Experimental investigation of pile-supported/floating breakwaters integrated with oscillating-water-column converters

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**NANYANG
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UNIVERSITY**

**EXPERIMENTAL INVESTIGATION OF
PILE-SUPPORTED/FLOATING BREAKWATERS
INTEGRATED WITH
OSCILLATING-WATER-COLUMN CONVERTERS**

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2013

**Experimental Investigation of
Pile-Supported/Floating Breakwaters Integrated
with Oscillating-Water-Column Converters**

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ABSTRACT

Nowadays, more than half of the world population live in coastal regions, and coastal areas are vital with many economic benefits. Breakwaters are commonly used to protect harbors and coasts from wave attack.

Traditional bottom-sitting breakwaters can effectively fulfill the demands of harbor protection in places where water is relatively shallow. However, the heavy traffic and large ship tonnage due to rapidly-developed international trade and maritime transportation are demanding much deeper water depth in harbors. As a result, new harbors are extending towards the ocean and traditional bottom-sitting breakwaters are no longer suitable economically. There is a need for new types of breakwaters that can effectively and economically be deployed in places where water is deep or bottom foundation is weak.

Since wave energy mainly concentrates near the water surface, and exponentially decreases with increasing distance from the water surface, pile-supported breakwaters and floating breakwaters may be good alternatives to traditional breakwaters. Most of the existing designs make use of vortex shedding, turbulence and/or wave breaking to enhance dissipation of wave energy. However, wave energy can also be used for electricity generation, and integration of a wave energy converter into a breakwater potentially can be a promising technology for waste-to-energy.

The structural simplicity, operating principle and their adaptability make oscillating-water-column types of converters very suitable for being integrated into breakwaters. The civil construction dominates the cost of most coastal structures, and integration of an oscillating-water-column converter into breakwater make it

possible to share the construction costs between power generation and harbor protection.

In this thesis, four novel designs, which are multi-functional and low in construction costs, were investigated experimentally. All these designs were originated with the idea of integrating a wave energy converter into a pile-supported/floating breakwater:

(1) Hydrodynamic performance of a pile-supported oscillating-water-column structure as a breakwater was experimentally investigated. The wave-transmission performance of the pile-supported OWC structure was remarkable compared with other types of pile-supported breakwaters, and the pile-supported OWC structure also had the potential for wave energy utilization.

(2) Hydrodynamic performance of two configurations of a pneumatic chamber in front of a vertical wall was experimentally investigated to examine their performance in reducing wave reflection. For a pneumatic chamber without a top opening, large energy dissipation occurred in a narrow range of frequency when the water column within the gap responded to incoming waves resonantly, resulting in very small reflection coefficients. For a pneumatic chamber with a small top opening, energy dissipation came mainly from the air flow through the small top opening and the vortex shedding at the tips of the pneumatic chamber walls; both small reflection coefficients and large energy extraction efficiencies were achieved when the rear wall of the pneumatic chamber is part of the vertical wall.

(3) Hydrodynamic performance of a floating breakwater with and without pneumatic chambers was experimentally investigated. The installation of pneumatic chambers to both sides of a floating breakwater was more effective for wave transmission reduction, and also had the potential for simultaneous wave energy conversion for electricity generation. However, given the same geometry of the two

pneumatic chambers, the rear chamber did not function as efficiently as the front chamber in terms of extracting wave energy.

(4) Hydrodynamic performance of a floating breakwater with asymmetric pneumatic chambers (a narrower chamber on the seaside and a wider chamber on the leeside) was experimentally investigated. The breakwater with asymmetric chambers performed as good as that with symmetric chambers in terms of wave transmission and motion responses. Meanwhile, an asymmetric configuration made it possible to increase the amplitude of the oscillating air-pressures inside both chambers without sacrificing the breakwater function.

The experimental investigation in this thesis demonstrated that integrating an oscillating-water-column converter into a pile-supported/floating breakwater could achieve both wave transmission reduction and wave energy extraction.

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LIST OF SYMBOLS

A_i	Incident wave amplitude
A_r	Reflected wave amplitude
A_t	Transmitted wave amplitude
A_{rb}	Amplitude of wave reflected from beach
A_w	Amplitudes of the water surface displacement in the gap
$A_{\bar{\eta}}$	Amplitude of averaged surface elevation inside the pneumatic chamber
A_{surge}	Amplitude of surge translation
A_{heave}	Amplitude of heave translation
A_{pitch}	Amplitude of pitch rotation
B	Breadth of the pneumatic chamber in Chapters 2&3 Breadth of floating breakwater bottom in Chapters 4&5
B_f	Breadth of front pneumatic chamber of floating breakwater
B_r	Breadth of rear pneumatic chamber of floating breakwater
C_r	Reflection coefficient
C_t	Transmission coefficient
C_d	Energy-dissipation coefficient
C_p	Pressure coefficient
C_a	Amplification coefficient
C_v	Vortex-shedding induced energy-dissipation coefficient
D	Outer diameter of the turbine rotor
D_r	Model draft

E_i	Incident wave energy per unit wave crest
E_r	Reflected wave energy per unit wave crest
E_t	Transmitted wave energy per unit wave crest
E_d	Dissipated wave energy per unit wave crest
G	Gap size between pneumatic chamber rear wall and vertical wall
g	Gravitational acceleration
H_i	Incident wave height
H_r	Reflected wave height
H_t	Transmitted wave height
h	Water depth
K	An empirical constant of the turbine
L	Wave length
l	Still water length of the water column
l'	Added length due to added mass
M	Mass
M_a	Added mass
N	Rotational speed of turbine blades
P_{out}	Period-averaged power extracted by a linear turbine
$\bar{P}_i$	Incident wave power per unit crest width
$\bar{P}_o$	Period-averaged power output of the pneumatic chamber per unit length
p	Pressure in the air inside the pneumatic chamber
RAO_{surge}	Surge RAO
RAO_{heave}	Heave RAO
RAO_{pitch}	Pitch RAO

S	Distance from pneumatic chamber front wall to vertical wall in Chapter 3 Waterline surface in Chapter 5
S_c	Pneumatic chamber cross-section area
S_o	Opening area
T	Wave period
T_{OWC}	Natural period of oscillating water column
T_{heave}	Natural period of the heave response of the breakwater
t	Time instant
t_0	Initial time instant
V	Volume of the air trapped inside the pneumatic chamber
v	Vertical velocity
v_{water}	Vertical velocity of water surface inside pneumatic chamber
v_{air}	Vertical velocity of airflow on the orifice or narrow slot
W	Distance from pneumatic chamber center to vertical wall in Chapter 3 Total breakwater width in Chapter 5
ΔP	Pressure fluctuation inside the pneumatic chamber
ε	Opening ratio in Chapter 2 Pneumatic energy extraction efficiency in Chapter 3
$\langle \eta \rangle$	Spatial-averaged surface elevation inside the pneumatic chamber
η	Surface elevation inside the pneumatic chamber
k	Wave number
ζ	Vertical displacement of the top of the pneumatic chamber
ξ	Heaving contribution to ζ
$r\theta$	Pitching contribution to ζ
r	Distance from the center of the chamber to the center of rotation

θ	Angle of rotation; clockwise direction is positive
ρ	Water density
ρ_a^0	Air density at rest
χ	A parameter describing the opening shape
ω	Wave angular frequency

LIST OF ABBREVIATIONS

AWACS	Active Wave Absorption Control System
CG	Center of Gravity
FB	Floating breakwater
OWC	Oscillating water column
PS	Pressure sensor
WC	Web camera
WEC	Wave energy converter
WG	Wave gauge

LIST OF PUBLICATIONS

He, F., Huang, Z. H., Law, A. W. K., (2013). "An experimental study of a floating breakwater with asymmetric pneumatic chambers for wave energy extraction". Applied Energy 106, 222-231.

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NOTES

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Chapter 5: He, F., Huang, Z. H., Law, A. W. K., (2013). "An experimental study of a floating breakwater with asymmetric pneumatic chambers for wave energy extraction". *Applied Energy* 106, 222-231.

CHAPTER 1 INTRODUCTION

1.1 Background

1.1.1 Breakwaters

Nowadays, more than half of the world population live in coastal regions, which are usually within about 200 kilometers from coastlines (Creel, 2003), and this figure keeps growing. Coastal areas are vital with many economic benefits, including international trade, maritime transportation, industrial development, urbanization, travel and tourism, and fishery. It is advisable to protect and maintain the coasts from wave attack, and breakwaters are commonly used for this purpose throughout the world.

A breakwater can reduce wave heights to an acceptable level in its leeside to prevent wave attack on the coast, a harbor or other artificial coastal structures. Traditional breakwaters are vertical caisson breakwaters, rubble mound breakwaters and composite breakwaters that are a combination of the previous two types (Kamphuis, 2010); all of them are bottom-sitting breakwaters. Fig. 1. 1 summarizes several traditional bottom-sitting breakwaters that are currently in use.

Traditional bottom-sitting breakwaters can effectively fulfill the demands of reducing waves in the leeside of the breakwaters in places where water is relatively shallow. However, the amount of materials used to construct rubble mound breakwaters quadratically increases with increasing water depth, leading to high construction costs in places where water is relatively deep. Moreover, in places where the bottom foundation is weak, they are no longer technically viable.

Since traditional bottom-sitting breakwaters block the water exchange between the two sides of the structures, they are adverse to the coastal environment.

Fig. 1. 1 Examples of traditional bottom-sitting breakwaters: a vertical caisson breakwater (upper); a rubble mound breakwater (middle); a composite breakwater (lower)

Since the 1980s, international trade and maritime transportation develop rapidly. The heavy traffic and large ship tonnage have increased significantly, demanding

much deeper water depth in harbors; as a result, new harbors are extending towards the ocean and traditional bottom-sitting breakwaters are no longer suitable economically. There is a need for new types of breakwaters that can effectively and economically be deployed in places where water is deep or bottom foundation is weak.

Many new designs have been proposed by researchers, such as submerged breakwaters (see e.g. Losada et al., 1996), submerged horizontal plates (see e.g. Patarapanich, 1984), pile-supported breakwaters (see e.g. Sundar and Subba rao, 2002), floating breakwaters (see e.g. Sannasiraj et al., 1998) and many variants of above-mentioned breakwaters. Fig. 1. 2 shows examples of the above-mentioned breakwaters.

Fig. 1. 2 Examples of four new types of breakwaters: (a) a submerged breakwater, (b) a submerged horizontal plate, (c) a pile-supported breakwater, and (d) a moored floating breakwater

In places where water is deep, the above-mentioned breakwaters are less expensive to construct than traditional bottom-sitting breakwaters. Since natural water circulation is permitted between the two sides of the breakwaters, these types of breakwaters are also environmentally friendly. In addition to protection against waves, these types of breakwaters can also fulfill the growing demands on ecological and environmental protection. However, submerged breakwaters and submerged horizontal plates reduce wave transmission by wave breaking and resonant wave scattering; their level of protection is usually low except in a narrow frequency band near the resonant frequency.

Wave energy mainly concentrates near the water surface, and exponentially decreases with increasing the distance from the water surface. Therefore, pile-supported breakwaters and floating breakwaters may be more cost-effective in reducing wave transmission.

A simplest pile-supported breakwater is a rectangular caisson sitting on piles. A pile-supported rectangular caisson reduces wave transmission mainly by wave blocking and resonant wave scattering, and a wide breakwater breadth and a deep breakwater draft are usually needed for better performance. To improve the performance of pile-supported breakwaters, many new designs have been proposed to enhance energy dissipation through vortex shedding, generation of turbulence, or wave breaking; a detailed review of this topic is given in Section 2.1.

A simplest floating breakwater is a rectangular caisson floating on the water surface and being slackly connected to the seabed by a mooring system. According to McCartney (1985), in addition to the superiority of environmental friendliness and low cost in deep water, floating breakwaters also surpass the traditional breakwaters because of their flexibility and mobility. Floating breakwaters can be easily deployed in different layouts in different seasons and at different sites. Sometimes floating breakwaters might be the only viable option for sites with poor bottom

foundation. Floating breakwaters can partially reflect, partially transmit and partially dissipate wave energy. Different from fixed breakwaters, the motion responses of floating breakwater also generate radiated waves, and it is also possible to achieve small wave transmission by destructive interaction between the transmitted waves and the radiated waves. However, if the phase difference between the transmitted waves and the radiated waves is small, the constructive interaction can also lead to large wave transmission. Moreover, large motion responses can increase dynamic loads in mooring lines. To improve the performance of floating breakwaters, efforts have been made to achieve small wave transmission without increasing motion responses. A detailed review of this topic is given in Section 4.1.

Most of new designs make use of vortex shedding, turbulence and/or wave breaking to enhance dissipation of wave energy. However, wave energy can also be used for electricity generation. Integration of a wave energy converter into a breakwater potentially can be a promising technology for waste-to-energy.

The objectives of this thesis are to introduce several novel designs, which are multi-functional and low in construction costs, to improve performance of pile-supported/floating breakwaters. All these novel designs were originated with the idea of integrating a wave energy converter into a breakwater.

1.1.2 A brief review of wave energy extraction principles

Fossil fuels contribute to the greenhouse effects and acid rain etc.; nuclear energy seems clean, but the earthquake and tsunami in Japan in 2011 show that an unexpected failure of the system may be a disaster to human beings. In contrast, renewable energy is a clean and safe energy source to meet our needs for energy.

The ocean occupies more than two thirds of the Earth's surface, and the potential of

marine renewable energy is tremendous. However, marine renewable energy is yet to be fully explored compared to the utilization of hydro, wind, and solar energy on land (Sabonnadière, 2010). Esteban and Leary (2012) estimated that the renewable energy production from various ocean-based devices could be capable of covering about 7% of the world's electricity production by 2050. Wave energy is one of the four main sources of marine renewable energy (wave energy, tidal energy, ocean thermal energy and offshore wind energy). Wave power flux can be well probabilistically forecasted 48 hours in advance (Pinson et al., 2012) and the annual average power flux per unit length of the wave front of wind-driven waves ranges from 10 kW/m to 100 kW/m (Mei, 2012). A typical wave energy power plant potentially can thus have a capacity that is comparable to the capacity of a typical conventional power plant (Mei et al., 2005).

There are numerous designs of wave energy converters. However, they are still in their infancy of development (Falcão, 2010). Main representative wave energy converters can be classified into three categories: overtopping devices, oscillating-body type converters and oscillating-water-column (OWC) type converters. Fig. 1. 3 shows examples of representative wave energy converters.

An overtopping device is equipped with a reservoir above the sea level. The ramp is designed to increase the amount of water rushing into the reservoir. Then the potential energy of the water inside the reservoir can be utilized by the same principle of hydropower plants - the water in the reservoir flows through a hydro-turbine and generates electricity.

Oscillating-body type converters include point absorbers, attenuators and terminators. This type of converter is fundamentally a floating body oscillating with waves. The relative motion between different parts or between the body and the seabed can drive a power-take-off mechanism, e.g. oil-hydraulic pump or linear electrical generator, to generate electricity.

Fig. 1. 3 Examples of representative wave energy converters: an overtopping device (upper); an oscillating body (middle) and an oscillating water column (lower).

Adapted from Li and Yu (2012)

A typical oscillating-water-column type converter consists of a hollow pneumatic chamber with a bottom opening below the water level, and air is trapped inside the chamber above the water surface. The incoming waves cause the internal water column to oscillate, and the oscillating air pressure inside the chamber can drive a turbine at the top to generate electricity.

Hagerman and Heller (1990) presented a comparative survey of eleven representative wave energy converters and made a classification based on operating principles. As shown in Fig. 1. 4, No.1 to No.6 and No.10 are oscillating-body type converters, No.7 to No.9 are oscillating-water-column type converters, and No.11 is an overtopping device.

Compared to other types of wave energy converters, oscillating-water-column types of converters have the following merits (Clément et al., 2002; Falcão, 2010; Heath, 2012):

- Its key oscillating part is a water column, not mechanical components, thus it is durable.
- Its power-take-off mechanism is out of water, thus it is reliable.
- The usage of air turbine as its power-take-off mechanism can avoid using mechanical components such as gearbox.
- Its structural simplicity is adaptable, and it can be deployed over a range of sites, from nearshore regions to offshore regions, as well as be integrated into coastal structures.
- It is easy to maintain.
- The space it requires is less.

Up to date, oscillating-water-column types of converters are in a leading position among a wide variety of wave energy converters (Heath, 2012), and they are believed to be the most studied and best developed. A number of prototypes of oscillating-water-column converters have been built and tested. Table. 1. 1 shows some examples of existing prototypes of OWC types of converters.

Fig. 1. 4 A classification of representative wave energy converters based on operating principles. Adapted from Hagerman and Heller (1990)

Table. 1. 1 Examples of existing prototypes of oscillating-water-column converters

Sources	Photos	Descriptions
LIMPET (Heath et al., 2000)		Coastal OWC 500 KW output 21 m width
Pico (Falcão, 2000)		Coastal OWC 400 KW output 12 m width
Vizhinjam (Thiruvenkatasamy and Neelamani, 1997)		OWC in front of a breakwater 150 KW output 14 m width
OSPNEY (Thorpe, 1999)		Nearshore OWC 2 MW output 20 m chamber width 20 m collector width
Oceanlinx (Finnigan, 2004)		Nearshore OWC 300 KW output 36 m total width 10 m chamber width
Shanwei (You et al., 2003)		Coastal OWC 100 KW output 20 m width

Mighty Whale (Osawa et al., 2002)		Floating OWC 110 KW output 50 m length 30 m breadth
Ocean Energy Buoy (O'Sullivan et al., 2011)		Floating OWC 12 m length
Sakata (Takahashi et al., 1992)		Breakwater OWC 60 KW output 5 m each chamber width 3 chambers
Mutriku (Torre-Enciso et al., 2009)		Breakwater OWC 296 KW output 440 m breakwater length 100 m OWC length

1.1.3 Integration of OWCs with breakwaters

The anticipated cost of wave energy conversion is still very high compared to the cost of electricity generated by large-scale coal-burning power plants. Integration of wave energy converters with other shore-protection structures can be a promising way to reduce the cost and make wave energy utilization more competitive.

The structural simplicity, operating principle and their adaptability make oscillating-water-column types of converters very suitable for being integrated into breakwaters. The civil construction dominates the cost of coastal structures, and

integration of an oscillating-water-column converter into a breakwater can share the construction costs between power generation and harbor protection. As shown in Table. 1. 1, breakwaters integrated with OWC devices have been built in Sakata, Japan and Mutriku, Spain.

The idea of integrating OWCs into breakwaters has been exploited by other researchers. In the early 1980s, Ojima et al. (1984) pioneered the fundamental research on combining OWC-type converters with fixed breakwaters and a test prototype was constructed in 1989 at Sakata Port (Takahashi et al., 1992). However, previous studies mainly focused on bottom-sitting breakwaters with OWCs, e.g. Thiruvankatasamy and Neelamani (1997), Tseng et al. (2000), Boccotti et al. (2007), Martins-Rivas and Mei (2009) and Boccotti (2012). Integrating OWCs to pile-supported breakwaters and floating breakwaters has not been sufficiently addressed in the literature. For pile-supported breakwaters with OWCs, to my best knowledge, no relevant literature can be found. For floating breakwater with OWCs, Hong and Hong (2007) made use of a pin-connected floating OWC as a breakwater to protect a very-long floating structure (VLFS) and showed that the hydroelastic responses of the VLFS could be significantly reduced; Vijayakrishna Rapaka et al. (2004) experimentally and Koo (2009) numerically studied a floating breakwater embedding an OWC in its middle section.

1.2 Objectives and scopes of research

The aim of this thesis is to examine the concept of integrating the oscillating-water-column converters with breakwaters, which involves the understanding of the power-take-off mechanism for an oscillating-water-column converter and several applications. The effects of opening size and shape, which are used to simulate the power-take-off mechanism, on the wave energy attenuation and hydrodynamic performance of a breakwater are investigated. Later, two applications

of pneumatic chambers as breakwaters are examined: one as pile-supported breakwater in the presence of a vertical wall, and another as floating breakwater in the absence of a vertical wall.

1.2.1 Objectives

The objectives of this study are to introduce several novel designs to integrate an oscillating-water-column converter into a pile-supported/floating breakwater. All these novel designs are originated with the idea of designing multi-functional coastal structures for cost sharing.

It is stressed here that the primary function of a breakwater with OWCs is still wave attenuation and the energy conversion is a secondary function. Thus, I mainly focus in this thesis on the breakwater function of different designs, i.e., the effects of oscillating-water-column converters on the performance of the breakwater. Nevertheless, the potential of wave energy extraction by different designs is also investigated and discussed. This study tests the concept of integrating the oscillating-water-column converters with breakwaters.

1.2.2 Scopes of research

Previous published studies mainly concentrated in the oscillating-water-column wave energy converters integrating into traditional bottom-sitting breakwaters. The integration of converters into new types of breakwaters has not been sufficiently addressed in the literature. In this thesis, four novel designs are originated with the idea of integrating a wave energy converter into a pile-supported/floating breakwater (oscillating water column and pneumatic chamber are used interchangeably in this thesis):

- (1) Hydrodynamic performance of a pile-supported oscillating-water-column structure as a breakwater is experimentally investigated, for which the air-flow through a small opening in the top cover contributes to energy extraction from waves and reduction in transmission coefficients. The effects of relative breadth, draft and opening conditions on wave reflection, wave transmission, energy dissipation and the pressure fluctuation inside the OWC chamber are examined.
- (2) A pile-supported rectangular pneumatic chamber with a fully-opened bottom is studied experimentally to examine its performance in reducing wave reflection from a vertical wall in a port/terminal where building a bottom-sitting structure is costly. Two types of configurations are examined: a pneumatic chamber with a small opening in its top face to simulate a power-take-off mechanism for electricity generation, and a pneumatic chamber without an opening in its top face. In particular, the effects of a gap between the rear wall of the pneumatic chamber and the vertical wall are investigated.
- (3) Hydrodynamic performance of a floating breakwater with pneumatic chambers on both sides is experimentally investigated. Its performance is compared with that of the original box-type floating breakwater without pneumatic chambers, focusing on effects of the pneumatic chambers, on wave transmission, wave energy dissipation and motion responses. The air-pressure fluctuations inside the pneumatic chambers and the effects of draft are also examined.
- (4) A floating breakwater with asymmetric pneumatic chambers (a narrower chamber on the seaside and a wider chamber on the leese) is proposed to increase the amplitude of the oscillating air-pressures inside both chambers over a wide range of wave frequency (thus to improve the performance in wave energy extraction). Effects of asymmetric pneumatic chambers on the hydrodynamic performance of the floating breakwater and on the oscillating air-pressures inside the two chambers are studied.

In the present experimental studies, two wave flumes are used according to the specific concerns of each problem:

- For the pile-supported breakwaters with OWCs, a glass-walled wave flume of 32.5 m in length, 0.55 m in width and 0.6 m in depth is used. This is because the water surface inside the pneumatic chamber needs to be monitored, which cannot be done using another flume in the Hydraulics Lab.
- For the floating breakwaters with OWCs, a concrete-walled wave flume of 45 m in length, 1.55 m in width and 1.5 m in depth is used. Since there is a possibility of a heavy moving model to damage the glass-walled flume, it is safer to study the floating structure in this flume. In addition, a larger model with a larger Reynolds number can also reduce the influence of viscous damping.

The waves in this thesis are limited to weakly-nonlinear waves. The dynamic pressure on the surface of the water inside the chamber is related to the square of the velocity of the air through the opening, thus the radiated waves will have higher harmonic components. The vortex shedding at the edges of the model will also generate some nonlinear effects. Since the dominating exciting force acting on the structure is still coming from the fundamental waves, the nonlinear responses of the structure are weak and it is not expected to give results much different from those obtained for linear waves. Highly-nonlinear waves (including breaking waves) and irregular waves are also important for understanding the survivability of such structures, which is out of the scope of this thesis.

1.3 Outline of thesis

Six chapters are included in this thesis:

Chapter 1 (this chapter) introduces the needs for new types of breakwaters, a general review on wave energy extraction principles, the study on integration of OWCs with breakwaters, and the objectives and scope of this thesis. A detailed topical review for each design will be given in each subsequent chapter.

Chapter 2 presents an experimental investigation of hydrodynamic performance of a pile-supported oscillating-water-column structure as a breakwater.

In Chapter 3, two configurations of pile-supported rectangular pneumatic chambers (one with a small opening in its top face to simulate a power-take-off mechanism for electricity generation, and one without an opening in its top face) are studied experimentally to examine their performance in reducing wave reflection from a vertical wall.

Chapter 4 reports a comparative experimental study of the hydrodynamic performance of a rectangular floating breakwater with and without pneumatic chambers.

Chapter 5 is a follow-up investigation of Chapter 4, and studies the hydrodynamic performance of a rectangular floating breakwater with asymmetric pneumatic chambers (a narrower chamber on the seaside and a wider chamber on the leeside of the rectangular floating breakwater).

Chapter 6 summarizes the major conclusions of this thesis and makes recommendations for future work.

CHAPTER 2 HYDRODYNAMIC PERFORMANCE OF PILE-SUPPORTED OWC-TYPE STRUCTURES AS BREAKWATERS

2.1 Introduction

As the demands of constructing deep-water harbors in relatively deep water progress, traditional rubble mound breakwaters are no longer economically viable. Since wave energy mainly concentrates near water surface, pile-supported breakwaters could be an economical option. This type of breakwater is also environmentally friendly, because water exchange and sediment transport are permitted underneath the breakwater. For these types of breakwaters, the relative breadth (the ratio of the breakwater breadth to wave length) and relative draft (the ratio of the breakwater draft to water depth) are two important parameters determining wave transmission performance as well as construction cost.

Recently, several types of pile-supported breakwaters have been proposed, including horizontal rows of half pipes (Koraim, 2013), partially-immersed caissons (Rageh et al., 2009), multiple-layer breakwaters (Wang et al., 2006), twin-plate wave barriers (Neelamani and Gayathri, 2006), box-type breakwaters with a porous plate (Koutandos et al., 2005), absorbing perforated-wall breakwaters (Brossard et al., 2003), $\perp$ -type breakwaters (Neelamani and Rajendran, 2002a), T-type breakwaters (Neelamani and Rajendran, 2002b), twin-vertical barriers (Neelamani and Vedagiri, 2002), quadrant front-face breakwaters (Sundar and Subba rao, 2002) and suspended double slotted barriers (Isaacson et al., 1999). All these pile-supported breakwaters were designed to dissipate more wave energy through vortex shedding, generation of turbulence, or wave breaking.

Oscillating-water-column devices are the most studied and best developed wave energy converters. A detailed discussion of the structure and the operating principle of OWC can be found in Heath (2012). The theoretical maximum efficiency is only 50% for pile-supported symmetric OWC structures (Sarmiento, 1992), however, the pile-supported OWC structures can also serve as pile-supported breakwaters with a potential to utilize wave energy for electricity generation.

The idea of integrating OWC into breakwaters has been exploited by other researchers. Ojima et al. (1984) advocated the integration of an OWC into a caisson-type breakwater; subsequently, a field experiment on this type of structure was conducted at Sakata Port to study the characteristics of wave-power generation (Takahashi et al., 1992). The bottom-sitting OWC caisson breakwaters were also studied by other researchers, e.g. Thiruvengkatasamy and Neelamani (1997), Tseng et al. (2000), Boccotti et al. (2007) and Boccotti (2012). Recently, Hong and Hong (2007) made use of a pin-connected floating OWC as a breakwater to protect a very-long floating structure (VLFS) and showed that the hydroelastic responses of the VLFS could be significantly reduced. A floating breakwater embedding an OWC in its middle section was studied experimentally by Vijayakrishna Rapaka et al. (2004) and numerically by Koo (2009). He (2012, 2013) proposed two configurations of integrating OWC with a floating breakwater and their experimental results showed that the OWC chambers could improve the performance of the floating breakwater in terms of wave transmission and motion responses. Recently, Sundar et al. (2010) reviewed extensively some conceptual designs of OWC converters combined with various breakwaters.

Using a pile-supported OWC structure as a breakwater for reducing waves in the leeside has not been sufficiently addressed in the literature. Sarmiento (1992) conducted experiments on a pile-supported OWC structure with a very small draft mainly for providing experimental data to validate the theoretical work of Sarmiento

and Falcão (1985); few data on wave transmission were provided in his study and the small draft made the breakwater perform inefficiently.

The main aim of the experimental study in this chapter is to investigate the hydrodynamic performance of pile-supported OWC-type structures as breakwaters. In the experiments, the hydrodynamic characteristics of the OWC chamber are controlled mainly by the size and shape of an opening in the top cover, which allows the air in the chamber to flow through and thus extracts extra energy from the wave field. The effects of relative breadth, draft and the size and shape of the opening on wave reflection, wave transmission, energy dissipation and the pressure fluctuation inside the chamber are investigated. A comparison of the wave transmission coefficients is made between the pile-supported OWC-type structures and other types of pile-supported breakwaters reported in the literature.

2.2 Experimental procedure

2.2.1 The OWC-type breakwater model

The symmetric OWC-type breakwater examined in the present study is shown in Fig. 2. 1, where the ‘symmetric’ means that the heights of the front and rear walls of the OWC chamber are equal. The breakwater model was made of 10-mm thick Perspex sheets. The interior length, breadth and height of the OWC chamber were 0.53 m, 0.4 m and 0.4 m, respectively. The bottom of the model was fully open. There was a slot in the top cover, and the slot occupied 20% of the total area of the top cover. Plates with different openings can be mounted to the slot to change opening size and shape. As shown in Fig. 2. 2, six openings were tested in the experiments: three rectangular slots and three circular orifices. The size of an opening can be described by the ratio of the opening to the total area of the top

cover. Three opening ratios were examined in the experiment: 0.625%, 1.25% and 1.875%. In addition, two extreme conditions were also tested: 20% opening and no opening (fully closed). In the experiment, the breakwater model was firmly fixed to an adjustable aluminum plate by screw bolts. When the desirable draft was adjusted, the aluminum plate was firmly tightened to a frame fixed to the flume by screw bolts. Special care had been taken to ensure that the model there was no relative motion between the model and the flume.

Fig. 2. 1 The geometric details of the OWC model

Fig. 2. 2 The six openings tested in the experiment: three rectangular slots (left panel) and three circular orifices (right panel); the two narrow parallel lines across each plate on the left panel represent the slot, which is perpendicular to the wave direction

2.2.2 Experimental setup and data acquisition

The experiments were conducted in a wave flume located in the Hydraulics Modeling Laboratory at Nanyang Technological University, Singapore. The dimensions of the glass-walled wave flume were 32.5 m in length, 0.55 m in width and 0.6 m in depth. A piston-type wave-maker was installed at one end of the flume, and a wave-absorbing beach of 1:15 slope was located at the other end to reduce wave reflection. The slope was covered with porous mats and the reflection coefficient of the wave absorbing beach was less than 0.05 for the tested wave conditions in this study.

Fig. 2. 3 shows a sketch of the experimental setup. The breakwater model was placed at the middle section of the flume, 12 m away from the wave-maker. Eight resistance-type wave gauges (WG1-WG8 in Fig. 2. 1) with resolution of 0.1 mm were used to measure the instantaneous surface elevations: three were placed in front of the model for separation of incident waves from reflected waves, three in the leeward side of the model for separation of the transmitted waves from the waves reflected from the wave-absorbing beach, and the other two for measuring the water surface inside the chamber. In the experiment, three piezoresistive pressure sensors were used to measure the pressure inside the chamber. A view of the breakwater model installed in the wave flume is shown in Fig. 2. 4a and a closer view of the breakwater model installed in the wave flume is shown in Fig. 2. 4b.

Fig. 2. 3 A sketch of the experimental setup

Fig. 2. 4a A view of the breakwater model installed in the wave flume

Fig. 2. 4b A closer view of the breakwater model installed in the wave flume

2.2.3 Test conditions

In the experiments, the still water depth h was fixed at 0.4 m and the target wave height H_i was fixed at 0.035 m. Three drafts were examined: 0.1 m, 0.15 m and 0.2 m. The wave periods varied from 0.9 s to 1.6 s at 0.1 s intervals. The ratio of the breadth of the chamber B to the wave length L varied from 0.14 to 0.33. Details of the test conditions and the geometric parameters of the breakwater model are summarized in Table. 2. 1.

Table. 2. 1 Test conditions and the geometric parameters of the breakwater model

Parameters	Ranges
Water depth (h)	0.4 m
Incident wave height (H_i)	0.035 m
Wave periods (T)	0.9-1.6 s at 0.1 s intervals
Wave length (L)	1.22-2.84 m
Model breadth (B)	0.4 m
Model draft (D_r)	0.10, 0.15, 0.20 m
Opening sizes and shapes	slot shape:0.625%, 1.25%, 1.875% orifice shape: 0.625%, 1.25%, 1.875% 20% (fully opened), 0% (fully closed)
h / L	0.14-0.33
H_i / L	0.012-0.029
B / L	0.14-0.33

2.2.4 Data analysis

The heights of incident waves (H_i), reflected waves (H_r) and transmitted waves (H_t) are obtained by a wave separation analysis. The two-point method proposed by Goda and Suzuki (1976) was employed to separate left-going waves from right-going waves. The reflection coefficient is defined as $C_r = H_r / H_i$ and the transmission coefficient $C_t = H_t / H_i$. An energy-dissipation coefficient C_d can be derived according to the following energy balance,

$$E_i = E_r + E_t + E_d \quad (2.1)$$

where E_i , E_r , E_t and E_d are incident, reflected, transmitted and dissipated wave energy per unit wave crest, respectively, and are proportional to the square of wave height. Dividing both sides of Eq. (2.1) by E_i , the equation becomes,

$$1 = (H_r / H_i)^2 + (H_t / H_i)^2 + E_d / E_i \quad (2.2)$$

where $C_d = E_d / E_i$ representing the fraction of the incident wave energy dissipated. Eq. (2.2) can be rearranged as,

$$C_d = 1 - C_r^2 - C_t^2 \quad (2.3)$$

The hydrodynamic performance of the breakwater, including wave reflection C_r , wave transmission C_t and the pressure fluctuation inside the chamber ΔP , can be described by the following functional relations:

$$C_r, C_t, \Delta P = f(B, D_r, \varepsilon, \chi, L, h, H_i, \rho, g) \quad (2.4)$$

where B is the model breadth, D_r the draft, ε the opening ratio, χ a

parameter describing the opening shape, L the wave length, h the water depth, H_i the incident wave height, ρ the water density, and g the gravitational acceleration. Eq. (2.4) can be presented in the following dimensionless form after performing a dimensional analysis using π -theorem,

$$C_r, C_t, C_p = f(B/L, D_r/h, \varepsilon, \chi, H_i/h, B/h) \quad (2.5)$$

where $C_p = \Delta P / 0.5 \rho g H_i$ is a pressure coefficient describing the pressure fluctuation inside the OWC chamber. Since H_i/h and B/h were kept constant in present experiments ($H_i/h = 0.0875$ and $B/h = 1$), only the effects of relative breadth B/L , relative draft D_r/h , opening ratio ε , and opening shape χ on the hydrodynamic performance of the breakwater will be examined.

2.3 Results and discussion

The measured pressure showed that the spatial variation of the air pressure was uniform inside the chamber, suggesting that the airflow inside the air chamber did not cause significant spatial variation of the air pressure inside the air chamber.

Most tests were repeated twice on different days, and the difference in the measured hydrodynamic coefficients between two tests was less than 3%, which was caused mainly by the small difference in the wave heights generated on different days.

2.3.1 Hydrodynamic performance for $D_r/h=0.25$

The measured transmission coefficient (C_t), reflection coefficient (C_r), pressure coefficient (C_p), and energy-dissipation coefficient (C_d) are summarized in Fig. 2.

5 for $D_r/h=0.25$ and various openings and will be discussed in below.

For the breakwater model with the 20% slot opening, the pressure fluctuation inside the OWC chamber was almost zero, suggesting that the 20% opening is large enough to be regarded as being fully opened and the breakwater is equivalent to the twin vertical plates studied by Stiassnie et al. (1986) and Neelamani and Vedagiri (2002). A minimum reflection coefficient of 0.05 was found at $B/L = 0.235$. With increasing wave frequency, the transmission coefficient dropped from 0.89 at $B/L = 0.153$ to 0.48 at $B/L = 0.327$, and the energy-dissipation coefficient increased from 0.19 to 0.54 within the same range of B/L . The energy loss is purely due to the vortex shedding at the tips of the vertical plates.

For the breakwater model without opening, indicted by 0% opening (fully closed) in Fig. 2. 5, large pressure fluctuation was built up inside the OWC chamber, impeding the up-and-down motion of the water surface inside the OWC chamber and generating out-going radiated waves. It is commented that the magnitude of the radiated waves is directly related to the magnitude of pressure fluctuation and a smaller pressure fluctuation implies a weaker radiated wave. Compared to the breakwater with the 20% opening, the radiated waves significantly increased the reflection coefficient (C_r) but lowered the transmission coefficient (C_t); the radiated waves also lowered the magnitude of the velocities at the tips of the vertical walls and thus reduced the energy loss due to the vortex shedding at the tips of the vertical walls. It is remarked that in Fig. 2. 5, the energy-dissipation coefficient for the 0% opening includes both the loss due to the vortex shedding and the loss related to the work done by the moving water surface on the air inside the chamber. Since the energy dissipation was significantly reduced to about 0.15 by closing up the chamber, the work done by the water surface on the air inside the chamber is at most 15% of the energy contained in the incoming waves. As shown in Fig. 2. 5, there is a correlation between the air pressure fluctuation and the wave reflection coefficient: increasing the reflection by the front wall means reducing the wave energy available for moving the water inside the OWC chamber; as a result,

the pressure fluctuation is expected to drop with decreasing wave length (i.e. increasing B/L) because of the increased blockage effect of the front wall for shorter waves.

A small opening in the top cover of the OWC chamber can release the high pressure inside the chamber and the high-speed air flow through the opening can further extract energy from the wave field and thus affect the wave reflection and transmission coefficients. For a given opening ratio, the shape of the openings did not have significant effects on the transmission coefficients, except that the transmission coefficient was only slightly lower for an orifice opening than for a slot opening with the same opening ratio. As shown in Fig. 2. 5, the pressure fluctuations for the breakwater models with the 0.625%, 1.25% and 1.875% slot/orifice openings were bounded by that with the 0% opening and that with the 20% opening. The effect of opening shapes on pressure fluctuation was noticeable only for smaller opening ratios, and slot openings normally gave slightly smaller pressure fluctuations than orifice openings did; possibly because an orifice opening has the smallest perimeter than other shapes of the same area. As expected for a given B/L , increasing opening ratio reduced both the pressure fluctuation and the reflection coefficient. It is interesting to note that the breakwater model with the 0.625% opening gave the smallest transmission efficient for a given B/L . The transmission coefficients for the 0.625% opening dropped from 0.70 at $B/L = 0.141$ to 0.28 at $B/L = 0.327$. For small marinas and recreational harbors, $C_t = 0.5$ is usually considered as a satisfactory level for breakwaters permitting waves partially transmitted beneath, and the construction costs of a pile-supported breakwater increase with B , the breadth of the breakwater. The breakwaters with the 20% and 0% openings could achieve $C_t = 0.5$ at, respectively, $B/L \approx 0.32$ and 0.25; however, the breakwater model with the 0.625% opening could achieve $C_t = 0.5$ at $B/L \approx 0.22$, suggesting that construction costs can be minimized by

optimizing the opening size.

It was stressed here that energy dissipation was from two sources: vortex shedding at the tips of the chamber walls and the air flow through the opening (i.e. pneumatic power). Based on potential flow theory, the theoretical value of maximum pneumatic power efficiency is 0.5 for a two-dimensional symmetric OWC-type wave energy converter (see Sarmento, 1992). The variation of energy-dissipation coefficient with B/L for the 0.625% opening behaved quite different from those for other opening ratios: For the 1.25%, and 1.875% openings, the peak values of C_d occurred around $B/L=0.274$, which is close to $B/L=0.327$ at which the energy loss for the 20% opening (two vertical plates) was entirely controlled by vortex shedding in the present experiments¹. However, for the 0.625% opening the peak of C_d occurred at $B/L=0.235$, suggesting that the energy dissipation associated with the high-speed air flow through the small opening is comparable to the energy loss due to vortex shedding.

2.3.2 Hydrodynamic performance for $D_r/h=0.375$ and 0.5

The variations of transmission coefficient (C_t), reflection coefficient (C_r), pressure coefficient (C_p), and energy-dissipation coefficient (C_d) for $D_r/h=0.375$ and 0.5 are shown in Fig. 2. 6 and Fig. 2. 7, respectively.

¹ Stiassnie et al. (1986) studied the vortex shedding dissipation of two vertical plates and found the energy dissipation was dependent on the distance between the two plates and the draft of the plates in addition to wave conditions; for the case with $B=0.4$ m and $D_r=0.1$ m, the value of B/L where the maximum vortex shedding induced energy dissipation occurred is about 0.32.

Fig. 2. 5 Variations of (a) transmission coefficient C_t , (b) reflection coefficient C_r ,

(c) pressure coefficient C_p and (d) energy-dissipation coefficient C_d versus

B/L for $D_r/h = 0.25$ (Figure continued on next page)

Fig. 2. 5 Variations of (a) transmission coefficient C_t , (b) reflection coefficient C_r , (c) pressure coefficient C_p and (d) energy-dissipation coefficient C_d versus B/L for $D_r/h = 0.25$

For all opening sizes and shapes, the variations of C_r (or C_t) with B/L for $D_r/h=0.375$ and 0.5 were similar to that for $D_r/h=0.25$; however, a deeper draft resulted in a larger C_r (or smaller C_t) because of the increased blockage effect of the front wall, especially for shorter waves. For $D_r/h=0.5$, the effects of the opening size and shape on the values of C_r (or C_t) were negligible when $B/L > 0.274$.

The variations of the pressure coefficients (C_p) for $D_r/h=0.375$ and 0.5 were similar to that for $D_r/h=0.25$, and increasing draft did not affect the effects of the opening size and shape on pressure fluctuation. The peak values of C_p for the 1.25% and 1.875% openings shifted towards smaller values of B/L . For the 0.625% opening, increasing draft did not significantly change the value of B/L at which the peak of C_p occurred.

Changing draft did not significantly change the peak values of C_d for the 0.625%, 1.25%, 1.875%, and 20% openings; however, deeper draft caused the peak of C_d to occur at longer waves.

In summary, small openings in the top cover of an OWC chamber could significantly affect the reflection and transmission coefficients for longer waves. By optimizing the opening ratio, it is possible to lower the transmission coefficient for longer waves and to reduce the construction costs of a pile-supported OWC-type breakwater without sacrificing its hydrodynamic performance.

Fig. 2. 6 Variations of (a) transmission coefficient C_t , (b) reflection coefficient C_r , (c) pressure coefficient C_p and (d) energy-dissipation coefficient C_d versus B/L for $D_r/h = 0.375$ (Figure continued on next page)

Fig. 2. 6 Variations of (a) transmission coefficient C_t , (b) reflection coefficient C_r , (c) pressure coefficient C_p and (d) energy-dissipation coefficient C_d versus B/L for $D_r/h = 0.375$

Fig. 2. 7 Variations of (a) transmission coefficient C_t , (b) reflection coefficient C_r , (c) pressure coefficient C_p and (d) energy-dissipation coefficient C_d versus B/L for $D_r/h = 0.5$ (Figure continued on next page)

Fig. 2. 7 Variations of (a) transmission coefficient C_t , (b) reflection coefficient C_r , (c) pressure coefficient C_p and (d) energy-dissipation coefficient C_d versus B/L for $D_r/h = 0.5$

2.3.3 A comparison with other types of pile-supported breakwaters

A comparison was made here between the pile-supported OWC-type breakwater and other types of pile-supported breakwaters reported in the literature. For comparison, the breakwater with the 0.625% orifice opening was selected. Three relative drafts D_r/h will be considered: 0.25, 0.375 and 0.5. The relative breadth B/L and relative draft D_r/h are two important parameters that affect the transmission coefficient and the construction costs of a pile-supported breakwater. When selecting data from the literature for comparison, the following six rules are followed:

- 1) Only the data for regular waves are chosen.
- 2) The relative drafts D_r/h are within or very close to the range of 0.25-0.5 (except the data in Wang et al., 2006 due to the permeable nature of their breakwater).
- 3) The values of H_i/h and B/h are as close as possible to the conditions in the present study ($H_i/h=0.0875$ and $B/h=1$).
- 4) The sizes of the supporting piles are small.
- 5) Only the data in the range of B/L less than 0.55 are selected.
- 6) If there are several sets of data satisfying the above criteria, the set of data that give the best performance is chosen.

A summary of the configurations and key parameters of the pile-supported breakwaters that satisfy the six rules is given in Table. 2. 2, where a sketch of the

configuration and parameters such as D_r/h , H_i/h , B/h and H_i/L are provided for each of the pile-supported breakwater used in the comparison.

Fig. 2. 8 shows the transmission coefficients for the pile-supported OWC-type breakwater and those breakwaters listed in Table. 2. 2. Note that the results presented in Fig. 2. 8 can be grouped according to their relative drafts: Those with D_r/h ranging from 0.24 to 0.28 are presented by various types of squares, those in the range of 0.29-0.39 are presented by various types of circles, and those in the range of 0.4-0.5 are presented by various types of triangles. Since the range of B/L in the present study is not wide enough to give a minimum transmission coefficient, the minimum C_t of the OWC-type breakwater for each D_r/h can be smaller than that shown in Fig. 2. 8. It is remarked that only one wave gauge was used in the lee side of their breakwaters in the experiments of Neelamani and Rajendran (2002a, 2002b), Neelamani and Vedagiri (2002), Sundar and Subba rao (2002), Neelamani and Gayathri (2006), Rageh et al. (2009) and Koraim (2013), thus the values of C_t in their results are wave amplification factors at the measurement location inside a harbor rather than the transmission coefficients defined in this study. The wave amplification factor can be approximately equal to the transmission coefficient if the wave reflection from the absorbing beach is very weak. In wave flume tests, the wave reflection from the absorbing beach can be significant for long period waves; as a result, the wave amplification factor can have noticeable difference from the wave transmission coefficient for long period waves (i.e., for small values of B/L). Because of this reason, comparison with these experimental results will not be made for smaller values of B/L .

Table. 2. 2 Configurations of the breakwaters reported in the literature

Sources	Definition sketch	D_r/h	Other experimental parameters
Suspended oscillating water column (Present study)		0.25, 0.375, 0.5	$B/h = 1$ $H_i/h = 0.0875$ $H_i/L = 0.01 - 0.03$ no pile
Suspended horizontal rows of half pipes (Koraim, 2013)		0.46	$B/h = 1.32$ $H_i/h = 0.25$ $H_i/L = 0.03 - 0.1$ no pile
Pile-supported caisson (Rageh et al., 2009)		0.4	$B/h = 1$ $H_i/h = 0.31$ $H_i/L = 0.01 - 0.1$ two rows of piles with porosity of 89%
Multiple-layer breakwater (Wang et al., 2006)		0.75	$B/h = 1$ $H_i/h = 0.295$ $H_i/L = 0.07 - 0.23$ pile parameters not reported
Pile-supported twin plate wave barrier (Neelamani and Gayathri, 2006)		0.4	$B/h = 2$ $H_i/h = 0.16$ $H_i/L = 0.01 - 0.04$ four rows of piles with porosities of 82% (lower part) and 77% (upper part)

Fixed floating breakwater (Koutandos et al., 2005) Model 1		0.33	$B / h = 1$ $H_i / h = 0.1$ $H_i / L = 0.004 - 0.03$ no pile
Fixed floating breakwater with attached front plate (Koutandos et al., 2005) Model 2		0.25	$B / h = 1$ $H_i / h = 0.1$ $H_i / L = 0.004 - 0.03$ no pile
Fixed absorbing perforated-wall breakwater (Brossard et al., 2003)		0.48	$B / h = 1.44$ $H_i / h = 0.152$ $H_i / L = 0.02 - 0.08$ no pile
⊥-type breakwater (Neelamani and Rajendran, 2002a)		0.36	$B / h = 1.43$ $H_i / h = 0.05 - 0.1$ $H_i / L = 0.005 - 0.05$ no pile
T-type breakwater (Neelamani and Rajendran, 2002b)		0.36	$B / h = 1.43$ $H_i / h = 0.087 - 0.099$ $H_i / L = 0.01 - 0.05$ no pile
Twin vertical barriers (Neelamani and Vedagiri, 2002)		0.29	$B / h = 1$ $H_i / h = 0.067 - 0.102$ $H_i / L = 0.007 - 0.05$ no pile
Pile-supported quadrant front-face breakwater (Sundar and Subbarao, 2002)		0.45	$B / h = 1$ $H_i / h = 0.08 - 0.32$ $H_i / L = 0.01 - 0.17$ four rows of piles with porosity of 83%

Submerged plate (Brossard and Chagdali, 2001)		0.24	$B/h = 1.33$; H_i not reported; no pile
Suspended double slotted barriers (Isaacson et al., 1999)		0.5	$B/h = 1.1$ $H_i/h = 0.08 - 0.38$ $H_i/L = 0.07$ plate porosity of 5%; no pile
Twin vertical barriers (Stiassnie et al., 1986)		0.26- 0.32	$B/h = 0.78 - 0.96$; H_i not reported; no pile

For $D_r/h = 0.25$, the OWC-type breakwater with the 0.625% orifice opening gives a minimum transmission coefficient of 0.28 at $B/L = 0.327$; this transmission coefficient is comparable to those of Koutandos et al. (2005) and significantly smaller than those of Brossard and Chagdali (2001) at the same B/L and with similar relative drafts.

For $D_r/h = 0.375$, the OWC-type breakwater with the 0.625% orifice opening gives a minimum transmission coefficient of 0.16 at $B/L = 0.327$. This minimum transmission coefficient is comparable to the transmission coefficients of Stiassnie et al. (1986) as well as the wave amplification factors of Neelamani and Rajendran (2002a) and Neelamani and Vedagiri (2002), but much smaller than the transmission coefficients of Koutandos et al. (2005) as well as the wave amplification factors of Neelamani and Rajendran (2002b), at the same B/L and with similar relative drafts.

Fig. 2. 8 Comparison of wave transmission between present study and previous studies; the values of D_r/h are in the bracket in the legend

For a deeper draft of $D_r/h = 0.50$, the OWC-type breakwater with the 0.625% orifice opening gives a minimum transmission coefficient as low as 0.06 at $B/L = 0.327$; this minimum transmission coefficient is much smaller than the transmission coefficients of Isaacson et al. (1999) and Brossard et al. (2003) as well as the wave amplification factors of Koraim (2013), Rageh et al. (2009), Neelamani and Gayathri (2006) and Sundar and Subba rao (2002), at the same B/L and with similar relative drafts. It is concluded from this comparison that the performance of the pile-supported OWC-type breakwater is not inferior to all other breakwaters reported in the literature.

2.4. Concluding Remarks

In the present study, the hydrodynamic performance of pile-supported OWC structures as breakwaters was experimentally investigated. The following key conclusions can be drawn from the study in this chapter:

- 1) The wave transmission coefficient monochromatically increased with decreasing B/L for all the opening ratios examined in the experiments.
- 2) Among all the openings tested, the orifice-shaped opening with an opening ratio of 0.625% could achieve the smallest transmission coefficient.
- 3) A deeper draft could result in a smaller transmission coefficient; for deeper drafts, the wave transmission coefficients for shorter waves were similar among different openings.
- 4) For the orifice-shaped opening with an opening ratio of 0.625%, the wave transmission coefficients could be smaller than 0.5 when the value of B/L was larger than a small value: $B/L < 0.220$ for $D_r/h = 0.25$, $B/L < 0.185$ for $D_r/h = 0.375$ and $B/L < 0.149$ for $D_r/h = 0.5$.
- 5) The performance of the pile-supported OWC-type breakwater in terms of wave transmission is not inferior to other pile-supported breakwaters.
- 6) The pile-supported OWC-type breakwaters could have the potential to utilize waves for electricity generation.

Appendix: remark on prototype cases

As an example, a typical sea state at a site is given as following: water depth $h = 10$ m, wave period $T = 6$ s, and incident wave height $H_i = 0.875$ m, and wave length $L = 48$ m.

The recommended structure dimensions are: breadth $B = 10$ m and orifice diameter $D = 1$ m. Based on Figs 2.5-2.7:

- if the structure draft $D_r = 2.5$ m, the leeward wave height $H_t = 0.473$ m ($C_t = 0.54$);
- if the structure draft $D_r = 3.75$ m, the leeward wave height $H_t = 0.376$ m ($C_t = 0.43$);
- if the structure draft $D_r = 5$ m, the leeward wave height $H_t = 0.28$ m ($C_t = 0.32$).

CHAPTER 3 REDUCTION OF WAVE REFLECTION FROM A VERTICAL WALL BY A PILE-SUPPORTED RECTANGULAR PNEUMATIC CHAMBER

3.1 Introduction

Coastal structures such as seawalls, quaywalls and breakwaters are conventionally constructed in the form of vertical walls or rubble mounds. Rubble mounds can effectively reduce the wave reflection, but usually a long armored slope is needed for breaking and dissipating waves and a high crest elevation is also needed for avoiding water overtopping, which makes rubble mounds occupying much more space than vertical walls, more costly to construct in relatively deep water and unsuitable for some of port and harbor operations. Vertical walls can avoid some of the undesirable features associated with the rubble mounds, but the standing waves in front of vertical walls may cause serious problems to ship navigation, craft berthing, fishery activities and cargo handling.

Innovative concepts have been studied by many researchers to reduce wave reflection from a vertical wall, including use of porous materials (Ijima et al., 1976; Madsen, 1983; Mallayachari and Sundar, 1994), perforated/slotted members (Jarlan, 1961; Kondo, 1979; Tanimoto and Yoshimoto, 1982), or combinations of these two (Isaacson et al., 2000; Liu and Li, 2006). Madsen (1983) studied the reflection characteristics of a vertical wall covered with a vertical porous wave absorber at the seaside. Mallayachari and Sundar (1994) discussed the reflection characteristics of various types of permeable walls. The reflection characteristics of porous wall highly depend on porosity, and the reflection generally decreases with decreasing wave period and increasing wave height. Ijima et al. (1976) placed a permeable

seawall in front of a vertical wall and formed a water chamber between the two walls. They found that the water chamber could remarkably reduce the wave reflection to the same degree of rubble mounds, and the use of water chamber was also effective for a perforated wall in front of vertical wall. Perforated/slotted structures are also commonly used in breakwaters/seawalls to reduce wave reflection. Since Jarlan (1961) initially proposed a breakwater consisting of a perforated front wall, a reflecting rear wall and a chamber between the walls, several variants (called Jarlan-type structures bearing Jarlan's name) have been proposed to improve the performance of reflection characteristics. Kondo (1979) studied the Jarlan-type structure with two perforated walls which formed two chambers in front of the vertical breakwater. Tanimoto and Yoshimoto (1982) proposed the Jarlan-type structure with partially perforated front wall. Isaacson et al. (2000) filled the chamber of Jarlan-type structure with a rock core, but found the reflection increased while wave force acting on the perforated front wall decreased. Liu and Li (2006) proposed submerged rock-filled core inside the chamber of Jarlan-type structure and revealed that both a lower wave reflection and a smaller force acting on the front wall can be achieved. A recent review of perforated/slotted marine structures can be found in Huang et al. (2011). In addition to the porous structures and perforated/slotted structures, there are many other remarkable solutions as well. For examples, Lebey and Rivoalen (2002) superposed a series of inclined plates in front of a vertical wall to reduce wave reflection. Neelamani and Sandhya (2003) proposed dentate and serrate seawalls.

Almost all of the above-mentioned measures to reduce wave reflection are making use of vortex shedding, turbulence and/or wave breaking to dissipate wave energy. Ideas of extracting wave energy for electricity generation, not just dissipating energy into waste, have been exploited since early 1980s. Ojima et al. (1984) proposed to integrate an oscillating-water-column (OWC) type of wave energy converter into a caisson-type breakwater for sharing the structure construction cost

between power generation and harbor protection. The structural simplicity and its operating principle make OWC devices very suitable for being integrated into breakwaters (a detailed review of OWC devices can be found in Heath, 2012). A caisson breakwater with wave-extracting devices has been built at Sakata Port for field tests (Takahashi et al., 1992). Bottom-sitting OWC caisson breakwaters have been studied by Thiruvengatasamy and Neelamani (1997), Tseng et al. (2000), Boccotti et al. (2007) and Boccotti (2012). Recently, Vijayakrishna Rapaka et al. (2004), Hong and Hong (2007), Koo (2009) and He et al. (2012, 2013) studied floating breakwaters with OWC devices.

Sarmiento and Falcão (1985) theoretically studied a suspended OWC in front of a vertical wall based on potential theory. In their study, the draft of OWC was zero, and there was a gap between the OWC and the vertical wall. To my knowledge, there are no similar experimental studies so far that examine the effects of a gap between the rear wall of the pneumatic chamber and the vertical wall on the reduction of wave reflection and the pneumatic efficiency of wave energy extraction.

In this chapter, a pile-supported rectangular pneumatic chamber with a fully-opened bottom is used to reduce wave reflection from a vertical wall. It is expected that a gap between the rear wall of the pneumatic chamber and the vertical wall is a key parameter affecting the reflection coefficient. The studies of Ijima et al. (1976) and Lebey and Rivoalen (2002) both indicated the resonance mechanism of the water inside the gap between their structure and a vertical wall could effectively reduce the wave reflection and the total distance from the structure to the vertical wall was an important parameter. The air pressure inside the rectangular pneumatic chamber is another important parameter affecting the reflection coefficient, and two types of configurations are proposed in this study: a pneumatic chamber without an opening in its top face, and a pneumatic chamber with an opening in its top face. The second

configuration is a typical OWC structure and the opening in the top face is used to simulate a power-take-off mechanism for electricity generation.

3.2 Descriptions of the experiment and data analysis

3.2.1 Physical model and experimental setup

The pneumatic chamber was a rectangular box without a bottom face. The model was fabricated with 10-mm thick Perspex sheets and its interior dimensions were 0.53 m in length, 0.4 m in breadth and 0.4 m in height.

In the experiment, the pneumatic chamber was placed in front of a vertical wall as shown in Fig. 3. 1, where the distance from the center of the pneumatic chamber to the vertical wall is denoted as W , the distance from the front wall of the pneumatic chamber to the vertical wall is denoted as S , the gap between the vertical wall and the rear wall of the pneumatic chamber is denoted as G . The breadth of the pneumatic chamber is denoted as B , so that,

$$W = G + B / 2 \quad (3.1)$$

and

$$S = G + B \quad (3.2)$$

Referring to Fig. 3. 2, two configurations were tested in this study: the top face without an opening and the top face with an opening. For the configuration of the top face with an opening, the opening is slot-shaped and the area ratio of the opening to the top face is 1.25%. In both configurations, the pressure of the air trapped inside the pneumatic chamber is affected by the up and down motion of the internal water surface.

Fig. 3. 1 Schematic diagram of a pneumatic chamber in the presence of vertical wall

Fig. 3. 2 The geometric details of the two configurations. Left: a rectangular pneumatic chamber without an opening in its top face; right: a rectangular pneumatic chamber with an opening in its top face

The experiments were conducted in a glass-walled wave flume located in the Hydraulics Modeling Laboratory at Nanyang Technological University, Singapore. The dimensions of the wave flume were 32.5 m in length, 0.55 m in width and 0.6 m in depth. A piston-type wave-generator was installed at one side of the flume, and a wave-absorbing beach of 1:15 slope was located at the other side.

Fig. 3. 3 shows a sketch of the experimental setup. The model was placed at 12 m away from the wave-generator. Five resistance-type wave gauges (WG1-WG5 in Fig. 3. 3), each with resolution of 0.1 mm, were used to measure the instantaneous surface elevations: three were placed in front of the model for separation of incident waves from reflected waves, and the other two for measuring the water surface inside the pneumatic chamber. It is stressed that measuring surface elevation at two points inside the pneumatic chamber allows us to consider the spatial variation of the instantaneous water surface inside the pneumatic chamber (see Section 3.2.3). Due to the presence of the holders used to secure the pneumatic chamber, no wave gauge was installed to measure the surface elevation between the rear wall of the pneumatic chamber and the vertical wall. In the experiment, two piezoresistive pressure sensors were used to measure the pressure inside the pneumatic chamber. A web camera, synchronized with other signals, was placed on one side of the flume to synchronously monitor the motion of the water surface in the vicinity of the pneumatic chamber. A view of the breakwater model with vertical wall installed in the wave flume is shown in Fig. 3. 4.

Fig. 3. 3 A sketch of the experimental setup

Fig. 3. 4 A view of the breakwater model with vertical wall installed in the wave flume

3.2.2 Test conditions

In the experiments, the still water depth h was fixed at 0.4 m and the target wave height H_i was fixed at 0.03 m. The wave period varied from 0.9 s to 1.6 s at 0.1 s intervals so that the wave length L varied from 1.22 to 2.84 m. The model was suspended at 0.1 m draft by using holders firmly attached to the wave flume. Four values of the gap size were examined in the experiments: $G=0$ cm, 9.7 cm, 19.3 cm and 38.7 cm ($G/B=0, 0.24, 0.48$ and 0.97). Details of the experimental conditions and the geometric parameters of the model are summarized in Table. 3. 1.

3.2.3 Surface elevation inside the pneumatic chamber

In almost all the previous laboratory studies of OWC devices, the water surface elevation inside the pneumatic chamber was measured only at one single point, ignoring the spatial variation of water surface, which is true only for the very long waves (Evans and Porter, 1995). The temporal surface elevations measured by WG4 and WG5 in Fig. 3. 5 show that the spatial variation can be significant.

Table. 3. 1 Test conditions and the geometric parameters of the model

Parameters	Ranges
Water depth (h)	0.4 m
Incident wave height (H_i)	0.03 m
Wave periods (T)	0.9-1.6 s at 0.1 s intervals
Wave length (L)	1.22-2.84 m
Model breadth (B)	0.4 m
Model height	0.4 m
Model draft (D_r)	0.1m
Gap size (G)	0, 9.7, 19.3, 38.7 cm
h / L	0.14-0.33
H_i / L	0.011-0.025
B / L	0.14-0.33
G / B	0, 0.24, 0.48, 0.97

In the present study, the surface elevation inside the pneumatic chamber was considered as a superposition of right-going and left-going waves. The amplitude and phase information of the right-going and left-going waves can be obtained by performing a wave separation analysis using wave gauges WG4 and WG5, and the instantaneous surface elevation inside the pneumatic chamber can be constructed by the superposition of the right-going and left-going waves. Stiassnie et al. (1986) studied the wave interaction with two fixed vertical plates and found that the evanescent waves between the two plates could be neglected when the L/B was up to 17. In this study, $3.0 < L/B < 7.1$, thus the evanescent waves inside the chamber can be neglected when reconstructing the instantaneous water surface inside the pneumatic chamber. A comparison between the observed (web-camera recording) and constructed surface elevations at six instants of time during one wave period is shown in Fig. 3. 6, where the sampling frequency of wave gauges was 50 Hz and the sampling frequency of web camera for this set of experiments was 15 Hz. It can be seen in Fig. 3. 6 that the spatial variation of the surface elevation inside the pneumatic chamber is well considered by the present method.

Fig. 3. 5 Examples of the time series of surface elevation measured by WG4 and WG5 for the rectangular pneumatic chamber with an opening in its top face with and wave period=1.2 s; the solid line is the spatial-averaged surface elevation inside the pneumatic chamber, calculated using Eq. (3.3)

For later discussion of the experimental results, the spatial-averaged surface elevation inside the pneumatic chamber is denoted as

$$\langle \eta \rangle (t) = \langle \eta(x, t) \rangle \quad (3.3)$$

where $\langle \cdot \rangle$ means taking the average over the cross-sectional area of the rectangular pneumatic chamber.

Fig. 3. 6 Left: the constructed surface elevations inside the pneumatic chamber at six instants of time during one wave period for the rectangular pneumatic chamber with a top opening, wave period=1.2 s and $G/B = 0$; Right: snapshots of video recordings at the same instants of time.

—:the reconstructed surface; $\square$: the surface elevation measured by WG4; $\circ$: the surface elevation measured by WG5

3.2.4 Hydrodynamic coefficients

The amplitudes of incident waves (A_i) and reflected waves (A_r) can be obtained through a wave separation analysis proposed by Goda and Suzuki (1976). The reflection coefficient is defined by $C_r = A_r / A_i$, and an energy-dissipation

coefficient C_d is defined according to the following energy balance,

$$C_d = 1 - C_r^2 \quad (3.4)$$

In addition, a pressure coefficient is defined as $C_p = \Delta P / \rho g A_i$, where ΔP is the amplitude of the pressure fluctuation inside the pneumatic chamber, ρ the water density, and g the gravitational acceleration. For later discussion, an amplification coefficient is defined as

$$C_a = A_{\bar{\eta}} / A_i \quad (3.5)$$

which describes the amplitude of averaged surface elevation inside the pneumatic chamber, $A_{\bar{\eta}}$.

3.2.5 Pneumatic energy extraction efficiency

The period-averaged power output of the pneumatic chamber per unit length can be expressed by

$$\bar{P}_o = \frac{B}{T} \int_{t_0}^{t_0+T} \langle p(t)v(x,t) \rangle dt \quad (3.6)$$

where $\langle \cdot \rangle$ represents averaging over the cross-section area of the pneumatic chamber, $p(t)$ is the instantaneous pressure of the air inside the pneumatic chamber, $v(x,t)$ the instantaneous vertical velocity of the surface oscillation at position x inside the pneumatic chamber.

After using linear wave theory, the incident wave power per unit crest width can be calculated by

$$\bar{P}_i = \frac{1}{4} \rho g A_i^2 \frac{\omega}{k} \left(1 + \frac{2kh}{\sinh 2kh} \right) \quad (3.7)$$

where k is wave number, ω wave angular frequency.

For both configurations, the pneumatic energy extraction efficiency by the pneumatic chamber can be directly calculated as

$$\varepsilon = \frac{\bar{P}_o}{\bar{P}_i} \quad (3.8)$$

which includes the energy used to compress/decompress the air inside the chamber and the energy dissipated by the air flow through the opening in the top face. The difference between energy-dissipation coefficient C_d and pneumatic energy extraction efficiency ε is the energy loss due to the vortex shedding at the tips of the plates forming the pneumatic chamber. The energy loss due to vortex shedding can be quantified by as the parameter C_v defined by

$$C_v = C_d - \varepsilon \quad (3.9)$$

It is expected that $C_v \approx C_d$ in the absence of an opening in the top face of the pneumatic chamber.

3.3 Results and discussion

The experimental results, including reflection coefficient C_r , energy-dissipation coefficient C_d , pressure coefficient C_p , amplification coefficient C_a and pneumatic energy extraction efficiency ε , are reported for the configuration with an opening in the top face. Since the surface elevation inside the pneumatic

chamber is always very small for the configuration without an opening in the top face, it is difficult to reconstruct the surface elevation. Only C_r , C_d and C_p are reported for the configuration without an opening in the top face. At the end of this section, the reflection coefficients for the two configurations (see Fig. 3. 2) are compared with those reported in Zhu and Chwang (2001). The pneumatic energy extraction efficiency of the configuration with an opening in the top face for $G/B=0$ is also compared with that in Morris-Thomas et al. (2007).

3.3.1 The configuration without an opening in the top face

Both the distance from the center of the pneumatic chamber to the vertical wall (W) and the wave length (L) are important parameters affecting the hydrodynamic performance of the system. The experimental results are presented as functions of W/L because the oscillation of the water column inside the pneumatic chamber can greatly influence the hydrodynamic coefficients of the breakwater and the pneumatic efficiency of wave energy extraction. Fig. 3. 7 - Fig. 3. 9 show the experimental results for C_r , C_d and C_p as functions of W/L for h/L ranging between 0.14 and 0.33, respectively.

Referring to Fig. 3. 7 for the measured C_r , in the absence of a gap between the pneumatic chamber and the vertical wall ($G/B=0$), i.e. the rear wall of the pneumatic chamber is part of the vertical wall, C_r varies within a narrow range of 0.86-0.95. When a gap existed between the pneumatic chamber and the vertical wall ($G/B \neq 0$), the reflection coefficient dropped sharply around $W/L \approx 0.18$: $C_r = 0.14$ for $G/B=0.24$ and $C_r=0.30$ for $G/B=0.48$. The minimum reflection coefficient was not measured for $G/B=0.97$.

Fig. 3. 7 Variation of reflection coefficient C_r versus W/L for the rectangular pneumatic chamber without top opening

Referring to Fig. 3. 8 for the measured energy-dissipation coefficients, in the absence of a gap ($G/B=0$), only up to 32% of the incoming wave energy can be dissipated, and the maximum energy dissipation rate occurs at $W/L \approx 0.17$. A gap between the pneumatic chamber and the vertical wall significantly enhances the energy dissipation. For $G/B \neq 0$, a significant portion of the incoming wave energy can be dissipated: 98% for $G/B=0.24$ and 90% for $G/B=0.48$, and both occur around $W/L \approx 0.18$. The reason why the gap can enhance energy dissipation will be explained at the end of this section.

Fig. 3. 8 Variation of energy-dissipation coefficient C_d versus W/L for the rectangular pneumatic chamber without top opening

Referring to Fig. 3. 9, the dependence of the pressure coefficient C_p turns to diminish when $W/L > 0.21$. When $W/L < 0.21$, the pressure coefficient C_p drops from 2.0 to 0.22 with an increase in W/L from 0.07 to 0.21. In the absence of an opening on the top face, the mass of the air is constant, and air pressure follows the Boyle's law. An increase in the air pressure turns to reduce the up and down motion of the water surface inside the pneumatic chamber; this results in a small surface elevation inside the pneumatic chamber, which can be within the range of the measurement error. Therefore, the surface elevation inside the chamber cannot be adequately reconstructed for this case.

Fig. 3. 9 Variation of pressure coefficient C_p versus W / L for the rectangular pneumatic chamber without top opening

Since the air pressure inside the chamber follows the Boyle's law, it can be concluded that the pneumatic energy extraction should be very small and the energy dissipation should be dominated by the vortex shedding at the tips of the vertical plates.

The surface elevation inside the pneumatic chamber is weak. As a result, the large energy dissipation occurred around $W / L \approx 0.18$ can only be explained by a resonance mechanism related to the motion of the water in the gap between the rear wall of the pneumatic chamber and the vertical wall. When the water in the gap between the rear wall of pneumatic chamber and the vertical wall is excited by the incident waves, a large difference exists in the water surface elevations on the two sides of the rear wall of pneumatic chamber, generating strong vortex shedding at the tips of the pneumatic chamber walls. Fig. 3. 10 shows an example of snapshots of the surface elevations at four instants of time during one wave period for $G / B = 0.24$ and $T = 1.2$ s. The amplitudes of the water surface displacement in the

gap A_w can be obtained by analyzing the recorded videos. Fig. 3. 11 shows the amplitude of the vertical velocity of the surface elevation inside the gap, ωA_w , as a function of W/L for $G/B=0.24$. It can be seen that peak value occurs around $W/L \approx 0.18$.

Fig. 3. 10 Video screenshots of surface elevations at four instants during one wave period; the experimental test conditions were: sealed pneumatic chamber, wave period=1.2 s, $G/B=0.24$

Fig. 3. 11 Variations of ωA_w versus W/L for the rectangular pneumatic chamber without top opening and $G/B = 0.24$

3.3.2 The configuration with an opening in the top face

The experimental results for the configuration with an opening in the top face are shown in Fig. 3. 12 - Fig. 3. 16 for the C_r , C_d , C_p , C_a and ε as functions of W/L for h/L ranging between 0.14 and 0.33, respectively.

Referring to Fig. 3. 12 for the measured reflection coefficients, C_r varies within the range of 0.23 and 0.70 for all four values of G/B . The maximum values occurred around $W/L \approx 0.21$ for $G/B = 0.24$ and 0.48. For each gap size (except for $G/B = 0.97$), a minimum reflection coefficient can be found for waves longer than $W/L = 0.21$; this minimum reflection coefficient is 0.30 for $G/B = 0$, 0.45 for $G/B = 0.24$, and 0.54 for $G/B = 0.48$. As indicated by the dashed line in Fig. 3. 13, reducing the gap size can reduce the value at which the minimum reflection coefficient occurs: the minimum reflection coefficient occurs at $W/L = 0.15$ for $G/B = 0.48$, $W/L = 0.14$ for $G/B = 0.24$ and $W/L = 0.11$ for $G/B = 0$. For

each gap size, another local minimum reflection coefficient may also exist when $W/L > 0.21$, but this local minimum reflection coefficient is less interested from practical point of view and the experiment was not designed to measure it. From practical point of view, a design with $G/B = 0$ might be preferable since it requires less space, which is a desirable feature of an engineering solution to reduce wave reflection from a vertical wall for a harbor.

Fig. 3. 12 Variation of reflection coefficient C_r versus W/L for the rectangular pneumatic chamber with a top opening

The theoretical study of Sarmento and Falcão (1985) for a pneumatic chamber with a zero draft showed that the pneumatic chamber did not extract energy when $W/L = 0.25$. Present experimental results showed that the pressure coefficient C_p was almost zero for W/L ranging between 0.21 and 0.25. As shown in Fig. 3. 14, a maximum pressure coefficient of 0.35 occurs at $W/L \approx 0.08$ for $G/B = 0$.

Fig. 3. 13 Variation of energy-dissipation coefficient C_d versus W/L for the rectangular pneumatic chamber with a top opening

Fig. 3. 14 Variation of pressure coefficient C_p versus W/L for the rectangular pneumatic chamber with a top opening

Referring to Fig. 3. 15 for the measured amplification factors, $C_a > 1$ can be found

in the range of $W/L < 0.14$ for $G/B = 0$ and 0.24. Weak wave amplification is found around $W/L \approx 0.21$. The trends of ωC_a and C_p are almost the same, indicating that the air compressibility is negligible when there is an opening in the top face of the pneumatic chamber (when the air is incompressible, the pressure is proportional to the vertical velocity of averaged water surface inside the pneumatic chamber (Evans, 1982); to save space, the trends of ωC_a is not plotted here).

Fig. 3. 15 Variation of amplification coefficient C_a versus W/L for the rectangular pneumatic chamber with a top opening

Referring to Fig. 3. 16 for the measured energy extraction efficiency, ε is almost zero around $W/L \approx 0.21$, which is in agreement with the conclusion of (Sarmiento and Falcão, 1985) for a pneumatic chamber with zero draft (they indicate when $W/L = 0.25$ efficiency is zero). In the range of $W/L < 0.21$, ε increased with decreasing W/L and a maximum extraction efficiency can be reached: a maximum energy extraction efficiency of 0.53 occurs at $W/L \approx 0.10$ for $G/B =$

0 and a maximum energy extraction efficiency of 0.29 occurs at $W/L \approx 0.11$ for $G/B = 0.24$ in the range of $W/L > 0.21$, another maximum extraction efficiency for shorter waves may also exist and this maximum extraction efficiency can be even larger than that occurred at $W/L \approx 0.10$, but this maximum extraction efficiency for shorter waves was not the focus of this study.

The measured vortex-shedding induced energy-dissipation coefficient (C_v) is shown in Fig. 3. 17. The peak values of C_v for different values of G/B occur in the range of $0.17 < W/L < 0.23$.

Fig. 3. 16 Variation of pneumatic energy extraction efficiency ε versus W/L for the rectangular pneumatic chamber with a top opening

Based on the present study, it is recommended that a pneumatic chamber with an opening in its top face should be constructed such that its rear wall is part of the vertical wall. The breadth of the pneumatic chamber should be determined according to $W/L = 0.10$, so that wave reflection is minimized and wave energy

extraction is maximized. Since there is no gap between the pneumatic chamber and the vertical wall, less space is required for the system to function.

Fig. 3. 17 Variation of vortex-shedding induced energy-dissipation coefficient C_v versus W/L for the rectangular pneumatic chamber with a top opening

3.3.3 A comparison with a slotted barrier in front of a vertical wall

Based on the present experimental results, the pneumatic chamber without an opening is recommended to be constructed with a small gap (Case A), and the pneumatic chamber with an opening is recommended to be constructed such that its rear wall is part of the vertical wall (Case B).

The reflection characteristics of Case A and Case B were compared with the experimental studies of porous structure reported in Twu and Lin (1991) and the slotted structure reported in Zhu and Chwang (2001). Since these two types of structures dissipate wave energy in a similar manner, I compare the results of Zhu

and Chwang (2001) with my results². Zhu and Chwang (2001) studied a slotted barrier in front of a vertical wall and the variation of S/L was achieved by varying the distance between the slotted barrier and the vertical wall. The relative draft (D_r/h) in their study was 0.25, same as in present study. The S/L was used in comparison since it can evaluate the space used to construct the structures.

Referring to Fig. 3. 18, when $S/L=0.25$, the waves reflected from the vertical wall are out of phase of the incident waves. In the absence of the slotted barrier, a node of surface displacement is formed at $S/L=0.25$, where the horizontal velocity of water particle is maximum, and more energy can be dissipated by water flow through the small gaps in the slotted barrier placed at $S/L=0.25$ (Huang et al., 2011), and a small reflection coefficient is expected to occur around $S/L=0.25$. Of course, the properties of the slotted barrier may slightly affect the value of S/L at which the minimum reflection coefficient occurs. However, this mechanism is not so effective for longer waves, since is hard to be achieved for longer waves due to the limited space inside a harbor. The comparison also shows that the slotted barrier is more effective in reducing wave reflection for shorter waves.

For the configuration without an opening in the top face, the energy-dissipation mechanism is different. Significant energy dissipation can be achieved by the resonant motion of the water in the gap between the rear wall of the pneumatic chamber and the vertical wall (see Fig. 3. 11). The natural period of the water column in the gap can be adjusted through the draft of the pneumatic chamber and the gap size. The air pressure inside the pneumatic chamber suppresses the surface

²Twu and Lin (1991) reported their measured reflection coefficients in the range of $1 < W/L < 1.5$. Theoretically, the reflection coefficient repeats itself every $W/L = 0.5n$ with n being a non-zero integer; however, the measured reflection coefficients in the range of $0 < W/L < 0.5$ may still slightly differ from those in the range $1 < W/L < 1.5$. Therefore, a direct comparison between the present results with those in Twu and Lin (1991) is not attempted here.

elevation inside and lead to larger water level difference on the two sides of the rear wall of pneumatic chamber by this mechanism. However, since the minimum reflection coefficient can be achieved only within a narrow range of wave periods near the resonance period for the water in the gap, this configuration is suitable only at the site where waves are stable narrow-banded waves.

Fig. 3. 18 Comparison of wave reflection C_r versus S/L between present study and Zhu and Chwang (2001) for slotted structures; Case A: the rectangular pneumatic chamber without an opening in its top face ($G/B=0.24$); Case B: the rectangular pneumatic chamber with an opening in the top face ($G/B=0$); the relative draft is same ($D_r/h=0.25$) in all cases.

For the configuration with an opening in the top face, both the vortex shedding at the tips of the pneumatic chamber walls and the pneumatic energy extraction contribute to the reduction of wave reflection. When the rear wall of the pneumatic

chamber is part of the vertical wall (i.e. $G/B=0$), the significant reduction of wave reflection can be achieved in a wider range of wave periods, comparable to that of slotted/perforated barriers (Zhu and Chwang, 2001). Moreover, the present configuration provides a promising option for reducing wave reflection from a vertical wall, with a potential for extracting wave energy for electricity generation.

Morris-Thomas et al. (2007) experimentally studied the pneumatic energy extraction efficiency of an oscillating-water-column (OWC) device attached to a vertical wall, a case similar to the Case B (the configuration with an opening in the top face and with $G/B=0$). The ratio of pneumatic chamber draft to water depth (D_r/h) in their study was 0.25, same as in present study, however, the ratio of opening in the top face in their study was 0.78%, which was smaller than ours (1.25%). Fig. 3. 19 shows a comparison of pneumatic energy extraction efficiency ε between the present study and study in Morris-Thomas et al. (2007). Through their numerical simulations, Liu et al. (2010) showed that increasing D_r/h would reduce the value of B/L at which the pneumatic energy extraction efficiency has its local maximum (Fig. 4 in Liu et al., 2010). Since the present study has a value of D_r/h same as that in Morris-Thomas et al. (2007), the difference in the peak value and its corresponding value of B/L is due mainly to the different opening sizes used in these two experiments. The size of the opening will affect the damping coefficient of the OWC system. As a result, a smaller opening turns to increase the damped resonance period (since the compressibility of the air can be neglected). Therefore, for a fixed chamber breadth, the value of B/L at which the maximum extraction efficiency occurs reduces with reducing size of the opening in the top face of the pneumatic chamber, as shown in Fig. 3. 19.

Fig. 3. 19 Comparison of pneumatic energy extraction efficiency ε versus B/L between the present study and Morris-Thomas et al. (2007); Case B: the rectangular pneumatic chamber with an opening in the top face ($G/B=0$)

3.4 Concluding Remarks

In this study, the hydrodynamic performance of two configurations of a pneumatic chamber in front of a vertical wall was studied experimentally: one with an opening in the top face of the rectangular pneumatic chamber, and the other without.

For the configuration of the pneumatic chamber without an opening in its top face, the air compressibility played an important role in building the air pressure inside the pneumatic chamber, and the energy used to compress/decompress the air inside the pneumatic chamber was negligible compared to the incoming wave energy. The gap distance between the rear wall of the pneumatic chamber and the vertical wall significantly affected the wave reflection. Large energy dissipation may occur when the water column within the gap between the rear wall of the pneumatic chamber and the vertical wall respond to incoming waves resonantly, resulting in very small reflection coefficients within a narrow range of wave periods.

For the configuration of the pneumatic chamber with an opening in its top face, the energy dissipation was from pneumatic energy extraction as well as vortex shedding at the tips of the pneumatic chamber walls. Both small reflection coefficients and large energy extraction efficiencies were achieved when the gap between the rear wall of the pneumatic chamber and the vertical wall is absent. This configuration provides a promising option for reducing wave reflection from a vertical wall, with a potential for extracting wave energy for electricity generation.

CHAPTER 4 HYDRODYNAMIC PERFORMANCE OF A RECTANGULAR FLOATING BREAKWATER WITH AND WITHOUT PNEUMATIC CHAMBERS

4.1 Introduction

Floating breakwaters are commonly used to protect shorelines, marine structures, moored vessels, marinas and harbors from wave attacks. Compared with permanently fixed breakwaters, floating breakwaters have superiority in terms of environmental friendliness, low cost, flexibility and mobility. They are especially competitive for coastal areas with a high tidal range or deep water depth. Moreover, they may even be the only viable option for locations with poor bottom foundation.

Different from bottom-fixed breakwaters such as rubble mound breakwaters which intercept all approaching waves, the hydrodynamic interactions between the incoming waves and the floating breakwater are complex with the wave energy being partially reflected, partially transmitted beneath the breakwater and partially dissipated. The incident waves excite motion responses of the breakwater, which in turn acts as a wave generator radiating waves away from the breakwater to both its seaward and leeward sides. Thus, the total transmitted waves include two components: the transmitted incident waves passing underneath and the radiated waves propagating to the leeward side of the breakwater. The wave transmission characteristic is an important consideration of the functional role of a breakwater towards the objective of wave protection.

The general desirable characteristics of a floating breakwater include high cost-effectiveness, good wave attenuation and low force requirements on the mooring system. Previously, Hales (1981) and McCartney (1985) reviewed

comprehensively various floating breakwater concepts to evaluate their performance and applicability. Since then, floating breakwaters with other novel configurations have also been proposed for better performance, such as the double Y-frame multifunctional floating breakwater (Murali and Mani, 1997), the spar buoy floating breakwater fences (Liang et al., 2004), the Π shaped floating breakwater with two additional side-boards (Gesraha, 2006), the thin plane board floating breakwater with rows of net underneath (Dong et al., 2008), the horizontally interlaced floating pipe breakwater with multi-layers (Hegde et al., 2008), the diamond-shape blocks assembled porous floating breakwater (Wang and Sun, 2010), and the floating breakwater with truss structures (Uzaki et al., 2011).

Hales (1981) pointed out that a floating breakwater should be as simple, durable and maintenance-free as possible for long-time operation in real seas, and that highly complex structures should be avoided. Floating breakwaters with a rectangular cross-section may thus be most suitable to satisfy these requirements. For various two-dimensional free or moored floating breakwaters with a rectangular cross-section, extensive theoretical, experimental and numerical research had been reported in the literature (Christian, 2000; Drimer et al., 1992; Fugazza and Natale, 1988; Koutandos et al., 2005; Rahman et al., 2006; Sannasiraj et al., 1998; Williams et al., 2000).

To be an effective floating breakwater, its movements should be of small amplitude so that the motion-generated radiated waves into the protected region will not be large. To achieve this, either a tensioned mooring system (Elchahal et al., 2008; Rahman et al., 2006; Wang and Sun, 2010; Williams and Abul-Azm, 1997) or vertical piles (Diamantoulaki et al., 2008; Isaacson et al., 1998; Kim et al., 1994) were proposed to restrain the motion of the breakwater in earlier studies. A taut mooring system can effectively restrict the motion amplitude, while piles can effectively restrict the horizontal motion but not the vertical motion. In practice, the

taut mooring system faces such problems as huge impulsive forces, high sensitivity to tidal change and construction difficulties, while the pile-restrained implementation also meets many problems including large loads on the piles, abrasion between piles and the breakwater, and infeasibility in deep water or poor foundation conditions where the floating breakwater should have been competitive (McCartney, 1985).

There have been few earlier studies on floating breakwaters with pneumatic effects. Vijayakrishna Rapaka et al. (2004) experimentally studied a floating multi-resonant structure of which the OWC-type wave energy devices were embedded into the middle of a floating breakwater. The dynamic behaviors of the structure were studied including the motion responses and mooring line forces. Koo (2009) developed a nonlinear numerical wave tank to study the pneumatic floating breakwater in one individual mode. The effects of pneumatic damping on the body motion and wave transmission were examined. As far as I am aware, there are no published studies so far that examine the pneumatic effects on the hydrodynamic performance of a floating breakwater, including wave reflection, transmission, energy dissipation and motion responses.

One of the aims of the present study is to provide an economical way to improve the performance of box-type floating breakwaters for long waves without significantly increasing its weight and construction cost. In this chapter, a novel configuration of a pneumatic floating breakwater is proposed for combined wave protection and potential wave energy capturing. The development of the concept originates from the oscillating-water-column (OWC) device commonly used in wave energy utilization (Falcão, 2010). The configuration consists of the box-type breakwater with a rectangular cross-section as the base structure, with pneumatic chambers (OWC units) installed on both the front and rear sides of the box-type breakwater without modifying the geometry of the original base structure. The pneumatic

chamber used in this study is primarily of a hollow chamber with a large submerged bottom opening below the water level. Air trapped above the water surface inside the chamber is pressured due to the water column oscillation inside the chamber, and it can exit the chamber through a small opening at the top cover with energy dissipation. Since the energy dissipated by the air flow is not directly related to both the reflected and transmitted waves, better wave attenuation can be potentially achieved with the chamber installation. The present proposed configuration mitigates the movements of the breakwater through the effects of pneumatic chambers instead. Hence, it should be more economical, and a feasible slack mooring system can be employed with the reduced motion.

In this chapter, the hydrodynamic performance of the proposed floating breakwater under regular waves (monochromatic waves) was investigated experimentally. The performance was compared with that of the original box-type floating breakwater without pneumatic chambers, including wave transmission, wave energy dissipation and motion responses, to elucidate the functional effects of the pneumatic chambers. Since the dynamic characteristics of the floating structure change with different drafts, three different drafts were tested in the experiments to investigate possible influences of draft. The air pressure fluctuations inside the chambers, which inferred the extent of water column oscillation, were also measured.

4.2 Experimental setup and test procedures

4.2.1 Physical model

The geometric details of the pneumatic floating breakwater and the original rectangular box-type breakwater model used in the experiments are shown in Fig. 4.

1. Pneumatic chambers were attached to the front and rear sides of the original

rectangular box-type structure (shown on the right of Fig. 4. 1) to form a new configuration (shown on the left of Fig. 4. 1). The models were made of 10-mm thick Perspex sheet; additional steel and Perspex plates were placed inside the breakwater as ballasts to adjust the draft. A narrow slot opening, which allowed an energy loss induced by the air flow in and out of the chamber, was constructed on the top plate of each pneumatic chamber to simulate a power-take-off mechanism. For convenience of description, I designate the proposed breakwater of 0.235 m draft as Model 1, the original rectangular box-type breakwater without chambers of 0.235 m draft as Model 2, the proposed breakwater of 0.299 m draft as Model 3 and the proposed breakwater of 0.177 m draft as Model 4. The details of these four models are summarized in Table. 4. 1, and a view of the physical model in the wave flume is shown in Fig. 4. 2.

B/L , where B is the breadth of the box-structure bottom and L is the wave length, is considered as an important factor to present the results. According to the waves the wave flume can generate, the breadth of the box-structure bottom B is determined to make sure the typical range of B/L could be covered in the experiments. Model 1 and Model 2 had the same draft of 0.235 m ($D_r/B=0.31$) to understand the effects of the pneumatic chambers. In addition, two other drafts, one deeper (0.299 m for Model 3, $D_r/B=0.40$) and another shallower (0.177 m for Model 4, $D_r/B=0.24$) were also examined to understand the effects of the draft on pneumatic floating breakwaters.

Fig. 4. 1 Details of the pneumatic floating breakwater and original box-type breakwater models

Fig. 4. 2 Physical model in the wave flume before running waves

Table. 4. 1 Details of the four models examined in the experiments

	Length (mm)	Bottom breadth B (mm)	Height (mm)	Draft D_r (mm)	Chamber breadth (mm)	Slot opening breadth (mm)	Mass (Kg)	Moment of inertia (Kg•m ²)	Gravity center above base (mm)
Model 1	1420	750	400	235	400	5	267	35.7	111.9
Model 2	1420	750	400	235	N/A	N/A	250	14.4	79.6
Model 3	1420	750	400	299	400	5	339	39.3	95.7
Model 4	1420	750	400	177	400	5	195	31.8	143.5

4.2.2 Experimental setup

The experiments were conducted in a wave flume at the Hydraulics Modeling Laboratory of Nanyang Technological University, Singapore. The dimensions of the wave flume were 45-m long, 1.55-m wide and 1.5-m deep. A piston-type wave-maker, equipped with a DHI Active Wave Absorption Control System (AWACS), was installed at one end of the flume, and a wave-absorbing beach was located at the other end to reduce the wave reflection.

Fig. 4. 3 shows a sketch of the experimental setup. The floating breakwater was slack-moored in its equilibrium position, which was 25m away from the wave-maker. Each chain mooring line was fastened to a concrete anchor (shown in Fig. 4. 4). The touchdown point of each mooring line was 1 m away from the model centerline and the anchor point was 3 m away from the model centerline. The mooring line was made of stainless steel and had a length of 3.0 m with a line density of 0.155 kg/m. The concrete anchor had an average weight of 2.265 kg and its small dimensions (0.1 m x 0.1 m x 0.1m) would not significantly disturb the flow field. Three sets of mooring cables were installed on each side of the floating breakwater. Vijayakrishna Rapaka et al. (2004) studied the effects of slack mooring-line scope (defined as the ratio of length of mooring line to water depth) on the motion responses of floating structures. They found that the motions in all surge, heave and pitch modes depicted similar behaviors and the difference was minor although the mooring-line scopes widely varied from 4 to 6. Since the effects of slack mooring lines on the motion responses were insignificant, the positions of the anchors were not changed in this study. The positions of the small concrete anchors were checked after each test, and it was confirmed that those anchors were not moved by the breakwaters during present experiments. The main function of the mooring lines actually is to resist the slow drift force and hold the floating breakwater in its dynamic equilibrium position. The present tests showed that the

relatively small concrete anchor was strong enough to resist the mooring forces.

Fig. 4. 3 Sketch of the experimental setup for the breakwater with pneumatic chambers

As shown in Fig. 4. 5, four ball bearings were installed on each lateral side of the model. The ball bearing can rotate in all directions and reduce the friction between the model and the walls; they also prevent the model from any possible colliding with the flume walls. In this manner, the motion of the breakwater can be restricted to two-dimensional only.

The target wave height H_i was fixed at 0.04m. Since the coastal mean water level changes with tides, four water depths h were examined in present study: 0.90 m, 0.70 m, 0.55 m and 0.45 m. Since the main focus of this study is to improve the performance of existing box-type breakwaters by installing the pneumatic chambers, it is natural to compare the modified model with the original model using a length scale that is common for both models to normalize the wave length L and to present the results. In this study, I chose B , the bottom breadth of the original breakwater, to compare the experimental results. The normalized B/L varied from 0.18 to 0.45. All the test wave conditions are listed in Table. 4. 2.

Fig. 4. 4 A view of the chain mooring line and the concrete anchor

Fig. 4. 5 Ball bearing structure; the circles indicated the installation of the ball bearings

Table. 4. 2 Experimental test conditions ($H_i = 0.04\text{m}$)

h (m)	T (s)	L (m)	B/L
0.9	1.1-1.7	1.88-4.00	0.187-0.399
0.7	1.1-1.8	1.85-4.03	0.186-0.404
0.55	1.1-1.9	1.81-3.96	0.189-0.415
0.45	1.1-2.0	1.75-3.88	0.193-0.430

4.2.3 Data acquisition system

Eight HR Wallingford wave gauges (WG1-WG8 in Fig. 4. 3) were used to measure the surface elevations; four were placed in front of the model for separation of the incident waves from the reflected waves, and the other four in the leeward side of the model for separation of the transmitted waves from the waves reflected from the wave absorbing beach. The distances between the wave gauges are listed in Table. 4. 3. The manufacturer-specified accuracy of the wave gauge is 0.1 mm. Before and after each set of tests, pre- and post-calibration were carried out to ensure the quality of the measured surface elevation. The two-point method, proposed initially by Goda and Suzuki (1976), was employed to separate the reflected waves from the incident waves. Different distances between the four wave gauges provide several sets of data available for wave separation.

Table. 4. 3 Distances between wave gauges

Wave gauges	Distances (cm)
WG1&WG2	20
WG2&WG3	40
WG3&WG4	40
WG5&WG6	40
WG6&WG7	40
WG7&WG8	20

An optical tracking system was installed to capture the motion of the floating breakwater. The system consisted of two ProReflex infrared cameras, data acquisition and processing software (Qualisys Track Manager) and retro-reflective markers. An earth-fixed Cartesian coordinate system can be established through calibration by using the standard calibration tools provided by the manufacturer.

Since the established coordinate system is in reference to the locations of the two cameras, the cameras cannot be moved after calibration. The trajectory of retro-reflective markers attaching to the floating breakwater can be tracked in the calibrated coordinate system by the two cameras, and Qualisys Track Manager can calculate the motion responses of the floating breakwater after the center of rotation is specified. In principle, the minimum number of markers required for the calculation is 3, but more markers can be used to ensure the data quality (in case that any marker is out of the field of view when the model moves). The setup of the infrared camera system over the wave flume is shown in Fig. 4. 6 and the corresponding established coordinate system in Qualisys Track Manager is shown in Fig. 4. 7. Sample temporal data of the measured surge, heave and pitch responses are shown in Fig. 4. 8. There are several possible explanations for the slow drift observed in the sample temporal data of surge motions: (1) the transient dynamics of the floating breakwater and the transient wave front, both include wave frequencies other than the target wave frequency. This slow drift clearly shifts from 800mm to about 1100mm within the first 80s of the start of the wave generator, and then slow-drift gradually damped out; (2) the waves generated by the wave maker are not pure at start-up phase; (3) the vortex shedding may also give rise to forces and unsteady flows whose frequency slightly differ from the incident wave frequency.

A Kistler pressure sensor was installed on the top of each pneumatic chamber (10 cm away from the slot opening) to measure the air pressures inside the chambers (PS1 and PS2 in Fig. 4. 3).

Fig. 4. 6 The setup of the infrared camera system over the wave flume

Fig. 4. 7 Established coordinate system in Qualisys Track Manager

Fig. 4. 8 Sample temporal data of motions including surge, heave and pitch; the experimental test conditions are: Model 1, wave height=0.04m, water depth= 0.9 m and wave period=1.4 s

4.3 Results and discussion

The amplitudes of incident waves (A_i) and reflected waves (A_r) were separated from the measured surface elevations by using a two-point method (Goda and Suzuki, 1976). I also separated the transmitted waves (A_t) from the waves reflected from the beach (A_{rb}) to check the dissipation performance of the beach. For floating breakwaters, I define the reflection coefficient C_r as A_r / A_i and the transmission coefficient C_t as A_t / A_i . Fig. 4. 9 and Fig. 4. 10 show the variations of C_r and C_t with B/L , respectively. I denote C_d as the fraction of incident wave energy dissipated, which can be estimated by examining the wave energy balance as follows:

$$C_r^2 + C_t^2 + C_d = 1 + C_{rb}^2 \quad (4.1)$$

where $C_{rb} = A_{rb} / A_i$ quantifies the wave energy reflected from the absorbing beach.

Fig. 4. 11 shows the variation of C_d with B/L .

The amplitudes of surge translation (A_{surge}), heave translation (A_{heave}) and pitch rotation (A_{pitch}) of the breakwater were captured by the infrared camera system. I define the surge, heave and pitch RAOs as A_{surge} / A_i , A_{heave} / A_i and A_{pitch} / A_i , respectively. Fig. 4. 12-Fig. 4. 14 show the variations of the surge, heave and pitch RAOs with B/L , respectively.

I define the pressure coefficient C_p as $\Delta P / \rho g A_i$, where ΔP is the amplitude of the pressure fluctuation inside the pneumatic chamber, ρ the water density, and g the gravitational acceleration. Fig. 4. 15 summarizes the variation of C_p with

B/L inside the front and rear chambers for Model 1, Model 3 and Model 4.

From the results, I found that the effect of D_r/h was insignificant for a fixed D_r/B . The subsequent focus is thus given to the effects of the pneumatic chambers and the draft. However, all the results for the four water depths are presented for completeness.

4.3.1 The effects of pneumatic chambers

The effects of the pneumatic chambers on the wave reflection and transmission, wave energy dissipation and motion responses are elucidated by comparing the hydrodynamic performances of Model 1 and Model 2.

4.3.1.1 Wave reflection and transmission coefficients

Referring to Fig. 4. 9, the wave reflection of Model 1 was stronger for relatively short period waves but weaker for longer period waves. The minimum reflection coefficient occurred around $B/L=0.23$. In contrast, the reflection coefficient for Model 2 varied in a narrow range roughly between 0.2 and 0.5.

Fig. 4. 9 Variation of reflection coefficient C_r versus B/L under four water depths; (a) Model 1, with chambers, $D_r/B = 0.31$; (b) Model 2, without chambers, $D_r/B = 0.31$; (c) Model 3, with chambers, $D_r/B = 0.40$; (d) Model 4, with chambers $D_r/B = 0.24$ (Figure continued on next page)

Fig. 4. 9 Variation of reflection coefficient C_r versus B/L under four water depths; (a) Model 1, with chambers, $D_r/B = 0.31$; (b) Model 2, without chambers, $D_r/B = 0.31$; (c) Model 3, with chambers, $D_r/B = 0.40$; (d) Model 4, with chambers $D_r/B = 0.24$

As shown in Fig. 4. 10, the wave transmission coefficient was reduced in the whole range of B/L by installing the pneumatic chambers. For Model 1, increasing B/L decreased C_t nearly monochromatically from a maximum value of 0.71 to a minimum value of 0.15. Note that this behavior is quite similar to that of a fixed box-type breakwater (see Fig. 3 in Drimer et al., 1992). In contrast, for Model 2, C_t reached a minimum value of 0.33 around $B/L=0.29$. In terms of maximum C_t , it was as large as 0.96 at $B/L=0.19$ for long period waves, and 0.63 at $B/L=0.42$ for short period waves. Drimer et al. (1992) pointed out that the floating breakwater is transparent for very long waves. However, the additional pneumatic chambers changed the wave scattering and energy dissipation. The present results showed that the breakwater with pneumatic chambers could still be effective in reducing wave energy transmission even for very long period waves.

4.3.1.2 Wave energy dissipation

Fig. 4. 11 shows the calculated energy dissipation coefficient C_d . Comparing the measured C_d for Model 1 and Model 2, it reveals that Model 1 dissipated much more energy for longer period waves when $B/L < 0.29$. However, there was no noticeable difference in the energy dissipation for shorter period waves when $B/L > 0.29$. The major benefit of using pneumatic chambers to dissipate wave energy is thus primarily for long period waves: for the longest wave in the experiments, C_d for Model 2 was only 0.05, while C_d was as large as 0.51 for Model 1. The additional energy dissipation for Model 1 came from the vortex shedding at the tips of the chamber front walls and the air flow through the slot openings at the top of the chambers.

Fig. 4. 10 Variation of transmission coefficient C_t versus B/L under four water depths; (a) Model 1, with chambers, $D_r/B = 0.31$; (b) Model 2, without chambers, $D_r/B = 0.31$; (c) Model 3, with chambers, $D_r/B = 0.40$; (d) Model 4, with chambers $D_r/B = 0.24$ (Figure continued on next page)

Fig. 4. 10 Variation of transmission coefficient C_t versus B/L under four water depths; (a) Model 1, with chambers, $D_r/B = 0.31$; (b) Model 2, without chambers, $D_r/B = 0.31$; (c) Model 3, with chambers, $D_r/B = 0.40$; (d) Model 4, with chambers $D_r/B = 0.24$

Fig. 4. 11 Variation of energy dissipation coefficient C_d versus B/L under four water depths; (a) Model 1, with chambers, $D_r / B = 0.31$; (b) Model 2, without chambers,

$D_r / B = 0.31$; (c) Model 3, with chambers, $D_r / B = 0.40$; (d) Model 4, with

chambers $D_r / B = 0.24$ (Figure continued on next page)

Fig. 4. 11 Variation of energy dissipation coefficient C_d versus B/L under four water depths; (a) Model 1, with chambers, $D_r/B = 0.31$; (b) Model 2, without chambers, $D_r/B = 0.31$; (c) Model 3, with chambers, $D_r/B = 0.40$; (d) Model 4, with chambers $D_r/B = 0.24$

For the concrete-walled wave flume, energy dissipation can be caused by the side walls and the bottom. A simple estimation can be made for the rate of wave height attenuation, α , following Treloar and Brebner (1970),

$$H'_i / H_i = e^{-\alpha \Delta x} \quad (4.2)$$

where, H'_i and H_i are the incident wave heights measured at two positions, Δx apart. For our pilot tests without the model installed in the flume, it was found that α was about 0.004. In our experiments, the largest distance between the wave gauges used to measure reflected and transmitted waves is 8 m, that means the energy loss due to the sidewalls and the bottom is about 6%. When the model is installed in the wave flume, both the reflected waves and transmitted waves are smaller than the incident waves, thus the energy loss due to the sidewalls and the bottom must be smaller than 6%.

4.3.1.3 Motion responses

In Fig. 4. 12, a comparison between the surge RAOs for Model 1 and Model 2 indicates that the surge motion of Model 1 was more modest than Model 2 in the whole range of B/L . This was because the water columns inside the chambers also moved back and forth with the structure in surge mode, and accordingly increased the virtual mass of the breakwater. When $B/L > 0.27$, the surge RAOs of Model 1 were nearly constant at 0.2. From $B/L = 0.27$, decreasing B/L increased surge RAOs nearly monochromatically to a maximum value of 1.06. In contrast, the surge RAOs of Model 2 was nearly constant at 0.3 only when $B/L > 0.35$; the maximum value was up to 1.66, which is much stronger than that of Model 1.

In Fig. 4. 13, a comparison between the heave RAOs for Model 1 and Model 2

shows that the heave motion of Model 1 was less than that of Model 2 in the whole range of B/L . The heave RAOs had similar decreasing trends when $B/L > 0.20$ for both models, while the maximum RAOs were 1.27 and 1.72 for Model 1 and Model 2, respectively. The reason for the similarity in heave RAOs could be attributed to the fact that the bottom shapes and masses (267 kg for Model 1 and 250 kg for Model 2) were similar for both models. Despite the similarity, due to the presence of the pneumatic chambers, the heave RAOs of Model 1 were somewhat lower than that of Model 2.

Fig. 4. 14 shows that the pitch motion of Model 1 was relatively smaller in the whole range of B/L . The reasons can be attributed to the larger moment of inertia of Model 1 (almost two and half times of Model 2) and the effects of the pneumatic chambers. The pitch RAOs of Model 1 had a decreasing trend from the maximum value of 3.22 to the minimum value of 0.44 with increasing B/L . In contrast, the pitch RAOs of Model 2 were much higher for short and medium period waves ($B/L > 0.24$), with the maximum value being 6.92 at $B/L = 0.32$.

In summary, the results showed that the motion responses of the floating breakwater were moderate with the installation of pneumatic chambers.

Fig. 4. 12 Variation of surge RAOs versus B/L under four water depths; (a) Model 1, with chambers, $D_r / B = 0.31$; (b) Model 2, without chambers, $D_r / B = 0.31$; (c) Model 3, with chambers, $D_r / B = 0.40$; (d) Model 4, with chambers $D_r / B = 0.24$

(Figure continued on next page)

Fig. 4. 12 Variation of surge RAOs versus B/L under four water depths; (a) Model 1, with chambers, $D_r/B = 0.31$; (b) Model 2, without chambers, $D_r/B = 0.31$; (c) Model 3, with chambers, $D_r/B = 0.40$; (d) Model 4, with chambers $D_r/B = 0.24$

Fig. 4. 13 Variation of heave RAOs versus B/L under four water depths; (a) Model 1, with chambers, $D_r / B = 0.31$; (b) Model 2, without chambers, $D_r / B = 0.31$; (c) Model 3, with chambers, $D_r / B = 0.40$; (d) Model 4, with chambers $D_r / B = 0.24$

(Figure continued on next page)

Fig. 4. 13 Variation of heave RAOs versus B/L under four water depths; (a) Model 1, with chambers, $D_r/B = 0.31$; (b) Model 2, without chambers, $D_r/B = 0.31$; (c) Model 3, with chambers, $D_r/B = 0.40$; (d) Model 4, with chambers $D_r/B = 0.24$

Fig. 4. 14 Variation of pitch RAOs versus B/L under four water depths; (a) Model 1, with chambers, $D_r / B = 0.31$; (b) Model 2, without chambers, $D_r / B = 0.31$; (c) Model 3, with chambers, $D_r / B = 0.40$; (d) Model 4, with chambers $D_r / B = 0.24$

(Figure continued on next page)

Fig. 4. 14 Variation of pitch RAOs versus B/L under four water depths; (a) Model 1, with chambers, $D_r/B = 0.31$; (b) Model 2, without chambers, $D_r/B = 0.31$; (c) Model 3, with chambers, $D_r/B = 0.40$; (d) Model 4, with chambers $D_r/B = 0.24$

4.3.2 The effects of draft

To illustrate the effects of draft, comparisons among the three models with the same pneumatic chambers but different drafts (Model 1, Model 3 and Model 4) were made, including wave reflection and transmission, wave energy dissipation, motion responses and air pressure fluctuations inside the chambers. The draft was adjusted by extra ballasts: the model with a deeper draft had a larger mass and thus larger moment of inertia; the model dynamic characteristics also changed with draft. Meanwhile, deepening the draft increased the height of the water column inside the pneumatic chamber and thus increased its natural period accordingly.

4.3.2.1 Wave reflection and transmission coefficients

Referring to Fig. 4. 9, a comparison of the reflection coefficients (C_r) for Model 1, Model 3 and Model 4 shows that the wave reflection was the strongest for Model 3 and the weakest for Model 4 in the whole range of B/L . This is expected as deepening the draft reduces the wave transmission beneath the breakwater, and accordingly increases the wave reflection. The measured reflection coefficient shows a similar variation with B/L for Model 1, Model 3 and Model 4. With the dynamic characteristics of the breakwater model changing with its weight, the minimum reflection coefficient occurred at slightly different values of B/L for different models.

Referring to Fig. 4. 10, the measured transmission coefficient (C_t) for Model 1, Model 3 and Model 4 decreased with B/L in a similar manner. The transmission coefficient of the model with a shallower draft was relatively low for medium period waves (B/L varied approximately from 0.26 to 0.38). For long period waves ($B/L < 0.26$) and very short period waves ($B/L > 0.38$), a deeper draft was

more efficient in reducing the transmitted waves. The maximum transmission coefficient for very long period waves reduced from 0.80 for Model 4 to 0.62 for Model 3. Comparatively, there was no noticeable difference in the minimum transmission coefficient for very short period waves, which decreased from 0.15 for Model 4 to 0.13 for Model 3.

4.3.2.2 Wave energy dissipation

In Fig. 4. 11, a comparison of the energy dissipation coefficients (C_d) for Model 1, Model 3 and Model 4 indicates that Model 4 and Model 3 dissipated the most and least wave energy, respectively, for both short and medium period waves. For long period waves, however, the results were opposite. This was because that a deeper draft increased the height of the water column inside the chamber and increased its natural period accordingly. The maximum energy dissipation of each model occurred at a different value of B/L : the peak values of 0.80 (Model 3), 0.87 (Model 1) and 0.90 (Model 4) occurred at $B/L=0.22$, 0.24 and 0.28, respectively.

4.3.2.3 Motion responses

A comparison of the surge RAOs for Model 1, Model 3 and Model 4 given in Fig. 4. 12 shows that the surge motion was similar for the three models despite the different drafts. This is expected because the draft is proportional to the model mass, hence the water resistance is also proportional to the model mass. When $B/L > 0.25$ (Model 3), 0.27 (Model 1) and 0.34 (Model 4), the surge RAOs were almost constant at 0.2.

In Fig. 4. 13, the comparison of heave RAOs for the models shows that deepening the draft reduced the heave motion slightly. With increasing the draft, the maximum

values of heave RAO decreased from 1.28 for Model 4 to 1.16 for Model 3.

A comparison of the pitch RAOs for Model 1, Model 3 and Model 4 is given in Fig. 4. 14, where there was no noticeable difference in the pitch motions with different drafts. The pitch RAOs of the models with deeper drafts were slightly lower than that with shallower drafts.

In general, deepening the draft reduced the surge, heave and pitch motions, but not very much. As a result, the change in the wave radiation due to the draft, which was primarily caused by the surge motion, was not significant.

4.3.2.4 Air Pressure Fluctuations inside the Pneumatic Chambers

Fig. 4. 15 compares the pressure fluctuations inside the front chambers of Model 1, Model 3 and Model 4. When the draft is shallow, wave energy can be transmitted more easily through the lip of the front chamber, and stronger water column oscillations are induced. As shown in Fig. 4. 15, the model with shallower drafts had larger pressure fluctuations in the whole range of B/L , and the peaks of pressure fluctuation were 0.127, 0.204 and 0.268 for Model 3, Model 1 and Model 4, respectively. Deepening the draft (increasing the weight) also increased the natural period of the water column, which caused the peaks of pressure fluctuation to occur at smaller values of B/L .

Compared with the front chamber, the air pressure fluctuation inside the rear chamber was generally weaker, especially for a shallower draft. The difference in the pressure fluctuations between the two chambers was significant for Model 4, but not so for Model 3. The pressure fluctuation inside a pneumatic chamber was primarily caused by the relative motion between the floating breakwater and the water column oscillation inside the chamber. However, since the motion of floating

breakwater was symmetric about the transverse axis through the center of rotation, the difference in water column oscillation should be the main factor that caused the difference in pressure fluctuation.

For very short waves, the blockage of waves by the floating breakwater can be effective (Drimer et al., 1992), thus the wave energy cannot be transmitted easily beneath the breakwater to the rear chamber. For waves of periods close to the natural period of the water column, a significant portion of incoming wave energy was dissipated by the large oscillation of the water column inside the front chamber, so only a small portion of the incoming wave energy was transmitted to the rear chamber. For very long period waves, waves were easily transmitted through the floating breakwater to the rear chamber; however, since their periods differed significantly from the designed natural period of water column, both chambers did not function effectively. This explains the observation that the pressure fluctuation inside the rear chamber was typically weak.

Finally, it is noted that the geometry of the two chambers was identical with the same designed natural period. Thus, strong water column oscillations inside the front and rear chambers could have been equally triggered by incoming waves with a period close to the natural period. Therefore, it was the balance between the energy dissipation (non-linear processes) and the energy input from the waves that determined the magnitude of the air pressure fluctuations inside a chamber.

Fig. 4. 15 Variation of pressure coefficient C_p fluctuations versus B/L under four water depths; (a) front chamber of Model 1, $D_r/B = 0.31$; (b) rear chamber of Model 1, $D_r/B = 0.31$; (c) front chamber of Model 3, $D_r/B = 0.40$; (d) rear chamber of Model 3, $D_r/B = 0.40$; (e) front chamber of Model 4, $D_r/B = 0.24$; (f) rear chamber of Model 4, $D_r/B = 0.24$ (Figure continued on next page)

Fig. 4. 15 Variation of pressure coefficient C_p fluctuations versus B/L under four water depths; (a) front chamber of Model 1, $D_r/B = 0.31$; (b) rear chamber of Model 1, $D_r/B = 0.31$; (c) front chamber of Model 3, $D_r/B = 0.40$; (d) rear chamber of Model 3, $D_r/B = 0.40$; (e) front chamber of Model 4, $D_r/B = 0.24$; (f) rear chamber of Model 4, $D_r/B = 0.24$ (Figure continued on next page)

Fig. 4. 15 Variation of pressure coefficient C_p fluctuations versus B/L under four water depths; (a) front chamber of Model 1, $D_r/B = 0.31$; (b) rear chamber of Model 1, $D_r/B = 0.31$; (c) front chamber of Model 3, $D_r/B = 0.40$; (d) rear chamber of Model 3, $D_r/B = 0.40$; (e) front chamber of Model 4, $D_r/B = 0.24$; (f) rear chamber of Model 4, $D_r/B = 0.24$

4.3.3 Discussion

The significance of the pneumatic chambers can be examined directly by comparing the results for Model 1 (with pneumatic chambers) and Model 2 (without pneumatic chambers). Since the wave reflection for Model 2 was not sensitive to the change of wave period, the wave transmission was controlled mainly by the energy dissipation. The energy dissipation of Model 2 can only be related to the frictional and flow-separation effects, which occurred mainly at the sharp edges of the breakwater, so its large motion responses to the incident waves caused the large energy dissipation, resulting in relatively small transmission coefficients: the maximum energy dissipation and minimum wave transmission occurred at a narrow range of wave periods corresponding to $B/L = 0.29 \sim 0.33$, which was also close to the range of wave period in which the breakwater had its the maximum pitch RAO (occurred near $B/L = 0.32$).

Clearly, the installation of two pneumatic chambers improved the hydrodynamic performance of Model 1, especially the transmission coefficient and the motion responses. Moreover, Model 1 might dissipate additional energy by the air flow through the opening on the top of each pneumatic chamber besides through the friction and flow separation. Both the maximum energy dissipation and maximum air-pressure fluctuation occurred at a wave period corresponding to $B/L = 0.24$; while the maximum pitch RAO also occurred around $B/L = 0.24$. In principle, decreasing the wave period weakens the interaction of the incident waves with the tips of the chamber walls (when one half of the wave length is smaller than the draft, there will be no such interaction). Hence, the two pneumatic chambers did not increase the energy dissipation for short period waves (see Fig. 4. 11), but rather helped dissipate more energy for long period waves with additional energy dissipation from the motion of the water inside the chamber (i.e., the additional vortex shedding at the tips of the chamber front walls and the air flow through the

slot openings). The motion responses of Model 1 were in general smaller than those of Model 2. In particular, the installation of the two pneumatic chambers significantly reduced the surge motion for the long and medium period waves ($B/L < 0.35$) and the pitch motion for the short and medium period waves ($B/L > 0.24$), while the heave motion slightly was reduced throughout the whole range of B/L . The smaller motion responses of Model 1 reduced the motion-generated radiated waves in the leeward side of the model. Therefore, the wave transmission was effectively reduced for all wave periods.

The addition of the two plates to form the pneumatic chambers should have also contributed to the wave scattering and the reduction of the transmission coefficient, as can be qualitatively inferred from Kagemoto (2011), who studied theoretically the wave transmission and reflection due to two vertical surface-piercing plates fixed in regular waves. His results showed that the transmission coefficient could be nearly zero if the ratio of spacing between two vertical plates to wave length satisfied certain conditions. Even though his model was fixed and there were no structural members between the two plates, his results still illustrated the importance of wave scattering. If motion responses of the two plates are allowed, they will inevitably change the performance of the breakwater studied by Kagemoto (2011). However, since there is no theory available currently for either the twin-plate floating breakwaters or the box-type floating breakwaters with pneumatic chambers, it is difficult to quantify in this study the contributions of the vertical plates, which were used to form the pneumatic chambers, to the transmission coefficients.

A deeper draft typically causes the breakwater to reflect more wave energy, especially for short period waves. In the experiments, when the draft was increased, lesser wave energy was transmitted through the lip of the front chamber, thus the energy dissipated by the pneumatic chambers was reduced. The maximum energy

dissipation of Model 3 (with a larger draft) was lower than that of Model 4 (with a smaller draft). Despite the different drafts, the maximum energy dissipation of the three models occurred around the wave period at which the maximum pressure fluctuation inside the front chamber also occurred, suggesting that the energy dissipation was caused mainly by the pneumatic chambers. Since the natural period of the pneumatic chamber increased with increasing draft, the pneumatic chambers of Model 3 and Model 4 functioned better for long and short/medium period waves, respectively. For the long and very short period waves, Model 3 (with larger draft) was the most efficient in terms of reducing transmitted waves.

Vijayakrishna Rapaka et al. (2004) experimentally studied a rectangular floating breakwater with two OWC (Oscillating Water Column) units embedded into its middle section. The surge and heave responses of my models were similar to theirs, but the pitch responses of my model were much smaller. The bulk density of my model was much smaller than theirs, but the surge RAOs were of little difference from theirs. This was because that the larger size of my pneumatic chambers significantly increased the virtual mass of the breakwater (when the breakwater surges with waves, it needs to move the water inside the pneumatic chambers). The installation of pneumatic chambers on both sides of the breakwater significantly increased the moment of inertia, so the pitch responses of my model were effectively reduced; however, the motion responses of my models were relatively insensitive to the change in wave period.

Uzaki et al. (2011) examined a floating breakwater model with a truss structure attached to both the front and rear sides of a box-type floating breakwater to increase the energy dissipation by extra wave breaking. In terms of transmission coefficient, their design improved the performance mainly for short waves, while the present design improved the performance over a wide range of wave frequencies, especially for long waves. The present design dissipated energy more efficiently for

long waves, while their design dissipated energy more effectively for short waves even though the energy dissipation for their model was found over a wide range of wave frequencies. It is remarked here that, rather than just dissipating wave energy, the present model has a potential to convert wave energy into electricity by installing Wells turbines to the pneumatic chambers, although this application potential needs to be further examined with the change in the air pressure dynamics by the installation of the turbines.

In the present study, the pressure fluctuations inside the rear chamber were always weak due to the limitation of the model size. However, even though the rear chamber did not function as effectively as the front in terms of dissipating energy, its effects on reducing the wave transmission coefficient were still significant. A key benefit of the present design is to dissipate more energy of the long period waves by the installation of the pneumatic chambers. A follow-up study, whereby the front and rear chambers have different geometries, with the natural period of the water column inside the rear chamber specifically designed for longer period waves, will be presented in the next chapter. In doing so, when the long period waves are transmitted beneath the bottom of the floating structure, the rear chamber may be more effective to dissipate the transmitted waves.

4.4 Concluding Remarks

A new design of floating breakwater equipped with pneumatic chambers is introduced in this study. The main findings from this experimental study are the following:

- 1) With the pneumatic chambers, the responses of the floating breakwater to regular waves were mitigated by the water mass inside the chambers and the increase in momentum of inertia.

- 2) The pneumatic chambers also effectively reduced the wave transmission for all wave periods. In addition to the wave scattering associated with the two plates forming the pneumatic chambers, the reduction in wave transmission also came from two other sources: (a) the motion-generated radiated waves into the leeward side of the breakwater were reduced, and (b) extra more energy was dissipated by the pneumatic chambers, thus lesser wave energy was reflected or transmitted.
- 3) Increasing the draft of the floating breakwater reduced the surge, heave and pitch motions, but not very much. The air pressure fluctuations inside the front chambers decreased with increasing draft. For the long as well as very short period waves, the breakwater with a deeper draft was more effective in reducing the transmitted waves.
- 4) Given the same geometry of the two pneumatic chambers, the rear chamber did not function as efficiently as the front chamber in terms of extracting wave energy. This may be improved in the future by varying the geometry of the rear chamber.

Overall, the results of the present study show that the installation of pneumatic chambers to a floating breakwater can be an effective way to improve its hydrodynamic performance as a breakwater. Moreover, pneumatic chambers can potentially be turned into devices converting wave energy to electricity by installing Wells turbines to the chambers.

CHAPTER 5 A FLOATING BREAKWATER WITH ASYMMETRIC PNEUMATIC CHAMBERS FOR WAVE ENERGY EXTRACTION

5. 1 Introduction

To date, most of OWC prototypes are fixed structures (at the coast or cliff, on the sea bottom or integrated with a fixed breakwater) (Clément et al., 2002; Falcão, 2010). These devices are generally deployed in coastal zones (onshore or nearshore) where the need for the deep-sea moorings and long undersea power-transmission cables can be avoided and the energy conversion devices be easily accessed for installation, operation and maintenance. However, the disadvantages are also obvious since the available wave energy at the shoreline is limited due to the sea bed friction and wave breaking. Although these disadvantages could be partially compensated by wave focusing due to diffraction and refraction, the high requirements on coastal geometry and a specific design for each local site make fixed OWC devices unsuitable for mass power generation. Moreover, the submergence depth of the chamber wall of an OWC device changes with the tidal level at a site, which makes the fixed OWC device often operate on off-design conditions. In contrast, stand-alone floating OWC devices may avoid the disadvantages that fixed OWC devices have, but they have to bear high costs on construction and installation. High costs may be one of the reasons that there have only been few floating OWC prototypes. Cost-sharing between floating OWC devices and floating breakwaters may improve the cost-effectiveness of wave energy utilization. Floating breakwaters can be flexibly deployed offshore (where wave energy is not dissipated by wave breaking) and can automatically adjust their elevation with tides. These merits make floating breakwaters ideal for integration

with OWC devices.

Wave transmission and motion responses are two important factors to be considered when designing floating breakwaters for shore protection. A good design should achieve both low wave transmission and low motion responses. Recently, He et al. (2012) showed that integrating OWC devices with a slack-moored floating breakwater could improve the performance of the breakwater in terms of wave transmission and motion responses. In particular, the motion responses of the floating breakwater were significantly reduced by the water mass inside the OWCs and the increased momentum of inertia of the breakwater.

Due to the difficulty in fabricating turbines for small-scale laboratory tests, it is difficult to directly measure the energy extraction efficiency in laboratory tests. In the previous experimental studies on OWC devices, orifices or narrow slots were usually used to simulate the power-take-off mechanism, and the so-called pneumatic power output was used to estimate the energy extraction efficiency. Mathematically, the period-averaged pneumatic power output can be calculated by,

$$\bar{P}_{o_water} = \frac{1}{T} \int_t^{t+T} \left(\int_{S_c} p(t) v_{water}(x, y, t) dA \right) dt \quad (5.1)$$

or

$$\bar{P}_{o_air} = \frac{1}{T} \int_t^{t+T} \left(\int_{S_o} p(t) v_{air}(x, y, t) dA \right) dt \quad (5.2)$$

where T is the wave period, $p(t)$ is the instantaneous pressure inside the OWC chamber relative to the atmosphere pressure (difference between the pressures inside and outside the chamber), S_c is the area of the chamber cross-section, $v_{water}(x, y, t)$ is the instantaneous vertical velocity of the water surface at the

position (x, y) inside the chamber, S_o is the area of the orifice or narrow slot and $v_{air}(x, y, t)$ is the instantaneous vertical velocity of the airflow at the position (x, y) on the orifice or narrow slot. If the air inside the chamber is incompressible, the pneumatic power calculated using these two equations should be the same. When using Eq. (5.1) to estimate the pneumatic power output, most of the previous experimental studies on OWC devices measured the water surface elevation at a single point inside the chamber, e.g. (Gouaud et al., 2010; Lopes et al., 2009; Thiruvengatasamy and Neelamani, 1997; Vijayakrishna Rapaka et al., 2004; Wang et al., 2002); however, the instantaneous water surface elevation is generally non-uniform across the cross section of the chamber unless for the limiting case of very long waves (Evans and Porter, 1995). Similarly, when using Eq. (5.2) to estimate the pneumatic power output, the air velocity across the cross section of the orifice is also generally non-uniform (McCormick and Canvin, 1986). The spatially non-uniform feature of $v_{water}(x, y, t)$ and $v_{air}(x, y, t)$ makes the accurate measurement of the pneumatic power output a challenging task. In this study, the amplitude of pressure fluctuation ΔP is chosen to be used as an indicator to discuss the performance of the OWC chamber in wave energy extraction.

It has been shown by theoretical studies of Sarmento and Falcão (1985) and Martins-Rivas and Mei (2009) that the period-averaged power extracted by a linear turbine (the pressure fluctuation is proportional to the airflow flux through the turbine) is

$$P_{out} = \frac{KD}{2N\rho_a^0} |\Delta P|^2 \quad (5.3)$$

where D is the outer diameter of the turbine rotor, N is the rotational speed of the turbine blades, ρ_a^0 is the air density at rest, and K is an empirical constant of

the turbine. Therefore increasing the air-pressure fluctuation inside the chamber may benefit the conversion efficiency. Since orifices or narrow slots are usually used in laboratory studies of OWC devices in place of a turbine, the power-take-off mechanism simulated by an orifice or a narrow slot is not linear. The mean airflow velocity, averaged over the cross-sectional area of the opening, is $V(t) = \langle v_{air}(x, y, t) \rangle$ where $\langle \cdot \rangle$ means taking the average over the cross-sectional area of the opening. The air can be assumed as incompressible fluid for a not-too-small opening (Wang et al., 2002) and the air-pressure fluctuation $p(t)$ is proportional to $|V(t)|^2$ (Streeter and Wylie, 1985). Therefore, the power taken out of the system by the airflow through the opening over one wave period, $P_{out} = \int_t^{t+T} p(t)V(T)S_o dt$, is proportional to $S_o \Delta P^{3/2}$, where S_o is the area of the opening. Again, increasing the air-pressure fluctuation inside the chamber will benefit wave energy extraction.

Present study is a follow-up investigation of He et al. (2012), who integrated a rectangular box-type breakwater (the base structure) with two identical pneumatic chambers (OWC): one on the seaside and the other on the leeside of the base structure. The results of He et al. (2012) showed that the air-pressure fluctuation inside the rear chamber was small, thus there is a need to find a way to increase the air-pressure fluctuation inside the rear chamber so that both the front and the rear chambers can function as energy converters. In the present study, a configuration with asymmetric chambers (a narrower chamber on the seaside and a wider chamber on the leeside of the base structure) is investigated. The design of the asymmetric chambers was based on the following considerations: (1) for spectral waves, longer period waves can be easily transmitted through the floating breakwater; in order to achieve wave energy extraction over a wider range of wave frequency, the front chamber should be designed for extracting shorter waves and

the rear chamber for longer waves; (2) the same opening ratio ensures geometric similarity among different chambers. To understand how the asymmetric pneumatic chambers may affect the hydrodynamic performance of the floating breakwater and wave energy extraction, a series of experiments were carried out under regular wave (monochromatic waves) conditions. The main focus of this study is to show experimentally that the asymmetric configuration can increase the air-pressure fluctuation inside both chambers without sacrificing the functions of the structure as a breakwater.

5.2 Description of experiments

5.2.1 Physical model

The geometric details of the floating breakwater with asymmetric pneumatic chambers examined in the present study are depicted on the left panel of Fig. 5. 1. Two pneumatic chambers of different sizes are attached to a box-type base structure, which provides the required buoyancy. The chamber on the seaside is narrower than that on the leeside. For later comparison and discussion, the floating breakwater with symmetric pneumatic chambers (He et al., 2012) is also shown on the right panel of Fig. 5. 1. The details of the two configurations are summarized in Table. 5. 1 for later reference. Note that the overall width of the breakwater W and the breadth of the base structure B are the same for both configurations. The ratio of the front chamber breadth to the rear chamber breadth $B_f / B_r = 0.33$ for the asymmetric configuration and 1 for the symmetric configuration.

Table. 5. 1 Details of the models

Model	Draft D_r (mm)	Length (mm)	Bottom breadth B (mm)	Height (mm)	Front and rear pneumatic chamber breadth B_f, B_r (mm)	Front and rear slot opening breadth (mm)	Mass (Kg)	Moment of inertia ($\text{Kg}\cdot\text{m}^2$)	CG above bottom (mm)
FB with asymmetric chambers	299	1420	750	400	200, 600	2.5, 7.5	339	42.4	97.7
	235	1420	750	400	200, 600	2.5, 7.5	267	39.4	115.1
	177	1420	750	400	200, 600	2.5, 7.5	195	34.9	148.8
FB with symmetric chambers	299	1420	750	400	400, 400	5, 5	339	39.3	95.7
	235	1420	750	400	400, 400	5, 5	267	35.7	111.9
	177	1420	750	400	400, 400	5, 5	195	31.8	143.5

Fig. 5. 1 Geometric details of (a) the new improved pneumatic floating breakwater and (b) the original pneumatic floating breakwater models

The model was fabricated and assembled using 10-mm thick Perspex sheets. The draft could be adjusted by ballast weights inside the base structure. Three drafts were examined in the present experiments: $D_r=29.9$ cm, 23.5 cm and 17.7 cm ($D_r/W=0.19$, 0.15 and 0.11). A narrow slot opening was constructed on the top plate of each pneumatic chamber to simulate a power-take-off mechanism. For each chamber, the ratio of the slot opening area to the cross-sectional area was 1.25%, which was the same as that used for the configuration with symmetric chambers. In the present experiments, the ratio of the slot opening area to the cross-sectional area was decided according to suggestions in other experimental studies of OWC devices. Basically, two factors need to be considered when choosing the opening ratio: if the ratio is too small, the chamber is similar to a closed chamber, and a large portion of wave energy will be used to compress the air inside the chamber; if

the ratio is too large, the chamber is similar to an open chamber, and large pressure fluctuation cannot be built up inside the chamber. Values of the slot-opening ratio reported in the literature are 0.67% (Wang et al., 2002), 0.78% (Morris-Thomas et al., 2007), 1.13% (Vijayakrishna Rapaka et al., 2004), 0.81%, 2.42% and 4.03% (Thiruvankatasamy and Neelamani, 1997). For a small value of 0.67%, Wang et al., 2002 (see Fig. 3 in Wang et al., 2002) synchronized pressure signal with the wave-elevation signal inside the chamber in their experiments; the data showed that the compressibility of the air inside the chamber was weak. For the largest value 4.03%, Thiruvankatasamy and Neelamani (1997) showed that the pressure drop across the opening was small and the energy extraction was very low (see Fig. 11 in Thiruvankatasamy and Neelamani, 1997). Since the effects of different ratios are not the focus of this chapter, the slot-opening ratio close to that used in Vijayakrishna Rapaka et al. (2004), which is in the suggested range of 0.67%-2.42%, was chosen.

5.2.2 Estimation of the natural periods of oscillating water columns and the heave response of the breakwater

It is stressed here that the mass of the water column inside each chamber also changes with draft. For a heaving object, the natural period can be estimated by

$$T = 2\pi \sqrt{\frac{M + M_a}{\rho g S}} \quad (5.4)$$

where M is the mass of the object, M_a is the added mass, S is the waterline surface, g is gravitational acceleration, and ρ is the density of water. For an oscillating-water-column system with a uniform cross-sectional area, Eq. (5.4) can be rewritten as

$$T = 2\pi \sqrt{\frac{l+l'}{g}} \quad (5.5)$$

where l is the still water length (submergence) of the water column, l' is the added length due to added mass (McCormick, 2003); information on the added mass or length can be found in Newman (1977). The designed natural periods of the heave motion of the breakwater and the water columns in the front and rear chambers are listed in Table. 5. 2 for the symmetric and asymmetric configurations of different drafts. Table. 5. 2 shows that the natural periods of the heave motion of the breakwater are longer than the natural periods of the oscillating water columns and the natural period of the front chamber is smaller than that of the rear chamber for the asymmetric configuration.

Table. 5. 2 Designed natural periods of heave mode of breakwater and water columns with different drafts

		Draft=29.9 cm $D_r / W = 0.19$	Draft=23.5 cm $D_r / W = 0.15$	Draft =17.7 cm $D_r / W = 0.11$
Heave motion of breakwater		1.56-1.61s	1.45-1.48s	1.34-1.36s
Asymmetric configuration	front chamber	1.23-1.24s	1.12-1.13s	1.01-1.04s
	rear chamber	1.46-1.50s	1.36-1.38s	1.26-1.29s
Symmetric configuration	front chamber	1.35-1.38s	1.25-1.27s	1.15-1.18s
	rear chamber	1.35-1.38s	1.25-1.27s	1.15-1.18s

5.2.3 Experimental setup

The experiments were conducted in a wave flume at the Hydraulics Modeling Laboratory of the Nanyang Technological University, Singapore. The wave flume

was 45 m long, 1.55 m wide and 1.5 m deep. A piston-type wave generator, equipped with an active wave absorption control system, was installed at one end of the flume, and a wave-absorbing beach was located at the other end to reduce wave reflection. Fig. 5. 2 shows a sketch of the wave flume and the experimental setup. The floating breakwater was slackly moored at a location 25 m away from the wave generator.

Fig. 5. 2 Sketch of the experimental setup for the improved pneumatic floating breakwater

5.2.4 Data acquisition system and data analysis

A two-point method, proposed by Goda and Suzuki (1976), was employed to separate left-going waves from right-going waves. Surface displacements at six locations were measured with resistive wave gauges (WG1-WG6 in Fig. 5. 2). Three gauges were placed between the breakwater and the wave generator, and the other three on the leeside of the breakwater. The manufacturer-specified accuracy of the wave gauge is 0.1 mm. The amplitudes of the incident waves, reflected waves and transmitted waves are denoted by A_i , A_r , and A_t , respectively. The

amplitude of the waves reflected from the absorbing beach is denoted by A_{rb} , which can be obtained by performing a wave separation analysis over the data collected by the wave gauges WG4-WG6. I define the reflection coefficient C_r as A_r / A_i , the transmission coefficient C_t as A_t / A_i , and the reflection coefficient of the beach C_{rb} as A_{rb} / A_i . Energy dissipation coefficient, denoted by C_d , is defined as the ratio of the dissipated energy to the energy in incident waves. The conservation of wave energy gives the following equation,

$$C_r^2 + C_t^2 + C_d = 1 + C_{rb}^2 \quad (5.6)$$

Note that C_d includes the contributions from both the vortex shedding at the edges of the structure (energy wasted) and the airflow through the slot openings (the part of energy used for generation of electricity). The calculated values of C_r , C_t and C_d already include the effects of radiated waves.

The motion responses of the floating breakwater were measured by an optical tracking system (see He et al., 2012 for details) and the amplitudes of the surge (A_{surge}), heave (A_{heave}), and pitch (A_{pitch}) responses can then be obtained. For later discussion, the surge, heave and pitch RAOs (Response Amplitude Operators) are defined as:

$$RAO_{surge} = \frac{A_{surge}}{A_i}; \quad RAO_{heave} = \frac{A_{heave}}{A_i}; \quad RAO_{pitch} = \frac{A_{pitch}}{A_i} \quad (5.7)$$

The air pressure inside each pneumatic chamber was measured by using a piezoresistive pressure sensor as shown in Fig. 5. 2. The amplitude of the pressure fluctuation inside each chamber, ΔP , was obtained from the measured time series of air-pressure. I define the pressure coefficient C_p as $\Delta P / \rho g A_i$.

5.2.5 Experimental conditions

The experimental results of He et al. (2012) showed that the responses of a slack-moored floating breakwater were insensitive to moderate changes in water depth, unless nonlinear taut status occurred in a mooring line. Therefore, the effects of water depth were not the focus of the present study. In all the experiments, the water depth was fixed at 0.90 m, and the target wave height was fixed at 4 cm.

A set of pilot tests without the model installed in the wave flume were first carried to examine the performance of the wave absorbing beach. Due to the limitation of the flume length and the wave-absorbing ability of the beach, the wave period varied from 1.1s to 1.7s at 0.1s intervals in the present experiments. Within this range of wave periods, the pilot tests showed that less than 4% of incident wave energy was reflected by the beach.

5.3 Results

5.3.1 Hydrodynamic performance of the floating breakwater with asymmetric pneumatic chambers for three drafts

Key results for the floating breakwater with asymmetric pneumatic chambers for three different values of D_r/W (0.19, 0.15 and 0.11) are discussed in this section. Since the draft of the floating breakwater was adjusted by using extra ballasts, the mass, the moment of inertia and the dynamic characteristics of the model varied with draft. The key parameters of the model are listed in Table. 5. 1 for the three drafts.

5.3.1.1 Reflection, transmission and energy dissipation coefficients

Fig. 5. 3 shows the variations of C_r , C_t and C_d as functions of W/L , where W is the distance between the two plates used to form the front and rear chambers (i.e. the overall width of the floating breakwater, see Fig. 5. 1). The wave reflection and transmission coefficients at each draft followed the similar trends throughout the range of the tested wave periods. For all three drafts, the reflection coefficients all had their minimum values at $W/L \approx 0.42$ and the transmission coefficients monochromatically decreased with increasing W/L . For all three drafts, the minimum reflection coefficient was about 0.1, and the transmission coefficient was less than 0.35 when $W/L > 0.5$. The dissipation of wave energy is related to the airflow through the slot openings on the top of the two chambers (the slot openings were used to simulate the power-take-off mechanisms) and the vortex shedding at the edges of the breakwater. A maximum energy dissipation coefficient existed for each draft, even though the energy dissipation coefficient varied with W/L differently for each draft. The value of the maximum energy dissipation coefficient decreased with increasing draft, and increasing draft increased the period at which the maximum energy dissipation occurred. It is remarked that C_d includes the contributions from the airflow through the openings and the vortex shedding at edges of the breakwater. For very long waves, the breakwater will move in phase with waves, thus the energy extraction by the airflow through the openings diminishes. In the present experiments, the wave amplitude was kept at 0.04 m for all wave periods; as a result, increasing wave period reduced the flow velocity and the vortex-shedding loss - the same trend has also been found by Stiassnie et al. (1984), who studied the vortex shedding loss induced by waves interacting with a surface-piercing plate. Therefore, increasing the period of long waves with other test conditions unchanged reduces C_d , as shown in Fig. 5. 3.

For box-type breakwaters, the wave reflection is generally stronger for deeper draft and shorter waves. In theory, a fixed box-type breakwater is almost transparent to very long waves, and the reflection coefficient approaches zero when W/L approaches zero. The existence of a minimum reflection coefficient is because C_r in the present study includes the contribution from the radiated waves generated by the motion of the floating breakwater. For a fixed box-type breakwater, very short waves can be completely blocked by the breakwater if $D_r/L > 1/2$ (where D_r is the draft), resulting in a near-zero transmission coefficient; therefore, increasing the draft can reduce the transmission coefficient. The non-zero transmission coefficients in the present experiments for short waves are the combined results of wave transmission and the wave radiation due to the motion of the floating breakwater. Floating breakwaters are usually considered as performing satisfactorily for shore/harbor protection when the wave transmission coefficients are less than 0.5 (Koutandos et al., 2005). Fixed floating breakwaters generally perform better than moored floating breakwaters except in the vicinity of dynamic resonance (see, e.g., Fig. 2 in Drimer et al., 1992). The experimental study of Koutandos et al. (2005) showed that their fixed breakwater with a rectangular cross-section (without pneumatic chambers) performed well when the breakwater breadth over wave length B/L was larger than 0.25. It was interesting to note that the trend of transmission coefficient for the present configuration appeared to behave similarly to that of a fixed breakwater although it was slack-moored. In addition, the present configuration performed satisfactorily when W/L was approximately larger than 0.4, 0.45 and 0.5 for $D_r/W = 0.19$, $D_r/W = 0.15$ and $D_r/W = 0.11$, respectively. Note that the three drafts normalized by water depth, D_r/h , in the present experiments were nearly the same as that in Koutandos et al. (2005). Moreover, the corresponding breadth of the box part was only $B/L = 0.2$ for $D_r/W = 0.19$, 0.22

for $D_r / W = 0.15$ and 0.25 for $D_r / W = 0.11$. Since the breadth of the box part (B) is crucial to the costs of a floating breakwater, the present design is cost effective.

5.3.1.2 Surge, heave and pitch RAOs

The responses of a floating structure to water waves are affected by factors such as the total mass, the mass distribution in the structure and the mooring system used. The mass and moment of inertia of a floating structure increase generally with its draft. Among the three drafts in the present experiments, the difference in the total mass is much greater than the difference in the moment of inertia (see Table. 5. 1).

The variations of surge, heave and pitch RAOs versus W / L are shown in Fig. 5. 4. For the three drafts studied in the present experiments, the draft did not have a significant effect on the trends of the RAOs varying with W / L . The surge and pitch RAOs monochromatically decreased with increasing W / L . Since the water inside the two chambers surged together with the breakwater, the surge RAOs decreased with increasing draft. The heave response for each draft had a peak within the tested range of W / L ; the peak heave response indicates a resonance and the corresponding period is the damped natural period of the heave response. The draft had an insignificant effect on the amplitude of the heave response at its natural period.

Fig. 5. 3 Variations of (a) reflection coefficient C_r , (b) transmission coefficient C_t and (c) energy dissipation coefficient C_d versus W/L for three drafts

($\blacksquare$ $D_r/W = 0.19$ $\circ$ $D_r/W = 0.15$ $\blacktriangle$ $D_r/W = 0.11$)

Fig. 5.4 Variations of (a) surge, (b) heave and (c) pitch RAOs versus W/L for three drafts

(■ $D_r/W=0.19$ ○ $D_r/W=0.15$ ▲ $D_r/W=0.11$)

5.3.1.3 Pressure fluctuation inside the pneumatic chambers

Fig. 5. 5 shows the variations of the pressure coefficient C_p inside the front and rear chambers versus W/L for three drafts. It is stressed here that the pressure fluctuation inside an OWC chamber attached to a floating structure is affected by the relative motion between the water column and the floating structure. At each draft, the maximum pressure fluctuation was typically observed inside the front chamber. Increasing the draft increased the wave period at which the maximum occurred, however it reduced the maximum pressure fluctuation due mainly to the increased reflection by the seaside wall of the front chamber. Increasing draft increases the water column length, causing an increase in inertia effect and natural period. Theoretically, for a fixed breakwater with a draft deeper than one half of the wave length, water waves can be completely reflected by the seaside wall of the front chamber, resulting in a zero pressure fluctuation inside the front chamber. Therefore, the amplitude of air-pressure fluctuation should decrease with increasing draft.

The amplitude of the pressure fluctuation inside the rear chamber is determined by factors such as the natural period of the water column in the rear chamber, the relative motion between the water column and the breakwater, and the amount of energy transmitted into the rear chamber. However, the amount of wave energy available for the rear chamber is not easy to measure directly. For the breakwater with $D_r/W = 0.19$ shown in Fig. 5. 5, the deeper draft increased the wave reflection and reduced the wave energy available for the rear chamber, weakening the water column oscillation in the rear chamber and its interaction with the motion responses of the breakwater, consequently resulting in small pressure fluctuations throughout the range of the wave periods in the experiments. For $D_r/W = 0.15$ and 0.11, the pressure fluctuation inside the rear chamber increased with decreasing

W/L . Since a shallower draft allows waves to be transmitted more easily into the rear chamber, larger pressure fluctuations are expected to be found in the rear chamber with shallower drafts.

Fig. 5.5 Variations of pressure coefficient C_p inside the (a) front and (b) rear chambers versus W/L for three drafts

($\blacksquare$ $D_r/W=0.19$ $\circ$ $D_r/W=0.15$ $\blacktriangle$ $D_r/W=0.11$)

5.3.2 Comparison of the hydrodynamic performance with the floating breakwater with symmetric pneumatic chambers

The present breakwater with asymmetric chambers is a modification of the breakwater with symmetric chambers reported by He et al. (2012). Comparisons of the results between these two models are given in Fig. 5. 6-Fig. 5. 8 for three drafts.

Referring to Fig. 5. 6 (a), Fig. 5. 7(a) and Fig. 5. 8(a), the difference in C_t between the two models was minor throughout the range of W/L . The difference in C_r between these two models was also minor, except that the model with asymmetric chambers gave slightly smaller reflection coefficients for both very long and very short waves when $D_r/W = 0.19$ and 0.15 . Since the energy dissipation coefficient C_d is derived from C_r and C_t , it was slightly larger in short waves for the asymmetric chambers with either $D_r/W = 0.19$ or 0.15 . As shown in Fig. 5. 6 (b), Fig. 5. 7 (b) and Fig. 5. 8 (b), for all three drafts, the difference in surge and pitch RAOs was generally negligible. However, the models with asymmetric chambers gave larger heave RAOs over a wide range of W/L .

Comparisons of the pressure coefficients inside the pneumatic chambers between the two models were shown in Fig. 5. 6 (c), Fig. 5. 7(c) and Fig. 5. 8(c) for three drafts. Significant differences in air-pressure fluctuation can be observed and are described in detail below.

Fig. 5. 6 Comparisons of (a) reflection coefficient C_r , transmission coefficient C_t and energy dissipation coefficient C_d ; (b) surge, heave and pitch RAOs; and (c) pressure coefficient C_p inside the front and rear chambers, between floating breakwaters with asymmetric and symmetric pneumatic chambers for $D_r/W = 0.19$

(Figure continued on next page)

Fig. 5. 6 Comparisons of (a) reflection coefficient C_r , transmission coefficient C_t and energy dissipation coefficient C_d ; (b) surge, heave and pitch RAOs; and (c) pressure coefficient C_p inside the front and rear chambers, between floating breakwaters with asymmetric and symmetric pneumatic chambers for $D_r/W = 0.19$

When $D_r/W = 0.19$, the model with asymmetric chambers significantly increased the pressure fluctuation inside the front chamber, but slightly reduced the air-pressure fluctuation inside the rear chamber. Inside the front chamber, the maximum pressure coefficient C_p increased from 0.12 for the symmetric chambers to 0.26 for the asymmetric chambers. However, the maximum pressure coefficient C_p dropped from about 0.08 for the symmetric chambers to about 0.04 for the asymmetric chambers. The increase of the air pressure inside the front chamber is a combined result of a smaller opening and an enhanced interaction between the oscillating water column and the motion responses; the decrease of the air pressure inside the rear chamber is also a combined result of a larger opening and insufficient wave energy available for the rear chamber to force the oscillating

water column to interact effectively with the motion of the breakwater. Since an increase of air-pressure inside the rear chamber was not obtained, this draft is not the design I am seeking.

Fig. 5. 7 Comparisons of (a) reflection coefficient C_r , transmission coefficient C_t and energy dissipation coefficient C_d ; (b) surge, heave and pitch RAOs; and (c) pressure coefficient C_p inside the front and rear chambers, between floating breakwaters with asymmetric and symmetric pneumatic chambers for $D_r/W = 0.15$ (Figure continued on next page)

Fig. 5. 7 Comparisons of (a) reflection coefficient C_r , transmission coefficient C_t and energy dissipation coefficient C_d ; (b) surge, heave and pitch RAOs; and (c) pressure coefficient C_p inside the front and rear chambers, between floating breakwaters with asymmetric and symmetric pneumatic chambers for $D_r/W = 0.15$

When $D_r/W = 0.15$, the model with asymmetric chambers also significantly increased the air-pressure fluctuation inside the front chamber, but did not cause significant changes in the air-pressure fluctuation inside the rear chamber. Inside the front chamber, the maximum pressure coefficient C_p increased from 0.19 for the symmetric chambers to 0.30 for the asymmetric chambers. The further increase of the air pressure inside the front chamber is due to the enhanced interaction between motion responses and the oscillating water column. Even though a larger opening was used for the rear chamber, the enhanced interaction between the motion responses and the oscillating water column was able to increase the air pressure to the level found in the symmetric configuration where a smaller opening was used. Comparing the heave responses for the two configurations, it seems that the increase of the heave responses for the asymmetric configuration might have

contributed more than the pitch responses to the increase of the air pressure inside the rear chamber. Even though the air pressure inside the rear chamber had been improved, this draft is still not the design I am seeking.

Fig. 5. 8 Comparisons of (a) reflection coefficient C_r , transmission coefficient C_t and energy dissipation coefficient C_d ; (b) surge, heave and pitch RAOs; and (c) pressure coefficient C_p inside the front and rear chambers, between floating breakwaters with asymmetric and symmetric pneumatic chambers for $D_r/W = 0.11$ (Figure continued on next page)

Fig. 5. 8 Comparisons of (a) reflection coefficient C_r , transmission coefficient C_t and energy dissipation coefficient C_d ; (b) surge, heave and pitch RAOs; and (c) pressure coefficient C_p inside the front and rear chambers, between floating breakwaters with asymmetric and symmetric pneumatic chambers for $D_r/W = 0.11$

When $D_r/W = 0.11$, the model with asymmetric chambers not only significantly increased the pressure fluctuation inside the front chamber, but also increased the pressure fluctuation inside the rear chamber. Inside the front chamber, the maximum pressure coefficient C_p increased from 0.26 for the symmetric chamber case to 0.43 for the asymmetric chamber case. The pressure coefficient C_p inside the rear chamber could reach 0.1 for the asymmetric chamber case. This is the design I am searching for: air-pressure increases were achieved inside both chambers. In this case, the motion responses are in the right conditions so that the feedback mechanism between the oscillating water column and the motion responses is effective. Comparing the heave responses for the two configurations, again, it seems

that the enhanced heave responses of the breakwater with asymmetric chambers might have contributed more than the pitch responses to the increase of the air pressures inside both the front and rear chambers.

For later discussion, the values of the maximum pressure coefficient C_p inside the front and rear chambers for the two models are summarized in Table. 5. 3, together with the value of W / L at which a maximum pressure fluctuation occurred. It can be seen from Table. 5. 3 that increasing draft reduced the pressure fluctuation inside the front chamber and also increased the natural period at which the peak pressure fluctuation occurred.

Table. 5. 3 Values of the maximum pressure coefficient C_p inside the front and rear chambers and corresponding W / L

Model	$D_r / W = 0.19$		$D_r / W = 0.15$		$D_r / W = 0.11$	
	Front	Rear	Front	Rear	Front	Rear
Asymmetric chamber case	0.26, 0.53	0.04, 0.42	0.30, 0.60	0.07, 0.42	0.43, 0.60	0.10, 0.42
Symmetric chamber case	0.12, 0.47	0.08, 0.47	0.19, 0.47	0.06, 0.39	0.26, 0.53	0.07, 0.39

5.4 Discussion

Even though the widths of individual chambers in the two configurations are different, the overall width of the breakwater is identical for both configurations. The similar behaviors in both the reflection and transmission coefficients for the two configurations suggested that the distance between the plates used to form the two chambers (overall width) played an important role in wave scattering by the breakwater. This point had been noticed earlier by Kagemoto (2011) as well.

The air-pressure fluctuation inside a pneumatic chamber is related to the rate of change of the volume of the air trapped inside the chamber, dV/dt with V being the instantaneous volume of the air trapped inside the chamber, and thus controlled by the relative motion between the chamber and the water column inside the chamber, as illustrated in Fig. 5. 9. The problem for the air-pressure inside the chamber is similar to the air-gap problem encountered in semi-submersibles studied by Kurniawan et al. (2009). Referring to Fig. 5. 9, let ζ be the vertical displacement of the top of the chamber, η the surface displacement of the water column inside the chamber, and S the cross-sectional area of the chamber, dV/dt can be written as

$$\frac{dV}{dt} = S \frac{d}{dt}(\zeta - \eta) = S \left(\frac{d}{dt}(\xi - r\theta) - \frac{d\eta}{dt} \right) \quad (5.8)$$

where ξ is the heaving contribution to ζ and $r\theta$ is the pitching contribution to ζ (r is the distance between the center of the chamber to the center of rotation and θ is the angle of rotation for which the clockwise direction is positive). The calculated natural periods for $\xi(t)$ (the heave responses of the breakwater) and the calculated natural periods for $\eta(t)$ (the motions of oscillating water columns) are listed in Table. 5. 2 for later discussion.

Fig. 5. 9 Illustration of a floating oscillating-water-column (OWC) unit. ξ = the heaving response; θ = pitching angle of the structure; r = the distance between the center of OWC unit and the center of rotation of the structure

Since the air-pressure $p(t)$ is related to dV/dt , the air-pressure inside the pneumatic chamber is affected by the oscillation of the water column, and the dynamic responses of the floating structure to waves. Formally, the air-pressure can be expressed as

$$p(t) = f\left(\frac{d\xi}{dt}, \frac{d\theta}{dt}, \frac{d\eta}{dt}\right) \quad (5.9)$$

In the present experiments, the heave responses were larger for the asymmetric configuration than for the symmetric configuration; the change of the air-pressure inside the pneumatic chambers might have contributed to the enhanced heave RAOs, and vice versa. To understand how different factors may affect the heave response of the breakwater, small responses and a linear turbine are assumed so that the air-pressure $p(t)$ can be linearized to give,

$$p(t) = a_1 \frac{d\xi}{dt} + a_2 \frac{d\theta}{dt} + a_3 \frac{d\eta}{dt} \quad (5.10)$$

where $a_j (j=1,2,3)$ are empirical parameters characterizing the floating

pneumatic chamber. Now, for the heave response, $\xi(t)$, of this floating structure, the air-pressure force serves as a damping force (because it has a term proportional to $d\xi(t)/dt$), which, together with other kinds of damping, can reduce the system's heave natural period.

For the asymmetric configuration with three different drafts: $D_r/W = 0.19$, 0.15 , and 0.11 , the undamped natural heave periods given by Eq. (5.4) are 1.56s ($W/L = 0.44$), 1.45s ($W/L = 0.50$), and 1.34s ($W/L = 0.57$), respectively. These three natural periods are the same for both the symmetric and asymmetric configurations. The measured peaks of the heave responses for three drafts occurred at $W/L \approx 0.42$ for $D_r/W = 0.19$, $W/L \approx 0.45$ for $D_r/W = 0.15$, and $W/L \approx 0.47$ for $D_r/W = 0.11$, which are all smaller than those calculated by Eq. (5.4). For the case of a deep draft ($D_r/W = 0.19$), the inertia force dominates over the damping force due to the airflow through the opening, as a result, the measured natural period ($W/L = 0.42$) is close to the undamped natural period ($W/L = 0.44$); for the case of a shallow draft ($D_r/W = 0.11$), the reduced inertia force amplified the effect of the damping force due to the airflow through the opening, making the measured natural period ($W/L = 0.47$) noticeably longer than the undamped period ($W/L = 0.57$).

For the motion of an oscillating water column, $\eta(t)$, the pressure force also serves as a damping force. However, the damped natural period of the oscillating water column is not easy to measure in the experiments. The calculated natural periods of the oscillating water column can be estimated by Eq. (5.5). For the asymmetric configuration, the calculated natural periods for the front chamber are 1.24s ($W/L = 0.66$), 1.12s ($W/L = 0.80$), and 1.01s ($W/L = 0.98$) for $D_r/W = 0.19$,

0.15 and 0.11, respectively, and the calculated natural periods for the rear chamber are 1.46s ($W/L = 0.49$), 1.36s ($W/L = 0.56$), and 1.26s ($W/L = 0.64$) for $D_r/W = 0.19, 0.15$ and 0.11 , respectively.

For the asymmetric configuration, the measured peaks of $p_{\max}$ for all three drafts all occurred between the natural periods of the oscillating water columns and the natural periods of the heave response, suggesting that the pitch response is not important since its natural period is even longer than the corresponding heave natural period. It is reasonable to expect that significant contributions of the oscillating water column and the heave response to the total air-pressure fluctuation ΔP may occur at its own natural period; Fig. 5. 10 qualitatively illustrates the possible contributions of the oscillating water columns and the motion responses to the amplitude of the air-pressure fluctuation ΔP ; the trend of ΔP in Fig. 5. 10 is consistent with those measured for both the symmetric and asymmetric configurations. Even though the dependence of the air-pressure inside a pneumatic chamber on the motion responses and the oscillating water column is complicated, the trends of ΔP in the long wave and short wave limits can still be qualitatively understood using results available in the literature. When waves are very short, the heave response becomes small (Koo, 2009) and the structure may move out of phase with the waves (Koutandos et al., 2004); the pitch response can also become as small as zero (e.g., Koo, 2009). Therefore, the breakwater becomes more like a fixed structure and the air-pressure fluctuation in the pneumatic chamber is affected mainly by the natural period of the oscillating column. In the present experiments, for waves of period 1.1s the motion responses were very small (see Fig. 5. 6(c), Fig. 5. 7(c) and Fig. 5. 8(c)), and thus the main contribution to the air-pressure fluctuation came mainly from the oscillating water column whose natural periods are short. For very long waves, the heave responses tend to 1 (e.g., He et al., 2012; Koutandos et al., 2004) and the breakwater moves in phase with waves (e.g.,

Koutandos et al., 2004), thus the air-pressure fluctuation decreases with increasing wave period beyond the natural period of the heave response (He et al., 2012).

Fig. 5. 10 Sketch illustrating the contributions to the air-pressure fluctuation inside a pneumatic chamber (not drawn to scale).

The results for the asymmetric configuration revealed that heave responses were enhanced for all three drafts and both the surge and pitch responses for the asymmetric configuration are similar to those for the symmetric configuration. Therefore, the difference between the two configurations in the heave responses and the motions of oscillating water columns should be responsible for the differences in the measured air-pressure fluctuations inside the front and rear chambers for the asymmetric configuration. However, the interaction between the motion responses and the water column in a pneumatic chamber is complicated, and it is difficult to have a complete picture of this interaction from only laboratory tests without the help of a theory or CFD simulations. As a hypothesis, it is possible that a feedback mechanism might have been built up between the water column oscillation and the heave response of the breakwater: the increased air-pressures inside both chambers can strongly affect the heave response and to a lesser extent affect the pitch response; if the heave response can further increase the air-pressure inside the two chambers, a positive feedback mechanism might be built up in both the front and

rear chambers, resulting in a significant increase of the air-pressure inside both chambers. For this feedback mechanism to work effectively, sufficient wave energy available for each chamber is required to force the motion of the oscillating water column; this can only be achieved in a shallower draft, which can make enough wave energy available for both chambers.

For the case of $D_r/W = 0.11$, large air-pressure fluctuations had been achieved over a wide range of wave frequencies for both the front and the rear chambers, with the peak value of ΔP inside each chamber occurring at a period longer than the natural period of the oscillating water column (T_{OWC}) but shorter than the natural period of the heave response of the breakwater (T_{heave}). Therefore, for coastal spectral waves, the breakwater with asymmetric pneumatic chambers should be designed such that the peak period of the wave spectral falls in the range of $[T_{OWC}$ and $T_{heave}]$.

Even though the shallower draft is beneficial as far as construction costs and air-pressure fluctuations inside the two chambers are concerned, other factors also need to be considered when selecting a draft. The mass of the structure with $D_r/W = 0.11$ was only 58% compared to that with $D_r/W = 0.19$, but its performance was similar to those with deeper draft in the motion responses and wave attenuation. Nevertheless, the draft cannot be too shallow: reducing the draft may increase the pressure fluctuation but may also increase the wave transmission. The breakwater function must be taken into account while improving the wave-energy-converter function. Moreover, if the air leakage via the bottom opening occurs due to insufficient draft, the energy extraction will also be impaired.

5.5 Concluding Remarks

The results from this study showed that the proposed floating breakwater with asymmetric chambers could function simultaneously well for both shore protection and wave energy capturing. The following key conclusions can be drawn from this study:

- 1) Compared with the breakwater with symmetric chambers, the asymmetric chambers increased the heave responses but did not significantly change the surge and pitch responses. The new configuration could achieve good performance as a floating breakwater, with both low wave transmission and mild motion responses.
- 2) Compared with the symmetric configuration, the asymmetric configuration with shallower draft could increase pressure fluctuations inside both the front and rear chambers without sacrificing the breakwater function.
- 3) Breakwaters with asymmetric pneumatic chambers should be designed such that the front chamber is narrower than the rear chamber and the peak period of the coastal waves is longer than the natural periods of the oscillating water columns in both chambers and shorter than the natural period of the breakwater's heave response.

The concept of floating breakwaters with asymmetric pneumatic chambers provides a promising way to improve the energy extraction by both pneumatic chambers over a wide range of frequencies, and it is suitable to be used in those places where wave characteristics may have seasonal variations.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In this thesis, four novel designs, which are multi-functional and low in construction costs, were investigated experimentally. All these designs, were originated with the idea of integrating a wave energy converter into a pile-supported/floating breakwater. The effects of oscillating-water-column converters on the performance of the breakwater were the focus of this thesis. Major conclusions from this study are summarized in the following:

- (1) In Chapter 2, the hydrodynamic performance of a pile-supported OWC structure as a breakwater was experimentally investigated. Effects of different openings, which are used to simulate power-take-off mechanisms, were systematically studied experimentally. For all the opening ratios examined in the experiments, the wave transmission monochromatically decreased with increasing relative breakwater breadth. A deeper draft resulted in a smaller wave transmission. Among all the openings tested, an orifice-shaped small opening with an opening ratio of 0.625% could achieve the smallest wave transmission, but the effects of opening were negligible on the wave transmission for deeper drafts and shorter waves. For the orifice-shaped opening with an opening ratio of 0.625%, the breakwater performed satisfactory ($C_t < 0.5$) when the relative breakwater breadth (B/L) was larger than 0.220 for the 10-cm draft, 0.185 for the 15-cm draft and 0.149 for the 20-cm draft. The wave-transmission performance of the pile-supported OWC structure was remarkable compared with other types of pile-supported breakwaters, and the pile-supported OWC structure also has the

potential for wave energy utilization.

- (2) In Chapter 3, the hydrodynamic performance of two configurations of a pneumatic chamber in front of a vertical wall was experimentally investigated to examine their performance in reducing wave reflection. One configuration had an opening in the top face of the rectangular pneumatic chamber, and the other without. For a pneumatic chamber without a top opening, large energy dissipation occurred in a narrow range of frequency when the water column within the gap responded to incoming waves resonantly, resulting in very small reflection coefficients. When a gap of 9.7 cm existed, the reflection coefficient reached as low as 0.14 at $W/L \approx 0.18$. For a pneumatic chamber with a small top opening, energy dissipation came mainly from the air flow through the small top opening and vortex shedding at the tips of the pneumatic chamber walls; both small reflection coefficients and large energy extraction efficiencies were achieved in the absence of the gap between the rear wall of the pneumatic chamber and the vertical wall. A minimum reflection coefficient of 0.30 was found at $W/L \approx 0.11$.
- (3) In Chapter 4, the hydrodynamic performance of a floating breakwater with and without pneumatic chambers was experimentally investigated. The experimental results showed that the pneumatic chambers significantly enhanced the wave energy dissipation as well as reduced the wave transmission. With the installation of the pneumatic chambers, the water inside the chambers helped to reduce the surge response, while the chamber walls increased the moment of inertia of the breakwater and thus mitigated the pitch response. Increasing the draft of the floating breakwater reduced the surge, heave and pitch motions, but not very much. The air pressure fluctuations inside the front chambers decreased with increasing draft. For both the long and very short period waves, the breakwater with a deeper draft was more effective in reducing the transmitted

waves. The overall results illustrated that the installation of pneumatic chambers to a floating breakwater was more effective for wave protection, and also had the potential for simultaneous wave energy conversion for electricity generation. However, given the same geometry of the two pneumatic chambers, the rear chamber did not function as efficiently as the front chamber in terms of extracting wave energy.

- (4) In Chapter 5, the hydrodynamic performance of a floating breakwater with asymmetric pneumatic chambers (a narrower chamber on the seaside and a wider chamber on the leeside) was experimentally investigated. It was shown that the breakwater with asymmetric chambers performed as good as that with symmetric chambers in terms of wave transmission and motion responses. Meanwhile, an asymmetric configuration made it possible to increase the amplitude of the oscillating air-pressures inside both chambers without sacrificing the breakwater function. The floating breakwater with asymmetric pneumatic chambers should be designed such that the front chamber is narrower than the rear chamber and the peak period of the coastal waves is longer than the natural periods of the oscillating water columns in both chambers and shorter than the natural period of the breakwater's heave response. The new design provides a promising way to extend the frequency range over which wave energy can be extracted.

To summarize, four novel designs for integrating an oscillating-water-column converter into a pile-supported/floating breakwater were experimentally investigated. It had been shown that both wave transmission reduction and wave energy extraction could be achieved. The experimental investigation in this thesis demonstrated that integrating an oscillating-water-column converter into a pile-supported/floating breakwater could improve wave transmission reduction through wave energy extraction.

6.2 Limitation of the present study

The waves used in the experiments were all transitional waves ($0.141 < h/L < 0.327$ for glass-walled wave flume and $0.141 < h/L < 0.479$ for concrete-walled wave flume) due to the limitations of the facility. The waves in this thesis are limited to weakly-nonlinear waves. Le Mehaute (1976) classified waves based on d/gT^2 and H/gT^2 as shown in Fig. 6. 1, where the water depths (d) and wave periods (T) are usually selected according to the wave flume in hydraulic tests. The maximum wave height (H) within small amplitude wave theory is very small for the model size I used in my study and may cause relatively large errors; relatively-higher wave heights are chosen according to my model size and flume dimensions. The values of H/gT^2 used in the experiments in this thesis fall in the range of Stoke 2nd waves, but the second harmonic components are all small compared to the fundamental waves. Therefore, the waves used in the experiments are weakly-nonlinear waves. Since the second harmonic components are small, it is not expected to give results much different from those obtained for linear waves. The highly-nonlinear waves, including breaking waves, are also important for understanding the survivability of such structures, which is out of the scope of this thesis.

For weakly-nonlinear waves, it is possible to use frequency-domain results to perform a theoretical time-domain simulation of motion responses of a structure without significant viscous damping. However, for my problem, the air flow through the opening and the vortex shedding dissipate significant amount of energy, it is necessary to perform tests under irregular waves to understand the behavior for the system in irregular waves (mild sea states or extreme sea states). Due to the constraints of our lab facility and time, this important aspect of the topic was not

pursued in this thesis. It is suggested that future work should focus on tests in irregular waves.

Fig. 6. 1 Recommended wave theory selection. Adapted from Le Mehaute (1976)

6.3 Recommendations for future research

The following recommendations are made for future research:

- The experimental investigation in this thesis demonstrated that the novel designs of integrating an oscillating-water-column converter into a pile-supported/floating breakwater could achieve both wave transmission reduction and wave energy extraction. An analytical theory is still needed for optimizing designs of such breakwaters with the empirical parameters obtained from the experiments.

- Vortex shedding is an important factor contributing to energy dissipation. It is an interesting topic to observe the interaction of periodic waves with the sharp edges of immersed structure with the help of Particle Image Velocimetry (PIV). The nature of eddy formation and its influence on the wave energy extraction can be studied.
- The interaction between the water column and breakwaters, especially floating breakwaters is complicated. CFD simulations, with the empirical parameters obtained from the experiments, can help to provide a complete picture. Using CFD simulations, modeling of a turbine can be included and the coupling effects between structure and turbine can be examined.
- The hydrodynamic performance of the proposed novel designs can be further experimentally investigated under spectrum waves, which are more close to the real sea conditions. A small prototype may also be tested in field conditions.
- In addition to wave transmission reduction and energy extraction, survivability of the designs, e.g. forces on the structures, piles (pile-supported breakwaters) and moorings (floating breakwaters), also need to be further investigated.

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