DYNAMIC MOTIONS OF PILED FLOATING PONTOONS AND THEIR IMPACT ON POSTURAL STABILITY

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Abstract

This study[1] presents results on the dynamic motions of piled floating pontoons resulting from boat wake and the 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 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 stipulating suitable motion limits to maintain the postural stability of users. This paper proposes a set of Safe Motion Limits (SMLs) 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 to obtain data on the motion response of piled floating pontoons resulting from regular boat wake conditions. The motions (accelerations and rotations) recorded via Inertial Measurement Units (IMU) are compared against the proposed SMLs to establish the potential impact on a standing person's stability.

Laboratory results showed that two scaled pontoons consistently exceeded the nominated SMLs under boat wake conditions. Results revealed 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. Laboratory results revealed the complex interaction between the piles and pontoon that resulted 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). Prototype (field) testing showed that under the relatively mild wave conditions the nominated SMLs were exceeded at three of the four sites and user discomfort was experienced at all four sites. Results from prototype testing showed peaks in acceleration for short period waves <3 seconds, similar to those reported in the laboratory.

Given the postural stability issues identified, the results suggest more data is needed to fully understand human perception and stability on floating pontoons under wave action. Furthermore, for better engineering design, consideration should be given to including a set of motion limits within guidelines and standards aimed at designing these structures with consideration given to the stability and comfort of users.

1. Introduction

Floating pontoons exist in many sheltered waterways around the world and provide an important point of access, facilitating the movement of people between vessels and land. In Sydney Harbour alone there are more than 137 public access points (wharves, jetties, and pontoons) for boat users (Transport NSW, 2012) frequented by more than 172,000 commuter passengers per month as well as thousands of tourists (FIGURE 1). To secure floating pontoons in place, they are often anchored to piles, dolphins, or catenary cables (Gaythwaite, 2016). The high inspection and maintenance costs associated with flexible mooring systems has resulted in a clear preference for piled restraining systems in sheltered harbours of depths less than 10 m (Cox, 2007).

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[1] The presented study is shown within the author's Master of Philosophy undertaken part time at the University of New South wales from 2016 to 2020. This paper provides insight into some of the main findings of the author's thesis.

FIGURE 1. IN THE FOREGROUND, A FERRY COMMUTER FLOATING PONTOON LOCATED AT MCMAHONS POINT IN SYDNEY HARBOUR, AUSTRALIA.

With increasing populations, the use of waterways is becoming more prominent. It is important to ensure that people using floating structures will be stable and comfortable. 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. 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 public.

This study is aimed at highlighting the importance of understanding the accelerations a pontoon might experience resulting from small amplitude boat wake and the impact of such accelerations on postural stability. Specifically, the study aims to do the following:

a) Nominate a set of motion limits aimed at ensuring a person standing on a floating pontoon would be able to remain both stable and comfortable;
b) Collect dynamic motion data from both laboratory and prototype testing of piled floating pontoons to understand motion response and how dimensional changes alter these motions; and,
c) Determine the potential impact the documented motions will have on a person's stability and comfort.

2. Safe Motion Limits (SMLs)

As piled floating pontoons are commonly used by the public, postural stability and safety should be considered at the design stage. Postural stability is the ability to maintain the body's centre of gravity over the base support during quiet standing and movement (Hageman, 1995). It is a complex, biomechanical process that involves coordinated actions of the sensory, motor and central nervous system (Forssberg, 1982) and it varies with the age of the subject (Riach, 1993; MacRae, 1992; Hageman, 1995; Blaszczyk, 1994). 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 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.

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 stability/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, 1984). 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 users 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 (that is, maintaining the structure) is to limit peak acceleration to 0.1g (NSW Maritime, 2005).

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 can 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.

For this study, 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 operation (stability) and comfort. TABLE 1 stipulates the SML to be adopted for this study for older children and adults (ages 7 – 65 years). These limits are intended to assist engineers in designing stable structures and fill the current gap in guidelines and standards. 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 1 were to act in isolation.

TABLE 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)

3. Laboratory Modelling

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 floating pontoons secured by piles 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 is 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 provides details of the laboratory methods used to investigate the dynamic motions of two varying width piled floating pontoons resulting from boat wake.

3.1 Setup

The physical model testing was conducted in the 0.6 m wide wave flume at the Water Research Laboratory at UNSW Sydney. The flume dimensions are 30 m long, 0.6 m wide and 0.7 m deep. Froude similitude is commonly applied in hydraulic structure model scale testing and was applied between prototype and model conditions using a length scale of 10 for these experiments. Froude scaling is the most appropriate for these set of experiments for several reasons, including that it emphasises the inertial and gravity forces, with the tests here focussing on the dynamic motions (accelerations) of the structure, which in Froude similitude have a scale factor = 1. The models tested were two piled rectangular floating pontoons of varying prototype beam widths (FIGURE 2) subsequently referred to as Narrow (2.83m beam) and Wide (5.63m beam). Similar to previous experiments, a narrow gap between the side wall of the flume and pontoon ensured that no collisions existed between wall and pontoon (Ning, 2018) and limited any side wall effects (Christensen, 2018).

Several physical characteristics of the pontoons influence the stability and dynamic motion of floating bodies, including the draft-to-water-depth ratio (D/d), the structure-beam-to-draft ratio (B/D), and the beam-to-wavelength ratio (B/L), the metacentric height (GM), the radius of gyration (K), as well as the wave direction and the degree of mooring restraint (Gaythwaite, 2016). These are summarised in TABLE 2. The metacentric height is the vertical distance between the centre of gravity (c.g.) and the Metacentre (M) and is calculated as follows:

$$GM = KB + BM - KG \tag{1}$$

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, 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 theoretically derived from the inertia of the water plane area (I) and the area of contact (A), where:

$$K = \sqrt{{}^{I}/_{A}} = {}^{B}/_{\sqrt{12}} = 0.29B \tag{2}$$

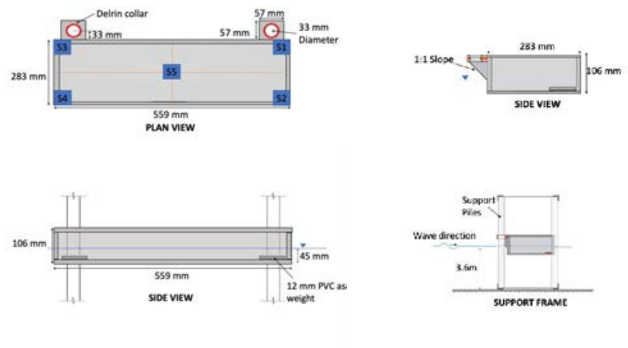
and represents the lower bound proposed by Gaythwaite (2016). As the pontoons tested were held in place by piles on the seaward side, pitch and yaw movements are highly restrained and not included here.

The pontoon models were constructed of grey PVC sheet, with additional PVC sheet used for internal ballast to alter the draft of the pontoon (e.g., Tabatabaei and Zeraatgar, 2019). The pontoons were connected to two, 330mm diameter (prototype) vertical piles located on the seaward side (FIGURE 2). Delrin, a highly-crystalline engineering thermoplastic specified for high load mechanical applications, was used to construct wear/impact buffers at the pontoon/pile interface. These buffers provided a low friction sliding connection between the restraining piles and the pontoon. The pontoon/pile connections (42 mm clearance at prototype scale between pile and collar) allowed free vertical movement and restrained (but measurable) lateral movement.

TABLE 2. PHYSICAL CHARACTERISTICS OF THE TWO PONTOONS TESTED. ALL VALUES PROVIDED IN PROTOTYPE.

Criteria	Narrow Pontoon	Wide Pontoon
Beam [m]	2.83	5.63
Length [m]	5.59	5.59
Draft [m]	0.455	0.455
Metacentric Height (GM) [m]	1.23 m	5.58 m
Radius of Gyration, roll (K) [m]	0.83	1.63
Displacement [Tonnes of water displaced]	7.41 tonnes	14.75 tonnes

NARROW PONTOON



WIDE PONTOON

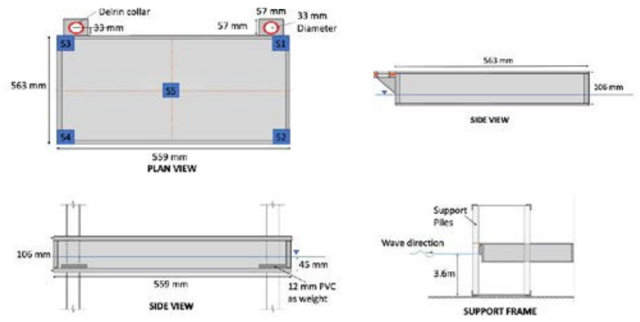


FIGURE 2. FLOATING PONTOON DESIGN (MODEL SCALE) FOR NARROW AND WIDE PONTOONS (DIAGRAM NOT TO SCALE).

The floating pontoons have 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)). On each pontoon, five *Life Performance Research* (LPMS-B2) Inertial Measurement Units (IMU) were used to measure triple-axis accelerations and triple-axis angles of each floating pontoon (LP-Research, 2016). Unless otherwise stated, all default settings of the IMUs were employed. The IMUs were positioned on each corner (Sensors 1-4, FIGURE 2 and FIGURE 3) of the pontoon, as well as in the centre of the top face (Sensor 5, FIGURE 2and FIGURE 3). 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 axes, where z is in the direction of earth's gravity (vertically down with -1g), x- in the direction of wave propagation and y- in the cross-tank direction, following a right-handed Cartesian coordinate system. The internal sampling and filtering of the IMU is 400Hz. Bluetooth connection between the IMUs and the log computer was used to allow immediate data recording of accelerations and rotations of the floating pontoons as the motions took place. 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 synchronised and recording at the same time. Calibration of each IMU requires determination of the gyroscope bias, gain, and movement threshold, as well as accelerometer misalignment, offset, gain, and magnetometer interference bias and gain. Each sensor comes fully calibrated from the factory. As the gyroscope sensor has a constant bias that may be influenced by environmental factors, such as temperature, gyroscope bias 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 IMUs 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. A cartesian coordinate system was employed for the physical 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.

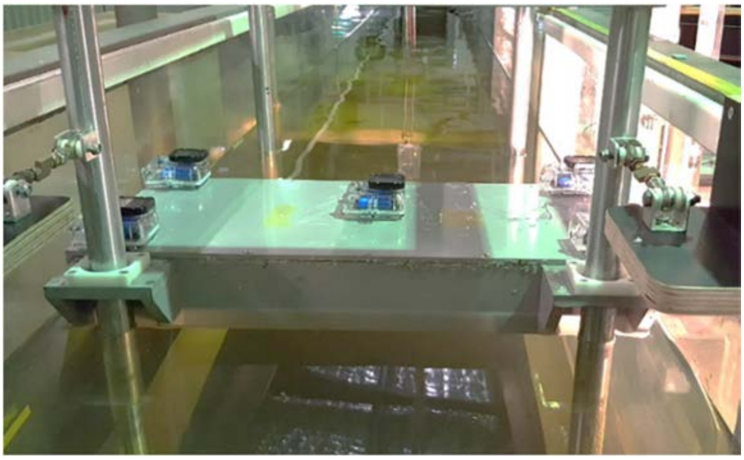


FIGURE 3. PHOTO OF NARROW PONTOON SHOWING SEAWARD FACE, PILE MOORING SYSTEM AND POSITIONING OF FIVE IMU.

3.2 Wave Environment

Waves were generated by a piston-type wave paddle situated at one end of the flume. A three-probe array was set up between the paddle and the structure. A fourth probe was positioned in the lee of the structure to measure the transmitted wave. In this study, monochromatic waves were tested. Wave heights and periods were representative of boat wake found in Sydney Harbour (Patterson Britton and Partners, 1987). Test conditions are summarized in TABLE 3. All dimensions and times given are prototype values unless otherwise specified. Triplicate runs, of duration 189 s, were conducted for each of the wave periods to ensure similarity between tests. All tests were completed in a water depth (d) of 3.6 m and both pontoons had a draft (D) of 0.45 m, (D/d=0.125). Due to the limited length of time a test could be run before waves reflected 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. 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 (ηr) 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 of the three trials for each wave period. A representative time slice of the incident waves for each of the 4 wave periods tested in provided in FIGURE 4.

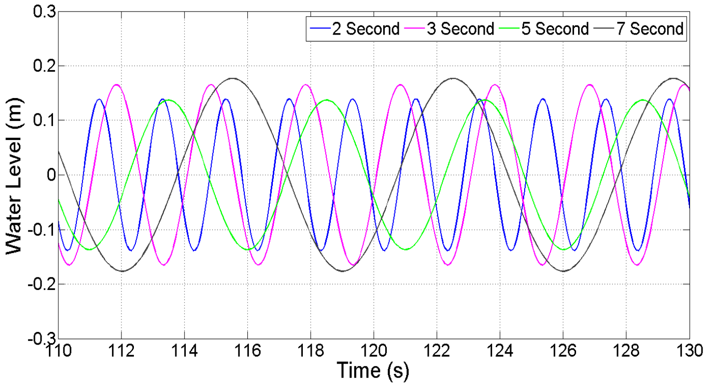


FIGURE 4. EXAMPLE INCIDENT BAND WATER LEVEL TIMESERIES FOR EACH OF THE 4 WAVE PERIODS TESTED. PROTOTYPE SCALE.

TABLE 3. MONOCHROMATIC WAVE TESTING PARAMETERS (PROTOTYPE SCALE)

Test ID	**Wave Period**	**Wave Height**	**Beam**	**Draft**	**Depth**
B1	2	300	2.83	0.45	3.6
B2	3	310	2.83	0.45	3.6
B3	5	290	2.83	0.45	3.6
B4	7	320	2.83	0.45	3.6
B5	2	300	5.63	0.45	3.6
B6	3	310	5.63	0.45	3.6
B7	5	290	5.63	0.45	3.6
B8	7	320	5.63	0.45	3.6

4. Prototype Testing

Prototype testing was 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 Section 2 and compare to the scaled laboratory model results. During the field experiments, the public (pontoon users) were invited to take part in a survey (UNSW ETHICS HC20003) ascertaining their level of stability and comfort/discomfort resulting from the pontoon movements.

4.1 Study Area

Data was collected from four piled floating pontoons. Two located in Sydney Harbour and two in the Shoalhaven, NSW, Australia (FIGURE 5.). 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 5.a,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 5.c) is a series of piled floating pontoons used by the defence force for boarding and alighting navy vessels and Orient Point (FIGURE 5.d) is a recreational boating pontoon and popular location for local fishermen.

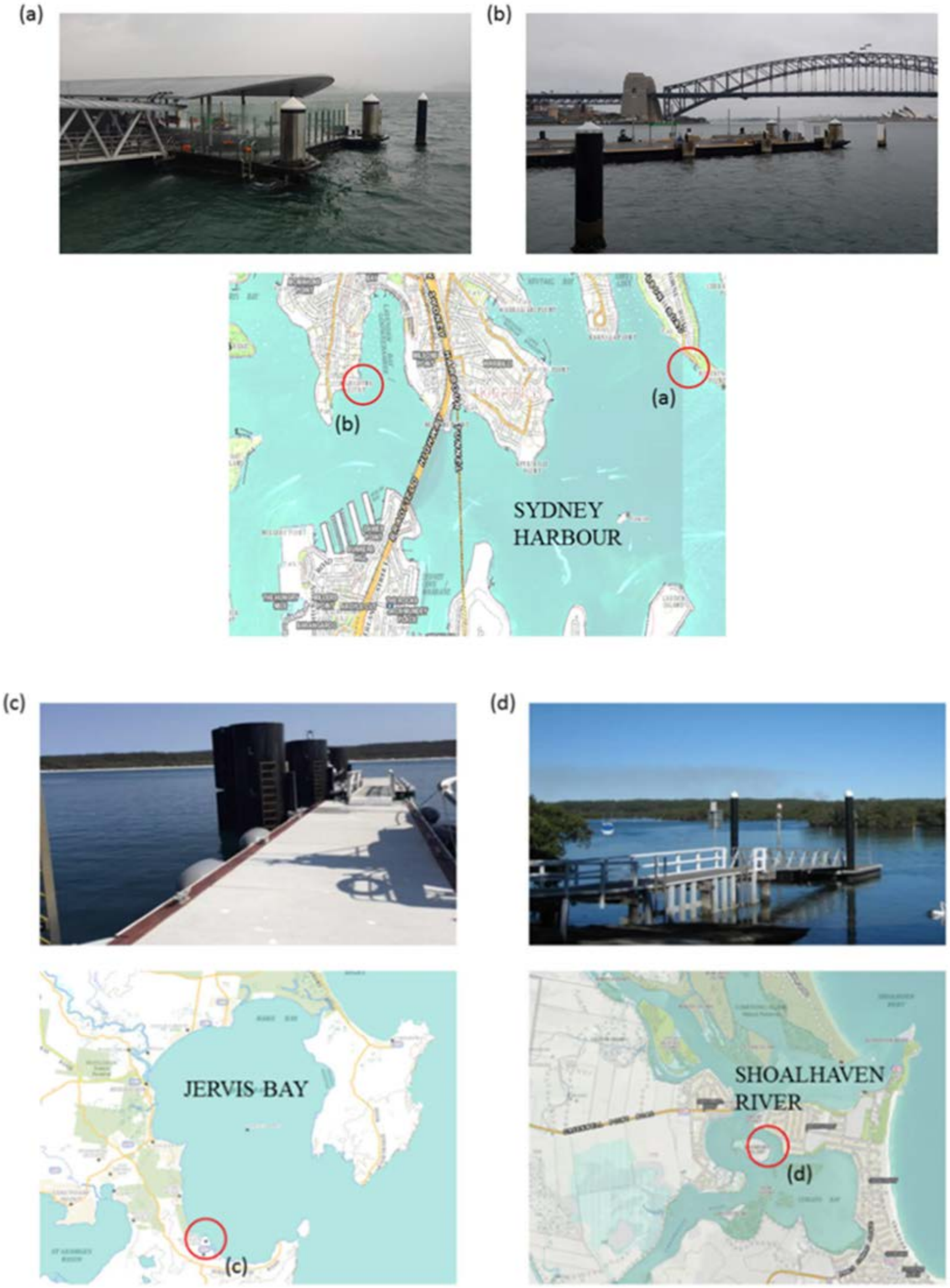


Figure 5. The Four Field Testing Sites. (a) Cremorne Point, Sydney Harbour (Top Left), (b) McMahons Point, Sydney Harbour (Top Right), (c) HMAS Creswell, Jervis Bay (Bottom Right) and (d) Orient Point, Shoalhaven.

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 are presented in TABLE 4. The pontoons located in Sydney Harbour (FIGURE 5.a,b) had piles located on each corner (4 off) and those in the Shoalhaven (FIGURE 5.b,c) had piles on one seaward side only (2 off). Of the 4 field test sites, Orient Point was most similar to the laboratory design conditions.

TABLE 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

4.2 Wave Environment

As this study was focused on assessing the effect of boat wake on the dynamic motions of piled floating pontoons, the days of field testing were selected based on ensuring boat wake was the main contributing factor and wind waves were negligible. Ultrasonic wave sensors were used to capture the water surface adjacent to the floating pontoons tested to estimate wave heights. 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. The sensors were calibrated in the 1.2m flume at the UNSW Water Research Laboratory (WRL), Manly Vale, following manufacturer specifications. 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 Section 6. Wave data obtained during the field testing is presented as a mean wave height and mean wave period. 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. At HMAS Creswell and Orient Point, targeted boat wake tests were conducted by passing a small personal watercraft 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.

4.3 Pontoon Motions

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. Units (IMUs) were positioned on one corner adjacent to the ultrasonic sensor and centrally on the pontoon (FIGURE 6). The accelerometers were contained in GoPro housing for waterproofing with double sided tape inside to secure them in place.

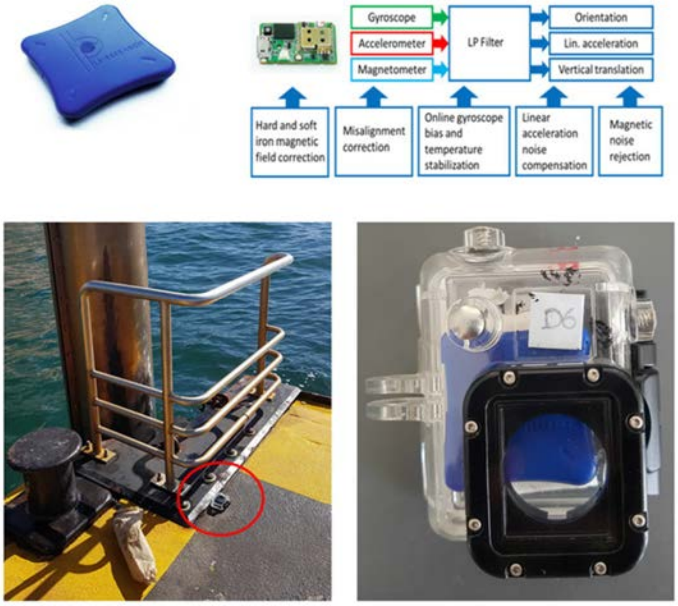
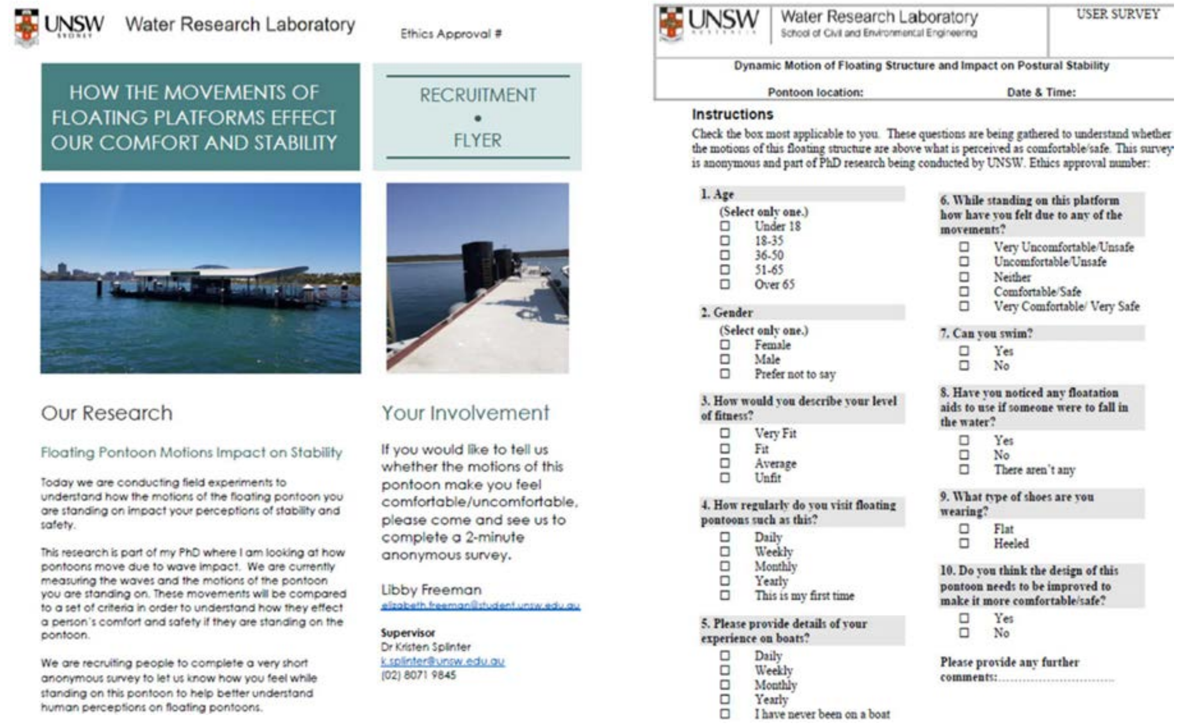


FIGURE 6. ACCELEROMETERS: HARDWARE, POSITIONING AND HOUSING

4.4 User Survey

Whilst recording the motions of each pontoon during the field campaign, people using the pontoons were provided with a research flyer to invite them to complete a short 2-minute survey (FIGURE 7). 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



UNSW Water Research Laboratory

Ethics Approval #

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.

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UNSW 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 7. RESEARCH FLYER AND SURVEY TO ASSESS USER COMFORT LEVEL

5. Selected Laboratory Results

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 pontoon 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 5. Individual results for each triplicate run are presented along with the calculated mean of the three tests.

TABLE 5. MONOCHROMATIC WAVE TESTING RESULTS INCLUDING TRANSMISSION AND REFLECTION COEFFICIENTS (PROTOTYPE SCALE)

Test ID	**Wave Period (s)**	**Wavelength L (m)**	**Wave Steepness H/L**	**Water depth to Wavelength d/L**	**Beam to Wavelength B/L**	**Transmission Kt=Ht/Hi**	**Reflection Kr=Hr/Hi**
B1	2	6.23	0.048	0.58	0.45	0.38	0.57
B2	3	13.17	0.024	0.27	0.22	0.94	0.10
B3	4	26.85	0.011	0.13	0.11	0.93	0.15
B4	7	39.59	0.008	0.09	0.07	0.94	0.20
B5	2	6.23	0.048	0.58	0.90	0.26	0.58
B6	3	13.17	0.024	0.27	0.43	0.96	0.13
B7	5	26.85	0.011	0.13	0.21	0.93	0.17
B8	7	39.59	0.008	0.09	0.14	0.99	0.21

5.1 Peak Vertical and Lateral Acceleration – Impact on Operation

The peak and vertical Safe Motion Limits (SMLs) are operational criteria aimed at ensuring people will remain stable while undertaking tasks on floating pontoons. As anticipated, the motions of the pontoons varied with wave period and pontoon width. 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 8a,b) compared to the Wide Pontoon (FIGURE 8c,d). 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 spikes in both vertical and lateral acceleration (FIGURE 8). The natural periods in heave and roll for both the Narrow and Wide pontoon were between the 2 and 3 second wave cases tested and as such, are not expected to have a strong influence on the resulting excitement of the pontoons or cause adverse motion response.

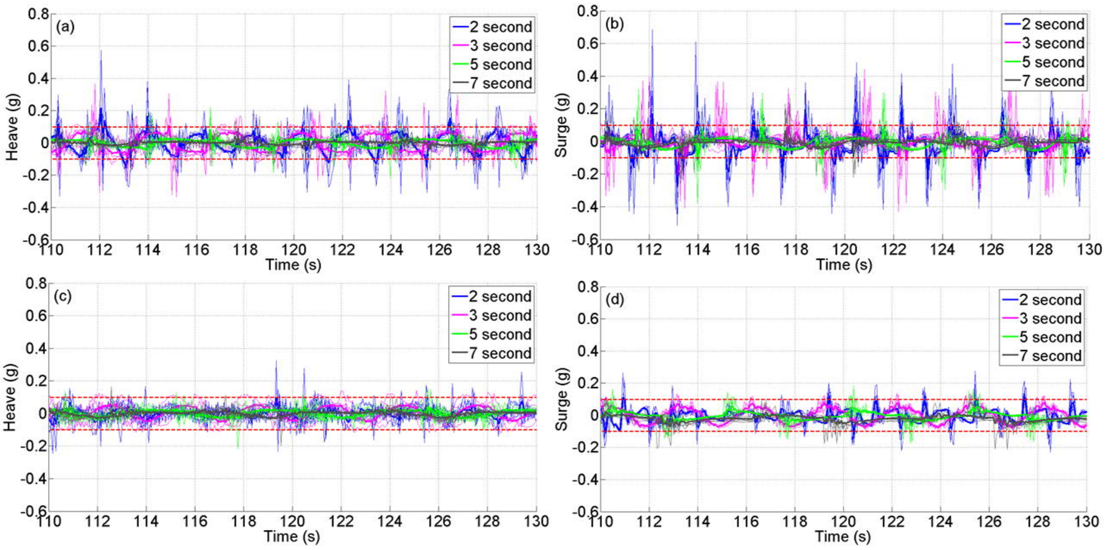


FIGURE 8. TWENTY-SECOND TIME SLICE OF RAW ACCELERATION VERSUS TIME: (A) NARROW PONTOON HEAVE ACCELERATION; (B) NARROW PONTOON SURGE ACCELERATION; (C) WIDE PONTOON HEAVE ACCELERATION; AND (D) WIDE PONTOON SURGE ACCELERATION. THE HORIZONTAL RED DASHED LINE INDICATES THE SAFE MOTION LIMIT OF 0.1G.

High frequency spikes in heave and surge acceleration 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 8a,b vs FIGURE 8c,d). To further understand the cause of these spikes, a 5 second time slice is presented in FIGURE 9 corresponding with a wave of 2 second period. At the crest of the wave, the pontoon is visibly pushed against the piles creating impact spikes in surge (FIGURE 9a,e). In some instances, the pontoon is observed to hang briefly on the pile due to the high roll angles (FIGURE 9d), leading to both high heave and surge accelerations when the pontoon subsequently falls and impacts the piles at the base of the wave (FIGURE 9c,e).

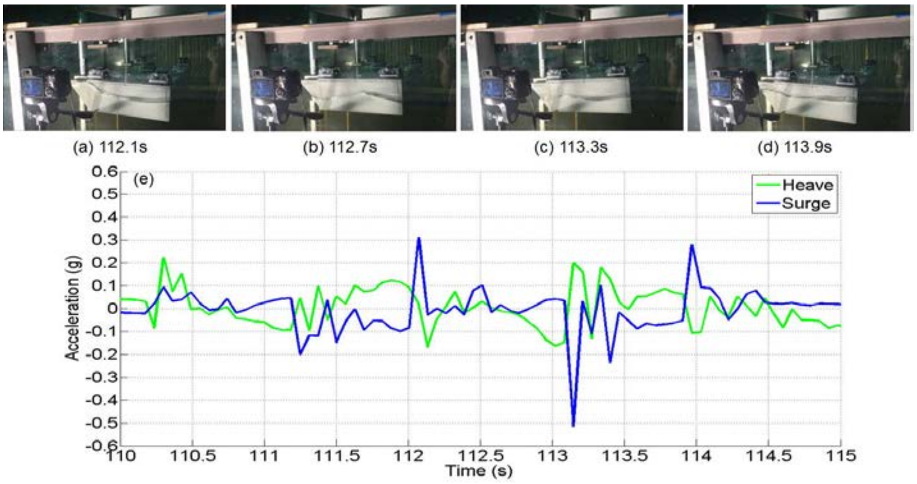


FIGURE 9. TIME SLICE OF NARROW PONTOON DURING THE 2 SECOND WAVE TEST. (A-D) SNAP SHOTS OF PONTOON MOTION AND (E) SENSOR 1 HEAVE AND SURGE ACCELERATIONS.

Considering the full time period of each experimental run (approximately 189 seconds), peak heave (z-axis) and surge (x-axis) accelerations (0.58g and 0.65g, respectively), were as high as six times the peak SML (0.1g) while sway (y-axis) peak accelerations reached three times the SML (0.32g) for the Narrow pontoon (FIGURE 10). All peak accelerations exceeded the SML, with the highest accelerations recorded for the 2 second period wave (B/L ~ 0.45, Narrow, Figure 10a and B/L ~ 0.90, Wide, Figure 10b). Additionally, peak accelerations showed a stronger dependence on B/L for the Narrow Pontoon compared to the Wide Pontoon (Figure 10a vs Figure 10b). The results presented here agree with previous studies by Cox et al. (2007).

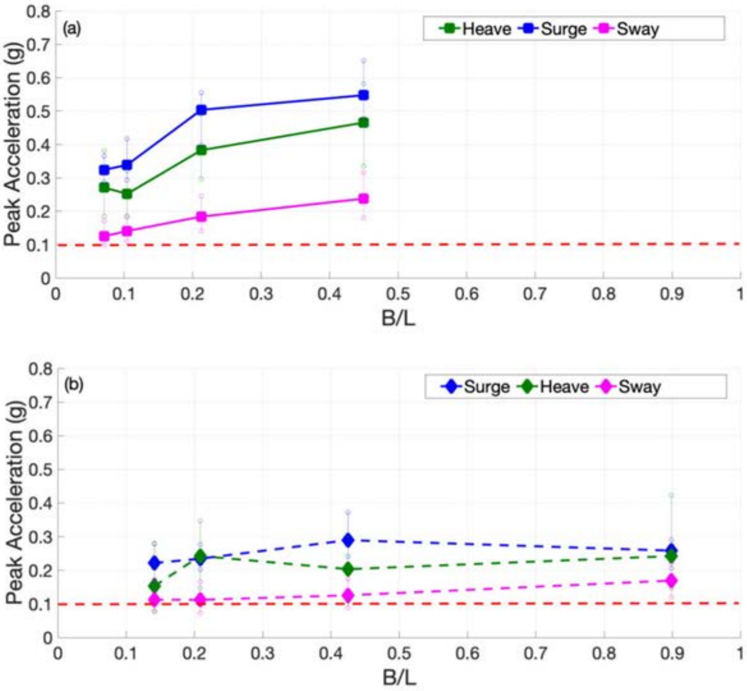


Figure 10. Peak in Single (Surge, Heave and Sway) Axis of Acceleration Plotted Against Beam to Wavelength Ratio and Compared Against the Safe Motion Limit of 0.1g. (a) Narrow Pontoon and (b) Wide Pontoon. Range between 5 sensors and 3 test repetitions shown by vertical lines and solid symbol being the average of the 15 results.

While peak accelerations shown in Figure 10 exceed the SML adopted for this study, examining the cumulative distribution functions (not shown) 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. This suggests that the peaks in acceleration (Figure 10) resulted from infrequent, short duration impacts due to the pontoon/pile interaction (Figure 8 and Figure 9) rather than the interaction with the incoming wave that was observed to be minimal when examining the reflection and transmission coefficients (not shown). Although of short duration these high accelerations due to pontoon/pile impact could cause moments of instability.

5.2 Root Mean Square Acceleration – Impact on Comfort

The nominated RMS acceleration limits relate to the comfort of people standing on pontoons. The RMS acceleration of the piled-pontoon represents overall variability in motion compared to the short duration peak accelerations reported in Section 5.1. Table 6 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 acceleration in both surge and heave was recorded when the beam was almost half the wavelength (B/L=0.43 and 0.45). Similar to the observed peak accelerations (Figure 10), 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) are primarily due to the pile-pontoon interaction rather than the wave itself (Figure 8) and are consistently large enough to cause discomfort for passengers using floating pontoons exposed to relatively small monochromatic boat wake.

Table 6. 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 Acceleration Criteria**	**B/L**							
		0.07	**0.11**	**0.14**	**0.21**	**0.22**	**0.43**	**0.45**	**0.90**
Test ID		B4	B3	B8	B7	B2	B6	B1	B5
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**

6. Selected Prototype Results

Field testing was undertaken to ensure that scaling effects from the laboratory work were not significantly impacting on the results. The particulars of each of the pontoons are presented in Table 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 4, 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 SMLs. Twenty-six users were surveyed to establish an understanding of their perception of the motions (Table 7). Field studies were limited due to the COVID-19 pandemic which began at the start of the field campaign.

Table 7. 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

6.1 Wave Characteristics

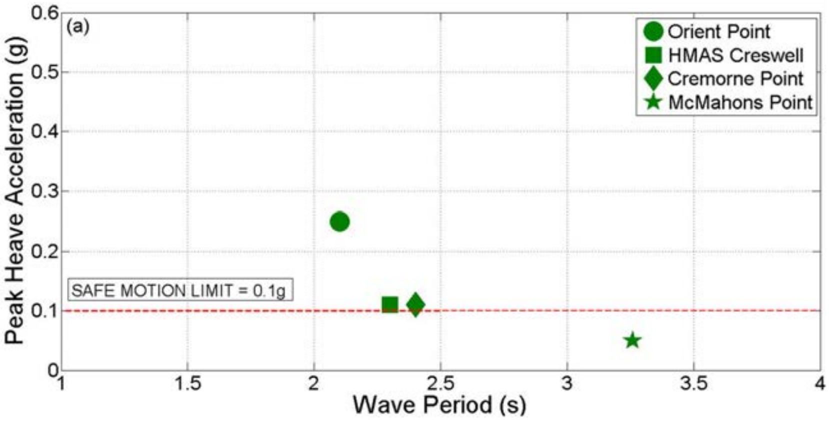
Table 8 provides results on the analysed wave parameters for each of the sites. Wave heights (H_m) and periods (T_m) presented are the mean determined using methods described in Section 4.3. Results are presented relative to Beam (B) to Draft (D), Beam (B) to wavelength (L), and pontoon displacement in tonnes for each location. At all four sites mean wave heights were relatively small with short wave periods, typical of pleasure craft boat wake and ferries. The largest waves were at the two sites in the Shoalhaven (HMAS Creswell (HC) and Orient Point (OP)) where individual boat passes were clearly identifiable. In contrast, the data from the two Sydney Harbour locations (Cremorne Point (CP) and McMahons Point (MP)) were influenced by both near-field boat traffic, as well as far-field boats, wind chop and reflections off the Harbour walls. As the dynamic motions of the pontoon will be directly related to wave steepness, this is also presented in Table 8 for the four sites. Orient Point experienced the steepest waves, followed by HMAS Creswell and Cremorne Point, with McMahons Point experiencing the mildest wave climate of the four sites.

Table 8. 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 Peak Vertical and Lateral Acceleration – Impact on Operation

Figure 11 shows peak in single (heave, surge and sway) axis of acceleration relative to wave period presented in Table 8. Orient Point recorded the highest peak for each axis of acceleration (Figure 11abc). 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 Section 5, 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 despite 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.



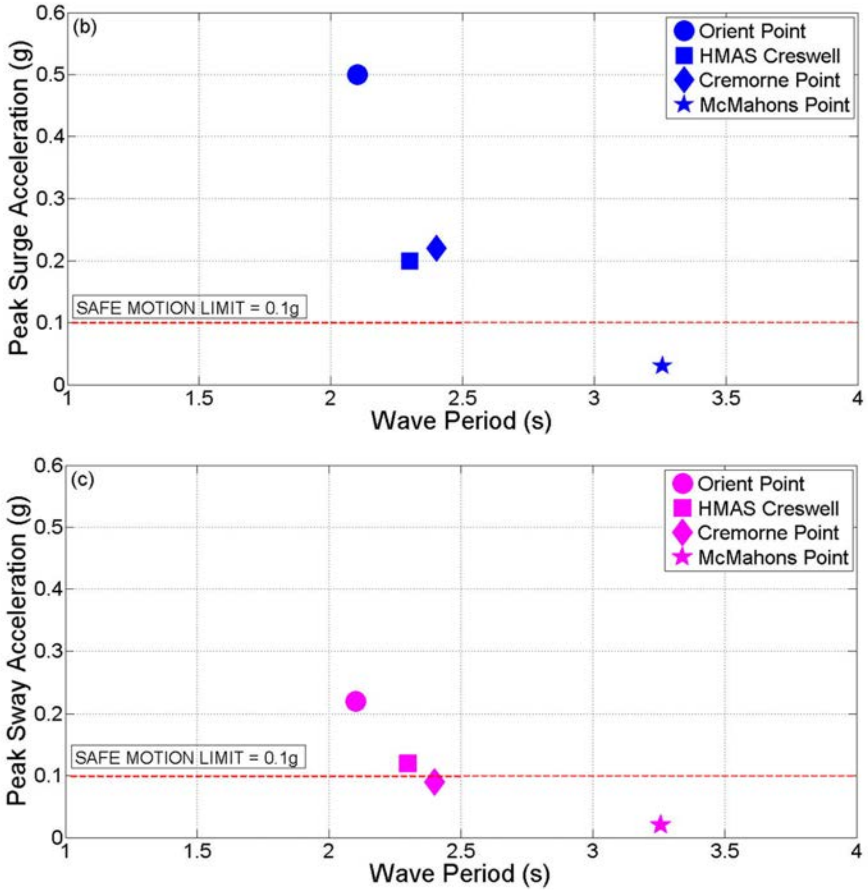


FIGURE 11. PEAK IN SINGLE (HEAVE, SURGE AND SWAY) AXIS OF ACCELERATION PLOTTED AGAINST WAVE PERIOD FOR EACH OF THE FIELD PONTOONS AND COMPARED AGAINST THE SAFE MOTION LIMIT OF 0.1G. (A) HEAVE ACCELERATION, (B) SURGE ACCELERATION AND (C) SWAY ACCELERATION. POINTS REPRESENT THE MEAN OF THE TWO SENSORS.

6.3 Root Mean Square Acceleration – Impact on Comfort

TABLE 9 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 11), 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 6), 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 9. 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.

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

6.4 User Perception

As detailed in Section 4.4, 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 7). 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 10 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.

Table 10. 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**

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 SMLs as detailed in TABLE 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 because of the short duration peaks in acceleration even on the mild days of testing and confirm the importance of understanding and limiting the motion response of floating pontoons.

7. Potential Contribution to Understanding Motions of Piled Floating Pontoons and Implication to Postural Stability

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. This study has presented a set of safe motion limits (SML) based on a review of available literature on human response to motion in a variety of situations. 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 pontoons 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 are 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.

The study has expanded the current understanding of the motion response of piled floating pontoons in both laboratory and field based situations. The study has identified how pontoon geometry and wave characteristics affect motion response as well as wave attenuation performance. By increasing beam width, peaks in acceleration were reduced, however RMS accelerations were still comparable and generally above the SMLs for both laboratory and field-based testing. Results indicate the most adverse motion response was observed when the beam approached half the wavelength (B/L = 0.43 and 0.45) and when wave periods were <3 second; 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.

Field testing has validated model results and shown it is the shorter period waves that produce the high peaks in surge acceleration irrespective of pontoon size. Further testing that examines larger pontoons, as well as pile location with respect to the incident waves and pile/pontoon connections is recommended.

8. Concluding Remarks

Floating pontoons are commonly used as public access structures in small craft harbours and as such, the comfort and safety of patrons must be considered during the design phase. Here, a new set of physical laboratory experiments and prototype testing were presented that specifically examined the dynamic motions of piled box-type floating pontoons of varying beam width under monochromatic boat wake conditions with periods from 2 to 7 seconds. The dynamic motions (accelerations and roll angles) were compared to safe motion limit criteria as defined in the literature for personal safety and comfort.

In the laboratory the most energetic behaviour occurred for beam to wavelength (B/L) ratios between 0.4 and 0.5, where there was visible wave-pontoon and pontoon-pile interaction. Notably, the most adverse conditions recorded in acceleration were due to pile-pontoon interaction as the pontoon was pushed against the piles or ‘hung’ off the piles as each wave passed. These consistent, but short-lived high accelerations resulted in peak accelerations in heave and surge more than six times the peak acceleration Safe Motion Limit (0.1g) and up to 6 times the limit in RMS accelerations. Encouragingly, despite the high peaks in acceleration observed, both pontoons had only a 5% probability of exceeding the nominated peak safe motion limit SML of 0.1g in heave and surge.

Laboratory results compared well with preliminary field testing of sheltered small craft pontoons exposed to boat wake with respect to the peak and RMS accelerations observed. In more diverse field situations, where multiple boat wakes may interact with each other forming complex 3D seas, as well as the presence of wind generated waves, pontoon accelerations are expected to be more complex. The results presented here highlight the need for more detailed understanding of the dynamic motions of public access structures, such as piled floating pontoons in order to fully consider public comfort and safety.

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