Dynamic Motions of Piled Floating Pontoons Resulting From Boat Wake and Their Impact on Postural Stability

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DYNAMIC MOTIONS OF PILED FLOATING PONTOONS RESULTING FROM BOAT WAKE AND THEIR IMPACT ON POSTURAL STABILITY

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A thesis in fulfilment of the requirements for the degree of

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Thesis Title

Dynamic Motions of Piled Floating Pontoons Resulting From Boat Wake and Their Impact on Postural Stability

Thesis Abstract

This research focuses on the dynamic motions of piled floating pontoons and their impact on a standing person's stability. Piled floating pontoons are public access structures that provide a link between land and sea. There is limited useful data on the dynamic motions (acceleration and rotation) of piled floating pontoons to wave excitation. Similarly, there are no design standards specific to floating pontoons specifying suitable motion limits in order to maintain the postural stability of users. This research first proposes a set of Safe Motion Limits (SML) in the form of lateral, vertical and rotational accelerations in order to maintain a standing person's stability. Both laboratory and prototype testing have been undertaken in order to record the motion response of piled floating pontoons, resulting from boat wake. The motions recorded are compared against the proposed Safe Motions Limits (SML), to ascertain the impact on a standing person's postural stability.

Extensive laboratory-scale physical model experiments were undertaken at UNSW Water Research Laboratory. Two varying width piled floating pontoons, of variable draft, subjected to regular boat wake conditions were tested. Five Inertial Measurement Units (IMUs), were positioned on each pontoon and used to record accelerations and rotations. Observed accelerations and roll angles were dependent on beam to wavelength (B/L). Internal mass played a secondary role, with larger mass structures resulting in overall lower accelerations for similar B/L ratios. Increasing draft improved attenuation performance, most notably at a wave period of 3 seconds. As draft increased peak heave acceleration decreased however the percentage exceedance of the lateral SML increased. Prototype testing documenting both pontoon motions and user's perception has been undertaken with motions recorded exceeding the nominated SML and user's conveying levels of discomfort.

Importantly, results have revealed the complex interaction between the piles and pontoon that result in peak accelerations more than six times the nominated operational SML of 0.1g. Root-mean-square accelerations were observed to be more than three times greater than the nominated comfort limit (0.02g) and angles of rotation more than double what would be perceived as safe/comfortable (6 degrees) for the mild wave conditions tested.

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Abstract

This research focuses on the dynamic motions of piled floating pontoons and their impact on a standing person's stability. Piled floating pontoons are public access structures that provide a link between land and sea. There is limited useful data on the dynamic motions (acceleration and rotation) of piled floating pontoons to wave excitation. Similarly, there are no design standards specific to floating pontoons specifying suitable motion limits in order to maintain the postural stability of users. This research first proposes a set of Safe Motion Limits (SML) in the form of lateral, vertical and rotational accelerations in order to maintain a standing person's stability. Both laboratory and prototype testing have been undertaken in order to record the motion response of piled floating pontoons, resulting from boat wake. The motions recorded are compared against the proposed Safe Motions Limits (SML), to ascertain the impact on a standing person's postural stability.

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Importantly, results have revealed the complex interaction between the piles and pontoon that result in peak accelerations more than six times the nominated operational SML of 0.1g. Root-mean-square accelerations were observed to be more than three times greater than the nominated comfort limit (0.02g) and angles of rotation more than double what would be perceived as safe/comfortable (6 degrees) for the mild wave conditions tested.

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Abbreviations

Abbreviation	Description	Units
A	Area of contact	[m^2]
ah	Wave amplitude	[m]
B	Width of pontoon	[m]
BM	Vertical distance from centre of buoyancy (c.b.) to metacentre (M)	[m]
c.b.	Centre of buoyancy	[m]
c.g.	Centre of gravity	[m]
d	Water depth	[m]
D	Draft	[m]
F	Force	[N]
g	Gravity	[m/s^2]
GM	Metacentric height	[m]
H	Wave height	[m]
Hi	Incident wave height	[m]
Hr	Reflected wave height	[m]
Ht	Transmitted wave height	[m]
I	Inertia of waterplane area	[m^4]
IMU	Intertial Measurement Unit	[-]
K	Radius of gyration	[m]
KB	Vertical distance from keel to centre of buoyancy (c.b.)	[m]
KG	Vertical distance from keel to centre of gravity (c.g.)	[m]
Kr	Reflection Coefficient	[-]
Kt	Transmission Coefficient	[-]
L	Wavelength	[m]
M	Metacentre	[m]
m	Metres	[m]
MII	Motion Induced Interruption	[-]
Nf	Froude number	[-]
R^2	Coefficient of determination	[-]
RAO	Response Amplitude Operator	[m/m]
RMS	Root Mean Square	[-]
s	Seconds	[s]
SML	Safe Motion Limit	[-]
T	Wave period	[s]
Th	Natural period of heave	[s]
Tn	Structure natural period	[s]
Tr	Natural period of roll	[s]
V	Volume of fluid displaced	[m^3]

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: ___________________________

Date: 08/12/2020

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To my husband Warwick, your help with both my lab and field data collection was very much appreciated. Your continual support when things weren't going to plan will never be forgotten and I appreciate everything you have done to help me get to this point.

CHAPTER 1: INTRODUCTION

1.1 SITUATION AND HISTORY

Floating pontoon structures have been used since ancient times to cross rivers and provide a safe path of access and egress to vessels from land and vice versa (FIGURE 1.1). Today, many sheltered, small craft harbours around the world utilise floating pontoons as landing stages for vessel passengers, pedestrians and small cargo (Transport for NSW, 2012), roll-on roll-off (Ro-Ro) berths, for mooring small boats (BSi, 2000), and naval operations (Niepert, 2018). There is an extensive variety of floating structures involved in oil and gas, transportation, exploration and production, marine operations, renewable energy, infrastructure and aquaculture (Faltinsen, 2015). The land sea connection in the form of floating pontoons will become greater as industries expand out to the oceans. In Sydney Harbour alone there are more than 137 public access points (wharves, jetties and pontoons) for boat users (Transport NSW 2014) frequented by more than 172,000 commuter passengers per month as well as thousands of tourists (FIGURE 1.2). Floating pontoons have a cost advantage over fixed structures and have the benefit of being easy to install and relocate (BSi, 2000).

FIGURE 1.1. ROMAN LEGIONARIES CROSSING THE DANUBE RIVER BY PONTOON BRIDGE, AS DEPICTED IN RELIEF ON THE COLUMN OF EMPEROR MARCUS AURELIUS (R. 161-180 AD) IN ROME, ITALY (SOURCE: PHOTOS BY CONRAD CICHORIUS)

FIGURE 1.2. A FERRY COMMUTER FLOATING PONTOON LOCATED AT BALMAIN EAST IN SYDNEY HARBOUR.

Floating pontoons are usually made in one of four basic hull configurations: the *solid single pontoon* (rectangular prism), *catamaran*, *raft* or *unitised floatation multi-pontoon* (see Chapter 2, Figure 2.1) (J. Gaythwaite, 2016a). They are predominantly constructed from steel; however, a disadvantage of steel construction is the ongoing high maintenance in the marine environment. Therefore, concrete and glass-reinforced plastic (GRP) are also used (BSi, 2000). To secure floating pontoons in place, they are often anchored to piles, dolphins, or catenary cables, which restrict movement under environmental and operational loading, such as waves, currents and ship wake (Gaythwaite, 1990). However, the high inspection and maintenance costs associated with flexible mooring systems have resulted in a clear preference within Australia over the past decade for piled restraining systems for the majority of floating pontoon installations (Cox, Coghlan and Kerry, 2007).

Understanding the hydrodynamics of these structures matters in their design. With increasing populations, the utilisation of our waterways is becoming more prominent. It is important to ensure that those people using the floating structures will be comfortable and safe. In order to do this the hydrodynamics and body/wave interactions need to be understood and the structures effectively designed to minimise excessive movements.

While data exists for acceptable dynamic response limits for both land-based structures and sea going vessels, piled floating pontoon structures fall somewhere in between. To date, there has been limited research on this topic. Currently design standards that define an acceptable level of motion for floating pontoons do not exist or at best are limited. Nor do any design standards exist defining how postural stability should be considered when designing floating pontoons, despite these structures being frequented by the general public. Piled pontoon structures are a particularly special case of floating pontoons in that they are fixed to piles allowing minimal lateral movement but are much less restricted in vertical movement and roll.

For floating structures utilised by the general public, safety and serviceability requirements indicate the need for limits to be applied to the movement as a result of external forces. The public using the pontoon often are not aware of the risks dynamic response may cause. This means limits should be set recognising the general public has limited knowledge regarding how the pontoon structure can be safely used.

1.2 THESIS OBJECTIVES AND OUTLINE

Previous research on the dynamic motions of piled floating pontoons to boat wake has been limited and the way in which the dynamic motions impact on a standing person's postural stability even less. Therefore, the three objectives of this thesis are as follows:

1. *Determine a set of safe motion limit criteria for piled floating pontoons with respect to postural stability.*

   Due to the lack of design guidelines on safe dynamic motions for floating pontoons an extensive literature review of dynamic motions of moving bodies (trains, ships, etc) was undertaken and a set of safe motion limit (SML) criteria for maintaining postural stability in able-bodied adults developed.

2. *Document the dynamic motions of piled floating pontoons under boat wake action within a laboratory setting and compare these to the safe motion limits derived.*

   To achieve this objective a series of controlled and scaled laboratory flume experiments of two piled floating pontoons under boat wake action were completed at UNSW Water Research Laboratory. The effects of beam width and draft on the resulting motions considered.

3. *Document the dynamic motions of floating pontoons under both wind and boat wake conditions and personal stability levels at field scale and compare these to the laboratory results and safe motion limits defined.*

   To achieve this objective a series of field experiments were conducted to measure the dynamic motions of floating pontoons and incident waves within Sydney Harbour and the Shoalhaven, NSW. A survey of patrons was conducted to determine their perceived level of safety while on the pontoons. These are compared to the laboratory results.

This thesis is set out as follows. The second chapter of this work provides the reader with a background into the design of floating pontoons. Postural stability is introduced along with a review of literature relevant to maintaining a standing person's comfort and safety. The magnitude of motion expected to cause postural instability in a range of different moving environments is outlined.

The third chapter contains details of the methodologies adopted for both laboratory (Chapters 4 and 5) and field (Chapter 6) testing. Modelling parameters, setup and equipment are explained.

Chapters 4 and 5 present the results from the controlled laboratory experiments conducted at the Water Research Laboratory. Chapter 4 focuses on the impact of altering the pontoon beam width and Chapter 5 focuses on the impact of altering draft. Results are compared with the safe motions limits (SML) with focus placed on the implications relative to postural stability.

Chapter 6 documents the outcomes from field testing including results from surveying pontoon users on their level of comfort. Motion and survey results are presented against the SMLs nominated in Chapter 2 and compared to the laboratory results of Chapters 4 and 5.

In the Discussion and Conclusion (Chapters 7 and 8), the most important findings of this work are highlighted and some recommendations for future research are given.

CHAPTER 2: LITERATURE REVIEW

This chapter provides the reader with a background into the design of floating pontoons. The motions associated with floating bodies and moving objects is then discussed relative to the potential impact on a standing person's postural stability. Details of the magnitude of motion that causes postural instability is reviewed and a set of limiting criteria adopted based on maintaining one's postural stability.

Some content of this chapter is taken from the following publications:

Journal Publications

Freeman, E., Splinter, K. and Cox, R. In review. 'Laboratory Experiments on the Dynamic Motions of Piled Floating Pontoons to Boat Wake and Their Impact on Postural Stability and Safety', *Journal of Ocean Engineering*

Conference Proceedings

Freeman, E.; Cox, R., and Splinter, K. 2017. 'Suitable Criteria for Safe Motion Limits of a Floating Pontoon Relative to the Postural Stability of a Stationary Standing Person', *Australasian Coasts & Ports 2017: Working with Nature*. Barton, ACT: Engineers Australia, PIANC Australia and Institute of Professional Engineers New Zealand, 2017: 476-482.

Freeman, E.; Cox, R., and Splinter, K. 2018. 'Floating Breakwaters as Public Platforms – Impact on Postural Stability', *Coastal Engineering Proceedings, 1*(36), structures.63.

Freeman, E.; Cox, R., Splinter, K., and Flocard, F. 2019. 'Floating Pontoon Motions, Operational Safe Motion Limits', Pacific International Maritime Conference.

2.1 DESIGN OF FLOATING PONTOONS

Floating pontoons, similar to fixed structures, are designed to accommodate deck live loads, vehicular and equipment loads, vessel berthing and mooring loads. However, the main difference when compared to a fixed structure is that the reaction forces caused by the deck loads are resisted by a uniformly distributed buoyancy force over the length of the structure's base. The structure is also subject to floating body motions and thus dynamic effects that are not experienced by fixed structures (Gaythwaite, 2016).

Floating pontoons are typically designed by either naval architects or engineers. When designed by a naval architect, pontoons are treated as a floating vessel. The dynamic motion response of the structure is considered and will adhere to Classification Society Rules, National Standard for Commercial Vessels (NSCV, 2010), Lloyds, as well as requirements dictated by the relevant Maritime Safety Authority. While considering a floating pontoon as a vessel may be reasonable for moored or cabled structures, treating a piled floating pontoon as a vessel may not effectively describe the behaviour nor account for the complex interaction between pontoon and piles resulting from waves.

The coastal or maritime engineer focuses on the dynamic loading on the structure itself as well as the support structure and therefore does not explicitly consider the pontoon-pile interaction with respect to the motions (Cox et al. 2007). They also consider the wave transmission, reflection and the role pontoon geometry has on these (Zidan et al. 2012; Williams et al. 1998). Standards/Guidelines including British Standard – Maritime Structures (BSi 2000), U.S.Army Corps of Engineers (2009), PIANC WG419 Guidelines for Marina Design (2016-2017), International Standard - Mechanical Vibration and Shock (ISO 1997), North Atlantic Treaty Organisation (NATO 2000), Design Criteria for Floating Walkways and Pontoons (QLD 2015) and NSW Maritime (2005) provide guidance on siting and load requirements, stability and natural frequency response to be considered when designing floating pontoons. Very rarely do engineers consider the influence boat wake will have on the motion response of the structure, the anticipated peaks in acceleration resulting from pontoon/pile interaction with respect to personal safety/comfort, nor the interactions and stability of people utilising the pontoons.

A civil engineer is required to produce structures that not only satisfy limit state design but also satisfy serviceability and safety requirements. This means in the absence of a fixed standard; good engineering judgement is required. Currently the Australian Standards AS3962 – 2020 '*Guidelines for Design of Marinas'* and AS4997 – 2005 '*Guidelines for the Design of Maritime Structures'* (Standards Australia, 2020 and Australia, 2005) are the most comprehensive standards covering the design of floating pontoon structures. Within both Australian Standards, requirements relating to site investigations, dimensional criteria of marinas including channel widths, depths etc., loading and stability are covered. Reference to stability relates to how a floating pontoon will respond to overturning forces or moments; however, there is no mention of how floating pontoons will move as a result of wave disturbance nor any mention of reducing motion response in order to maintain the comfort and stability of people standing on the structure. Wave size (significant wave height) is briefly discussed in Section 4.8 Table 4.2 of AS3926 criteria for a 'good' wave climate in small craft harbours. This is generally related to wind waves; however, floating pontoons are frequently located in close proximity to regular ferry routes in order to be easily accessible for public transport. Hence, it's not always a 'good' wind wave climate that should solely set the design criteria and boat wake excitation is an equally important consideration.

Floating pontoons are found in most marinas and in areas with high tidal range or deep bathymetry. They are also used as landing stages and increasingly as floating breakwaters. A floating pontoon differs to a floating breakwater in terms of its design and intended use with floating pontoons typically not designed to minimise wave attenuation. The mooring system of a floating pontoon can be broadly categorized as fixed (whereby the structure is secured directly to a fixed pier, dolphin, or cantilever pile) or free (with the structure tethered via cables or chains to anchors in the bottom soil) (Gaythwaite, 2016). There is a large variety of commercially available floating pontoons on the market. Some generic types, their usual construction and behaviour under wave action are shown in FIGURE 2.1. This research focuses on a solid box pontoon moored using a fixed pile connection.

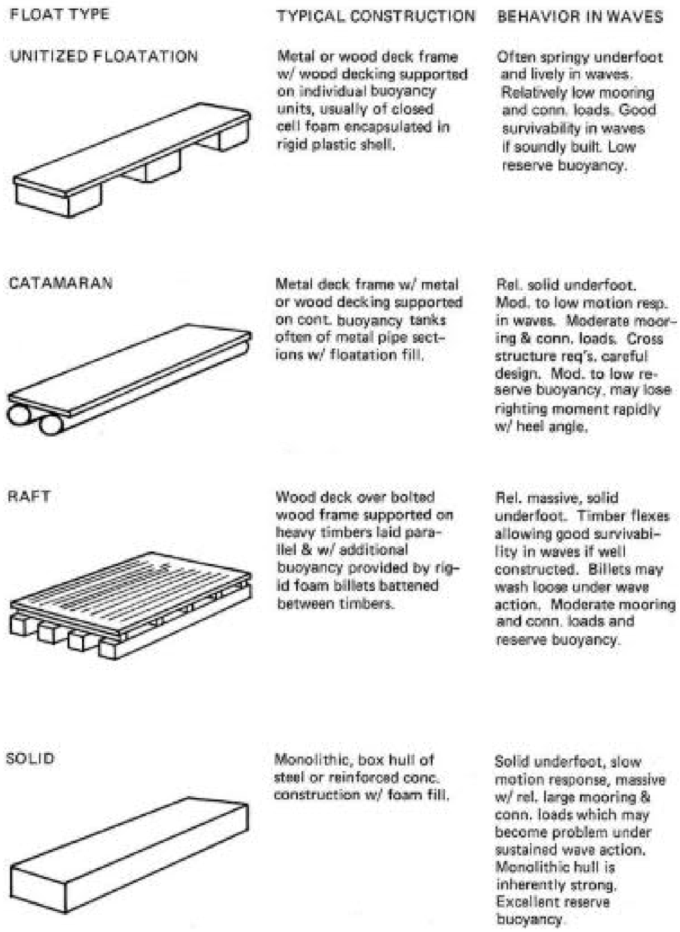


FIGURE 2.1. FLOATING PONTOON DECK TYPES, CONSTRUCTION AND TYPICAL MOTION RESPONSE (GAYTHWAITE, 2016).

While clear design standards exist within the literature pertaining to loading, stability and frequency response with respect to structural integrity, there are no clear guidelines for floating pontoons that focus on accelerations related to postural stability of patrons.

2.2 MOTIONS OF A FLOATING PONTOON

When installed in a marine environment, a floating pontoon undergoes dynamic motions. These dynamic motions of a rigid body interacting with fluid motions are governed by the combined external forces, such as wind and waves interacting with the structure, as well as by the internal inertia of the floating pontoon itself (Journee & Pinkster, 2002). Numerical methods of describing a floating pontoon's response to waves have originated largely from ship hydrodynamics. The motions of a floating body are a combination of the three translations of the centre of gravity in the *x*-, *y*- and *z*- axis, corresponding with surge (longitudinal, x_b), sway (lateral, y_b) and heave (vertical, z_b), as well as the three rotations around the centre of gravity (roll (ϕ), pitch(θ) and yaw (ψ)) (Journee & Pinkster 2002) as depicted in FIGURE 2.2.

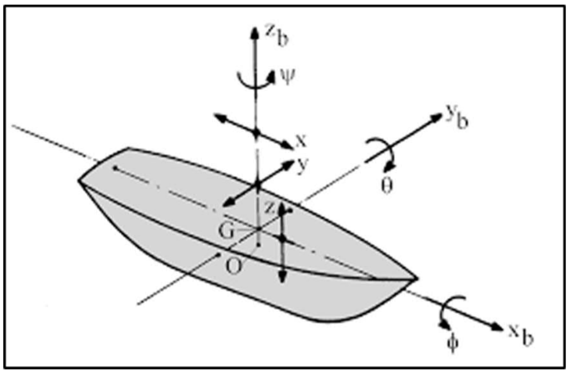


FIGURE 2.2. DEFINITION OF SHIP MOTIONS IN SIX DEGREES OF FREEDOM (SOURCE: INTRODUCTION TO SHIP HYDRODYNAMICS DELFT UNIVERSITY)

Understanding the motion response of a floating pontoon in a given wave climate is important to the planning, design and operation of the facility. A pontoon's response depends importantly on its orientation to the sea as well as to the wave heights and periods (Gaythwaite, 2016). The following section examines this in more detail.

2.2.1 HYDROSTATICS AND STABILITY

Understanding why objects float and the stability of those object is an important aspect of water-body interactions. A floating body is in equilibrium when no net external forces act on it and its centre of gravity (c.g.) and centre of buoyancy (c.b.) lie in the same vertical plane as shown in FIGURE 2.3 (Gaythwaite, 2016). Fluid pressure acts all over the wetted surface of a floating body and the resultant pressure acts in a vertical upward direction, this is termed buoyancy (Nakayama, 1998). In a floating body in equilibrium, the weight of the object is balanced by this upward buoyancy force.

The dynamic effect of the movement of water on floating bodies and its impacts on buoyancy and stability is complex. In the past, dynamic effects caused by ship's motions were accounted for in a very simple way, or even ignored (Journee and Pinkster, 2002). This is also the case for floating pontoon design, with very little guidance given for designing for and limiting excessive motions.

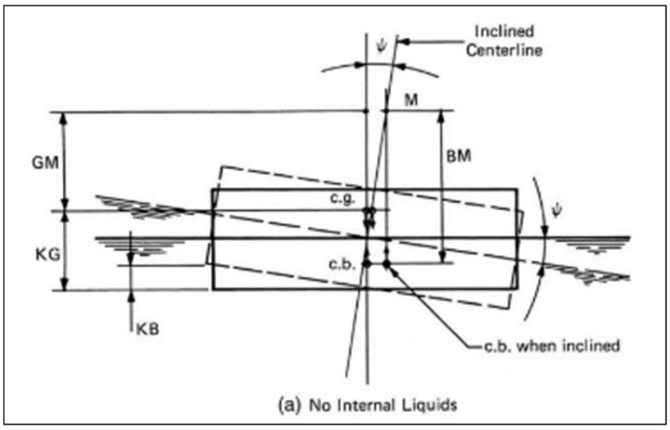


FIGURE 2.3. HYDROSTATIC STABILITY DEFINITION SKETCH – NO INTERNAL LIQUIDS (SOURCE: GAYTHWAITE 2016)

Generally speaking, the relative motion response of a floating pontoon depends on the following criteria (J. Gaythwaite, 2016b).

- Water depth (d) to draft (D) ratio, d/D;
- Beam width (B) to draft (D) ratio, B/D. This effects the virtual mass, and;
- Beam width (B) to wavelength (L) ratio, B/L.

Another important criteria of pontoon stability is the Metacentric Height (GM). The metacentric height is the vertical distance between the centre of gravity (c.g.) and the Metacentre (M) (FIGURE 2.3) and is calculated as follows:

$$GM = KB + BM - KG \tag{2.1}$$

Where KB is the vertical distance from keel to centre of buoyancy (c.b.) in metres and is equal to the exact middle of the volume of displaced water. BM is the vertical distance from the centre of buoyancy (c.b.) to the metacentre (M), and KG is the vertical distance from the keel to the centre of gravity (c.g.). According to Gaythwaite (2016), the radius of gyration (K) for a floating pontoon is between 0.29B and 0.35B, where B is the beam. Here, K in the roll direction is calculated from the inertia of the water plane area (I) and the area of contact (A), where:

$$K = \sqrt{I/_A} = B/_{\sqrt{12}} = 0.29B \tag{2.2}$$

and represents the lower bound proposed by Gaythwaite (2016). The vertical distance BM is calculated as follows:

$$BM = I/V \tag{2.3}$$

Where I is the inertia of the water plane area as mentioned above, and V is the volume of fluid displaced. For a rectangular water plane area:

$$I = \frac{l\ x\ b^3}{12}\ and\ V = l\ x\ b\ x\ d \tag{2.4}$$

It is found that ships with large initial metacentric height can be inconvenient (uncomfortable); high dynamic acceleration levels are often the result of small natural roll periods. A combination of the acceleration level and its average frequency of oscillation rules the amount of comfort onboard (Journee and Pinkster, 2002). The lower the value of the metacentric height the slower the rocking, that is the longer the period of roll. Due to diversity of structures it is not possible to define minimum values for the metacentric height (GM), however typical design guidelines for a floating pontoon are between 1 and 15. The metacentric height (GM) can be used to calculate both the natural frequency of a pontoon and estimates of the peak accelerations the pontoon may experience resulting from the predominant wave climate and dimensional characteristics of the structure.

2.2.2 NATURAL FREQUENCY

Waves continuously disturb a floating body resulting in both horizontal and vertical motions (Küchler et al., 2011). The response of the floating body to the waves is highly dependent on wave period and wave length, with the maximum response likely to occur when the wave period coincides with the natural frequency of motion of the structure or when the wave length coincides with the structure's wavelength (BSi, 2000). Generally speaking, the horizontal motions are dependent on the mass of the structure and stiffness of mooring. The vertical motions are dependent on mass of structure, hydrostatic properties and wave characteristics (BSi, 2000). Surge and sway amplitudes will equal horizontal wave particle amplitudes and heave will equal vertical wave particle amplitude in a free-floating body. Roll and pitch should equal wave slope in a free-floating body. These assumptions cannot be used when the natural frequency of the floating body equals the forcing frequency.

A number of methods are available to determine the natural frequency of a floating pontoon including Gaythwaite (2016); BSi (2000) and DNV (2012). Rigid maritime structures, such as those supported by piles, tend to have high natural frequencies due to the stiffness of the moorings. This high natural frequency means that the amplitude of motion can be large for shorter wave periods.

For this thesis the natural frequencies have been determined both experimentally accounting for the restraint resulting from the piles and by adopting methods proposed by Gaythwaite (2016) for a free-floating body. The theoretical natural period of roll of an unrestrained free-floating body is calculated using the following equation, frequency is the reciprocal of this value:

$$T_r = 2\pi\sqrt{\frac{K^2}{g(GM)}}\ where\ K = 0.29B\ to\ 0.35B \tag{2.5}$$

For a typical floating pontoon, period of roll is generally within the range of 2.5 to 4 s (Gaythwaite, 2016). As can be seen from equation 2.5 the natural period of roll will increase for low values of GM. Heave is affected by the amount of damping present and can be altered by adding mass to the floating pontoon. The natural period of heave (T_h) for a free floating rectangular pontoon is calculated using the following equation or FIGURE 2.4 (Gaythwaite, 2016):

$$T_h = 1.108\sqrt{C_m D} \tag{2.6}$$

The added mass coefficient (C_m) varies with pontoon properties (B/D) and relative water depth to draft (d/D).

In many cases the motions of a floating structure have a linear behaviour. This means that, at each frequency, the ratios between the motion amplitudes and the wave amplitudes and also the phase shifts between the motions and the waves are constant. Doubling the input (wave) amplitude results in a doubled output amplitude, while the phase shifts between output and input does not change. It is important that the natural frequency of the structure does not coincide with the natural frequency of the predominant wave climate. When the pontoon natural frequency and forcing frequency coincide resonance results in dynamic amplification.

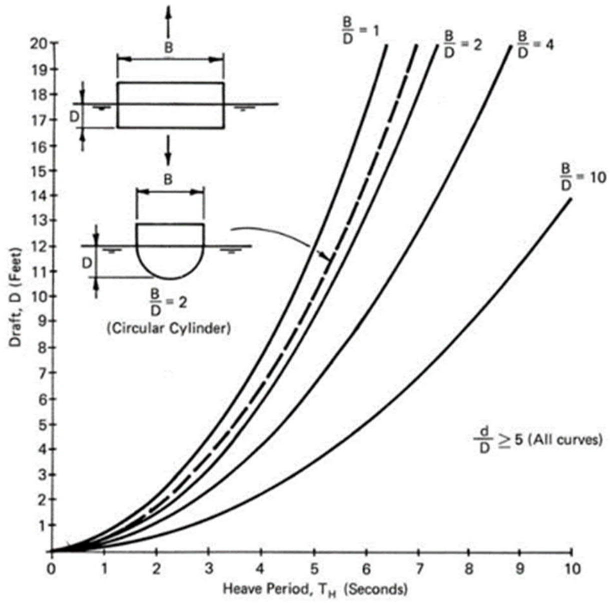


FIGURE 2.4. NATURAL PERIOD OF HEAVE VERSUS DRAFT FOR RECTANGULAR PONTOON (SOURCE: GAYTHWAITE, 2016)

2.2.3 ACCELERATION

This research is aimed at highlighting the importance of understanding the accelerations a pontoon might experience resulting from small amplitude boat wake in order to assess and better understand the potential impact on postural stability. There are currently no compulsory design standards nominating limits on floating pontoon motions nor standards/codes clarifying how to calculate anticipated peak accelerations resulting from wave/structure interaction. For desktop assessment purposes as part of this thesis, maximum heave acceleration (α_h) of a free-floating body is calculated following Gaythwaite (2016) equation (2.7). From a design viewpoint if approximate accelerations are calculated at the design stage it is possible to make amendments if safe motion limits (TABLE 2.1) are exceeded, enabling better design. The equation takes into consideration the wave period (T) and wave amplitude (a_h) and is suitable for estimating heave accelerations of a rectangular free-floating box pontoon.

$$\alpha_h = \frac{4\pi^2}{T^2} a_h \tag{2.7}$$

Gaythwaite (2016) states that in general, the heave response is negligible for L < 0.75B and near unity for L > 4B. It is important to note that this approach does not consider the pontoon-pile interactions, as is the focus of this thesis, which may result in high short duration peaks in acceleration.

2.2.4 RESPONSE AMPLITUDE OPERATOR

The response of a floating structure or vessel is usually summarized in terms of Response Amplitude Operators (RAOs). The response amplitude operator defines the response to a wave of unit amplitude (BSi 2000). In sheltered locations, for vessels or pontoons, the stiffness of a flexible mooring system can generally be neglected. If the structure is considered as freely floating, conservative estimates of response by assuming RAOs of unity can be obtained. As mentioned in Section 2.2.2, for a freely floating body, surge and sway amplitudes equal horizontal wave particle amplitudes and heave amplitude equals vertical wave particle amplitude. Roll and pitch amplitude equal the maximum wave slope. This assumption cannot be used when the natural frequency/period of the structure is near the forcing frequency/period. For stiff restraining systems such as pontoons held by piles, the horizontal motions are theoretically governed by the stiffness of the restraining system. However, the deflections of structures such as piles are generally small, and it will normally be adequate to assume that a floating structure will move within the tolerances of any fendering and guide system.

Now that the basics of design of floating pontoons has been discussed, the following section summarizes the literature related to documented dynamic motions of floating structures relevant to this thesis.

2.3 PREVIOUS EXPERIMENTAL AND NUMERICAL RESULTS ON THE DYNAMIC MOTIONS OF FLOATING BREAKWATERS

Very few studies to date have focussed on the dynamic motions, in the form of accelerations, of floating structures. Those that do consider motions tend to focus on displacements rather than accelerations and the floating structures are usually moored with chains rather than piles (Huang et al. 2014). While floating breakwaters are more commonly studied and differ from floating pontoons in their primary purpose and their design criteria (transmission coefficients and load on mooring), they both undergo dynamic motions due to wave-structure interaction. Several studies have documented the amplitudes (displacement) of motion for heave and surge of floating breakwaters under both regular and irregular wave action with emphasis given to how alterations (slotted barriers, suspended balls, pneumatic chambers, width and draft) to the floating breakwater impact on wave transmission, reflection and amplitudes with findings presented in Section 2.3.1 and 2.3.2 (Huang et al. 2014; Ji et al. 2015; He et al. 2012, and Williams et al. 1998).

2.3.1 BEAM TO WAVELENGTH

A number of studies have reported on the impact of beam (that is, width) on the dynamic motions of floating structures. He et al. (2012) conducted scaled laboratory experiments on the effect of adding pneumatic chambers to a slack moored floating box structure (FIGURE 2.5). When the structure was exposed to a target experimental wave height of 0.04 m and wave periods ranging from 1.1 – 2.0 s the pneumatic chambers enhanced wave energy dissipation, reduced wave transmission and mitigated motion response. They also found that an increase in draft saw a slight reduction in amplitudes of motion (surge, heave and pitch) (Section 2.3.2). They presented results on wave energy dissipation, reflection and transmission coefficients as well as amplitudes of motion (heave, surge and pitch). They compared the above-mentioned results against the beam to wavelength (B/L) ratio as well as investigated the effect of draft on the mentioned results. Results were not presented on the accelerations experienced by the floating breakwater. Carver (1979) conducted 2D wave flume experiments looking at various sized floating breakwaters moored with chains and documented their effectiveness of wave dissipation. He claimed efficiency in dissipating the wave energy increased with width to wavelength ratio. The highest transmission (Kt) occurred for B/L=0.15 (Kt=0.9), reducing to a B/L=0.4 (Kt=0.4).

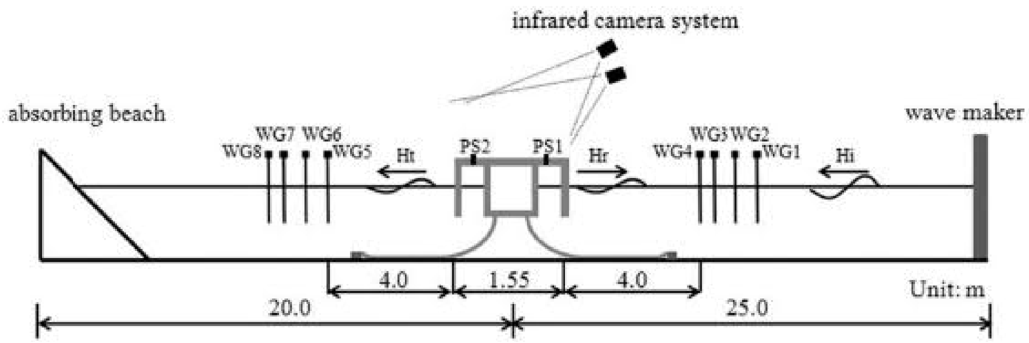


FIGURE 2.5. EXPERIMENTAL SETUP OF HE ET AL. FLOATING BREAKWATER WITH PNEUMATIC CHAMBERS (SOURCE: HE ET AL. (2012))

2.3.2 DRAFT EFFECT

The effect of draft is more commonly studied than the effect of beam on floating breakwaters, with a number of studies focussing on novel methods to increase the effective draft using barriers and meshes. Most commonly, the structures were also secured via mooring lines, rather than piled, which would affect their dynamic response. For example, Huang et al. (2014) conducted laboratory experiments to examine the hydrodynamic performance of a floating box breakwater secured via mooring lines with and without slotted barriers (FIGURE 2.6). They tested wave periods of 1.1 – 1.7 s and wave heights of 0.02 - 0.06 m (model scale). They presented their results in terms of Response Amplitude Operators (RAO). They found that slotted barriers attached to the bottom of the floating breakwater lowered the wave transmission coefficient without adversely impacting the dynamic motions of heave and surge, while for pitch, the addition of slots was mixed. Under shorter waves, pitch was reduced but for longer waves pitch was increased.

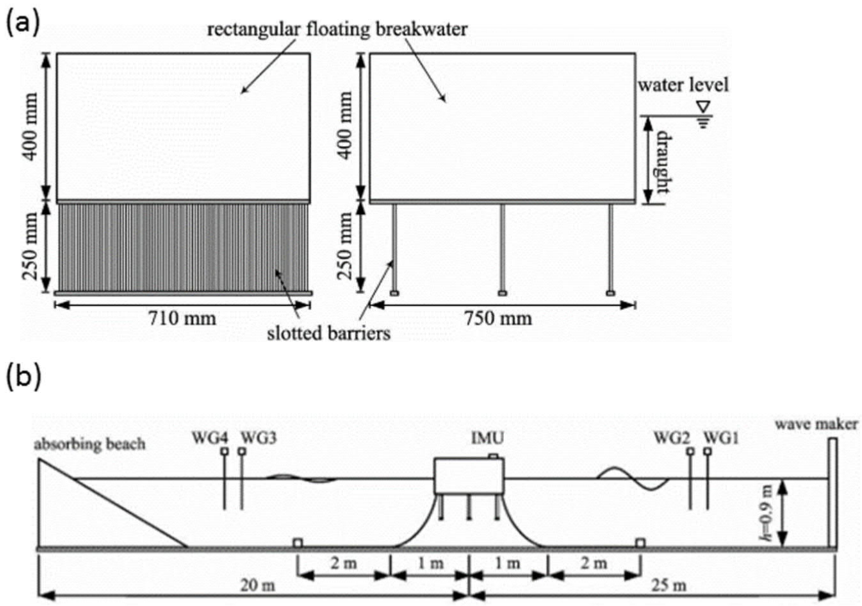


FIGURE 2.6. DETAILS OF HUANG ET AL. EXPERIMENTAL WORK: (A) FLOATING BREAKWATER WITH SLOTTED BARRIER AND (B) EXPERIMENTAL SETUP (SOURCE: HUANG ET AL. (2014))

The work described in Section 2.3.1 undertaken by He et al (2012) showed that increasing draft by the addition of pneumatic chambers enhanced wave energy dissipation and reduced wave transmission. Their results also provided a brief discussion on how increasing draft saw a slight reduction in amplitudes of motion (surge, heave and pitch).

Ji et al. (2015) undertook experimental investigations on a slack moored floating breakwater. They tested at a scale of 1:20 a new type of floating breakwater comprising two cylinders with a suspended mesh cage hung underneath as well as testing a double floating pontoon and a box breakwater (FIGURE 2.7). Their research documented the wave attenuation performance of the breakwaters as well as the amplitude of motion in sway, heave and roll when the breakwaters were subjected to regular waves of heights 2, 2.5, 3, 3.5 and 4m (prototype) and wave period ranging from 4.02 to 6.26s. Their work identified that the mesh cage reduced the amplitudes of motion for heave and roll; however, the sway motion was increased. The new configuration breakwater with the suspended mesh cage had better wave attenuation performance than the double pontoon and box breakwater suggesting that draft had a stronger control on the observed attenuation performance than beam width.

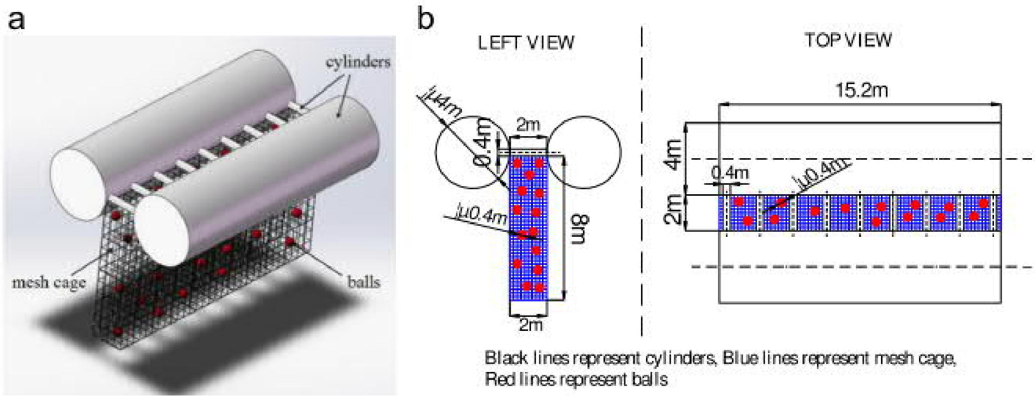


FIGURE 2.7. JI ET AL. MESH CAGE FLOATING BREAKWATER: (A) 3D SKETCH OF MESH CAGE AND (B) DIMENSIONS OF CONFIGURATIONS (SOURCE: JI ET AL. (2015))

Delavari et al. (2017) deduced that by decreasing draft the heave motion of the structure generally increased at the same ratio as B/L. Reynolds (2003) outlined that by increasing the immersed surface area, virtual mass is increased. This increases the radii of gyration and moves the natural period into lower frequencies.

As hydrodynamic performance (transmission and reflection) are key criteria in the design of floating breakwaters, a number of studies have also reported on wave attenuation properties but not reported on the dynamic motions of the floating structure itself. Recently, Qiao et al. (2018) examined the effect of attached porous plates on wave attenuation performance and hydrodynamic loading of an unsecured floating box. Results from their laboratory experiments indicated that wave transmission and reflection properties were dependent on the porous properties of the attached plates, as well as the relative water depth, and relative size of the pontoon. Ning et al. (2016) undertook numerical investigations looking at the effect of draft on the transmission coefficients of a fixed breakwater structure. They found that increasing relative draft lead to a reduction in the transmission coefficient (Kt,). However, as the structure they examined was fixed, they could not measure or report on any motion response. They also stated the blockage effect of the front wall of a floating breakwater is more significant with increasing draft. This relates to the draft-to-water-depth ratio (D/d), an important criterion when assessing the effectiveness of a floating breakwater. Generally speaking, lower values of D/d led to higher Kt values. Brebner et al. (1968) carried out experiments in a two-dimensional wave channel to determine wave damping characteristics of model floating breakwaters. They reported that draft played a significant role in reducing coefficients of transmission. They proposed that Kt<0.5 can be achieved by tuning the structural natural period to wave period ratio (T_n/T) to be greater than 0.65.

The hydrodynamic problem of floating breakwaters/pontoons is extremely complex prohibiting accurate analytical predictions of performance. Some numerical studies have been conducted and compared to experimental results, with varying levels of success (Isaacson et al. 1988; Sannasiraj et al. 1998; Williams et al. 1998 and Koutandos et al. 2005). Numerical model solutions are limited by the simplifying assumptions necessarily made in their establishment. Numerical models have been developed to predict the motion response of floating breakwaters secured with mooring lines (Rahman et al. 2006 and Peng et al. 2013). Both Rahman et al. (2006) and Peng et al. (2013) investigated both numerically and experimentally the motion response in the form of displacements of sway, heave and roll of a submerged floating breakwater.

The above laboratory-scale studies and numerical modelling all concentrated on wave attenuation performance, loading and amplitude of motion of floating breakwaters/pontoons secured with mooring chains under mixed wave action. The high inspection and maintenance costs associated with flexible mooring systems have resulted in a clear preference within Australia over the past decade for piled restraining systems for the majority of floating breakwater/pontoon installations within sheltered environments (Cox et al. 2007). Cox et al. (2007) conducted a series of scaled physical laboratory experiments to examine the effect of both monochromatic and irregular waves on the dynamic motions of a piled floating pontoon breakwater. The waves tested ranged in period from 2 to 5 s and wave heights of 0.4 – 0.8 m (prototype scale). They reported peak vertical accelerations ranging from 0.1g up to approximately 2.25g for a wave height of 0.4 m for the monochromatic waves. Although they did not report on accelerations for the larger wave heights it was observed that both the vertical and roll motions of the floating breakwater were of greater magnitude and more violent when subjected to larger waves. Aside from Cox et al. (2007), there has been minimal research on the dynamic motions, specifically accelerations, of a floating pontoon secured by piles. Furthermore, rigid maritime structures, such as those supported by piles, tend to have high natural frequencies due to the stiffness of the moorings. This high natural frequency means that the amplitude of motion is large for shorter wave periods such as those produced by boat wake, however in typical design situations consideration of the effect of boat wake on a floating structure is often neglected.

Now that the foundations of floating pontoon design have been summarised, the remainder of this literature review focuses on Objective 1 of this thesis: Defining and summarizing the human element of postural stability that is often overlooked during the design of pontoons despite them being public access ways.

2.4 POSTURAL STABILITY

Postural stability is the ability to maintain the body's centre of gravity over the base support during quiet standing and movement (Hageman et al. 1995). It is a complex process involving coordinated actions of biomechanical sensory, motor and central nervous system components (Forssberg & Nashner 1982) and changes with age. In quiet standing postural control, a necessary condition of static equilibrium is that the vertical line of the centre of gravity must fall within the area of the base support (Riach & Starkes 1993). A small sway deviation from a perfect vertical position leads to a torque due to gravity that moves and accelerates the body further away from the upright neutral position (Hue et al., 2007) Biomechanically, the degree of stability is proportional to the size of the base of support and stability is maximised in any direction when the line of gravity is furthest inside the edge of the base of support (Posner et al., 1982).

A standing person is exposed to dynamic motions in daily tasks. These motions may be experienced whilst travelling on various modes of transport; trains, buses or ships, or whilst standing on a floating structure such as a floating pontoon. The translational and rotational motions experienced by standing passengers and crew on various forms of transport and floating structures can affect their postural stability. As summarized in Nawayseh & Griffin (2006, p726), 'The prediction of the postural stability of standing persons exposed to external perturbations requires the identification of the relationships between the characteristics of the input motion and the consequent response of the human body'. The motions of a floating pontoon have the potential to cause a standing person to lose postural control. If the magnitude of motion can be minimised the postural stability of a standing person on a floating pontoon can be preserved.

2.4.1 AGE EFFECT ON STABILITY

There are distinctive age classified groups that have been studied relative to postural stability. The postural control capability of young children (< 7 years) and the elderly (>65 years) is different from older children and adults in several aspects. As floating pontoons are often public spaces, all these groups and their postural control require consideration when developing a suitable set of motion limit criteria for the allowable dynamic motions of floating pontoons. Those that require special consideration (the young and the elderly) are briefly discussed here.

Young Children (Birth – 7 Years)

Young children have lower stability limits compared to adults. They also sway more than adults in quiet standing conditions. These two factors combined contribute to children being much less stable than adults. As children develop, they gain in postural stability. How much of this development is physical (e.g. height, weight, strength, foot size) and how much is sensorimotor development is unknown; however, there is a definite rise in normalised stability limits to adult levels at age 7 (Riach and Starkes, 1993). Despite their centre of gravity being lower than adults, young children will be more susceptible to a loss in stability when compared with adults whilst standing on a floating pontoon undergoing dynamic motions.

Elderly (> 65 Years)

The elderly are also observed to have a lower level of postural control than adults, with one third of the population aged 65 years and older reporting falls each year (MacRae, Lacourse and Moldavon, 1992). Hageman et al. (1995) considered six variables that affect postural control and found that age had a significant effect on all six. Differences were found in the elderly subjects' ability to lean both backward and to the left, which would have a significant impact on a person's ability to react to a moving body to maintain a stable line of their centre of gravity. In a study undertaken observing the postural stability changes in the elderly (Blaszczyk, Lowe and Hansen, 1994), it was concluded that the well documented decline of integrity in many physiological systems in the elderly has a profound effect on the range of stability during upright stance.

2.4.2 MOTION INDUCED INTERRUPTION

Literature reviews indicate a lack of specific research relating to the comfort and postural stability of a person standing or walking on a floating pontoon. There is, however, information relating to the comfort and postural stability of crew and patrons (namely able-bodied adults) on board vessels.

In the past, seakeeping criteria to represent the effects of motion on operational performance on-board vessels have been based on the following four parameters; roll, pitch, and lateral and vertical acceleration. These may be incomplete physical parameters for expressing performance of personnel, as operations are not limited by any one of these parameters individually, but rather by some combination of all four (Graham, Baitis and Meyers, 1992). Although not specific to floating pontoons, these four parameters could inform the design of floating pontoons.

In the 1980s, sea trials on-board the U.S.S. Oliver Hazard Perry (FFG7) were carried out and the term Motion Induced Interruption (MII) presented. MIIs were described as representing 'the unavoidable circumstances when ship motion-induced forces produce instabilities in the person's stance which can only be countered successfully by either holding on to some part of the ship or by significantly altering the posture to re-establish personal stability' (Baitis et al. 1983, p195). The definition of MIIs, as described by Baitis , Applebee and Mcnamara, (1983), states that they are caused by the vector sum of all the forces generated by the ship's motions, and not by any one motion as previously adopted for vessel seakeeping criteria. A simple mathematical model was derived by Graham (1990) who introduced a frequency domain method for predicting the incidence of MII on a rigid body for simple standing tasks that includes the effects of both lateral and vertical acceleration. Graham (1990) proposed that a rational seakeeping criterion for deck operation involving personnel could be developed in terms of the incidence of MIIs per unit. This definition of seakeeping criteria was further developed theoretically to represent the onset of loss of balance due to tipping or sliding, whereby a tipping coefficient based on half stance width over height was nominated as 0.25 (Graham, Baitis and Meyers, 1992). The criteria of the tipping that would lead to the occurrence of an MII were based on completely unpredictable motions and the presence of combined vertical, lateral and longitudinal acceleration.

Crossland & Rich (1998) validated the previously derived theoretical tipping coefficients of the MII predictive model by physically testing a person’s stability when standing on a motion simulator. The MII model was shown to predict when a person will lose balance due to high accelerations caused by the moving platform. In this model, the ratio of half stance width over the vertical height of the person's centre of gravity, the theoretical tipping coefficient, is a key term in evaluating the probability of a MII occurring. Crossland & Rich (1998) recommended adopting a tipping coefficient of 0.27 for general seakeeping assessment purposes.

In more recent research (Langlois et al., 2012), on-board trials were conducted to document the occurrence of MIIs on dynamic systems, mimicking more closely the actual attributes of the human system rather than the previously adopted rigid body theoretical approach. The research extended MII modelling capability to increase the practical utility of MII models both for investigating stand-alone MII occurrence rate as well as MII rates when interacting with unsteady dynamic loads. Langlois et al. (2012) developed a quasi-static model generalised to three dimensions from the planar (Graham, Baitis and Meyers, 1992) model and a fully dynamic inverted pendulum model (Mackinnon, Langlois and Duncan, 2008).

2.4.3 PEAK VERTICAL, PEAK LATERAL AND ROOT MEAN SQUARE ACCELERATION

There are numerous documents available, none specific to floating pontoons, that specify the limiting peak vertical, peak lateral or root mean square (RMS) acceleration to be adopted to ensure the comfort of a person is maintained. Peak vertical acceleration relates to heave and pitch, while peak lateral relates to the horizontal components of acceleration (Mathisen, 2012). Root mean square (RMS) acceleration is the square root of the mean squared acceleration in any one axis over time period *t* (Pauschke 1987).

Based on the general effects of motion on human performance, Stevens and Parsons (2002) presented tables of acceleration that are acceptable under differing conditions. Values were presented for light manual work, heavy manual work, intellectual work, transit passengers and cruise liners. The latter two criteria may be considered as the most appropriate for comparison with the general public on a floating pontoon. Transit passenger criteria requires an RMS limiting vertical acceleration of 0.05g. Cruise liners have a limiting RMS vertical acceleration criteria of 0.02g. For improving passenger comfort and to reduce the incidence of motion sickness American Bureau of Shipping (2014) recommended a maximum RMS acceleration value of approximately 0.007g in order to restrict the incidence of motion sickness to 10% or less among passengers.

STANAG 4154 (NATO, 2000) specifies a default criteria to adopt a peak vertical acceleration of 0.2g and lateral acceleration of 0.1g both relative to the bridge of the vessel. NORDFORSK (1987) specifies for cruise liners a vertical RMS acceleration limit of 0.02g and a lateral RMS acceleration limit of 0.03g for passengers to remain comfortable. Within Australia the criteria for a floating pontoon relative to serviceability (i.e. maintaining the structure) is to limit peak acceleration to 0.1g (NSW Maritime, 2005).

Similar in design to floating pontoons, floating bridges are cost-effective options for crossing large bodies of water with unusual depth and very soft bottom where conventional piers are impractical (Chen and Duan, 2000). For the specific case of wave loading on a floating bridge, Chen & Duan (2000) nominated the following maximum motion limits for car passenger comfort during a normal 1 – yr. storm; vertical (heave) acceleration of 0.5 m/s^2, lateral acceleration (sway) of 0.5 m/s^2 and rotation (roll) of 0.05 rad/s^2. The lateral and vertical accelerations equate to approximately 0.05g (RMS), corresponding with the transit passenger limiting vertical acceleration proposed by Stevens and Parsons (2002).

While not of maritime nature, land based moving systems and their design criteria may also be of relevance. For example, in Great Britain, the Rail Safety and Standards Board estimate that around 15% of on-board harm in the railway network in the last 10 years (measured by fatalities and weighted injuries) can be attributed to 'injuries attributable to sudden movements of the train due to lurching or braking' (Rail Safety and Standards Board (RSSB), 2014). This lurching or braking relates to the acceleration and deceleration of the train. A study undertaken by British Rail looking at the effect of lateral acceleration on standing passengers found that 0.1g was the maximum level of acceleration that could be attained by the train without causing discomfort , 0.12g was defined as uncomfortable (Powell and Palacín, 2015). A study on the limits of acceleration the human body can withstand without losing balance by De Graaf & Van Weperen (1997), found that participants were most vulnerable to sideways acceleration and least vulnerable to backwards acceleration. De Graaf & Van Weperen (1997) found that a standing person could endure a maximum forward acceleration of 0.054g, maximum sideward acceleration of 0.045g and a maximum backward acceleration of 0.061g.

2.4.4 FREQUENCY OF ACCELERATION

As well as the magnitude of acceleration, it is important to assess the frequency at which acceleration is changing. Research has identified that humans are more likely to have unfavourable response to motion within a frequency band of 1 - 80 Hz (Brown et al. 2001; Nawayseh & Griffin 2006; Baker & Mansfield 2010). Nawayseh & Griffin (2006) discussed how the frequency of fore-and-aft and lateral oscillation impact on a standing person's postural stability. They tested a range of frequencies between 0.125 – 2.0 Hz and identified that higher frequencies for the lateral oscillation are more likely to result in instability. During pitch and roll oscillation with the same angular displacements, subjects became more unstable with higher frequencies of oscillation. For the fore-and-aft oscillation, there was a peak in instability at approximately 0.5 Hz, with instability decreasing as the frequency increased. Sari & Griffin (2010) examined how the frequency of lateral oscillations impacts on a walking person's stability. They documented that within the 0.5 - 2.0 Hz range of lateral oscillation the probability of participants losing balance decreased as frequency increased and that the highest incidence of losing balance peaked at 0.5 Hz, in agreement with the results of Nawayseh and Griffin (2006).

Motion sickness, which also should be considered for public platforms occurs for motions between 0.1 - 0.5 Hz (Matsangas et al. 2014; American Bureau of Shipping 2014). Shupak and Gordon (2006) examined how the frequency of acceleration impacted on seasickness. They identified the greatest incidence of seasickness was found at a linear vertical frequency of approximately 0.2 Hz, increasing with the acceleration level from a threshold value of $0.1 m/s^2$ (0.01g).

2.4.5 ANGLES OF MOTION

As well as the magnitude and frequency of acceleration, the angles of motion of a dynamic body need to be considered for the comfort and safety of the users. Within the literature, a range of angles of motion are quoted related to the stability of the pontoon itself, and to crew working on vessels. NSW Maritime (2005) nominates an angle of tilt of no more than 15° to be used when designing floating pontoons. No details are provided on whether this relates to all three axes or a dominant one. BSi (2000) provides intact stability guidelines for floating pontoons. Within the standard, a suitable pontoon range of intact stability is nominated as between 25°-50°. This nominated range is to ensure the floating pontoon remains intact and does not relate to ensuring a standing person's postural stability is maintained.

With respect to postural stability and comfort of people on floating structures, several studies have provided guidelines. For small craft harbours, Rosen et al. (1984) discussed maximum allowable vessel movements to ensure tasks of the crew are able to be completed. They nominated a roll angle (x-axis) of 6° and a maximum angular acceleration of $2°/sec^2$. Stevens and Parsons (2002) presented tables for root mean square (RMS) roll that are acceptable under differing conditions. Similar to design accelerations, values are given for light manual work, heavy manual work, intellectual work, transit passengers and cruise liners. The maximum allowable RMS roll for transit passenger is 2.5°, while for cruise liners it is 2.0°. NORDFORSK (1987) provides criteria for an allowable RMS roll of 2.0°. These values are substantially smaller than those quoted for pontoon stability given by NSW Maritime and BSi.

2.5 SAFE MOTION LIMIT CRITERIA

For this thesis, the Safe Motion Limits (SML) related to postural stability of a patron with respect to dynamic motions of a floating pontoon will be related to those motions originating from the moving environments described above, due to the absence of information directly relating to floating pontoons. Dynamic motions exceeding those identified in the literature have the potential to result in motion sickness, body instability, fatigue and discomfort. Defining these safe motion limits can be classified into age related groups, as well as allowable limits for both comfort and operation (stability). Table 2.1 stipulates the SML to be adopted for this research for older children and adults (ages 7 - 65 years).

TABLE 2.1. SAFE MOTION LIMITS (SML) FOR OLDER CHILDREN AND ADULTS (AGES 7 – 65 YEARS)

Criteria	Limit	Reference
Operation (Peak values)		
Peak Vertical Acceleration	0.1g	(NSW Maritime, 2005)
Peak Lateral Acceleration	0.1g	(NSW Maritime, 2005)
		Powell and Palachin (2015)
		NATO (2000)
Peak angle of tilt	6°	Rosen et al. (1984)
Comfort (RMS values)		
RMS Vertical Acceleration	0.02g	NORDFORSK (1987)
		Stevens and Parson (2003)
RMS Lateral Acceleration	0.03g	NORDFORSK (1987)
RMS Roll	2°	NORDFORSK (1987)
		Stevens and Parsons (2002)

It should be noted that the complex multidirectional behaviour of a floating pontoon is expected to create more instability than if the criteria identified in Table 2.1 were to act in isolation.

CHAPTER 3: SETUP AND METHODOLOGY

This chapter describes the methods adopted for the experimental and field testing of floating pontoons. It includes details of the data collection and analysis methods, pontoons tested and wave climate.

Some content of this chapter is taken from the following publications:

Journal Publications

Freeman, E., Splinter, K. and Cox, R. In review. 'Laboratory Experiments on the Dynamic Motions of Piled Floating Pontoons to Boat Wake and Their Impact on Postural Stability and Safety', *Journal of Ocean Engineering*

Conference Proceedings

Freeman, E.; Cox, R., and Splinter, K. 2017. 'Suitable Criteria for Safe Motion Limits of a Floating Pontoon Relative to the Postural Stability of a Stationary Standing Person', *Australasian Coasts & Ports 2017: Working with Nature*. Barton, ACT: Engineers Australia, PIANC Australia and Institute of Professional Engineers New Zealand, 2017: 476-482.

Freeman, E.; Cox, R., and Splinter, K. 2018. 'Floating Breakwaters as Public Platforms – Impact on Postural Stability', *Coastal Engineering Proceedings*, *1*(36), structures.63.

Freeman, E.; Cox, R., Splinter, K., and Flocard, F. 2019. 'Floating Pontoon Motions, Operational Safe Motion Limits', Pacific International Maritime Conference.

3.1 INTRODUCTION

The performance of any floating structure is a function of size and type, water depth, mooring system and the environmental loading applied to the structure (Ansari, 1999). With increasing interest by engineers, developers and port operators in floating pontoons, the need to understand the dynamic response of such structures increases. To date very few experiments investigating pile secured floating pontoons have been published and yet design guidelines recommend referencing previous experimental or field work in order to design floating pontoons effectively (BSi, 2000). Theoretical determination of dynamic motions is complex and are based on free bodies thus often cannot account for the complex interaction between pile and pontoon. As such, for important pontoon structures physical wave flume testing to measure motion response and accelerations is recommended.

The following sections provide the reader with details of the methods used to investigate the dynamic motions of piled floating pontoons both in the laboratory and in the field in order to achieve Objectives 2 and 3 as stated in Chapter 1.

3.2 PHYSICAL MODEL EXPERIMENTAL TESTING

3.2.1 Model Scale

The most important requirement when undertaking model testing is that the model provides a true representation of the prototype environment and structure. When the prototype environment is dominated by wave action and inertia of a body, similitude between model and prototype is achieved using Froude Scaling (Rong, 1995). The Froude number expresses the relative influence of inertial and gravity forces and must remain constant between model and prototype. The Froude number (N_F) is given by the following:

$$N_F = \frac{V}{\sqrt{gL}} \qquad (3.1)$$

Where V represents velocity, g, gravity and L, length. It should be noted that N_f may be based upon water depth or the length of the waterline of the floating body. The relationship between any linear dimension (L) for a linear scale of $1{:}L$ and other dimensional units in Froude scaling are:

$$Acceleration, \alpha \quad \propto 1:1$$
$$Velocity, V \quad \propto \sqrt{L}$$
$$Time, t \quad \propto \sqrt{L}$$
$$Force, F \quad \propto L^3$$
$$Mass, M \quad \propto L^3$$

By scaling the model such that the Froude numbers are identical in the model and the prototype the gravitational forces in the model will be scaled in correct proportion to those in the prototype. As accelerations are the dominant forces of interest in this study, the dynamic behaviour of the model will be a relatively accurate representation of that of the prototype with a 1:1 scaling ratio.

A length scale of $1:10$ was used for the tests. The corresponding scales for other units are determined using Froude number similitude and are given in TABLE 3.1. **All lengths and times given in this thesis are prototype values unless otherwise specified.**

TABLE 3.1. SUMMARY OF SCALE FACTORS

Unit	Scale Factor	Value
Length	L	10
Time	$L^{0.5}$	3.1623
Acceleration	1	1
Gravity	1	1
Density	1	1
Force	L^3	1000
Mass	L^3	1000

3.2.2 MODEL CONSTRUCTION AND SETUP

Physical model testing was conducted in both the 0.6 m and 1.2 m wide wave flumes at the Water Research Laboratory, UNSW Sydney, with main flume dimensions as shown in TABLE 3.2.

TABLE 3.2. SUMMARY OF FLUME DIMENSIONS

Flume ID	Length (m)	Width (m)	Height (m)
0.6	30	0.6	0.7
1.2	44	1.2	1.6

The models tested were two piled floating pontoons of varying width/beam constructed of grey PVC sheet. The pontoon dimensions chosen for laboratory testing were of a typical size commonly installed in Sydney Harbour for private and public use. PVC sheet was used for internal ballast while iron and steel weights were used to alter the draft of the pontoons. The pontoons were constructed to have uniformly distributed internal ballast over the pontoon plan area to achieve desired buoyancy and freeboard based on the prototype design. Delrin, a highly-crystalline engineering thermoplastic specified for high load mechanical applications, was used to construct wear/impact buffers and provide a low friction sliding connection between restraining piles and the pontoon. The pontoons were restrained by two vertical piles located on the seaward side (FIGURE 3.1), allowing for relatively free vertical motion and restrained lateral movement. However, there was enough horizontal play (42 mm (prototype) clearance all round) in the pile brackets, as well as deflection in the piles that acceleration due to translation in the horizontal (x- and y-) axis was quantifiable. The scaled laboratory experiments were split into three sets of tests focussed on the design considerations of: (a) beam width, (b) draft and relative freeboard and (c) skirt attachments on the overall dynamic motions of the floating pontoon structures (TABLE 3.3). FIGURE 3.1 details the floating pontoon dimensions for the Narrow and Wide Pontoons at a draft of 455 mm (prototype). FIGURE 3.2 depicts the three skirt arrangements used on the Narrow Pontoon: (a) solid front skirt, (b) perforated front skirt (17% porosity based on Coghlan et al. (2007)) and (c) perforated front skirt/solid back skirt. Skirts were attached using a slotted bolt connection on the front face of the pontoon and extended an additional 900 mm (prototype) below the bottom of the pontoon.

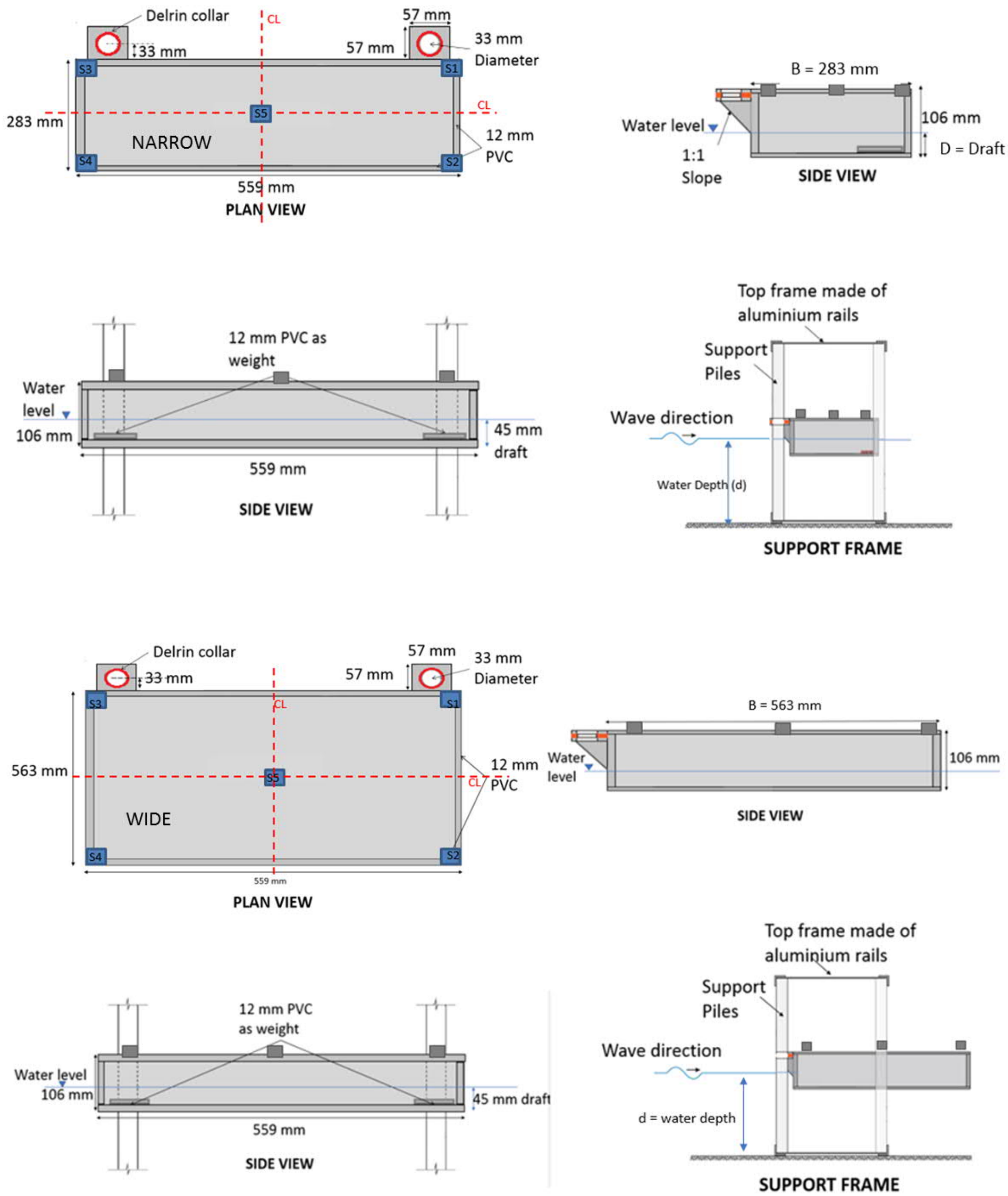


FIGURE 3.1. FLOATING PONTOON DESIGN (MODEL) FOR NARROW AND WIDE PONTOONS (DIAGRAM NOT TO SCALE).

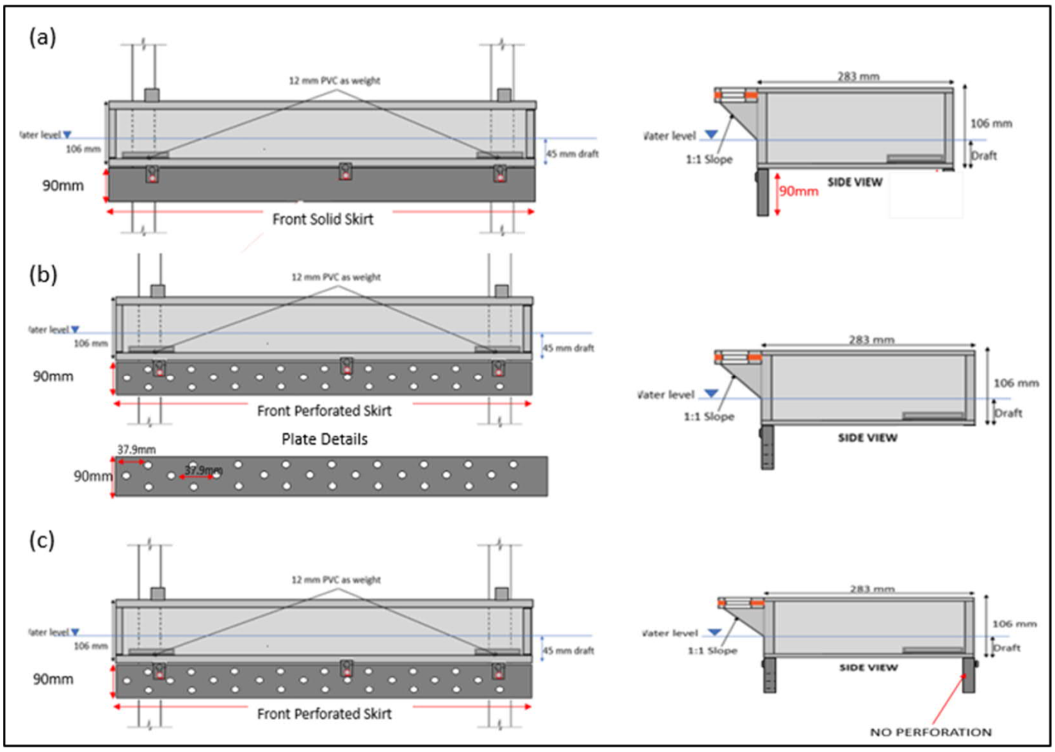


FIGURE 3.2. FLOATING PONTOON SKIRT DESIGN (MODEL) FOR NARROW (PONTOON 1) PONTOON (DIAGRAM NOT TO SCALE). (A) SOLID FRONT SKIRT, (B) PERFORATED FRONT SKIRT AND (C) PERFORATED FRONT SKIRT AND SOLID BACK SKIRT.

The floating pontoons tested in the flume had six degrees of freedom: surge (in the direction of wave propagation, x_b), sway (perpendicular to the direction of wave propagation, y_b) and heave (vertical, z_b), as well as the three rotations around the centre of gravity (roll (ϕ), pitch (θ) and yaw (ψ)) (FIGURE 3.3).

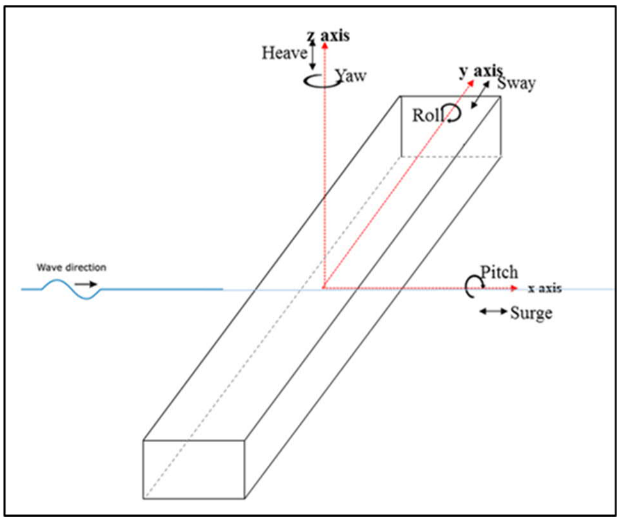


FIGURE 3.3. FLOATING PONTOON COORDINATE SYSTEM.

On each pontoon, five *Life Performance Research* Inertial Measurement Units (IMU) in the form of accelerometers were used to measure triple-axis accelerations and triple-axis gyrations of each floating pontoon. The IMUs were positioned on each corner (Sensors 1-4, FIGURE 3.1) of the pontoon, as well as in the centre of the top face (Sensor 5, FIGURE 3.1). A cartesian coordinate system was employed for the model testing with the origin located at still water level and centrally on the floating pontoon. The x-axis was positive in direction of wave propagation and the z-axis positive upward. Three capacitance wave probes were used to capture the time-varying incident free surface directly in front of the pontoon structure, and one was positioned leeward of the structure to measure the transmitted wave height. The flume setup is shown in FIGURE 3.4 for the Narrow Pontoon.

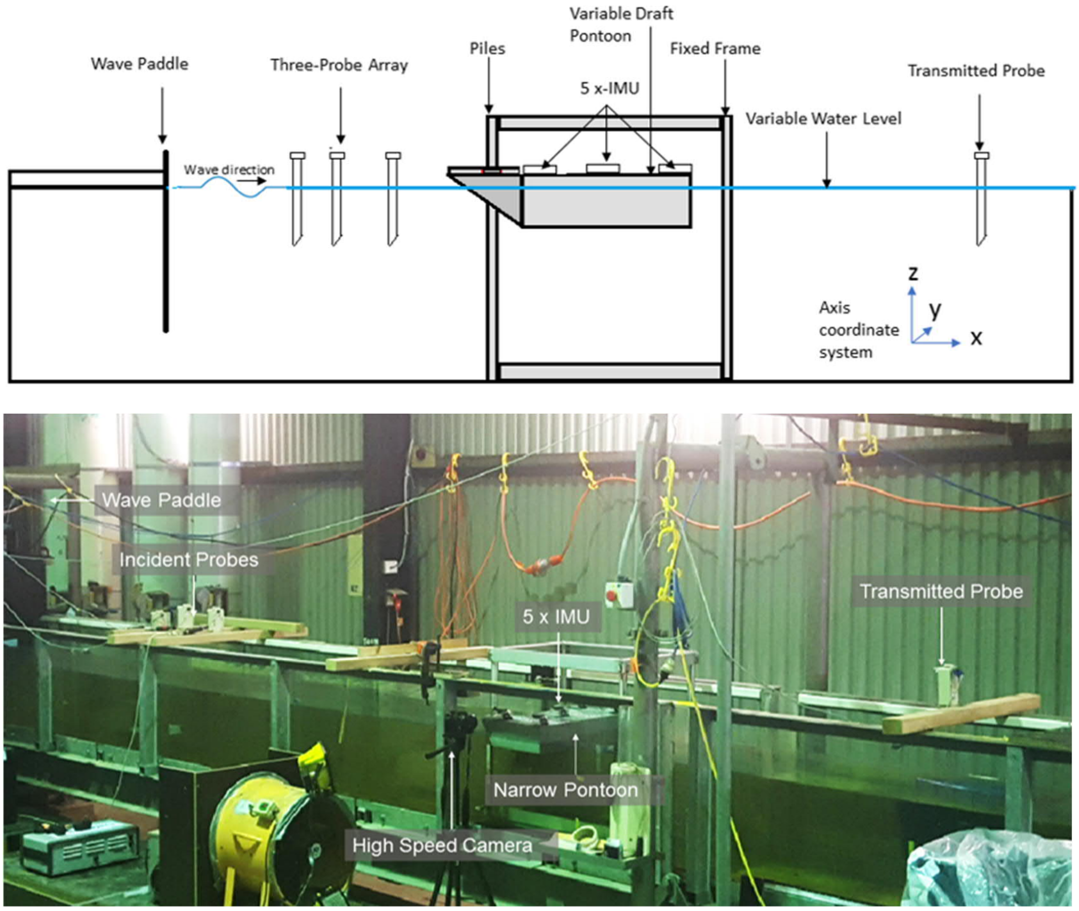


FIGURE 3.4. FLUME SETUP FOR LABORATORY TESTING OF FLOATING PONTOONS. WRL 0.6M FLUME (TOP FIGURE NOT TO SCALE).

3.2.3 INSTRUMENTATION AND CALIBRATION

Wave Paddle and Wave Generating Software

Wave paddle control software developed at UNSW WRL allowed for generation of monochromatic waves representative of boat wake. Waves were generated by a vertical piston wave paddle situated at one end of the flume.

Wave Probes

Capacitance wave probes with a range of +/- 10 volts were used to capture the free surface along the flume. The probes were manufactured by Manly Hydraulics Laboratory in Sydney and were fitted with a 200 mm long, 0.2 mm diameter dielectric coated wire suspended within a metal frame. The wave probes work through electrical resistance, such that the changing resistance in the wire can be converted to water level differences. This signal is captured digitally using a National Instruments PCI-6225 data acquisition card at 1 kHz sample rate per channel. Probe resolution is 0.1 mm with the linearity of ±0.2 mm over the 200 mm length.

In order to calibrate the wave probes, the probes were placed in water at a height where the voltage was approximately zero. The probes were then lowered or raised a known distance and the corresponding voltage recorded. This process was repeated until five points were analysed for each of the probes being used. To verify the wave probe linearity, the coefficient of determination (R^2) value for each wave probe was checked and the probes with R^2 less than 0.999 were recalibrated.

Accelerometers

As detailed in Section 3.2.2 five, nine axis Inertial Measurement Units (IMUs) were positioned centrally and on the corners of the pontoons tested (FIGURE 3.5). Bluetooth connection between the IMU's and the log computer was used in order to allow for immediate data recording of accelerations and rotations of the floating pontoons as the motions took place. The accelerations recorded were in units of g (gravity, m/s^2). The units were able to measure orientation in 360 degrees about all three global axes. Data was recorded at a rate of 50Hz. Sampling at a rate above this caused Bluetooth connection errors. Sync mode was used for each run of testing to ensure all IMUs were synced and recording at the same time, each IMU would flash a blue light in time with the other IMUs when all units were synced. Gyroscope calibration was undertaken for each round of testing using manual calibration whereby the sensors were placed in a motionless state and firmware command used to trigger gyroscope calibration. The accelerometers were contained in GoPro housing for waterproofing with double sided tape inside to secure them in place. Each GoPro was secured to the pontoons using adhesive Velcro located on the corners and centrally of the pontoons.

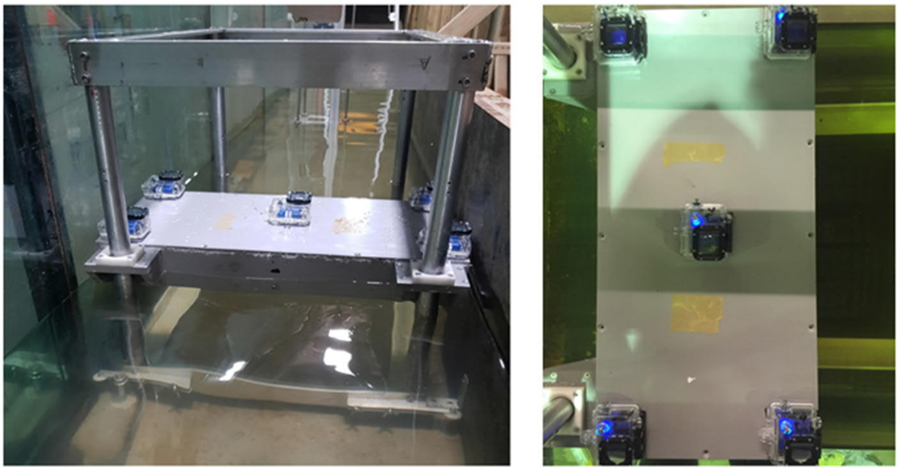


FIGURE 3.5. ACCELEROMETER POSITIONING

High Speed Camera

A Casio EX-F1 high speed camera was used to acquire video recording (30fps) of the motions of the pontoons (FIGURE 3.6). The high-speed video was used to record the displacements of the pontoons in order to obtain results of the Response Amplitude Operator (RAO) which is a measure of the amplitude of displacement divided by the wave amplitude, a common parameter used to describe ship motions. The displacements measured from the camera data were also used to cross-check the recorded accelerations from the IMUs.

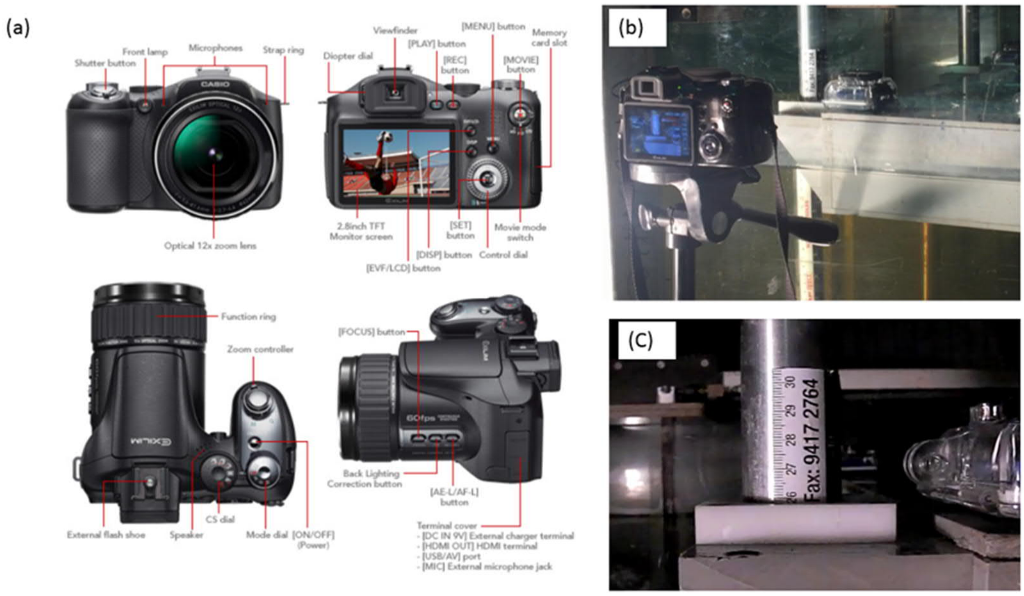


FIGURE 3.6. CASIO EX-F1 HIGH SPEED CAMERA AND MEASURE OF DISPLACEMENTS. (A) CAMERA PART IDENTIFICATION, (B) CAMERA RECORDING LOCATION AND (C) DISPLACEMENT MEASURE.

3.2.4 WAVE ENVIRONMENT

This thesis is focused on assessing the effect of boat wake on the dynamic motions of piled floating box pontoons. The wave heights and periods adopted during testing were based on those typically found in Sydney Harbour (Patterson Britton and Partners, 1987 and Miller, 2005), where there are more than 137 public access points (wharves, jetties and pontoons) for boat users (Transport NSW, 2014). Prototype wave periods ranged from 2 – 7 seconds with corresponding boat wake heights of approximately 300mm. It is noted that design storm wind wave heights within Sydney harbour at the majority of the 137 public access points are significantly greater than these tested boat wake wave conditions.

3.2.5 TEST CONDITIONS

Triplicate runs, of 189 seconds, were conducted for each of the wave periods being tested to ensure similarity between tests. The testing parameters shown in TABLE 3.3 are the average from triplicate runs with each of the three runs an average of three probes. All tests were completed in a water depth (d) of 3.6 m (prototype) and both pontoons had equivalent draft (D). A total of 60 individual tests (180 runs) were completed. Testing was split into three criteria based on (a) assessing the effect of beam width, (b) assessing the effect of draft and (c) assessing the influence of skirts TABLE 3.3.

TABLE 3.3. MONOCHROMATIC WAVE TESTING PARAMETERS (PROTOTYPE SCALE). PARAMETERS PRESENTED ARE THE AVERAGE OF THE THREE TESTS FOR EACH TESTING ID. (A) IMPACT OF BEAM, (B) IMPACT OF DRAFT AND (C) IMPACT OF SKIRTS.

Test ID	**Wave Period T (s)**	**Wave Height H (mm)**	**Beam B(m)**	**Wavelength L (m)**	**B/L (m)**	**Draft D(m)**	**Depth d(m)**
		(a) Beam Effect – Testing Parameters (0.6m Flume)					
B1-N	2	300	2.8	6.23	0.45	0.45	3.6
B2-N	3	310	2.8	13.17	0.22	0.45	3.6
B3-N	5	290	2.8	26.85	0.11	0.45	3.6
B4-N	7	320	2.8	39.59	0.07	0.45	3.6
B1-W	2	300	5.6	6.23	0.9	0.45	3.6
B2-W	3	310	5.6	13.17	0.43	0.45	3.6
B3-W	5	290	5.6	26.85	0.21	0.45	3.6
B4-W	7	320	5.6	39.59	0.14	0.45	3.6
		(b) Draft Effect – Testing Parameters (1.2m Flume)					
D1-N455	2	330	2.8	6.23	0.45	0.45	3.6
D2-N455	3	370	2.8	13.17	0.22	0.45	3.6
D3-N455	5	330	2.8	26.85	0.11	0.45	3.6
D4-N455	7	330	2.8	39.59	0.07	0.45	3.6
D1-W455	2	330	5.6	6.23	0.9	0.45	3.6
D2-W455	3	370	5.6	13.17	0.43	0.45	3.6
D3-W455	5	330	5.6	26.85	0.21	0.45	3.6
D4-W455	7	330	5.6	39.59	0.14	0.45	3.6
D1-N560	2	330	2.8	6.23	0.45	0.56	3.6
D2- N560	3	370	2.8	13.17	0.22	0.56	3.6
D3- N560	5	330	2.8	26.85	0.11	0.56	3.6
D4- N560	7	330	2.8	39.59	0.07	0.56	3.6
D1-W560	2	330	5.6	6.23	0.9	0.56	3.6
D2- W560	3	370	5.6	13.17	0.43	0.56	3.6
D3- W560	5	330	5.6	26.85	0.21	0.56	3.6
D4- W560	7	330	5.6	39.59	0.14	0.56	3.6
D1-N585	2	330	2.8	6.23	0.45	0.585	3.6
D2-N585	3	370	2.8	13.17	0.22	0.585	3.6
D3-N585	5	330	2.8	26.85	0.11	0.585	3.6
D4-N585	7	330	2.8	39.59	0.07	0.585	3.6
D1-W585	2	330	5.6	6.23	0.9	0.585	3.6
D2-W585	3	370	5.6	13.17	0.43	0.585	3.6
D3-W585	5	330	5.6	26.85	0.21	0.585	3.6
D4-W585	7	330	5.6	39.59	0.14	0.585	3.6
D1-N635	2	330	2.8	6.23	0.45	0.635	3.6
D2-N635	3	370	2.8	13.17	0.22	0.635	3.6
D3-N635	5	330	2.8	26.85	0.11	0.635	3.6
D4-N635	7	330	2.8	39.59	0.07	0.635	3.6
D1-W635	2	330	5.6	6.23	0.9	0.635	3.6
D2-W635	3	370	5.6	13.17	0.43	0.635	3.6
D3-W635	5	330	5.6	26.85	0.21	0.635	3.6
D4-W635	7	330	5.6	39.59	0.14	0.635	3.6
D1-N680	2	330	2.8	6.23	0.45	0.68	3.6

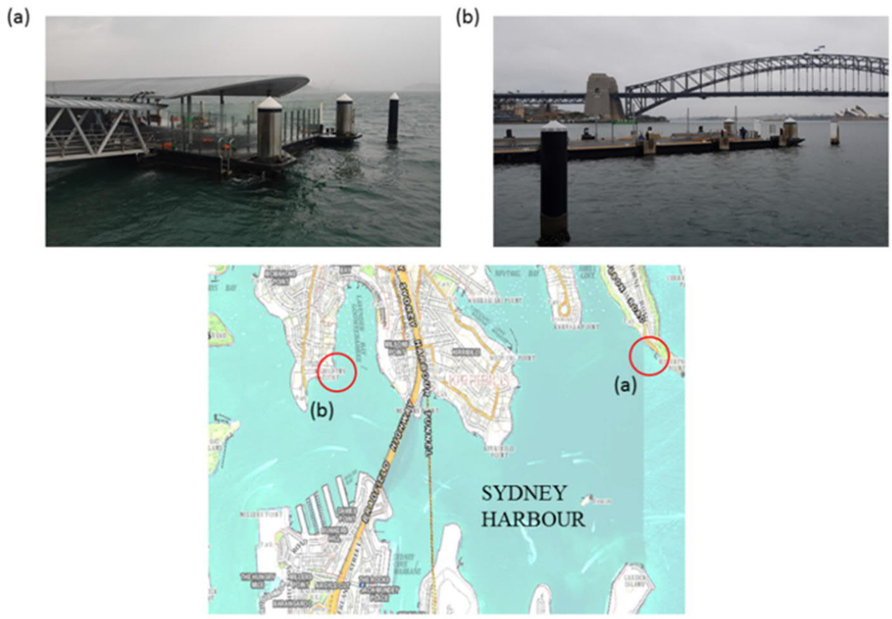
D2-N680	3	370	2.8	13.17	0.22	0.68	3.6
D3-N680	5	330	2.8	26.85	0.11	0.68	3.6
D4-N680	7	330	2.8	39.59	0.07	0.68	3.6
D1-W680	2	330	5.6	6.23	0.9	0.68	3.6
D2-W680	3	370	5.6	13.17	0.43	0.68	3.6
D3-W680	5	330	5.6	26.85	0.21	0.68	3.6
D4-W680	7	330	5.6	39.59	0.14	0.68	3.6
(c) Skirt Effect – Testing Parameters (1.2m Flume)							
S1-SolidN	2	330	2.8	6.23	0.45	1.35	3.6
S2-SolidN	3	370	2.8	13.17	0.22	1.35	3.6
S3-SolidN	5	330	2.8	26.85	0.11	1.35	3.6
S4-SolidN	7	330	2.8	39.59	0.07	1.35	3.6
S1-PerfN	2	330	2.8	6.23	0.45	1.35	3.6
S2-PerfN	3	370	2.8	13.17	0.22	1.35	3.6
S3-PerfN	5	330	2.8	26.85	0.11	1.35	3.6
S4-PerfN	7	330	2.8	39.59	0.07	1.35	3.6
S1-Perf/SolidN	2	330	2.8	6.23	0.45	1.35	3.6
S2-Perf/SolidN	3	370	2.8	13.17	0.22	1.35	3.6
S3-Perf/SolidN	5	330	2.8	26.85	0.11	1.35	3.6
S4-Perf/SolidN	7	330	2.8	39.59	0.07	1.35	3.6

3.3 FIELD TESTING

As part of Objective 3 of this thesis, field testing has been undertaken to acquire motion response data of public pontoons and the corresponding incident wave information in order to relate these responses back to the SML described in Chapter 2 and compare to the scaled laboratory measurements described in Chapter 3.2. During the field experiments, the public (pontoon users) were invited to take part in a survey (UNSW ETHICS HC20003) ascertaining their level of comfort/discomfort resulting from the pontoon movements (TABLE 6.1 and TABLE 6.2). Twenty-six users were surveyed in order to ascertain an understanding of their perception of the motions and to compare their level of comfort against the safe motion limits nominated (TABLE 2.1) with results presented in Section 6.2.4. This was done to determine if the pontoon motion was considered safe/comfortable by similar standards/codes. Field studies were limited due to the COVID-19 pandemic which began at the start of the field campaign.

3.3.1 STUDY AREA

Data was collected from four piled floating pontoons. Two located in Sydney Harbour and two in the Shoalhaven, NSW, Australia (FIGURE 3.7). Three of the four sites are public access structures that can be used by any member of the public, while the fourth is a Navy pontoon used by members of the Defence Force. All four sites are exposed to boat wake resulting from passing and berthing vessels as well as local wind-generated waves. Cremorne and McMahons Point (FIGURE 3.7a,b) are ferry commuter wharves, constructed in 2015 as part of the NSW Government Transport Access Program – an initiative to deliver modern, safe and accessible transport. HMAS Creswell (FIGURE 3.7c) is a series of piled floating pontoons used by the defence force for boarding and alighting navy vessels and Orient Point (FIGURE 3.7d) is a recreational boating pontoon and popular location for local fishermen.



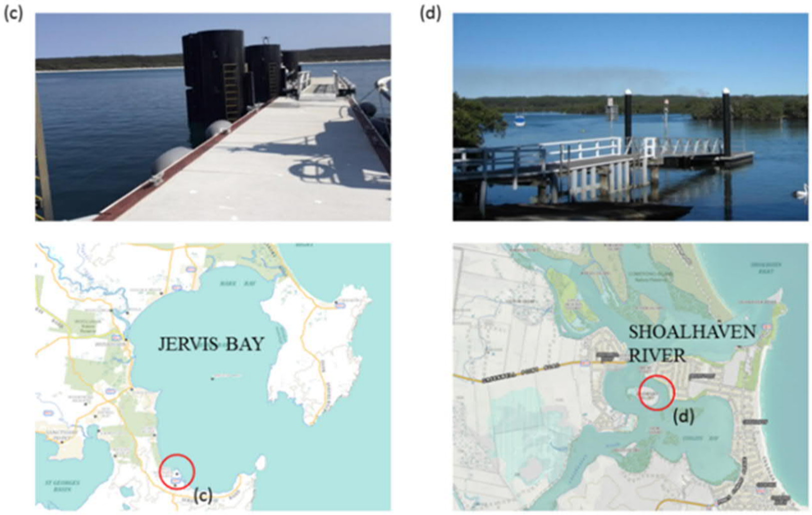


Figure 3.7. The Four Field Testing Sites. (a) Cremorne Point, Sydney Harbour (Top Left), (b) McMahons Point, Sydney Harbour (Top Right), (c) HMAS Creswell, Jervis Bay (Bottom Right) and (d) Orient Point, Shoalhaven.

Each of the pontoons tested were piled rectangular box floating pontoons. They had six degrees of freedom: surge (in the direction of wave propagation, x_b), sway (perpendicular to the direction of wave propagation, y_b) and heave (vertical, z_b), as well as the three rotations around the centre of gravity (roll (ϕ), pitch (θ) and yaw (ψ)) similar to those pontoons tested in the laboratory. The dimensions of each pontoon and number of piles is presented in Table 3.4. The pontoons located in Sydney Harbour (Figure 3.7a,b) had piles located on each corner (4 off) and those in the Shoalhaven (Figure 3.1b,c) had piles on one seaward side only (2 off). Of the 4 field test sites, Orient Point was the most similar to the laboratory design conditions.

Table 3.4. Summary of Field Pontoon Dimensions

Location	Width (m)	Length (m)	Draft (m)	Displacement (t)	Piles
Cremorne Point	10	27	1.0	276	4
McMahons Point	10	27	0.9	249	4
HMAS Creswell	3	16	0.6	30	2
Orient Point	4	8	0.55	18	2

3.3.2 INSTRUMENTATION AND CALIBRATION

Ultrasonic Wave Sensor XB

Ultrasonic wave sensors were used to capture the water surface adjacent to the floating pontoons tested in order to estimate wave heights (Figure 3.8). The basic operating principle of the sensors is to measure the ultrasound travel time from the instrument to the water surface. The result is then scaled with a Micro Processer in the unit, and then transmitted over the Xbee's wireless network to an Xbee USB adapter. A Windows USB to Serial Converter (driver) connects the USB Adapter port to the User Interface Software (GUI). The sensors recorded data at a sample rate of 32Hz.

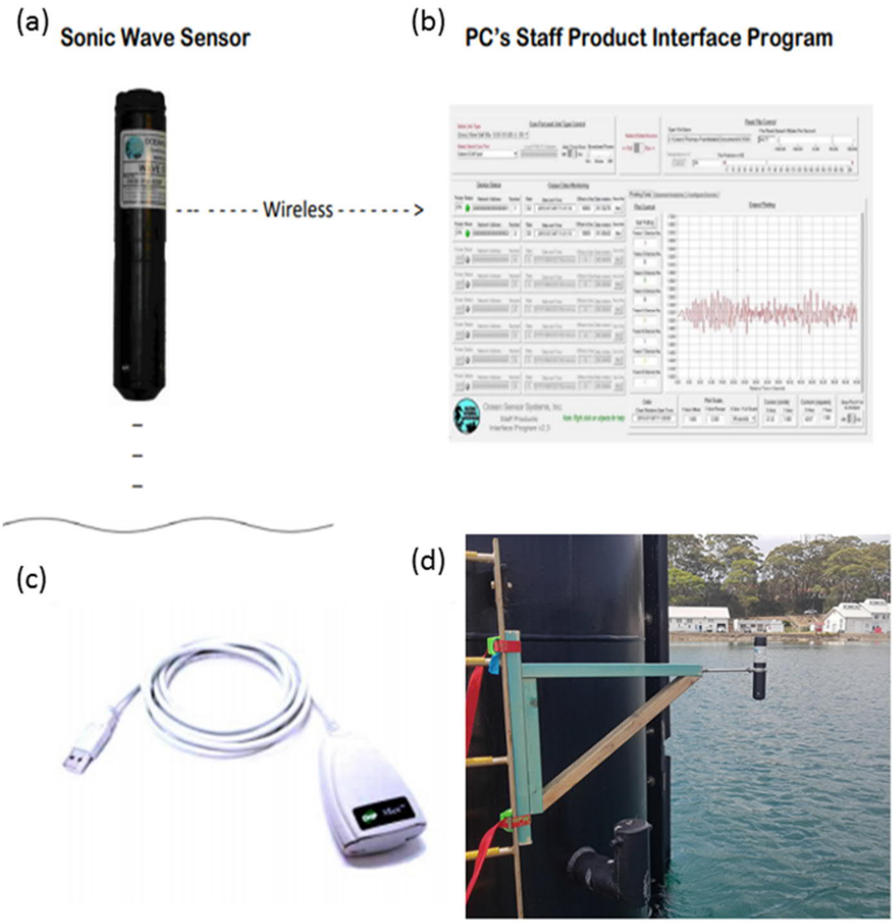


FIGURE 3.8. ULTRASONIC SENSOR COMPONENTS. (A) SONIC WAVE SENSOR (TOP LEFT), (B) PC INTERFACE PROGRAM (TOP RIGHT), (C) USB ADAPTER (BOTTOM RIGHT) AND (D) MOUNTING ARRANGEMENT (BOTTOM LEFT).

The sensors were calibrated in the 1.2m flume at the UNSW Water Research Laboratory (WRL), Manly Vale, following manufacturer specifications. Five calibration points were selected on the ground, recorded using the ultrasonic sensors and then compared against physical measurements recorded using a measuring tape. A linear regression analysis of the recorded points was completed for each sensor. The R^2 values were 0.9985 and 0.9994 for each of the two devices calibrated. An additional check was done in order to ensure that the ultrasonic wave sensors were accurately measuring waves. Each sensor was positioned in the flume approximately 60 cm from the water surface. A calibrated capacitance wave probe was positioned in the flume (FIGURE 3.9). A scaled (1:10) 7 second period wave was generated in the flume and results from the capacitance wave probe and ultrasonic sensor compared by plotting time against water level for both probes during the testing. A cross correlation between the two signals was done in order to measure similarity of the two signals with a cross correlation coefficient of 0.97. Test were completed three times to check for consistency.

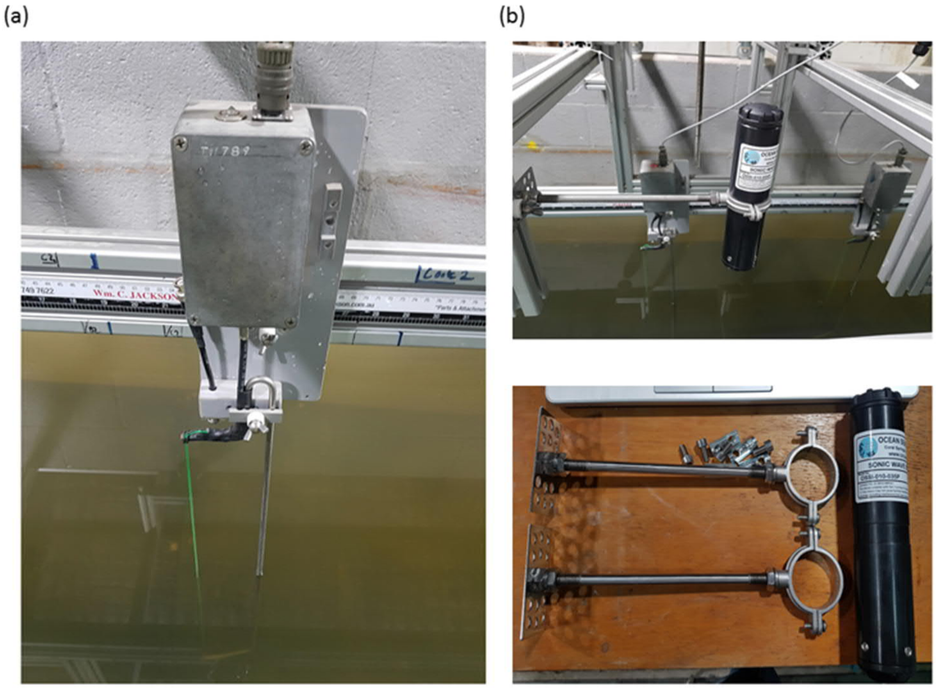


FIGURE 3.9. CALIBRATION OF ULTRASONIC SENSORS. (A) CAPACITANCE WAVE PROBE AND (B) ULTRASONIC SENSOR AND MOUNTING EQUIPMENT.

Accelerometers

On each pontoon tested in the field, two *Life Performance Research Inertial Measurement Units* (IMU) in the form of accelerometers were used to measure triple-axis accelerations and triple-axis gyrations of each floating pontoon tested. Units (IMUs) were positioned on one corner adjacent to the ultrasonic sensor and centrally on the pontoon (FIGURE 3.10). The accelerometers were contained in GoPro housing for waterproofing with double sided tape inside to secure them in place.

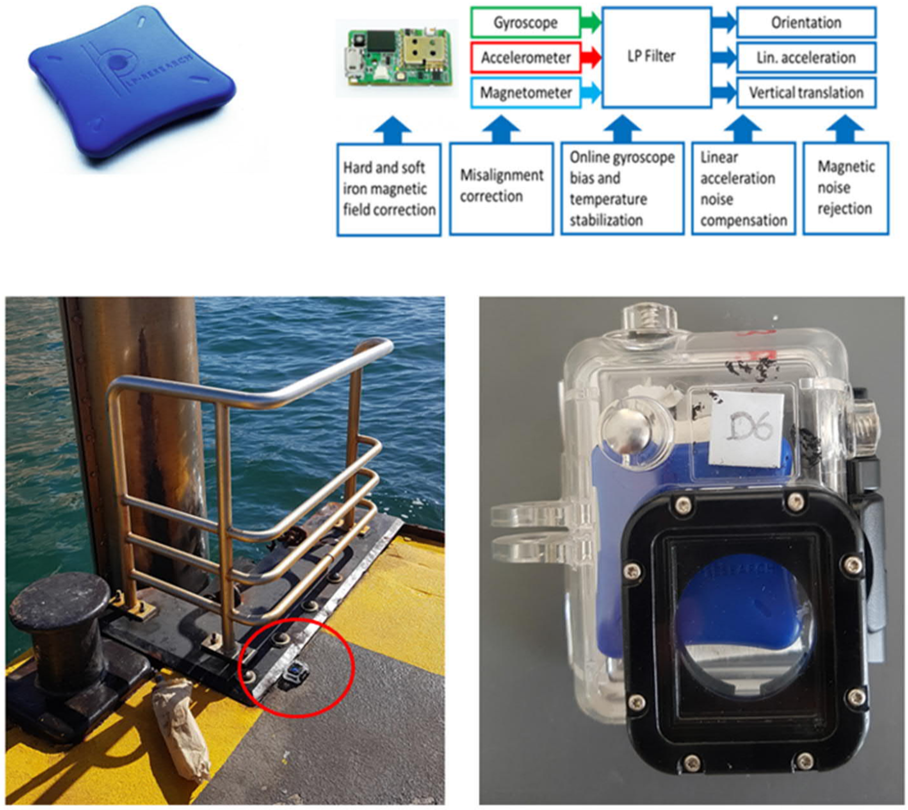


FIGURE 3.10. ACCELEROMETERS: HARDWARE, POSITIONING AND HOUSING

3.3.3 WAVE ENVIRONMENT

As this thesis is focused on assessing the effect of boat wake on the dynamic motions of piled floating box pontoons, the days of field testing were selected based on ensuring boat wake was the main contributing factor and wind waves were negligible. Using the ultrasonic sensors, wave heights and periods were obtained for each day of testing at each of the selected sites and are presented in Chapter 6. Details of post processing of field wave data is described in Section 3.4.

3.3.4 USER SURVEY

Whilst recording the motions of each pontoon during field testing, people using the pontoons were provided with a research flyer to invite them to complete a short 2-minute survey (FIGURE 3.11). The surveys were aimed at gathering information on how comfortable/uncomfortable people of different age, gender and level of fitness were while standing on the pontoons. Surveys were dated, timestamped and correlated to the dated and timestamped motion response data with comparisons made against the nominated SML detailed in Chapter 2. Results are presented in Chapter 6, section 6.2.4.

UNSW SYDNEY Water Research Laboratory

Ethics Approval #HC200031

HOW THE MOVEMENTS OF FLOATING PLATFORMS EFFECT OUR COMFORT AND STABILITY

RECRUITMENT • FLYER

Our Research

Floating Pontoon Motions Impact on Stability

Today we are conducting field experiments to understand how the motions of the floating pontoon you are standing on impact your perceptions of stability and safety.

This research is part of my PhD where I am looking at how pontoons move due to wave impact. We are currently measuring the waves and the motions of the pontoon you are standing on. These movements will be compared to a set of criteria in order to understand how they effect a person's comfort and safety if they are standing on the pontoon.

We are recruiting people to complete a very short anonymous survey to let us know how you feel while standing on this pontoon to help better understand human perceptions on floating pontoons.

Your Involvement

If you would like to tell us whether the motions of this pontoon make you feel comfortable/uncomfortable, please come and see us to complete a 2-minute anonymous survey.

Libby Freeman
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Supervisor
Dr Kristen Splinter
k.splinter@unsw.edu.au
(02) 8071 9845

UNSW AUSTRALIA | Water Research Laboratory
School of Civil and Environmental Engineering | USER SURVEY

Dynamic Motion of Floating Structure and Impact on Postural Stability

Pontoon location: **Date & Time:**

Instructions

Check the box most applicable to you. These questions are being gathered to understand whether the motions of this floating structure are above what is perceived as comfortable/safe. This survey is anonymous and part of PhD research being conducted by UNSW. Ethics approval number:

1. Age

(Select only one.)

- ☐ Under 18
- ☐ 18-35
- ☐ 36-50
- ☐ 51-65
- ☐ Over 65

2. Gender

(Select only one.)

- ☐ Female
- ☐ Male
- ☐ Prefer not to say

3. How would you describe your level of fitness?

- ☐ Very Fit
- ☐ Fit
- ☐ Average
- ☐ Unfit

4. How regularly do you visit floating pontoons such as this?

- ☐ Daily
- ☐ Weekly
- ☐ Monthly
- ☐ Yearly
- ☐ This is my first time

5. Please provide details of your experience on boats?

- ☐ Daily
- ☐ Weekly
- ☐ Monthly
- ☐ Yearly
- ☐ I have never been on a boat

6. While standing on this platform how have you felt due to any of the movements?

- ☐ Very Uncomfortable/Unsafe
- ☐ Uncomfortable/Unsafe
- ☐ Neither
- ☐ Comfortable/Safe
- ☐ Very Comfortable/ Very Safe

7. Can you swim?

- ☐ Yes
- ☐ No

8. Have you noticed any floatation aids to use if someone were to fall in the water?

- ☐ Yes
- ☐ No
- ☐ There aren't any

9. What type of shoes are you wearing?

- ☐ Flat
- ☐ Heeled

10. Do you think the design of this pontoon needs to be improved to make it more comfortable/safe?

- ☐ Yes
- ☐ No

Please provide any further comments:…………………………..

FIGURE 3.11. RESEARCH FLYER AND SURVEY TO ASSES USER COMFORT LEVELS

3.4 POST-PROCESSING OF RAW DATA

The following sections describe the methods for processing data collected during both the experimental and field testing.

3.4.1 WAVE DATA

Laboratory Wave Data Processing

Due to the limited length of time a test could be run before waves reflected from the floating pontoons and returned to the paddle, standard signal processing tools for wave analysis did not provide robust results. Therefore, to determine the incident and reflected wave heights from the recorded timeseries a multi-step process of signal optimization was developed. Firstly, a Savitzky-Golay filter, polynomial order of 3, was applied to eliminate any high frequency noise in the signal. The incident wave timeseries was determined from the first portion of the recorded timeseries prior to wave reflections off the pontoon structure for each probe (FIGURE 3.12). This comprised approximately 4 - 14 waves depending on the wave period being analysed. Wave height and period were first estimated using the zero-crossing method. An exhaustive search was done around the estimated wave period in order to generate the optimum incident wave signal based on cross-correlation analysis of the measured and generated free surface. This was done to determine the best-fit wave period. The reflected wave free surface (η_r) was then determined using the relationship $\eta=\eta_i+\eta_r$ from the latter end of the raw wave probe time series comprising approximately 5 – 19 waves depending on wave period. This was completed for each probe and each of the three trials for all tests listed in TABLE 3.3. A representative time slice of the incident waves for each of the 4 wave periods tested is provided in FIGURE 3.13

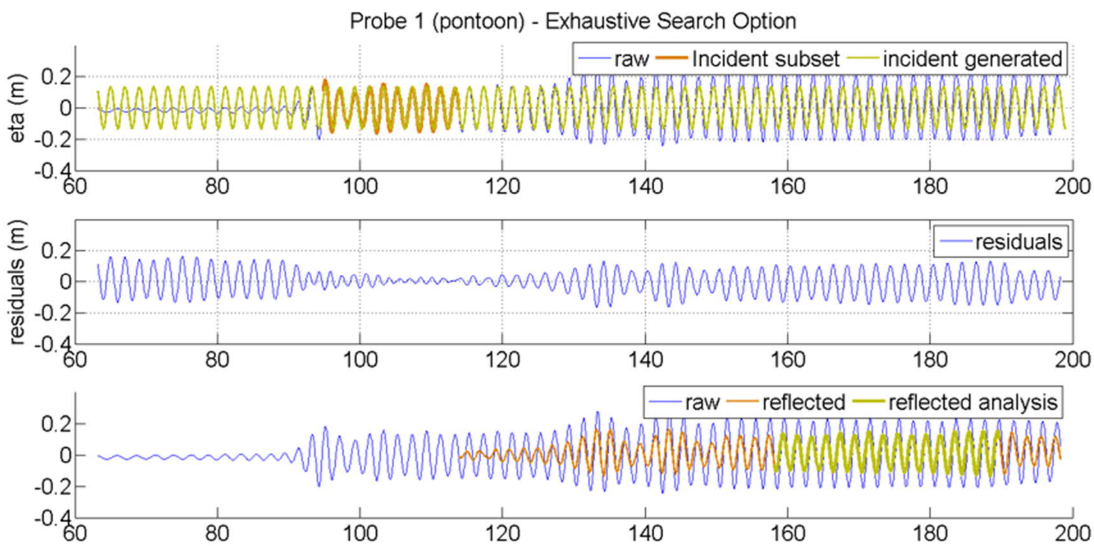


FIGURE 3.12. EXAMPLE WATER LEVEL TIME SERIES FOR 2 SECOND PERIOD WAVE TO DETERMINE INCIDENT, TRANSMITTED AND REFLECTED WAVE HEIGHTS (PROBE 1).

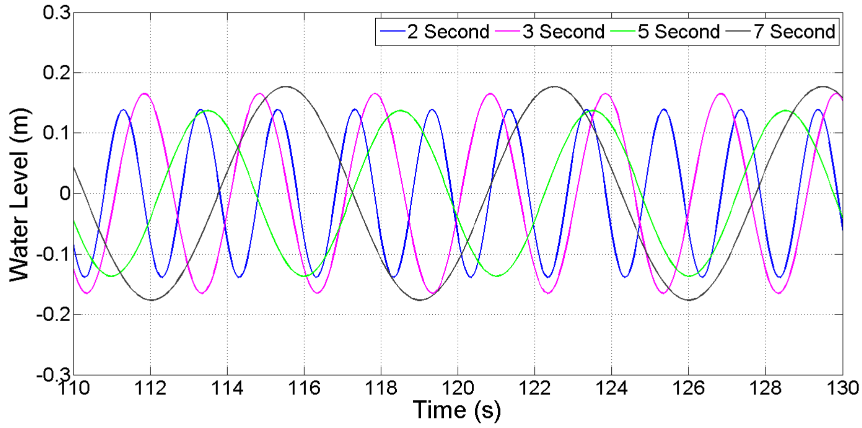


FIGURE 3.13. EXAMPLE INCIDENT BAND WATER LEVEL TIMESERIES FOR EACH OF THE 4 WAVE PERIODS TESTED.

Field Wave Data Processing

Wave data obtained during the field testing is presented as a mean wave height and mean wave period. FIGURE 3.14 displays 100 seconds of water level data obtained from one of the four sites, McMahons Point. Using the raw time signal of water level obtained from each site wave height and period were determined using the zero-crossing method. The mean wave height and period has been used in order to provide a comparison with the mean wave heights and periods from laboratory testing presented in Chapters 4 and 5. At HMAS Creswell and Orient Point, targeted boat wake tests were conducted by passing a small personal water craft repeatedly passed the floating pontoon. Therefore, the wave heights and periods determined for HMAS Creswell and Orient Point are based on the overall average mean wave height and period of each boat pass determined using the zero-up-crossing method for the section of time series corresponding to each boat pass. Similarly, the recorded accelerations and angles determined from the IMUS are based on the time intervals associated with the passing boats at these 2 locations.

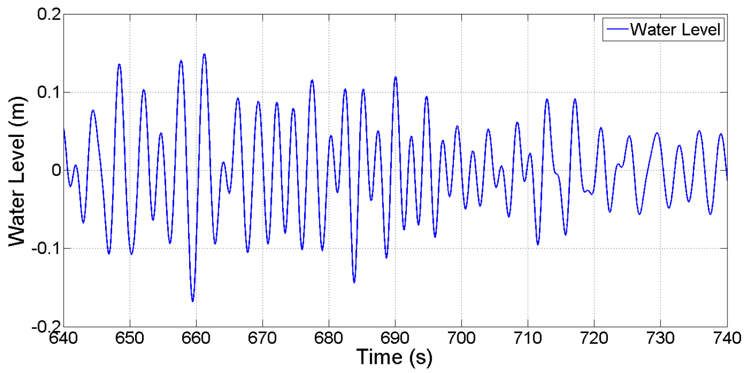


FIGURE 3.14. 100 SECONDS OF WATER LEVEL TIME SERIES OBTAINED AT MCMAHONS POINT.

3.4.2 ACCELERATIONS AND ANGLES

Analyses of the IMU output was undertaken in MATLAB to ascertain results relative to all three axis of motion (-x, -y and -z). Each of the triplicate runs was analysed and then the average for each test was determined. Acceleration and angle results are presented relative to peak, root mean square (RMS) as well as 1% and 5% exceedance relative to the nominated safe motions limits. Root mean square (RMS) acceleration/angles is the square root of the mean squared acceleration/angles in any one axis over time period *t* (Pauschke 1987). RMS acceleration and angles represents overall variability in motion compared to the short duration peak accelerations and angles. The RMS values have been calculated by squaring acceleration/angles at each timestep for all five sensors, summing the squares and dividing by the number of samples to find the mean square acceleration/angles and then taking the square root.

3.4.3 FREQUENCY

As detailed in Section 2.5.4 the frequency at which the acceleration is occurring is critical to ascertain the possible effect on a standing person's stability and comfort. MATLAB was used to analyse the IMU data for all three axis (-x, -y, and -z). A low pass filter ranging from 0.1 - 8Hz (prototype) was applied to acceleration and angle (-x, -y, and -z) data in order to ascertain results relative to the peak accelerations and angles occurring at each cut-off frequency in order to understand exceedance relative to the nominated SML. Similarly, for Root Mean Square (RMS) acceleration and angles a low pass filter of 0.1 to 0.5Hz (prototype) was applied to the time series data and the filtered series analysed to determine RMS accelerations and angles at each of the cut-off frequencies.

3.4.4 NATURAL PERIOD OF MOTION

The response of the floating body to waves is highly dependent on wave period and wavelength, with the maximum response likely to occur when the wave period coincides with the natural frequency of motion of the structure or when the wavelength coincides with the structures wavelength (BSi, 2000). The natural period of motion of the pontoons both as freely floating objects and supported by piles has been determined. As a freely floating object the equations presented in Section 2.2.2 were used to calculate the natural period of heave and roll. Experimentally with the pontoon supported by piles decay tests were performed in order to ascertain natural periods in both heave and roll. Decay tests were carried out in still water and motions recorded using the 5 IMU positioned centrally and on the corners of the pontoons (FIGURE 3.1). The decay tests were undertaken in heave by pushing the pontoons down so there was no freeboard and releasing. This was done three times for all drafts tested and results analysed to determine the natural period of the pontoon. The same was done for roll by inclining the pontoons approximately 20° and releasing while the IMU recorded the motions. The time between adjacent crests/troughs was determined for the natural roll period. The average was taken of the three tests in both heave and roll to determine the natural periods.

3.5 PRESENTATION OF RESULTS

The results are presented in three parts. The first two parts (Chapters 4 and 5) answer Objective 2 of this thesis and focus on the controlled laboratory experiments while the last part (Chapter 6) answers Objective 3 and presents field scale results. In Chapter 4, assessing the effect of beam width (TABLE 3.3) on the recorded accelerations is presented relative to B/L with comparisons made against the nominated safe motion limits (TABLE 2.1). In Chapter 5 the impact of draft (TABLE 3.3) on the recorded accelerations is discussed relative to wave period. All results are compared against the nominated SML (TABLE 2.1).

Chapter 6 presents results obtained during field testing comprising wave data, motion data and synthesis of survey results to highlight user comfort. The motion data is presented relative to the nominated SML (Table 2.1).

CHAPTER 4: THE EFFECT OF BEAM WIDTH ON THE DYNAMIC MOTIONS OF A PILED FLOATING PONTOON UNDER BOAT WAKE WAVES

This chapter presents the results from a series of controlled laboratory experiments to examine the effect beam width has on the motion response of a piled floating pontoon under the influence of boat wake. Results are presented looking at the hydrodynamic behaviour as well as for peak, cumulative and root mean square accelerations and angles with emphasis given on comparing against the safe motions limits nominated in Section 2.5.

Some content of this chapter is taken from the following publications:

Journal Publications

Freeman, E., Splinter, K. and Cox, R. In review. 'Laboratory Experiments on the Dynamic Motions of Piled Floating Pontoons to Boat Wake and Their Impact on Postural Stability and Safety', *Journal of Ocean Engineering*

Conference Proceedings

Freeman, E.; Cox, R., and Splinter, K. 2017. 'Suitable Criteria for Safe Motion Limits of a Floating Pontoon Relative to the Postural Stability of a Stationary Standing Person', *Australasian Coasts & Ports 2017: Working with Nature*. Barton, ACT: Engineers Australia, PIANC Australia and Institute of Professional Engineers New Zealand, 2017: 476-482.

Freeman, E.; Cox, R., and Splinter, K. 2018. 'Floating Breakwaters as Public Platforms – Impact on Postural Stability', *Coastal Engineering Proceedings*, *1*(36), structures.63.

Freeman, E.; Cox, R., Splinter, K., and Flocard, F. 2019. 'Floating Pontoon Motions, Operational Safe Motion Limits', Pacific International Maritime Conference.

4.1 INTRODUCTION

Beam (B) to wavelength (L) is an important aspect that is considered when designing marine structures such as floating pontoons. For small beam to wavelength ratios, the structure will ride on the incident wave, resulting in accelerations related to the incoming wave, very little reflection, and nearly 100% transmission. Gaythwaite (2016) identified that at a beam to wavelength ratio of 0.2 or less, a floating breakwater essentially follows the wave contour with little or no wave attenuation. For the testing undertaken results are presented for both the Narrow and Wide Pontoons relative to wave period and the beam to wavelength ratios presented in TABLE 3.3 and TABLE 4.1. Individual results for each triplicate run are presented along with the calculated mean of the three tests.

TABLE 4.1. MONOCHROMATIC WAVE TESTING KEY PARAMETERS (PROTOTYPE SCALE)

TestID	Wavelength L (m)	Wave Steepness H/L	Water depth to Wavelength d/L	Beam to Wavelength B/L
B1-N	6.23	0.048	0.58	0.45
B2-N	13.17	0.024	0.27	0.22
B3-N	26.85	0.011	0.13	0.11
B4-N	39.59	0.008	0.09	0.07
B1-W	6.23	0.048	0.58	0.90
B2-W	13.17	0.024	0.27	0.43
B3-W	26.85	0.011	0.13	0.21
B4-W	39.59	0.008	0.09	0.14

4.2 RESULTS

4.2.1 NATURAL PERIOD

The natural periods in heave and roll for the Narrow and Wide Pontoons have been calculated using equations 2.5 and 2.6 (Section 3.4.4) and experimentally by performing decay tests as detailed in Section 3.4.4. The experimental results presented in TABLE 4.2 are the average of the 3 decay tests performed and are based on both pontoons with a prototype draft of 0.455 m being supported by piles in water depth of 3.6m – depth and draft remained consistent for all beam tests (see TABLE 3.3).

TABLE 4.2. SUMMARY OF NATURAL PERIOD/FREQUENCY IN HEAVE AND ROLL FOR BOTH THE NARROW AND WIDE PONTOONS

Natural Period (s)	Narrow	Wide
Theoretical		
T_N - heave	3.1	4
T_N - roll	1.5	1.4
Experimental		
T_N - heave	2.44	2.61
T_N - roll	2.91	2.64

As can be seen in Table 4.2 increasing the beam of the pontoon results in the natural period in heave increasing and natural period of roll decreasing for both theoretically and experimentally derived cases.

4.2.2 OPERATIONAL CRITERIA: REFLECTION AND TRANSMISSION COEFFICIENTS

Dynamic motions of floating bodies are highly dependent on the structure beam to draft ratio (B/D) and the beam to wavelength ratio (B/L), as well as the wave direction and the degree of mooring restraint (Gaythwaite 2016). Transmission ($K_t = \frac{H_t}{H_i}$) and reflection ($K_r = \frac{H_r}{H_i}$) coefficients, where H_t is the transmitted wave height, H_i is the incident wave height and H_r is the reflected wave height are summarized in TABLE 4.1 and FIGURE 4.1. FIGURE 4.1a shows wave transmission relative to wave period and includes comparative results from Cox and Beach (2006) and Cox et al. (2007). Their tests were of similar beam width (2.4m and 4.8m), however had much larger draft (1.7m compared with 0.455m used in the present study). They tested monochromatic waves, wave heights ranging from 0.4 – 1.2m, wave periods of 2 - 5 seconds in a water depth of 4.2m.

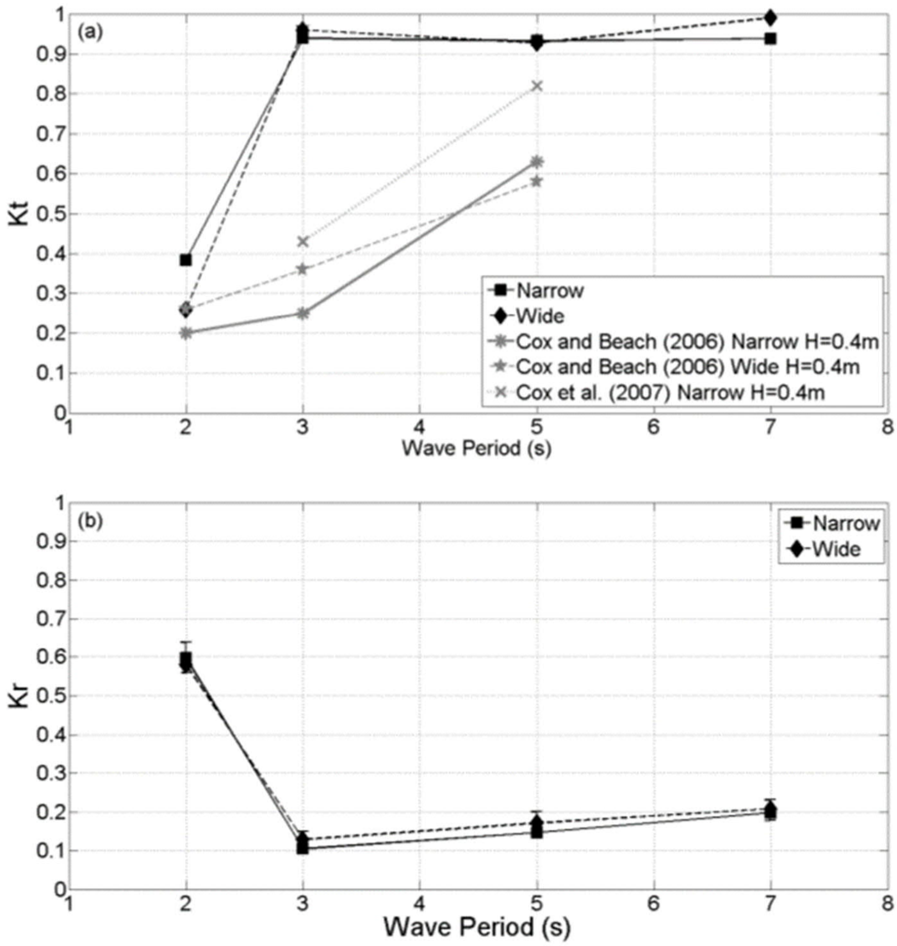


FIGURE 4.1. VARIATION OF (A) TRANSMISSION AND (B) REFLECTION VERSUS WAVE PERIOD FOR THE NARROW AND WIDE PONTOON. TRIPLICATE RESULTS ARE PLOTTED AS A VERTICAL RANGE WITH THE MEAN OF THE THREE TESTS REPRESENTED BY THE LINE

As shown in FIGURE 4.1a, at 2 seconds all pontoons, including those tested by previous studies demonstrated effective attenuation performance with little variation resulting from differences in beam or draft. Transmission was strongly dependent on wave period with wave attenuation performance being significantly reduced for wave periods greater than 2 seconds, consistent with Gaythwaite (2016) who stated a pontoon effectively rides the wave for B/L<0.2. Draft effect was most noticeable at 3 seconds where the pontoons tested by Cox et al. (2007) for D/d = 0.4 displayed better attenuation performance compared with the Narrow and Wide Pontoons tested here (D/d = 0.13). For wave periods of 3 seconds or above, beam had minimal effect on Kt for the new tests presented here compared to previous work. The highest reflection (Kr = 0.60 and 0.58) occurred during the 2 second period wave (FIGURE 4.1b) with both pontoons experiencing strong interaction with the incoming waves and pile structure that resulted in shock accelerations as they were pushed against the pile by the incoming wave.

4.2.3 OPERATIONAL CRITERIA: PEAK VERTICAL AND LATERAL ACCELERATION

For desktop assessment purposes peak heave accelerations have been calculated using equation (2.7) (Section 2.2.3) proposed by Gaythwaite (2016). Results for both pontoons are presented in TABLE 4.3. The equation is based on wave period and amplitude and treats the pontoon as a freely floating body. Due to the equation being purely based on the wave parameters with no accounting for beam width, both pontoons have the same calculated peak heave acceleration. Experimental results will be discussed relative to these theoretically derived values.

TABLE 4.3. THEORETICALLY DERIVED PEAK HEAVE ACCELERATION RELATIVE TO B/L. ALL VALUES GIVEN IN G. BOLD INDICATES EXCEEDANCE OF SML.

Axis and Test ID	**B/L**							
	0.07	**0.11**	**0.14**	**0.21**	**0.22**	**0.43**	**0.45**	**0.90**
Test ID	**B4-N**	**B3-N**	**B4-W**	**B3-W**	**B2-N**	**B2-W**	**B1-N**	**B1-W**
a_z heave (g)	0.01	0.02	0.01	0.02	0.07	0.07	**0.15**	**0.15**

As anticipated, the dynamic motions of the pontoons varied with wave period and pontoon width. Dimensionless parameters of beam to wavelength (B/L) and structure beam to draft (B/D) are relevant. Shocks (short period spikes) in both heave and surge acceleration that exceeded the theoretical accelerations of an un-restrained free floating body occurred at both the crest and trough of the wave for shorter waves, particularly when combined with the lower B/D ratio of the Narrow Pontoon (FIGURE 4.2a,b vs FIGURE 4.2c,d).

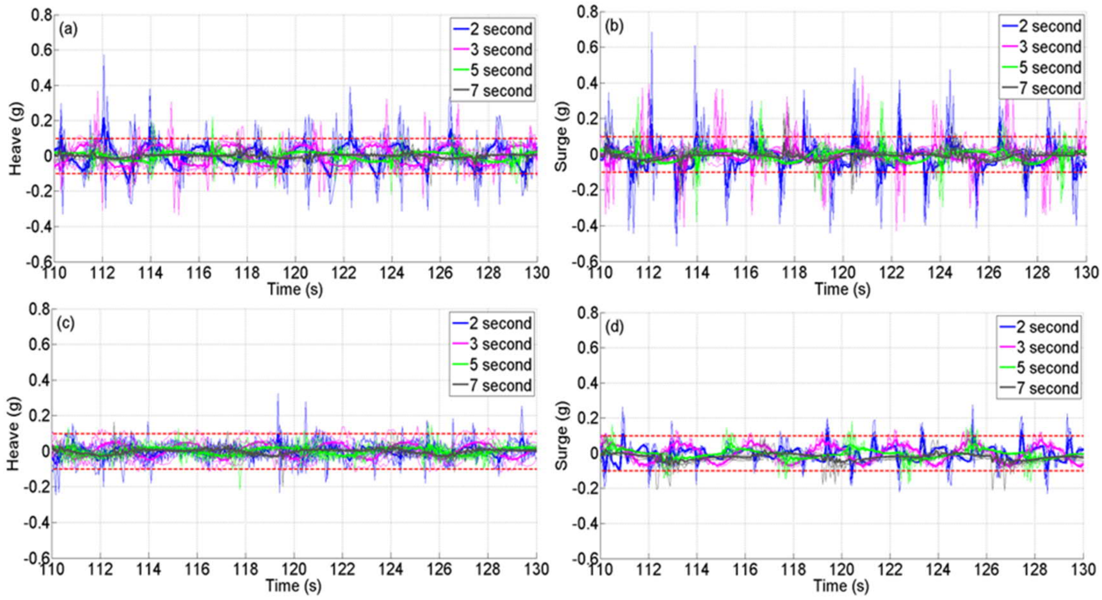


FIGURE 4.2. TWENTY SECOND TIME SLICE OF RAW ACCELERATION VERSUS TIME: (A) NARROW PONTOON HEAVE ACCELERATION; (B) NARROW PONTOON SURGE ACCELERATION; (C) WIDE PONTOON HEAVE ACCELERATION; AND (D) WIDE PONTOON SURGE ACCELERATION. THE HORIZONTAL RED DASHED LINE INDICATES THE SAFE MOTION LIMIT OF 0.1G.

In contrast to the theoretical peak accelerations (Table 4.3) there was significant wave-structure interaction (and high energy losses) that produced higher accelerations more frequently exceeding the operational SML of 0.1g for the Narrow Pontoon (FIGURE 4.2a,b) compared to the Wide Pontoon (FIGURE 4.2c,d). At the crest of the wave, the pontoon is visibly pushed against the piles creating shocks in surge (FIGURE 4.3a and Figure 4.3e (see 112.1s)). In some instances, the pontoon is observed to hang briefly on the pile due to the high roll angles, leading to both high heave and surge accelerations when the pontoon subsequently falls and impacts the piles at the base of the wave (FIGURE 4.3c and Figure 4.3e (see 113.3 s)). For longer wave periods (lower B/L), both pontoons acted slightly more like a floating vessel, riding over the waves, experiencing less wave-structure interaction and smaller shocks in both vertical and lateral acceleration (FIGURE 4.2).

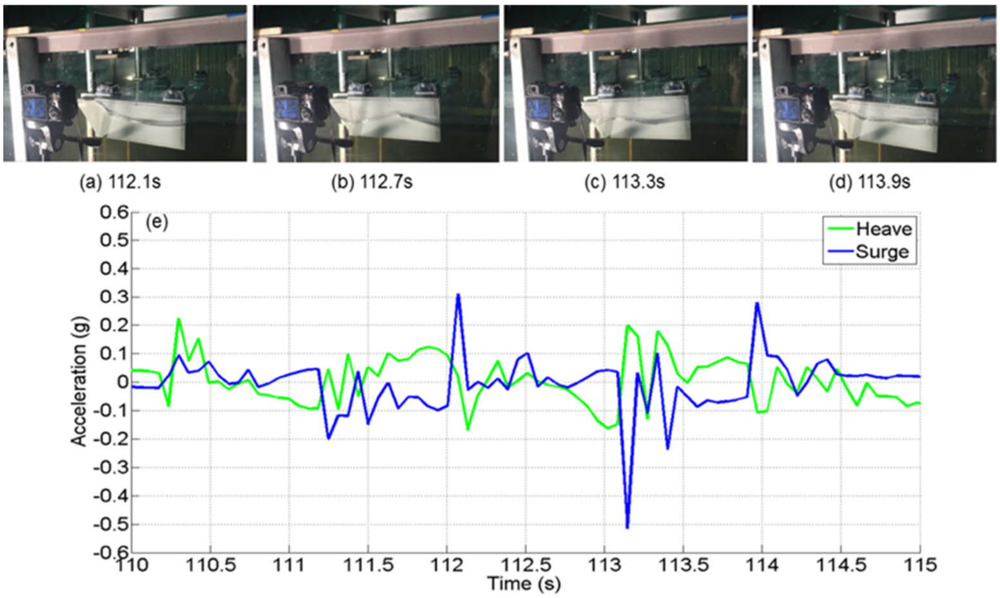


FIGURE 4.3. TIME SLICE OF NARROW PONTOON DURING THE 2 SECOND WAVE TEST. (A-D) SNAP SHOTS OF PONTOON MOTION AND (E) SENSOR 1 HEAVE AND SURGE ACCELERATIONS.

Considering the full time period of each experimental run (approximately 189 seconds), recorded peak heave (z-axis) and surge (x-axis) accelerations were nearly six times (0.45g and 0.55g, respectively) the nominated SML (0.1g).and significantly higher than the theoretically derived peak heave in TABLE 4.3 (0.01g-0.15g) for a free-floating body, while sway (y-axis) peak accelerations reached nearly three times (0.23g) the SML for the Narrow Pontoon (FIGURE 4.4). All peak accelerations exceeded the safe motion limits, with the highest accelerations recorded for the 2 second period wave (B/L ~ 0.45, Narrow, FIGURE 4.4a and B/L ~ 0.90, Wide, FIGURE 4.4b). For similar B/L, lower B/D ratios resulted in higher peak accelerations. Additionally, peak accelerations showed a stronger dependence on B/L for the Narrow Pontoon compared to the Wide Pontoon (FIGURE 4.4a vs FIGURE 4.4b). The results presented here are in agreement with previous studies by Cox et al. (2007).

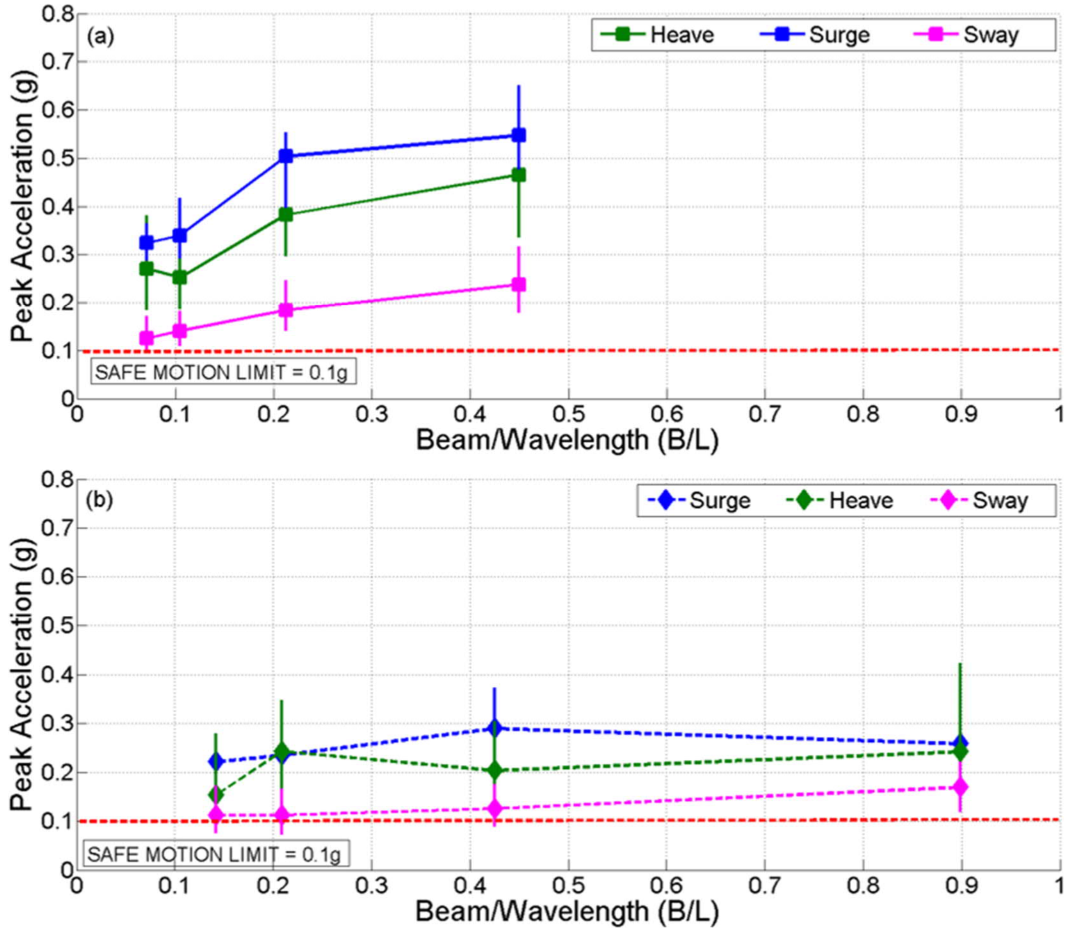


Figure 4.4. Peak in Single (Surge, Sway and Heave) Axis of Acceleration Plotted Against Beam to Wavelength Ratio and Compared Against the Safe Motion Limit of 0.1g. (a) Narrow pontoon and (b) wide pontoon. Range Between 5 Sensors and 3 Test Repetitions Shown by Vertical Lines and Solid Symbol Being the Average of the 15 Results.

While peak accelerations shown in Figure 4.4 exceed the SML adopted for this study, examining the cumulative distribution functions (Figure 4.5) provides further insight into the probability that a person standing on a floating pontoon would experience accelerations that exceed the safe motion limit criteria. In general, less than 5% of the data in surge or heave exceeded the peak SML = 0.1g (Figure 4.5a,b). This further emphasizes that the observed peaks in acceleration (Figure 4.4) resulted from infrequent, short duration impacts due to the pontoon/pile interaction as detailed in Figure 4.2 and Figure 4.3. When considering the linear vector accelerations of all three axes combined (Figure 4.5c), the probability of exceeding the peak SML=0.1g was as high as 12% for the 3 second wave on the Wide pontoon (B/L=0.43 and B/D= 12.5) and may be influenced by the proximity to the derived natural period of the structure (Table 4.2).

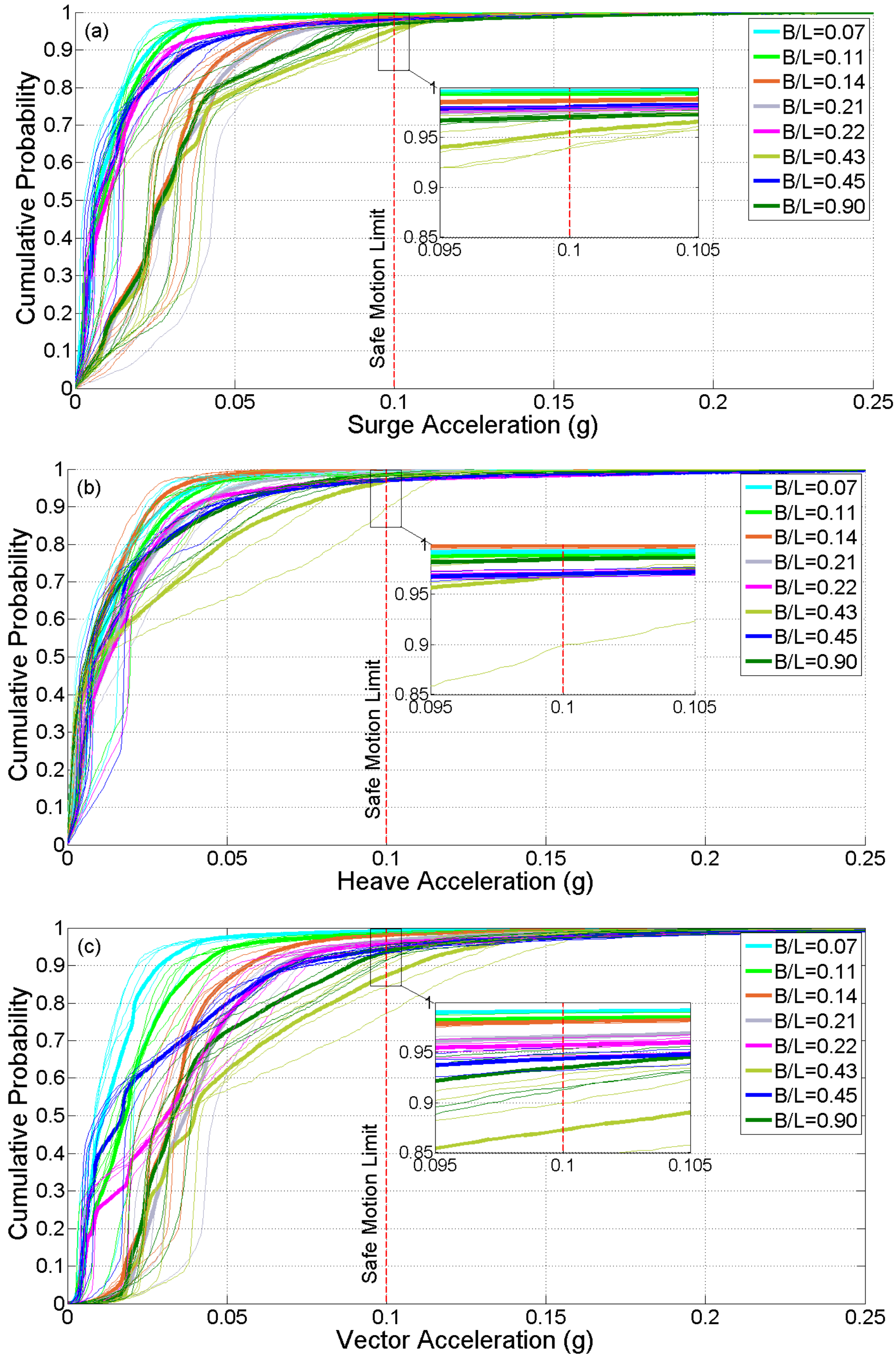


FIGURE 4.5. CUMULATIVE DISTRIBUTION FUNCTIONS FOR DIFFERENT BEAM TO WAVELENGTH RATIOS. (A) SURGE (X-AXIS), (B) HEAVE (Z-AXIS) AND (C) VECTOR ACCELERATION (XYZ-AXIS). THIN LINES INDICATE INDIVIDUAL SENSORS (1-5) AND THICK LINES REPRESENT THE MEAN OF ALL 5 SENSORS.

As stated in Section 2.5.4, humans are more likely to have unfavourable response to motion within a frequency band of 1 – 80 Hz (Brown et al. 2001; Nawayseh & Griffin 2006; Baker & Mansfield 2010). A low pass filter was applied to each of the test cases at various cut off frequencies between 1 – 8 Hz (prototype) in order to obtain maximum absolute acceleration for each of the three axis (-x, -y and -z) (FIGURE 4.6). In surge (FIGURE 4.6a) the nominated safe motion limit was exceeded at a frequency as low as 0.4 Hz (B/L=0.22, 0.43 and 0.45). At 3 Hz, all B/L ratios exceeded the SML in surge. B/L=0.45 (2 second period wave, Narrow pontoon), experienced the highest short duration peak accelerations at a cut off of 8 Hz (0.52g, FIGURE 4.6a). In sway (FIGURE 4.6b) the nominated SML was not exceeded by any B/L ratios until a frequency of approximately 3Hz, after which the maximum absolute acceleration in sway increased as cut off frequency increased. All beam to wavelength ratios recorded relatively similar maximum acceleration in sway. At a 1 Hz cut-off frequency the higher B/L ratios recorded the higher heave accelerations (FIGURE 4.6c) (B/L=0.45 (0.13g), B/L=0.43 (0.11g), B/L=0.22 (0.11g) and B/L=0.9 (0.08g)) compared to the lower B/L ratios which were below the 0.1g limit. As frequency cut-off increased it was not until 5 Hz that all B/L ratios exceeded the nominated SML. B/L=0.45 (2 second period wave, Narrow) recorded the highest peak heave (0.41g) at 8 Hz cut-off followed by the Wide Pontoon (B/L=0.14 (0.35g), 0.21 (0.35g) and 0.90 (0.28g)). These results further emphasize that the high-impact pontoon-pile interactions are a key contributor to the accelerations that exceed the nominated SML and are likely to result in patron discomfort and instability.

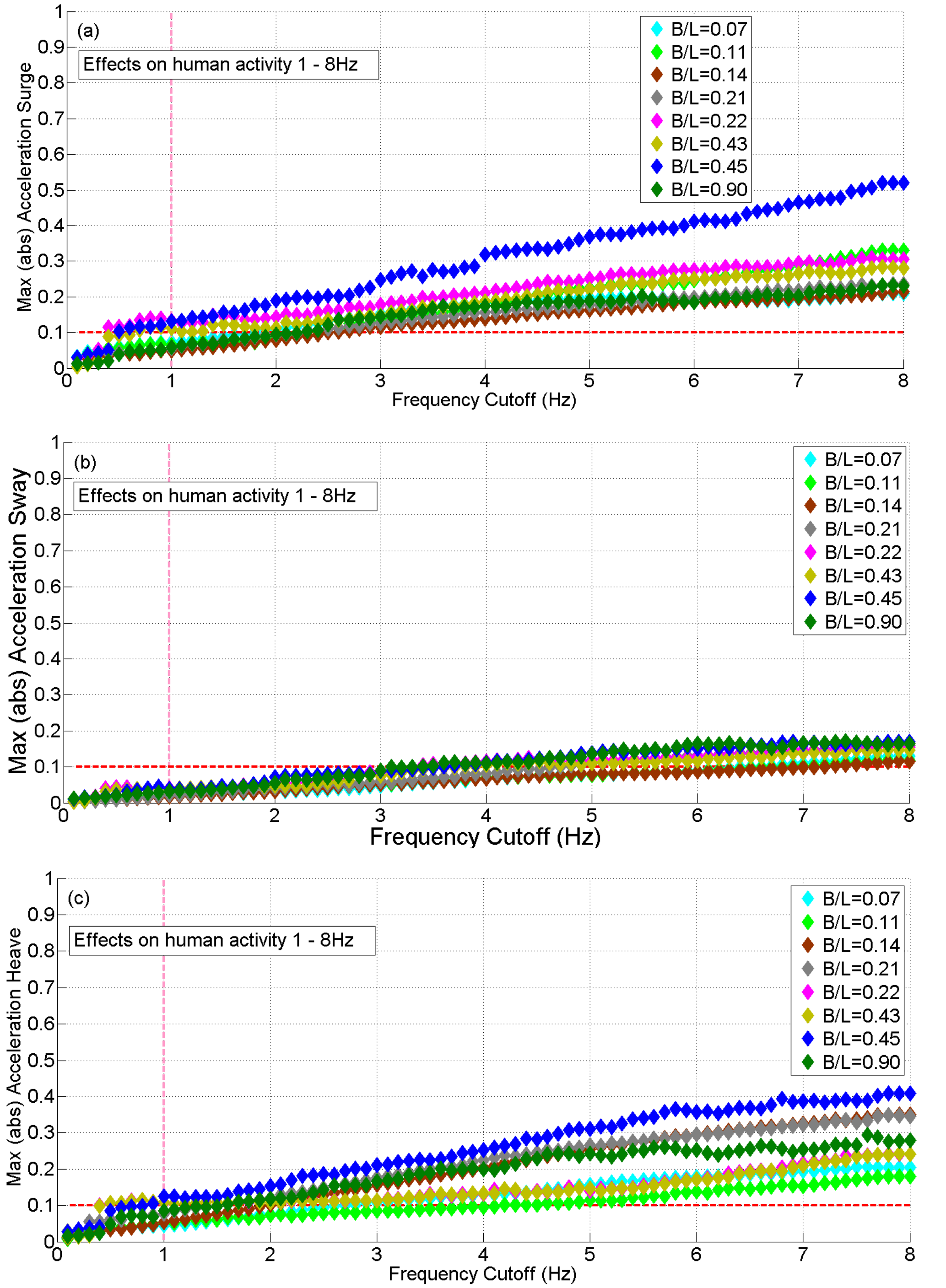


FIGURE 4.6. ABSOLUTE MAXIMUM ACCELERATION FOR VARIOUS CUT OFF FREQUENCIES BETWEEN 1 – 8 HZ PLOTTED RELATIVE TO BEAM TO WAVELENGTH RATIOS. (A) SURGE (X-AXIS), (B) SWAY (Y-AXIS) AND (C) HEAVE (Z-AXIS). RED HORIZONTAL DASHED LINE REPRESENTS NOMINATED SAFE MOTION LIMIT OF 0.1G.

4.2.4 COMFORT CRITERIA: ROOT MEAN SQUARE ACCELERATION

The RMS acceleration represents overall variability in motion compared to the short duration peak accelerations reported in Section 4.2.3. TABLE 4.4 summarizes the mean RMS accelerations calculated for each of the axes (x-, y-, z-) based on the triplicate runs. For both pontoons, the highest RMS accelerations in both surge and heave were recorded when the beam was almost half the wavelength (B/L=0.43 and 0.45). Similar to the observed peak accelerations (FIGURE 4.4), the RMS acceleration for surge (x-axis) exceeded the comfort SML (0.03g) for all tests and was as high as 0.09g. Heave (z-axis) RMS accelerations exceeded the SML (0.02g) for all tests apart from the 7 second period waves for both narrow and wide pontoons (B/L=0.07 and 0.14). The RMS sway (y-axis) acceleration did not exceed the SML (0.03g) criteria for any of the scenarios tested. These results indicate that accelerations in the direction of wave propagation (surge) and vertically (heave) are consistently large enough to cause discomfort for passengers using floating pontoons exposed to relatively small monochromatic boat wake.

TABLE 4.4. ROOT MEAN SQUARE (RMS) ACCELERATION IN X-, Y-. AND Z-AXIS FOR EACH OF THE TESTED WAVE PERIODS FOR NARROW AND WIDE PONTOONS. ALL VALUES GIVEN IN G. BOLD INDICATES EXCEEDANCE OF SML.

Axis and Test ID	SML Criteria (g)	B/L							
		0.07	**0.11**	**0.14**	**0.21**	**0.22**	**0.43**	**0.45**	**0.90**
Test ID		**B4-N**	**B3-N**	**B4-W**	**B3-W**	**B2-N**	**B2-W**	**B1-N**	**B1-W**
a_x surge	**0.03**	**0.04**	**0.04**	**0.04**	**0.06**	**0.05**	**0.07**	**0.09**	**0.05**
a_y sway	**0.03**	0.01	0.02	0.01	0.01	0.02	0.02	0.03	0.02
a_z heave	**0.02**	0.02	**0.06**	0.02	**0.03**	**0.06**	**0.04**	**0.06**	**0.03**

The onset of motion sickness is very much dependent on the individual, the exposure time, the level of motion and the frequency at which it occurs. Motion sickness occurs for motions between 0.1 – 0.5 Hz (Matsangas et al. 2014 and ABS 2014) with ABS (2014) recommending a maximum RMS acceleration of 0.007g. Examining the RMS accelerations between these frequency limits, for the Narrow Pontoon, the maximum RMS in surge ranged between 0.027g and 0.051g (3.8 to more than 7 times the SML). Similarly, in heave maximum RMS accelerations ranged between 0.01g and 0.039g (1.4 to more than 5.5 times the SML). For the Wide Pontoon, the highest RMS recorded in surge ranged from 0.007g to 0.043g (at or more than 6 times the SML). In heave, the maximum RMS acceleration ranged from 0.018g to 0.039g (2.5 to 5.5 times the SML). These results clearly show that within the frequency bands where motion sickness may be induced, RMS accelerations significantly exceed the recommended limit, adversely impacting patron comfort.

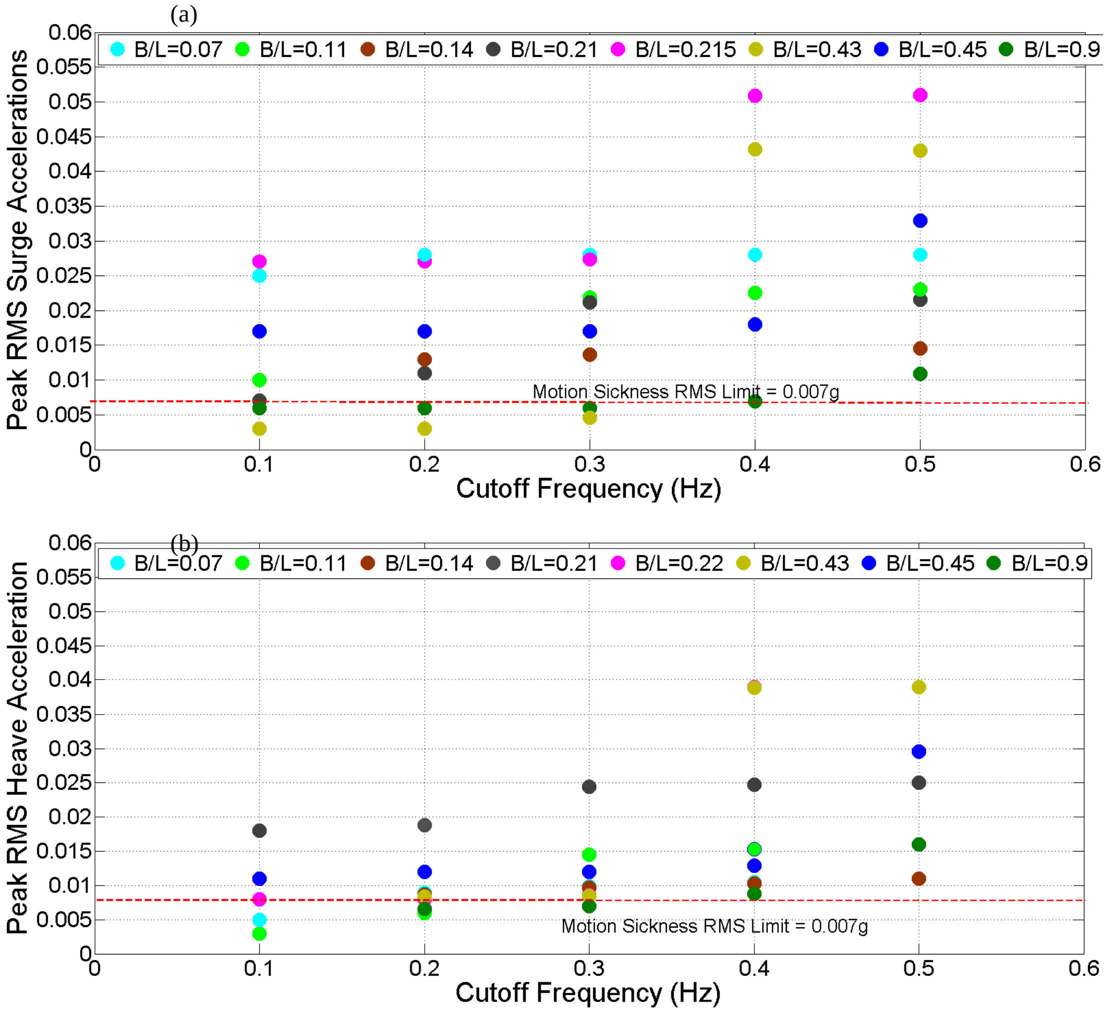


FIGURE 4.7. PEAK RMS ACCELERATION PLOTTED AGAINST CUT OFF FREQUENCY FOR DIFFERENT BEAM TO WAVELENGTH RATIOS: (A) PEAK RMS IN SURGE AND (B) PEAK RMS IN HEAVE. RED DASHED LINES SHOWS MOTION SICKNESS RMS LIMIT IN SURGE AND HEAVE AS NOMINATED BY ABS (2014).

4.2.5 ANGLES OF MOTION

Both the peak angle limit (operational SML = 6°), which may induce tipping, and the RMS angle limit (comfort criteria SML = 2° RMS), which refers to overall variability are considered here. Given the unidirectionality of the wave in the 2D flume, roll (y-axis) was the primary angle of motion of the pontoons. Roll motion may be affected by a combination of wave steepness (H/L), natural period of roll (TABLE 4.1), beam to wavelength (B/L), beam to draft (B/D) and pontoon-wave interaction.

Roll rotations were observed above the recommended operational SML 6° (Peak) and comfort SML 2° (RMS) limit (FIGURE 4.8ab). For the Narrow pontoon (FIGURE 4.8a) both peak and RMS SML criteria were only exceeded once the B/L exceeded 0.2 (wave period less than 5 seconds). For the Wide pontoon (FIGURE 4.8b) both peak and RMS SML criteria were exceeded for all tests other than the 7 second wave period (B/L=0.9). For both pontoons, the highest roll angles observed corresponded to when the pontoon was observed to hang on the piles as the crest of the wave pushed up the front face of the pontoon (e.g. FIGURE 4.2).

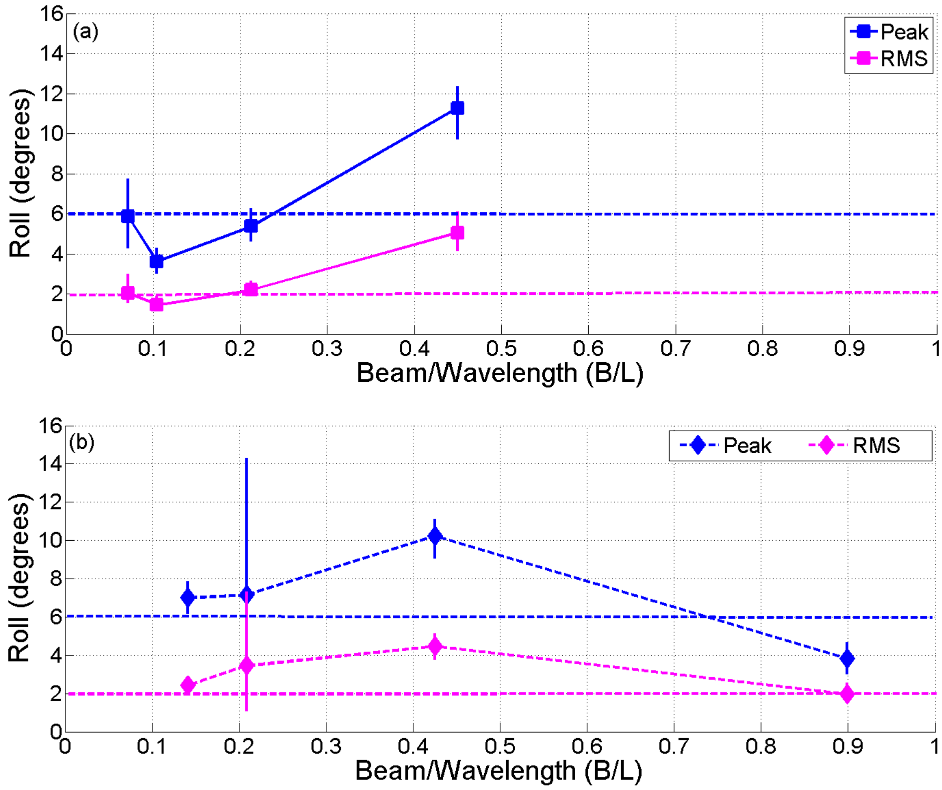


FIGURE 4.8. PEAK AND RMS ROLL PLOTTED AGAINST BEAM TO WAVELENGTH FOR: (A) NARROW PONTOON AND (B) WIDE PONTOON. UPPER BLUE DASHED LINES SHOW PEAK SML AND LOWER PINK DASHED LINE RMS SML. RANGE BETWEEN 5 SENSORS AND 3 TEST REPETITIONS SHOWN BY VERTICAL LINES AND SOLID SYMBOL BEING THE AVERAGE OF THE 15 RESULTS.

The distribution of wave angles observed during testing is provided in FIGURE 4.9. There is a clear dependency in roll exceedance and B/L, with B/L approaching half a wavelength resulting is significantly higher exceedance of the SML = 6 degrees (36.27%, B/L=0.45 Narrow and 23.22%, B/L=0.43 Wide pontoon).

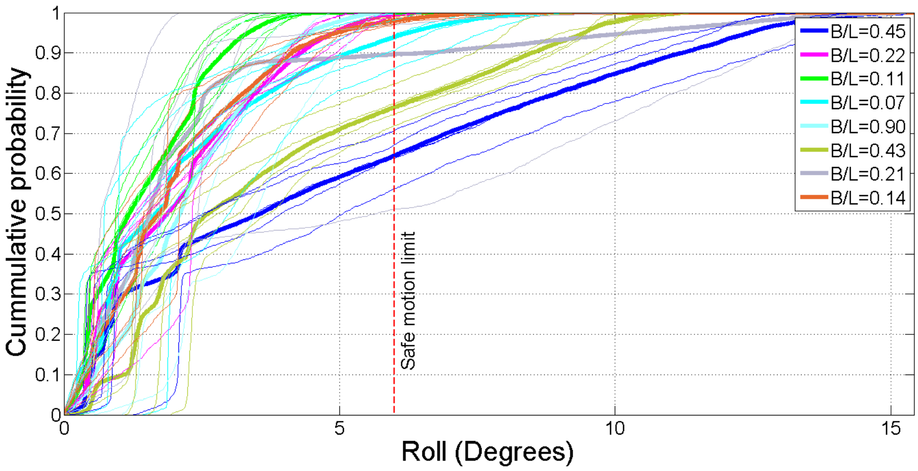


FIGURE 4.9. ROLL CUMULATIVE PROBABILITY. THIN LINES INDICATE INDIVIDUAL SENSORS (1-5) AND THICK LINES REPRESENT THE MEAN OF ALL 5 SENSORS.

4.3 SUMMARY

This chapter presented the results of the effect of beam width on wave attenuation performance and dynamic motion response of piled floating pontoons subject to boat wake. For the data presented here, wave attenuation was strongly dependent on wave period, with little variation resultant from an increase in beam width. Wave attenuation was best for a wave period of 2 seconds and significantly reduced above this. For the data presented, as B/L increased there was a general trend for an increase in peak acceleration, reflecting the expectation that the steeper, short period waves would illicit larger accelerations for a floating body (FIGURE 4.4). For the Narrow Pontoon (FIGURE 4.4a) peak accelerations (heave, surge and sway) increased by approximately 100% as B/L increased (wave period decreased from 7 to 2 seconds). However, for the Wide Pontoon (FIGURE 4.4b) as wave period decreased (B/L increased), increases in peak accelerations were smaller (at most only 50%). There was also a measurable difference in the magnitude of peak accelerations for similar B/L ratios between the two pontoons. This difference in peak accelerations for similar B/L ratios is due to the inertia effect of the pontoons with the Wide Pontoon recording lower peaks in acceleration due to the increased mass.

For both pontoons the highest RMS accelerations in both surge and heave occurred when the beam was approximately half the wavelength (B/L=0.43 and 0.45). This was close to the natural periods of motion (Table 4.2) where periods ~ 2-3 seconds would likely cause some level of excitation. The SML (0.03g) was exceeded in surge for all tests and was as high as 0.09g. Heave (z-axis) RMS accelerations exceeded the

SML (0.02g) for all tests apart from the 7 second period waves for both narrow and wide pontoons (B/L=0.07 and 0.14). In sway the RMS SML was not exceeded. Relative to the angles of motion, roll rotations were observed above the recommended operational SML 6° (Peak) and comfort SML 2° (RMS). Both peak and RMS roll was highest when the beam was approximately half the wavelength and when the natural period of roll was similar to the incoming incident wave period.

The following chapter provides results from the remainder of the laboratory scale wave flume tests in fulfillment of Objective 2 of this thesis. Chapter 5 focuses on how draft effects the hydrodynamic properties and motion response of both the Narrow and Wide Pontoons and compares the results to the SML criteria.

CHAPTER 5: THE EFFECT OF DRAFT ON THE DYNAMIC MOTIONS OF A PILED FLOATING PONTOON UNDER MONOCHROMATIC WAVES

Building on from Chapter 4 examining the effect beam width has on the dynamic motions of floating pontoons, this chapter presents the effect of altering draft on wave attenuation and dynamic motions of both the Narrow and Wide Pontoons. Results are presented for coefficients of transmission and reflection along with peak, cumulative and root mean square accelerations and angles. Comparisons are made with the nominated SML (Section 2.6).

Some content of this chapter is taken from the following publications:

Conference Proceedings

Freeman, E.; Cox, R., and Splinter, K. 2017. 'Suitable Criteria for Safe Motion Limits of a Floating Pontoon Relative to the Postural Stability of a Stationary Standing Person', *Australasian Coasts & Ports 2017: Working with Nature*. Barton, ACT: Engineers Australia, PIANC Australia and Institute of Professional Engineers New Zealand, 2017: 476-482.

Freeman, E.; Cox, R., and Splinter, K. 2018. 'Floating Breakwaters as Public Platforms – Impact on Postural Stability', *Coastal Engineering Proceedings, 1*(36), structures.63.

Freeman, E.; Cox, R., Splinter, K., and Flocard, F. 2019. 'Floating Pontoon Motions, Operational Safe Motion Limits', Pacific International Maritime Conference.

5.1 INTRODUCTION

The draft of a pontoon is the vertical distance between the waterline and the bottom of the pontoon. The relative motion response of a floating structure depends upon the relative draft (D)-to-water-depth (d) ratio (D⁄d), the structure-beam (B)-to-draft (D) ratio (B⁄D) as it affects the virtual mass of the structure, as well as the wave direction and the degree of mooring restraint (Gaythwaite, 2016). Previous research has examined the effect of draft on hydrodynamic performance (transmission and reflection) of floating breakwaters (Section 2.2.1) but minimal research has focused on the effect of draft on the dynamic motion response of floating pontoons. This chapter presents results based on assessing the impact of altering draft on the wave transmission and reflection along with the motion response of the two pontoons presented in Chapters 3 and 4. TABLE 5.1 and TABLE 5.2 detail the key testing parameters of this component of the research. In TABLE 5.1 and TABLE 5.2, N stands for Narrow, W Wide and the numerical values (i.e. 455) after the letters represent the prototype draft in mm. Draft was altered in two ways: the first was by adding mass in order to lower the structure in the water, resulting in a reduction in freeboard; the second was through the addition of 3 different skirt configurations (perforated front skirt, solid front skirt and perforated front skirt/solid back skirt). The testing conditions adopted are detailed in Chapter 3. All results presented are based on the mean of the triplicate test runs performed.

TABLE 5.1. DRAFT TESTING KEY PARAMETERS (PROTOTYPE SCALE)

Test ID	**D/d**	**B/D**	**B/L**
Draft Effect – Testing Parameters (1.2m Flume)			
D1-N455	0.126	6.154	0.45
D2-N455	0.126	6.154	0.22
D3-N455	0.126	6.154	0.11
D4-N455	0.126	6.154	0.07
D1-W455	0.126	12.308	0.90
D2-W455	0.126	12.308	0.43
D3-W455	0.126	12.308	0.21
D4-W455	0.126	12.308	0.14
D1-N560	0.156	5	0.45
D2-N560	0.156	5	0.22
D3-N560	0.156	5	0.11
D4-N560	0.156	5	0.07
D1-W560	0.156	10	0.90
D2-W560	0.156	10	0.43
D3-W560	0.156	10	0.21
D4-W560	0.156	10	0.14
D1-N585	0.163	4.786	0.45
D2-N585	0.163	4.786	0.22
D3-N585	0.163	4.786	0.11
D4-N585	0.163	4.786	0.07
D1-W585	0.163	9.573	0.90
D2-W585	0.163	9.573	0.43
D3-W585	0.163	9.573	0.21
D4-W585	0.163	9.573	0.14
D1-N635	0.176	4.409	0.45
D2-N635	0.176	4.409	0.22
D3-N635	0.176	4.409	0.11
D4-N635	0.176	4.409	0.07
D1-W635	0.176	8.819	0.90
D2-W635	0.176	8.819	0.43
D3-W635	0.176	8.819	0.21
D4-W635	0.176	8.819	0.14
D1-N680	0.189	4.118	0.45
D2-N680	0.189	4.118	0.22
D3-N680	0.189	4.118	0.11
D4-N680	0.189	4.118	0.07
D1-W680	0.189	8.235	0.90
D2-W680	0.189	8.235	0.43
D3-W680	0.189	8.235	0.21
D4-W680	0.189	8.235	0.14

TABLE 5.2. SKIRT TESTING KEY PARAMETERS (PROTOTYPE SCALE)

Test ID	**D/d**	**B/D**	**B/L**
Skirt Effect – Testing Parameters (1.2m Flume)			
S1-SolidN	0.375	2.074	0.45
S2-SolidN	0.375	2.074	0.22
S3-SolidN	0.375	2.074	0.11
S4-SolidN	0.375	2.074	0.07
S1-PerfN	0.375	2.074	0.45
S2-PerfN	0.375	2.074	0.22
S3-PerfN	0.375	2.074	0.11
S4-PerfN	0.375	2.074	0.07
S1-Perf/SolidN	0.375	2.074	0.45
S2-Perf/SolidN	0.375	2.074	0.22
S3-Perf/SolidN	0.375	2.074	0.11
S4-Perf/SolidN	0.375	2.074	0.07

5.2 RESULTS

5.2.1 NATURAL PERIOD

The mass of the pontoon changed with draft which also resulted in a change in the natural frequency of the pontoon and the wave transmission and reflection coefficients. For both the Narrow and Wide Pontoons, the natural period has been determined both theoretically as a free body and experimentally (supported by piles) for each draft as detailed in Section 3.4.4. The experimental results presented in TABLE 5.3 are the average of the 3 decay tests performed.

TABLE 5.3. SUMMARY OF THEORETICALLY AND EXPERIMENTALLY DERIVED NATURAL PERIOD IN HEAVE AND ROLL FOR THE NARROW AND WIDE PONTOONS

Natural Frequency and Period	**Draft (mm)**				
	455	**560**	**585**	**635**	**680**
Theoretical (free body)					
Narrow Pontoon					
$T_{N\text{ - heave}}$ (s)	2.7	2.8	2.9	3.0	3.1
$T_{N\text{ - roll}}$ (s)	1.5	1.7	1.8	1.9	2.1
Wide Pontoon					
$T_{N\text{ - heave}}$ (s)	3.8	3.7	3.6	3.6	3.5
$T_{N\text{ - roll}}$ (s)	1.4	1.6	1.6	1.7	1.7
Experimental					
Narrow Pontoon					
$T_{N\text{ - heave}}$ (s)	2.44	2.87	2.66	2.64	2.64
$T_{N\text{ - roll}}$ (s)	2.91	3.15	3.16	3.16	3.35
Wide Pontoon					
$T_{N\text{ - heave}}$ (s)	2.61	2.84	3.29	3.23	3.27
$T_{N\text{ - roll}}$ (s)	2.64	3.16	3.16	3.16	3.16

As can be seen in TABLE 5.3, the natural period of roll increases with increasing draft for both pontoons when calculated both theoretically and experimentally. The shallowest draft records the lowest natural period in heave except for the theoretically derived natural heave period for the Wide pontoon which decreases with increasing draft. Experimentally for the Narrow pontoon a draft of 560mm records the highest natural heave period (2.87s) and for the Wide pontoon a draft of 585mm (3.29s). Examining the experimental results compared to the incident wave conditions tested here, it is anticipated that the wave period cases around 3 seconds may adversely impact on the dynamic motions of the pontoons.

5.2.2 Operational Criteria: Reflection and Transmission Coefficients

The influence of draft on transmission (Kt) and reflection (Kr) coefficients is presented in FIGURE 5.1 and FIGURE 5.2. FIGURE 5.2 shows that for short waves (2 and 3 seconds) a deeper draft generally results in better attenuation performance due to the blockage effect of the front face of the pontoon being more significant. This was not the case for the Narrow pontoon at 3 seconds where the shallowest draft (N455) had better attenuation performance (0.91), this may be due to the natural roll period matching the forcing period at 3 seconds. At 5 seconds (B/L = 0.11 and 0.21), draft had an inverse effect with shallower drafts (N455 and W455) recording lower Kt values (~0.8). FIGURE 5.2 shows Kr was relatively unchanged as a result of increasing draft. The most obvious influence of draft was seen at 2 seconds with the shallowest draft recording the highest reflection for both pontoons, this contradicts what would be expected and was as a result of high wave/pontoon interaction.

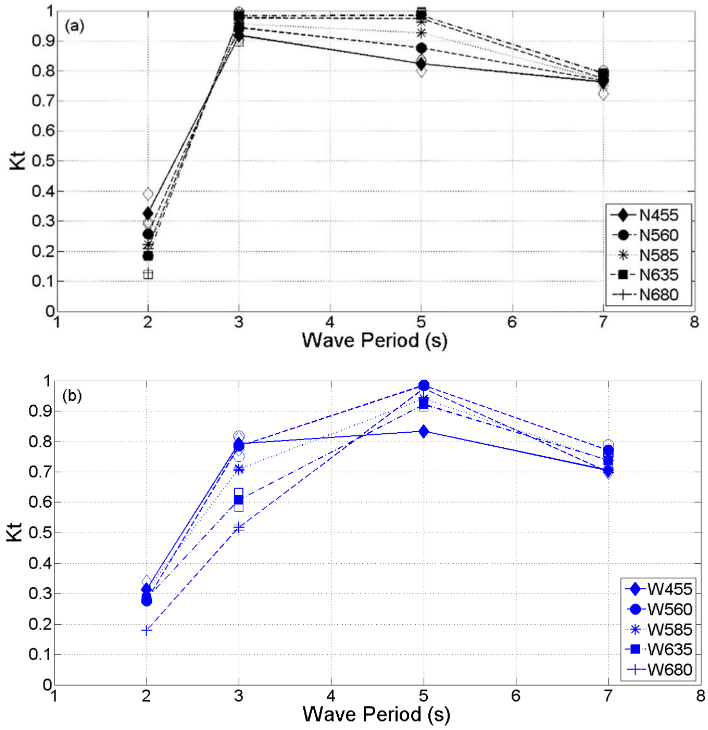


FIGURE 5.1. VARIATION OF TRANSMISSION FOR (A) NARROW PONTOON AND (B) WIDE PONTOON VERSUS DRAFT AND PLOTTED RELATIVE TO WAVE PERIOD. TRIPLICATE RESULTS ARE PLOTTED AS INDIVIDUAL SYMBOLS WITH THE MEAN OF THE THREE TESTS REPRESENTED BY THE LINE.

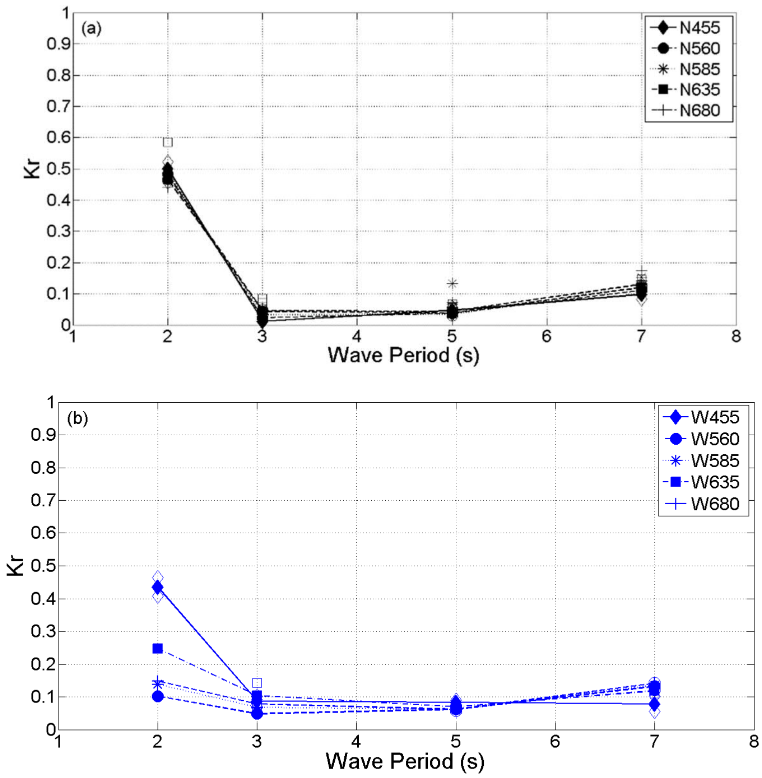
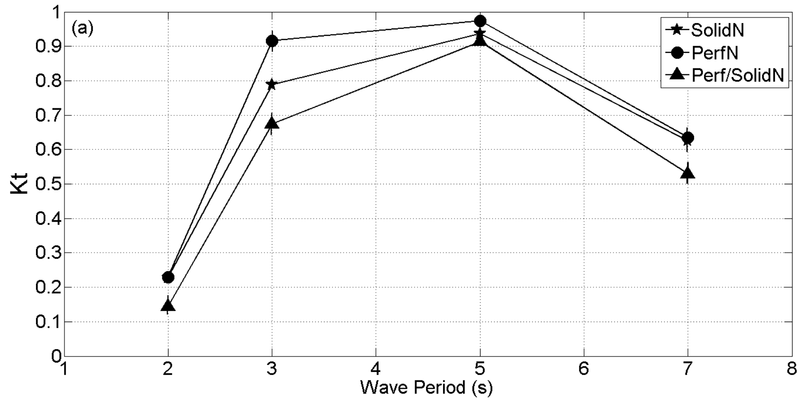


FIGURE 5.2. VARIATION OF REFLECTION FOR (A) NARROW PONTOON AND (B) WIDE PONTOON VERSUS DRAFT AND PLOTTED RELATIVE TO WAVE PERIOD. TRIPLICATE RESULTS ARE PLOTTED AS INDIVIDUAL SYMBOLS WITH THE MEAN OF THE THREE TESTS REPRESENTED BY THE LINE.

Due to the dimensions of the pontoons, with the adopted constant water depth of 3.6m for testing, changes in draft were limited compared to the depth (D/d). As such, three skirt arrangements were tested to determine their effect on the transmission and reflection coefficients of the Narrow pontoon (FIGURE 5.3). The skirt arrangements tested were: front solid (FrontN); front perforated (PerfN); and perforated front/solid back (Perf/SolidN), as detailed in Chapter 3 and summarised in TABLE 5.2. The addition of the skirts increased the overall prototype draft of the pontoon to 1.35m. Not unsurprisingly, the double skirt arrangement (Perf/SolidN) had overall better attenuation performance for each wave period tested (FIGURE 5.3a). At 3 seconds, the largest spread in attenuation performance is observed with the single perforated front skirt (PerfN) recording the highest value of Kt (0.91) compared with the double skirt arrangement (Perf/SolidN (0.67)). Comparing with FIGURE 5.1, adding skirts in general improved attenuation of the Narrow Pontoon markedly at 3 seconds (0.91 (no skirts 455mm draft)) compared with 0.67 (with double skirts)). There is minimal effect on Kr by increasing draft through the addition of skirts for the Narrow Pontoon. This is most likely a result of the low B/L ratios (Chapter 4) for most of the tests where the pontoons generally rode the waves rather than have strong interaction. The most obvious effect was seen at 2 seconds where the double skirt arrangement (Perf/SolidN) recorded the highest reflection (0.59) compared to the other single skirt arrangements (~0.4). The highest reflection recorded (Perf/SolidN (0.59)) was higher than that observed without skirts (0.5).



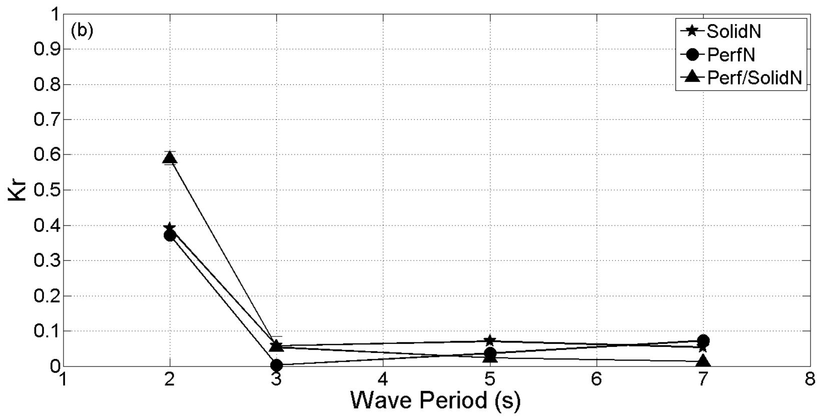


FIGURE 5.3. VARIATION OF (A) TRANSMISSION AND (B) REFLECTION FOR THE NARROW PONTOON WITH THREE DIFFERENT SKIRT ARRANGEMENTS. TRIPLICATE RESULTS ARE PLOTTED AS A VERTICAL RANGE WITH THE MEAN OF THE THREE TESTS REPRESENTED BY THE LINE.

5.2.3 Operational Criteria: Peak Vertical and Lateral Acceleration

For the tests presented here (FIGURE 5.4ab and FIGURE 5.5ab), which examined a change in draft from 455 – 680 mm in a water depth of 3.6m (D/d 0.12 – 0.19) for both the Narrow and Wide pontoons, peak vertical and lateral accelerations generally decreased with increasing wave period from 2 to 7 seconds - the Narrow pontoon showed a 50% decrease in heave (FIGURE 5.4a) and 43% in surge (FIGURE 5.5a). As reported in Chapter 4, peak accelerations significantly exceeded the SML value of 0.1g for these tests as well. The literature references motion response being influenced by the beam (B) to draft (D) ratio as it effects virtual mass (B/D range 2.07 – 12.3). For a given wave period and beam width, increasing draft had a measurable effect. At 2 seconds for the Narrow Pontoon (FIGURE 5.4a), increasing draft reduced peak heave by approximately 0.1g (N560(0.6g) – N680(0.45g)), whereas for the Wide Pontoon (FIGURE 5.4b), increasing draft reduced peak heave by roughly 0.2g (W455(0.42g) – W635(0.2g)), showing a clear B/D influence on peak heave accelerations.

Altering draft impacted peak surge accelerations (FIGURE 5.5ab), however the relationships are less well-defined. For the Narrow pontoon at 2 seconds, the shallowest draft (N455(0.68g)) recorded the highest peak in surge acceleration with all other drafts comparatively similar. In contrast, at 3 seconds the deepest draft recorded the highest peak in surge (N680(0.68g)). Above 3 seconds all draft tests were comparable, with generally deeper draft resulting in higher peak surge values. For the Wide pontoon at 2 and 7 seconds the deepest draft recorded the highest peak surge acceleration (W680(0.42g and 0.4g)). However, at 3 and 5 seconds an intermediate draft (W560) recorded the highest peak surge acceleration. For this draft (W560) the natural period in both heave and roll was ~ 3 seconds. The effect of altering draft on peak surge was most obvious for the wide pontoon with a general increase in peak surge acceleration as draft increased.

Comparing with Chapter 4 and for the Narrow and Wide pontoon tests presented here, as B/D increased vertical acceleration increased due to decreasing draft and therefore less mass. In contrast, lateral acceleration decreased due to less surface area for the waves to push the pontoon against the piles – this being most obvious for the Wide pontoon. Given the percentage change in draft was small ~ 50% increase (455mm-680mm) and the difference in D/d was minor, the small difference in recorded peak accelerations at each wave period in both heave and surge for both pontoons is to be expected. However, for the tested pontoon/pile systems, water depths and wave conditions, the results indicate that by increasing draft a decrease in one axis (heave) of acceleration results in an increase to the other (surge).

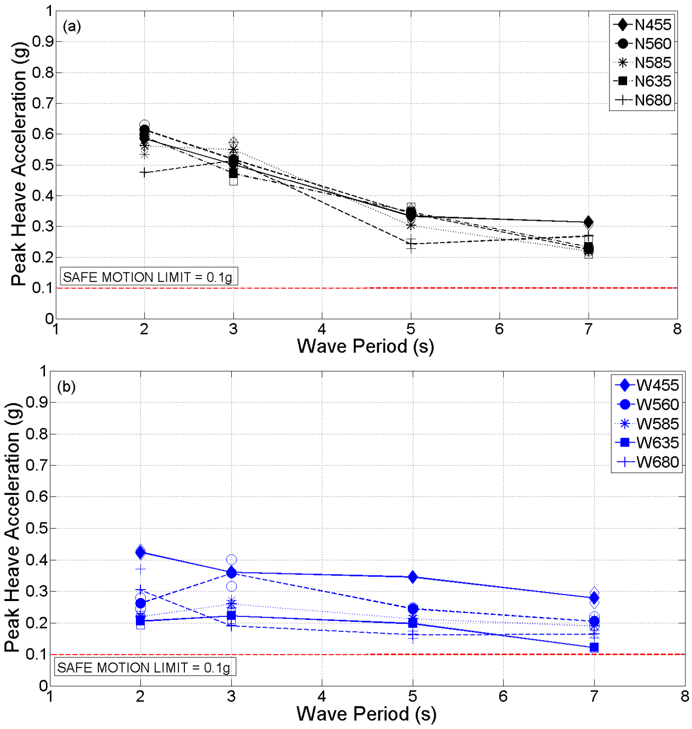


FIGURE 5.4. PEAK IN HEAVE ACCELERATION PLOTTED AGAINST WAVE PERIOD AND COMPARED AGAINST THE SAFE MOTION LIMIT OF 0.1G. (A) NARROW AND (B) WIDE PONTOONS. RESULTS PLOTTED FOR ALL THREE TESTS REPRESENTED BY INDIVIDUAL OPEN SYMBOLS AND SOLID SYMBOLS WITH LINE SHOWING THE MEAN.

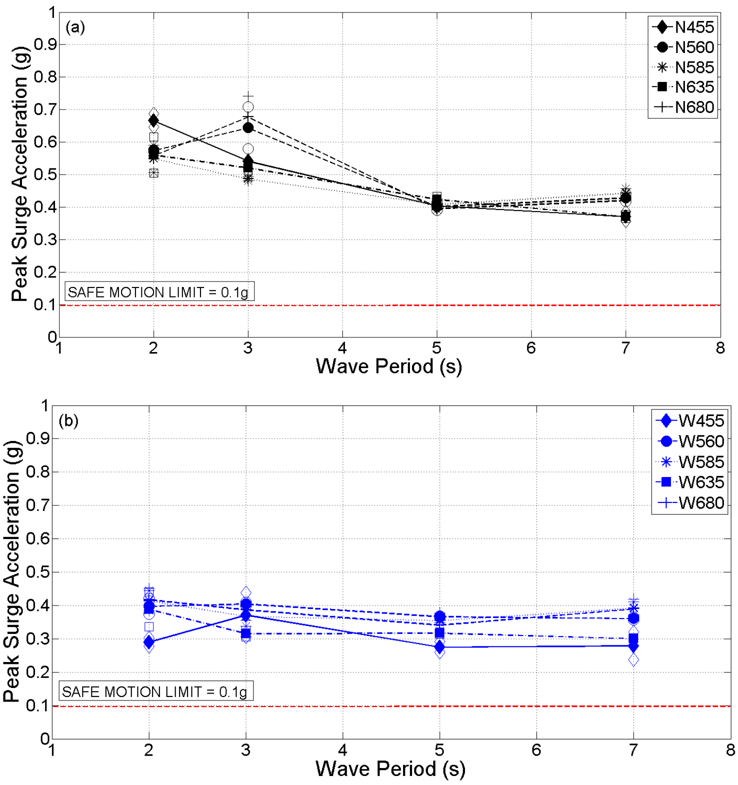


FIGURE 5.5. PEAK IN SINGLE SURGE AXIS ACCELERATION PLOTTED AGAINST WAVE PERIOD AND COMPARED AGAINST THE SAFE MOTION LIMIT OF 0.1G. (A) NARROW AND (B) WIDE PONTOONS. RESULTS PLOTTED FOR ALL THREE TESTS REPRESENTED BY INDIVIDUAL OPEN SYMBOLS AND SOLID SYMBOLS WITH LINE SHOWING THE MEAN.

Looking at the effect of the three skirt designs on peak heave and surge acceleration for the Narrow Pontoon (FIGURE 5.6) there was minimal change to peak heave when compared with FIGURE 5.4a. Peak surge acceleration increased from those results recorded without the skirts (FIGURE 5.5a) with the highest peak in surge acceleration recorded at 2 seconds (0.81g), solid front skirt, compared with 0.67g, no skirts, showing that increasing draft increases lateral acceleration most obvious for shorter waves (T ≤ 3 seconds). Above 3 seconds each skirt arrangement recorded similar results at each wave period with very little spread due to the addition of skirts. This was because for T>=3 seconds the pontoons rode the waves with and without skirts.

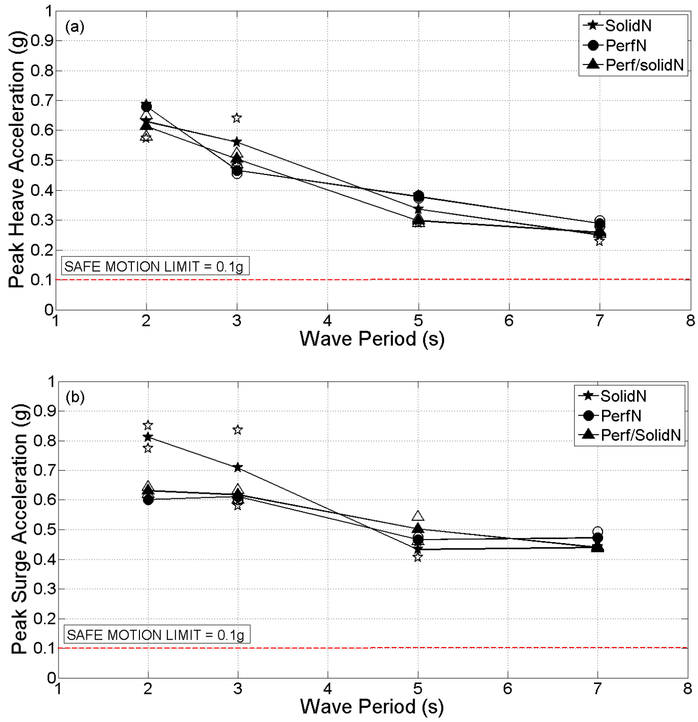


FIGURE 5.6. PEAK IN SINGLE (A) HEAVE AND (B) SURGE AXIS ACCELERATION PLOTTED AGAINST WAVE PERIOD AND COMPARED AGAINST THE SAFE MOTION LIMIT OF 0.1G FOR THE THREE DIFFERENT SKIRT ARRANGEMENTS – NARROW PONTOON. RESULTS PLOTTED FOR ALL THREE TESTS REPRESENTED BY INDIVIDUAL OPEN SYMBOLS AND SOLID SYMBOLS WITH LINE SHOWING THE MEAN.

The influence of altering draft on the cumulative probability of exceeding the nominated safe motion limits (0.1g) is shown for each wave period in FIGURE 5.7 to FIGURE 5.8. At 3 seconds, the effect of draft changed the percent exceedance in heave (FIGURE 5.7b) from ~10% (N455mm) to ~20% (N680mm) for the Narrow Pontoon. As observed in the peak heave accelerations (FIGURE 5.4) a shift is observed at 3 seconds where the deeper drafts record equal to or greater peak accelerations. The highest exceedance of the SML occurred during the 3 second period wave (FIGURE 5.7b and FIGURE 5.8b) for all drafts and both pontoons, corresponding with what would be expected to happen as a result of correspondence between the natural period of heave/roll and the forcing period (TABLE 5.3). FIGURE 5.7 and FIGURE 5.8 show the probability of exceeding our safe motion limit in heave for the 3 second period wave peaks at a draft of 585mm for the Narrow Pontoon (20.64%) (FIGURE 5.7b) and a draft of 560mm for the Wide Pontoon (14.9%) (FIGURE 5.8b). At 3 seconds instead of increasing draft resulting in decreasing heave accelerations it is observed that the deeper drafts exceed the SML approximately 20% compared with a draft of 455mm (10%), this relates to the forcing period matching the natural period of the pontoons (TABLE 5.3). FIGURE 5.9 shows the effect that adding skirts has on the cumulative probability of exceeding the SML in heave. There is again a higher exceedance at 3 seconds (FIGURE 5.9b) with results comparative to those recorded without skirts (FIGURE 5.7b) with exceedance peaking at approximately 20%.

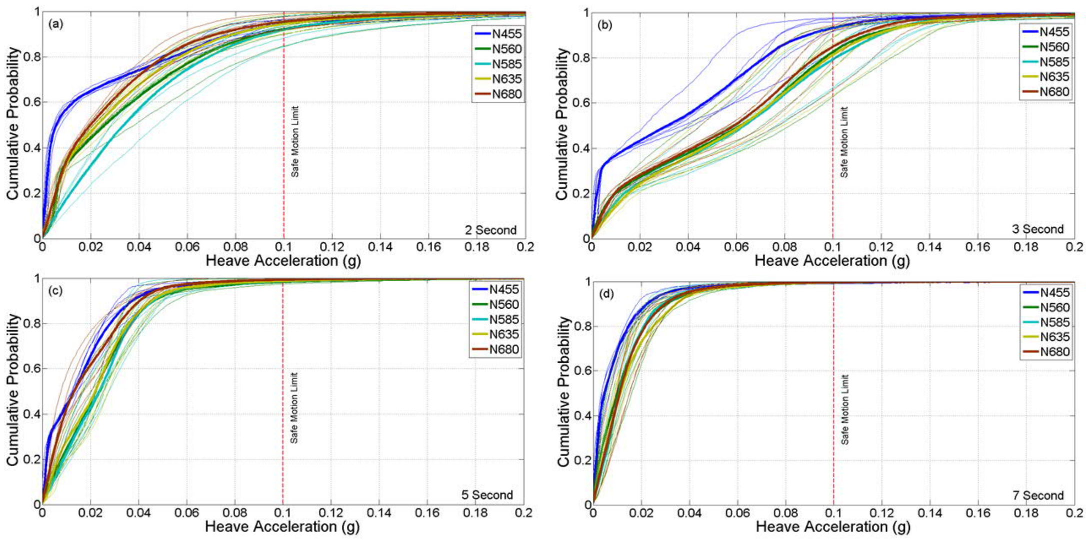


FIGURE 5.7. CUMULATIVE DISTRIBUTION FUNCTIONS FOR THE NARROW PONTOON IN HEAVE. (A) 2 SECOND PERIOD, (B) 3 SECOND PERIOD, (C) 5 SECOND PERIOD AND (D) 7 SECOND PERIOD WAVE. THIN LINES INDICATE INDIVIDUAL SENSORS (1-5) AND THICK LINES REPRESENT THE MEAN OF ALL 5 SENSORS.

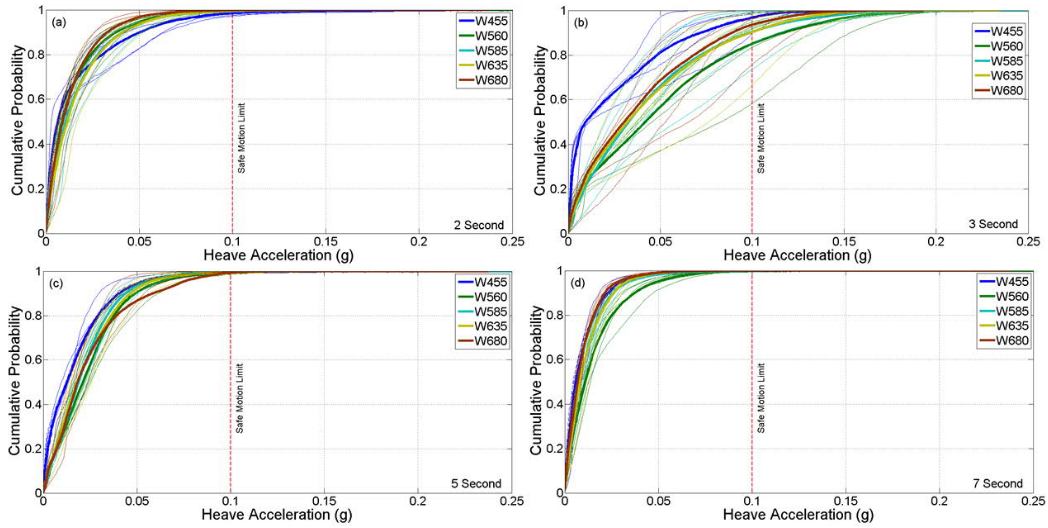


FIGURE 5.8. CUMULATIVE DISTRIBUTION FUNCTIONS FOR THE WIDE PONTOON IN HEAVE. (A) 2 SECOND PERIOD, (B) 3 SECOND PERIOD, (C) 5 SECOND PERIOD AND (D) 7 SECOND PERIOD WAVE. THIN LINES INDICATE INDIVIDUAL SENSORS (1-5) AND THICK LINES REPRESENT THE MEAN OF ALL 5 SENSORS.

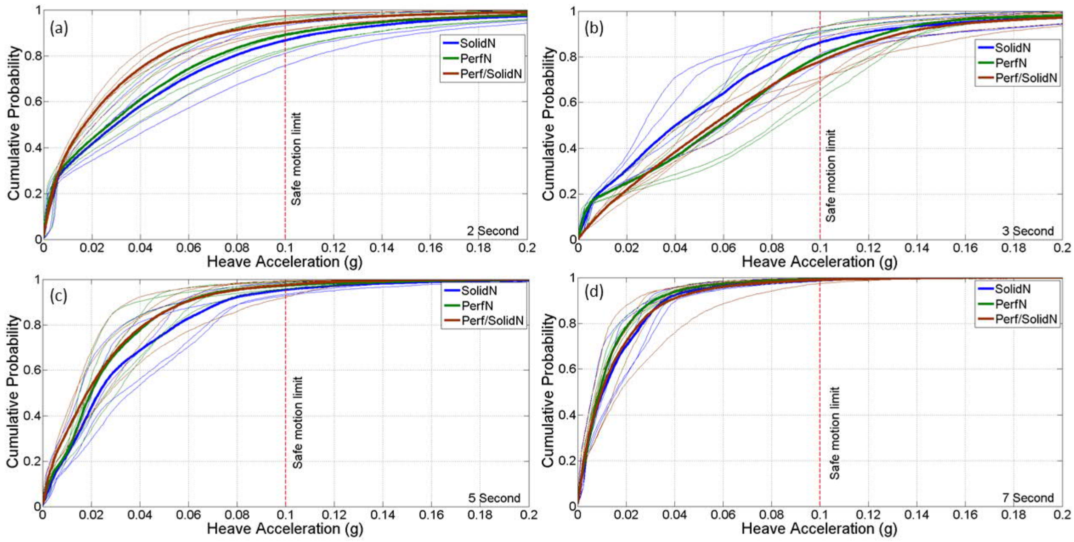


FIGURE 5.9. CUMULATIVE DISTRIBUTION FUNCTIONS FOR THE NARROW PONTOON IN HEAVE WITH THREE DIFFERENT SKIRT ARRANGEMENTS. (A) 2 SECOND PERIOD, (B) 3 SECOND PERIOD, (C) 5 SECOND PERIOD AND (D) 7 SECOND PERIOD WAVE. THIN LINES INDICATE INDIVIDUAL SENSORS (1-5) AND THICK LINES REPRESENT THE MEAN OF ALL 5 SENSORS.

Surge acceleration occurs in the direction of wave propagation (x-axis). TABLE 5.3 indicated how natural period in roll changed with draft for each pontoon. The natural period in roll relates to the surge acceleration as detailed by Boccadamo and Rosano (2019), where the lateral acceleration acting on a fixed point along the hull is a function of roll period and distance from the roll axis. A reduction in roll period causes an increase in lateral acceleration and vice versa. The change in roll period is due to the change in metacentric height resulting from changing draft. As the natural period in roll changes from approximately 2s up to approximately 3s (TABLE 5.3) it is expected that the exceedance curves (surge) change accordingly. FIGURE 5.10 and FIGURE 5.11 show the cumulative probability of exceeding the safe motion limit in surge for each wave period and draft combination. For the Narrow Pontoon, the highest percent exceedance occurred for a draft of 585mm (FIGURE 5.10) with the 2 second period wave exceeding the SML 18.06% of the time, followed by 3 second (15.39%), 5 second (14.16%) and 7 second (13.95%). For all other wave periods, the different drafts all had percent exceedances of the SML = 0.1g < 10%.

There was a more significant influence in altering draft for surge than heave. The effect of draft was more influential on the wider pontoon when compared with the narrow pontoon in exceeding the SML in surge (FIGURE 5.11) where a greater spread of results for each draft tested is observed. For the Wide Pontoon both the 560mm and 635mm draft had similar results, with approximately 33% exceedance of the SML for all wave periods, this was the highest exceedance observed. FIGURE 5.12 shows the effect on surge acceleration due to the addition of skirts. It is again observed that the highest exceedance of SML occurs for a wave period of 3 seconds with the single solid skirt (SolidN) recording the highest exceedance of approximately 40%, higher than results without skirts (FIGURE 5.10b). During testing a significant jolt resulting from skirt/pile interference was observed for the solid front skirt (SolidN) arrangement, as shown in the results where it is seen that SolidN records higher exceedance than the other arrangements for each wave period tested.

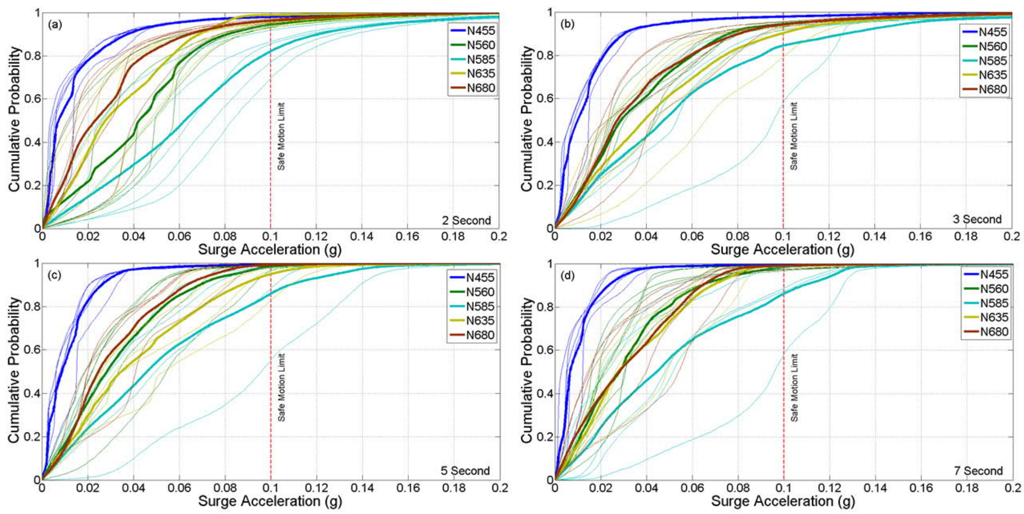


FIGURE 5.10. CUMULATIVE DISTRIBUTION FUNCTIONS FOR THE NARROW PONTOON IN SURGE. (A) 2 SECOND PERIOD, (B) 3 SECOND PERIOD, (C) 5 SECOND PERIOD AND (D) 7 SECOND PERIOD WAVE. THIN LINES INDICATE INDIVIDUAL SENSORS (1-5) AND THICK LINES REPRESENT THE MEAN OF ALL 5 SENSORS.

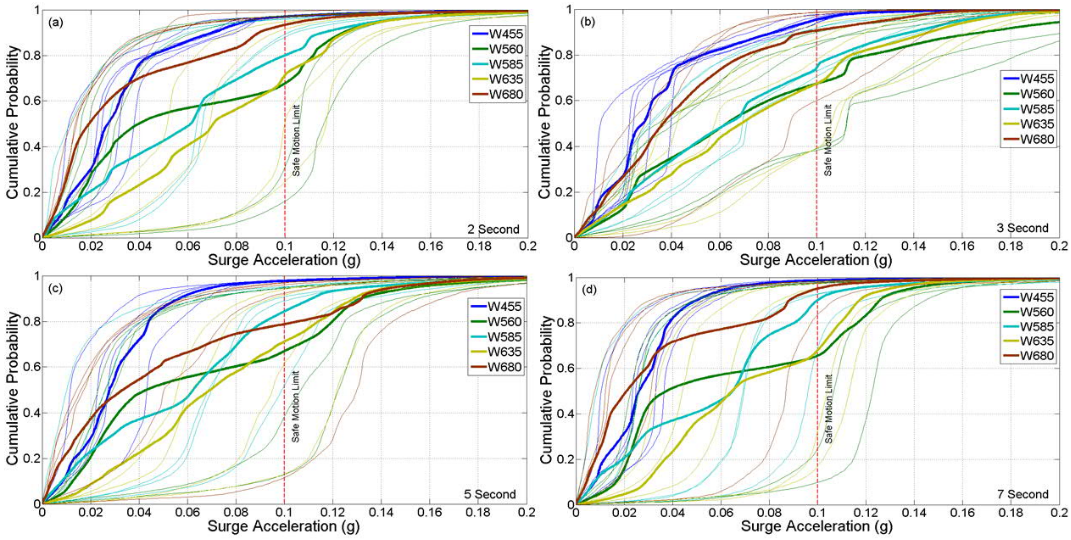


FIGURE 5.11. CUMULATIVE DISTRIBUTION FUNCTIONS FOR THE WIDE PONTOON IN SURGE. (A) 2 SECOND PERIOD, (B) 3 SECOND PERIOD, (C) 5 SECOND PERIOD AND (D) 7 SECOND PERIOD WAVE. THIN LINES INDICATE INDIVIDUAL SENSORS (1-5) AND THICK LINES REPRESENT THE MEAN OF ALL 5 SENSORS.

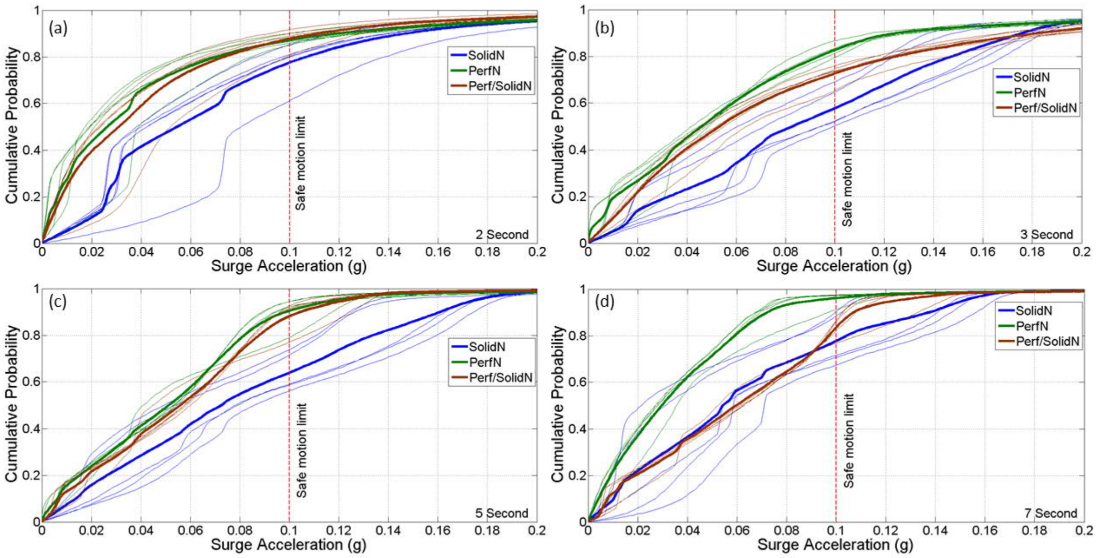


FIGURE 5.12. CUMULATIVE DISTRIBUTION FUNCTIONS FOR THE NARROW PONTOON IN SURGE WITH THREE DIFFERENT SKIRT ARRANGEMENTS. (A) 2 SECOND PERIOD, (B) 3 SECOND PERIOD, (C) 5 SECOND PERIOD AND (D) 7 SECOND PERIOD WAVE. THIN LINES INDICATE INDIVIDUAL SENSORS (1-5) AND THICK LINES REPRESENT THE MEAN OF ALL 5 SENSORS.

5.2.4 Comfort Criteria: Root Mean Square Acceleration

Mean RMS heave acceleration for each draft tested is presented in FIGURE 5.13. It is noted that the heave RMS SML of 0.02g is exceeded in all tests other than for some drafts of the Wide Pontoon under 7 second waves. Similar to the results presented for peak heave acceleration (Section 5.2.3), draft showed minor effect on

RMS heave acceleration (FIGURE 5.13ab) except for the 3 second tests which were closely related to the natural period of the pontoon structures (TABLE 5.3).

As discussed in Section 5.2.3, draft had a significant impact on RMS surge acceleration (FIGURE 5.14). It is noted that the surge RMS values are significantly higher than the RMS heave accelerations and that the surge RMS SML of 0.03g is exceeded in all tests. Generally, for both pontoons, the shallowest draft (455mm) recorded the lowest RMS surge acceleration, consistent with the cumulative values presented in FIGURE 5.10 and FIGURE 5.11. Above 2 seconds a draft of 585mm recorded the highest RMS surge acceleration for the Narrow pontoon as per results presented in FIGURE 5.10. Results show draft does influence mean RMS acceleration, predominantly in the surge axis and when looking at all axes combined (FIGURE 5.15).

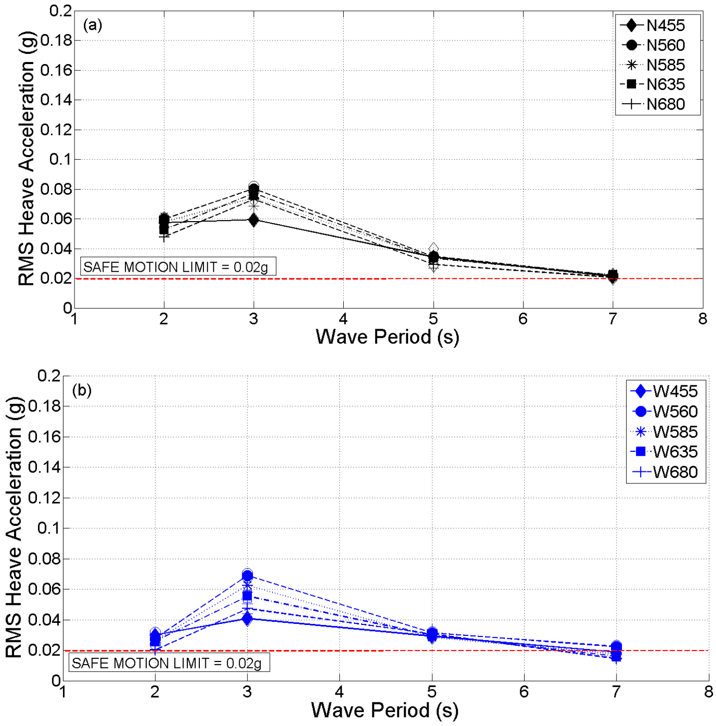


FIGURE 5.13. RMS HEAVE ACCELERATION PLOTTED AGAINST WAVE PERIOD FOR EACH DRAFT TESTED: (A) NARROW AND (B) WIDE PONTOONS. RED DASHED LINE REPRESENTS RMS SML. RESULTS PLOTTED FOR ALL THREE TESTS REPRESENTED BY INDIVIDUAL OPEN SYMBOLS AND SOLID SYMBOLS WITH LINE SHOWING THE MEAN.

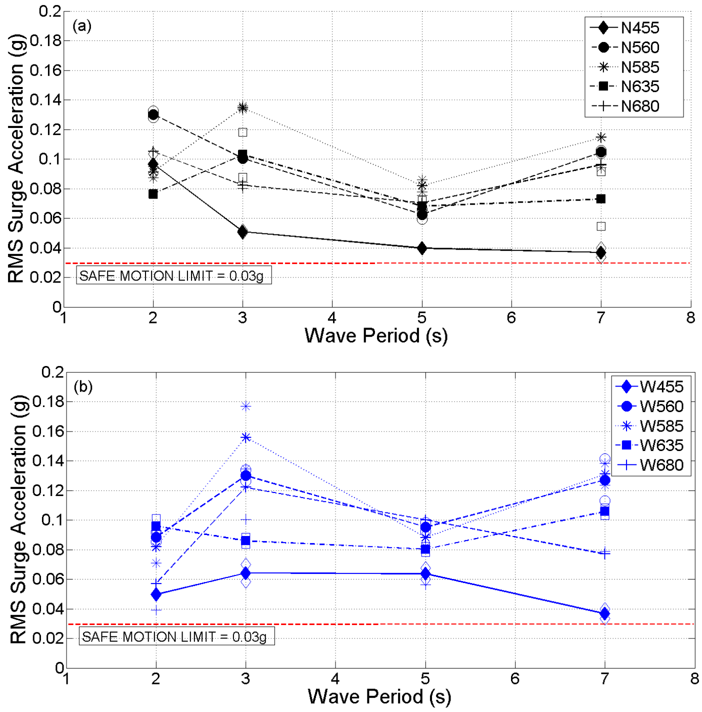


FIGURE 5.14. RMS SURGE ACCELERATION PLOTTED AGAINST WAVE PERIOD FOR EACH DRAFT TESTED: (A) NARROW AND (B) WIDE PONTOONS. RED DASHED LINE REPRESENTS RMS SML. RESULTS PLOTTED FOR ALL THREE TESTS REPRESENTED BY INDIVIDUAL OPEN SYMBOLS AND SOLID SYMBOLS WITH LINE SHOWING THE MEAN.

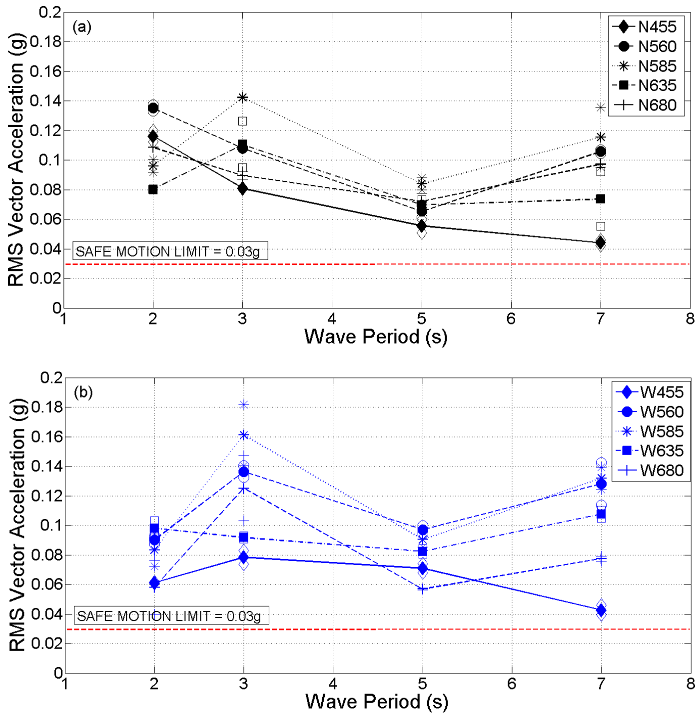


FIGURE 5.15. RMS VECTOR ACCELERATION PLOTTED AGAINST WAVE PERIOD FOR EACH DRAFT TESTED: (A) NARROW AND (B) WIDE PONTOONS. RED DASHED LINE REPRESENTS RMS SML. RESULTS PLOTTED FOR ALL THREE TESTS REPRESENTED BY INDIVIDUAL OPEN SYMBOLS AND SOLID SYMBOLS WITH LINE SHOWING THE MEAN.

Comparing the three skirt arrangements there was minimal variation to RMS heave and significant influence to RMS surge acceleration (FIGURE 5.16). At periods above 3 seconds the double skirt arrangement (Perf/SolidN) showed a significant influence on reducing RMS surge from 0.12 (PerfN) to less than 0.06 (Perf/SolidN) (FIGURE 5.16b). Comparing results with those obtained for no skirts (FIGURE 5.13a FIGURE 5.14a), the double skirt arrangement recorded lower RMS surge accelerations when compared with the deepest draft tested (FIGURE 5.13a), and were comparative to those recorded for the shallowest draft (0.04g – 0.1g).

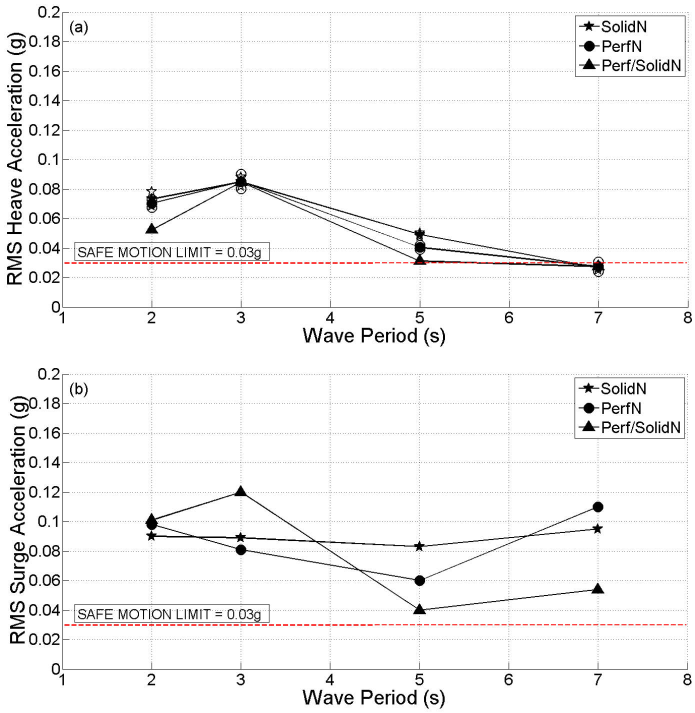


FIGURE 5.16. RMS (A) HEAVE AND (B) SURGE ACCELERATION PLOTTED AGAINST WAVE PERIOD FOR EACH SKIRT ARRANGEMENT TESTED – NARROW PONTOON. RED DASHED LINE REPRESENTS RMS SML. RESULTS PLOTTED FOR ALL THREE TESTS REPRESENTED BY INDIVIDUAL OPEN SYMBOLS AND SOLID SYMBOLS WITH LINE SHOWING THE MEAN.

As discussed in Section 4.2.4, the onset of motion sickness is very much dependent on the individual, the exposure time, the level of motion and the frequency at which it occurs. Motion sickness occurs for motions between 0.1 – 0.5 Hz (Matsangas et al. 2014 and ABS 2014) with ABS (2014) recommending a maximum RMS acceleration of 0.007g within this frequency range. Examining the RMS surge acceleration for the Narrow Pontoon at cut off frequencies between 0.1 to 0.5Hz and looking at the effect of draft FIGURE 5.17, it can be seen that deeper drafts (635 and 680mm) generally record the highest RMS surge acceleration for each wave period tested except for 3 seconds where a draft of 560mm records the highest RMS Surge acceleration for each cut off frequency. As per the results presented in TABLE 5.3, a draft of 560mm recorded a natural period in heave and roll of 2.87 and 3.15 respectively, the closest match to the forcing period (3 second wave). The values recorded for a draft of 560mm at a wave period of 3 seconds (FIGURE 5.17b) peak at a value of 0.075g, with the values higher than those recorded for each of the other wave periods tested. The results presented in FIGURE 5.17b, at cut off frequencies of 0.4 and 0.5Hz are consistent with the peak RMS surge acceleration results presented in FIGURE 5.14a. It is observed that a draft of 560mm records the highest RMS acceleration in surge and 455mm draft the lowest. The SML for motion sickness is exceeded for almost all drafts and cut off frequencies. Comparing with results presented in Chapter 4, increasing draft saw higher values of RMS surge acceleration than those resulting from an increase in beam at each of the cut off frequencies. Results were comparable for the Wide pontoon (FIGURE 5.18) except it was a draft of 635mm (W635) that consistently recorded the higher RMS in surge at each cut off frequency. Results in heave relative to cut off frequency and RMS acceleration showed little variation due to altering draft so are not presented here.

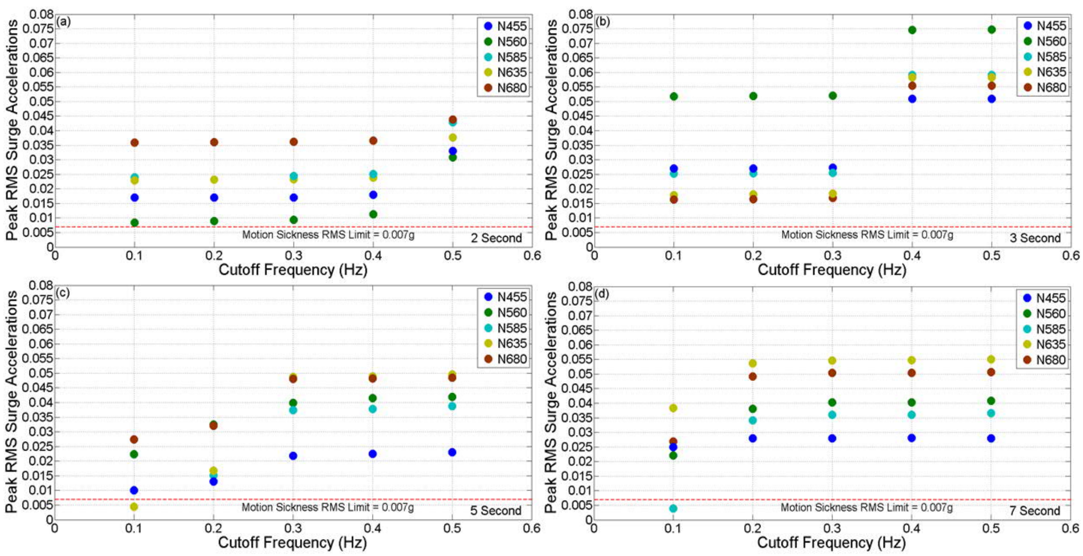


FIGURE 5.17. PEAK RMS SURGE ACCELERATION PLOTTED AGAINST CUT OFF FREQUENCY FOR EACH DRAFT TESTED NARROW PONTOON: (A) 2 SECOND, (B) 3 SECOND, (C) 5 SECOND AND (D) 7 SECOND. RED DASHED LINES SHOWS MOTION SICKNESS RMS LIMIT IN SURGE AND HEAVE AS NOMINATED BY ABS (2014).

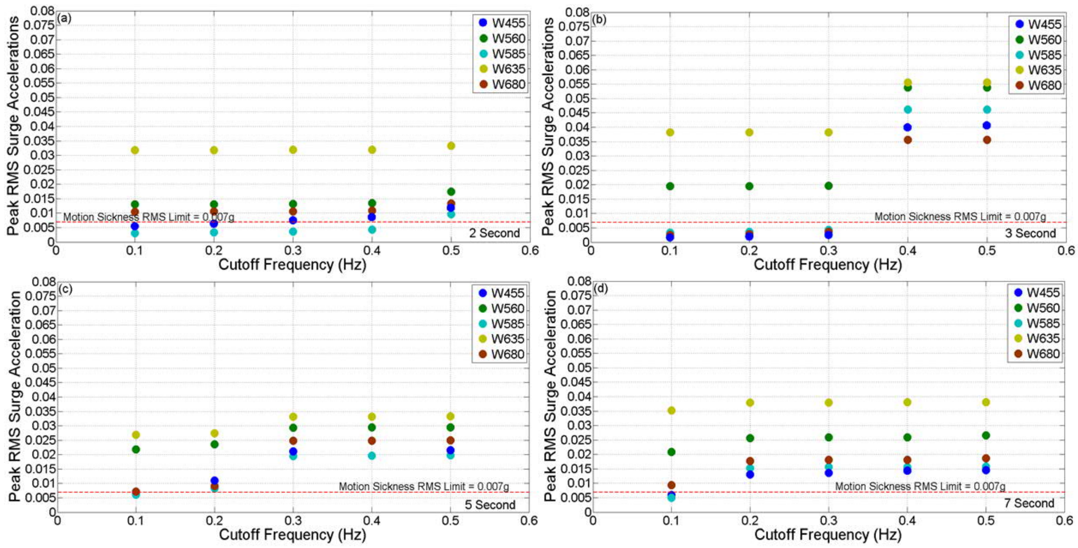


FIGURE 5.18. PEAK RMS SURGE ACCELERATION PLOTTED AGAINST CUT OFF FREQUENCY FOR EACH DRAFT TESTED WIDE PONTOON: (A) 2 SECOND, (B) 3 SECOND, (C) 5 SECOND AND (D) 7 SECOND. RED DASHED LINES SHOWS MOTION SICKNESS RMS LIMIT IN SURGE AND HEAVE AS NOMINATED BY ABS (2014).

5.2.5 ANGLES OF MOTION

Similar to the results presented for the effect of beam on angles of motion (Section 4.2.5), roll rotations were observed above the recommended operational SML 6° (Peak) and comfort SML 2° (RMS) limit for most of the drafts tested here (FIGURE 5.19, FIGURE 5.20 and FIGURE 5.21). For both pontoons the highest peak roll angle was recorded at a wave period of 7 seconds (FIGURE 5.19) and the highest RMS roll angle at a wave period of 3 seconds (FIGURE 5.20). For the Narrow Pontoon (FIGURE 5.19a and FIGURE 5.20a) both peak and RMS roll SML criteria were exceeded for all draft/wave period combinations excluding N455 at 3 and 5 seconds. Generally, for the Narrow Pontoon, for wave periods above 3 seconds as draft increased roll response increased, peaking at 7 seconds (~18°, N680). Interesting behaviour is observed at 3 seconds where N585 recorded the highest peak (~15°) and RMS (~7°) roll, where the natural period is approximately equal to the forcing period. This behaviour is consistent with the RMS surge accelerations (FIGURE 5.14a) where N560 and N585 recorded the highest results at 3 seconds. For the Wide Pontoon (FIGURE 5.19b and FIGURE 5.20b) there was not a general trend for an increase in draft resulting in an increase in roll. Draft caused the most variation in observed roll above a wave period of 2 seconds for the Wide Pontoon, with the maximum roll angle recorded at 7 seconds (~20°, W560). The addition of skirts increased roll response further, with peak and RMS roll SML exceeded for all skirt arrangement and all wave periods. The maximum peak roll was recorded at 3 seconds (~27°) for the skirt combination Perf/SolidN and maximum RMS roll at a wave period of 3 seconds (~14°, Perf/SolidN). At 7 seconds the perforated front skirt recorded a much higher roll angle compared with the other two skirt arrangements (~22° compared with 5 - 9°), this may be due to the uneven weight distribution associated with having only one skirt.

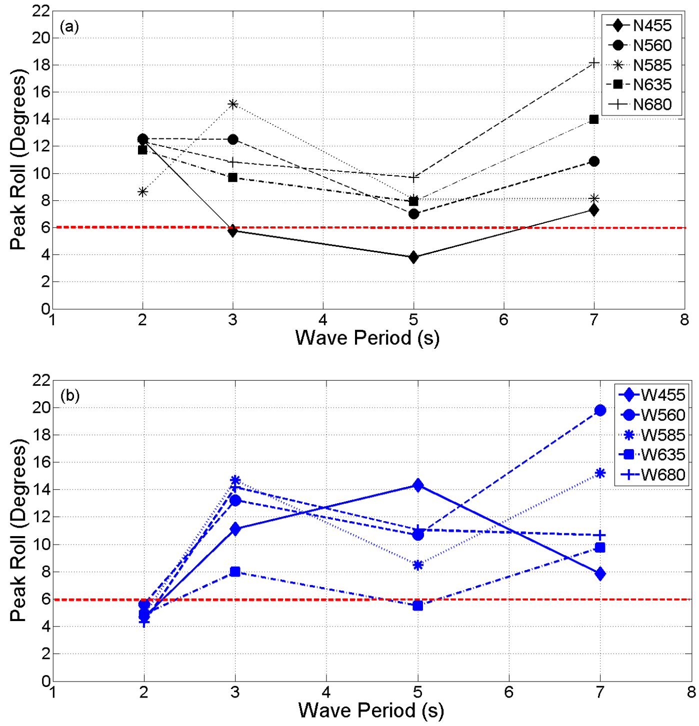


FIGURE 5.19. PEAK ROLL PLOTTED AGAINST WAVE PERIOD RELATIVE TO DRAFT FOR: (A) NARROW PONTOON AND (B) WIDE PONTOON. RED DASHED LINES SHOWS PEAK SML. RESULTS PRESENTED ARE THE MEAN OF THE TRIPLICATE RUNS.

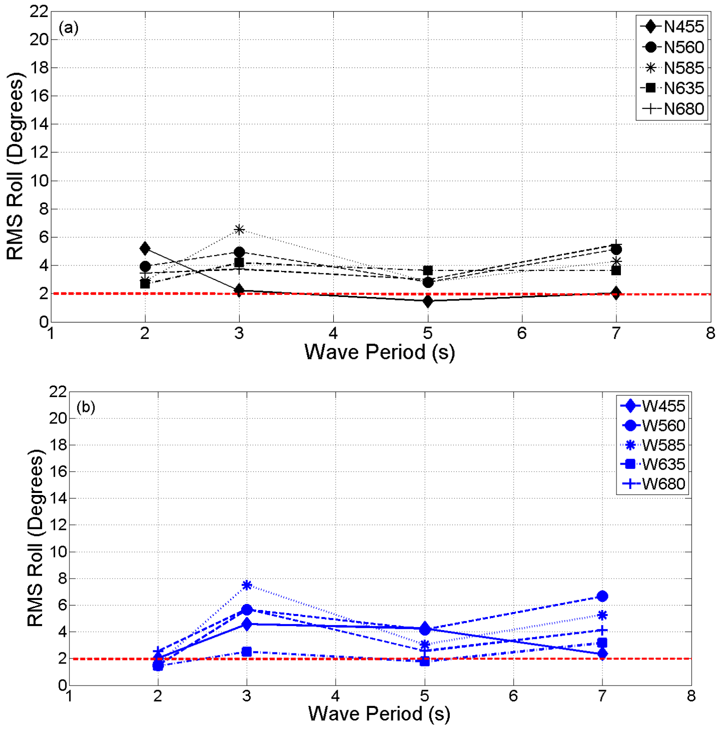


FIGURE 5.20. RMS ROLL PLOTTED AGAINST WAVE PERIOD RELATIVE TO DRAFT FOR: (A) NARROW PONTOON AND (B) WIDE PONTOON. RED DASHED LINES SHOWS RMS SML. RESULTS PRESENTED ARE THE MEAN OF THE TRIPLICATE RUNS.

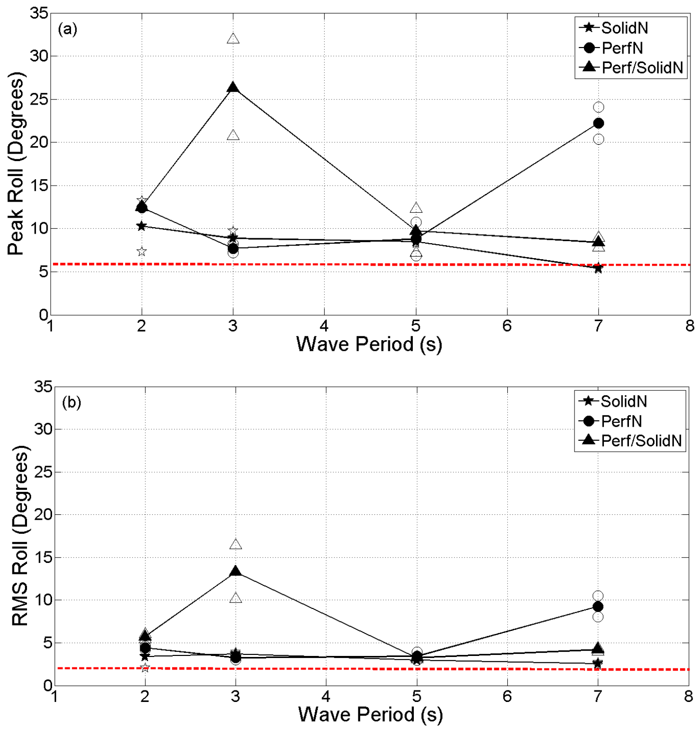


FIGURE 5.21. PEAK AND RMS ROLL PLOTTED AGAINST WAVE PERIOD RELATIVE TO SKIRT TESTING: (A) PEAK ROLL AND (B) RMS ROLL. RED DASHED LINES SHOW PEAK AND RMS SML. TRIPLICATE RESULTS ARE PLOTTED AS INDIVIDUAL SYMBOLS WITH THE MEAN OF THE THREE TESTS REPRESENTED BY THE LINE.

5.3 SUMMARY

This chapter has presented the influence draft (through addition of mass and skirts) has on the motion response and wave reflection and transmission properties of both the Narrow and Wide Pontoons. As draft increased attenuation performance (as measured by Kt) improved for the shorter waves. The effect of draft was most noticeable around the natural period of the structure (T=3 seconds) with an increase in draft improving attenuation performance. Draft influenced heave with an increase in draft leading to a reduction in peak heave of ~17% and 50% for the Narrow and Wide pontoons, with the greatest spread of results recorded at 2 seconds. By contrast, increasing draft generally saw surge accelerations increase. Interesting behaviour was observed at drafts of 560mm and 585mm (N560/W560 (D/d = 0.156) and N585/W585 (D/d = 0.163)) which consistently recorded peak, RMS, vector and roll results higher than the other drafts tested, most obvious at 3 seconds. Draft was observed to have a significant impact on peak roll response; however, it was not always the deeper draft that recorded the highest peak roll. When comparing the results from Chapter 4 (beam) and Chapter 5 (draft), beam had a more significant effect on heave acceleration, while draft had a more significant effect on surge accelerations and roll. This highlights the complex nature of the dynamic motion response of the piled floating pontoons with respect to design considerations of beam and draft, with no clear leader in reducing accelerations and roll below the SML derived in Chapter 2. This is further discussed in Chapter 7.

CHAPTER 6: FIELD SCALE MEASUREMENTS OF THE DYNAMIC MOTIONS OF PILED FLOATING BOX PONTOONS

This chapter focusses on Objective 3 of this thesis and presents the results of the motion response of floating box pontoons supported by piles, located within Sydney Harbour and the Shoalhaven, NSW. Results are presented for peak, cumulative and root mean square accelerations and angles with emphasis given on comparing against the safe motion limits nominated in Section 2.6. User perception of the motions has been obtained through surveys and results presented. These are briefly compared to the laboratory results presented in Chapters 4 and 5.

Some content of this chapter is taken from the following publications:

Conference Proceedings

Freeman, E.; Cox, R., and Splinter, K. 2017. 'Suitable Criteria for Safe Motion Limits of a Floating Pontoon Relative to the Postural Stability of a Stationary Standing Person', *Australasian Coasts & Ports 2017: Working with Nature*. Barton, ACT: Engineers Australia, PIANC Australia and Institute of Professional Engineers New Zealand, 2017: 476-482.

Freeman, E.; Cox, R., and Splinter, K. 2018. 'Floating Breakwaters as Public Platforms – Impact on Postural Stability', *Coastal Engineering Proceedings*, *1*(36), structures.63.

Freeman, E.; Cox, R., Splinter, K., and Flocard, F. 2019. 'Floating Pontoon Motions, Operational Safe Motion Limits', Pacific International Maritime Conference.

6.1 INTRODUCTION

Following on from the experimental tests which showed that two scaled pontoons consistently exceeded the nominated safe motion limits (TABLE 2.1) under boat wake conditions, field testing was undertaken to ensure that scaling effects from the laboratory work were not significantly impacting on the results. Field testing was also underataken to further understand people's perceptions on comfort and stability while on floating pontoons. The particulars of each of the pontoons was presented in Chapter 3, TABLE 3.4, with Orient Point the most comparable to the pontoons tested in the flume. The other pontoons tested were much larger in terms of width, length, and overall displacement. As described in Section 3.3, field testing incorporated measurements of wave data, corresponding pontoon motion data along with public (pontoon users) surveyed perception of the motions in order to relate them to the experimental results and the nominated SML. Twenty-six users were surveyed in order to establish an understanding of their perception of the motions (TABLE 6.1). Field studies were limited due to the COVID-19 pandemic which began at the start of the field campaign.

TABLE 6.1. USER SURVEY DATES AND PARTICIPANT NUMBERS

Pontoon	Date	Number of Surveys
Cremorne Point	15/03/2020	13
McMahons Point	15/03/2020	10
Orient Point	13/02/2020	3
HMAS Creswell	16/12/2019	0

6.2 RESULTS

6.2.1 DATA COLLECTED

As detailed in Chapter 3 wave data was collected using one Ultrasonic Wave Sensor XB positioned on a fixed pile adjacent to the pontoons being tested. FIGURE 6.1 shows a sample of the water level time series for each of the chosen sites, prior to filtering to remove the short duration peaks observed in FIGURE 6.1 which did not correspond to actual wave data. Data was collected over a one-hour period for each site. Cremorne Point (FIGURE 6.1a) and McMahons Point (FIGURE 6.1b) are located in Sydney harbour and are influenced by heavy and consistent ferry and boat traffic along with wind waves. In contrast HMAS Creswell (FIGURE 6.1c) and Orient Point (FIGURE 6.1d) are sheltered locations with the waves generated by passing small recreational boat craft. Both wave and acceleration data were time-stamped for comparison and analysis. All additional data such as boat name, boat speed and direction were recorded by hand and photo.

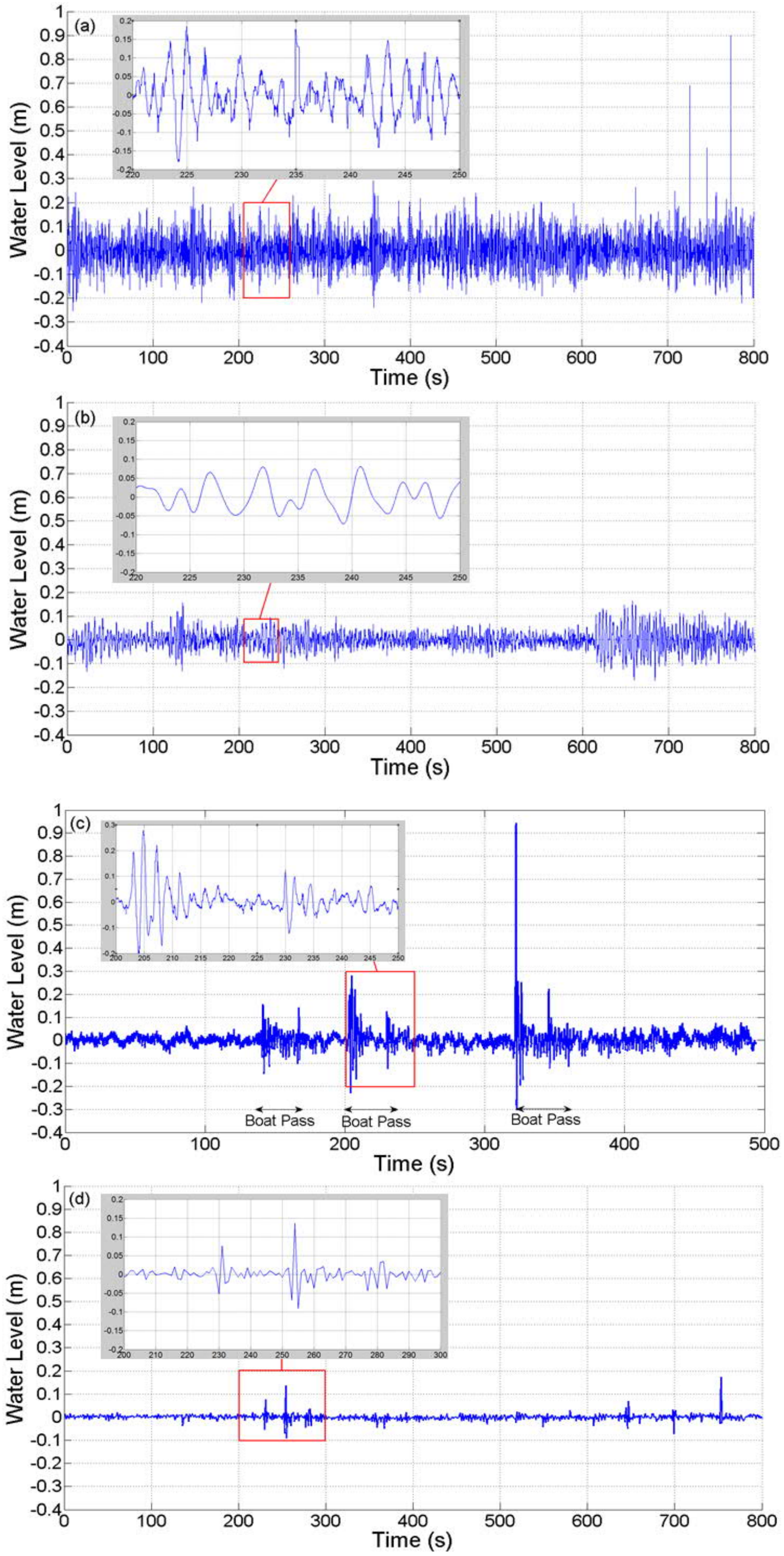


FIGURE 6.1. SAMPLE SECTION OF WATER ELEVATION TIME SERIES FOR EACH FIELD SITE: (A) CREMORNE POINT; (B) MCMAHONS POINT; (C) HMAS CRESWELL; AND (D) ORIENT POINT. A SECTION OF WAVE HAS BEEN MAGNIFIED FOR INFORMATION ONLY.

TABLE 6.2 provides results on the analysed wave parameters for each of the sites. Wave heights and periods presented are the mean over the time period of testing, determined using the zero-up-crossing method of the filtered water level time series. The mean wave height and period has been used in order to provide a comparison with the mean wave heights and periods presented in Chapters 4 and 5. Two sites, HMAS Creswell and Orient Point were targeted field campaigns with a dedicated small water craft passing the pontoon in an otherwise calm water environment to replicate the laboratory experiments. It should be noted that the wave heights and periods determined for HMAS Creswell and Orient Point are based on the overall average mean wave height and period of each boat pass determined using the zero-up-crossing method for the section of time series corresponding to each boat pass, they are not based on the complete ~1hr time series. Comparing TABLE 6.2 with TABLE 4.1 and TABLE 5.1 , wave heights in the field were lower than equivalent prototype scaled from laboratory testing for three of the sites, Orient Point was comparable (0.3m). Field wave periods at the four sites were small <=3 seconds compared to the laboratory testing that ranged from 2-7 seconds. Overall, Orient Point was most comparable to the laboratory work.

TABLE 6.2. FIELD TESTING PARAMETERS FOR EACH SITE

Location	B/D	B/L	H_m (m)	T_m (s)	H/L	Displacement (t)
Cremorne Point	10.0	0.94	0.16	2.4	0.015	276
McMahons Point	11.1	0.78	0.08	3.26	0.006	249
HMAS Creswell (Boat Pass)	5.0	0.22	0.25	2.3	0.018	30
Orient Point (Boat Pass)	7.2	0.33	0.3	2.1	0.025	18

6.2.2 OPERATIONAL CRITERIA: PEAK VERTICAL AND LATERAL ACCELERATION

As detailed in Chapter 2 theoretical peak heave acceleration can be calculated based on wave amplitude and period (Eq.2.7). Examining the physical characteristics of each of the floating pontoons and the measured wave conditions during testing, theoretical peak accelerations (assuming a free-floating body, Eq. 2.7) ranged from

0.06g (Cremorne Point) to 0.14g (Orient Point) (TABLE 6.3), suggesting that it was unlikely that SML criteria would be exceeded at most of the sites. The highest expected accelerations are for Orient Point, which was the smallest pontoon (18t) and the steepest wave (H/L=0.025). In contrast the lowest accelerations are expected at Cremorne Point, the largest pontoon (276t) and second smallest wave (H=0.16, H/L=0.015). The experimental results agree with the ranking of the theoretical (Orient Point the highest expected and Cremorne the lowest) but are significantly different in magnitude. Orient Point recorded peak accelerations almost twice what was theoretically predicted (0.25g), HMAS Creswell and Cremorne Point 0.11g and McMahons Point 0.05g. HMAS Creswell was the closest in agreement between theoretical and field.

TABLE 6.3. THEORETICALLY DERIVED AND FIELD BASED PEAK HEAVE ACCELERATION FOR EACH SITE. BOLD INDICATES EXCEEDANCE OF THE NOMINATED SML.

Location	Theoretical Peak Heave (g)	Field Peak Heave (g)
Cremorne Point	0.06	**0.11**
McMahons Point	0.015	0.05
HMAS Creswell (Boat Pass)	**0.10**	**0.11**
Orient Point (Boat Pass)	**0.14**	**0.25**

FIGURE 6.2 shows peak in single (heave, surge and sway) axis of acceleration relative to wave period presented in TABLE 6.2. Orient Point recorded the highest peak for each axis of acceleration (FIGURE 6.2abc). This pontoon had the smallest displacement (18t) and was subject to the largest wave (0.3m) of the smallest period (2.1 seconds). The only pontoon to not exceed the SML in each axis was McMahons Point. This pontoon had a large displacement (249t) and was subject to much smaller waves (0.08m) of longer period (3.26s). As presented in Chapter 4, it is the shorter wave periods that result in high peaks in acceleration. Even with significant differences between the size of each pontoon three out of the four sites exceeded the nominated SML even in the mild conditions. Orient Point was the pontoon that most closely resembled the laboratory work; however, it had a larger displacement (18t) compared with the laboratory tested Narrow pontoon (~8t) and the Wide pontoon (~14t). Peak heave accelerations were similar for similar displacements (0.25g Wide

Pontoon vs 0.25g Field), suggesting laboratory results were representative of similar full-scale conditions.

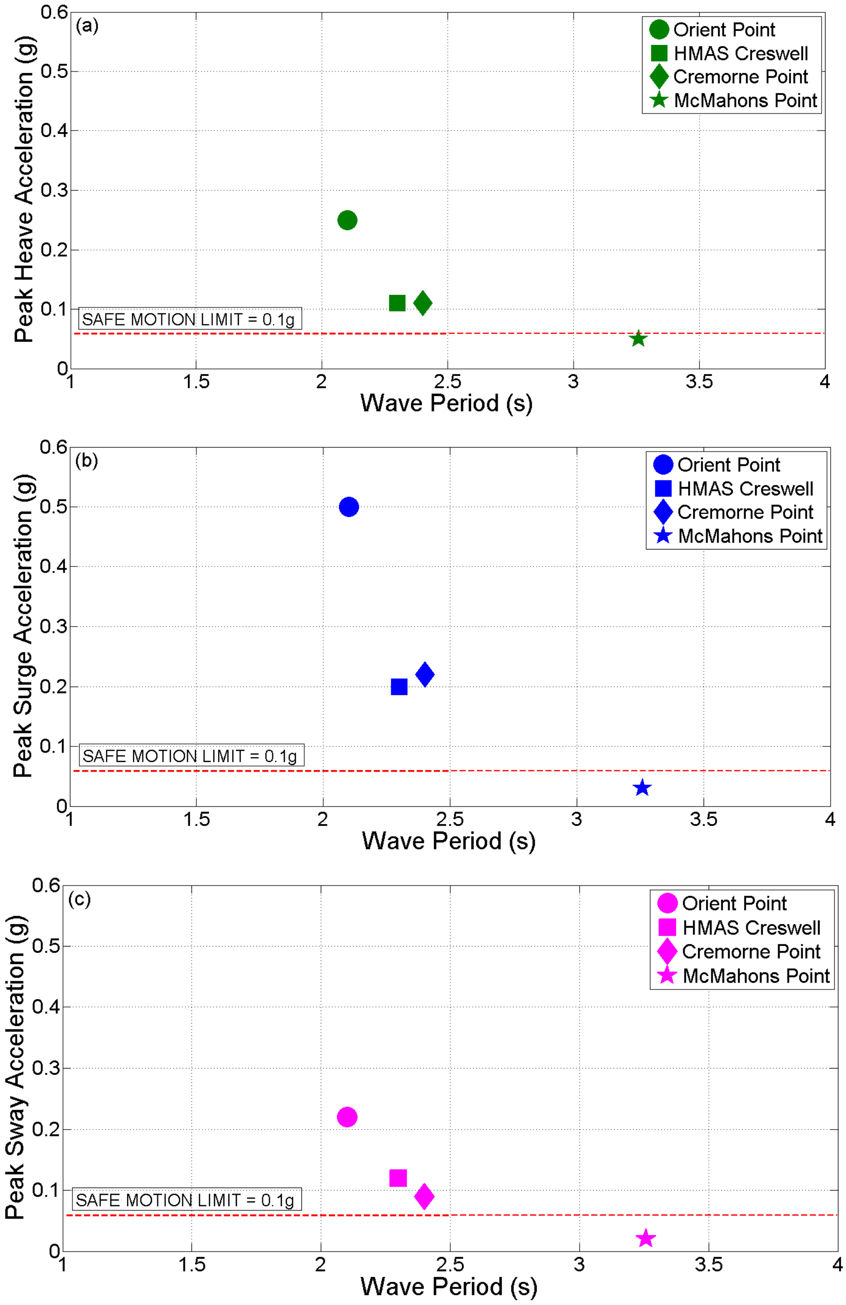


FIGURE 6.2. PEAK IN SINGLE (HEAVE, SURGE AND SWAY) AXIS OF ACCELERATION PLOTTED AGAINST WAVE PERIOD FOR EACH OF THE FIELD PONTOONS AND COMPARED AGAINST THE SAFE MOTION LIMIT OF 0.1G. (A) HEAVE ACCELERATION, (B) SURGE ACCELERATION AND (C) SWAY ACCELERATION. POINTS REPRESENT THE MEAN OF THE TWO SENSORS.

6.2.3 COMFORT CRITERIA: ROOT MEAN SQUARE ACCELERATION

TABLE 6.4 summarizes the RMS accelerations calculated for each site and each of the axes (x-, y-, z-). These values are based on the mean RMS of the two sensors used at each site. The highest RMS accelerations in both surge and heave was recorded for Orient Point, (0.09 and 0.01g, respectively). Similar to the observed peak accelerations (FIGURE 6.2), the RMS acceleration for surge (x-axis) exceeded the comfort SML (0.03g) for all sites except McMahons Point. Heave (z-axis) RMS accelerations did not exceed the SML (0.02g). The RMS sway (y-axis) acceleration exceeded the SML (0.03g) criteria at three of the four sites and was as high as 0.07g (Cremorne Point). These results indicate that accelerations in the direction of wave propagation (surge and sway) are consistently large enough to cause discomfort for passengers using floating pontoons exposed to relatively small monochromatic boat wake. Comparing the field results from Orient Point with the laboratory results for both the Narrow and Wide pontoon for a 2 second period wave (TABLE 4.4), surge and sway RMS were comparable (Narrow RMS Surge 0.09g, Wide RMS Surge 0.05g, Narrow RMS Sway 0.03g and Wide RMS Sway 0.02g), heave RMS was slightly lower for Orient Point, when compared with the Wide pontoon of similar displacement (0.01g compared with 0.03g (Wide)).

TABLE 6.4. ROOT MEAN SQUARE (RMS) ACCELERATION IN X-, Y-. AND Z-AXIS FOR EACH OF THE TESTED SITES RELATIVE TO B/L. ALL VALUES GIVEN IN G. BOLD INDICATES EXCEEDANCE OF SML. VALUES ARE BASED ON THE MEAN RMS FROM THE TWO SENSORS.

Axis and Test ID	SML Acceleration Criteria (g)	Orient Point	HMAS Creswell	Cremorne Point	McMahons Point
a_x surge	**0.03**	**0.09**	**0.06**	**0.08**	0.003
a_y sway	**0.03**	**0.05**	**0.03**	**0.07**	0.001
a_z heave	**0.02**	0.01	0.01	0.01	0.005

6.2.4 COMFORT CRITERIA: USER PERCEPTION

As detailed in Section 3.3.4, whilst recording the motions of each pontoon, people using the pontoons were provided with a research flyer to invite them to complete a short 2-minute survey (Figure 3.11). The surveys collected information on the demographic, level of comfort and comments on potential improvements that could be made to each of the pontoons in question. TABLE 6.5 summarises the results from the surveys collected. It should be noted that people were apprehensive about completing surveys due to the onset of COVID-19, as such survey numbers were limited.

Based on the survey results collected from a varied demographic of adults, more than half the users felt uncomfortable at the time of data collection. At Cremorne

Point, 7 out of 13 users reported levels of discomfort, 6 out of 10 users at McMahons Point and 3 out of 3 users at Orient Point even on the relative mild days of testing. McMahons Point did not exceed the peak or RMS SML as detailed in TABLE 2.1; however, more than half the people felt uncomfortable. Daily users at Cremorne Point reported that at times 'the rocking can be disconcerting'. One of the users at McMahons Point (over 65 years) said she often 'feels motion sickness at Circular Quay Pontoon'. Orient Point users felt unstable during the peaks in acceleration resulting from the passing boat. It was the 'bumps' that people found uncomfortable with one user at McMahons Point commenting that it can be 'uncomfortable when the ferry bangs against the wharf'. These results indicate that users felt uncomfortable as a result of the short duration peaks (FIGURE 6.2) in acceleration even on the mild days of testing and confirm the importance of understanding and limiting short-duration peaks in acceleration that result from the pile-pontoon reaction and described in Chapters 4 and 5.

TABLE 6.5. SURVEY RESULTS FROM THREE OF THE FOUR FIELD TESTING LOCATIONS.

Cremorne Point (13)		Comfort Level	
Age	People Count	Uncomfortable	Comfortable
18-35	3	2	1
36-50	5	3	2
51-65	4	1	3
Over 65	1	1	0
Total	13	7	6
McMahons Point (10)		Comfort Level	
Age	People Count	Uncomfortable	Comfortable
18-35	2	1	1
36-50	2	1	1
51-65	1	1	0
Over 65	5	3	2
Total	10	6	4
Orient Point (3)		Comfort Level	
Age	People Count	Uncomfortable	Comfortable
18-35	2	2	0
36-50	-	-	-
51-65	-	-	-
Over 65	1	1	0
Total	3	3	0

6.2.5 ANGLES OF MOTION

FIGURE 6.3 presents the peak and RMS roll of each of the tested pontoons. Results show that the highest peak and RMS roll occurred for HMAS Creswell followed by Orient Point, the two smaller pontoons (30t and 18t, respectively) subject to the steeper waves (H/L=0.018 and 0.025, respectively). All peak roll values were below the nominated SML (FIGURE 6.3a). Comparing Orient Point with the laboratory results for the Wide pontoon (2 second wave) which are most comparable, peak and RMS roll are similar. Orient Point recorded a peak roll of ~3.5° and RMS roll of ~0.5° compared with the Wide pontoon peak roll ~4° and RMS roll 2°. All RMS roll were below the nominated SML, except at HMAS Creswell (3.4°). Roll response was influenced by a combination of wave steepness (H/L, TABLE 6.2), B/D and B/L with the steeper waves, lower B/D and B/L ratios recording higher roll response.

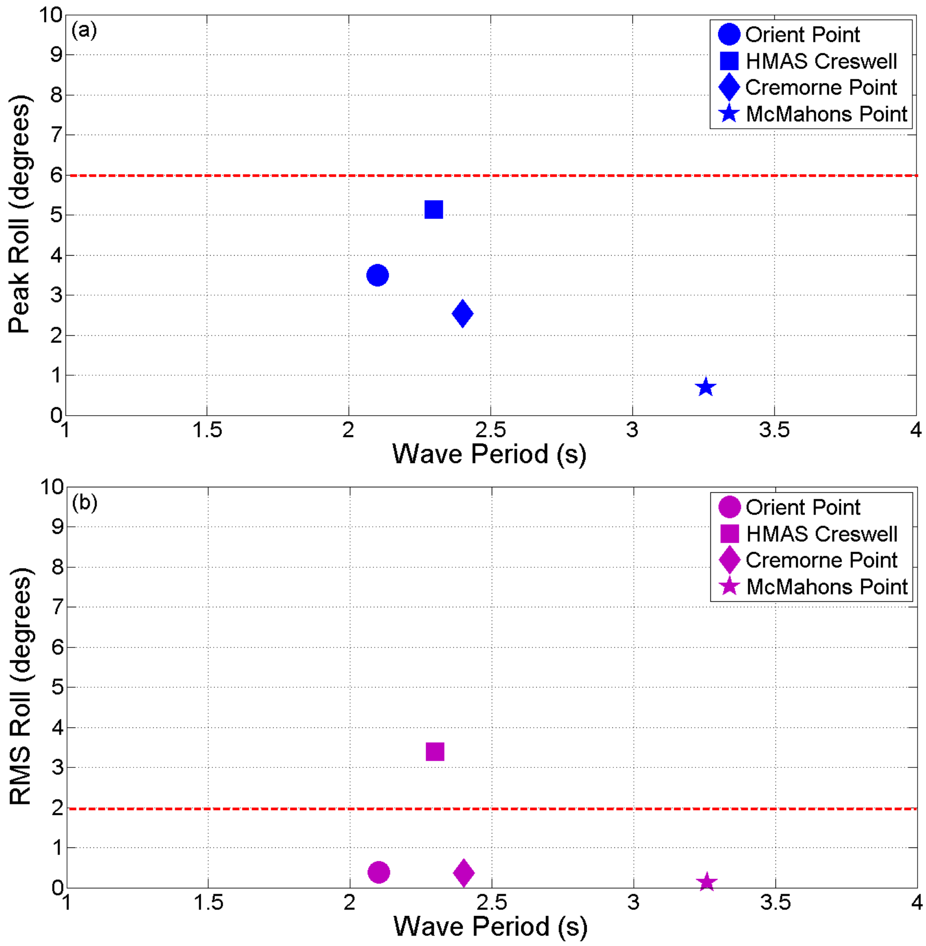


FIGURE 6.3. PEAK AND RMS ROLL PLOTTED AGAINST BEAM WAVE PERIOD FOR EACH FIELD LOCATION. (A) PEAK ROLL AND (B) RMS ROLL. RED DASHED LINES SHOW PEAK AND RMS SML. POINTS PLOTTED ARE THE AVERAGE OF THE TWO SENSORS LOCATED AT EACH SITE.

6.3 SUMMARY

Field testing at four distinct sites under typical wave conditions has shown that even under the relative mild wave conditions the nominated peak SML were exceeded at three of the four sites and user discomfort was experienced at all four sites. Orient Point, the most comparable in size and design to the laboratory testing recorded the highest peaks in all axes (0.25g (heave), 0.5g (surge) and 0.22g (sway) and all surveyed users were uncomfortable. While measured RMS heave for the four pontoons tested was substantially lower than laboratory results it should be noted that wave heights were lower than what was tested in the laboratory and displacements (tonnes) of each pontoon significantly larger, leading to a reduction in RMS heave. In surge and sway the RMS comfort criteria was exceeded at three of the four sites with results comparable to the laboratory data, seen most evidently at Orient Point. This high lateral RMS was a result of the constant 'bump' of the pontoon against the piles which was also noted in the laboratory data. It was also noted that these levels of movement were considered uncomfortable by users. Results from field testing show peaks in acceleration for short period waves < 3 seconds were similar to those reported in the laboratory as detailed in Chapters 4 and 5, reinforcing that accelerations and roll angles above what patrons considers comfortable are cause for concern and require further attention. Peak and RMS roll were influenced by a combination of wave steepness (H/L), B/D and B/L with motion roll response higher for steeper H/L and lower B/D and B/L ratios. Field testing has indicated that the nominated SML may underestimate the level of discomfort users of floating pontoons experience with many indicating discomfort even though peak SML were not exceeded, clear indication that extended field user survey are needed after COVID-19.

CHAPTER 7: DISCUSSION

This chapter combines and discusses the results from previous chapters on laboratory testing of beam effect (Chapter 4), draft effect (Chapter 5) and prototype field measurements (Chapter 6) to obtain a better definition of the dynamic motions of piled floating pontoons and their effect on the comfort and stability of people standing on these moving platforms.

Some content of this chapter is taken from the following publications:

Journal Publications

Freeman, E., Splinter, K. and Cox, R. In review. 'Laboratory Experiments on the Dynamic Motions of Piled Floating Pontoons to Boat Wake and Their Impact on Postural Stability and Safety', *Ocean Engineering*

Conference Proceedings

Freeman, E.; Cox, R., and Splinter, K. 2017. 'Suitable Criteria for Safe Motion Limits of a Floating Pontoon Relative to the Postural Stability of a Stationary Standing Person', *Australasian Coasts & Ports 2017: Working with Nature*. Barton, ACT: Engineers Australia, PIANC Australia and Institute of Professional Engineers New Zealand, 2017: 476-482.

Freeman, E.; Cox, R., and Splinter, K. 2018. 'Floating Breakwaters as Public Platforms – Impact on Postural Stability', *Coastal Engineering Proceedings*, *1*(36), structures.63.

Freeman, E.; Cox, R., Splinter, K., and Flocard, F. 2019. 'Floating Pontoon Motions, Operational Safe Motion Limits', Pacific International Maritime Conference.

7.1 INTRODUCTION

Despite their use throughout history and their gaining popularity, research on how the motions of floating pontoons impact on a person's comfort and stability are rare. There are limited guidelines or standards nominating suitable motion limits for floating pontoons as public access structures that specifically focus on patron safety and comfort. Perhaps most similar to the work presented in this thesis, Wang et al. (2020) developed a process (FIGURE 7.1) to direct design of Modular Floating Structures, for residential occupation, to ensure the comfort of occupants is considered.

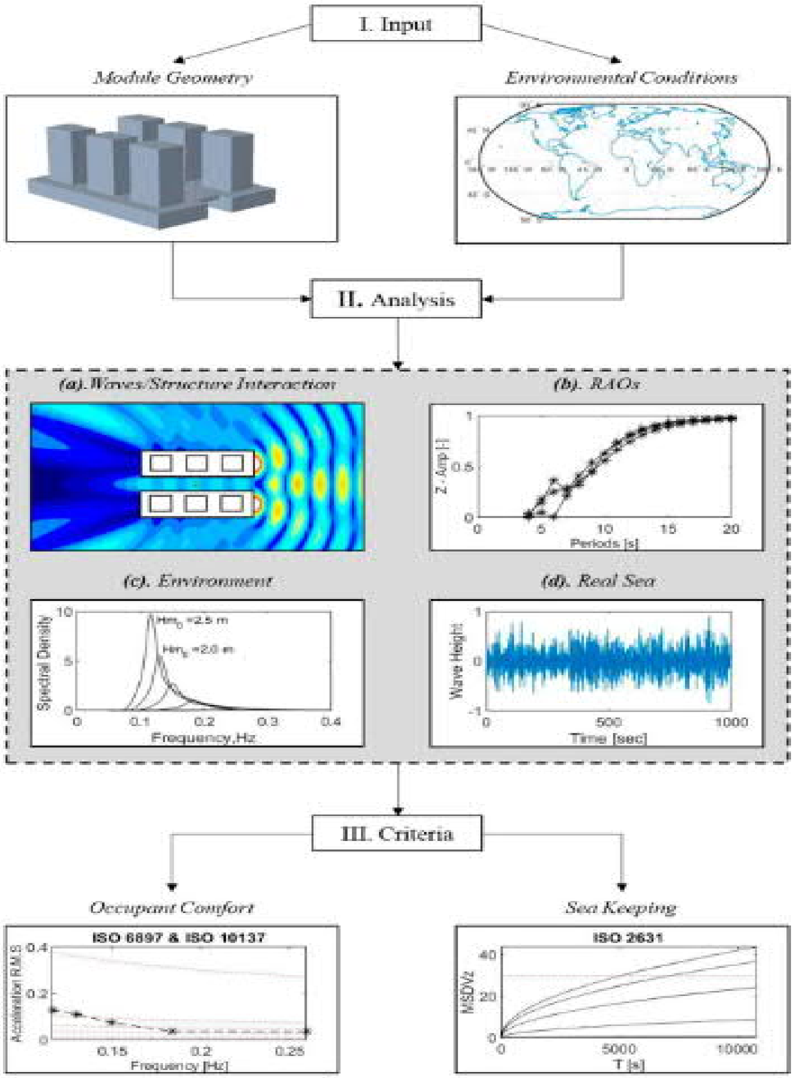


FIGURE 7.1. FLOWCHART SHOWING WANG ET AL. ANALYSIS PROCESS. THE CHART SHOWS THE ITERATIVE PROCESS NEEDED FOR DESIGN REFINEMENT BASED ON SEAKEEPING AND RESIDENTIAL BUILDINGS COMFORT CRITERIA.

Floating pontoons, as shown in FIGURE 7.2 are public access structures and as such, the comfort and stability of patrons should be considered during the design phase. The prototype wave conditions tested in this research represented typical monochromatic boat wake and ranged from 2 to 7 second period and limited in wave height from 0.29 to 0.32 m. In field-based situations waves can be multi-directional and a result of multiple coinciding boat wakes, as well as wind-generated waves producing far more complex seas and complex dynamic motions of floating bodies. The 2D dynamic motions resulting from monochromatic waves presented in Chapters 4 and 5 are thus idealized, with patrons likely to be more adversely affected in field-based situations as was detailed in Chapter 6.

FIGURE 7.2. A PUBLIC ACCESS FLOATING PONTOON LOCATED AT MAN-O-WAR STEPS IN SYDNEY HARBOUR.

7.2 SAFE MOTION LIMITS

In order to define a set of safe motion limits for patron safety on floating pontoons, this research has reviewed available literature on human response to motion in a variety of situations in order to nominate upper limits of acceleration and angles of rotation (TABLE 7.1). Experimental and field-based testing has recorded the dynamic motion response of piled floating pontoons to boat wake (accelerations and wave angles) in order to compare against the SML nominated. The research focussed on two key design aspects with respect to the dynamic motion response: the dimensional criteria of beam (B), and draft (D), which in both cases also included the effect of added mass. Due to COVID-19, the planned field measurement program and user survey was restricted to one day at each of four pontoons. User perception from the surveys found that short duration peaks in acceleration resulting from pontoon/pile interaction were a main cause of increased levels of discomfort. This corresponds with the laboratory results where spikes in acceleration were predominantly limited to pontoon/pile interaction of passing waves.

TABLE 7.1. SAFE MOTION LIMITS (SML) FOR OLDER CHILDREN AND ADULTS (AGES 7 – 65 YEARS)

Criteria	Limit	Reference
Operation (Peak values)		
Peak Vertical Acceleration	0.1g	(NSW Maritime, 2005)
Peak Lateral Acceleration	0.1g	(NSW Maritime, 2005)
		Powell and Palachin (2015)
		NATO (2000)
Peak angle of tilt	6°	Rosen et al. (1984)
Comfort (RMS values)		
RMS Vertical Acceleration	0.02g	NORDFORSK (1987)
		Stevens and Parson (2003)
RMS Lateral Acceleration	0.03g	NORDFORSK (1987)
RMS Roll	2°	NORDFORSK (1987)
		Stevens and Parsons (2002)

Days of field testing were mild and yet the nominated peak SML (all axes) and lateral RMS criteria were exceeded at three out of four of the pontoons tested. 62% of surveyed users felt uncomfortable/unstable with many identifying the ‘bumps’ associated with pontoon/pile interaction as disconcerting, clear indication that extended field user survey is needed after COVID-19. Only one of the tested pontoons (the second largest, 249t at McMahons Point) had a life ring available; however, it was the most stable of the four pontoons tested. For ‘safe’ structures, life rings should be implemented on all public pontoons.

Field testing has validated model results and shown that it is the shorter period waves that produce the high peaks in surge acceleration irrespective of pontoon size, as it is the gap between the pontoon and pile that allows for the high peaks in lateral acceleration as the pontoon bumps against the pile. Pontoon beam to draft ratio, B/D is an important criterion that influences heave acceleration with an increase in B/D leading to a reduction in peak heave. The field data showed that the largest peaks in acceleration were in the lateral directions compared to in the lab where heave acceleration was the largest contributor. This may be due to several differences between the two testing arrangements, including pontoon dimensions, mass, and pontoon/pile spacing. Further testing that examines larger pontoons, as well as pile location with respect to the incident waves and pile/pontoon connections is recommended.

Examining the laboratory data, peak accelerations resulting from pontoon/pile interactions were almost six times higher than the nominated SML criteria and were the main driver of SML exceedance. This reinforces the importance of considering the pontoon/pile interaction when designing a pontoon with patron safety and comfort in mind. RMS values in the laboratory were generally higher than field measurements but these were only recorded for a set of passing boat wake/waves, whereas the field data included the constant effect of wind chop and multiple boat wakes from a distance within the harbour so had a reduced overall RMS motions.

The nominated SML fill a gap in literature and provide quantifiable criteria for ensuring that comfort/stability is considered in floating pontoon design. However, the Safe Motion Limits (SMLs) adopted for this study were based on literature describing able-bodied adults. Young children (< 7 years) and the elderly (> 65 years) frequent public wharves and have significantly lower stability limits (Assaiante, 1998). Of the patrons surveyed during field testing generally those over the age of 65 indicated levels of discomfort even at McMahons Point which recorded peaks in acceleration of approximately 0.05g, notably lower than the 0.1g limit. Considering that floating pontoons are public access structures, the safe motion limit criteria presented here should be considered as a guideline for upper limits in design. Future surveys of patrons over a wide range of conditions is recommended to improve understanding of the suitable safe motion limits for public access floating pontoons over a variety of demographics, including the age of the patron.

7.3 WAVE ATTENUATION VERSUS MOTION STABILITY

Floating breakwaters, although different in their primary purpose to floating pontoons, may be multi tasked and used as public access structures. The design criteria of a floating breakwater is primarily focused on wave attenuation. Wave attenuation is achieved through the mechanisms of reflection, out of phase damping, interference with water particle motions and viscous damping. As floating pontoons/breakwaters do not extend the full depth of the water column their economic effectiveness is generally limited to short period waves depending on water depth and the size, configuration and natural roll period of the structure (Wright, 1989). Effective attenuation generally requires excessive pontoon movement, which contrasts with the criteria for designing a stable/comfortable floating pontoon. There is a sizable compromise between being an effective wave attenuation device and limiting motion.

Laboratory data has shown wave attenuation to be influenced by a combination of width (B), draft (D) and added mass (FIGURE 7.3). An increase in width (2.83 – 5.63m) and draft (0.455 – 0.680m) of the structure resulted in reduction of wave transmission with the best attenuation performance observed for wave periods close to the natural roll period (2 and 3 seconds). When combining added mass and increasing draft far superior wave attenuation was observed at a wave period of 3 seconds (FIGURE 7.3b) when compared with the narrower (lesser mass) pontoon (FIGURE 7.3a). The introduction of skirts to the narrow pontoon saw attenuation performance improve, most notable at wave periods of 2, 3 and 7 seconds (FIGURE 7.3c) indicating that the addition of skirts provides better wave attenuation for a broader range of wave periods.

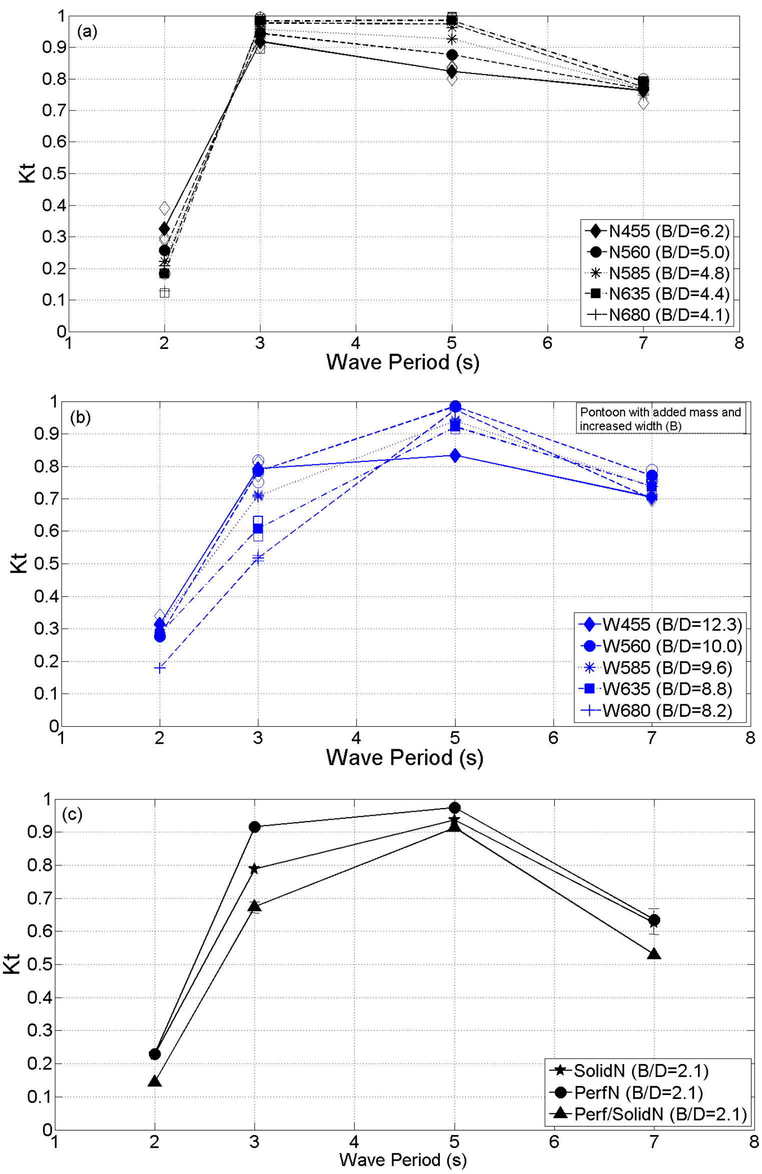


FIGURE 7.3. EFFECT OF BEAM (B), DRAFT (D) AND ADDED MASS ON WAVE ATTENUATION PERFORMANCE: (A) NARROW PONTOON, (B) WIDE PONTOON AND (C) NARROW PONTOON WITH SKIRTS.

The pontoons tested were not good wave attenuation devices for wave periods greater than 3 seconds, where they effectively rode the incident wave. At 2 and 3 seconds, when wave attenuation was best, the most adverse dynamic motions were recorded with high peaks in acceleration (FIGURE 4.4, FIGURE 5.5 and FIGURE 5.6) and significant roll response (FIGURE 4.8). RMS acceleration was highest when attenuation was best (TABLE 4.4) indicating that consideration needs to be given to whether effective attenuation or a stable structure is paramount.

7.4 DESIGN CONSIDERATIONS

As detailed in Chapter 4, Gaythwaite (2016) identified that at a beam to wavelength ratio of 0.2 or less, a floating breakwater essentially follows the wave contour with little or no wave attenuation. This corresponds with the laboratory data presented here, where lower values of B/L between 0.07 and 0.22 (wave periods between 5 and 7 seconds) saw almost 100% transmission and corresponded to lower peak accelerations (FIGURE 4.4). In contrast, large B/L (shorter waves) resulted in high reflection, lower transmission and higher peak accelerations related to the interaction between the structure and the wave (FIGURE 4.4). The correspondence between high peaks in acceleration and short waves was also observed during field testing (Chapter 6) where those sites with the shorter waves (~ 2 seconds) generally recorded higher peak lateral accelerations irrespective of pontoon size. At the design stage, consideration needs to be given to the influence of short period waves and the potential short durations peaks in lateral acceleration from the pontoon/pile interaction.

Laboratory results indicate the most adverse motion response was observed when the beam approached half the wavelength (B/L = 0.43 and 0.45). This also coincided with the wave period corresponding closely with the natural period of the structure in heave so further tests are needed to ascertain whether a B/L~0.5 still has the most adverse motion response when the natural and forcing period do not coincide.

Combining results from Chapters 4, 5 and 6 it has been shown that there exists a relationship between beam and draft with respect to the dynamic motion response of a piled floating pontoon structure. By increasing draft, lower B/D value, surge acceleration increases due to the blockage effect of the wave pushing against the increased surface area of the pontoons front face (FIGURE 7.4a). Larger values of B/D in both laboratory and field-based testing recorded lower peak heave accelerations (FIGURE 7.4b) as a result of an increased added mass, indicating that B/D is an important design consideration and generally the larger values of B/D provide a more stable structure. As draft is altered the natural period of motion of the pontoon is altered which in turn alters the motion response, so the above does not hold true when the natural period of the structure matches the forcing period, an important design consideration when designing floating pontoons. By adopting a combination of changes in the form of increasing draft, mass and beam width of the structure and considering what the natural period of the pontoon is at the design stage, the motion response can be reduced.

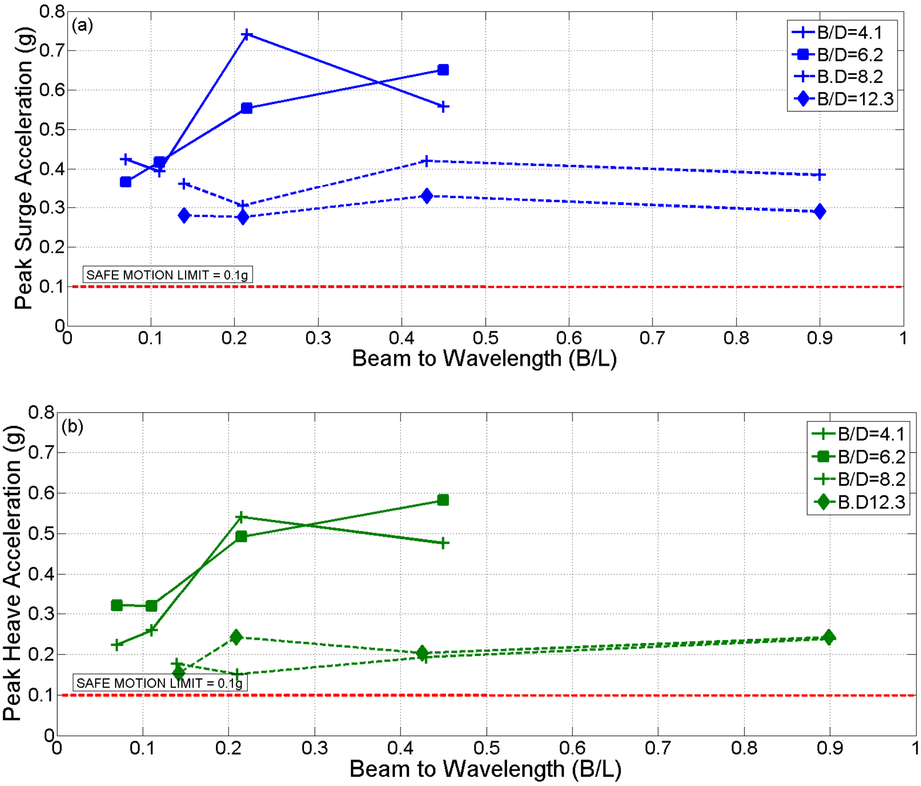


FIGURE 7.4. INFLUENCE OF BEAM TO WAVELENGTH (B/L), ADDED MASS AND BEAM TO DRAFT (B/D) ON PEAK IN (A) SURGE AND (B) HEAVE AXIS OF ACCELERATION. RED DASHED LINE REPRESENTS NOMINATED SML OF 0.1G. BLUE AND GREEN DASHED LINES REPRESENT WIDE PONTOON.

7.5 TESTING LIMITATIONS

Laboratory based testing was limited to two pontoons of limited draft variation in a constant water depth supported by two piles. Draft to depth (D/d) was small compared to previous referenced literature and the natural periods of the pontoons were similar to some of the forcing periods. These factors influenced the recorded accelerations. Testing was limited to waves representative of monochromatic boat wake, 2 to 7 second period of ~0.3m wave height.

In the field, Orient Point was the most comparable to the laboratory work in terms of both pontoon dimensions and incident wave conditions. The other pontoons, specifically Cremorne Point and McMahons Point were of larger beam, length and had four piles rather than two. Waves were smaller in the field and so limited the ability to compare with the laboratory work. However, even with small wave heights in the field, three of the four field sites still exceeded the nominated SML, signifying that the additional piles and increased dimensions do not necessarily mean motions will be reduced significantly and improved design is needed.

7.6 OUTCOMES

The study has identified how pontoon geometry and wave characteristics affect motion response as well as wave attenuation performance. It has been observed that short period waves (<3 second) cause the most adverse motion response; however, this was when wave attenuation was optimal. By considering the predominant wave climate and altering the mass, beam width and draft of the pontoon the motion response can be reduced. It has been identified that the gap between pontoon and pile is the cause for increased lateral acceleration and further testing should investigate motion response with a reduced aperture between pontoon and pile.

Although the motion response was reduced through increase in beam width, added mass and altering draft, the study was unable to produce a pontoon that did not exceed the SML. Future work could include further investigation into firstly calculating the natural period of pontoon motion to ensure it does not coincide with the wave period and then testing the above pontoon geometry (beam, mass and draft) to see if it is possible to obtain motions below the SML.

CHAPTER 8: CONCLUSIONS AND FUTURE RESEARCH

This chapter summarises the present study and provides ideas for future research to expand knowledge in the field of piled floating pontoons and postural stability.

8.1 CONCLUSIONS

As detailed in Chapter 1 floating pontoons move due to wave/wind action. Presently there are limited design standards defining a suitable level of motion for floating pontoons in order to maintain the comfort and stability of users. Previous research on the dynamic motions of piled floating pontoons to boat wake has been limited and the way in which the dynamic motions impact on a standing persons stability even less. The objective of this study was first to define a set of motion limit criteria in order to maintain a person's stability while standing on a floating pontoon. The second stage of the research was to document the motions of piled floating pontoons under boat wake in both a laboratory and field-based setting. Thirdly compare these motions against the safe motion limit criteria in order to ascertain whether people would feel unstable and/or uncomfortable.

The present study introduced a new set of motion limits for engineers/naval architects to use as a guide to design more stable and comfortable floating pontoons. These limits were established based on a review of literature of motion limits nominated for various modes of transport; trains, buses or ships; floating bridges and vibration limits of fixed structures. Peak acceleration and angle limits were nominated as a peak operational (stability) criteria and RMS acceleration and angle limits as a comfort criteria.

The present study expanded the current understanding on the wave attenuation performance and motion response of piled floating pontoons in both laboratory and field-based situations. Attenuation performance was best for short period waves (<= 3 seconds); however, this coincided with the most adverse motion response with high peaks in acceleration (lateral and vertical) as the pontoon was pushed against the piles. By increasing beam width peaks in acceleration were reduced, however RMS accelerations were still comparable and generally above the SML for both laboratory and field-based testing. As draft increased attenuation performance (as measured by Kt) improved for the shorter waves. By increasing draft peak heave acceleration was reduced and field-based testing highlighted that larger displacements (B x D) results in heave acceleration (peak and RMS) below the nominated SML. By contrast increasing draft generally saw an increase in peak and RMS surge and in both laboratory and field testing the constant 'bump' of the pontoons against the piles resulted in accelerations above the nominated SML and the feeling of 'discomfort' for many of the users surveyed.

8.2 FUTURE WORK

This study has identified SML based on review of literature of comparative structures to floating pontoons. It is recommended that future work be done to obtain additional field measurements and document user perception and levels of comfort/stability in order to understand whether the nominated motions limits are adequate.

The study investigated in laboratory testing two pontoons of differing width but of limited draft variation in a constant water depth. Future work should investigate how an extended range of pontoon dimensions and variations in water depth effect wave attenuation and motion response. The pontoons tested had natural periods of motion similar to the forcing boat wake/wave periods. Further laboratory testing should investigate the motion response of floating pontoons with natural period removed from the forcing period in order to better understand how the B/L ratio can be used to predict behaviours.

It is recommended that future work investigate the capability of computational fluid dynamics (CFD) in effectively modelling the pontoon/pile interaction, often unaccounted for when floating pontoons are designed assuming free body behaviour. Importantly, although not specifically tested, this thesis highlighted the influence of the pontoon/pile connection on the dynamic motion response. Therefore, it is recommended that future work, whether it be laboratory or CFD based, examine the importance of the pontoon to pile connection. Research into the restriction of lateral movement whilst still allowing vertical motion would be beneficial.

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