STUDY OF MOTION RESPONSES OF THE H-TYPE FLOATING BREAKWATER

by

AWANG KHAIRUL AMZAR BIN AWG YUSUF

Supervisor: Dr Teh Hee Min

Civil Engineering Department

Study of Motion Responses of the H-Type Floating Breakwater

by

Awang Khairul Amzar bin Awg Yusuf

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Civil Engineering)

19th August 2013

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Study of Motion Responses of the H-Type Floating Breakwater

by

Awang Khairul Amzar bin Awg Yusuf

A project dissertation submitted to the
Civil Engineering Department
Universiti Teknologi Petronas
in partial fulfillment of the requirements for the
Bachelor of Engineering (Hons)
(Civil Engineering)

Approved by,

____

(Dr. Teh Hee Min)

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons

(Awang Khairul Amzar bin Awg Yusuf)

ACKNOWLEDGEMENT

The author would first like to express his gratitude to Allah S.W.T for all the strength and chance to be involved in this project. A special appreciation to my supervisor, Dr. Teh Hee Min, lecturer of Civil Engineering Department, Universiti Teknologi PETRONAS, Tronoh for all his guidance and commitments in the completion of the project. A very deep thank you for the support and assistance throughout the process of completing this study.

I would like to extend my gratitude to the technicians of Offshore Laboratory, Block A, Universiti Teknologi PETRONAS, especially to Mr Meor Asnawan, Mr Mohd Zaid, and Mr Iskandar for their guidance and assistance during the process of carrying out the experiment throughout this study. I would also like to express my appreciation to the postgraduate students, Miss Nur Zaidah and Miss Noor Diyana for their help and teachings throughout the study period.

To my mother and my family, thank you for all the support and guidance that leads to the completion of this study. A special thank you to all of my friends, especially to Mr Mark Dexter, Miss Nadia Aida, Mr Mohd Syahmi and Miss Farahin for the help and support during the process of completing this study.

Last but not least, I would like to thank you to everyone who involved directly and indirectly in this project. Thank you for making the project a success.

AWANG KHAIRUL AMZAR BIN AWG YUSUF

Civil Engineering Department

Universiti Teknologi PETRONAS

ABSTRACT

This study focuses on the hydrodynamics behavior of a floating breakwater with taut leg mooring configuration. The aim of the study is to understand the motion responses of the H-type floating breakwater and the effects of the mooring system on the motion responses of the floating breakwater. This study focuses only on the heave, surge and pitch movements, whilst the other motion responses were restricted. In order to quantify the motion responses of the floating breakwater, the Response Amplitude Operator (RAO) was utilized in the study. The RAO values for heave, surge and pitch obtained in the study will provide an insight on the extent of the movement of the H-type floating breakwater subjected to various wave conditions. The results show that the motion responses of the floating breakwater are heavily affected by the breakwater's drafts and the wave period. The recorded RAO values show that the motion responses of heave and surge decreased with an increase of the breakwater draft. However, as for the case of pitch RAOs, no specific pattern can be recorded; a clear indication that the pitch responses are less significant as far as changing the drafts is concerned. All of the RAO values of the heave, surge and pitch are rather sensitive to the change of wave period, as the RAOs vary significantly with the increasing wave period. The motion responses for all the heave, surge and pitch also show significant differences when subjected to different wave steepness, with lower RAO values recorded milder wave steepness (H/L = 0.04). However, the RAOs are less sensitive at higher wave steepness (H/L = 0.06 and H/L = 0.08) and the effect are rather scarce. The RAO's patterns for both regular and random waves are almost identical; with the RAOs for regular waves tend to produce larger values as compared to random waves.

LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENT

CHAPTER 1

INTRODUCTION

1.1 Background of study

The destructive power of the sea waves has been a challenge for coastal engineers to combat for a long time. The best known and universally-used method of wave energy wave energy suppression has been a bottom-seated (or fixed) breakwater. One of the most conventional fixed breakwaters is rubble-mound breakwater which is typically constructed with a core of quarry-run stone, sand, or slag, and protected from wave action by one or more stone underlayers and a cover layer composed of stone or specially shaped concrete armour units. The fixed breakwaters may vary in profile from vertical to the gently sloping (usually no flatter than 1 to 10). They offer advantage in the form of excellent storm protection; however, at the same time they contribute several drawbacks to the environment. The fixed breakwater can be a total barrier to close off a significant portion of a waterway or entrance channel, thereby causing a faster river flow in the vicinity as well as potentially trapping debris on the updrift side. The presence of these gigantic structures may also create unacceptable sedimentation and poor water circulation behind the structures

Another shortcoming of a fixed breakwater is that its wave dampening power decreases rapidly as the tide level rises due to the fact that wave dissipation over the breakwater is mainly caused by wave breaking on the slope. It is often uneconomical and impractical to build a fixed breakwater in water deeper than about 20 feet as the construction cost of the breakwater is proportional to the square of water depth (McCartney, 1985). Very careful thought must be given to the design of fixed breakwaters and its effects on the physical system in which it is to be placed because, once constructed, very few are ever removed. They become a permanent part of the landscape and any environmental damage they may cause must either be accepted or the breakwater must be removed. This may be a very expensive penalty for a mistake

Due to the short-comings of the fixed breakwaters, engineers have come up with various types of floating breakwaters. The development of floating breakwaters has been enormous throughout these years, as the technology being recognized even more. According to McCartney (1985), there are four general types of floating breakwaters, namely pontoon type, mat type, box type and tethered float type of floating breakwater. Some of the advantages of floating breakwaters are its low construction cost, quick installation at sites, less environment impact, removable and easy to be fixed. At present, the increase demand for the application of floating breakwater at sites has led to further research on the design optimization of the breakwater. These optimizations aimed to increase the performance of the floating breakwater in attenuating the incident waves. A lot of factors have to be considered in the design of a floating breakwater, such as its overall design and geometry, the mooring orientation and etc. As far as this study is concerned, the main focus of the study is to investigate the effect of mooring design in the hydrodynamic performance of a floating breakwater.

1.2 Problem Statement

In the endeavour to meet a wave protection problem with a functional cost-effective engineering design, an H-shaped floating breakwater was specially developed in 2005. Experimental studies showed that it was capable of attenuating the incident wave height up until 80%.

It is worthwhile to note that the floating breakwater was tested using a small scale experiment which was subjected to the following drawbacks:

i) <u>Scale Effects</u>

   The experiment will be done by means of testing a small-scale test model of the floating breakwater. The major concern of the small scale experiments is the risk of the scale effects, in which the test model in reduced size does not behave in the similar manner to the prototype that it is intended to emulate. The problem can only be minimized by adopting a model in a larger or similar scale as the proposed prototype.

ii) Inadequate measurement technique for wave hydrodynamics

Wave hydrodynamics is a very subjective subject, in which the quantification of the wave hydrodynamics, either the motion or the forces acted on the breakwater due to the wave movement need be studied with a proper mechanism. The available measuring technique is subjected to errors due to manual observations and individual preferences. The limitation on the measuring equipment also might become a limitation in obtaining a more accurate result

iii) Poor understanding of hydrodynamics and motion responses of the breakwater

A study of energy dissipations and movements of the breakwater due to the respond from the wave movement upon the breakwater is a wide field of study. Thus, it is important for us to tackle the basic studies and have the main ideas on how does the system works. A lack in this field of study might affect our judgment in providing good final findings

iv) Limited test cases

Due to the limitation of study in the field, especially in the case of mooring configurations that are opted to be used in the study, there are limited numbers of references that can be used to compare the results of the test. Thus, this may limit the validity of the testing results, as there are limited benchmark values that can be used.

The present research is aimed at tackling the abovementioned limitations of the previous experiments, with the aids of physical modeling of larger scales. It is hoped that the research work carried out could provide greater insight on the hydrodynamics performance of the floating breakwater under various sea conditions

1.3 Significance of study

Apart from suppressing waves for temporary ports and marinas, breakwater also functions to perform the following tasks:

- Provide perimeter protection
- Provide certain extent of shoreline erosion control
- Serve as floating pontoon in marinas
- Act as swim area barrier
- Function as debris boom to keep floating rubbish from entering open sea
- Provide access from one place to another
- Function as net panel and aquaculture fish cage

This study is undertaken with the aim to develop an innovative floating breakwater that provides good hydraulic performance and is particularly suitable to be installed in Malaysian seas for protection of onshore and offshore facilities in Malaysia. It is hope for this research to expand the understanding of the hydrodynamic behaviour of the newly-designed breakwater by both physical and numerical simulations, and to establish radical procedures in providing quick response in withstanding the storm waves. The results obtained in this study will provide a valuable information in the process of designing the H-type floating breakwater in its real-life applications, especially in the design of its mooring lines.

1.4 Objective of the study

The objectives of this study are as follows:

a) To design the mooring configurations of the H-type floating breakwater, and
b) To investigate the motion responses of the floating breakwater in both regular and random waves

1.5 Scope of study

In order to achieve the objectives mention in section 1.4, the scopes of study are stated as follows:

1. Literature survey

    - A comprehensive desk study and patent search of the latest floating breakwater designs is to be undertaken

2. Enhancement of the breakwater design (complete with proper mooring system)

    - Additional features are introduced to the existing floating breakwater design so as to enhance the overall hydraulic performance of the breakwater. The geometrical and hydraulic properties of the breakwater are to be ascertained

3. Selection of construction materials for the proposed breakwater

    - Construction materials are proposed to stimulate both geometrical and dynamic properties of the newly proposed floating breakwater. A ballast tank is to be designed within the breakwater so as to provide arbitrary immersion depths by filling the tank with water/sand. The test model must be waterproof and has high resistance to wave impact

4. Fabrication of the breakwater models and the mooring systems

    - The test models are to be fabricated according to appropriate scale. Froude similitude is to be applied as the tests mostly deal with gravity, free surface waters

5. Laboratory set-up for physical modeling simulation

    - All test apparatus and equipment are to be calibrated with care so as to prevent systematic error during measurements. These measurement equipments include submersible load cells, optical tracking system, wave probes and velocimeters. The wave-structure interactions and underwater activities will be captured by a water-proof still camera and a video-camera

6. Laboratory tests

- Extensive laboratory tests are to be carried out to quantify the hydrodynamic behavior of the test models. Some of the dependant variables considered in this study are wave types (monochromatic and random waves), wave heights breakwater drafts and water depths. Both head-on and oblique waves will be considered in physical modeling.

CHAPTER 2

LITERATURE REVIEW

This chapter outlines the fundamental concepts on the hydrodynamics of a floating structure. It reports on the previous studies done by other researcher on this aspect of the study. This information will be the benchmark for the evaluation of the hydrodynamics of the floating breakwater that will be used for this study.

2.1 Hydrodynamics Motions and Floating Body

Hydrodynamics of floating breakwater refers to the study of the dynamics, or motion of a floating body. This section of study will emphasize on the hydrodynamics motion of a floating body, as well the hydrodynamics forces acted upon the mooring lines due to the dynamic behavior. The 6 degree of freedom concept will be further discussed in this section.

2.1.1 Six Degree of Freedom of a Floating Body

For a floating body in a definite space, there is a series of motion set that will be acted on the body. The hydrodynamic motion of these bodies acted in a three-dimensional plane, acted in a way in such resulted in a six degree of freedom. These six degrees of freedom are acting at the centre of its gravity and every motion is based on its own axis, as shown in figure 2.1.

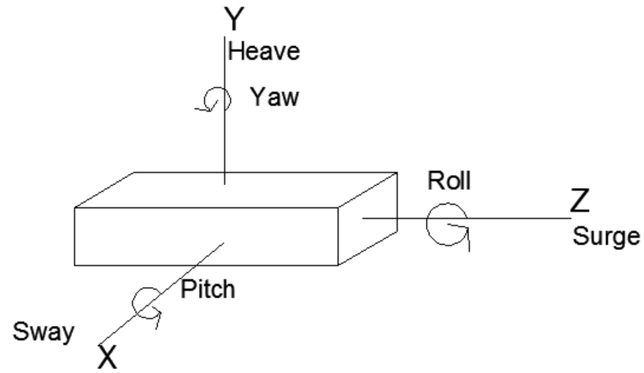


Figure 2.1: Six degree of freedom movement

In every directional axis, there will be two types of movement involved, which are the transitional movement, which moves along the axis, and the rotational movement, which moves around the axis. Each directional axis has its own transition and rotational movements, namely surge and roll for x-axis, heave and yaw for y-axis, and sway and pitch for z-axis. Table 2.1 summarizes the details of a floating body.

Table 2.1: Movement of degree of freedom with respect to its axis

Axis	Movement	Transitions	Rotations
Horizontal axis (x)	Left-Right	Surge	Roll
Vertical axis (y)	Up-Down	Heave	Yaw
Horizontal trans-axial (z)	Forward-Back	Sway	Pitch

In order to quantify the displacement of the movement for each degree of freedom, the Response Amplitude Operator (RAO) method can be used. RAO measures the amplitude movement of a particular degree of freedom with respect to the wave amplitude. The quantification of the RAO can be further simplified by using the following formulas, which will give the value of RAO for each degree of freedom, as according to Loukogeorgaki and Angelides (2005). In the formula, the RAO for each of the degree of freedom is represented by the constant *j*. Each *j* value represents each degree of freedom movement of the floating body, as being shown in table 2.2.

$$RAO_j = \frac{\xi_j}{A} \tag{2.1}$$

Where: ξ_j = Amplitude of motion in 6 degree of freedom

A = Wave Amplitude

j = degree of freedom (1,2,3,..,6)

Table 2.2: Value of *j* and its representation in respect to type of motion

j	**Type of Motion**
1	Surge
2	Sway
3	Heave
4	Roll
5	Pitch
6	Yaw

2.2 Types of Moorings

Mooring refers to the way the floating breakwater is anchored to the seabed by means of using a line to restrain the movement of the floating breakwater. There are several types of mooring configurations that are commonly used for floating breakwater applications, such as the pile moorings, hinged moorings, caternary moorings, taut-leg moorings, and taut-line with spring support

2.2.1 Pile Moorings

Pile mooring is one of the three most common types of mooring system used in the application of floating breakwater, as being proposed by McCartney (1985). In this system, the floating breakwater is hold onto its position by a set of pile moored into the bottom of the seabed. This type of mooring restrains the lateral movement of the breakwater, which allows the breakwater to move only in vertical axis direction. It is more suitable to be used in a shallow area due to its economical limitations. Figure 2.2 illustrate the set up of pile moorings, with a set of piles is connected from the breakwater to the bottom of the seabed. The studies of application of piled mooring in floating breakwater were done by Mani and Jayakumar (1985) and Diamantoulaki *et al* (2009). Both studies indicate that the stiffness of the piled system plays an important part in the performance of the breakwater, as well as forces acted on the support itself.

2.2.2 Hinged Moorings

Apart from of those proposed by McCartney, Leach *et al* (1985) also proposed another mooring configuration for a floating breakwater, namely the hinged mooring. Hinged mooring uses the idea of a piled mooring system, with an additional hinged mechanism added at the bottom of the pile, as shown in figure 2.3. The introduction of hinge at the bottom of the pile gives the pile the ability to incline itself when the wave hits. This system will give the floating breakwater more degree of freedom than of that in a pile mooring system. The hinged pile is held by mooring lines, as being illustrated in figure 2.3. The incline-ability of the piles will help to reduce mooring forces acting on the lines. The application of using hinged moorings has been also supported by the study done by Diamantoulaki and Angelides (2010), which confirms the practicality of the hinged moorings.

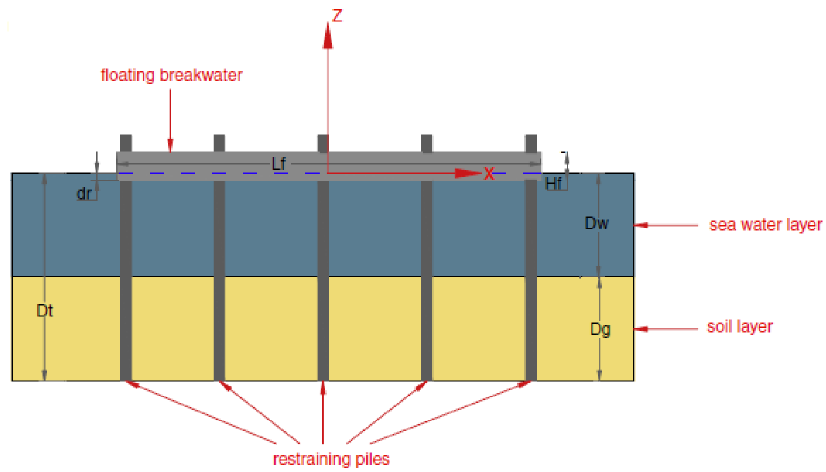


Figure 2.2: Pile-restrained floating breakwater (Sources: Diamantoulaki *et al*, 2009)

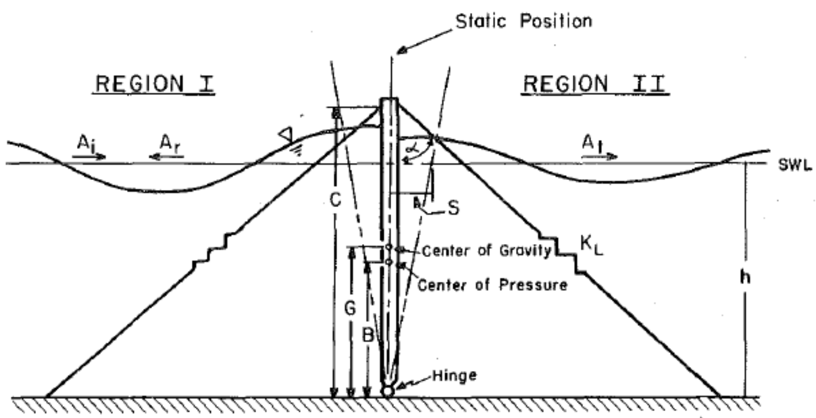


Figure 2.3: A hinge floating breakwater (Source: Leach *et al*, 1985)

2.2.3 Caternary Moorings

Caternary mooring is one of the conventional ways of connecting the taut line to the floating breakwater. Caternary mooring consists of a mooring line, connected to the anchor or a pile stake, located at the bottom of sea bed. In this type of mooring system, some part of the mooring line lay on the bed of the sea. Given this condition, the tension of the line is higher than the weight of the submerged line itself, as being described in the study by Nielsen and Bidingbo (2000). The illustration of such configuration is described in figure 2.4, in which some part of the mooring line is shown laying at the bottom of the seabed

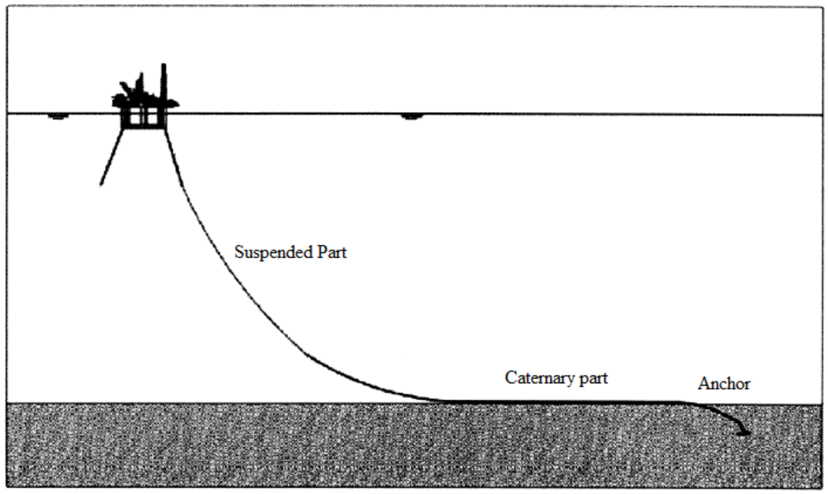


Figure 2.4: Catenary mooring system (Source: Nielsen and Bidingbo, 2000)

The caternary mooring system is the most common mooring system used in the floating breakwater applications. The length of the caternary line must be longer than the depth of the water, as some of the line needs to be horizontally laid on the seabed. Due to this condition, the mooring lines only need to withstand the horizontal tension from the weight of the lines. However, this kind of mooring system is not suitable for deep water, as a longer line means a higher loading from the floating breakwater will act upon the mooring lines. Thus, as the water gets deeper, the less significant the usage of caternary mooring system will be

In the study done by Garza-Rios *et al* (1997), it is concluded that the horizontal tension of a caternary mooring line can be found by using the following formula:

$$\frac{T_o}{P}\sinh\left(\frac{Pl}{T_o}\right) = \sqrt{h(h + 2\,\frac{T_o}{P})}$$

Where: T_o = Horizontal tension of catenary line

P = Vertical force unit per catenary length

l = horizontally projected length of the suspended portion of the cartenary

h = water depth

The equation shows a relationship between the amount of horizontal tension of the caternary line and the length of suspended portion of the caternary. Based on the equation, it is understood that the horizontal tension decreases when the length of suspended caternary increases. This happens due to the presence of more vertical tension acting on the lines with respect to the suspended carternary lines.

2.2.4 Taut-leg Moorings

Another conventional way of connecting mooring line to the floating breakwater is the taut-leg mooring system. The taut-leg mooring system can be defined as a straight string of line connected directly from the anchor at the sea bottom to the floating breakwater. As far as the system goes, the mooring line attached is fully suspended, with no line resting on the sea bed, as opposed to the caternary mooring system, as described in the following figure 2.5. Note that in the figure, the mooring line is completely suspended with no lines being rested on the seabed

Due to the suspended nature of the taut line system, it is subjected to both horizontal and vertical tension on the mooring line. The line can be attached either in a vertical direction or slightly inclined. Both these difference in ways of connecting the taut lines will have an effect to the instantaneous movement of the floating breakwater, as being studied by Rahman *et al* (2006). Based on the figure 2.6, the response of the floating breakwater towards wave action differs depending on the way the floating breakwater is moored, either in a straight vertical direction or slightly inclined.

Due to its ways of connection, taut-leg mooring system is most suitable to be used in a deep water condition. Furthermore, anchor type embedment is most suitable to be used with taut-leg system, as it provides more strength in terms of withstanding capability in handling the vertical and horizontal forces acting on the line. Due to this nature, the usage of synthetic lines is more advisable as compared to metal chains.

The effectiveness of the taut line is subjected to various factors that may affect the performance of the taut line and the breakwater as a whole. These factors will be discussed further in this chapter in order to understand their effects towards floating breakwater behavior.

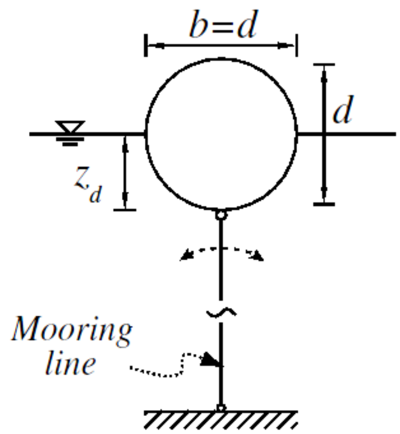


Figure 2.5: Taut Mooring system (Source: Ozeren *et al*, 2011)

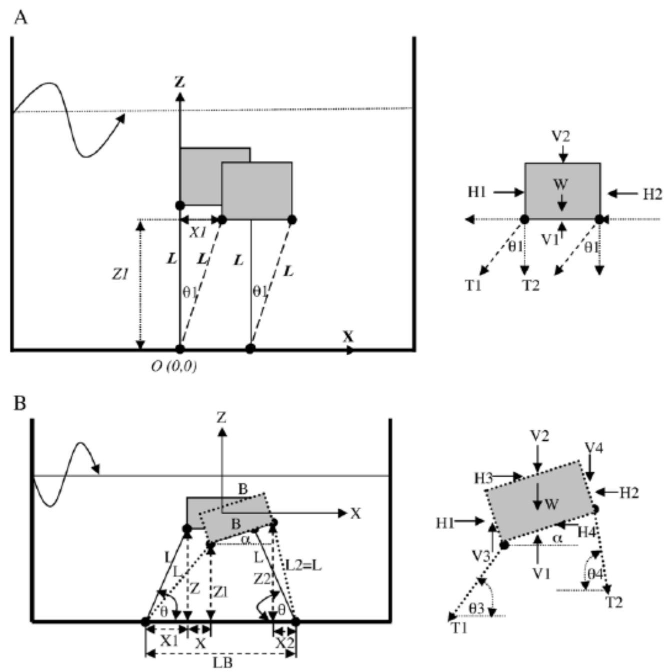


Figure 2.6: Instantaneous movement for submerged body for (A) Vertical moored body and (B) Inclined moored body (Source: Rahman *et al*, 2006)

2.2.5 Taut-leg with Spring Support

This mooring system is the least used in the real-life application of the floating breakwater. The insertion of spring or suspended materials will help to reduce the damping effects and impact loads on the mooring lines. Mavrakos *et al* (1994) and Chen *et al* (2001) have developed a study on the insertion of a spring in the mooring lines system. The purpose of adding the spring is to help to increase the overall stiffness of the mooring lines. The addition of the springs will help to increase the trajectory of the mooring lines, in which will help them to be able to withstand the forces acting on the mooring line. The addition of springs to the mooring line also helped when there are no suitable materials available in the market to adopt the required forces acted on the lines

There are many factors that may affect the performance of these mooring lines as a whole, and stiffness is one of the things that need to be considered. Thus, the introduction of the spring inside the mooring lines will give the mooring line extra advantage. The nature of the string will help to adjust the stiffness of the line accordingly, and thus, helps to maintain or adjust the stiffness of the line depending on the condition required.

2.3 Factors Affecting Hydrodynamics of the Floating Breakwater

As being mentioned in the previous chapter, there are some parameters that may affect the hydrodynamics behavior of the floating breakwater. The variability of these parameters may affect the hydrodynamics motion and forces of the floating breakwater, such as the heave, roll, moore tension and etc. Various studies and experiments has been done to determine the effect of such parameters and what are the optimum values of these parameters in order for us to get maximum efficiency of the floating breakwater

2.3.1 Mooring Line Stiffness

The stiffness of mooring line will decide on the motion of the floating breakwater subjected to the wave movement, as well as the damping forces acted on the mooring line itself. Thus, it is important for us to find the correct mooring line tension in order to obtain the best stiffness line to get an efficient floating breakwater performance.

The stiffness of the mooring line might go down to the configuration of the mooring line system that being used, as both taut line and catenary mooring system gives different mooring stiffness value. Besides that, alternating the mooring line stiffness also might give us an advantage depending on the type of waves that are being considered throughout the process.

Loikogeorgaki and Angelides (2005) have done a study based on the effect of the mooring line stiffness of the hydrodynamics of the floating breakwater, as being shown in Figure 2.7. In the figure, the graph C1 denotes the base case of the study, which is at 0 pre-tension stresses and graph C2 denotes the variation in the tensile force with a pre-tensile stress applied to the mooring line. From the result, it is clear that the lines with a higher stiffness value produce a higher mooring tension. Thus, it can be said that there are considerable effects of the mooring line stiffness to the dynamic of the floating breakwater, in a sense that both the hydrodynamics motion and forces are being affected in the process. The effect of the mooring stiffness also can be found in the studies of Diamantoulaki and Angelidis (2011), Matulea *et al* (2008), Rahman *et al* (2006) and Gobat and Grosenbaugh (2001), in which all of these studies underline the significant impact of various mooring line stiffness to the hydrodynamics of the floating breakwater.

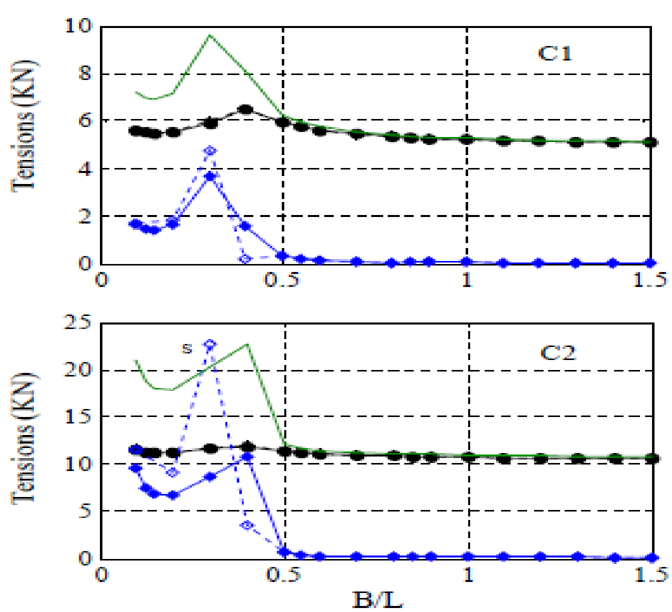


Figure 2.7: Variation of mooring line tension based on different stiffness (Source: Loukogeorgaki and Angelides, 2005)

2.3.2 Mooring Lines Materials

In the configuration of the mooring system by using lines, the type of lines that being used might affect the hydrodynamics behavior of the mooring line. The mooring lines is the material that connected the floating breakwater with the anchor at the sea bottom, in which holding the breakwater in its place. The suitability of the material that need to be used as the mooring lines are dependent on many factors, such as the elasticity and stiffness of the material, as well as the type of mooring configuration itself. The two common types of the materials that conventionally used are chains and synthetic lines.

a) Chain

Chain mooring line is made up of heavy steel and was used in most of the mooring line. Chains come in different grades and diameters, which will be used in different situations. Chains are preferably used in the catenary mooring line, in which some part of the lines need to lay on the sea bottom in order to give the line only horizontal force acting on it, as shown in figure 2.8. Furthermore, chains are more preferable to be used for permanent moorings, as it gives the mooring line extra strength in withstanding the movement of the breakwater structures

Due to the heavy nature of the chains, it is not preferable to use the chains in the mooring line for a modern floating breakwater. The heavy nature of the chain caused some difficulties in installing the mooring system, especially in a deep water condition. While the usage of chain in mooring line might be a suitable material in the catenary mooring system, it is less preferable to be used in other kind of mooring systems, especially in the taut leg mooring system. The requirement of additional buoyancy in a taut leg system makes the mooring system using chain lines seem to be less preferable. The hydrodynamic behavior of a taut chain line, which may exert an extra vertical and horizontal force on the mooring line, makes this option less preferable. Thus, there is a need of having alternative options as far as the mooring line materials is concerned

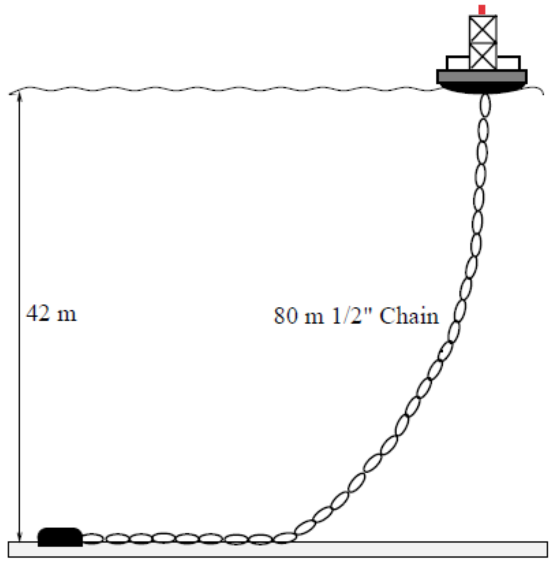


Figure 2.8: Chain mooring line for a catenary mooring (Source: Gobat and Grosenbaugh, 2001)

b) Synthetic Line

In order to overcome the weaknesses of the chain lines, researchers have came up with another options as far as the mooring line materials is concerned, which is by using synthetic lines. Synthetic lines are cables that are made up of a set of materials with different composition in order to give the lines extra characteristics that can overcome the weakness of the chain mooring lines. The synthetic lines might be produced form a completely different materials, such as synthetic fiber, or a composition of two or more materials, such as in a polymer lines. The synthetic lines are more preferable in a straight vertical connection, such as the taut leg mooring system, as it does not exert too much pressure on the anchor in which can avoid the line to break loose from the anchorage bond, but in the same time, provide strength strong enough to withstand the vertical and horizontal tension. The characteristics of a mooring line can be modified accordingly, which gives the mooring line advantages to be used under various sort of wave and sea conditions.

Ridge (2009) has tested a few synthetic mooring lines of different materials and configurations in a study to test for the strength of different materials subjected to axial loading. Figure 2.9 denotes the result of the experiment. And based on the figure, it is known that the different composition of synthetic lines do behave differently, in which signals that the different type of materials do affect the performance of the mooring system accordingly

Apart from that, Tahar and Kim (2008) also tested a synthetic polymer line in order to compare the performance of such lines as compared to a normal synthetic line. Based on the study, it can be said that a polymer-enhanced synthetic lines do give an upgraded performance to the normal synthetic line up to a certain extend. Huang *et al* (2012) also tested a synthetic fibre line enhanced in a polyster case to check for the strength of such configuration. In the end of the study, it is found that the presence of polyster-case helps to increase the tension capability of a synthetic fibre line. This is important feature, as tension capability is important to ensure that the mooring line that we provide do not snap easily once it is exposed to the hydrodynamic forces acting on the line when it is being installed.

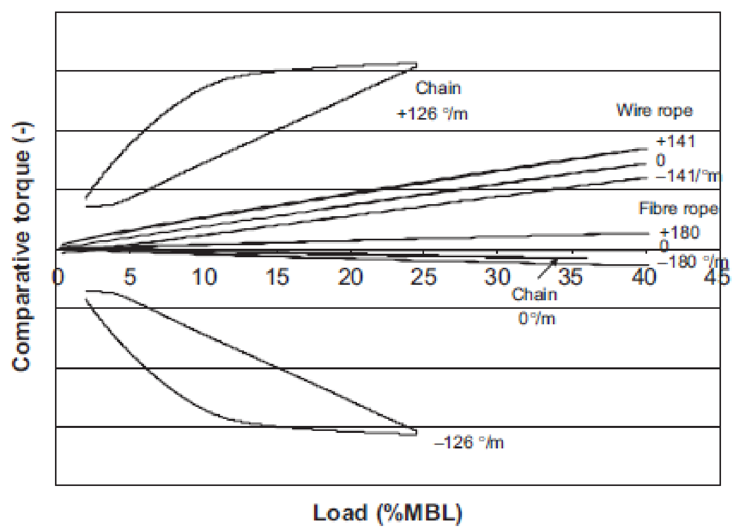


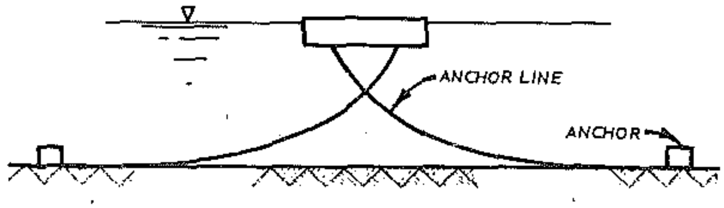
Figure 2.9: Torsional response of different lines under axial load (Source: Ridge, 2009)

Another advantage of using synthetic line is that the stiffness and elasticity of the mooring line can be adjusted to ensure that the mooring line can be enhanced to allow less hydrodynamic effects acting on it. As being said in the previous section, stiffness is one of the parameters that may affect the hydrodynamic performance of a breakwater (see section 2.3.1). Thus the introduction of spring line as being studied by Chen *et al* (2001) will help to bring more stiffness factor in the mooring lines, thus helps it to perform accordingly.

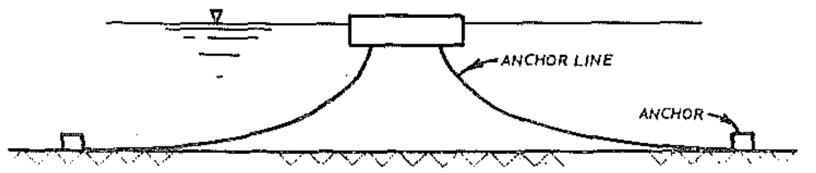
2.3.3 Mooring Line Configurations

According to the study done by McCartney (1985), there are two ways to attach the breakwater and the lines of the mooring. The mooring lines can be attached either by straight configurations or by crossing the lines, as being shown in the Figure 2.10. The ways of attaching the lines to the breakwater may have an impact on the hydrodynamics of the breakwater, as it can restrict the movement of the floating breakwater. Keel clearance for boats moored alongside the breakwater can be provided by giving the breakwater a crossed line configurations. However, crossed line will also caused an increase in the heave and sway motion of the breakwater, subsequently affecting the performance of the breakwater. This theory is supported by a study done by Whiteside (1994). In the study, the effect of the position of the moored on the breakwater is also being studied. According to the study, by placing the mooring attachment points at the site of the breakwater, the sway motion can be restricted as compared to placing the attachment points directly at the bottom of the breakwater.

Sannasiraj *et al* (1995) also suggested that crossed mooring produced a higher transmission coefficient values and higher mooring forces. Thus, it is not advisable to use crossed moorings, as it will significantly affect the performance of the floating breakwater. Another mooring line configuration factor that can affect the performance of the hydrodynamics of the floating breakwater is the number of attachment points provided for the mooring. A more mooring attachment points on the breakwater will give the breakwater a more stable posture, in which restricted the sway motion due to wave’s impact. Thus, this will directly give the floating breakwater a better wave transmission ability.



(a)



(b)

Figure 2.10 Crossed (a) and uncrossed (b) mooring lines (Source: McCartney, 1985)

2.3.4 Length of Mooring Lines

The taut-leg moorings and the carternary mooring types are determined by the length of the mooring lines provided, as being discussed in section 2.3. The difference in the configuration does have an impact in the behavior of the floating breakwater, both in motion-wise and performance-wise. As being suggested by Whiteside (1994), the changes of the mooring line from slack to taut mooring give a less sway motion on the breakwater, subsequently reduced the mooring forces acting on the mooring lines. These hydrodynamic impacts will then contribute to the performance of the breakwater, as less movement and mooring forces acting on the line will increase the transmission efficiency of the floating breakwater

Apart from that, the length of the mooring lines will also affect the draft of the floating breakwater. As a result, the wave transmission ability will also be affected. When the draft or mass of the floating breakwater is being manipulated, it will affect the performance of the breakwater, especially on the sway amplitude. Thus, by varying the draft of the floating breakwater accordingly, we can adjust the sway amplitude and the damping resonance accordingly. A larger draft means that a larger momentum that will grow faster than the resistance, causing an increased in the resonance peak (Foursert, 2006). With an increasing width to the floating breakwater caused a decrease in the draft. This will lead to an increase in wave sway amplitude motion. Thus, in other words, we can say that the amplitude of the motion increases when the decrease of wave exiting forces is less than the decrease in the hydromechanical forces, and vice versa

The effect of such parameter has also been studied in previous past studies, such as in the studies by Murali and Mani (1997), Diamantoulaki *et al* (2009), and Hedge *et al* (2007). The results that have been yielded by these studies do inflicted that there are significant effects of the floating breakwater by changing the width and draft of the floating breakwater accordingly. This theory is also supported by He *et al* (2012), in which suggested that the increase in the draft of the floating breakwater will produce a less heave, surge and pitch motion up to certain extent.

2.4 Past Studies on Hydrodynamics of Floating Breakwater

In the recent years, there are various studies that have been done in understanding the hydrodynamics of the floating breakwater of various configurations. The hydrodynamics of the floating breakwater gives out different behavior due to the changes of the configurations. There are several factors that may lead to the difference in terms of the behavior of the breakwater (refer section 2.3). Thus, the goal of these studies being done is to obtain the most effective design, in which a minimal hydrodynamics behavior is obtained, and in the same time, an effective performance is expected from the breakwater. Although it is near impossible to find the ultimate configurations of the floating breakwater behavior, due to the fact that the subject itself is too subjective, but the combinations of various design together with its testing may give us another new set of point of view towards this matter

2.4.1 Hydrodynamics of Pontoon-type Floating Breakwater

The studies of the hydrodynamics behavior of a pontoon floating breakwater have been done in various studies, such as those that have been done by Sannasiraj *et al* (1996), Abdl-Azm and Gesraha (1998), Williams *et al* (2000) and Gesraha (2007). In all these studies, the pontoon-shaped floating breakwater was tested under various waves' condition and various configurations were tested. The goal of the studies was to investigate the effects of various configurations towards the hydrodynamics behavior of the floating breakwater, especially on the heave, sway and roll motions. In the latest studies of the pontoon-shaped floating breakwater, the breakwater was compared with a regular rectangular floating breakwater in order to study the effect of adding the side plates on the performance of the breakwater. It was found out that while the heave damping coefficients increases, the other damping coefficients are lowered, up until certain limits. Figure 2.11 shows the results from the study done by Gesraha (2007). The figure shows that the heave RAO increases with an increase in the ratio of the side plate length and length of half of the floating breakwater beam (b/a). This happens due to the increase in damping resonance acting on the floating breakwater.

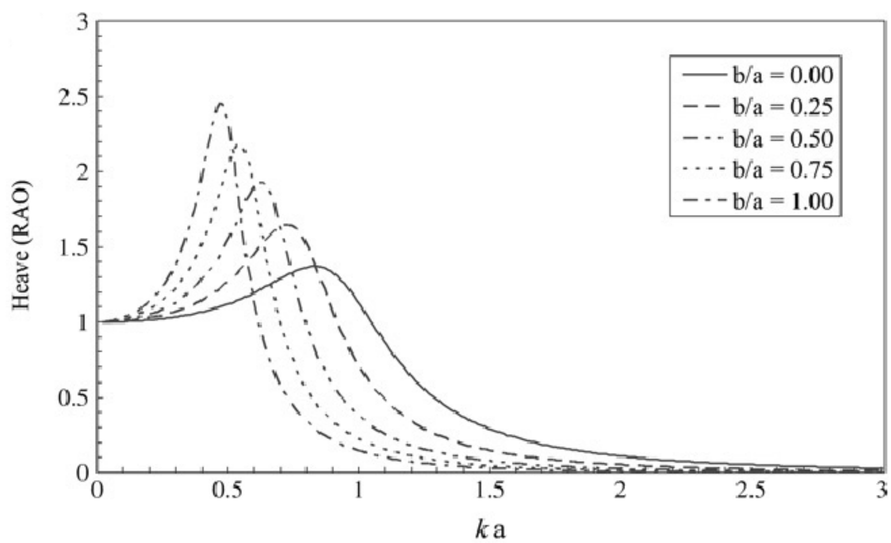
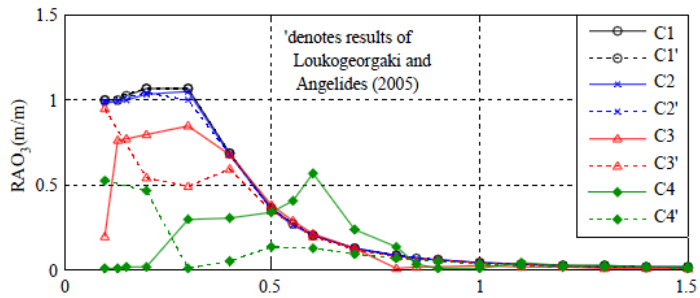


Figure 2.11: Influence of different side plate height to the Heave RAO (Source: Gesraha, 2007)

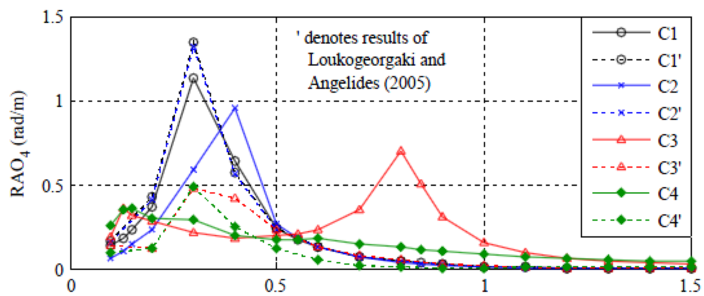
2.4.2 Effect of Mooring Lines to Floating Breakwater

The ways of connecting the floating breakwater to the mooring system also can affect the performance of the floating breakwater considerably. The mooring configuration may affect the hydrodynamic behavior of the breakwater as far as the motion and forces are concerned (Mays *et al*, 1998). In the effort to find the effect of different kind of moorings to the performance of a floating breakwater, Whiteside (1994) has done a study in comparing the result of different kind of moorings to the performance of a floating breakwater, as being mentioned in the previous section. In this study, different type of mooring lines of different materials and different configuration was tested. The lines configurations that are being used are slack mooring and taut mooring, with crossed and uncrossed configuration. Apart from the mooring configurations, the materials were also varied in the study, which synthetic nylon and metal chain is being used. At the end of this study, it is concluded that the type of materials used in mooring lines do not affect the performance of the floating breakwater. The study also indicates that with a slacker mooring line, the hydrodynamics motion will become much more, but reduced the hydrodynamic forces acted on the mooring lines.

Loukogeorgaki and Angelides (2005) studied various kind of mooring lines configuration and how do this affect the floating breakwater. In their studies, it is known that the modification on the configuration of the mooring line affects the damping and the stiffness of the mooring line, in which will subsequently affect its performance. The variation of heave and roll RAO of the study can be observed in Figure 2.12. From the figure, it can be said that the various configuration of mooring lines will definitely cause some changes in the hydrodynamic behavior. It is worth to note that from this study, the performance of the floating breakwater, such as the wave attenuation potential, is said to be affected by the stiffness and damping of the mooring lines. The stiffness and damping of the mooring line also affect the mooring forces acting on the line, especially of those that involved the taut leg mooring systems.



(a)



(b)

Figure 2.12: Variation of heave and roll RAO from various moore configuration (Soucre: Loukogeorgaki and Angelides, 2005)

2.4.3 Effect of Mooring Configuration on Hydrodynamics Motion of Floating Breakwater

On the other hand, Diamantoulaki and Angelides (2010) studied the effect of hinged floating breakwater towards the hydrodynamics of the mooring configuration. The configuration of the hinged floating breakwater has been discussed in the section 2.3.3. In this study, the main goal of the study is to investigate the performance of the floating breakwater in respect to the hinged mooring configuration and the number of hinges provided. Based on the study, it is learned that the number of hinges may have an effect on the hydrodynamics behavior of the floating body. The difference in number of hinges may also affect the number of degree of movement of the floating breakwater, as being demonstrated in Figure 2.13. The figure shows that for floating breakwater that is moored using hinged-mooring with only one hinge, there are less degree of freedom for the floating breakwater as compared to such configuration using two hinges.

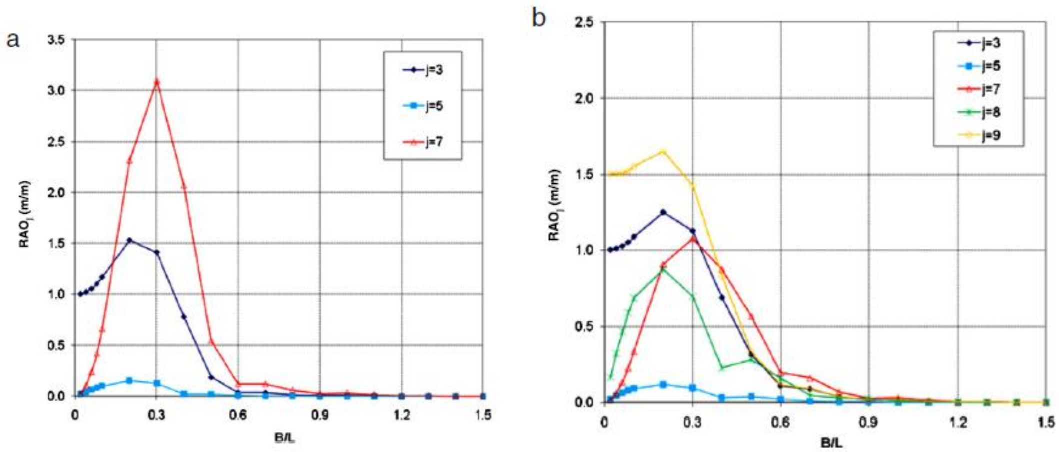


Figure 2.13: The hydrodynamics behavior of floating breakwater with (a) one hinge and (b) two hinges (Source: Diamantoulaki and Angelides, 2010)

In another study done by Manuel (1995), the effect of pile mooring to the heave motion is being studied. As being said in the previous part of this chapter, pile mooring system will restrict the movement of the floating breakwater to only heave motion. In this study, different factors were taken into consideration to study its effect on the heave motion of the floating breakwater model. Among the parameters that being considered were different gap between two piles, as well as the wave steepness. Based on the result, it is understood that a bigger gap between one pile and another will cause a higher RAO of heave motion to be recorded. This was the case for higher wave steepness as well. This is said due to the presence of lateral movement within the breakwater model itself. These lateral movements will then may caused some sway and roll movement to occur, which played a role in increasing the heave RAO values

In the effort of studying the effect of all three mooring systems to the movement of the breakwater, Ruol and Martinelli (2006) has developed a test involving these three set ups of different pre-tensile stress of the mooring line. The three mooring systems, which are the pile mooring, the slack or caternary mooring, and the taut leg mooring, was being tested, with different line stiffness was pre-set prior to the tests. At the end of the experiment, it is understood that the movement of the floating breakwater affected by the mooring configuration used. From Figure 2.14, it is understood that the stiffer the mooring lines, as it changes from slack mooring to taut-leg mooring, the higher the heave motion displacement of the floating breakwater. The figure also shows that the heave motion is at the highest when pile mooring is used. It is also being said in the study that the dissipation of the waves are directly proportional with the movement of the floating breakwater. Thus, the difference in mooring configuration and tension may have a direct impact towards the performance of the floating breakwater.

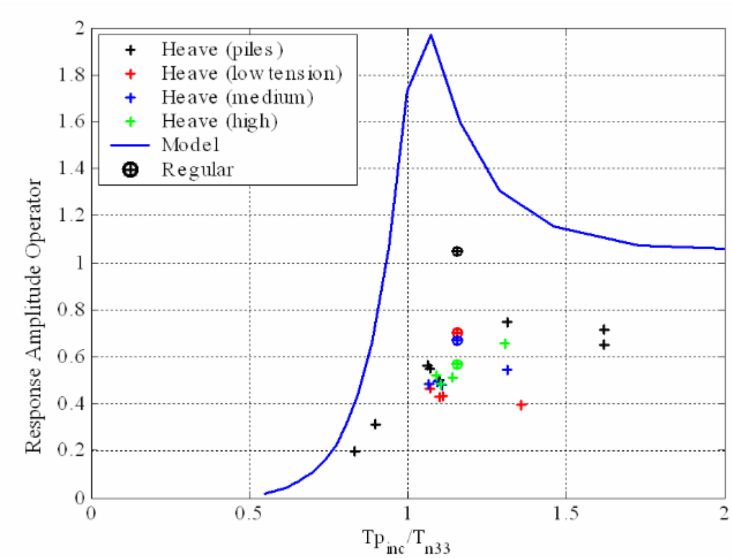


Figure 2.14: RAO values of heave motion with respect to different type of mooring configurations (Source: Ruol and Martinelli, 2006)

CHAPTER 3

METHODOLOGY

The focus of this chapter is to discuss on the equipments that are to be used in the testing of the test model. The testing and experiments will be done in the Offshore Laboratory, Block A, at Universiti Teknologi Petronas (UTP). This chapter will further explained on the strategy that will be used to undergo this testing. Since interested area of the study is only in the hydrodynamics of the test model, more concern is being focus on the Response Amplitude Operators (RAO) of 6 degree of freedom motion. The chapter will also discuss on the process in conducting the study and the planned Gantt chart for the overall study.

3.1 H-shaped Floating Breakwater

A floating breakwater model with a certain design criteria is to be designed with the aim of having a floating breakwater with effective wave attenuating ability. The design that is introduced for the study is a continuation to the past studies done in the previous years by other UTP students. The design of the new novel breakwater will include some enhancement on the previous design, as well as introduction of new mooring system. This will give the floating breakwater model different sets of data as compared to the previous studies.

3.1.1 Model Description

In this study, an H-shape floating breakwater was developed according to model scale. The general dimensions of the test model are 1000 mm width x 1480 mm length x 1000 mm height. The breakwater was constructed by plywood and was made waterproof by a layer of fiberglass coating on the surfaces of the body. Plywood is chosen as the primary construction material because it is a lightweight material that provides high resistance to external force impacts. The fiberglass coating was injected with yellow colouring pigment for better visibility of the model during experiment.

The breakwater has a pair of upward arms and a pair of downward legs, with both connected to a rectangular body as shown in Figure 3.1. The seaward arm, body and leg act as the frontal barrier in withstanding the incident wave energy mainly by reflection. Some wave energy is anticipated to be dissipated through vortices and turbulence at the 90^{o} frontal edges of the breakwater. When confronted by storm waves, the H-type floating breakwater permits water waves to overtop the seaward arm and reaches the U-shape body as seen in Figure 3.2. The overtopped water trapped within the U-shape body heavily interacts with the breakwater body, and the flow momentum is subsequently retarded by shearing stresses (frictional loss) developed along the body surfaces. The excessive waves in the U-shape body may leap over the shoreward arm and reaches the lee side of the floating body, making a new wave behind the breakwater which is termed as the transmitted waves.

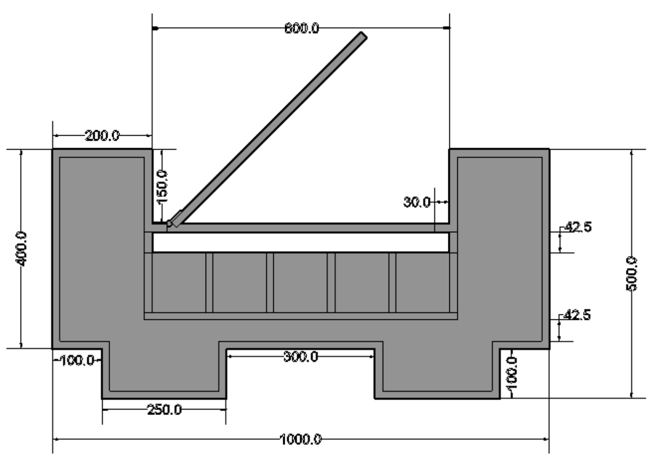


Figure 3.1: Cross section of the outline of novel breakwater with dimensions

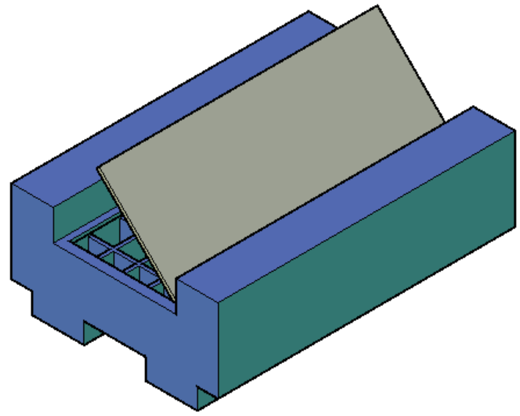


Figure 3.2: Isometric view of novel breakwater design drawing

Apart from the energy dissipation mechanisms exhibited at the upper body of the breakwater, both seaward and leeward legs, which are constantly immersed in water, are particularly useful in intercepting the transmission of wave energy beneath the floating body through formation of bubbles and eddies near the sharp edges as well as underwater turbulence. The remaining undisturbed energy past underneath the floating body and contributes to the transmitted waves behind the breakwater.

As breakwater immersion depth is an important parameter controlling the hydrodynamic performance of the floating breakwater, a ballast chamber located within the breakwater body was designed for adjustment of immersion depth of the breakwater with respect to still water level, in a freely floating condition. For the breakwater model, a 5 x 9 matrix wooden grid system was developed for the placement of sandbags for weight control of the breakwater. The ballast chamber was covered by transparent lid made of Plexiglas, as shown in Figure 3.3. The gap between the breakwater body and the transparent lid was tightly sealed by adhesive tapes so as to prevent the seepage of water to the ballast chamber.

The sides of the floating body facing the flume walls were coated with polystyrene foams to prevent direct collision between the concrete wall and the fiberglass coated breakwater body. The implementation of the polystyrene foams at both sides of the breakwater would not pose significant disturbance to the movement of the floating body.

Figure 3.3 Wooden grid chambers for the placement of sandbags into floating breakwater

The proposed materials that are to be used for this new design model are plywood, coated with fibre-glass coating which will act as water-proof membrane to the surface of the test model. Plywood is choosen based on its capability to resist high, as well as being light-weight, in which is important in order to ensure the model can float. In the process of choosing the materials for the test model, it is important to consider the strength of the model wall due to mooring tension. The wall of the test model must be capable enough to withstand the vertical and horizontal forces due to restriction of mooring tension on the mooring line. Thus, plywood is considered to be one of the suitable choices. Figure 3.4 shows the end product of the test model after fabrications.

Figure 3.4: Fabricated test model

3.1.2 Mooring Systems

In order to hold the test model in its position, a mooring mechanism is required. In the past studies, the pile mooring system has been opted. However, in this study, a taut-leg mooring system is opted to be used, in which gives the model up to six degree of freedom movement. Due to this, a mooring connection has to be established between the floating breakwater model and the floor.

In taut-leg mooring system, the mooring line is connected in a straight line from the floating breakwater model to the anchor located at the floor of the wave flume. Such configuration will give the mooring line a pre-tensile stress prior to the test. The mooring line will be connected to the wall of the floating breakwater by means of hooking the end of the line to the designated hooking point on the wall of the test model. The general configuration of the taut leg mooring system is shown in the figure 3.5.

Four hooks were attached to the bottom corners of the floating model, as shown in Figure 3.6, for mooring purposes. A taut-leg mooring was adopted in this study as it provides greater efficiency to the performance of floating breakwaters. The taut-leg mooring lines were almost straight with minimal slacking when in operation in water. For the present experiment, the pre-tensile stress of the mooring cables was set as zero in still water level. The build-up of the tensile stress in the mooring cables during the experiment is mainly posed by the wave force acting on the floating breakwater. The setting of present experiment allows heave, surge and pitch responses to the floating breakwater, and the other motion responses (*i.e.* sway, yaw and roll) were restricted.

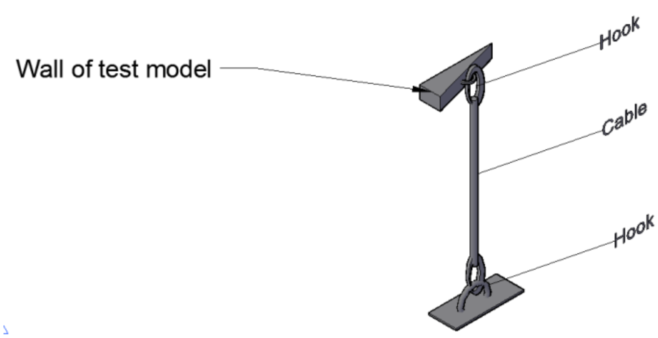


Figure 3.5: Configuration of mooring system for test model

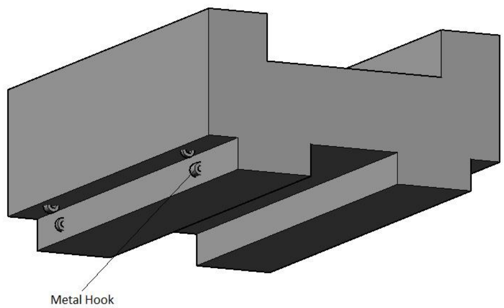
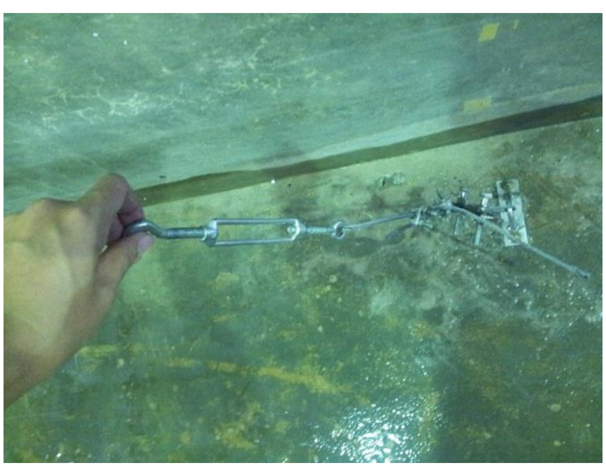


Figure 3.6 Position of hooking points on the test model

As far as the mooring system is concerned, this will be the first time such configuration used on the said test model. Thus, the previous studies by other researchers will be used as benchmarked to the study. A greater movement by the test model will also be expected, together with a higher force on the mooring line, due to the pre-tension configuration; as compared to the previous studies by the other students. In order to hook the test model with the floor of the wave flume, a thin metal rope with low elasticity was tied to each hook beneath the breakwater and the other end was attached to the floor of the wave flume. The attachment of the metal cable is shown in figure 3.7(a). Meanwhile, Figure 3.7(b) shows the position of 4 metal hooks at the bottom of the wave flume floor. The configurations of these metal hooks will be discussed in the later part of this chapter.

(a)



(b)

Figure 3.7: Mooring connection set up showing (a) mooring lines cable and (b) ground attachment points

3.2 Laboratory Equipments and Instrumentations

3.2.1 Wave Flume

A series of experiment are to be conducted in a 25 m long, 1.5 m width and 3 m high wave flume as shown in the Figure 3.8. The maximum permitted wave depth in the flume is up to 1.2 m. The walls of the wave flume are made of reinforced concrete, with 6 transparent flexiglasses located at both side of the wave flume. The purpose of providing these glasses is to easily monitor the test models during the experiment

3.2.2 Wave Paddle

The wave paddle is used to generate waves to mimic the real sea condition in a real world. The wave paddle is installed at the one end of the wave flume, as shown in Figure 3.9, and it is able to generate both regular and irregular waves. It is powered by a single motor generator, with a capability of generating waves up to 2 second wave period, and maximum wave heights of 0.3 m. The wave paddle was fabricated by the Edinburgh Design Ltd., United Kingdom and is capable of absorbing the re-reflected waves

Figure 3.8: Wave fume

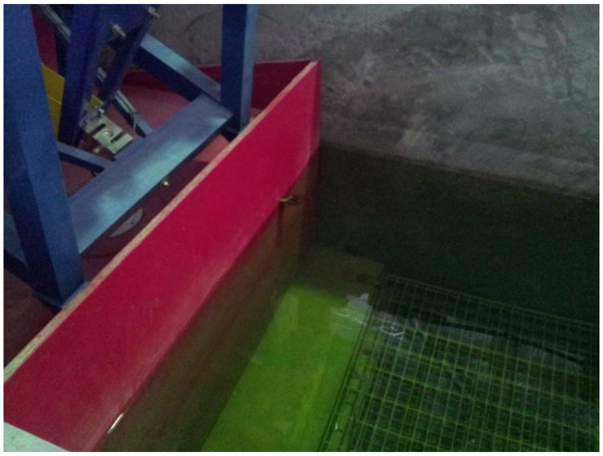


Figure 3.9: Wave paddle

3.2.3 Wave Absorber

At the other end of the wave flume, a wave absorber is placed to absorb the remaining wave energy from the incident waves generated by the wave flume, as shown in Figure 3.10. This is to avoid any reflection from the waves that may alter the values of the subsequent waves, which may affect the readings. As a requirement, the wave absorber must be made up of a material that can absorb up to 90% energy from the incident waves.

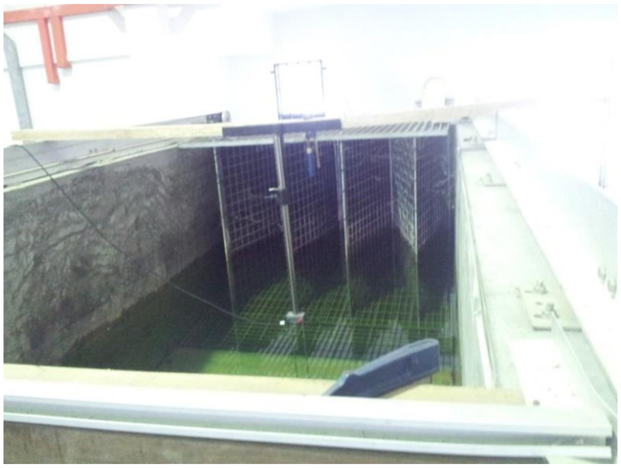


Figure 3.10: Wave absorber

(a) (b)

Figure 3.11: (a) Optical Tracking System camera, (b) reflective balls

3.2.4 Optical Tracking System (OPTITRACK)

In order to record the hydrodynamic motion of the test model, we are using an Optical Tracking System attached at the side of wave flume. The advantage of using this instrument is it can detect all 6 degree of movements immediately during the testing process. The movements of the test model will be detected by the camera (refer Figure 3.11(a)) through the reflective balls (refer Figure 3.11(b)), located at the top of the test models. In the testing, 3 different cameras are used and all the data from all the cameras will be used and analyzed.

3.2.5 Wave Probes

The wave probes will be used to measure both the incident and reflected wave heights value throughout the testing. However, in the study, the focus is more on the incident wave heights rather than the reflected wave heights. Three wave probes will be placed in front of the test model for such purposes. The decomposition of the wave heights will use the three-points method (Mansard and Funke, 1980). Prior to the test, the wave probes will need to be calibrated beforehand by letting the wave flume runs without any obstruction at different wave period and wave heights. Figure 3.12 shows the placement of the wave probes inside the wave flume.

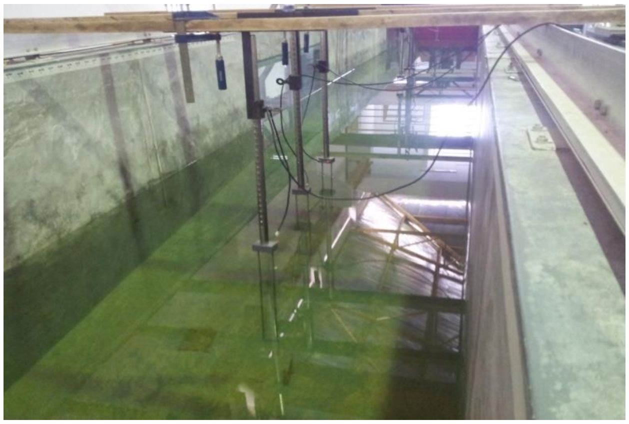


Figure 3.12: Wave probes

3.2.6 Data Logger

All of the instruments mentioned above will be connected to a data logger. The data logger will be acted as a central nerve system, where all of the obtained values and data from the instruments will be collected inside the data logger. This data logger will then transmit all the required data into the PC system inside the laboratory, to be analyzed accordingly. Figure 3.13 shows the type of data logger that will be used in the study.

Figure 3.13: Data logger

3.2.7 Experimental Set up

The complete experimental set-up is presented in Figure 3.14. The test model was located at the mid-length of the wave flume, which is 4 m apart from the wave paddle. The test model was anchored to the floor of the wave flume by the means of metal cables and hooks. Load cells were installed at the mid-point of the respective mooring lines for the measurement of the mooring forces.

Three wave probes were located both seaward and shoreward of the model (with the nearest probe located away from the model at 2.5 m) for the measurement of water level fluctuation at the respective locations. These time series data were then further analyzed using computer tools to yield some significant wave parameters, *e.g.* significant wave height, peak wave period, etc. Mansard and Funke's method (1983) was adopted to decompose the wave signals from the three probes into incident and reflected wave components. To achieve this, the probes were carefully arranged according to the spacing requirement set by Mansard and Funke (1980).

A number of reflective balls were attached to the test model. The movement of these balls, which is equivalent to the movement of the model, was captured by three optical tracking cameras located at close proximity of the model.

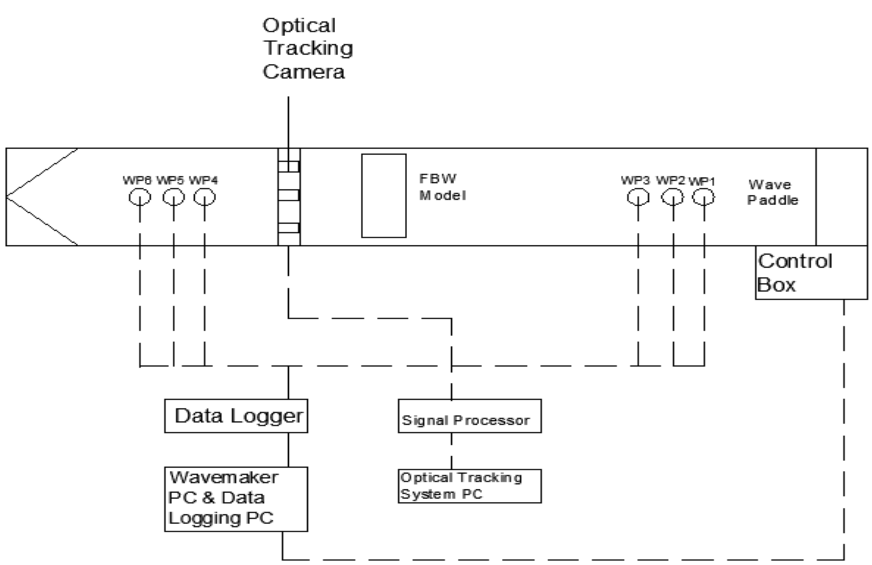


Figure 3.14: Experimental Set-Up

3.3 Experimental Test-Run

In testing the test model, the behavior of the floating breakwater model under different sets of condition is to be monitored. Thus, all the fixed and manipulated parameters that will be tested are to be established. The variables that are going to be used in these experiments are listed in the table 3.1.

In each of the dependant variables, the values of each parameter are varied. Noticed that in each wave depth, the test model will be tested at different wave period, which is at 0.2 second interval. Furthermore, in each wave period, the floating breakwater model will be tested at different wave height, corresponds to the H/L values. It is worth to note that in this study, both regular waves and random waves are to be considered. The number of runs that was conducted throughout the testing is shown in Table 3.2. Overall, a set of 74 tests were conducted throughout the period of this study for both regular and random waves.

Fixed Variables	Dependant Variables
Mooring method	Water drafts, *D*
Model orientation	Wave period, *t*
Water depth, *d*	Wave height (*H/L*)

Table 3.1 Variables used in the testing

Table 3.2 (a): Number of testing done throughout the experiment (D/d = 0.243)

a)

Water Draft, D	Wave Condition	Time Period	H/L
0.17	Random	1.0	0.04
			0.06
			0.08
		1.2	0.04
			0.06
			0.08
		1.4	0.04
			0.06
			0.08
		1.6	0.04
			0.06
		1.8	0.04

Table 3.2 (b): Number of testing done throughout the experiment (D/d = 0.343)

b)

Water Draft, D	Wave Condition	Time Period	H/L
0.24	Random	1.0	0.04
			0.06
			0.08
		1.2	0.04
			0.06
			0.08
		1.4	0.04
			0.06
		1.6	0.04
		1.8	0.04
		2.0	0.04
	Regular	1.0	0.04
			0.06
			0.08
		1.2	0.04
			0.06
			0.08
		1.4	0.04
			0.06
			0.08
		1.6	0.04
			0.06
			0.08
		1.8	0.04
		2.0	0.04

Table 3.2 (c): Number of testing done throughout the experiment (D/d = 0.400)

c)

Water Draft, D	Wave Condition	Time Period	H/L
0.27	Random	1.0	0.04
			0.06
			0.08
		1.2	0.04
			0.06
			0.08
		1.4	0.04
			0.06
		1.6	0.04
		2.0	0.04
	Regular	1.0	0.04
			0.06
			0.08
		1.2	0.04
			0.06
			0.08
		1.4	0.04
			0.06
			0.08
		1.6	0.04
		1.8	0.04
		2.0	0.04

Table 3.2 (d): Number of testing done throughout the experiment (D/d = 0.443)

d)

Water Draft, D	Wave Condition	Time Period	H/L
0.31	Random	1.0	0.04
			0.06
			0.08
		1.2	0.04
			0.06
			0.08
		1.4	0.04
			0.06
		1.6	0.04
		2.0	0.04
	Regular	1.0	0.04
			0.06
			0.08
		1.2	0.04
			0.06
			0.08
		1.4	0.04
			0.06
			0.08
		1.6	0.04
		1.8	0.04
		2.0	0.04

3.4 Gantt Chart

In the first half of the study, the focus is more on the introduction and preparation towards the further study of the test model. Thus, it is important to have a Gantt chart in which will help in keeping track of the progress and proceed accordingly. The Gantt chart will give a clear indication on the tasks that will be done and to ensure the feasibility of the study as it is initially planned in the beginning of the study. The extended Gantt chart is shown in Figure 3.15.

3.5 Flow Chart of Research Activities

In completing the studies, a series of activities need to be done in order to ensure the feasibility of the study. These set of tasks will be done in a number of stages in order to ensure the unobstructed flow of the study. The flow chart of the research activities is given in Figure 3.16.

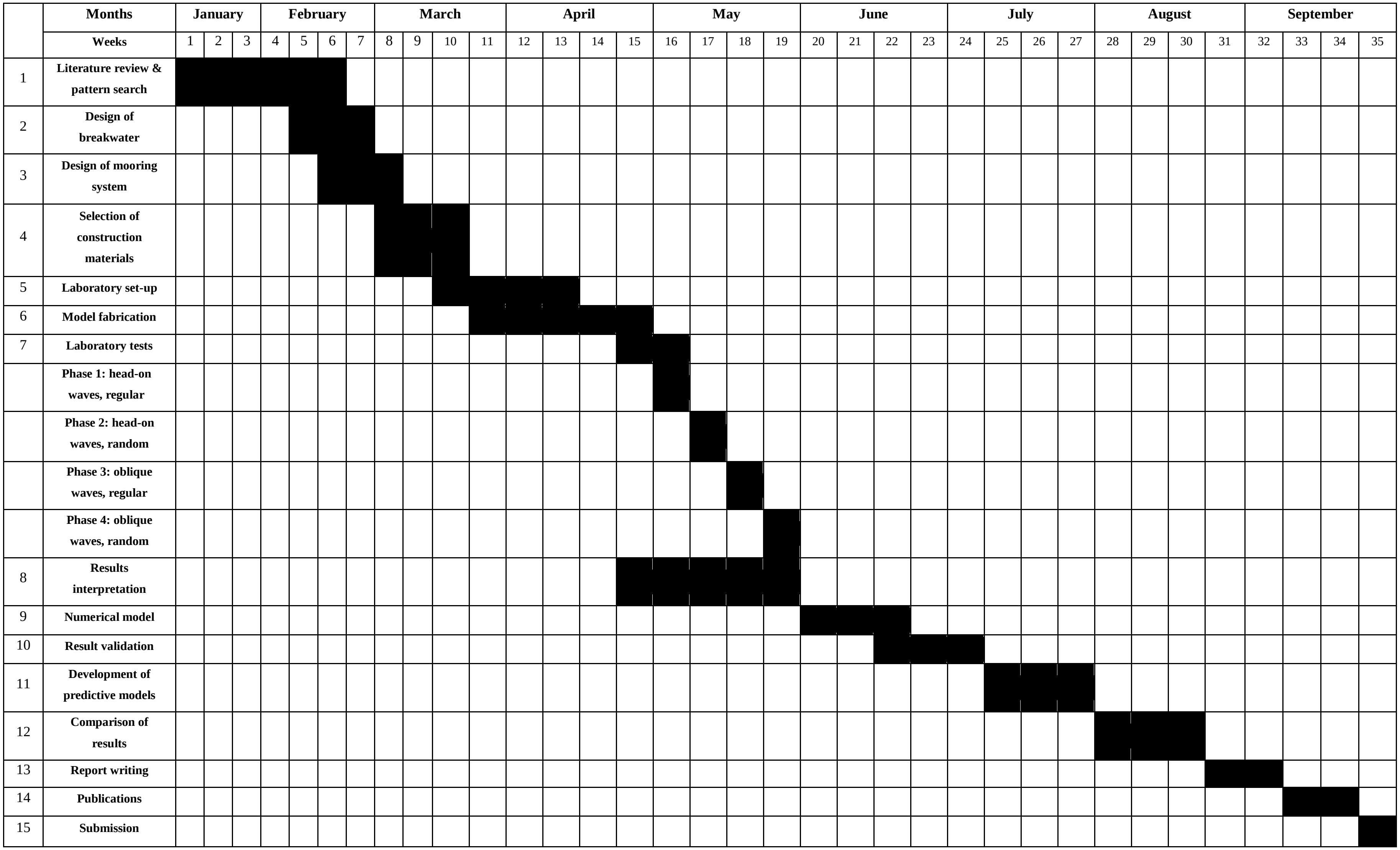


Figure 3.15: Extended Gantt chart of research activities

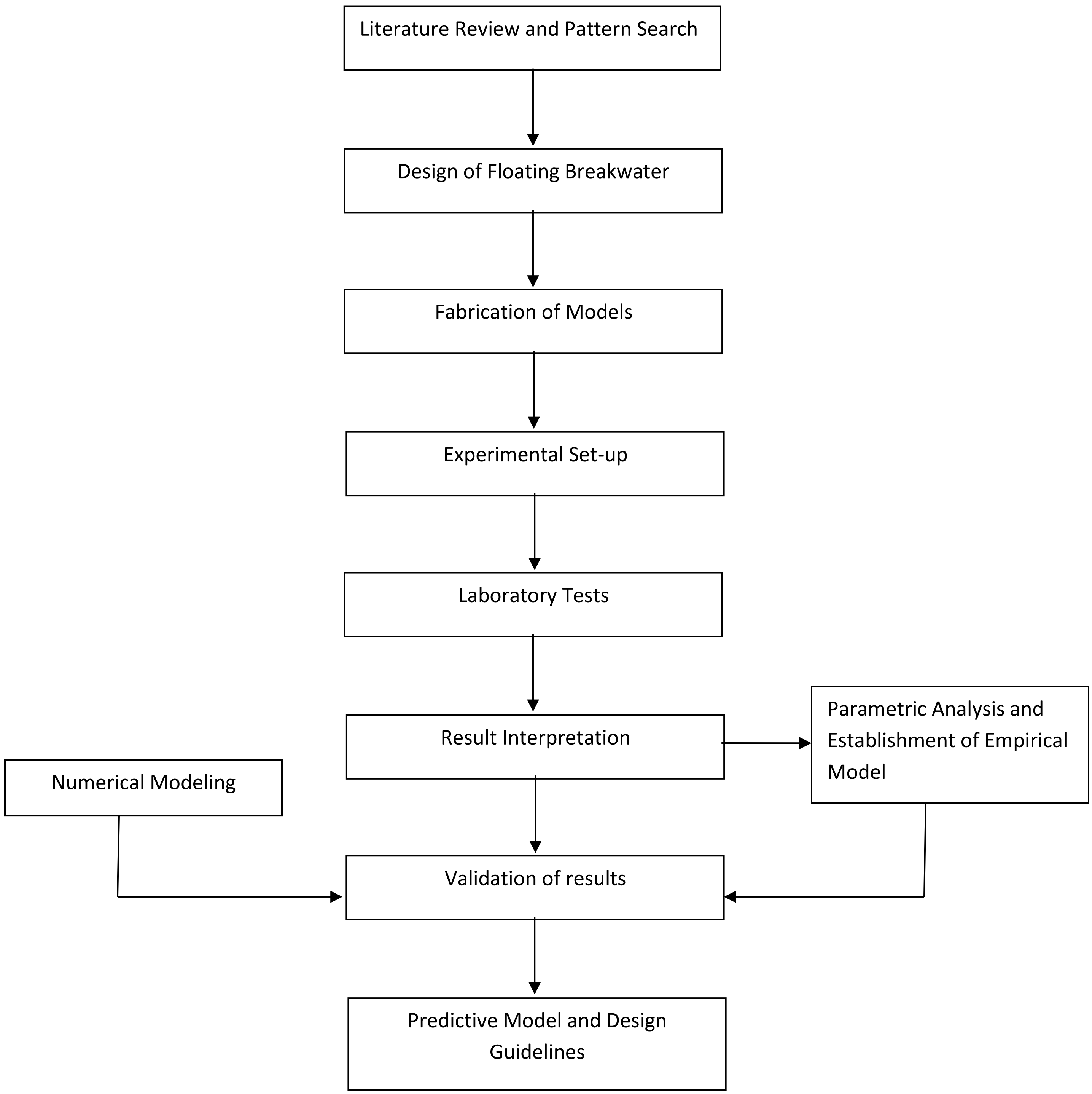


Figure 3.16: Flow Chart of Research Activities

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter presents the measured motion responses of the H-type floating breakwater in the forms of time series and frequency domains for each set of experiment conducted in the wave flume. These analyses are particularly important in providing better interpretations of the results in the later stage of the study. The details of the analyses are to be thoroughly discussed in this chapter. The motion responses (*i.e.* heave, surge and pictch) of the breakwater model are presented in respective Response Amplitude Operators (RAO). A parametric analysis is also conducted to give a complete representation of all the experimental tests that were carried out in this study, and some key conclusions are drawn at the end of this chapter.

4.1 Calibration of Wave Probes and Wave Flumes

The calibrations of the wave flume and wave probes will be done by using the three-point method proposed by Mansard and Funke (1985), as being mentioned in the previous chapter. The basis of this method is to measure simultaneously the waves in the flumes at three different points with an adequate distance between one set of probe to another. The wave probes will be located parallel to the wave's direction inside the wave flume. The set-up of all the equipment for the calibration is shown in the figure 4.1, where it indicates the length of the probes from the wave paddle (X1), the length of first probe to the second probe (X12) and the length of first probe to the third probe (X13). As according to the method, the proposed spacing between the probes is given as follows:

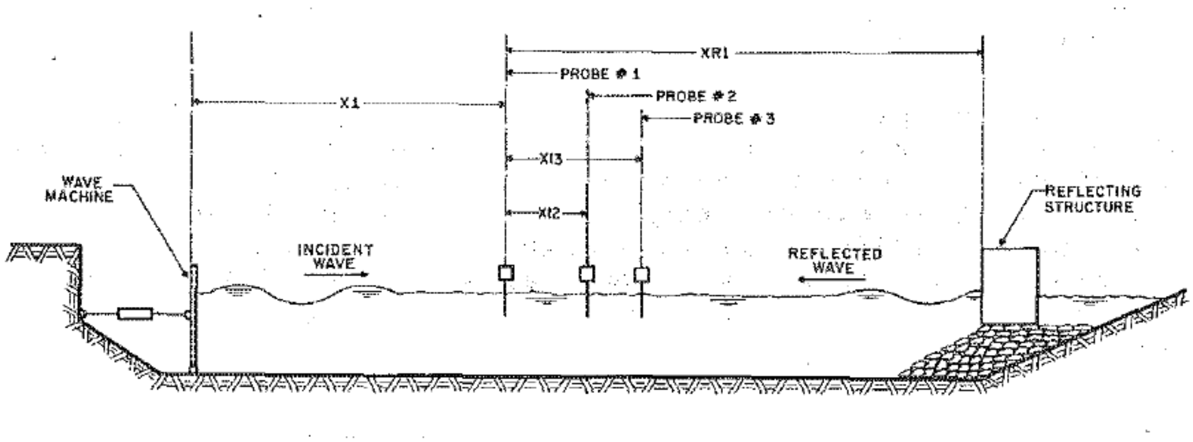


Figure 4.1: Three-point method calibration set up (Source: Mansard and Funke, 1985)

$X12 = L_p/10$ $L_p/6 < X13 < L_p/3$ $X13 \neq L_p/5$ and $X13 \neq 3L_p/10$

Where L_p is the overall length of the wave flume. The importance of following the spacing requirement as stated in the study is to ensure that there are no singularities in the wave probe readings. The distance between the final wave probes and the reflective structures is also being defined. The recommended distance between the two points must be at least one wave length away from each other.

Since this study will only be dealing with the regular waves testing, there are two options in which calibrations of the wave flume can be done. The calibration for the regular wave can be done by directly selected the pre-determined values of wave height and wave period for the testing into the computer software. The wave paddle will then be automatically adjusted to suit the numbers that have been commanded in the computer. However, the drawback of such method is that there might be some irregularities with the waves that will be produced. The actual reading of the wave that will be generated by the wave paddle might vary from the commanded values that have been key-in into the computer software. This happens due to the limitation of the software to get a fully accurate value of the wave properties in the wave flume, as well as other external factors that might affect these values. In order to overcome this drawback, the manual command method can be used.

In manual command method, the values of the wave parameters, such as the wave height and the frequencies, can be independently defined by the user itself. The advantage of using the command method is that the user can check the accuracy of the wave being generated by the wave paddles and then adjust them accordingly. This, however, need to be done in a series of trial-and-error method up until the desired value is achieved. This method proved to be more reliable and it helps to maintain the accuracy of the generated waves. The command that will be key-in into the software is in a script method, depending on the type of wave wanted to be produced by the user

As far as the study is concerned, it will only deal with regular waves. Thus, the following script can be used to calibrate the wave flume for a singular regular wave:

```
"begin

run "1 Hz 6 cm wave for 64 secs (1)" with (10)

makewave x=1.0*single (1, 0.06) on 1;

end; "
```

In the command given, the wave paddle is expected to produce wave with 6 cm wave height, at the frequency of 1Hz, or 1 second of wave period. However, the generated wave that being recorded by the wave probes might not give the similar values as the commanded values. Thus, the values must be corrected accordingly by introducing a gain value, represented by x, in which will adjust the wave parameters value. Since there are no definite ways to determine gain values, trial-and-error method is going to be used to calibrate the wave paddle until the reading on the wave probes result in the desired value. Based on this command, the data that have been collected can be synthesized and plotted in a series of graph and the expected pattern of the graph is represented in Figure 4.2. Based on the graph, the final gain value that will be used to get the desirable wave height can be found. For instance, assuming the graph in Figure 4.2 is the results of all the generated waves by using the trial-and-error command method, in order to generate 6 cm of wave heights on the wave paddle, the gain value of x=0.5 is to be used inside the command.

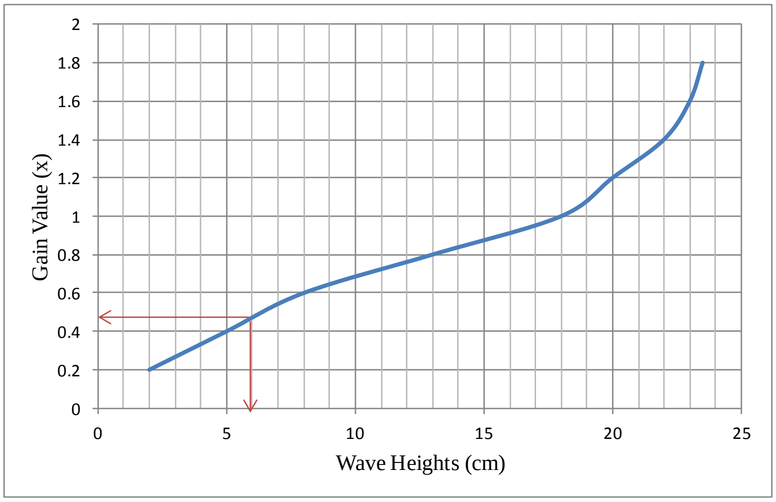


Figure 4.2: Expected pattern of gain value with respect to wave height reading on probes

4.2 Experiment Configuration

As being discussed in the previous chapter, the equipment that were used in this study were set-up inside a wave flume, which will generate the required wave conditions throughout the testing. The testing of the floating breakwater model will be done as planned, with four different water drafts, a number of distinguished wave periods and wave steepness of random and regular waves were being tested in order to study the effect of these drafts to the movement of the model as far as the RAOs are concerned. The placement of the model and the equipment is illustrated as shown in Chapter 3 (refer section 3.2.8). The full experiment configuration is illustrated in Figure 4.3.

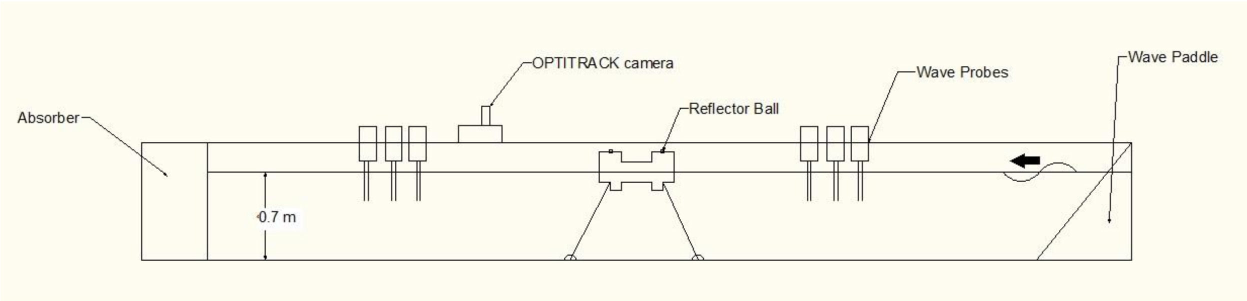


Figure 4.3: Experiment Set-up

4.3 Measured Results

Series of experiments were rigorously conducted in the wave flume to study the motion responses of the H-type floating breakwater in both regular and random waves. It is worthwhile to mention that only heave, surge and pitch motions are measured whilst the sway, roll and yaw motions are restricted by the setting of the experiment. These motions were recorded by an optical tracking system (OPTITRACK) operated by 3 high speed cameras (see Section 3.2.5 for more details). The present experiments considers two wave types (*i.e.* regular and random waves), three wave steepness (*i.e.* H_i/L = 0.04, 0.06 and 0.08) and four relative breakwater immersion depths (*i.e.* D/d = 0.243, 0.343, 0.400 and 0.443). Nevertheless, some tests involved high steepness waves could not be carried out in the wave flume due to mechanical restriction of the wave paddle. A total of 74 tests were completed within the capability of the test facilities and apparatus.

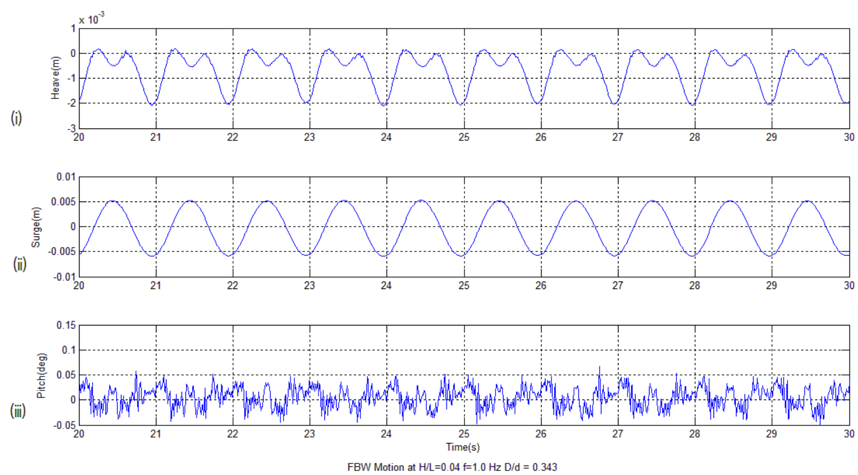
The motions of the H-type floating breakwater are often quantified by the Response Amplitude Operators (RAO), which is amplitude of motion relative to the wave amplitude. Higher RAO values indicate greater motion response at the degree of freedom, and vice versa. This section presents some samples of raw data and the related analyses of the data. Note that it is not possible to display the above results of all the tests conducted here as these will overload the thesis. The measured data were first observed using time series analysis and the characteristics of the data were subsequently assessed by the frequency domain analysis.

4.3.1 Time Series Analysis

The time series signals of heave, surge and pitch motions of the H-type floating breakwater subjected to regular waves of H_i/L = 0.04 are respectively plotted in a 10-s window with a start-up time of 20 s, as shown in Figure 4.4 (a). It is seen from the time series plots in the figures that the signals are rather regular in terms of the periods and amplitudes throughout the sampling period. Some irregularities are observed in the signals in regular waves due to the wave interference effect resulted by both incident and reflected waves in front of the test model.

For random waves of H_i/L_p = 0.04, the time series signals of heave, surge and pitch motions of the test model are respectively shown in Figure 4.4 (b), plotted in a start-up time of 20 s for a 30 s time window. It can be observed from the plots that the motion signals of the model become highly irregular, in which the amplitude of the waves are in a less uniform manner and are difficult to be quantified in time series manner.

(a)



(b)

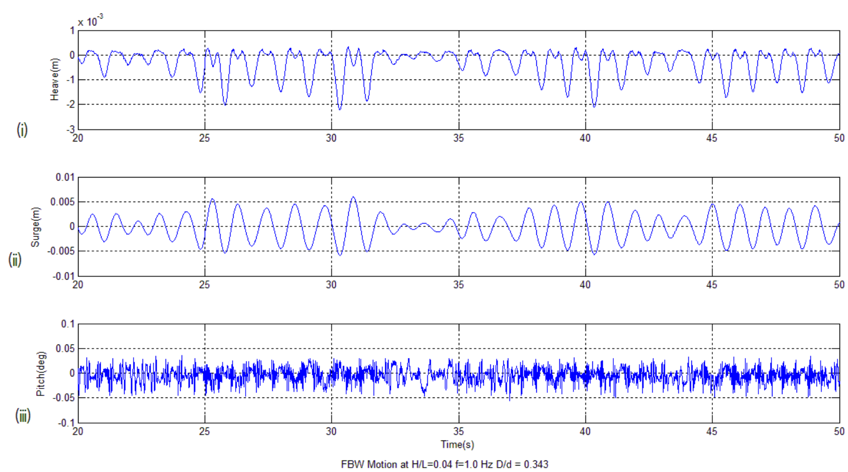


Figure 4.4: Time Series graph for (i) heave, (ii) surge and (iii) pitch responses for H/L = 0.04, frequency = 1.0 Hz, and D/d = 0.343 subjected to: (a) regular waves, and (b) random waves

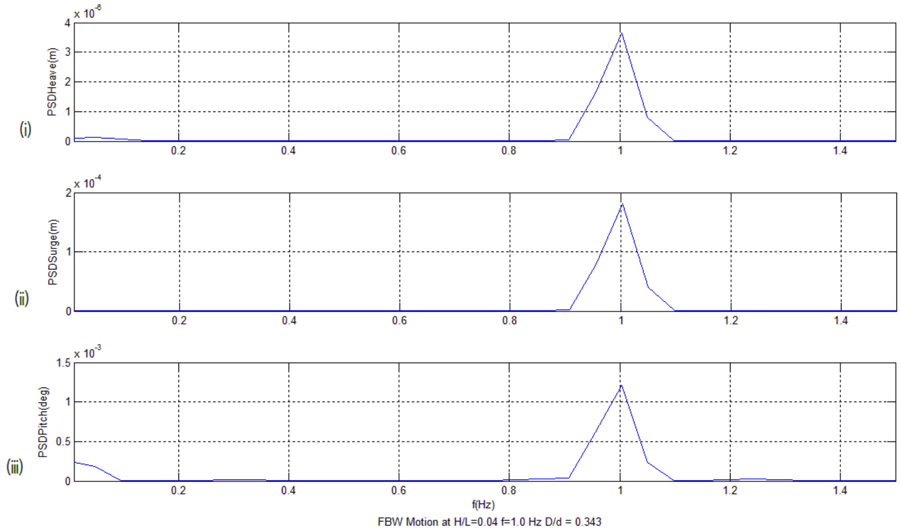
4.3.2 Frequency Domain Analysis

The characteristics of the regular signals might be feasibly and sufficiently evaluated using time series analysis. However, the characteristics of the irregular signals can only be identified by transforming the time series data into a frequency domain, where the *x*-axis appears in the form of frequency, *f* (unit: Hz) and the *y*-axis appears to be an energy density, *S*(*f*) (unit: m^2s). For this study, the use of JONSWAP spectrum was utilized in the conversion of the time series analysis graph into frequency domain analysis graphs.

Figure 4.5 shows the corresponding spectral energy densities of the time series signals for heave, surge and pitch motions of the H-type floating breakwater as shown in Figure 4.4. For regular wave condition, the energy of the respective motions surge at a particular frequency, in which the frequency is close to the natural period of the incident waves, and the energies at remaining frequencies are inappreciable. For instance, in Figure 4.5 (a), it can be observed that the amplitude of the spectral can be found peaking sharply at only one point of the spectral graph. The frequency in which this amplitude is found closely corresponded with the natural period of the incident waves

For the case of random waves, an inverted bell shape curve is distributed across the frequency domain whereby signals of various periods/frequencies and amplitudes are observed and the peak of the curve refers to the peak frequency of the motion mode. For instance, a significant energy density peak can be observed in all of the motion response graphs for heave, surge and pitch in frequency domain analysis, as can be observed in Figure 4.5 (b). However, whilst the peak is positioned almost at the same frequency as the natural period of the incident waves, which was also the case for regular waves, the spectral energy peak for random waves are less obvious, with the existence of some other energy spectral readings at both lower and higher frequency than the natural frequency of the incident waves.

(a)



(b)

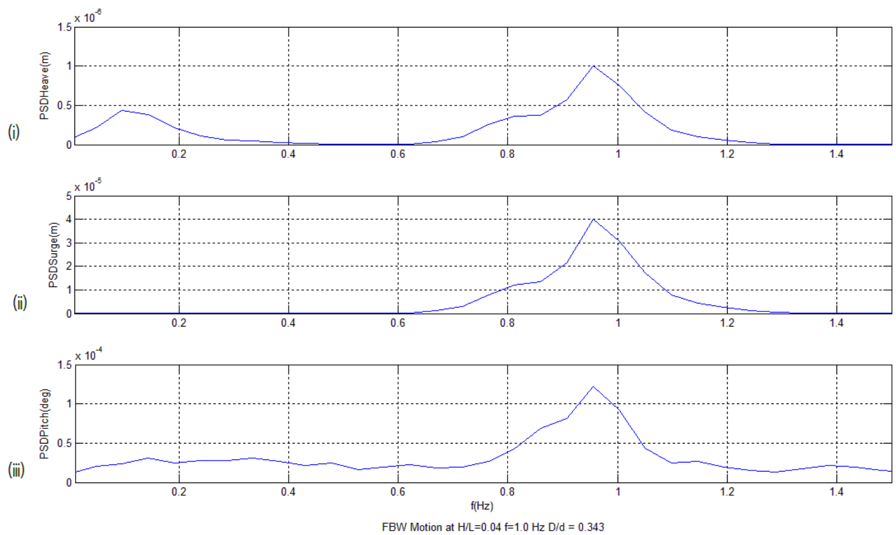


Figure 4.5: Energy Spectral Density graphs for (i) heave, (ii) sway and (iii) pitch responses for H/L = 0.04, frequency = 1.0 Hz, and D/d = 0.343 subjected to: (a) regular waves, and (b) random waves

4.4 Result Interpretation

Section 4.4.2 presents the variations of RAO in frequency domains for the H-type floating breakwater exposed to both regular and random waves. The RAO-peaks of the entire tests were recorded and evaluated based on the relative breakwater width, *B/L*, which is one of the most accepted design parameter for breakwaters. The RAO results for heave, surge and pitch motions of the test model exposed to regular and random waves of H_i/L = 0.04, 0.06 and 0.08 are to be thoroughly discussed in the following sections.

4.4.1 Response Amplitude Operators

In order to quantify the movement of the floating breakwater model with respect to the wave action acting on the model, a dimensionless parameter is used for the study. The dimensionless parameter, known as Response Amplitude Operator (RAO) defined as the motion response of the floating body per wave height amplitude. In the study, the motion response of the floating breakwater based on the energy spectral density with respect to the wave energy acting upon the floating breakwater model were being considered. As being mentioned in section 4.4, the study will only considered the three degree of freedom for the floating body, namely the heave, surge and pitch responses due to the limitations of the apparatus and equipments. Thus, the formula used to calculate the RAO for heave, surge and pitch motion is defined as follows:

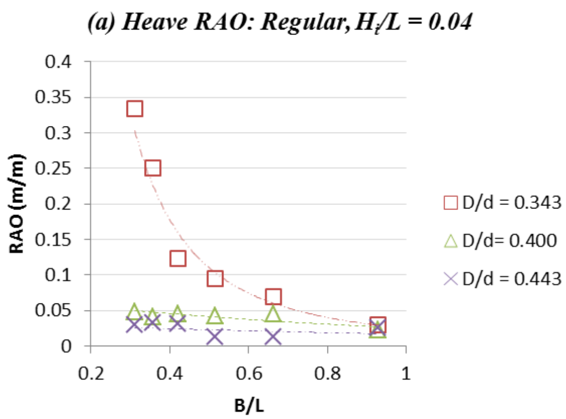
$$RAO_n({}^{m}/_{m}) = \sqrt{\frac{S_{f,motion}}{S_{f,wave}}} \tag{4.1}$$

Where RAO_n is the RAO response of the floating body (*n*= heave, roll, pitch), $S_{f,motion}$ is the amplitude of motion spectral energy response and $S_{f,wave}$ is the wave energy amplitude based on the spectral energy density graphs.

4.4.2 Heave

The peaked heave-RAOs for the H-type floating breakwater with taut leg mooring subjected to regular and random waves of H_i/L = 0.04, 0.06 and 0.08 are demonstrated in Figures 4.3, 4.4 and 4.5, respectively. The test model was immersed at four different ratios whereby D/d = 0.243, 0.343, 0.400 and 0.443, which are represented by different plots in the figures.

In mild regular wave environment (H_i/L = 0.04) as shown in Figure 4.6 (a), the heave-RAOs of D/d = 0.343, 0.400 and 0.443 decrease with an increase of B/L. This implies that the heave motion of the test model increase with the increasing period of the incident waves. This is sensible because the size (*i.e.* the width) of the breakwater is relatively small compared to the wavelength, and consequently the breakwater tends to move along with the incoming waves. On the other hand, the breakwater has more resistance towards smaller waves with shorter wavelength due to its higher effective mass in the water. It is also observed that the heave-RAOs decrease as D/d increases from 0.343 to 0.443, indicating that the test model heaves considerably in shallow drafts. This is also expected because the stability of the floating structure increases with the increasing immersion depth. In another word, the immersion part of the breakwater will act as ballast in retarding the movement of the structure when exposed to wave actions.



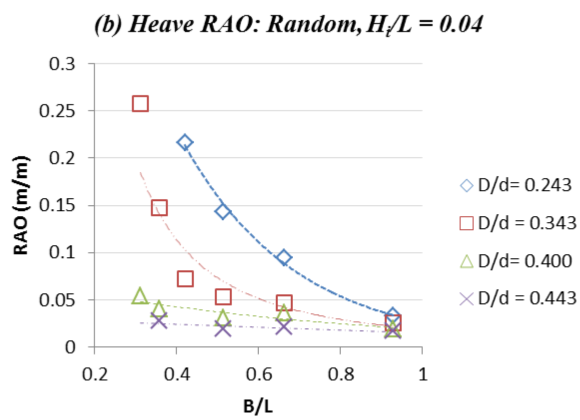


Figure 4.6: Peaked heave-RAOs of the test model subjected to milder wave condition (H_i/L = 0.04) subjected to: (a) Regular waves, and (b) Random waves

The heave-RAOs of the test model for random waves of mild condition (H_i/L = 0.04) is illustrated in Figure 4.6 (b). It is apparent from the figure that the heave-RAOs act in the same way as those of the regular waves when corresponding to *B/L* and *D/d*. The heave-RAOs of random waves might be a little lower than those of regular waves when the wave steepness is mild.

The heave-RAOs of the test model subjected to higher steepness waves (H_i/L = 0.06 and 0.08) are presented in Figures 4.7 and 4.8. Similarly, the heave-RAOs of the test model decreases with an increase of *B/L* and *D/d* in both regular and random waves. It is noticed that the heave-RAOs of regular waves are higher than those of random ones. Again, this is expected as the energy carried by the regular waves is higher than that carried by the random waves of the similar frequency within the given sampling period.

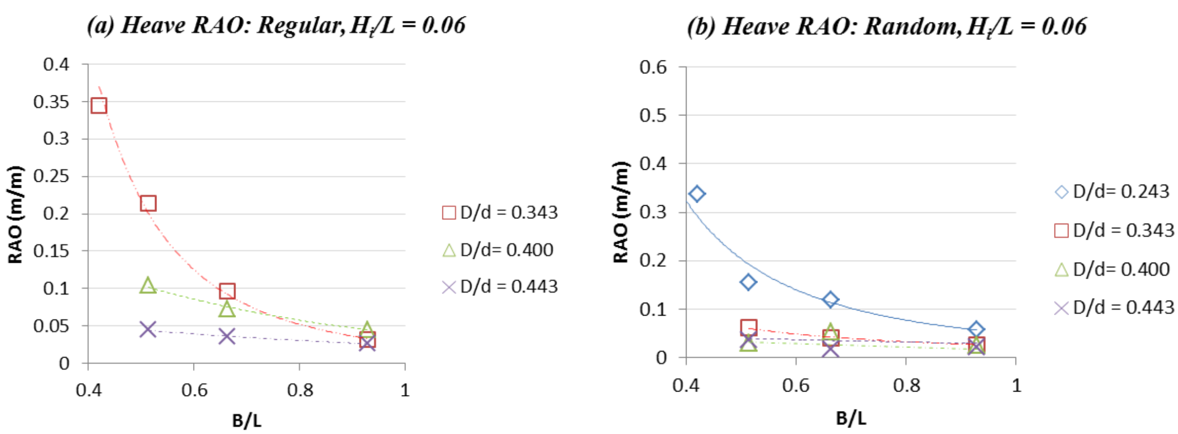


Figure 4.7: Peaked heave-RAOs of the test model subjected to moderate wave condition (H_i/L = 0.06) subjected to: (a) Regular waves, and (b) Random waves

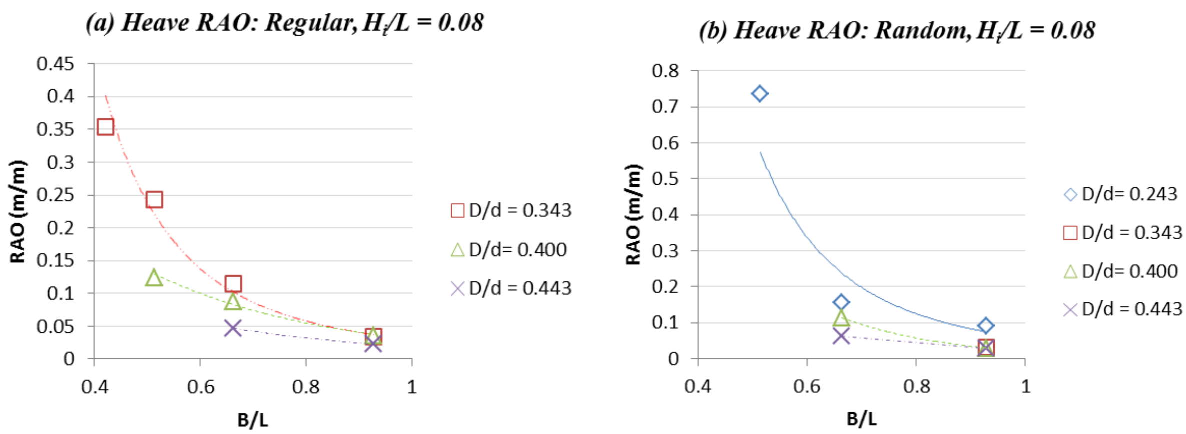


Figure 4.8: Peaked heave-RAOs of the test model subjected to severe wave condition (H_i/L = 0.08) subjected to: (a) Regular waves, and (b) Random waves

It is also worth to note that in the event of a steeper wave steepness (Hi/L = 0.06 and Hi/L = 0.08), it can be found that there is little significance in the difference of the heave-RAOs of the two wave steepness. This may be caused by the stable connection established by the mooring lines, in which restricted the movement of the floating breakwater. Thus, this is expected to cause very little response in the heave direction of motion, in which particularly affected the heave-RAO in the two wave steepness. This trend can be observed in both regular and random waves.

In the case of heave-RAO subjected to random waves, an additional peak can be observed at a lower frequency as compared to the dominant frequency at the same point as the incident waves, as shown in Figure 4.9. The additional peak at the lower frequency may be caused by the slodging effect, due to the effect of the movement of the model. Slodging effect caused a disturbance within the motion of the responses at a longer period, thus causing a slight increment in the heave-RAO at a lower frequency. This trend is more significant in random waves and can be found occuring at different wave period. It is also can be observed that the slodging effect is less significant in a higher draft, in which the connection are much more stable as compared to lower draft.

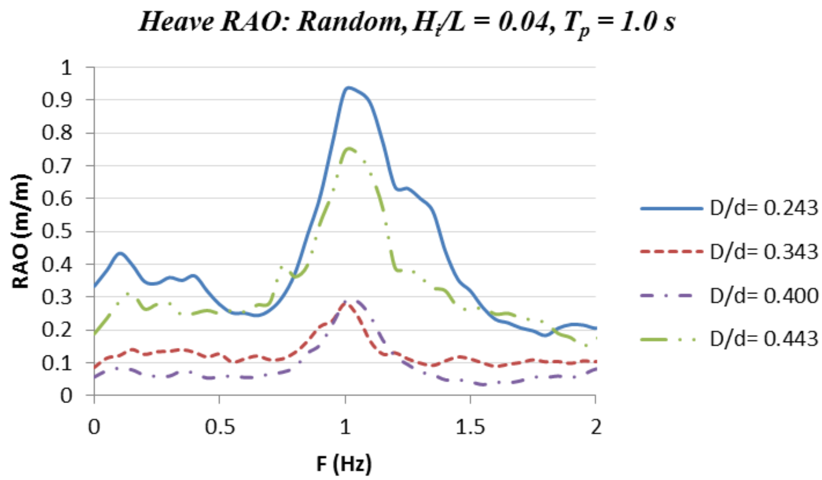


Figure 4.9: Variation of Heave-RAO of different water drafts subjected to random waves of H_i/L = 0.04, and Tp = 1.0s

4.4.3 Surge

The peaked surge-RAOs of the H-type floating breakwater exposed to both regular and random waves derived from the frequency domain analysis are shown in Figures 4.10-4.12. The format of the plots is similar to Figures 4.6-4.8. In mild regular and random wave environments (H_i/L = 0.04) as indicated in Figure 4.10, the surge-RAOs of $D/d \geq 0.343$ decrease with the increasing *B/L*. This can be explained by the fact that the surge motion of the floating structure is strongly governed by the advancing wavelength, *i.e.* the greater the magnitude of the wavelength, the larger will be the surge response of the breakwater. However, for $D/d < 0.343$ the variation of the RAOs with *B/L* is almost insignificant due to increased effective mass of the floating object in restricting the surge response of the structure as *D/d* increases. Besides, an increment of surge-RAOs is seen from Figure 4.10 as *D/d* decreases from 0.443 to 0.243. Once again, this is attributed to the increased effective mass of the floating body as it is further immersed in the water.

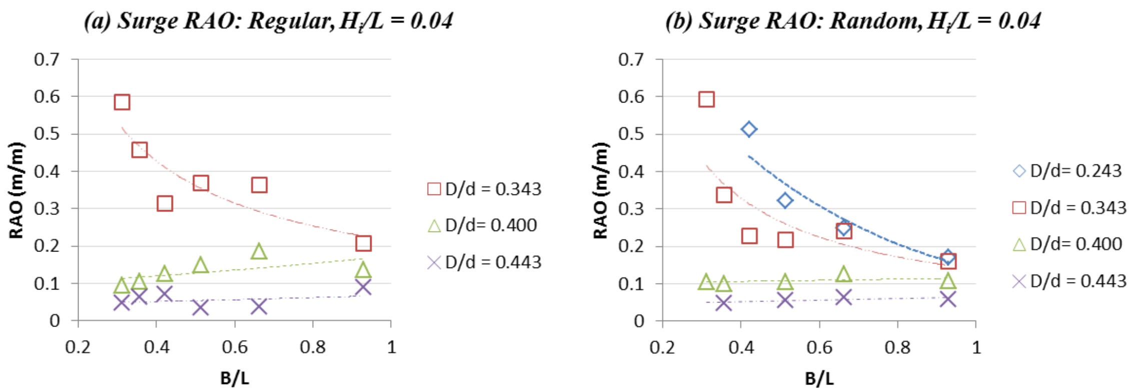


Figure 4.10: Peaked surge-RAOs of the test model subjected to milder wave condition (H_i/L = 0.04) subjected to: (a) Regular waves, and (b) Random waves

In steeper waves (H_i/L = 0.06 and 0.08), the surge-RAOs of regular and random waves are generally decrease at different rates with the increasing *B/L* and *D/d*. In comparison with the random waves, the surge-RAOs of the regular waves are much higher for $0.06 \leq H_i/L \leq 0.08$. The finding is expected as the floating bodies are more heavily driven by the rhythmic waves of constant beats and amplitudes than the irregular ones. No significant increment of surge-RAOs is observed as H_i/L increases from 0.06 to 0.08. This is due to that fact that the taut leg mooring lines restrict the model from surging further despite the increase of wave steepness.

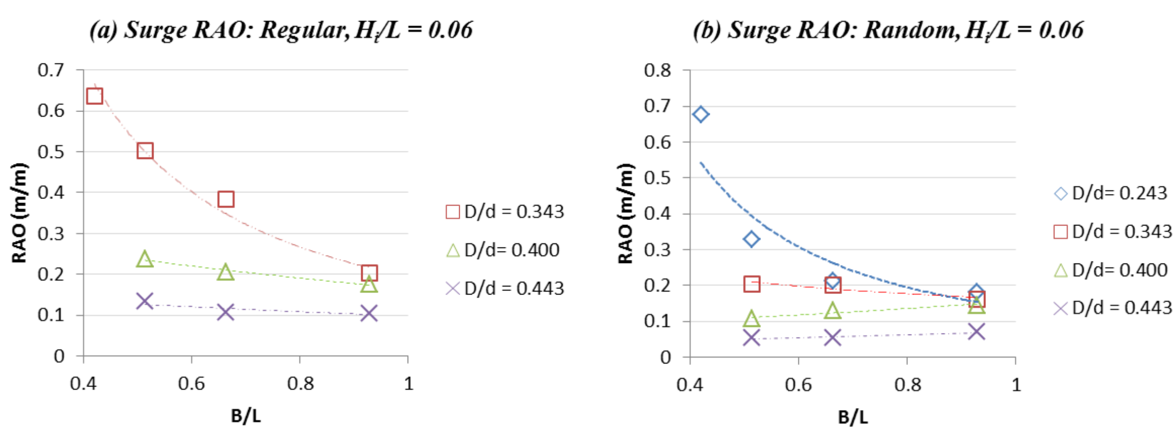


Figure 4.11: Peaked surge-RAOs of the test model subjected to moderate wave condition (H_i/L = 0.06) subjected to: (a) Regular waves, and (b) Random waves

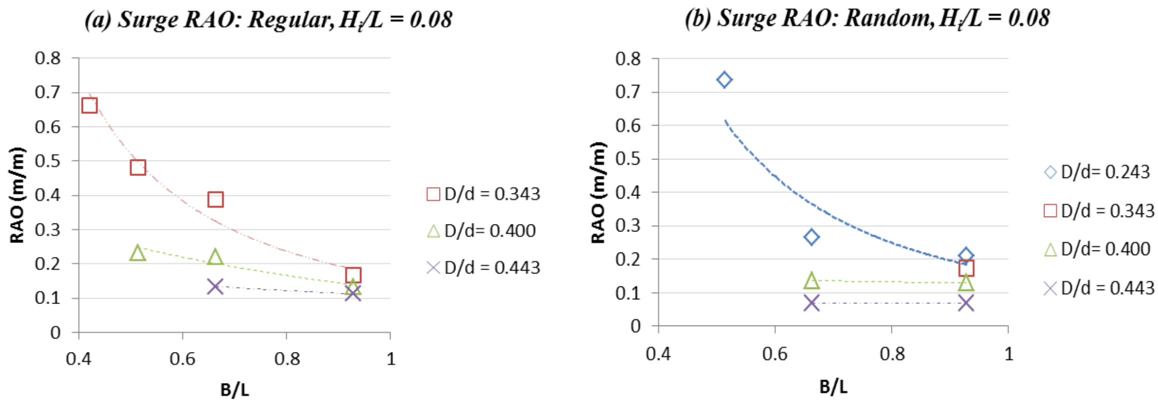


Figure 4.12: Peaked surge-RAOs of the test model subjected to severe wave condition (H_i/L = 0.08) subjected to: (a) Regular waves, and (b) Random waves

It was also found that in the case of surge responses subjected to regular waves, a secondary peak is occuring at exactly double the wave frequency at a particular wave period. The secondary peak, while having much smaller values for most of the cases, are occuring due to the effect of harmonic wave acting within the wave flume. The harmonic effect is common within a regular wave set-up and this pattern is largely expected. As can be observed in Figure 4.13, the harmonic effect due to this wave actions are recorded in the surge RAO responses graph, showing a relationship between the motion responses of the floating breakwater with the type of waves acting on it. In the figure, the secondary peak of the harmonic effect happened at exactly doubled the wave frequency of the particular period, which supports the earlier mentioned theory. Note that this pattern happens across all surge responses for all wave steepness subjected to only regular waves, but not in random waves.

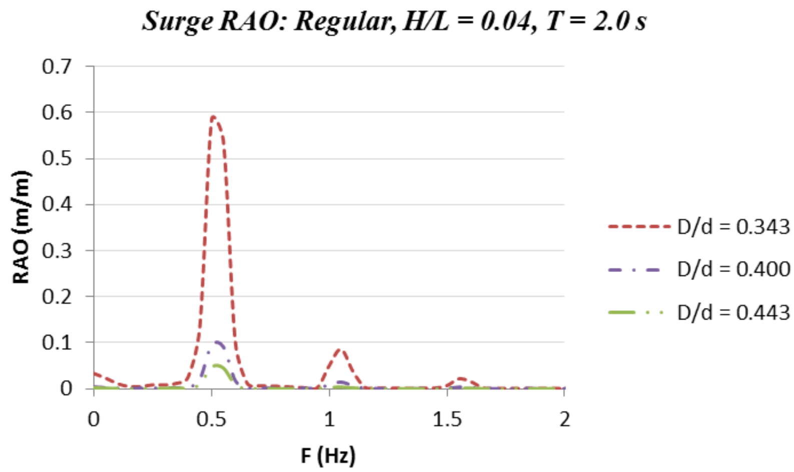


Figure 4.13: Harmonic effect of surge RAO for different water draft subjected to regular waves of *H/L* = 0.04 in period of *T* = 2.0s

4.4.4 Pitch

The pitch-RAOs of the H-type floating breakwater of different immersion depths subjected to both regular and random wave environments are demonstrated in Figures 4.14-4.16. For the case of mild steepness waves (H_i/L = 0.04) as shown in Figure 4.14, an increasing pitch-RAOs is seen for $D/d \leq 0.343$ as B/L increases. The pitch response of the model is found to be significant when immersed moderately. However, the RAOs are not sensitive to the change of B/L as $D/d > 0.343$. This is because the heavily immersed floating body is too stable to be disturbed from rotating along the horizontal trans-axial. It is noted from the Figure 4.14 that the pitch-RAOs are set off from the others in both regular and irregular waves. This might be due to the effect of wave overtopping on the limited freeboard floating body whereby waves overtop the crest of the floating breakwater resulting in clock-wise rotation (pitch).

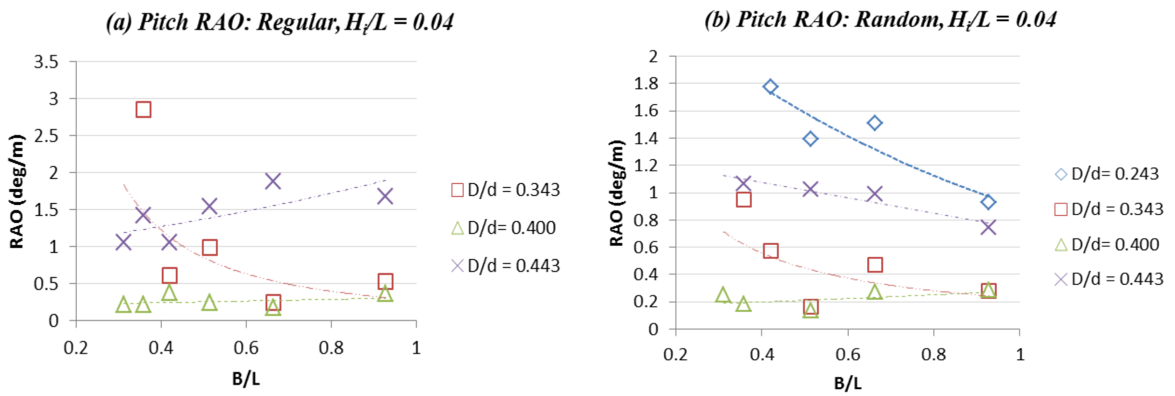


Figure 4.14: Peaked pitch-RAOs of the test model subjected to milder wave condition (H_i/L = 0.04) subjected to: (a) Regular waves, and (b) Random waves

At harsher wave conditions (H_i/L = 0.06 and 0.08), similar observations of the pitch-RAOs were obtained. As the breakwater is largely immersed, the pitch-RAOs surge considerably due to the increased number of wave overtopping events on the floating breakwater. It is worthwhile to report that there is a little variation of the surge-RAOs in both H_i/L = 0.06 and 0.08. This is mainly attributed to the restriction caused by the mooring lines.

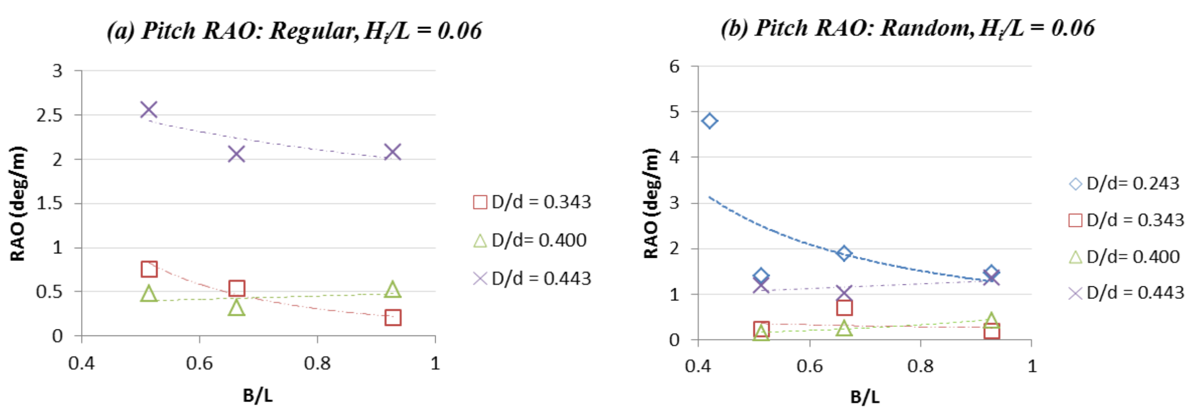


Figure 4.15: Peaked pitch-RAOs of the test model subjected to moderate wave condition (H_i/L = 0.06) subjected to: (a) Regular waves, and (b) Random waves

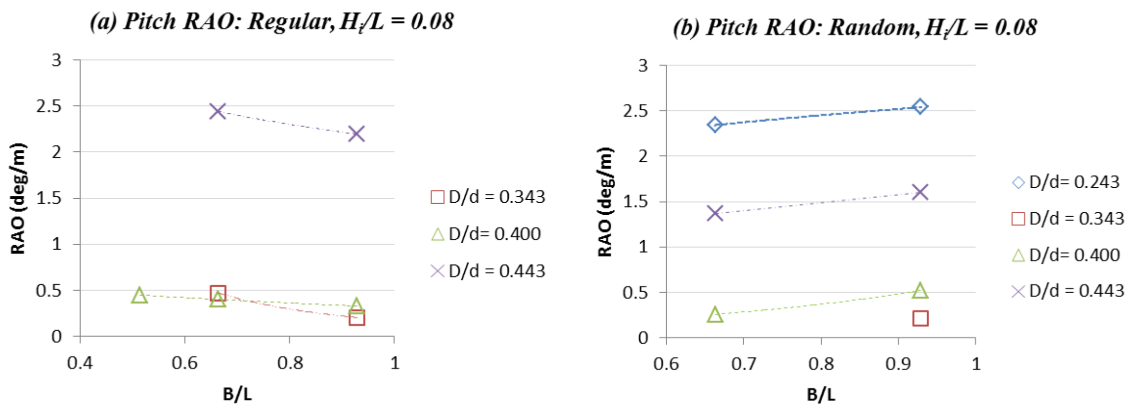


Figure 4.16: Peaked pitch-RAOs of the test model subjected to severe wave condition (H_i/L = 0.08) subjected to: (a) Regular waves, and (b) Random waves

As far as the changes pattern for the pitch-RAO is concerned, it is worth to note that the pitch responses carried no specific pattern with the changes in the breakwater draft and the wave period. Thus, the pitch motion is considered to be less predictable. Hence, it is important to consider the effect of pitch responses in the process of designing the breakwater. As being mentioned in the earlier part, the rotational changes are less sensitive in a stable connection, in which causes such pattern as far as pitch-RAO is concerned.

4.5 Concluding Remarks

The study of motion responses of the H-type floating breakwater is important in understanding the movement behavior of the structure when subjected to different wave conditions. This information serves as a basis or reference to the floating breakwater design in which the performance is not merely based on the structure configurations. The raw data of the existing experiment were evaluated by both time series and frequency domain analyses, for which the peaked-RAOs for heave, surge and pitch were identified numerically. These data were subsequently represented in a dimensionless design graphs for the ease of interpretation. In comparison with the primary motions of the floating breakwater, it was found that the surge response of the structure is more severe than the heave response particularly at smaller immersion depths. Pitch response of the breakwater is another important aspect to be considered in the design of the mooring lines to the H-type floating breakwater if wave overtopping is allowed. The motion responses in terms of RAO obtained from this study will help to provide valuable information, especially in the design of the mooring connection of the breakwater. Each RAO values obtained in the study carried a unique representation on the motion responses and the wave actions based on different set of conditions of the floating breakwater. The heave, surge and pitch RAOs can be used to predict the respective motion responses of the floating breakwater given the particular wave conditions.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The analysis that has been conducted throughout this study has yielded a few major conclusions. These are the conclusion that can be made based on the end products of the study:

- The motion responses of the floating breakwater vary significantly with the changes in the water draft. This is clearly shown in the RAO results that have been obtained in the study, particularly of heave and surge RAOs. As the draft of the floating breakwater increases, a significant restriction to the movement of the floating breakwater can be observed, causing a significant decrease in RAO values.
- As the wave period increases, causing a decreased in the wave frequency, the motion of the floating breakwater can be seen significantly increasing. The increased in the motion responses particularly can be observed through the increasing values of the RAO recorded based on the study. This was the case for both regular and random waves. The increment in the wave period caused a higher energy within the wave system, in which causes more vigorous movement of the floating breakwater. The trend is recorded in all three degree of motions, regardless of the water draft.
- The effect of wave steepness are particularly minimal in both heave and surge RAOs, especially at more severe wave condition (H/L = 0.06 and H/L= 0.08). The difference of the heave and surge RAOs at higher wave steepness is considered to be very minimal. However, in the case of pitch RAO, the effect of wave steepness for all the three cases

that have been tested (*H/L* = 0.04, 0.06, 0.08) is appeared to be very significant. This pattern occurred under both regular and random waves.

- Both heave and surge RAO have a definite trend with respect to the changes in the system, as far as the breakwater draft and the wave period are concerned. As for pitch RAO, no definite trend can be observed with respect to the changes, with the motion responses are acting in a less predictable manner.
- The usage of RAO can help to predict the motion responses of the floating breakwater with respect to the wave actions. Each motion responses will give different RAO value and this is clearly shown in the data obtained from this study, for both regular and random waves.
- The RAO values obtained in this study is rather significance in providing information in the design of the H-type floating breakwater. The RAO of motion response of heave, surge and pitch obtained in this study will help the designer in predicting the behavior of the floating breakwater in real sea and thus, help to decide on the optimum mooring configurations for the H-type floating breakwater depending on the wave conditions of the sea state.
- The experimental procedure carried out in this study has shown some promising end products on the response of the H-type floating breakwater with respect to wave actions. The study has also met its primary objectives in analyzing the behavior of the floating breakwater under both regular and random waves.

5.2 Recommendations

The recommended activities that can be done in the future in order to enhance further potential of the study are given as follows:

- The study of the forces in the mooring lines can be done in order to study the effect of the mooring lines towards the motion responses of the floating breakwater. The mooring lines recorded data, coupled with the data obtained from this study, will produce a valuable information which will assist in the design of the floating breakwater in real life applications
- In order to verify the potential of the system used in the study, a separate study of the H-type floating breakwater moored with other type of mooring configurations can be done. Such study considered to be helpful, as comparison of the motion responses and the performance of the floating breakwater can be evaluated in order to obtain an optimum configurations for the H-type floating breakwater
- The scale effect study of the H-type floating breakwater can be done in the future. This piece of information will help in further verifying the RAO values obtained from this study and tested on the effect of scaling of the testing to the RAO values
- The study can be repeated at a bigger scale by using bigger facilities, such as wave tank, and better equipment with better capabilities. An upgraded version of the study can be done by fully obtained all of the 6 degree of freedom responses and their RAOs due to various wave conditions. The response of the mooring lines during the testing can also be recorded in order to study the hydrodynamic forces acting on the mooring lines for a more advanced analysis of the data.

REFERENCES

Abdl-Azm, A.G. and Gesraha, M.R., (2000). Approximation to the hydrodynamics of floating pontoons under oblique waves. *Ocean Engineering*, **27**(4), pp. 365-384.

Chen, X., Zhang, J., Johnson, P. and Irani, M., (2001). Dynamic analysis of mooring lines with inserted springs. *Applied Ocean Research*, **23**(5), pp. 277-284.

Diamantoulaki, I. and Angelides, D.C., (2010). Analysis of performance of hinged floating breakwaters. *Engineering Structures*, **32**(8), pp. 2407-2423.

Diamantoulaki, I. and Angelides, D.C., (2011). Modeling of cable-moored floating breakwaters connected with hinges. *Engineering Structures*, **33**(5), pp. 1536-1552.

Diamantoulaki, I., Angelides, D.C. and Manolis, G.D., (2008). Performance of pile-restrained flexible floating breakwaters. *Applied Ocean Research*, **30**(4), pp. 243-255.

Fousert, M.W., **(**2006). Floating breakwater: A theoretical study of a dynamic wave attenuating system. Faculty of Civil Engineering and Geosciences, Delft University of Technology.

Garza-Rios, L., Bernitsas, M., Nishimoto, K., (1997). Caternary mooring lines with nonlinear drag and touchdown. Department of Naval Architecture and Marine Engineering, College of Engineering, University of Michigan

Gesraha, M.R., (2006). Analysis of shaped floating breakwater in oblique waves: I. Impervious rigid wave boards. *Applied Ocean Research*, **28**(5), pp. 327-338.

Gobat, J.I. and Grosenbaugh, M.A., (2001). A simple model for heave-induced dynamic tension in catenary moorings. *Applied Ocean Research*, **23**(3), pp. 159-174.

He, F., Huang, Z. and Wing-Keung Law, A., (2012). Hydrodynamic performance of a rectangular floating breakwater with and without pneumatic chambers: An experimental study. *Ocean Engineering*, **51**(0), pp. 16-27.

Hegde, A., Kamath, K. and Magadum, A., (2007). Performance characteristics of horizontal interlaced multilayer moored floating pipe breakwater. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, **133**(4), pp. 275-285.

Huang, W., Liu, H., Lian, Y. and Li, L., (2013). Modeling nonlinear creep and recovery behaviors of synthetic fiber ropes for deepwater moorings. *Applied Ocean Research,* **39**(0), pp. 113-120.

Leach, P., McDougal, W. and Sollitt, C., (1985). Hinged floating breakwater. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* **111**(5), pp. 895-909.

Lee, J., & Cho, W. (2003). Hydrodynamic analysis of wave interactions with a moored floating breakwater using the element-free Galerkin method. *Canadian Journal of Civil Engineering*, **30**(4), pp. 720-733.

Loukogeorgaki, E. and Angelides, D.C., (2005). Performance of moored floating breakwaters. *International Journal of Offshore and Polar Engineering*, **15**(4), pp. 264-273.

Loukogeorgaki, E. and Angelides, D.C., (2005). Stiffness of mooring lines and performance of floating breakwater in three dimensions. *Applied Ocean Research,* **27**(4–5), pp. 187-208.

Mani, J. and Jayakumar, S., (1995). Wave transmission by suspended pipe breakwater. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, **121**(6), pp. 335-338.

Mansard, E., Funke,E., (2011). The measurement of incident and reflected spectra using a least squares method. *Coastal Engineering Proceedings,* **1**(17),.

Manuel, B., (1997). Response of a pile restrained floating breakwater, Department of Civil Engineering, University of Western Ontario, Canada

Matulea, I.C., Năstase, A., Tălmaciu, N., Slămnoiu, G. and Gonçalves-Coelho, A.M., (2008). On the equilibrium configuration of mooring and towing cables. *Applied Ocean Research*, **30**(2), pp. 81-91.

Mavrakos, S.A., Papazoglou, V.J., Triantafyllou, M.S., Chatjigeorgiou, J., (1996). Deep water mooring dynamics, Marine Structures, 9, pp. 181-209.

Mays, T.W., Plaut, R.H. and Liapis, S.I., (1999). Three-dimensional analysis of submerged, moored, horizontal, rigid cylinders used as breakwaters. *Ocean Engineering,* **26**(12), pp. 1311-1333.

McCartney, B., (1985). Floating breakwater design. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* **111**(2), pp. 304-318.

Murali, K. and Mani, J., (1997). Performance of cage floating breakwater. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* **123**(4), pp. 172-179.

Nielsen, F.G. and Bindingbø, A.U., (2000). Extreme loads in taut mooring lines and mooring line induced damping: An asymptotic approach. *Applied Ocean Research,* **22**(2), pp. 103-118.

Ozeren, Y., Wren, D., Altinakar, M. and Work, P., (2011). Experimental investigation of cylindrical floating breakwater performance with various mooring configurations. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* **137**(6), pp. 300-309.

Peña, E., Ferreras, J. and Sanchez-Tembleque, F., (2011). Experimental study on wave transmission coefficient, mooring lines and module connector forces with different designs of floating breakwaters. *Ocean Engineering,* **38**(10), pp. 1150-1160.

Rahman, M.A., Mizutani, N., Kawasaki,K., (2006). Numerical modeling of dynamic responses and mooring forces of submerged floating breakwater. *Coastal Engineering*, **53**(10), pp. 799-815

Ridge, I.M.L., (2009). Tension–torsion fatigue behaviour of wire ropes in offshore moorings. *Ocean Engineering,* **36**(9–10), pp. 650-660.

Ruol, P. and Martinelli, L., (2007). Wave flume investigation on different mooring systems for floating breakwaters. *Submitted to Coastal Structures,* **7**.

Sannasiraj, S.A., Sundar, V. and Sundaravadivelu, R., (1998). Mooring forces and motion responses of pontoon-type floating breakwaters. *Ocean Engineering,* **25**(1), pp. 27-48.

Shazwina, A.R., (2006). Wave attenuation performances of wave suppress system (WSS) with respect to various mooring configurations. Department of Civil Engineering, Universiti Teknologi PETRONAS

Tahar, A. and Kim, M.H., (2008). Coupled-dynamic analysis of floating structures with polyester mooring lines. *Ocean Engineering*, **35**(17–18), pp. 1676-1685.

Whiteside, N.H., (1994). Performance of a circular cross-section moored floating breakwater. faculty of graduate studies, Civil Engineering Department, University of Alberta, Canada

Williams, A.N., Lee, H.S. and Huang, Z., (2000). Floating pontoon breakwaters. *Ocean Engineering*, **27**(3), pp. 221-240.