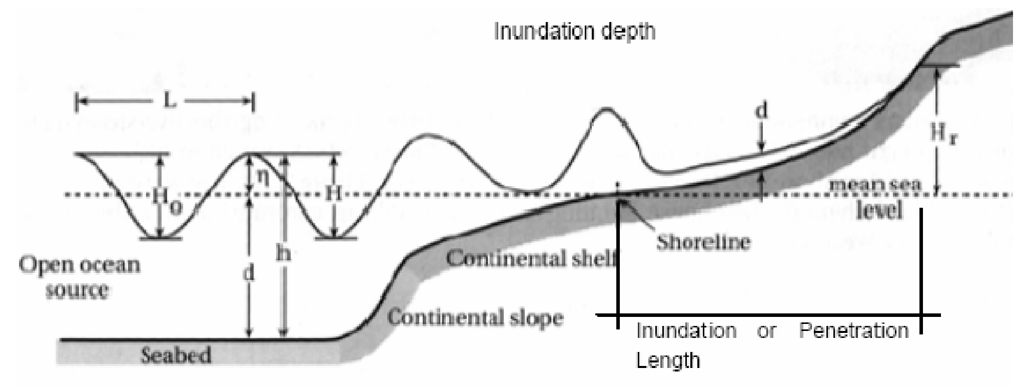
LITERATURE REVIEW

2.1 Tsunami

The term tsunami comes from the Japanese word meaning harbour ("tsu", 津) and wave ("nami", 波). For the plural form, one can either follow ordinary English practice and add an" s", or use an invariable plural as in Japanese. Tsunamis are common throughout Japanese history; approximately 195 events in Japan have been recorded. More than 1000 events occurred in the Pacific and about 100 events in the Atlantic and Indian oceans.

This kind of wave is defined as surface gravity waves. They occur in the ocean as a result of large-scale short term perturbations. They can be generated by many causes such as: underwater earthquakes, eruption of underwater volcanoes, submarine landslides, underwater explosion, rock and asteroid falls, avalanche flows in the water from land mountains and volcanoes and sometimes drastic changes of water conditions.

In the open ocean, tsunamis would not be felt by ships because the wavelength would be hundreds of miles long, with amplitude of only a few feet. This would also make them unnoticeable from the air. As the waves approach the coast, their speeds decrease and their amplitudes increase. Unusual wave heights have been known to be over 30 m high. Waves that are 3 to 6 m high can be very critical and cause many deaths or injuries. As these waves approach coastal areas, the time between successive wave crests varies from 5 to 90 minutes. The first wave is usually not the largest in the series of waves and it is not the most significant one. Terminology of the tsunami waves are illustrated in Figure 2.1.



L	=	Wavelength (m)
H_0	=	Wave height in deep water
d	=	Water depth (m)
η	=	Wave elevation (m)
h	=	Water elevation (m)
H	=	Wave height (m)
H_r	=	Wave run-up (m)

Figure 2.1 Terminology of Tsunami Waves (Source: Van der Plas 2007)

2.2 Causes of Tsunami Generation

Tsunami may be generated by different sources. Some of the most important causes of tsunami generation are as follows:

2.2.1 Earthquakes

Thucydides, a Greek historian was the first person who related tsunami to the earthquake in 426 BC (Shuto 2001). The most common cause of tsunamis is seismic activity. Earthquakes are responsible for 75% of all events. Almost all large earthquakes occur at the boundary of tectonic plates, where one plate slides over another. Earthquakes can be classified into three types of faults, depending on how the relative motion of adjacent plates affects the shape of the solid earth. They include:

(a) Thrust fault- where one tectonic plate moves up and over an adjacent plate.

(b) Normal fault- occurs when one plate moves down relative to an adjacent plate.

(c) Strike-slip- occurs when they slide past each other horizontally with neither plate being raised or lowered significantly.

The different types of faults which can generate the tsunami are shown in Figure 2.2. During tsunami generation, a thrust fault raises the floor of the ocean, which in turn raises the water above it and creates a positive water wave. A normal fault lowers the floor of the ocean, so it creates a negative water wave above it.

Strike slip faults do not change the shape of the ocean floor and they do not generate a tsunami. Therefore the magnitude of an earthquake by itself does not determine whether that earthquake will generate a significant tsunami (Segur 2006). Figure 2.3 illustrates a fault which causes an earthquake and therefore generates a tsunami.

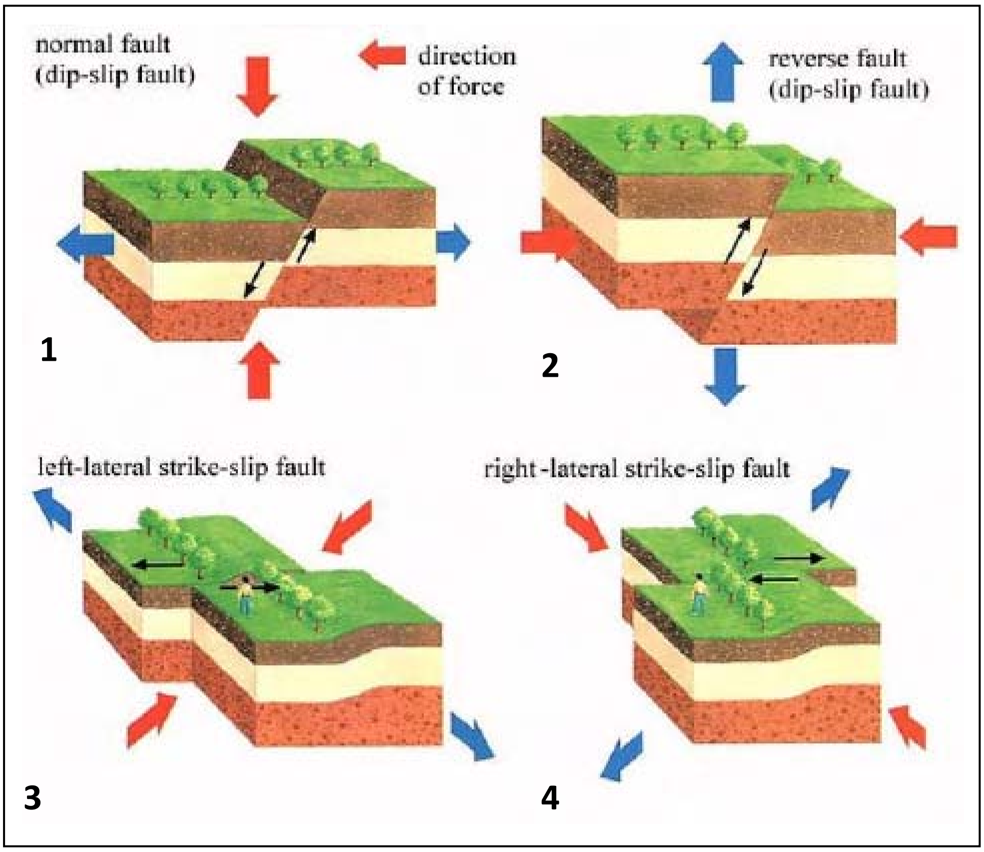


Figure 2.2 Different Types of Faults which can Generate an Earthquake (Source: Van der Plas 2007)

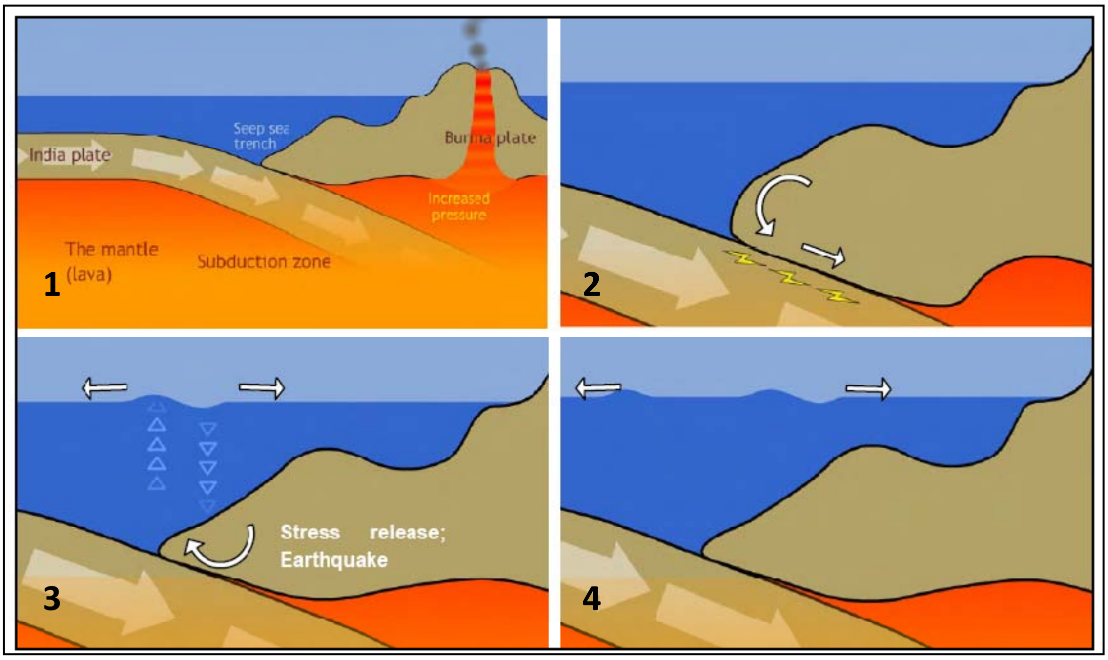


Figure 2.3 Tsunami Generated by a Normal Fault (Source: Van der Plas 2007)

Although earthquakes are the most common cause of tsunami generation, not every earthquake is powerful enough to trigger a tsunami. According to Pelinovsky (2005) the effective radius, R_e and water displacement, H_e of a tsunami can be roughly estimated through the earthquake magnitude, M by Equations 2.1 and 2.2 below:

$$\log R_e = 0.5M - 2.2 \tag{2.1}$$

$$\log H_e = 0.8M - 5.6 \tag{2.2}$$

where:

R_e	=	Effective radius (km)
H_e	=	Effective water displacement (m)
M	=	Earthquake magnitude (Richter)

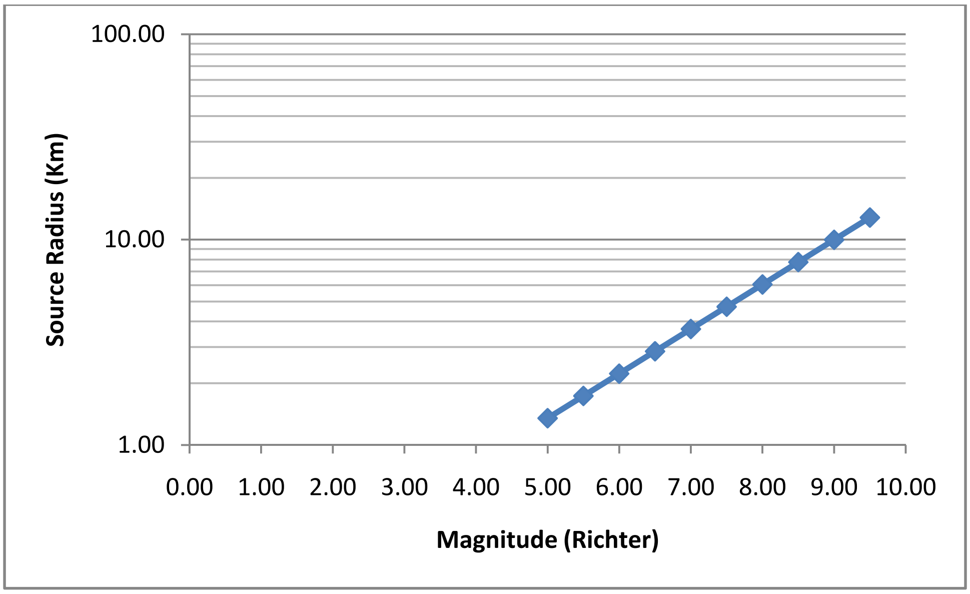


Figure 2.4 Rough Estimates of the Tsunami Parameters in the Source Versus Earthquake Magnitude Using Eqn. 2.1 (Source: Pelinovsky 2005)

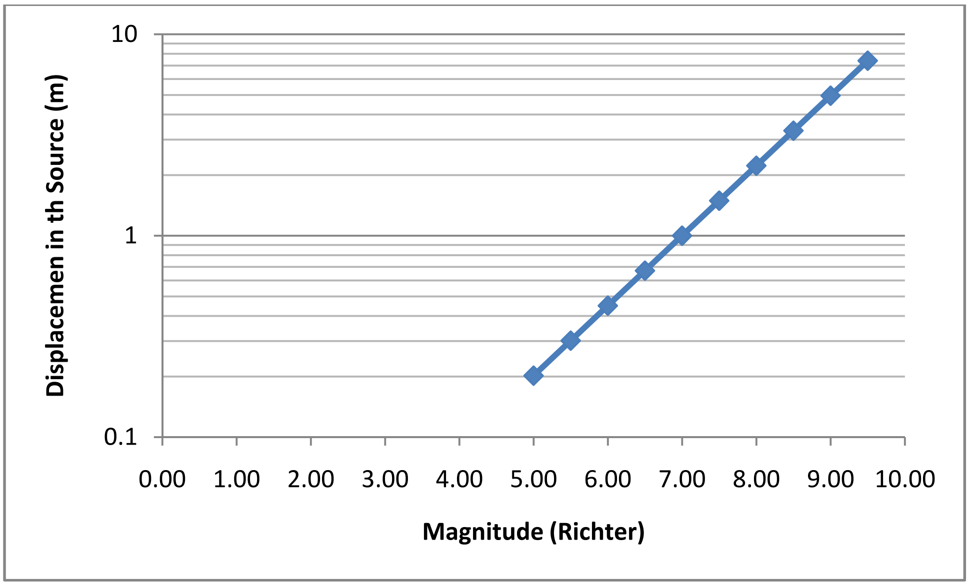


Figure 2.5 Rough Estimates of the Tsunami Parameters in the Source Versus Earthquake Magnitude Using Eqn. 2.2 (Source: Pelinovsky 2005)

From Figures 2.4 and 2.5 it is clear that strong earthquakes with magnitudes greater than 7 on the Richter scale can generate large tsunami wave several meters in height and one hundred kilometres in length. For example, an earthquake with a magnitude of 8.5 Richter can generate a tsunami wave of almost 3.32 meter height and 7.7 kilometre length at the source.

2.2.2 Landslides

According to Bardet et al (2003), the potential that a major tsunami could be generated by massive submarine mass failure was recognized a century ago by many scientists such as Milne (1898) and De Ballore (1907). In recent years, many studies have supported this idea that a major tsunami could be generated by a large submarine mass failure itself or triggered by a large earthquake in the coastal area.

Although there is not much information available to describe landslide tsunami generated events, a few well documented events have helped focus the attention on landslide generated tsunamis. This includes that during the 1992 Flores Island, Indonesia earthquake, at the village of Riangkroko, where the run up was measured to be 26 m, which was the highest on Flores Island. The waves which destroyed the village and killed 122 people probably originated from a nearby underwater landslide.

The most usual mechanism of the starting failure of submarine slopes is over steepening which will happen because of rapid deposition of sediments, generation of gas created by decomposition of organic matter, storm waves, and earthquakes, which are the major causes of landslides on continental slopes (Todorovska et al 2001). The failed material is driven by gravity forces.

Not all submarine landslides are capable of generating tsunamis. As mentioned by Murty (2003) tsunami generation by submarine landslides depends mainly on the volume of the slide material and to a lesser degree on other factors such as: angle of the slide, water depth, density and speed of the slide material, duration of the slide, etc. He also derived a simple linear regression relationship between H "maximum amplitude of the resulting tsunami" and V "volume of the slide material" as given in Eqn. 2.3 and 2.4 respectively. Normally, the wavelengths and periods of landslide-generated tsunami are between 1 to 10 km and 1 to 5 minutes respectively. These values are much shorter than tsunami produced by earthquakes (Van der Plas 2007).

$$\mathrm{H} = 0.3945\ \mathrm{V} \tag{2.3}$$

$$\mathrm{V} = 2.3994\ \mathrm{H} \tag{2.4}$$

where

H = Maximum amplitude of the resulting tsunami (m)

V = Volume of submarine landslide (million m^3)

2.2.3 Volcanic Eruptions

Volcanic eruptions can generate tsunami in many different ways. Volcanic activity can also induce submarine landslides and submarine eruptions/explosions. Detailed experiments have been performed with underwater explosion with low energies, when the generated waves have small wave lengths compared with the water depth (Pelinovsky 2005). For example, the 1952-1953 Mijojin underwater volcano eruption had energy of 1016 J and caused a tsunami where the parameters of its source were, $R_e \approx$ 2-3 kilometre and $H_e \approx$100-200 meter.

2.2.4 Meteor Impacts

Asteroids larger than 200 meters in diameter hit the earth about every 3000-5000 years. Most objects smaller than 100 - 200 m in diameter explode in the atmosphere and will not produce significant waves. Unlike earthquakes the potential tsunami height caused by meteor-impact is almost unlimited (Van der Plas 2007).

2.3 Propagation of Tsunami Wave

According to Segur (2006), Stokes was the first scientist who developed a mathematical theory for water waves. He wrote down the equations for the motion of an incompressible, inviscid fluid, subject to a constant gravitational force, in which the fluid was bounded below by a rigid bottom and above by a free surface.

As discussed by Segur (2006) linear wave equation can be used to describe the propagation of the tsunami far from the shoreline. In the coastal regions as water depth decreases, wave lengths become shorter and wave amplitude becomes larger as illustrated in Figure 2.6. Therefore the linear equations are not valid for use any longer.

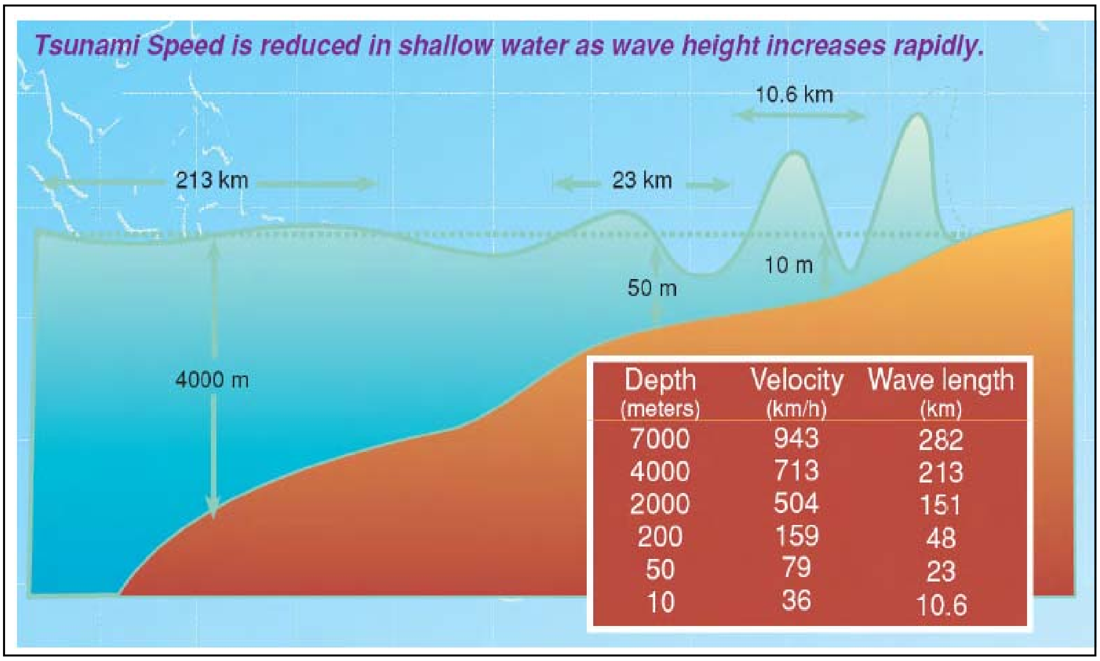


Figure 2.6 Typical Changes in Tsunami Wave as it Reaches Shallow Water (Van der Plas 2007)

Segur (2006) also described that by using two assumptions that is (1) the ocean depth, h(x,y), is constant and (2) the surface motion is one dimensional, a linear wave equation can be written as follows:

$$\partial_t^2 \zeta = \partial_x \,(\mathrm{u.h}) + \partial_y \,(\mathrm{v.h}) = 0 \tag{2.5}$$

$$\partial_t \,(\mathrm{u.h}) + \mathrm{c}^2 \partial_x \zeta = 0 \tag{2.6}$$

$$\partial_t \,(\mathrm{v.h}) + \mathrm{c}^2 \partial_y \zeta = 0 \tag{2.7}$$

where:

c^2	=	gh(x,y)
x,y	=	Orthogonal horizontal coordinate
u(x,y,t)	=	Component of horizontal velocity
v(x,y,t)	=	Component of horizontal velocity
ζ(x,y,t)	=	Height of free surface above the still-water level

If the surface motion happens to be one dimensional then v in Equations 2.5 and 2.7 will be zero and can be ignored. Therefore, Equations 2.5 to 2.7 can be combined into a single equivalent equation:

$$\partial_t^2 \zeta = \partial_x (g.h(x,y)\partial_x \zeta) + \partial_y \left(g.h(x,y)\partial_y \zeta\right) \tag{2.8}$$

Equation 2.8 is a two dimensional linear wave equation, with a spatially variable speed of propagation. It can be solved numerically by a variety of methods. Some conclusions can be drawn directly from the structure of this equation even without solving it numerically.

One of the important conclusions that could be derived is that any solution of Equation 2.8 propagate with local speed

$$\mathrm{c} = \sqrt{\mathrm{g.h(x,y)}} \tag{2.9}$$

where:

c	=	Wave celerity (m/s)
g	=	Gravitational acceleration (m/s²)
h(x,y)	=	Water displacement (m)

Also the time required for a wave that starts at the epicentre of the earthquake to reach any particular coastal region can be determined by

$$\mathrm{T} = \int_0^s \frac{ds}{\sqrt{\mathrm{gh(x(s),y(s))}}} \tag{2.10}$$

where:

s	=	Arch length along the given starting point to the identified coastal region

c	=	Wave celerity (m/s)
T	=	Wave propagation time (s)

2.4 The Interaction of Tsunami Wave with Structures

As presented in Section 1.2, there are different types of structures which can be used to protect coastal areas against tsunami waves. The energy of a tsunami wave, which is either dissipated on land or reflected when there is no structure, must now be reflected by the structure. The resulting forces on the structure as well as current velocities depend highly on the wave height and waveform. The effect of waves and wave transition over some types of structures is described in the following sections.

2.4.1 Submerged Breakwaters

The efficiency of submerged structures and the resulting shoreline response mainly depends on transmission characteristics and the layout of the structure.

Pilarczyk (2003) gives an overview of the formula to determine the wave transmission coefficient K_T for different values of relative crest width, B/L_0, and crest height, R_c/H_{si}, where R_c is the height of the breakwater above water level and H_{si} is the incident significant wave height (refer to Figure 2.7)

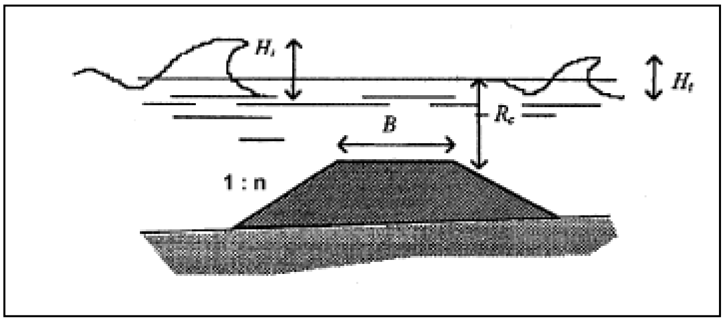


Figure 2.7 Wave Reduction Caused by a Submerged Structure (Source: Pilarczyk 2003)

The wavelength on the crest can be determined by $L_c = 0.5T_p(gR_c)$, at the toe by $L_h = 0.5T_p(gR_c)$ and in deepwater by $L_o = gT^2/2\pi$ .In order to find the efficiency of a submerged breakwater he used the L_c definition (instead of L_o) and two numerical coefficients that is, C=0.64 for a permeable and C=0.80 for an impermeable structure in the original d'Angremond et al (1996) formula as given by Equation 2.11. By using this equation he found a good agreement between calculated wave transmission and the measured one for The Amwaj Islands Development Project in Bahrain. The Amwaj Islands Development Project involves the construction of new islands on the existing coral reef. In order to protect the waterfront developments on the mentioned island from wave attack a submerged breakwater was proposed. The wave transmission for the proposed submerged breakwater is illustrated in Figure 2.8 and demonstrated that the effectiveness of a submerged structure depended on the ratio B/L and R_c/H_{si}. Decreasing these ratios would increase the transmission and thus decrease the effectiveness of the structure. The wave transmission over a submerged breakwater formula is given by:

$$K_t = -0.4\frac{R_c}{H_i} + 0.64\left(\frac{B}{H_{si}}\right)^{-.31}\left(1 - e^{-.5\xi}\right) \qquad (2.11)$$

where

K_t	=	Transmission coefficient
R_c	=	Crest freeboard (m)
H_{si}	=	Incident significant wave height (m)
B	=	Crest width (m)
ζ	=	Surf similarity parameter

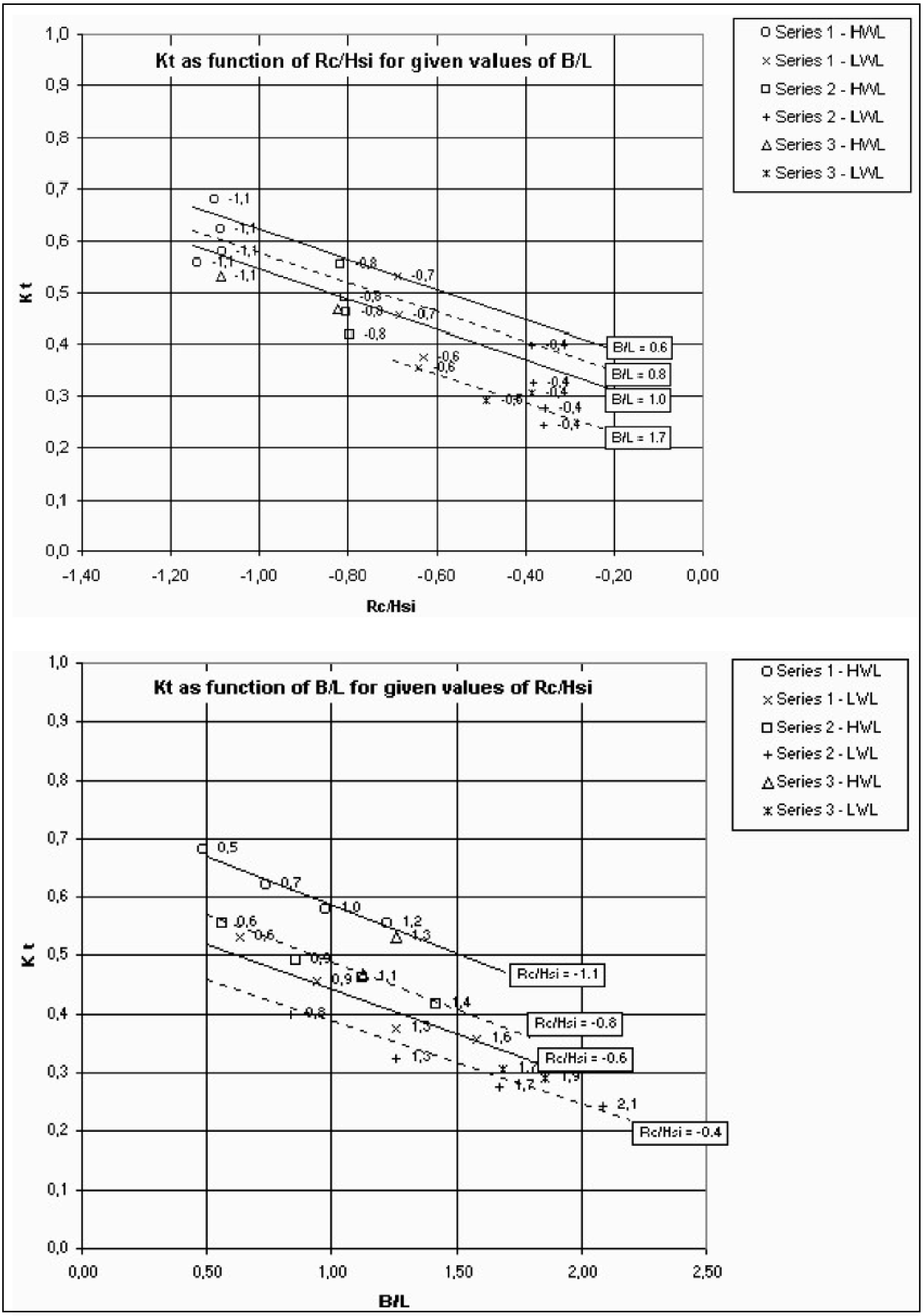


Figure 2.8 Wave Transmissions over Reef Structures in Amwaj Project (Source: Pilarczyk 2003)

Tokura and Ida (2005) investigated the propagation of waves over rigid and flexible mounds as shown in Figure 2.9. They used a rectangular model (3600 mm × 1800 mm) for the rigid mound and an elliptic model for the flexible one. Although flexible mounds have some advantageous compared to common rigid ones, both structures showed similar wave dissipating capability.

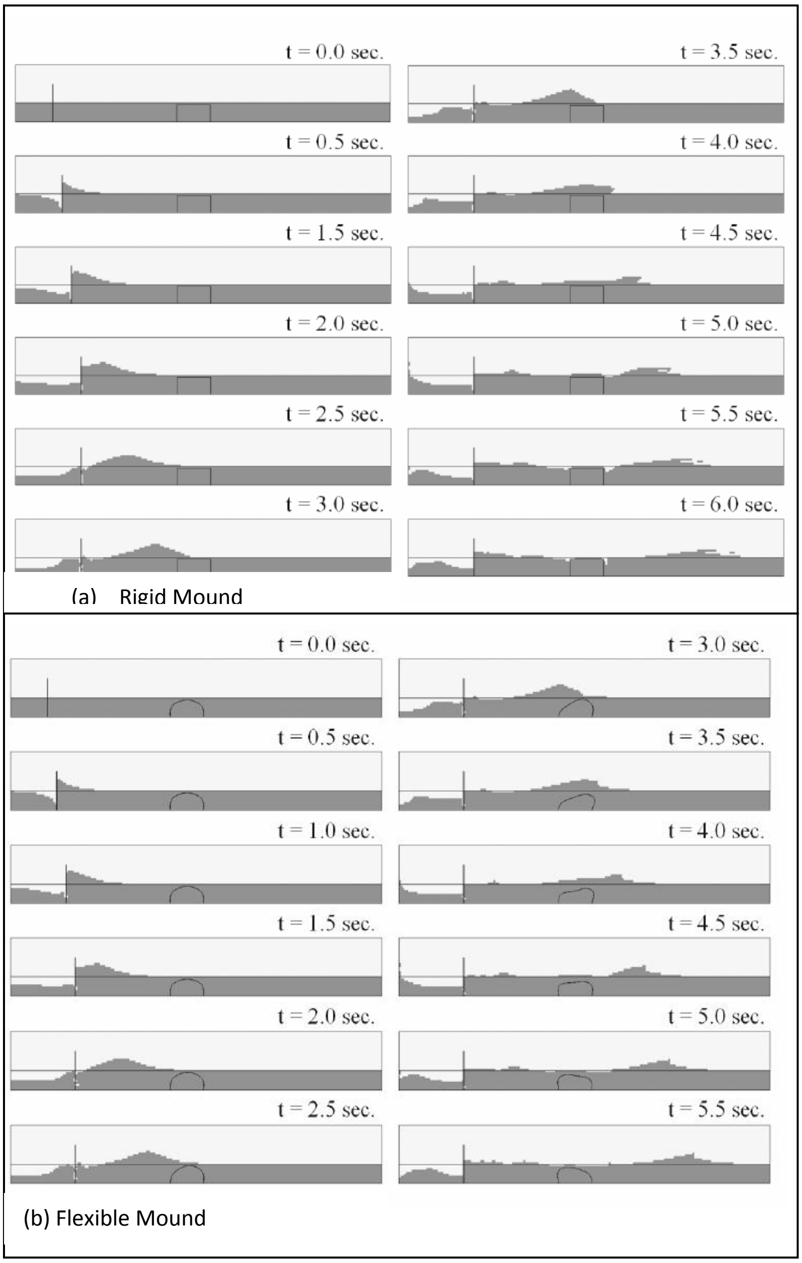


Figure 2.9 Wave Propagation Passing Over (a) Rigid Mound (b) Flexible Mound (Source: Tokora and Ida 2005)

2.4.2 Wave Transmission Over Low-Crested Structures (LCS)

Waves propagating from deep water may reach a structure after refraction, shoaling and breaking. As soon as the waves reach a structure, they undergo several processes. The waves may break on the structure, overtop it, generate waves behind the structure and reflect from the structure. Also waves may penetrate through openings between structures. Wave penetration and diffraction do not depend on the fact whether the structure is low-crested or not. The main effect of an LCS is that energy can pass over the crest and generate milder waves behind the structure.

There are at least 14 variables which control the relationship between an offshore breakwater and response of the shoreline. Among these variables eight are considered primary namely:

(a) distance offshore
(b) length of the structure
(c) transmission characteristics of the structure
(d) beach slope and/or depth at the structure (controlled in part by the sand grain size)
(e) mean wave height
(f) mean wave period
(g) orientation angle of the structure
(h) predominant wave direction

For segmented detached breakwaters and artificial reefs, the gap between segments becomes another primary variable. The main parameters that can describe wave transmission over a low crested breakwater are illustrated in Figure 2.10.

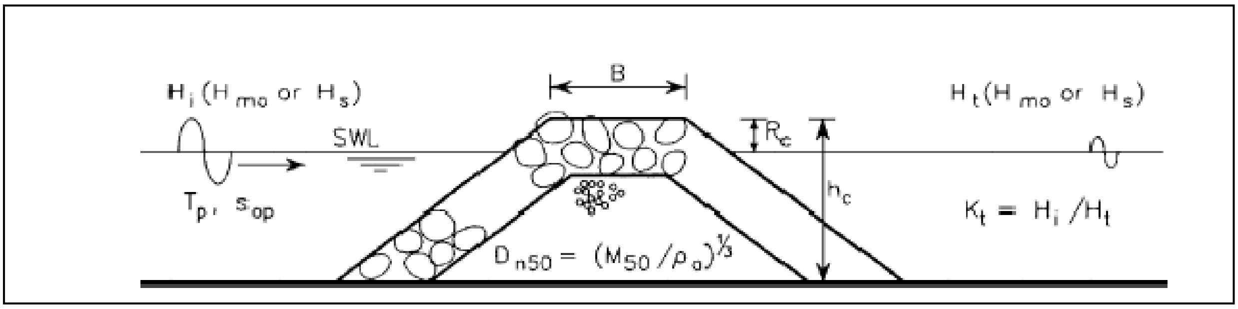


Figure 2.10 Definitions of Governing Parameters Involved in Wave Transmission through LCS (Source: Van der Meer et al 2005)

The parameters defined for a rubble mound breakwater as given in Figure 2.10 can be listed as:

H_i	=	Incident significant wave height, preferably H_{m0i}, at the toe of the structure (m)
H_{moi}	=	Incident zero moment wave height (m)
H_{mot}	=	Transmitted zero moment wave height (m)
H_t	=	Transmitted significant wave height, preferably H_{m0t} (m)
T_p	=	Peak period (s)
S_{op}	=	Wave steepness, $S_{op} = 2\pi H_i \, / \, (gT_p^2)$
R_c	=	Crest freeboard (m)
h_c	=	Structure height (m)
B	=	Crest width (m)
D_{n50}	=	Nominal diameter of armour rock for rubble mound structure (m)
K_t	=	Transmission coefficient = H_t / H_i
ζ_{op}	=	Breaker parameter $= \tan a/(S_{op})^{0.5}$
tan α	=	Seaward slope of structure

Two phenomena that allow wave energy to pass over or through low crested structures are wave transmission and overtopping. The rest of the wave energy will be dissipated by wave breaking on and over the structure and some of the energy will be reflected. Since these structures are usually used for coastal protection, the prediction of the amount of energy transmitted behind them is a crucial point in design practice and research. Therefore various design formulae for wave transmission have been developed to be used in engineering practices but each one has its own limitations.

Van der Meer et al (2005) gathered a database made up of 2337 tests to study wave transmission over LCS. The summary of the results of the research work is shown in Table 2.1 and the armour types used in the experiments are illustrated in Figure 2.11.

Table 2.1 Summary of the Ranges of Parameters Involved in 2D Wave Transmission Tests at LCS (Source: Van der Meer et al 2005)

Database	Armour type	R_c/H_i	B/H_i	B/L_{op}	ξ_{op}	H_i/D_{n50}	H_i/h	s_{op}	Tests #
Old database	Various	−8.7	0.37	0.009	0.7	0.3	0.03	$2*10^{-4}$	398
		4.0	43.48	0.51	8.26	6.62	0.62	0.06	
UCA	Rubble mound	−1.5	2.67	0.04	3.97	0.84	0.1	0.002	53
		1.53	30.66	0.4	12.98	2.42	0.37	0.02	
UPC	Rubble mound	−0.37	2.66	0.07	2.69	2.65	0.17	0.02	24
		0.88	8.38	0.24	3.56	4.36	0.33	0.034	
GWK	Rubble mound	−0.76	1.05	0.02	3	1.82	0.31	0.01	45
		0.66	8.13	0.21	5.21	3.84	0.61	0.03	
M & M	Core locks	−8.2	1.02	0.02	2.87	0.68	0.05	0.01	122
		8.9	7.21	0.13	6.29	4.84	0.5	0.054	
Seabrook	Rubble mound	−3.9	1.38	0.04	0.8	0.78	0.11	0.01	632
		0	74.47	1.66	8.32	3.2	0.58	0.06	
Aquareef	Aquareef	−4.77	1.24	0.02	1.78	0.59	0.1	0.01	1063
		−0.09	102.12	2.1	5.8	4.09	0.87	0.08	

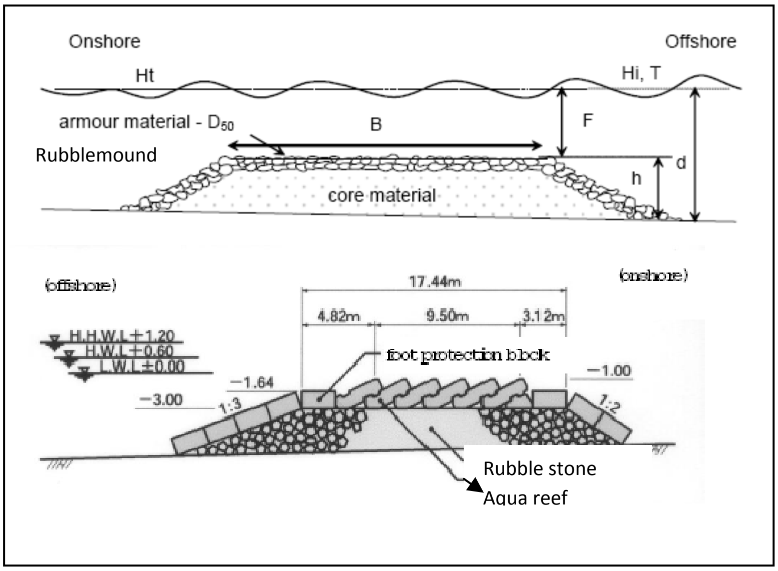


Figure 2.11 Typical Armour Type for Submerged Breakwater Used in Van der Meer et al's Research Works (Source: Pilarczyk 2003)

They found that structures armoured with Aquareef showed higher maximum values of K_t compared to the other structures which is due to the high permeability of the armour layer or due to the definition of the crest height. In order to determine K_t, they developed Equation 2.12 for structures with $B/H_i < 10$ and Equation 2.13 for structures with $B/H_i > 10$.

$$K_t = -0.4\frac{R_c}{H_i} + 0.64\left(\frac{B}{H_i}\right)^{-.31}\left(1 - e^{-.5\xi}\right) \quad \text{when} \quad \frac{B}{H_i} < 10 \tag{2.12}$$

$$K_t = -0.35\frac{R_c}{H_i} + 0.51\left(\frac{B}{H_i}\right)^{-.65}\left(1 - e^{-.41\xi}\right) \quad \text{when} \quad \frac{B}{H_i} > 10 \tag{2.13}$$

where

K_t	=	Transmission coefficient
R_c	=	Crest freeboard (m)
H_i	=	Incident significant wave height (m)
B	=	Crest width (m)
ζ	=	Surf similarity parameter

2.5 The December 2004 Tsunami Event

At 00:58:53 UTC or 08:59 Malaysian time on December 26, 2004 a major earthquake with a magnitude of between 9.1 and 9.3 on the Richter scale occurred off the West Coast of Sumatra, Indonesia. This earthquake generated a devastating tsunami and killed more than 225,000 people in eleven countries as illustrated in Table 2.2 and Figure 2.12. The earthquake occurred on the tectonic boundaries where the Indian plate and Sunda plate met each other. It triggered a 1200 km slip of fault line. Unlike normal tsunamis, the 2004 tsunami triggered along this fault line with an elliptic shape and propagated to the east and west of the fault line (Komoo and Othman 2006).

Table 2.2 Damage and Casualties due to the Tsunami 2004 Event

Country	Deaths		Injured	Missing	Displaced
	Confirmed	Estimated			
Indonesia	130,736	167,736	-	37,063	500,000+
Sri Lanka	35,322	21,411			516,150
India	12,405	18,405	-	5,640	647,599
Thailand	5,395	8,212	8,457	2,817	7,000
Somalia	78	289	-	-	5,000
Myanmar	61	400-600	45	200	3,200
Maldives	82	108	-	26	15,000+
Malaysia	68	75	299	6	-
Tanzania	10	13	-	-	-
Seychelles	3	3	57	-	200
Bangladesh	2	2	-	-	-
South	2	2	-	-	-
Yemen	2	2	-	-	-
Kenya	1	1	2	-	-
Madagascar	-	-	-	-	1,000+
Total	≈184,168	≈230,210	≈125,000	≈45,752	≈1.69million

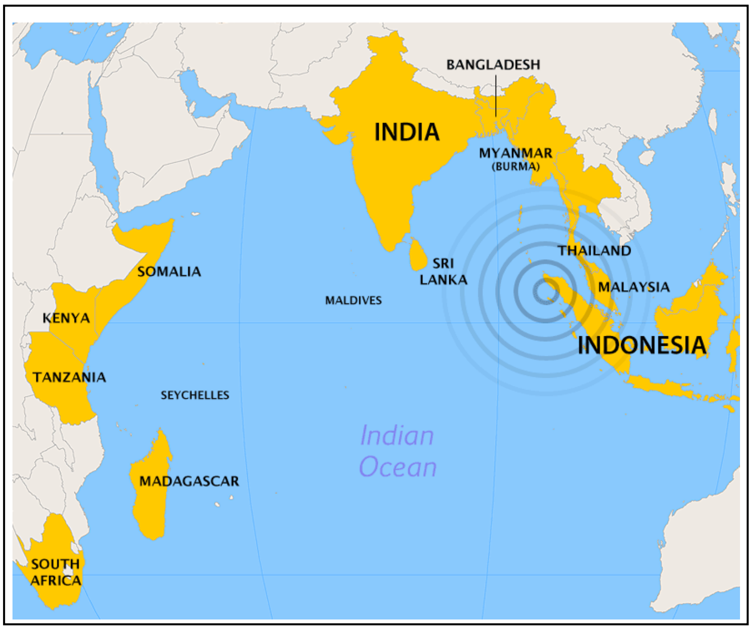


Figure 2.12 Countries Affected by the 2004 Tsunami

An earthquake with a magnitude greater than 9.0 had not occurred in this area since 200 years ago (Van der Plas 2007). It was the second largest earthquake ever recorded on a seismograph and it had the longest fault duration, between 8.3 and 10 minutes. It caused the entire planet to vibrate as much as 1 cm and triggered other earthquakes as far away as Alaska. After its generation, it took only a few minutes to reach the northern shore of North Sumatra while it reached the coastline of Sri Lanka and the eastern coast of India between 90 to 120 min. The north-western shoreline of Peninsular Malaysia experienced this disaster after 3 to 4 hours. Due to the morphology of the Malacca Straits and the reduction of sea water to about 50 meter the tsunami became more widely disturbed and undergo refraction and reflection. Therefore its speed and energy decreased and its wave height reduced to 2 to 5 m (Komoo and Othman 2006).

Pulau Pinang was one of the places in Malaysia which was impacted by this tsunami. It was believed that the tsunami hit the shoreline of Pulau Pinang several times between 1.15 p.m. and 1.30 pm on that day. In total, thirteen places in the western and northern parts of the island had recorded death and loss of property. The tsunami killed 52 people in Penang. Most of them were trapped while swimming and having a picnic on the beach. The areas in Penang affected by the tsunami (see Figure 2.13) were Kg. Perlis, Kuala Jalan Baru, Kuala Sg. Pinang, Kg. Pantia Malindo, Kg. Permatang Damar Laut, Kg. Pulau Bentong, Kg. Aceh, Sg. Batu, Kg. Teluk Kumbar and Pantai Pasir Panjang which are in Balik Pulau to the west of the Island and the northern coast of Island, i.e. Tg. Bungah, Tg. Tokong, Batu Ferringi, Teluk Bahang and Pantai Miami (Komoo and Othman 2006). Although many areas were affected in Penang, the study area sited in this research work is limited to the Tg. Bungah area only.

Figure 2.13 Some of the Tsunami Affected Areas in Penang

(Source: Komoo and Othman 2006)

CHAPTER 3

METHODOLOGY

3.1 Introduction

The objectives of this research are two fold. The first is to design the layout of an offshore barrier to dissipate tsunami wave energy. The second objective is to execute a computer model to evaluate the performance of the structure in dissipating tsunami wave energy at the northern shoreline of Penang Island. The flowchart shown in Figure 3.1 illustrates the proposed methodology adopted for the present work. The design criteria utilized and the Surface Water Modelling System which has been used to simulate wave propagation and to design the wave barrier is discussed in detail in the following sections.

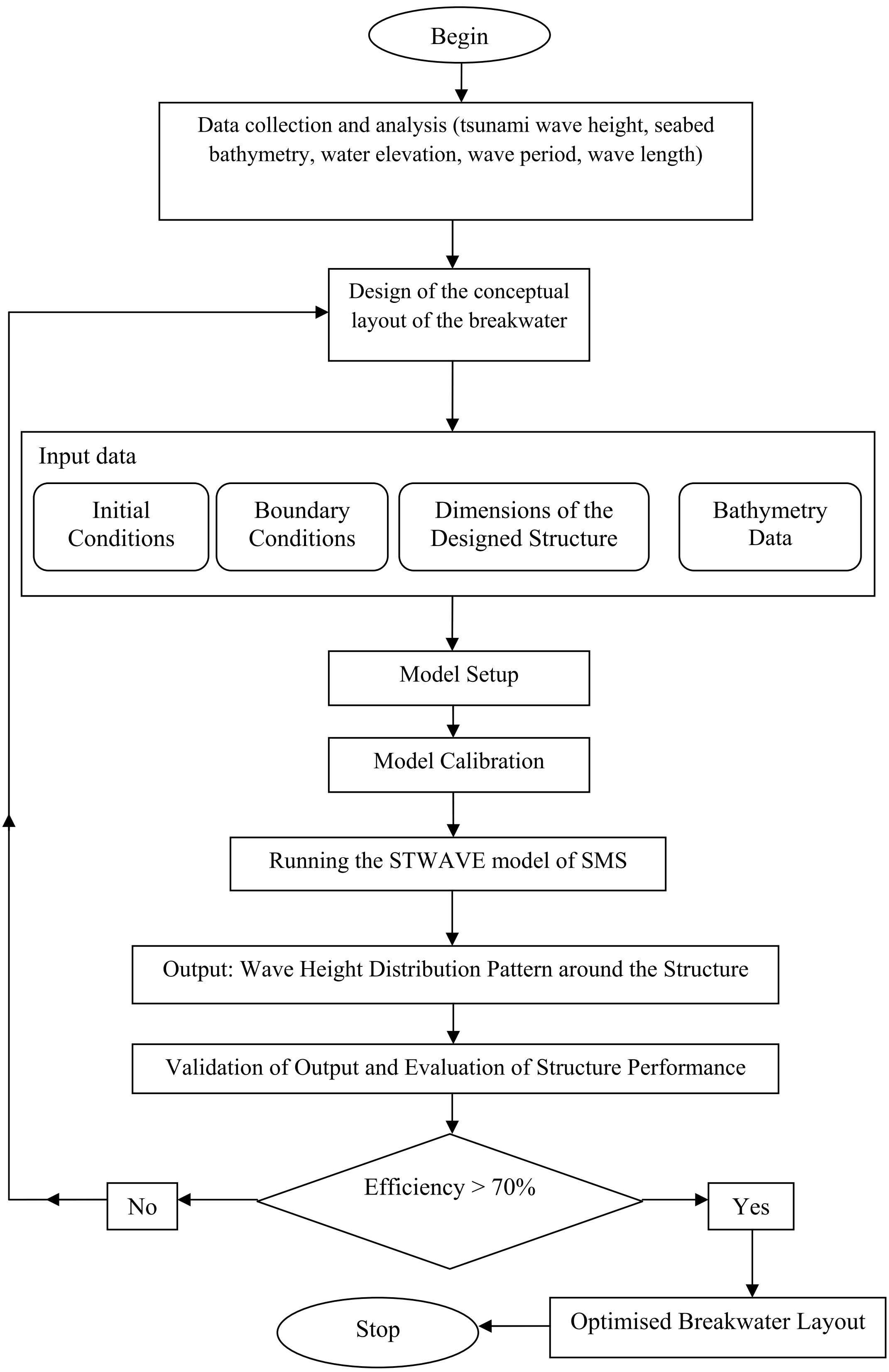


Figure 3.1 Flowchart of the Proposed Methodology

Both partially and fully submerged breakwaters can be built as rubblemound structures (Pencev 2004). In the following sections the design of a rubblemound structure is discussed in detail.

3.2 Design of the Rubblemound Breakwater

Rubblemound breakwaters can be divided into two main groups. They are include:

(a) Attached breakwater

(b) Detached breakwater

Due to the location of the shoreline and the area to be protected, the breakwater can be designed to be attached or detached from the shoreline. An attached breakwater is a breakwater which is extended from a natural headland and it could be used to protect a pocket beach. On the other hand detached breakwaters are those which are small, relatively short, non shore-connected and located near shore (USACE 2006). If a breakwater were required to protect a coastal area which was open to offshore waves and major wave crests approached parallel to the coastline, a detached offshore breakwater might be the better option for use in design (Sheppard 2004).

Both attached and detached breakwaters have their own advantages and limitations. An advantage of attached breakwaters is that they are easily accessible for construction, operation and maintenance. However high construction cost and negative impact on the neighbouring area are two main disadvantages. Detached breakwaters are more environmental friendly but their construction and maintenance costs are higher.

According to Sheppard (2004) rubblemound breakwaters can be designed as overtopped or non-overtopped structures. In overtopped structures, crown elevation allows larger waves to move across the crest. Overtopped structures are more difficult to design because their stability response is strongly affected by small changes in the still water level. In non-overtopped structures the elevation of the crown prevents any significant amount of wave energy from crossing the crest. They can provide protection from many waves, but they are more costly to build because of the increased volume of materials required.

Submerged breakwaters are commonly used for coastal protection and erosion control at beaches. A desirable feature of submerged breakwaters (and low-crested structures, in general) is that they do not interrupt the clear view of the sea from the beach. This aesthetic feature is important for maintaining the touristic value of many beaches and it is usually one of the considerations in using such structures for shoreline protection (Prions et al 2004). The main idea of using this type of structure is to reduce the wave energy reaching the beach by triggering wave energy dissipation over the structure. In other words, their purpose is to reduce the hydraulic loading to a required level that maintains the dynamic equilibrium of the shoreline. To attain this goal, they are designed to allow the transmission of a certain amount of wave energy over the structure by overtopping and also some transmission through the porous structure as in permeable breakwaters or wave breaking and energy dissipation on the shallow crest as at submerged structures (Pilarczyk 2003).

Usually, offshore breakwaters, and especially, the low-crested submerged structures, provide environmentally friendly coastal solutions. However, high construction cost and the difficulty of predicting the response of the beach are the two main disadvantages that inhibit the use of offshore breakwaters.

3.2.1 Breakwater Design Description

A typical breakwater can be described and constructed with at least three major layers as follows:

(a) Outer layer called the armour layer (this is composed of the largest units, stone or specially shaped concrete armour units)
(b) One or more stone underlayers.
(c) Core or base layer of quarry-run stone, sand or slag (as bedding or filter layer below)

The armour layer may need to be covered with specially shaped concrete armour units (such as Dolos, Tetrapod, Quadripod and Tribar) in order to provide an economic construction of a stable breakwater (Sheppard 2004).

3.2.2 Design Parameters

In order to design a typical rubblemound breakwater there are some parameters which should be considered and these are shown in Figure 3.2. They include:

h	=	Water depth of structure relative to design high water (DHW)
h_c	=	Breakwater crest relative to DHW
R	=	Freeboard, peak crown elevation above DHW
h_t	=	Depth of structure toe relative to still water level (SWL)
B	=	Crest width
B_t	=	Toe apron width
A	=	Front slope (seaside)

α_b	=	Back slope (lee)
t	=	Thickness of layers
W	=	Armour unit weight

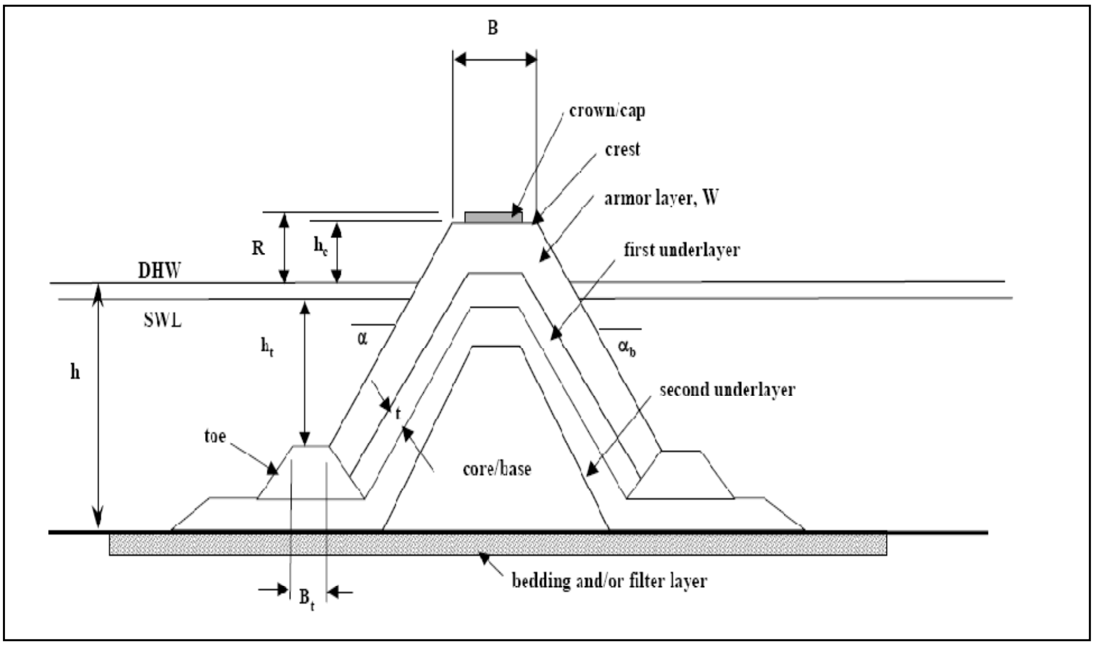


Figure 3.2 Parameters used in Rubblemound Design (Source: Sheppard 2004)

The design high water (DHW) level varies. It can be MHHW, storm surge. SWL or MSL, MLLW, etc. Wave setup is generally neglected in determining the DHW level.

3.2.3 Breakwater Design Procedure

According to Sheppard (2004) in order to design a rubblemound breakwater the following steps can be undertaken:

(a) Specify design condition such as design wave ($H_{1/3}$, H_{max}, T_o, L_o, depth, water elevation, overtopping, breaking, purpose of structure, etc.)

(b) Set breakwater dimensions such as h, h_c, R, h_t, B, α, α_b

(c) Determine the armour unit size/ type and under layer requirements.

(d) Develop the toe structure and filter or bedding layer.

(e) Analyze the foundation settlement, bearing capacity and stability.

(f) Adjust parameters and repeat as necessary.

Typical rubblemound cross sections are shown in Figures 3.3 and 3.4 in which the first figure illustrates the cross-sectional features typical of designs for breakwaters exposed to waves on one side (seaward) and intended to allow minimal wave transmission to the leeward side. Breakwaters of this type are usually designed with crests elevated to allow overtopping only in very severe storms with long return periods. Figure 3.4 shows features common to designs where the breakwater may be exposed to substantial wave action from both sides and where overtopping is allowed to be more frequent.

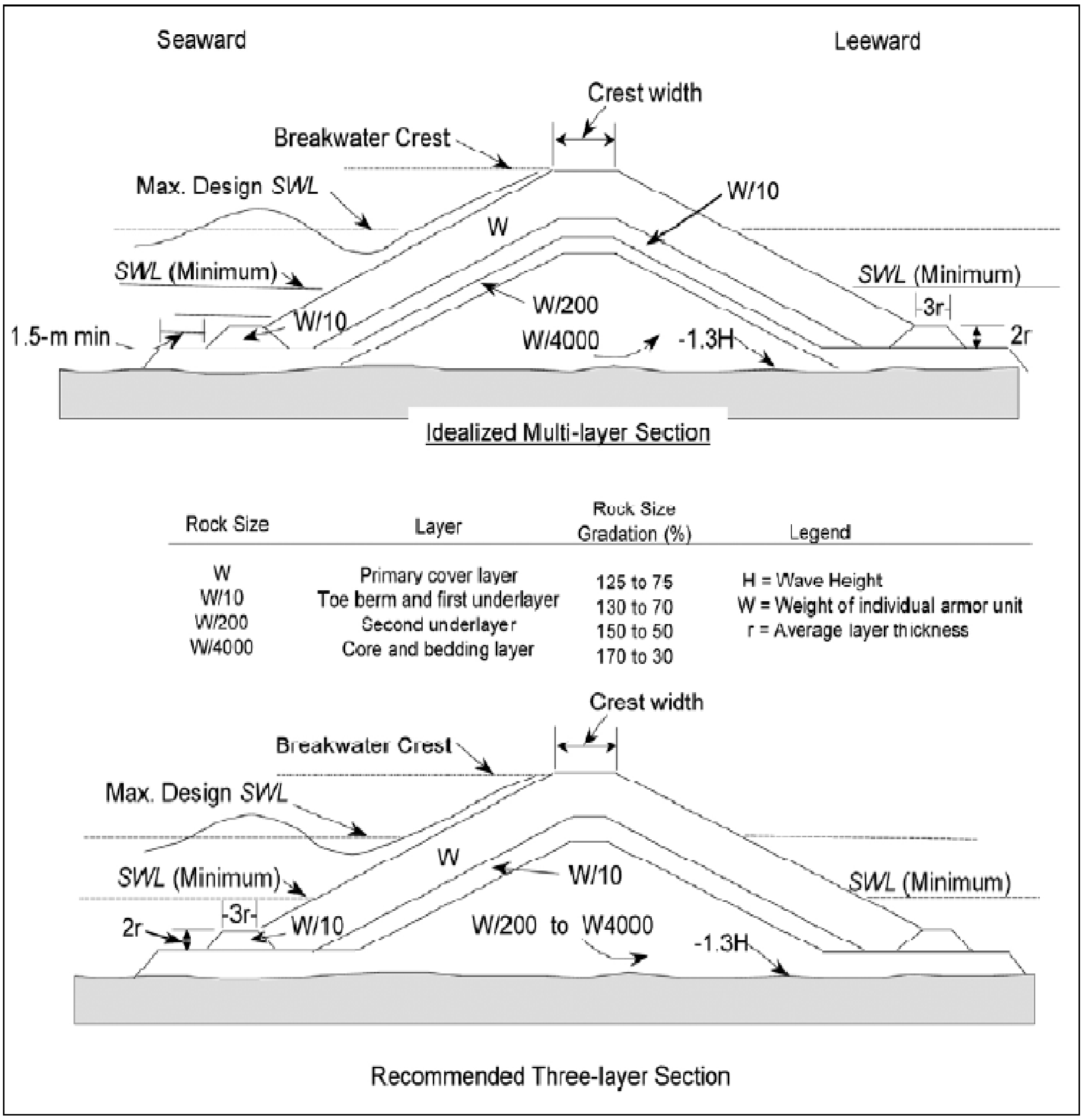


Figure 3.3 Rubblemound Section for Seaward Wave Exposure with Zero-to-Moderate Overtopping Conditions (Source: USACE 2006)

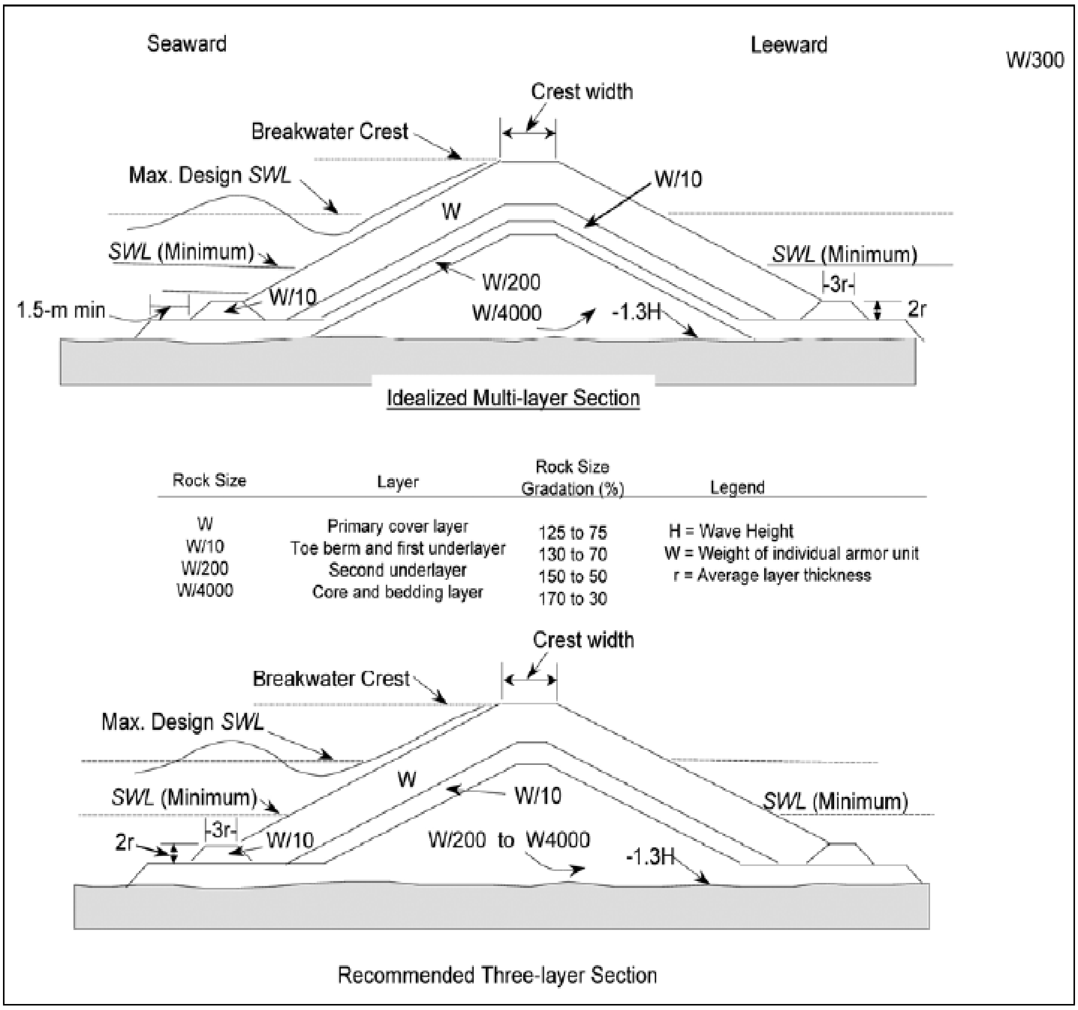


Figure 3.4 Rubblemound Section for Wave Exposure on Both Sides with Moderate Overtopping Conditions (Source: USACE 2006)

3.3 Surface Water Modelling System (SMS)

Surface Water Modelling System (SMS) is a graphical program that allows engineers and scientists to visualize, manipulate and understand numerical data. SMS comprises one, two, and three dimensional numerical models including finite element and finite difference models. This software is a product of the environmental modelling research laboratory of Brigham Young University and new enhancements and developments continue in cooperation with the U.S. Army Corps of Engineers (USACE), Engineer Research and Development Centre (ERDC) and the U.S. Federal Highway Administration (FHWA) (SMS Manual 2004).

SMS contains different tools for surface water modelling, analysis and design. It includes tools for:

(a) Managing, editing and visualizing geometric and hydraulic data
(b) Creating, editing and formatting mesh/grid data for use in numerical analysis which includes:
  (i) Finite Element Meshes (unstructured grids). The tools support:
    - Linear and quadratic elements.
    - All triangular or mixture of triangular and quadrilateral meshes.
    - Incorporation of 1D elements into 2D and 3D meshes.
  (ii) Finite Difference Grids (structured grids). The tools support:
    - Rectilinear grids at specified rotation.
    - Boundary fitted (curvilinear) grids.
  (iii) Triangulated Irregular Networks (TINS)

Interfaces have been specifically designed to facilitate the utilization of several numerical models in SMS. Supported models in SMS include:

(a) United States Army Corps of Engineers (USACE)
  (i) Engineer Research and Development Centre (ERDC)
    - TABS-MD (GFGEN, RMA2, RMA4, RMA10, SED2D-WES)

- ADCIRC
- CGWAVE
- STWAVE (is a steady-state finite difference model based on the wave action balance equation)
- HIVEL2D
- CH3D

(ii) Hydrologic Engineering Centre (HEC)

- HEC-RAS

(b) Federal Highway Administration (FHWA)

(i) FESWMS-FlO2DH

(c) Independent/Commercial Licenses

(i) M2D

(ii) Generic 2D Finite Element Interface

(iii) Generic 2D Finite Difference Interface

In the SMS manual these models have been described to be able to compute a variety of information applicable to surface water modelling. The principle application is hydrodynamic modelling. This involves the calculation of water surface elevations and flow velocities for shallow water flow problems. It supports both a steady-state and dynamic model. Additional applications include the modelling of contaminant migration, salinity intrusion, sediment transport (scour and deposition), wave energy dispersion, wave properties (directions, magnitudes and amplitudes) and many others.

3.3.1 Steady-State Spectral Wave Model (STWAVE Model)

Important work components in most coastal projects are to predict bathymetric and shoreline change, to design or repair coastal structures, to assess navigation conditions and to estimate the nearshore wave growth and transformation. Nearshore wave propagation is influenced by many parameters such as complex bathymetry, tide, wind and wave generated currents, tide and surge induced water level variation and coastal structures.

The purpose of applying nearshore wave transformation models is to describe the change in wave parameters for example wave height, period, direction and spectral shape between the offshore and the nearshore. In relatively deep water, the wave field is fairly homogeneous on a scale of kilometres; but in the nearshore, where waves are strongly influenced by variations in bathymetry, water level and current, wave parameters may vary significantly on the scale of tens of meters. Offshore wave information is typically available from a wave gauge, or a global scale or regional scale wave hindcast or forecast (Smith et al 2001).

STWAVE simulates depth-induced wave refraction and shoaling, current induced refraction and shoaling, depth- and steepness-induced wave breaking, diffraction, wind-wave growth, and wave-wave interaction and whitecapping that redistribute and dissipate energy in a growing wave field (Smith et al 2001).

3.3.2 Model Assumptions and Limitations

Like other computer models, STWAVE has been developed based on a few assumptions. The assumptions made in STWAVE by Smith et al (2001) are as follows:

(a) Mild bottom slope and negligible wave reflection.

Wave energy in the STWAVE model can only propagate from offshore towards the nearshore. Therefore waves which are reflected from the shoreline or from steep bottom features and travel in directions outside this half plane (from shoreline to the sea) are neglected. Moreover forwardscattered waves, for example waves reflected off a structure but travelling in the +x-direction are also neglected.

(b) Spatially homogeneous offshore wave conditions.

The input spectrum in STWAVE is constant along the offshore boundary because the variation in the wave spectrum along the offshore boundary with a large domain is expected to be small.

(c) Steady-state waves, currents and winds.

In order to reduce the computation time, STWAVE is formulated as a steady-state model.

(d) Linear refraction and shoaling.

Only linear wave refraction and shoaling are included is STWAVE, thus the accuracy of the model is reduced.

(e) Depth-uniform current.

The wave-current interaction is based on a current that is constant through the water column.

(f) Bottom friction is neglected.

Bottom friction is neglected in STWAVE because determining the proper friction coefficient is difficult and the cumulative bottom friction dissipation in nearshore is small.

(g) Linear radiation stress.

Radiation stress in STWAVE is calculated based on linear wave theory.

3.3.3 Governing Equations of STWAVE

Some of the governing equations which are used in STWAVE can be listed as follows:

The wave dispersion relationship is given in the moving reference frame as:

$$\omega_r^2 = gk \tanh kd \tag{3.1}$$

where

ω_r	=	Angular frequency (hz)
g	=	Gravitational acceleration (m/s²)
k	=	Wave number
d	=	Water depth (m)

In the absolute frame of reference, the dispersion equation is:

$$\omega_a = \omega_r + kU \cos(\delta - \alpha) \tag{3.2}$$

where:

U	=	Current speed (m/s)
δ	=	Direction of the current relative to a reference frame or the x-axis (deg)
α	=	Wave orthogonal direction or normal to the wave crest (deg)

Refraction and shoaling are calculated from the conservation of wave action along a ray by using the following equation:

$$\left(C_{ga}\right)_i \frac{\partial}{\partial x_i} \frac{C_a\, C_{ga} \cos(\mu-\alpha) E(\omega_a,\alpha)}{\omega_r} = \sum \frac{S}{\omega_r} \tag{3.3}$$

where

E	=	Wave energy density divided by (ρ_w g), where ρ_w is density of water
S	=	Energy source and sink terms
C_{ga}	=	Group celerity (m/s)
μ	=	Wave ray direction (deg)
ω_r	=	Dispersion in moving reference
ω_a	=	Dispersion in absolute frame of reference
α	=	Wave orthogonal direction (deg)
C_a	=	Wave celerity in absolute reference (m/s)

Diffraction is included in STWAVE in a simple manner through smoothing of wave energy. The model smoothes energy in a given frequency and direction band using the following form:

$$E_J(\omega_a, \alpha) = 0.55 E_J(\omega_a, \alpha) + 0.225\left[E_{J+1}(\omega_a, \alpha) + E_{J+1}(\omega_a, \alpha)\right] \tag{3.4}$$

where:

E	=	Energy density in a given frequency and direction band
J	=	Indicates the grid row index (alongshore position)

Wave breaking is applied in STWAVE Version 3 by using the following equation as a maximum limit on the zero moment wave height.

$$H_{mo\,max} = 0.1\, L \tanh kd \tag{3.5}$$

where:

L	=	Wave length (m)
k	=	Wave number
d	=	Water depth (m)

3.3.4 Numerical Discretization

As mentioned in the STWAVE User Manual by Smith et al (2001), STWAVE is a finite-difference numerical model, formulated on a Cartesian grid. Grid cells are square ($\Delta x = \Delta y$). Variable grid resolution can be obtained by nesting model runs. This is accomplished by running the model at a coarse resolution and saving a spectrum at a near shore point. This near shore spectrum can then be used as a boundary condition for another grid of finer resolution. STWAVE operates in a local coordinate system, with the x-axis oriented in the cross-shore direction with the origin offshore and the y-axis oriented alongshore, forming a right-handed coordinate system as shown in Figure 3.5

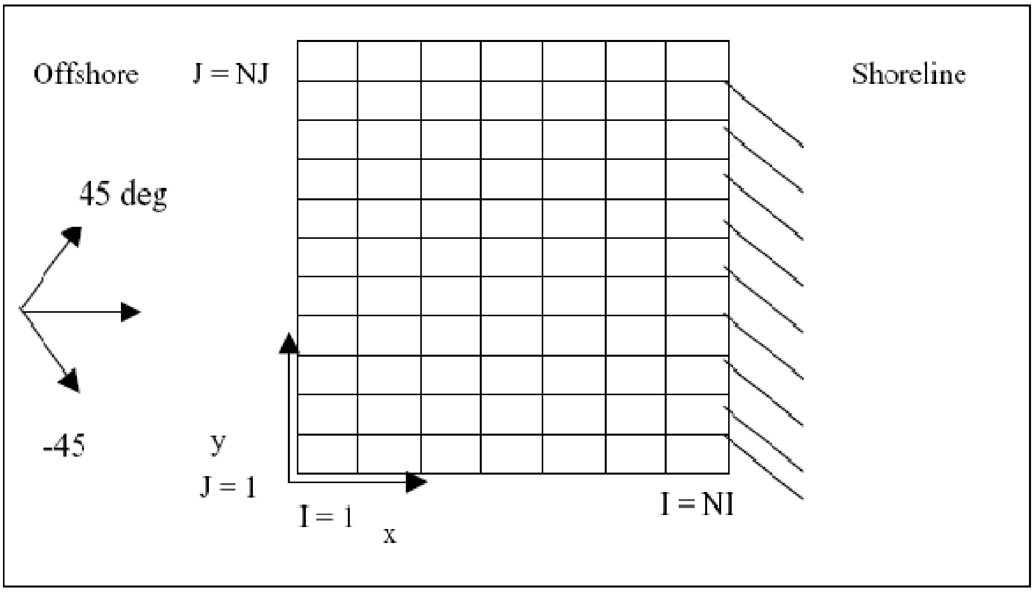


Figure 3.5 Schematic Grid of STWAVE (Source: Smith et al 2001)

3.3.5 Model Input and Output Files

STWAVE has four input files which specify model parameters, bathymetry, incident wave spectra and current field. The first three files are compulsory for the model to run but the current field file is required only if the wave current interaction is specified. A description of procedures to generate and use these files are given in Chapter 4. STWAVE uses the four mentioned input files to generate five output files which contain wave spectra at the selected output point; wave height, direction and period at the selected output points; fields of wave height, period and direction over the entire STWAVE model domain and fields of radiation stress gradient over the entire domain. Figure 3.6 is illustrates the input/output files of the model.

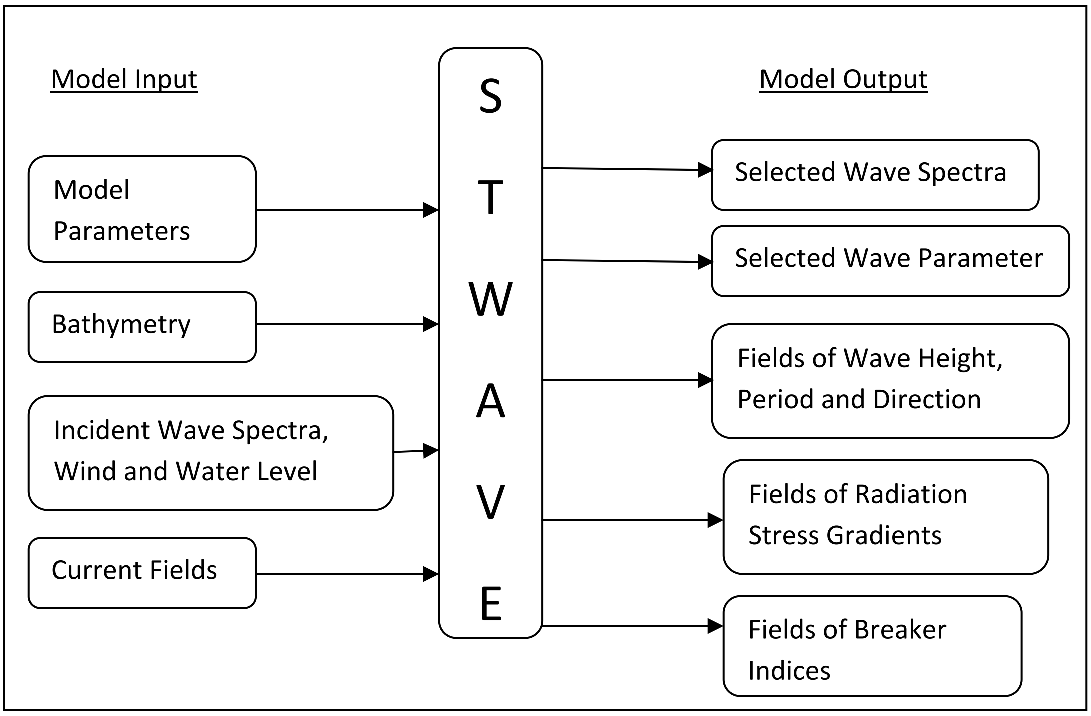


Figure 3.6 Schematic Input/Output Files of STWAVE (Source: Smith et al 2001)

Brief descriptions of some of the input files are as follows:

3.3.5.1 Model Parameter File

Model parameter file specifies option for running STWAVE and special output points. These options include the following information:

a) Whether the model should consider propagation only or both propagation and source terms.

b) Wave current interaction should be included or not.

c) Wave breaking should be written in a separate file or not.

d) If the calculation of radiation stress gradient is needed then it should be specified in the model parameter file.

e) The number of special output points should also be specified in this file therefore the two dimensional wave spectra will be saved only for these points.

3.3.5.2 Bathymetry File

The bathymetry files define the grid size, spacing and grid bathymetry for the model. Therefore three values should be specified in this file. The number of cross shore grid cells or columns which together with the grid spacing, determines the cross shore extent of the modelling domain and the location of the offshore grid boundary. The number of along shore grid cells or rows should be specified. This value, together with grid spacing will determine the alongshore extent of the modelling domain and location of the lateral grid boundary. The third parameter is the grid spacing which is the same in both X and Y directions. After that the water depth for each cell should be specified in this file.

3.3.5.3 Incident Wave Spectra File

Incident wave spectra for STWAVE are specified as energy density which is a function of frequency and direction. The number of frequency bins in the spectra and the number of direction bins are the two first parameters in this file. Typically 20-30 bins are used for the number of frequency bins in the wave spectra. The value of direction bins should be set to 35 in order to give 5-degree resolution in direction (Smith et al 2001).

The other parameters which should be specified in this file include:

(a) Spectrum identifier

(b) Wind speed

(c) Wind direction

(d) Peak spectra frequency

(e) Water elevation

CHAPTER 4

DATA COLLECTION AND STWAVE MODEL SETUP

4.1 Introduction

In order to conduct an analysis of the physical phenomena of any coastal engineering problem sufficient data and information are needed. Therefore prior to the start of using the STWAVE model of SMS some initial data should be gathered. These data will form the input files. In this chapter the source of the required data obtained for this research and the procedure of generating the input files in SMS will be presented.

4.2 Data Collection

In order to achieve a reasonable output from a computer model it is important to collect the necessary data for the modelling works. The required data for this research are bathymetric data, tsunami wave height data and tsunami wave direction for the study area. The study area which is located to the North East of Penang Island affected by the 2004 tsunami is bounded between longitudes 100˚16′ E and 100˚18′ E and latitudes 5˚27′40″ N and 5˚30′ N. Details of the compiled data are given in the following subsections.

4.2.1 Bathymetric Data

Bathymetry is the measurement of water depths at various places in a body of water. At present the Hydrographic Directorate of the Royal Malaysian Navy is responsible for the production, updating and publication of hydrographic charts of the Malaysian waters. As presented in Section 3.3.5, the bathymetry data forms one of the inputs required to run STWAVE. The data for this research work has been obtained from Admiralty Chart No.1366, Approaches to Penang Harbour with a scale of 1:60000 published by Hydrographer of the Navy, United Kingdom (2002). It was digitised for use in STWAVE using the SURFER Version 8.0 program. Figure 4.1 illustrates the bathymetry map of the study area. A rectangular grid is established based on this map which cover coordinates (5˚25′ N, 100˚15′ E) to (5˚32′ N, 100˚15′ E) and (5˚32′ N, 100˚20′ E) to (5˚25′ N, 100˚20′ E).

Figure 4.1 Bathymetry Map of Study Area (Source: Admiralty Chart No.1366)

4.2.2 Tsunami Wave Data

In order to generate the spectral input file for STWAVE model the tsunami wave height and tsunami wave direction are required. For this research the wave height data is obtained from a tsunami field survey which was conducted on July 2005 by Yalciner et al (2005). The offshore wave height and the wave direction have been obtained from the output of TUNAMI-N2 program as illustrated in Figures 4.2 and 4.3. This output data has been made available with courtesy from the Coastal and Offshore Engineering Institute of Universiti Teknologi Malaysia International Campus. Nearshore Tsunami wave amplitude is obtained from the 2005 tsunami field surveying data.

Tohoku University's Numerical Analysis Model for Investigation of Near-field Tsunamis No.2 (TUNAMI N2) is a tsunami numerical simulation program incorporating the linear theory in deep sea and the shallow water theory in shallow sea and on land. The program uses a constant grid in the whole region and is capable of calculating runup, tsunami arrival time and tsunami wave height (Imamura et al 2006).

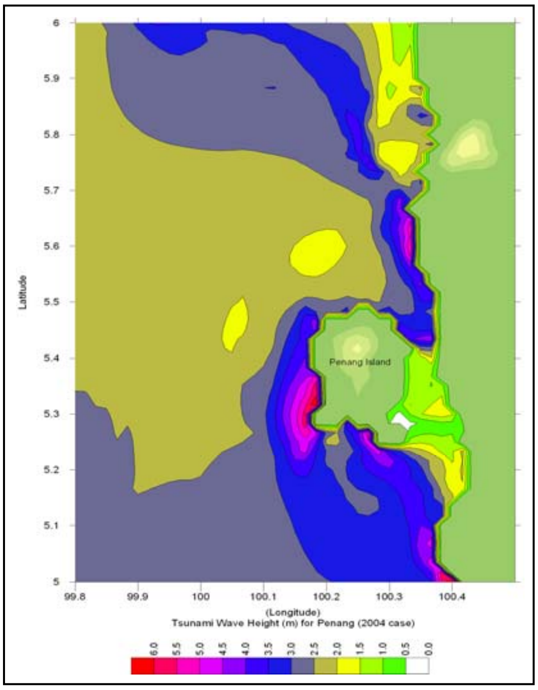


Figure 4.2 Offshore Tsunami Wave Height Generated Using TUNAMI N2 (Source: COEI, UTM)

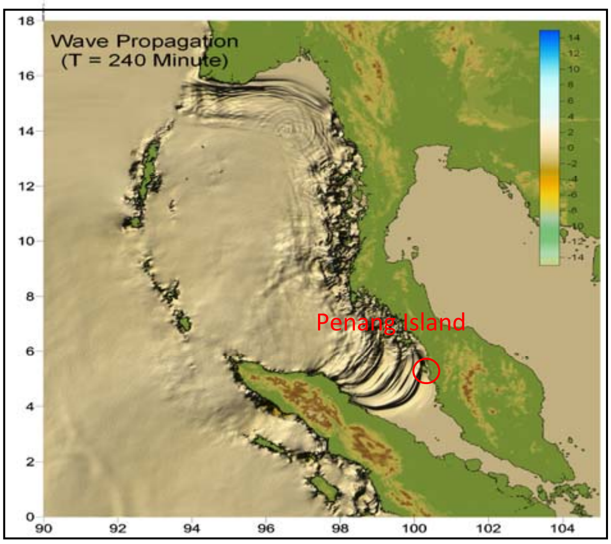


Figure 4.3 Tsunami Wave Direction Generated Using TUNAMI N2 (Source: COEI, UTM)

4.3 Generating Input Files

In order to generate the input files two programs have been applied as described in following subsections.

4.3.1 Application of Surfer Version 8.0

Surfer is a grid based graphics program used for Mapping XYZ data into grids. These grids can be used to create many map types including Contour Maps, Vector Maps, Wire Frame Maps and Surface Maps. Surfer has been used to digitize the bathymetry map of the study area and to create a detail ASCII XYZ file. This file was subsequently read by SMS and used to generate the input bathymetry file for the STWAVE. A general window of Surfer is shown in Figure 4.4, the Contour Map, 3D Surface and Wire Frame Map of the study area are illustrated in Figures 4.5 to 4.7.

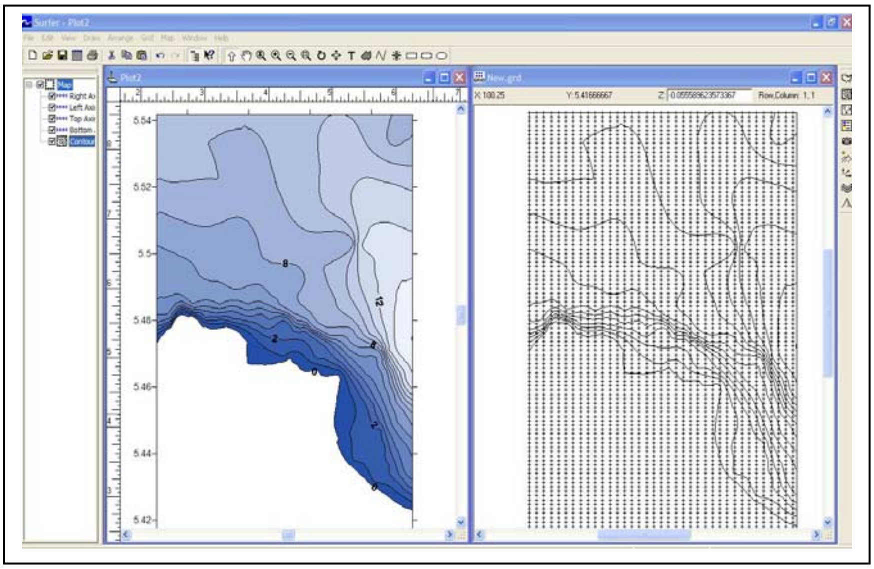


Figure 4.4 Application of SURFER to Generate an ASCII XYZ File of the Study Area

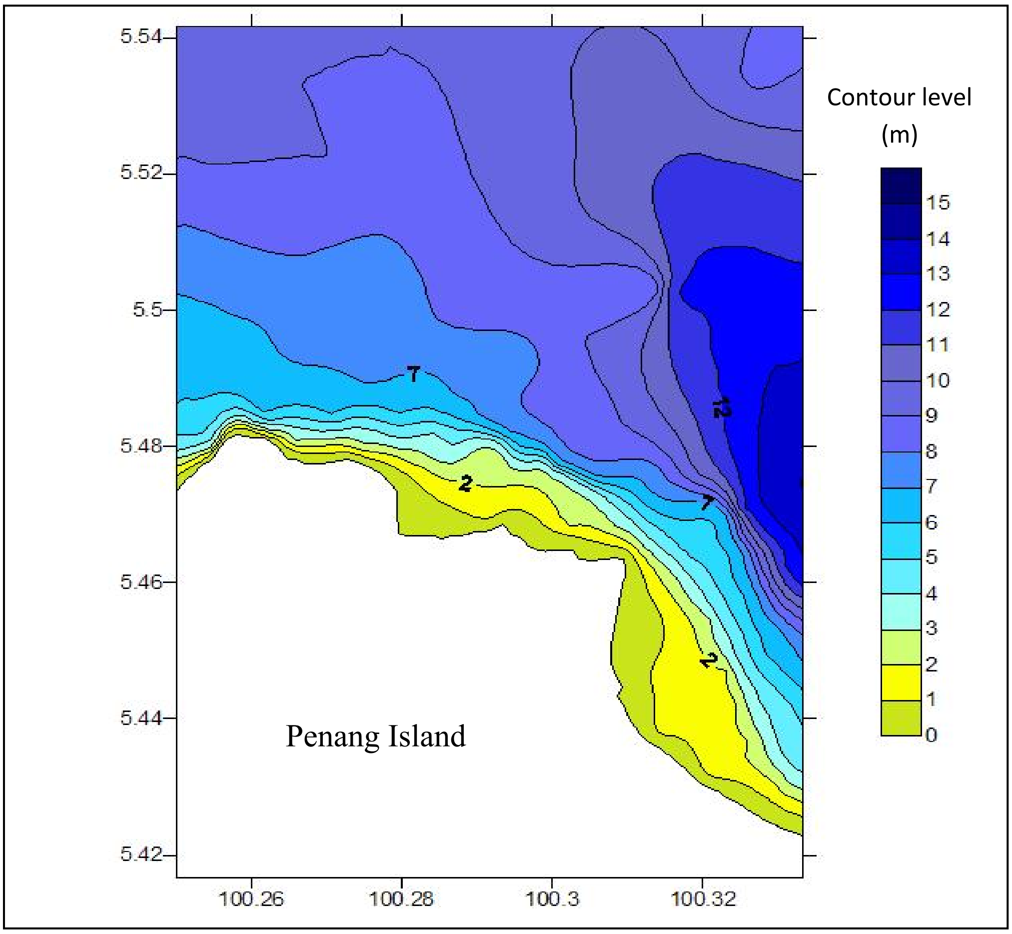


Figure 4.5 Contour Map of the Study Area as Generated by SURFER Version 8.0

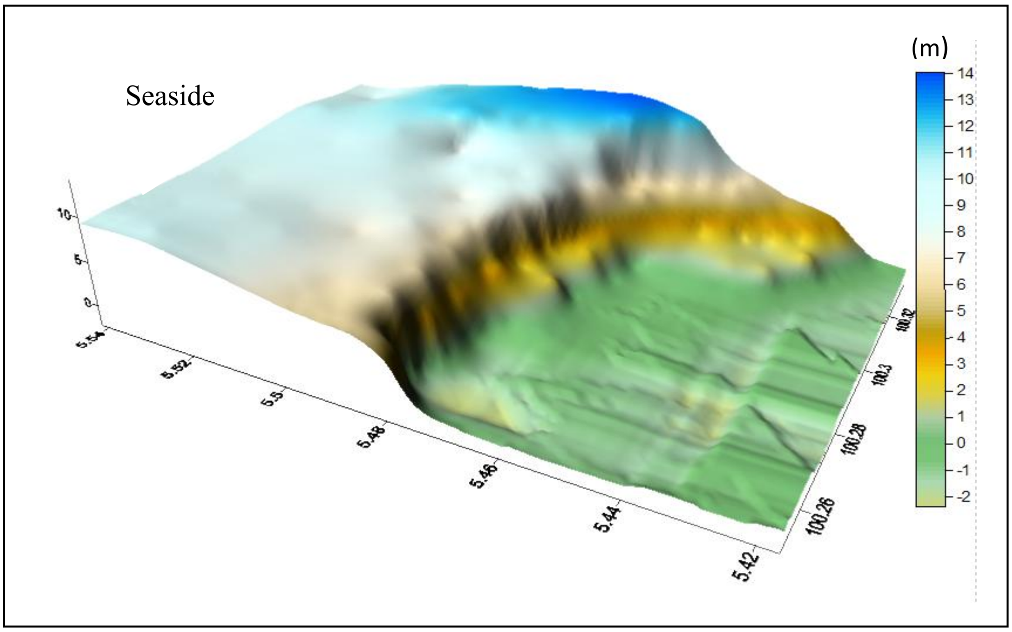


Figure 4.6 3D Seabed Surface within Study Area as Generated by SURFER Version 8.0

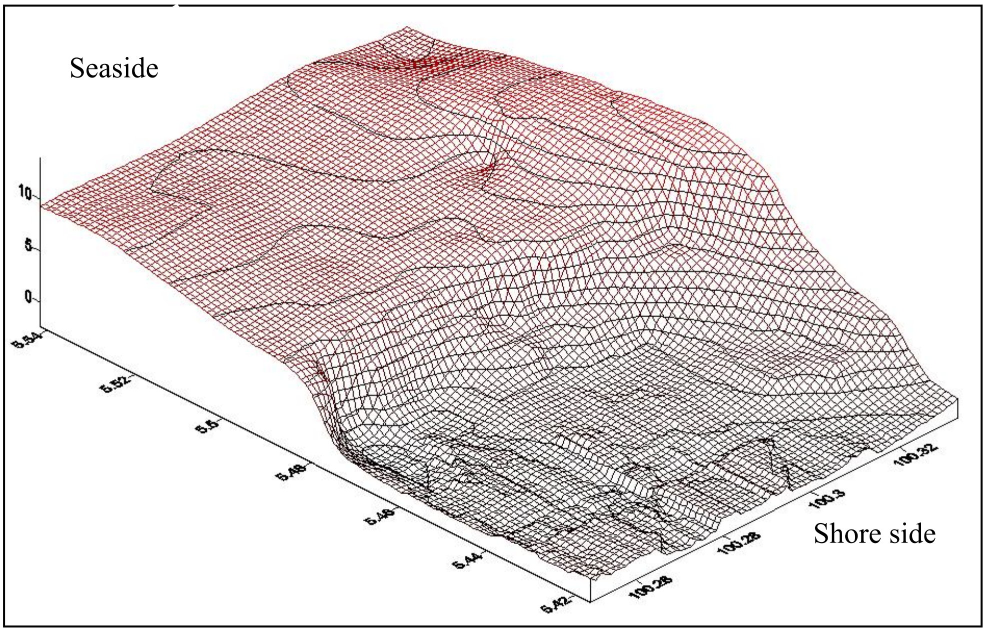


Figure 4.7 Wire Frame Map of the Study Area as Generated by SURFER Version 8.0

4.3.2 Application of the Surface Water Modeling System (SMS) Version 8.1

In order to generate the input files the following procedures were undertaken in SMS:

(a) The ASCII XYZ file in SMS was opened and the file type to XYZ files set. The file import wizard procedure should be followed to open the file as a scatter set of data as shown in Figure 4.8. This data set was used by SMS to generate the input file.

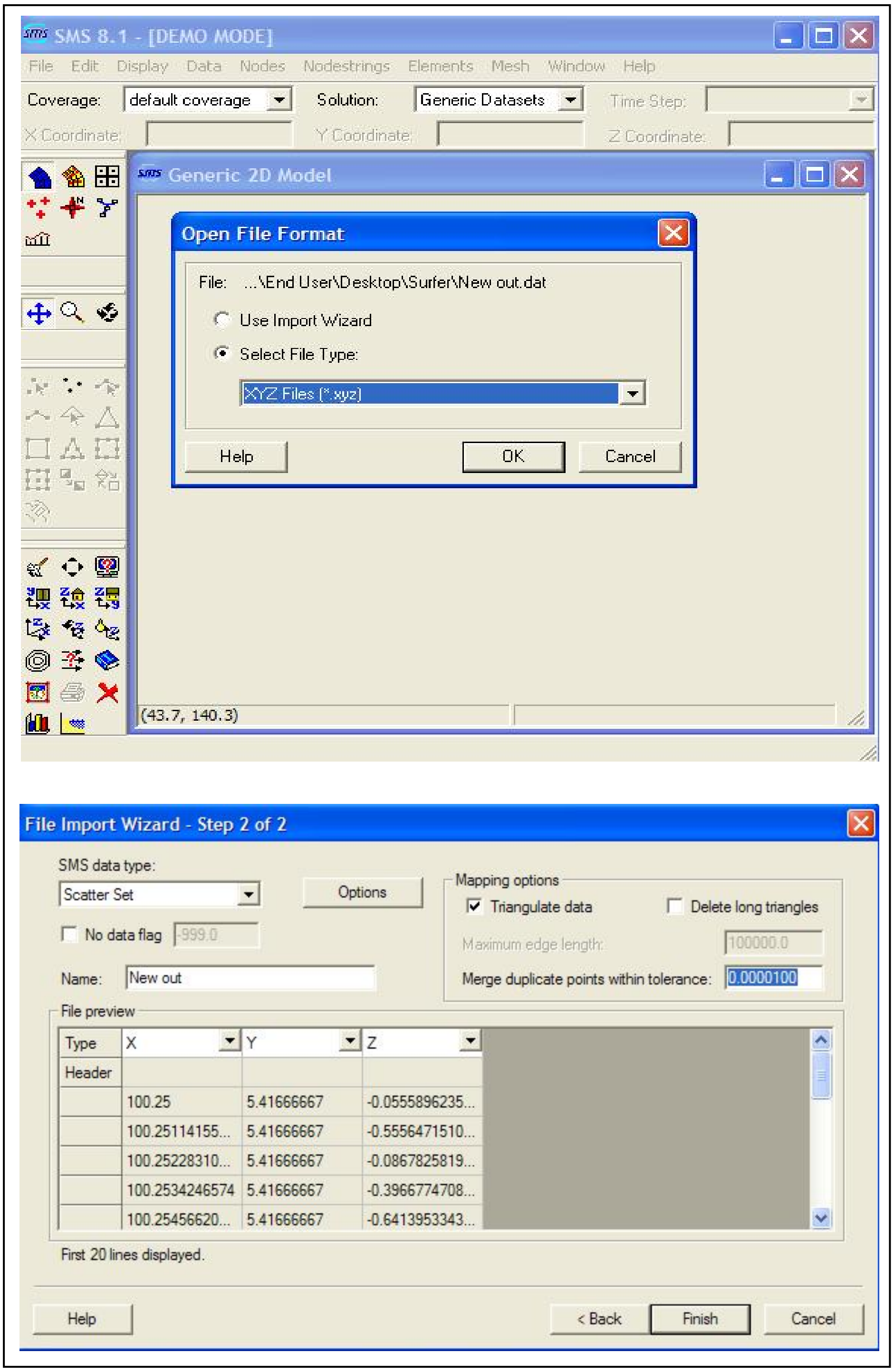


Figure 4.8 Window for Opening the ASCII XYZ file in SMS

(b) The study area bathymetry map was opened and registered by inputting the coordinates of three known points as illustrated in Figure 4.9. The bathymetry file and the scatter data was then visible in the graphical screen.

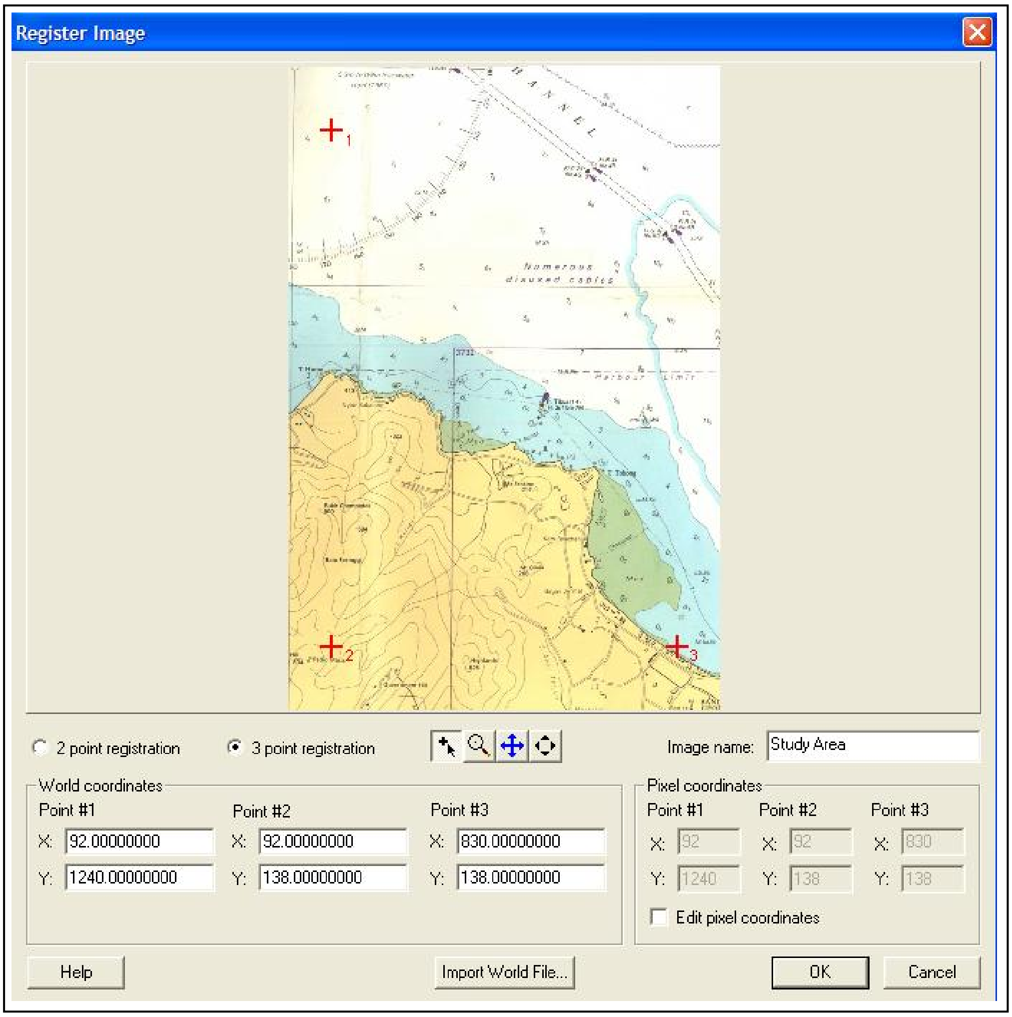


Figure 4.9 Window for Registering the Bathymetry Map of the Study Area

(c) From the module box, the current module was changed to Map Module  then from the Feature Objective menu the Coverage option was chosen and the coverage type was set to STWAVE. Refer to Figure 4.10.

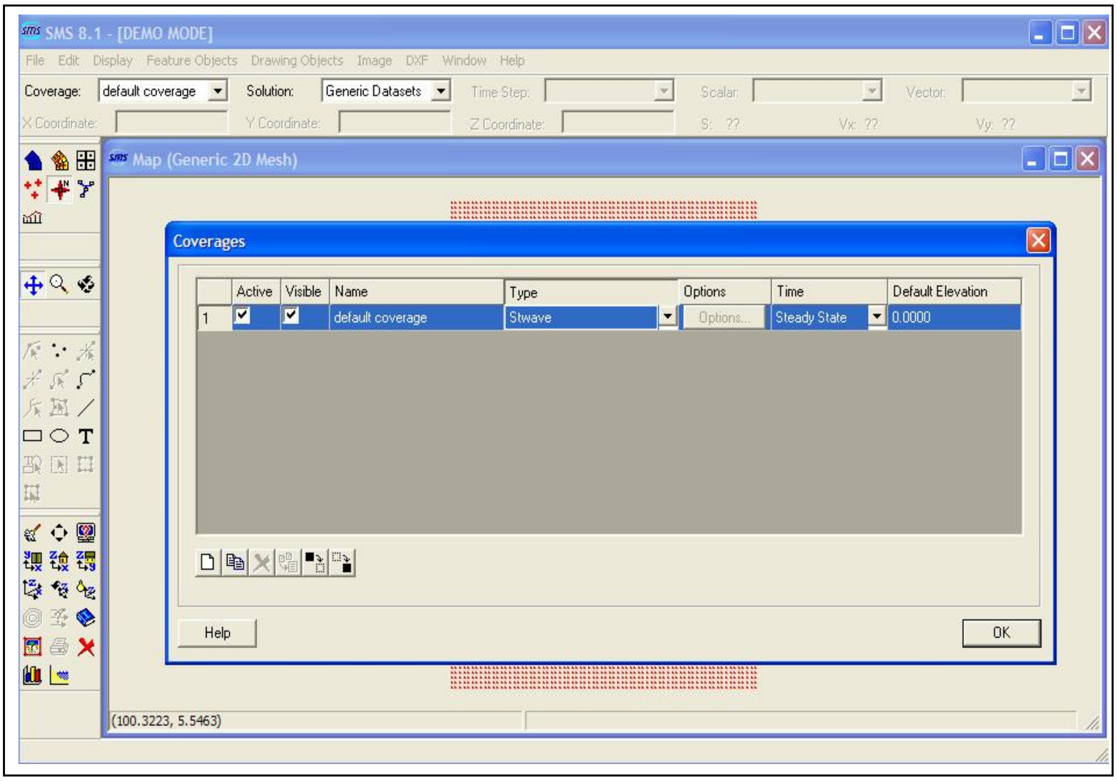


Figure 4.10 Window to Set the Coverage Type to STWAVE

(d) From the toolbox at the right side of the screen the Create 2-D Grid Frame tool was chosen and three corners of the grid were clicked to create the grid frame.

(e) The grid frame was selected by using the select tool and the grid frame resized. The grid was rotated and the origin at 270 degree set. As a result the i-axis of the frame was turned towards the shore line.

(f) The Create Arc tool was selected from toolbox and an arc was created on the shore line. Then from the Feature Objects menu the Build Polygons option was selected. Therefore a polygon was created around the land part of the map as shown in Figure 4.11.

(g) From the Feature Objects menu the Map to 2-D Grid menu was selected. Grid geometry, cell option and Depth Option have been specified in the mentioned menu. For this research work the value of grid spacing was set to 0.0005 therefore a 30 meter grid was generated. Refer to Figures 4.12 and 4.13.

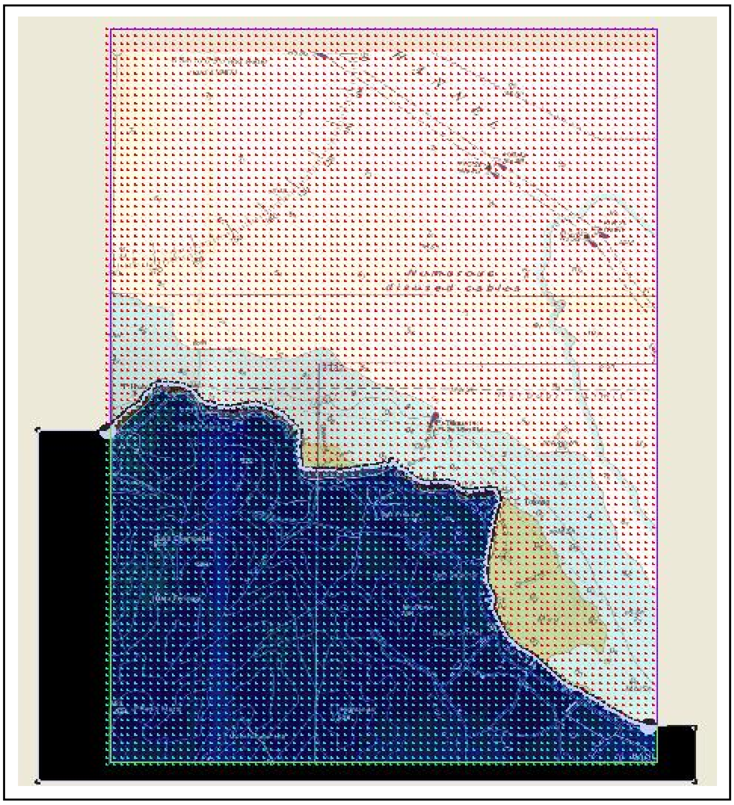


Figure 4.11 Creating a Polygon around the Land

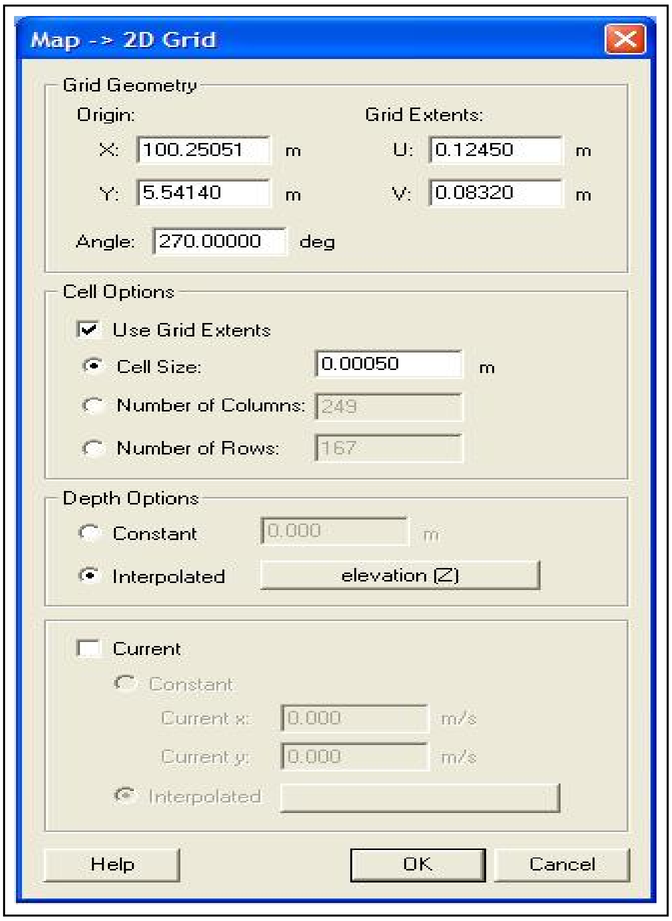


Figure 4.12 Map to 2-D Grid Window

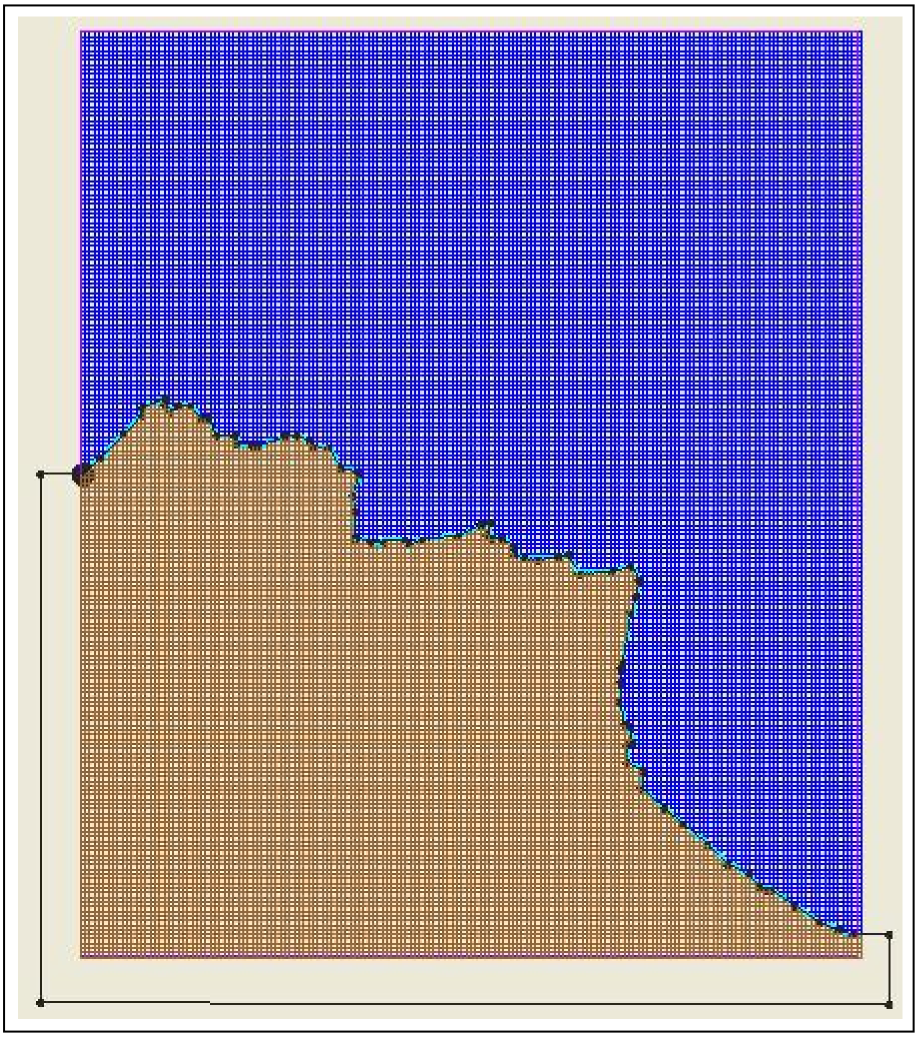
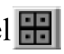


Figure 4.13 Generated 2-D Grid for the Study Area

The next step was to generate the spectral energy file and the model parameter file.

(h) In order to generate the spectral energy file, the Cartesian Grid Model  from the module box was selected and selected from the STWAVE menu. Generate Grid bottom from Spectral Energy option was clicked and a new grid generated. Then Generate Spectra bottom was clicked and the wave height, wave period, wave direction and the depth of water where the wave was measured were inputted. Therefore the Spectral Energy file was created for STWAVE.

(i) From the STWAVE option the Model Control option was selected (see Figure 4.14) and the necessary changes made.

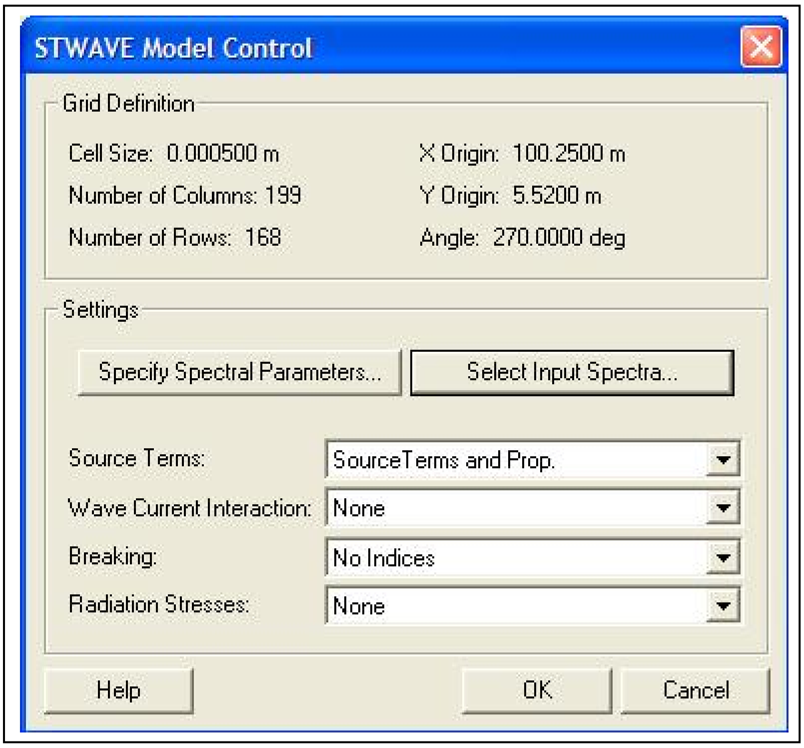
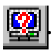


Figure 4.14 STWAVE Model Control Windows

Finally, the file was saved and the STWAVE executed. After execution the output file was generated. The output files were visualized from the Display Option tool .

4.4 STWAVE Model Calibration

Calibration is the process whereby the model is adjusted to reproduce the behaviour of the prototype for a given set of conditions. Normally an extensive set of field data is collected as input and these are reproduced and represented in the model.

For this research the model has been calibrated against the field data which was obtained from the tsunami field surveying conducted on July 9-10, 2005 by Yalciner et al (2005). Field data at three points in the study area was available for use to calibrate the model. This is shown in Figure 4.15. The results of the calibration showed good agreement where the percentage differences between computed and observed wave heights at three points were found to be less than 15%. This is also illustrated in Table 4.1 and Figure 4.16.

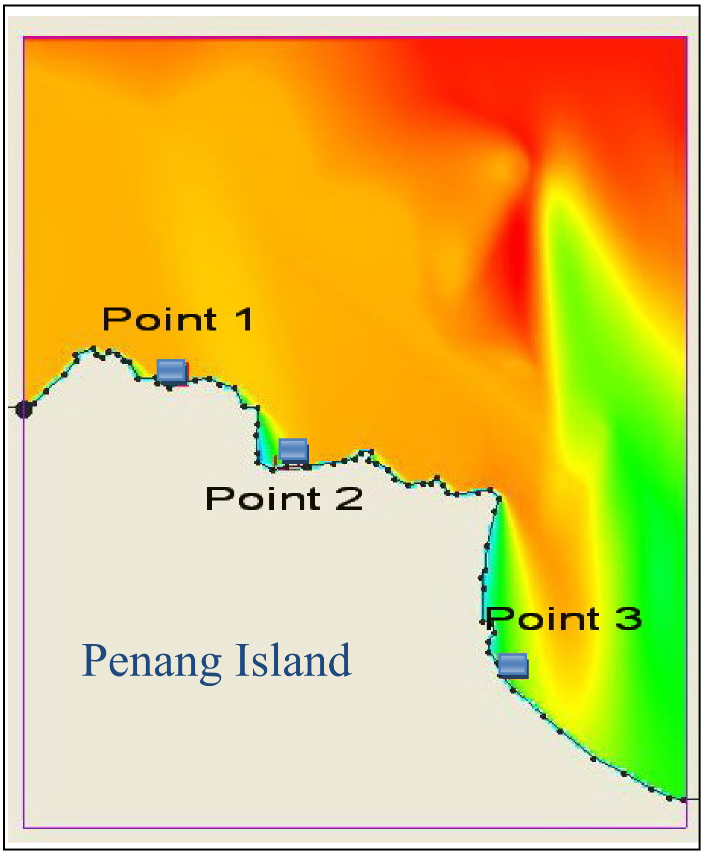


Figure 4.15 Points Used in the Calibration Works

Table 4.1 Results Obtained Upon Calibration of the Model

Point Number	Wave Height from Field Survey (m) (Yalciner et al 2005)	Computed Wave Height from STWAVE (m)	Difference between Computed and Observed Wave Height (m)	% Difference in Wave Heights (m)
1	6	5.11	-0.89	15%
2	5	4.79	-0.21	4%
3	5	4.27	-0.73	15%

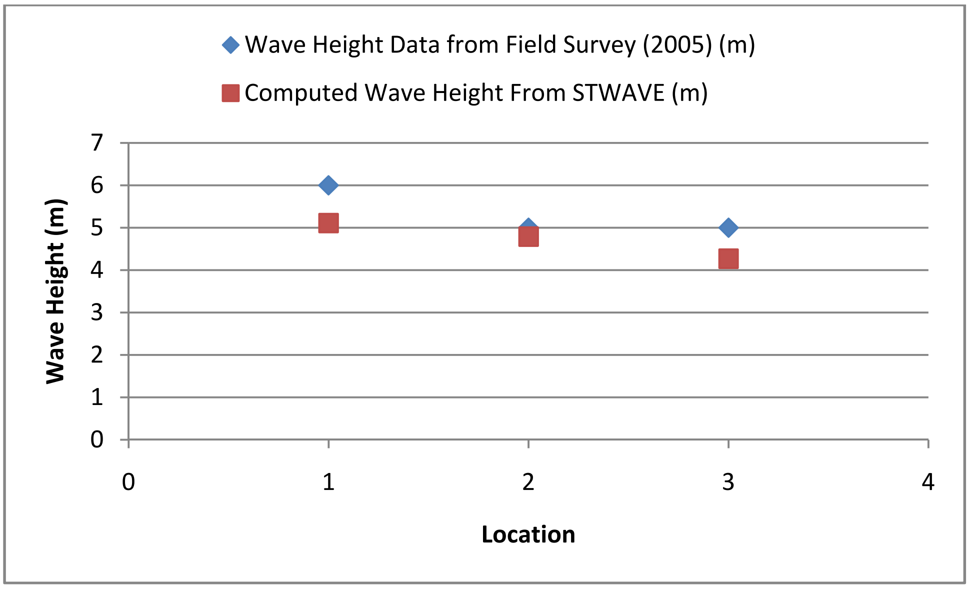


Figure 4.16 Plot Showing Observed and Computed Wave Heights at the Location Points

CHAPTER 5

DISCUSSION AND ANALYSIS OF THE COMPUTATIONAL RESULTS

5.1 Introduction

As presented earlier in Section 3.3.5, STWAVE is capable of producing five output files which contained wave spectra at the selected output point; wave height, direction and period at the selected output points; fields of wave height, period and direction over the entire STWAVE model domain and fields of radiation stress gradient over the entire domain.

Amongst these outputs the generated wave height distribution plot is more significant for use in this research work. The main objective of the present research is to design an optimised offshore breakwater layout and to determine the wave height distribution at the lee side of breakwater impacting on the shoreline. Therefore the procedure employed to determine the optimal layout of the proposed breakwater which could function to attenuate tsunami wave energy along the North East coastline of Penang Island is discussed in this chapter.

5.2 Proposed Breakwater Layout and Optimization

Once the calibration of the model has been completed, several layouts of breakwaters to be located around the study area were proposed for the modelling exercises. Thirty nine different breakwater layouts were tested as shown in Table 5.1 where wave height distribution patterns around them were simulated in the model domain. The wave height obtained at ten points along the shoreline were compared to that of the existing condition that is, without the breakwater condition as shown in Figure 5.1.

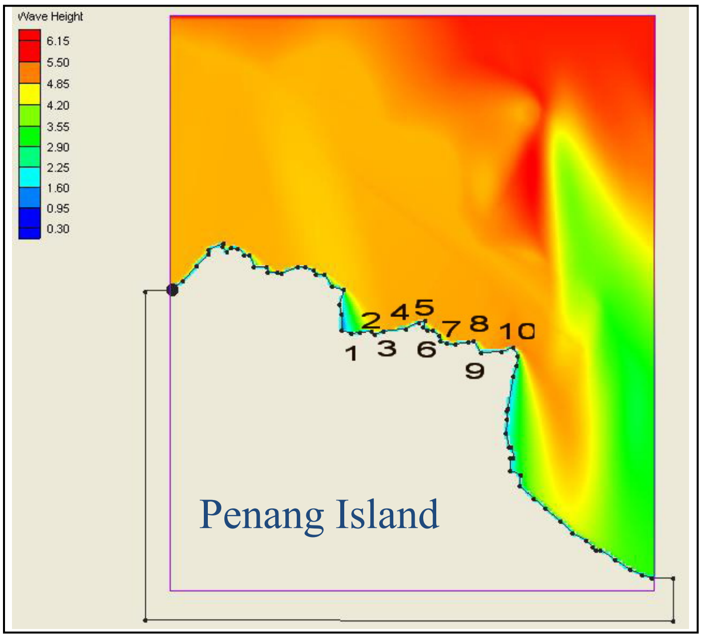


Figure 5.1 Typical Outputs of Wave Heights Generated By STWAVE for the Existing Condition Without Any Structure

Table 5.1 Details of Various Layouts Generated to Test for Efficiency as Modelled in STWAVE

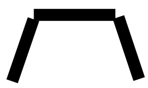
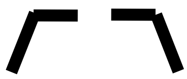
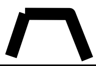
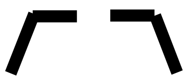
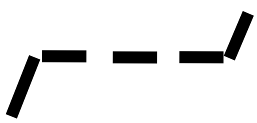
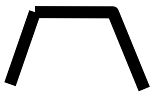
Layout Number	Plan View of Layout	Freeboard on Crest (m)	Breakwater Width (m)	Distance from Shoreline (m)	Breakwater Gap (m)
1		0	30	1000	0
2		1	30	1000	0
3		2	30	1000	0
4		3	30	1000	0
5		4	60	1000	0
6		4	60	1000	0
7		3	60	1000	0
8		2	60	1000	0
9		1	60	1000	0
10		0	60	1000	0
11		0	60	1000	0
12		0	60	1000	0
13		1	60	1000	0
14		2	60	1000	0
15		3	60	1000	0
16		4	60	1000	0
17		4	60	1000	210
18		3	60	1000	210
19		2	60	1000	210
20		1	60	1000	210
21		0	60	1000	210
22		0	30	1000	180
23		0	30	1000	180
24		0	30	1000	180
25		0	30	1000	120
26		0	30	1000	0
27		0	30	1000	120
28		0	30	1000	90
29		0	30	1000	90
30		0	30	1000	90
31		0	30	700	0

Table 5.1 Details of Various Layouts Generated to Test for Efficiency as Modelled in STWAVE (Cont.)

Layout	Plan View of Layout	Freeboard on Crest (m)	Breakwater Width (m)	Distance from Shoreline (m)	Breakwater Gap (m)
32		0	30	700	0
33		1	30	700	0
34		1	60	700	0
35		1	90	700	0
36		2	90	700	0
37		2	90	700	120
38		0	60-90	700-1000	300
39		0-2	30-90	700-1000	300

The first proposed layout was a single breakwater, located at a 1 kilometre distance from the shoreline with a total length of 1800 meter. The freeboard was assumed to be zero. The output from the modelling with this layout in place is illustrated in Figure 5.2. From the results obtained, this breakwater layout was found not to be appropriate since the tsunami wave height was still high at the shoreline and the wave was able to penetrate from both ends of breakwater. Wave heights generated at the shoreline were observed to range from 0.95 m to 3.45 m.

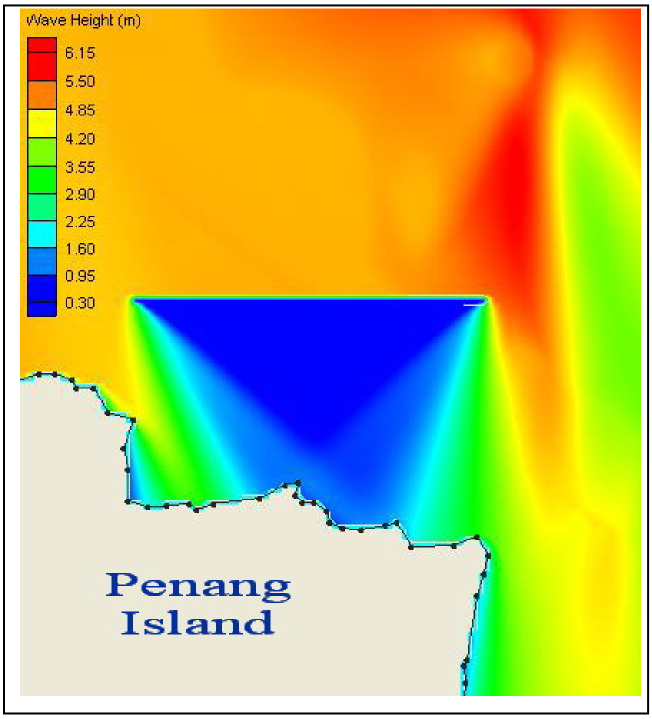


Figure 5.2 Distribution of Wave Height on the Shoreline Due to the Presence of Breakwater Layout 1

In order to reduce the penetration of tsunami wave from left and right of the proposed breakwater two diagonal arms were added to both sides of the breakwater as shown in Figure 5.3. This new layout was simulated in the STWAVE using different freeboards and width. It was also simulated at a different location which is closer to the shoreline. The overall results obtained from the whole modelling exercise showed that, 11 layouts produced efficiencies where the reduction in wave heights at the shoreline was greater than 70%. A summary to indicate the performance of the breakwater to attenuate the tsunami waves along the shoreline for the entire modelling exercise is illustrated in Table 5.2.

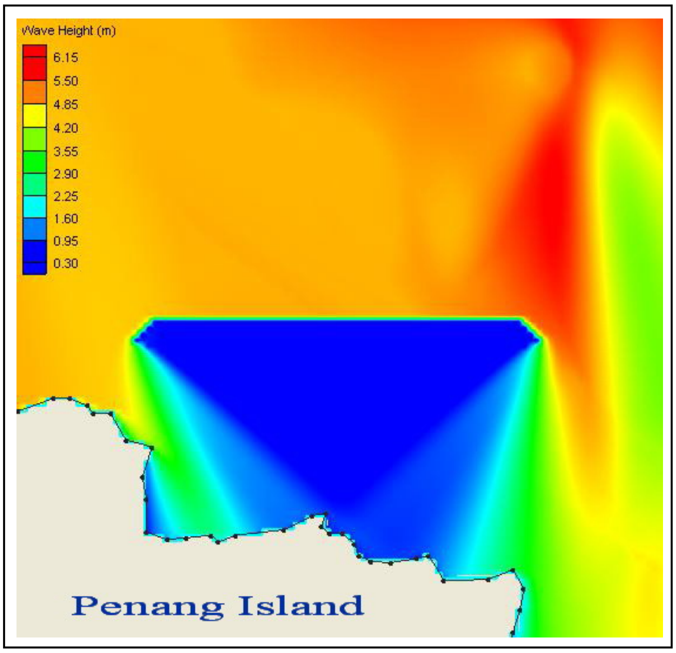


Figure 5.3 Distribution of Wave Height along the Shoreline Due to the Presence of Breakwater with Two Arms.

Detail results of wave height magnitude impacting the shoreline due to the presence of breakwater layouts are presented in Appendix A. The results are also summarized in Table 5.2 for breakwater layouts which reduced the tsunami wave by more than 70% are. Plots of wave height distribution patterns around the structures are illustrated in Figure 5.4 to 5.9.

Table 5.2 Performance of Proposed Breakwater Layouts to Attenuate the Tsunami Wave Height

Layout	Wave Height at Shoreline Without Barrier (m)	Average Wave Height at Shoreline with Barrier (m)	Average Difference in wave height(m)	Efficiency of Barrier (%)
1	4.962	2.056	2.906	59%
2	4.962	2.149	2.813	57%
3	4.962	2.327	2.635	53%
4	4.962	2.629	2.333	47%
5	4.962	3.027	1.935	39%
6	4.962	2.917	2.044	41%
7	4.962	2.486	2.476	50%
8	4.962	2.232	2.729	55%
9	4.962	2.050	2.912	59%
10	4.962	1.964	2.998	60%
11	4.962	1.446	3.516	71%
12	4.962	1.253	3.708	75%
13	4.962	1.772	3.190	64%
14	4.962	1.919	3.042	61%
15	4.962	2.261	2.701	54%
16	4.962	2.738	2.224	45%
17	4.962	3.099	1.863	38%
18	4.962	2.724	2.238	45%
19	4.962	2.497	2.465	50%
20	4.962	2.420	2.542	51%
21	4.962	2.111	2.851	57%
22	4.962	3.562	1.400	28%
23	4.962	2.737	2.225	45%
24	4.962	2.370	2.592	52%
25	4.962	2.336	2.626	53%
26	4.962	1.012	3.949	80%
27	4.962	1.659	3.302	67%
28	4.962	2.022	2.940	59%
29	4.962	1.715	3.247	65%
30	4.962	1.805	3.157	64%
31	4.962	1.092	3.869	78%
32	4.962	0.542	4.420	89%
33	4.962	1.508	3.454	70%
34	4.962	1.233	3.729	75%
35	4.962	0.633	4.329	87%
36	4.962	1.109	3.852	78%
37	4.962	1.290	3.671	74%
38	4.962	1.048	3.914	79%
39	4.962	1.073	3.889	83%

Note: Rows Highlighted Represent the Tsunami Barrier which Generated Greater than 70% Efficiency to Attenuate Waves on Its Lee

As shown in Table 5.1, layouts 32 and 35 performed at an efficiency of 89% and 87% respectively to reduce the tsunami wave height. This also has been illustrated in Figures 5.4 to 5.9. Breakwater layout 32 was located at 700 meter from the shoreline and the freeboard was assumed to be zero. Therefore it is visible during the low tide and cannot preserve the aesthetic value of the area. Moreover, since there is no gap proposed in this layout, it could affect the self circulation of water nearshore and has adverse affect on the environment of neighbouring areas. It may also create problems for any vessel movement in the area during normal conditions.

Layout number 35 was also located at the same position as layout number 32. The freeboard of this layout was assumed to be one meter but it could also cause problems for any vessel movement in the area during normal conditions. Besides that the large crest width (90 meter) of layout 35 may cause this proposal to become less cost effective.

Even though layouts 32 and 35 performed much better (at an efficiency of 89% and 87% respectively) than layout 39 which only performed at a lower efficiency of 83%, this layout has been selected to be the most optimal layout. This is because layout 39 has the advantages given below when compared to the other two layouts:

a) Segment A with a total length of 1236 m was placed 1 km from the shoreline in deep water in the model domain. Segment A is a partially submerged breakwater which is visible during low tide but it is located away from the shoreline to not affect the aesthetic value of the shoreline in the study area.

b) Segment B with a total length of 1234 m is nearer to the shoreline being at 700 meter from shoreline. Since the freeboard is 2 meter below MSL the breakwater is totally submerged at all times and is not visible at all during the low tide.

c) A 300 m gap between the two segments allows self circulation of water. During normal condition this gap may provide a safe passage for vessels manoeuvring around its lee.

Schematic diagrams of layout 39 are represented in Figures 5.10 to 5.12. Wave height distribution pattern around the breakwater as generated by STWAVE is illustrated in Figure 5.13.

Table 5.3 Details of the Tsunami Wave Heights at the Shoreline for Barriers which Performed at Greater than 70% Efficiency

	Without Structure	Layout 11	Layout 12	Layout 26	Layout 31	Layout 32	Layout 34	Layout 35	Layout 36	Layout 37	Layout 38	Layout 39
Location Point	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)
1	3.500	2.039	1.679	0.939	1.509	0.600	1.070	0.540	0.949	0.949	1.559	0.689
2	4.710	2.339	1.909	1.090	1.639	0.730	1.429	0.680	1.230	1.220	1.759	0.860
3	5.099	1.789	1.470	1.029	1.269	0.959	1.809	0.860	1.289	1.289	1.350	0.484
4	5.050	0.940	0.959	0.709	0.829	0.200	1.179	0.340	0.949	0.959	0.959	0.293
5	5.170	0.400	0.209	0.019	0.019	0.007	0.310	0.310	0.939	0.949	0.600	0.680
6	5.090	0.670	0.560	0.419	0.230	0.009	0.550	0.310	0.879	1.000	0.529	0.790
7	5.190	0.610	0.569	0.550	0.569	0.119	1.529	0.389	0.930	1.169	0.490	0.939
8	5.190	0.740	0.649	0.629	0.610	0.449	1.830	0.519	1.050	1.389	0.610	1.090
9	5.289	2.150	1.940	2.029	1.759	0.879	1.080	0.910	1.220	1.759	1.019	1.129
10	5.329	2.780	2.589	2.710	2.490	1.470	1.539	1.470	1.659	2.220	1.600	1.299

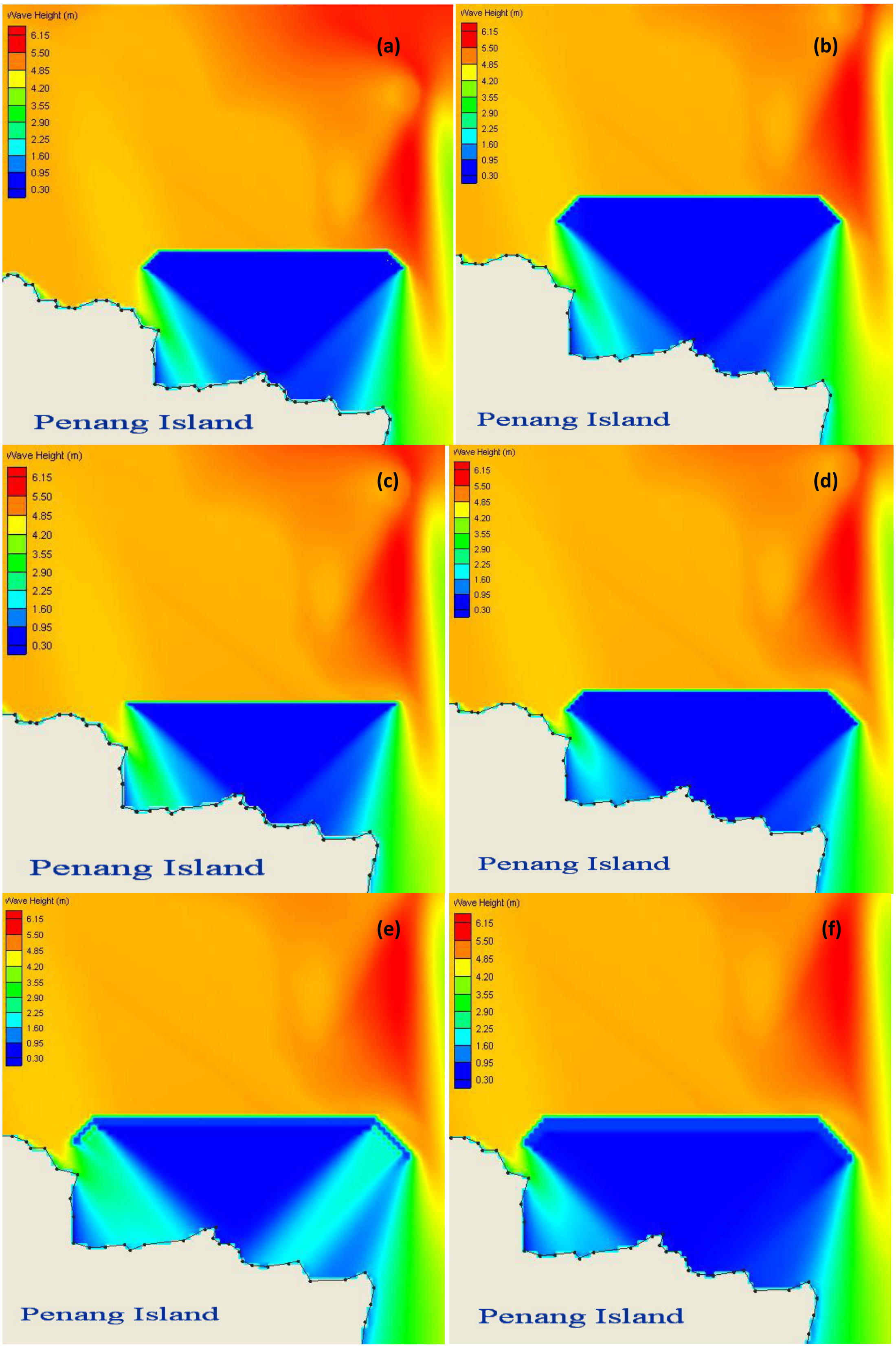


Figure 5.4 Distribution of Wave Height on the Shoreline Due to the Presence of a) Layout 12 (b) Layout 26 (c) Layout 31 (d) Layout 32 (e) Layout 34 (f) Layout 35

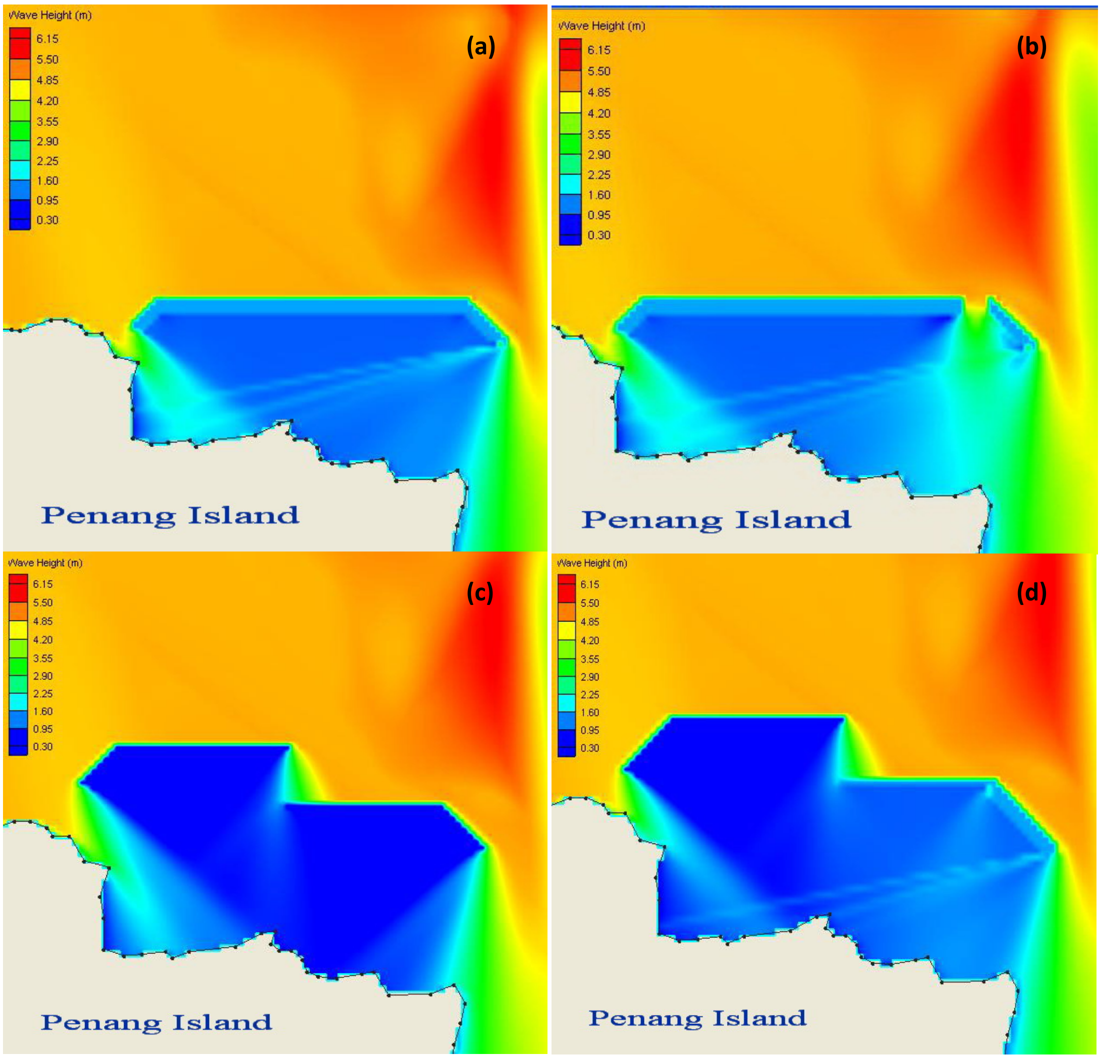


Figure 5.5 Distribution of Wave Height on the Shoreline Due to the Presence of (a) Layout 36 (b) Layout 37 (c) Layout 38 (d) Layout 39

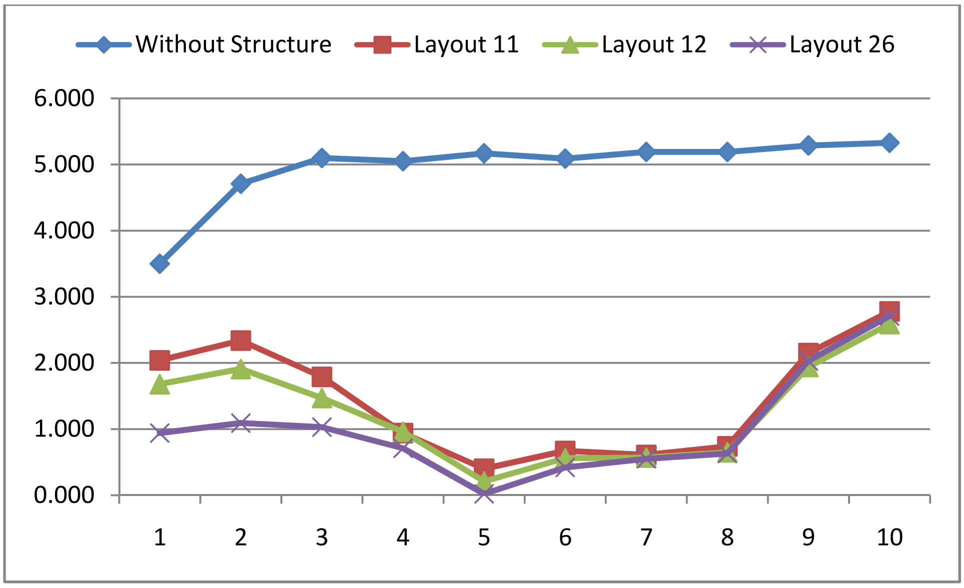


Figure 5.6 Attenuation of Tsunami Wave Height on the Shoreline for Without Structure and With Layouts 11, 12 and 26 Conditions.

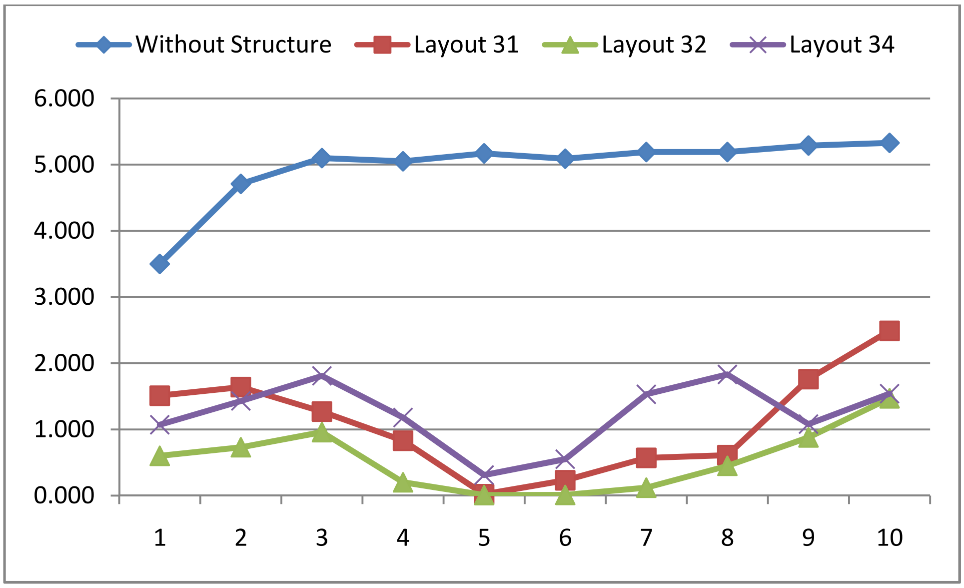


Figure 5.7 Attenuation of Tsunami Wave Height on the Shoreline for Without Structure and With Layouts 31, 32 and 34 Conditions.

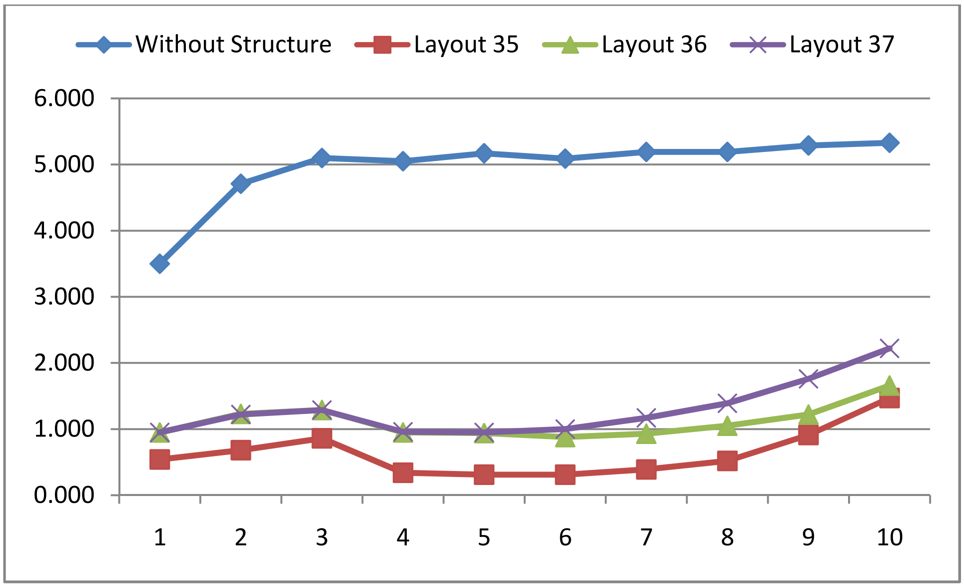


Figure 5.8 Attenuation of Tsunami Wave Height on the Shoreline for Without Structure and With Layouts 35, 36 and 37 Conditions.

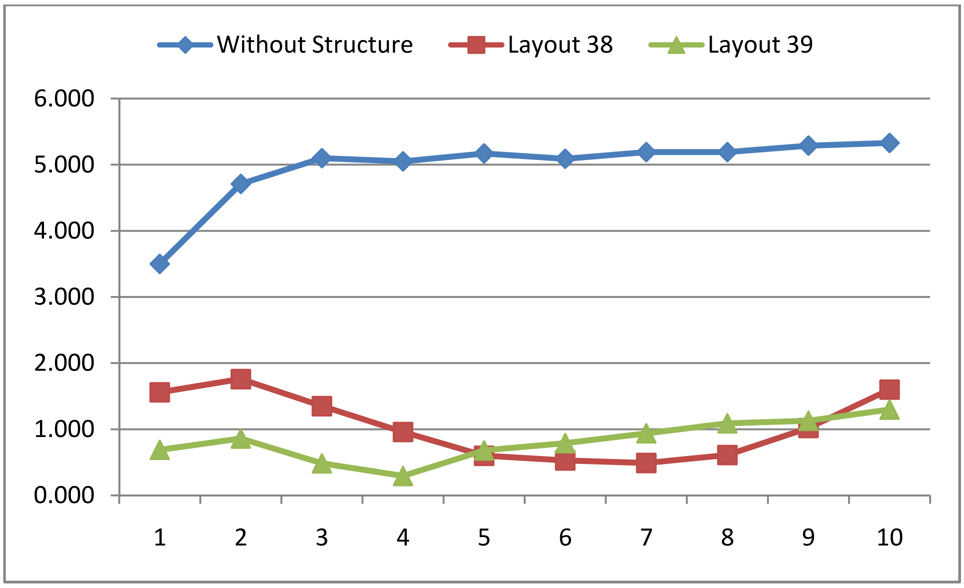


Figure 5.9 Attenuation of Tsunami Wave Height on the Shoreline for Without Structure and With Layouts 38 and 39 Conditions.

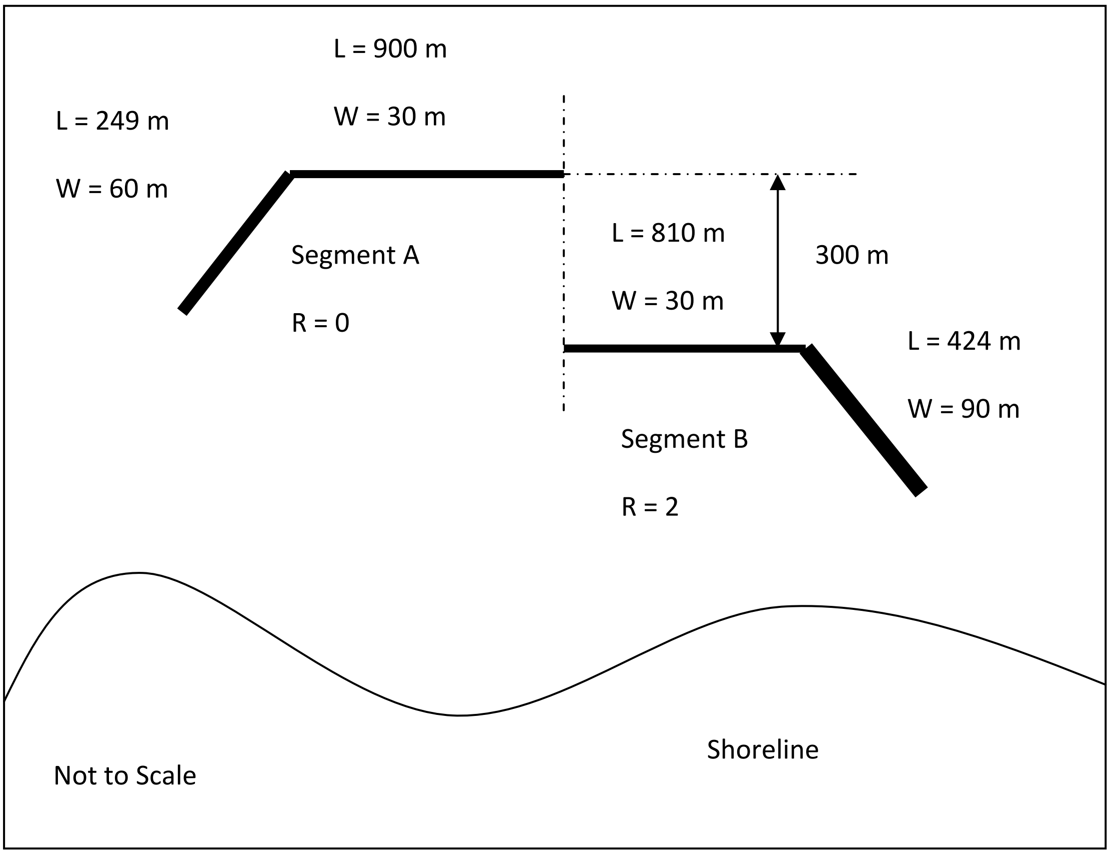


Figure 5.10 Plan of the Optimized Breakwater for Layout No.39

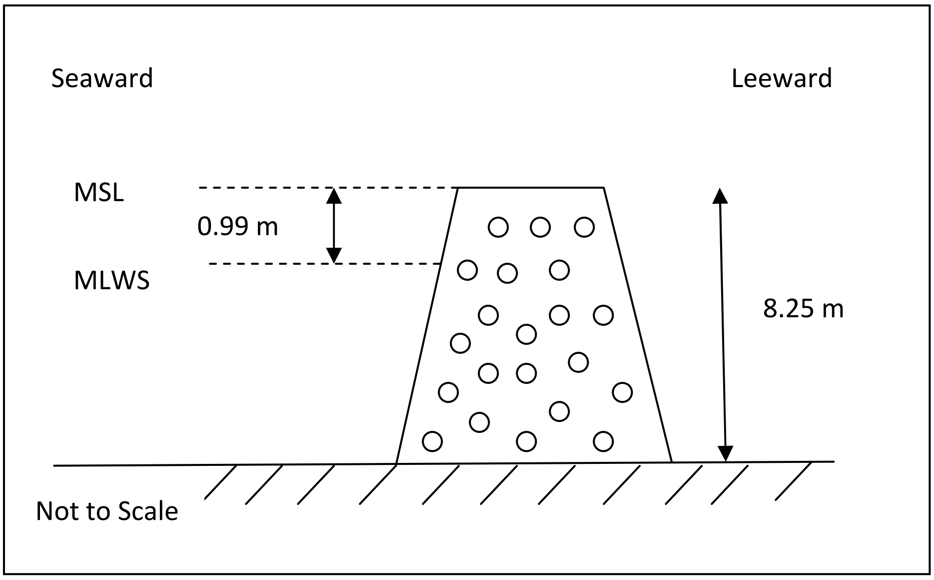


Figure 5.11 Cross Section of Segment A for Layout No.39

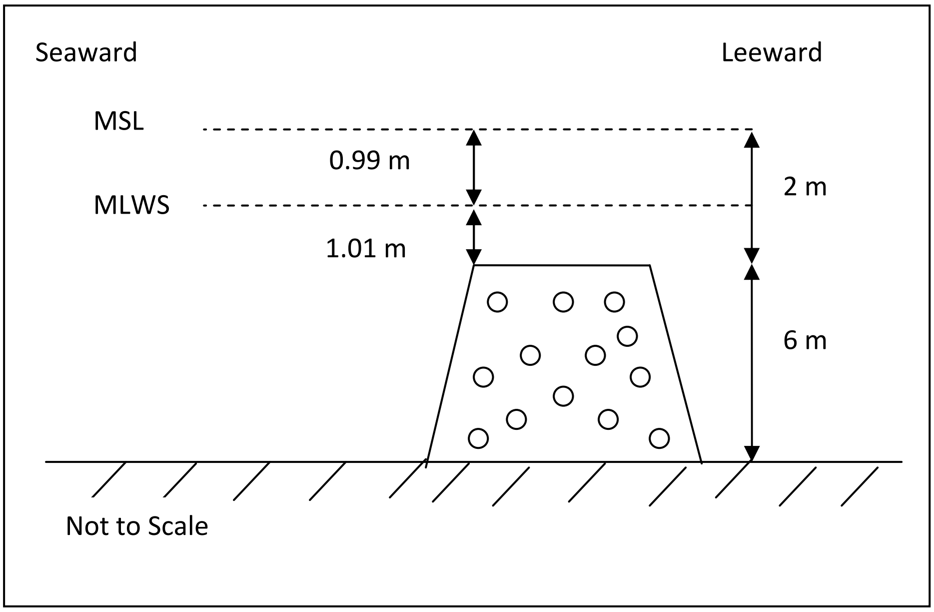


Figure 5.12 Cross Section of Segment B for Layout No.39

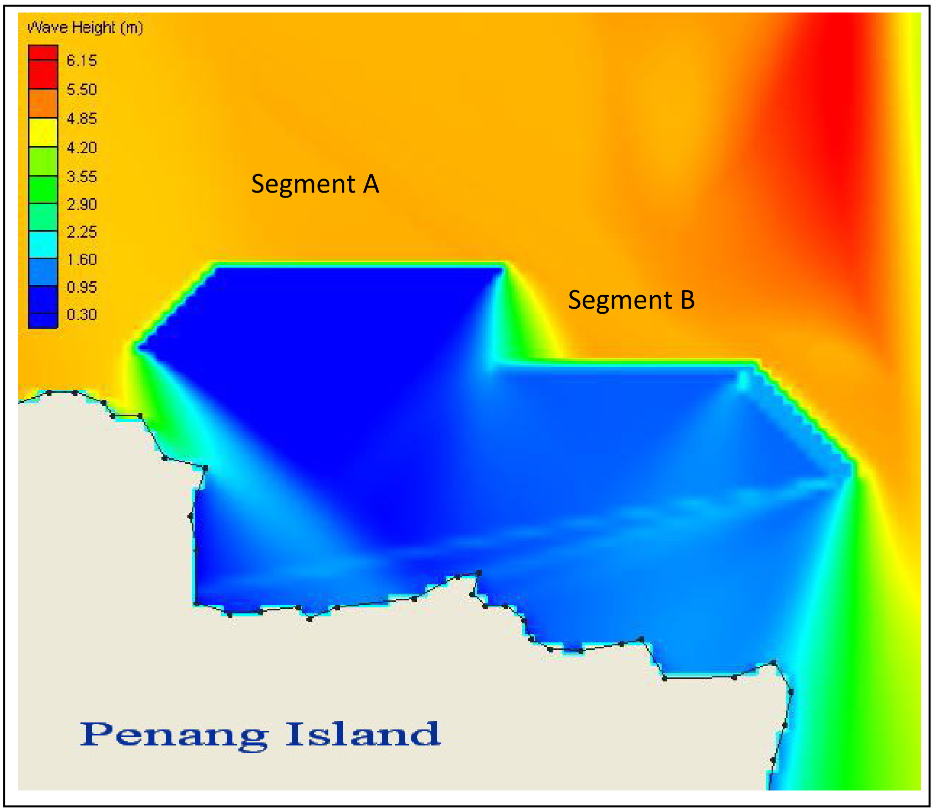


Figure 5.13 Distribution of Tsunami Wave Heights on the Shoreline with the Construction of Breakwater Layout 39

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The Steady-State Spectral Wave (STWAVE) Module of the Surface Water Modelling System (SMS) has been applied to simulate the impact of a tsunami wave when directed towards the north of Penang Island. The model has been calibrated against field data which was collected during a tsunami field survey by Yalciner et al (2005) for three points in the study area.

An offshore breakwater has been conceptually designed to dissipate tsunami wave energy. Thirty nine different layouts have been tested in the STWAVE model in order to find the most suitable conceptualized layout to construct in the study area.

Eleven layouts showed that an efficiency of greater than 70% was obtained whereby the breakwaters managed to reduce the tsunami wave heights from a range of 0.6 to 1.5 meter at the shoreline. From the analysis, breakwater layout number 39 has been selected as the optimized layout in which the breakwater performed to reduce the tsunami wave height by 83%. Furthermore, it has been selected because layout number 39 preserved the aesthetic value of the study area and provided sufficient safe passage for vessel movements to manoeuvre nearshore during the normal conditions.

6.2 Recommendations

The following highlights some of the future works which could be included in further study:

(a) A finer grid may be applied in order to find the wave height on the submerged structure and also increase the accuracy of the design.

(b) Hydrodynamic and sediment transport models could be used to evaluate the response of shoreline and its surroundings due to the effect of constructing the proposed breakwater.

(c) A 3D numerical model could be utilized to evaluate the effect and performance of the breakwater when a tsunami wave is directed on the structure.

(d) Cost estimation and economic analysis could also be undertaken to check the feasibility of construction of the proposed layout.

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APPENDIX A

DETAILS OF THE TSUNAMI WAVE HEIGHTS AT THE SHORELINE FOR ALL THE PROPOSED LAYOUTS

Details of the Tsunami Wave Height at the Shoreline for All the proposed Layouts											
	Without Structure	**Layout 1**	**Layout 2**	**Layout 3**	**Layout 4**	**Layout 5**	**Layout 6**	**Layout 7**	**Layout 8**	**Layout 9**	**Layout 10**
Point Number	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)
1	3.500	2.839	2.849	2.880	2.930	2.980	2.900	2.830	2.809	2.789	2.779
2	4.710	3.450	3.470	3.519	3.619	3.740	3.609	3.480	3.420	3.369	3.349
3	5.099	2.920	2.950	3.040	3.240	3.460	3.319	3.049	2.920	2.819	2.779
4	5.050	1.190	1.320	1.610	2.000	2.490	2.400	1.830	1.500	1.230	1.090
5	5.170	0.970	1.200	1.440	1.860	2.480	2.359	1.700	1.350	1.080	0.860
6	5.090	0.949	1.179	1.370	1.850	2.450	2.349	1.700	1.289	1.040	0.870
7	5.190	1.000	1.200	1.480	1.950	2.589	2.470	1.799	1.378	1.050	0.899
8	5.190	1.240	1.299	1.700	2.160	2.759	2.640	2.000	1.580	1.220	1.149
9	5.289	2.700	2.710	2.839	3.099	3.450	3.359	2.990	2.759	2.650	2.630
10	5.329	3.299	3.309	3.390	3.579	3.869	3.769	3.480	3.319	3.250	3.230

	Layout 11	Layout 12	Layout 13	Layout 14	Layout 15	Layout 16	Layout 17	Layout 18	Layout 19	Layout 20	Layout 21
Point Number	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)
1	2.039	1.679	1.990	2.019	2.099	2.220	2.299	2.150	2.049	2.009	1.690
2	2.339	1.909	2.069	2.210	2.450	2.750	2.819	2.500	2.250	2.089	1.929
3	1.789	1.470	1.690	1.940	2.329	2.789	2.880	2.410	1.990	1.740	1.519
4	0.940	0.959	1.700	1.840	2.099	2.579	2.789	2.309	2.009	1.940	1.340
5	0.400	0.209	0.839	1.139	1.730	2.430	3.000	2.470	2.140	2.099	1.929
6	0.670	0.560	1.460	1.389	1.830	2.450	3.200	2.849	2.700	2.799	2.460
7	0.610	0.569	1.440	1.659	2.029	2.640	3.470	3.160	3.059	3.000	2.690
8	0.740	0.649	1.190	1.629	2.180	2.819	3.490	3.130	2.869	2.670	2.460
9	2.150	1.940	2.279	2.349	2.680	3.170	3.400	2.970	2.720	2.640	2.339
10	2.780	2.589	3.059	3.019	3.180	3.529	3.640	3.290	3.180	3.210	2.750

Point Number	**Layout 22** Wave Height at Shoreline (m)	**Layout 23** Wave Height at Shoreline (m)	**Layout 24** Wave Height at Shoreline (m)	**Layout 25** Wave Height at Shoreline (m)	**Layout 26** Wave Height at Shoreline (m)	**Layout 27** Wave Height at Shoreline (m)	**Layout 28** Wave Height at Shoreline (m)	**Layout 29** Wave Height at Shoreline (m)	**Layout 30** Wave Height at Shoreline (m)	**Layout 31** Wave Height at Shoreline (m)	**Layout 32** Wave Height at Shoreline (m)
1	2.640	2.000	1.629	1.179	0.939	0.940	1.159	1.159	1.159	1.509	0.600
2	3.269	2.390	1.929	1.639	1.090	1.100	1.580	1.580	1.580	1.639	0.730
3	3.309	2.380	1.940	1.960	1.029	1.059	1.809	1.799	1.799	1.269	0.959
4	3.150	2.269	1.899	2.470	0.709	0.980	1.960	1.850	1.850	0.829	0.200
5	3.410	2.410	1.960	2.500	0.019	1.649	1.940	1.240	1.250	0.019	0.007
6	3.420	2.440	2.000	2.470	0.419	1.919	1.929	1.139	1.110	0.230	0.009
7	3.670	2.730	2.319	2.640	0.550	2.029	1.990	1.259	1.259	0.569	0.119
8	3.930	3.059	2.690	2.579	0.629	1.820	2.069	1.600	1.769	0.610	0.449
9	4.289	3.650	3.430	2.799	2.029	2.259	2.630	2.480	2.890	1.759	0.879
10	4.530	4.039	3.900	3.119	2.710	2.839	3.150	3.039	3.380	2.490	1.470

	Layout 33	**Layout 34**	**Layout 35**	**Layout 36**	**Layout 37**	**Layout 38**	**Layout 39**
Point Number	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)	Wave Height at Shoreline (m)
1	1.500	1.070	0.540	0.949	0.949	1.559	0.889
2	1.409	1.429	0.680	1.230	1.220	1.759	1.049
3	1.830	1.809	0.860	1.289	1.289	1.350	1.139
4	1.269	1.179	0.340	0.949	0.959	0.959	0.879
5	0.310	0.310	0.310	0.939	0.949	0.600	0.889
6	0.610	0.550	0.310	0.879	1.000	0.529	0.800
7	1.570	1.529	0.389	0.930	1.169	0.490	0.980
8	1.990	1.830	0.519	1.050	1.389	0.610	1.100
9	1.860	1.080	0.910	1.220	1.759	1.019	1.280
10	2.730	1.539	1.470	1.659	2.220	1.600	1.720