# FLOATING PONTOON MOTIONS, OPERATIONAL SAFE MOTION LIMITS

Elizabeth Freeman, Water Research Laboratory, UNSW Sydney,
elizabeth.freeman@student.unsw.edu.au.

Ron Cox, Water Research Laboratory, UNSW Sydney, r.cox@unsw.edu.au.

Kristen Splinter, Water Research Laboratory, UNSW Sydney, k.splinter@unsw.edu.au.

Francois Flocard, Water Research Laboratory, UNSW Sydney, f.flocard@unsw.edu.au

## ABSTRACT

Increasing Navy Fleet size requires an increase and diversity of maritime facilities.

By 2035, around half of the world's submarines will be operating in the IndoPacifc region (Defence 2016). Submarines offer a unique defence capability and play an essential role in supporting Australia's maritime security. When berthed, submarines sit lower in the water than other large military vessels and experience more excessive motions in operational wave conditions. As such, shore connected floating pontoons are an important option for developing and operating submarine facilities and are particularly appropriate for both the docking and loading of submarines. The safety of Navy personnel during loading of munitions and general operational tasks require that safe working limits be placed on the motions of these piled floating pontoons. At present, there are no standards assigning suitable limits of motion for floating pontoons in order to maintain the safety/comfort of users undertaking operational activities.

This research proposes a set of operational safe motion limits in the form of accelerations to ensure the comfort and safety of floating pontoon users. Experimental work has been undertaken and data collected on the motions of a piled floating pontoon subjected to regular waves, representative of a harbour environment. Pontoon widths, drafts and skirts have been examined under varying wave conditions.

The research has found that in many circumstances, the pontoon motions exceed proposed safe working limits and that the application of different pontoon design features can be used to reduce the accelerations of motion to within operational safe motion limits.

## 1 INTRODUCTION

Piled Floating pontoons are public access structures that provide a point of access and egress to vessels. They undergo dynamic motions resulting from wind, current, wave and berthing forces. Piled floating pontoons are an important option for developing and operating submarine facilities and are particularly appropriate for both the docking and loading of submarines. The safety of Navy personnel during loading of munitions and general operational tasks require that safe working limits be placed on these motions as excessive motions have the potential to cause a standing person to become unstable. Currently, no design standards exist defining these allowable limits for floating pontoons. Nor do any standards exist defining how postural stability should be considered when designing floating pontoons.

This paper firstly provides a set of motion limit criteria to aid floating pontoon design to ensure the comfort and stability of users (Section 2). The limits have been determined based on an extensive review of literature specific to how humans respond to motion. Methods for calculating the natural frequency of heave and roll along with heave accelerations are presented (Section 3). Section 5 summarises the results from a set of laboratory experiments (Section 4) on the dynamic motions of a box type piled floating pontoon subjected to boat wake conditions, modelled as regular waves with a height of 330mm (prototype) and period ranging from 2-7 seconds (prototype), with emphasis given on what happens when the forcing frequency corresponds with the calculated natural frequency of the pontoon. The effect of draft on recorded accelerations is examined and discussed for each of the tested scenarios. Testing has shown that the motions (accelerations) and displacement tend to peak when the natural frequency and forcing frequency correspond. Equations for calculating heave acceleration whilst providing simplistic estimates of heave, underestimate the acceleration when resonance occurs.

## 2 SAFE MOTION LIMITS (SML)

For this research, the Safe Motion Limits (SML) relating postural stability of a standing person with respect to dynamic motions of a floating pontoon will be associated to those motions originating from the moving environments described by Freeman et al. (Freeman et al. 2017). Dynamic motions exceeding those identified in the literature have the potential to result in motion sickness, postural 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. The level of training of person's standing on the floating pontoon should also be considered (civilian or naval). Table 1 stipulates the SML to be adopted for this research based on a minimum level of training (civilian), for age bracket older children and adults (ages 7 to 65 years). 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)<br>Powell and Palachin (2015) |
| Peak angle of tilt | 6° | Rosen et al. (1984) |
| **COMFORT (RMS VALUES)** | | |
| RMS Vertical Acceleration | 0.02g | NORDFORSK (1987)<br>Stevens and Parson (2003) |
| RMS Lateral Acceleration | 0.03g | NORDFORSK (1987) |
| RMS Roll | 2° | NORDFORSK (1987)<br>Stevens and Parsons (2002) |

# 3 STRUCTURAL RESPONSE DUE TO WAVE LOADING

Correctly analysing wave loading and the response of a floating structure to wind, wave and current requires advanced numerical or physical modelling techniques. Simplified desktop methods do exist and can be used in cases where suitable and required.

A brief description of a proposed desktop method for undertaking a simplistic analysis of the motion response of a floating pontoon is detailed below. Further discussion on how the results correlate with this method is provided in Section 5.

## 3.1 Analysis Method

### 3.1.1 Natural Frequency of Structure

In order to understand the motion response of a floating structure the natural frequency of the various axis needs to be determined. A number of methods are available 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 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. It is important that the natural frequency of the structure does not coincide with the natural frequency of the predominate wave climate. When the pontoon natural frequency and forcing frequency coincide resonance results in dynamic amplification.

The relative motion response of a floating structure depends upon the relative water-depth (d)-to-draft (D) ratio (d⁄D), the structure-beam (B)-to-draft (D) ratio (B⁄D) as it affects the virtual mass of the structure, and the beam (B)-to-wavelength (L) ratio (B⁄L), as well as the wave direction and the degree of mooring restraint (Gaythwaite 2016). Gaythwaite (2016) states that in general, the heave response is negligible for $L < 0.75B$ and near unity for $L > 4B$.

The natural frequencies, horizontal and vertical, have been calculated for the pontoon tested. The results will be discussed relative to the natural frequencies calculated to determine if peak accelerations occur when the natural frequency of the structure coincides with the forcing frequency.

### 3.1.2 Accelerations of Structure

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 several methods available to determine the acceleration of a floating body. For desktop assessment purposes we have calculated the heave acceleration with two alternative methods. The first method, (DNV 2012) includes consideration of draft but no inclusion of wave period. The second method (Gaythwaite 2016), includes wave period but no draft component. Results will be discussed relative to these estimates.

From a design viewpoint if approximate accelerations are cacluated at the design stage it is possible to make amendments if the safe motion limits (Table 1) are exceeded enabling better design. These caclulated accelerations will be discussed relative to the recorded data.

### 3.1.3 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 we consider the structure as freely floating, we can obtain conservative estimates of response by assuming RAOs of unity. 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.

Summarising the response of a floating structure in this way does not provide the designer with acceleration motion data. The designer will not know how a person's stability will be affected by the motions. However, an analysis of RAOs has been included to better understand how RAOs and accelerations can be related.

## 4 METHODS

A testing program was developed to obtain the dynamic motions (accelerations and RAO) of two varying width floating pontoons when subjected to regular waves, typical of boat wake. The following sections detail the testing undertaken and the results obtained. This paper presents the results for the narrow pontoon. Full analysis of results including those obtained from the wider pontoon and skirt testing is to be presented as part of PhD thesis.

### 4.1 Experimental Setup

Laboratory testing was undertaken to investigate the dynamic motions of two piled box pontoons. The narrow pontoon (Pontoon 1) was approximately half the beam width of the wide pontoon (Pontoon 2) in the direction of wave propagation. The main aim of the investigations was to record the accelerations experienced as a result of various tested wave scenarios. The work investigated how altering the beam and draft impacted on the recorded accelerations and then compared these accelerations to the safe motion limits nominated above (Section 2).

#### 4.1.1 Model Construction

Both piled floating pontoon models were constructed of grey PVC sheet at a scale of 1:10 prototype. PVC sheet was also used for internal ballast while iron and steel weights were used to alter the draft of the pontoons. Delrin, a highly crystalline engineering thermoplastic specified for high load mechanical applications, was used to construct wear/impact buffers at the pontoon/pile interface. They provided a low friction sliding connection between restraining piles and the pontoon with a 42mm (prototype) annular clearance in order to better reproduce the typical pile to HDPE fender typically used on floating pontoon projects. The pontoon/pile connections were such to allow free vertical movement under the tested wave conditions as would be experienced in real world settings.

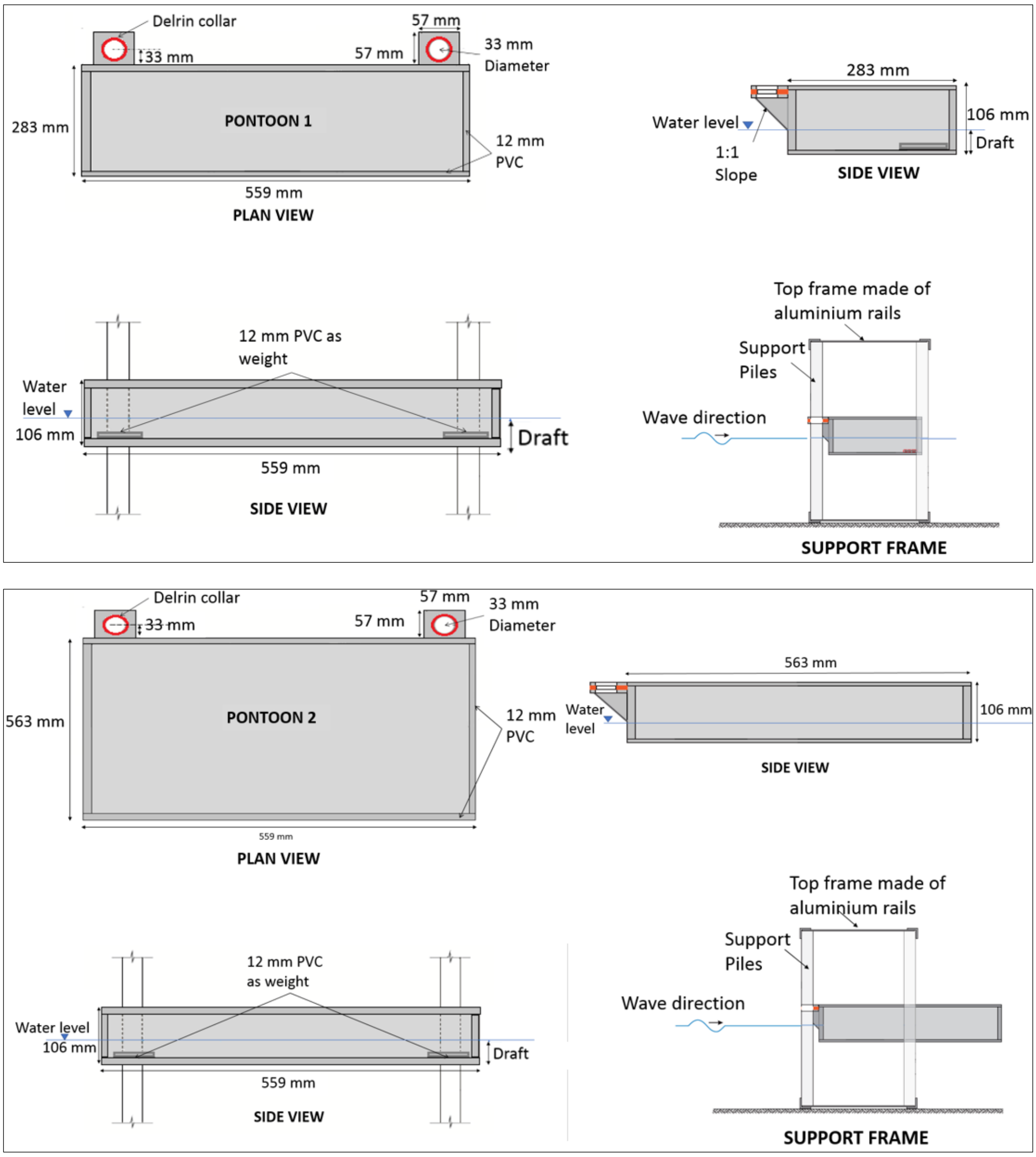
Both pontoon models were constructed to have uniformly distributed internal ballast over pontoon plan area in order to achieve desired buoyancy and draft based on the prototype being tested. Figure 1 details the model floating pontoon dimensions as tested.

#### 4.1.2 Setup

The physical model testing was conducted in the 1.2 m wide wave flume at UNSW Water Research Laboratory, with flume main dimensions as follows, 44 m long, 1.2 m wide and 1.6 m deep. The floating pontoons tested were rectangular prisms with 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, pitch and yaw). On each pontoon, five Inertial Measurement Units (IMU) were used to measure triple-axis accelerations and triple-axis gyrations of each floating pontoon. The IMUs were positioned on each corner of the pontoon, as well as in the centre of the top face. The accelerations recorded were in units of g (gravity, m/s2).

Figure 1. Floating Pontoon Design (model) for Narrow (Pontoon 1) and Wide (Pontoon 2)



Pontoons (Diagram not to scale).

The draft of each pontoon was altered to four different depths (560mm, 585mm, 635mm and 680mm prototype) by adding lead and steel weights. Accelerations were recorded for each wave period/draft combination. The results presented are at prototype scale.

### 4.1.3 Wave Environment

Wave paddle control software developed at UNSW WRL allowed for generation of monochromatic waves for each wave period against each draft. Waves were generated by a vertical wave paddle situated at one end of the flume. Two probes were set up between the paddle and the structure to measure the incident and reflected waves. A third probe was positioned in the lee of the structure to measure the transmitted wave characteristics. In this study, only monochromatic waves representative of boat wake conditions were tested. The wave heights and periods adopted were based on those typically found in Sydney Harbour (Patterson Britton and Partners, 1987), where more than 137 public access points (wharves, jetties and pontoons) for boat users (Transport NSW 2014) are currently in use. The corresponding prototype wave period and wave height are presented in Table 2. Three runs, of approximately 189 seconds (prototype), were conducted for each of the wave periods to ensure similarity. All tests were completed in a water depth of 3.6 m (prototype).

**Table 2.** Monochromatic Wave Testing Parameters (Prototype Scale)

| **WAVE PERIOD (s)** | 2 | 3 | 5 | 7 |
|---|---|---|---|---|
| **MEAN INCIDENT WAVE HEIGHT (mm)** | 330 | 380 | 330 | 320 |

## 5 RESULTS AND DISCUSSION

The results presented in this paper are for the narrow pontoon (Pontoon 1). Exceedance of the safe motion limits in the vertical (heave) and horizontal (surge) planes is presented and discussed for each of the drafts tested. The effect of equivalence between natural frequency and forcing frequency is analysed relative to exceedance of the SML. The RAO in heave is presented along with discussion on the dynamic amplification resulting from natural frequency resonance.

### 5.1 Operational Criteria: Peak Vertical and Lateral Acceleration

### 5.1.1 Natural Frequency

The natural frequency in heave and roll (narrow pontoon) has been calculated for each draft tested, using methods presented in Gaythwaite (2016) and is presented in Table 3.

**Table 3.** Natural Frequency for Each Draft Tested – heave and roll (Prototype)

| **NATURAL FREQUENCY AND PERIOD** | **DRAFT (m)** | | | |
|---|---|---|---|---|
| | **0.560** | **0.585** | **0.635** | **0.680** |
| **$F_{N\text{ - heave}}$ (Hz)** | 0.37 | 0.36 | 0.34 | 0.33 |
| **$T_{N\text{ - heave}}$ (s)** | 2.7 | 2.8 | 2.9 | 3.0 |
| **$F_{N\text{ - roll}}$ (Hz)** | 0.43 | 0.42 | 0.39 | 0.36 |
| **$T_{N\text{ - roll}}$ (s)** | 2.319 | 2.404 | 2.585 | 2.764 |

As detailed in Table 3, the natural frequency in heave for each draft tested is approximately 3 seconds. We would expect dynamic amplification and resonance when the wave period coincides with the calculated natural frequency. Figure 2 shows the cumulative probability plots for heave accelerations for each draft tested. The figure shows the probability of exceeding our peak vertical safe motion limit of 0.1g for each of the tested wave periods. In heave, exceedance of our safe motion limit occurs a higher percentage of the time for the 3 second period wave for each of the drafts tested, corresponding well with what we would expect to happen as a result of correspondence between the natural frequency and forcing frequency. The plots show the probability of exceeding our safe motion limit for the 3 second period wave peaks at a draft of 585mm (20.64%) (top right). All other wave periods recorded very similar percentage exceedance for each draft and wave period. As discussed in Section 3.1.1, heave acceleration is predominantly dependent on the beam to wavelength ratio (B/L) and as such altering draft has minimal impact.

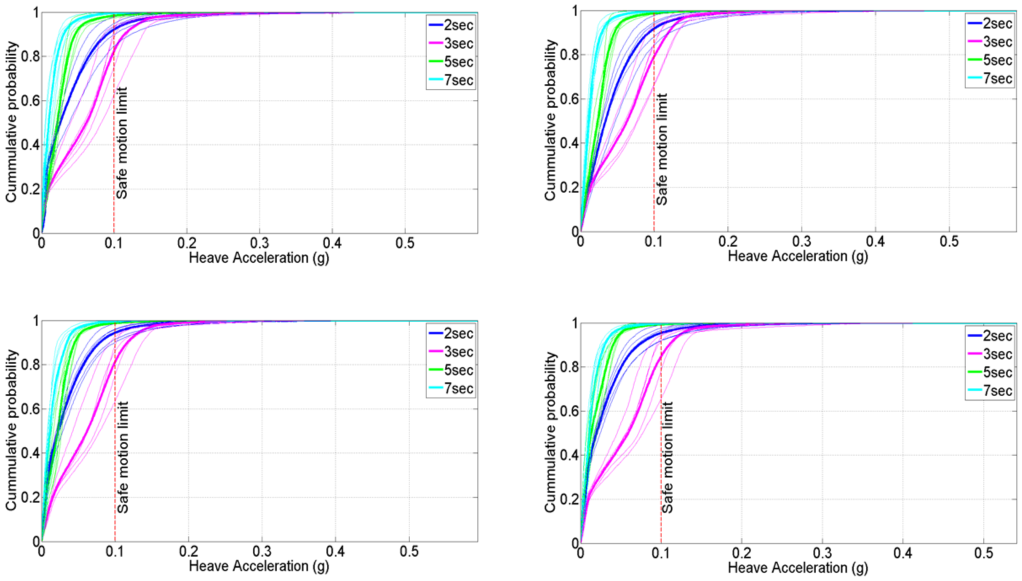


Figure 2. Cumulative Distribution Functions for the Narrow Pontoon in heave for each draft: (top left) 560mm, (top right) 585mm, (bottom left) 635mm and (bottom right) 685mm. Thin lines indicate individual sensors (1-5) and thick lines represent the mean of all 5 sensors.

Surge acceleration occurs in the direction of wave propagation (x-axis). It can be reduced by altering the amount of play between the pile and pontoon, however, there needs to be enough space to allow free vertical movement as the pontoon passes over the wave. Table 3 indicates how our natural period in roll changes with draft. The natural period in roll relates to the surge acceleration. The natural period in roll changes from approximately 2.3s (560mm) up to 2.76s (685mm). The change in roll period is due to the change in metacentric height resultant from changing draft. As our natural period in roll changes from approximately 2s up to approximately 3s we would expect our exceedance curves (surge) to change accordingly.

Figure 3 shows the cumulative probability in surge of exceeding the safe motion limit for each of the tested wave periods and each of the tested drafts. The highest exceedance occurred for a draft of 585mm (prototype) (top right) with the 2 second period wave exceeding the SML 36.31% of the time, followed by 5 second (27.19%), 3 second (26.78%) and 7 second (26.26%). A draft of 635mm (bottom left) then recorded the highest exceedance however for this situation the 3 second period wave had the highest probability (27.79%) followed by 5 second (24.62%), 2 second (14.97%) and 7 second (13.42%). 560mm (top left) was next in terms of exceedance with the 2 second period wave recording the highest exceedance followed lastly by 685mm (bottom right) where the 3 second period wave recorded the highest exceedance. The natural roll frequencies presented in Table 3 correspond well with the exceedance curves, whereby we see our predominant exceedance change from being the 2s period (560mm) up to the 3s period (685mm).

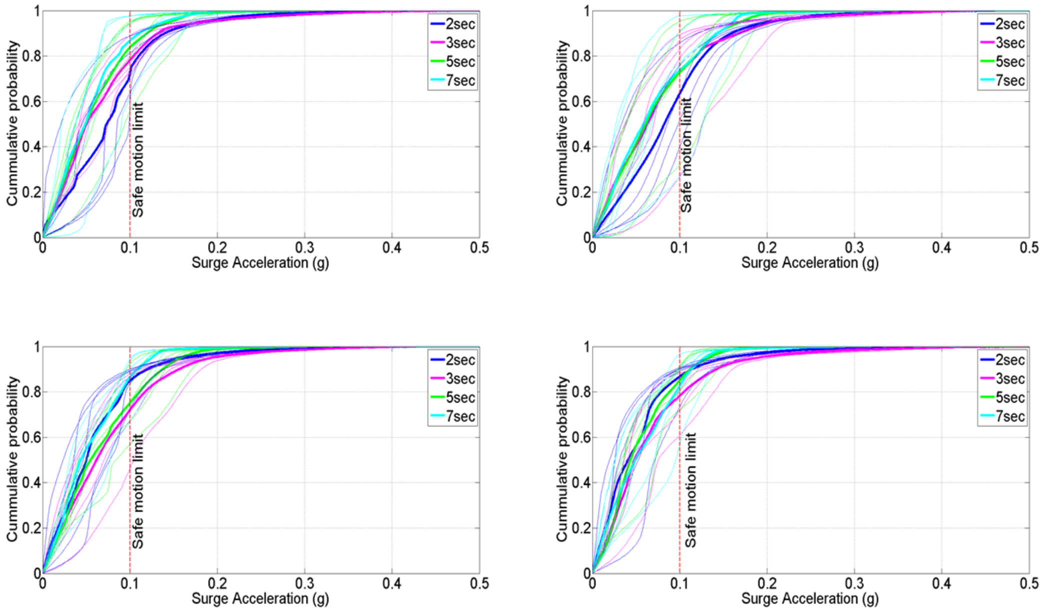


Figure 3. Cumulative Distribution Functions for the Narrow Pontoon in surge for each draft: (top left) 560mm, (top right) 585mm, (bottom left) 635mm and (bottom right) 685mm. Thin lines indicate individual sensors (1-5) and thick lines represent the mean of all 5 sensors.

These curves show significant exceedance even in the very mild tested wave climate (330mm prototype). The short period waves resulting from boat wake have the potential to cause dynamic amplification of a floating pontoon if the natural frequency is not considered.

### 5.1.2 Comparison Between Calculated and Recorded Acceleration

An effective method for calculating the projected accelerations of a floating pontoon at the design stage would be useful to minimise exceedance of the SML. Prior to this work there have been minimal guidelines on suitable acceleration limits of floating pontoon motions. Estimates of the heave accelerations have been calculated (Table 4 and Table 5) for each wave period/draft combination using the two methods mentioned in Section 3.1.2.

**Table 4.** Calculated Heave Acceleration and Effect of Altering Draft Using DNV (2012) (Prototype)

| **CALCULATED** | **DRAFT (mm)** | | | |
|---|---|---|---|---|
| | **560** | **585** | **635** | **685** |
| **HEAVE ACCELERATION (g)** | 0.29 | 0.286 | 0.275 | 0.266 |

**Table 5.** Calculated Heave Acceleration and Effect of Wave Period Using Gaythwaite (2016) (Prototype)

| **CALCULATED** | **WAVE PERIOD (s)** | | | |
|---|---|---|---|---|
| | **2** | **3** | **5** | **7** |
| **HEAVE ACCELERATION (g)** | 0.4 | 0.17 | 0.06 | 0.03 |

The calculated accelerations presented in Table 4 and Table 5 highlight that increasing draft reduces heave acceleration and as wave period increases magnitude of heave acceleration reduces. The recorded peak heave accelerations obtained during testing are presented in Table 6 for each draft and wave period combination.

**Table 6.** Maximum Recorded Heave Acceleration for Draft and Wave Period

| | | **Draft (mm)** | **Wave Period (s)** | | | |
|---|---|---|---|---|---|---|
| | | | **2** | **3** | **5** | **7** |
| **Peak** | **Heave (g)** | **560** | 0.60 | 0.53 | 0.34 | 0.22 |
| | | **585** | 0.59 | 0.57 | 0.30 | 0.22 |
| | | **635** | 0.59 | 0.50 | 0.33 | 0.21 |
| | | **685** | 0.48 | 0.54 | 0.26 | 0.22 |

Comparing the calculated accelerations (Table 4 and Table 5) with Table 6 the method proposed by DNV (2012) shows the closest correspondence with the recorded results. For a draft of 685mm using DNV (2010) method the calculated heave acceleration was 0.266g (Table 4) compared with the recorded peak acceleration, ranging from 0.48g to 0.22g (685mm) (Table 6). Similarly, for the other tested drafts DNV (2012) underestimates maximum heave acceleration at the resonance frequency however provided good agreement outside of this.

### 5.1.3 Response Amplitude Operator

Dynamic amplification occurs when the natural frequency of the structure corresponds with the forcing frequency. When dynamic amplification occurs heave response will be larger than unity and it cannot be assumed that the heave amplitude of the structure will equal the wave amplitude. Figure 4 shows the response amplitude operator for each of the drafts tested. RAOs for drafts of 560mm (top left) and 685mm (bottom right) indicate dynamic amplification at the 3 second period wave with amplitude of motion above the wave amplitude. This corresponds with the natural period in heave presented in Table 3. For a draft of 585mm peaks in the RAO occur at 3 and 5 second however amplitudes of motion are approximately equal to the wave amplitude. Dynamic amplification occurs at a period of 5 seconds for a draft of 635mm (bottom left) which is relatively different from the calculated natural frequency.

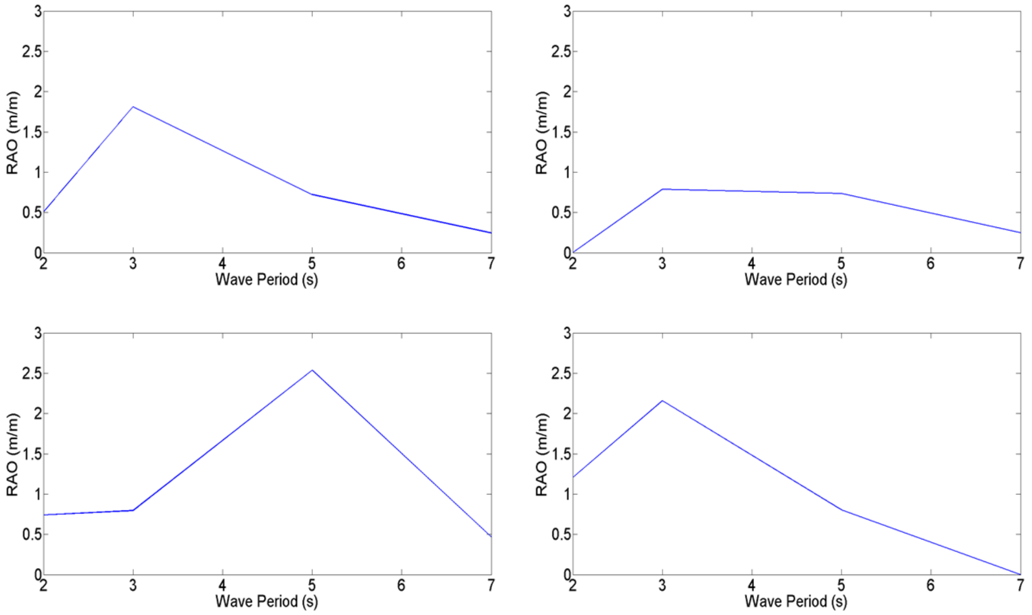


Figure 4. Response Amplitude Operator in heave for each draft: (top left) 560mm, (top right) 585mm, (bottom left) 635mm and (bottom right) 685mm.

## 6 CONCLUSION

A series of physical laboratory experiments were conducted to examine the dynamic motions of a piled floating box pontoon of varied draft under boat wake conditions (prototype = 330 mm) in order to compare these to safe motion limit criteria as defined in the literature for personal safety and comfort. The paper has highlighted how the dynamic nature of the pontoon relates to the natural frequency with exceedance of the safe motion limit occurring when the natural frequency corresponds with the forcing frequency. The DNV (2012) method for estimating heave acceleration underestimates heave acceleration when the natural frequency and forcing frequency correspond however provided good approximate values outside of resonance. Floating pontoon design can be bettered by considering the nominated SML (Table 1), calculating both the natural frequency and heave acceleration and ensuring the forcing frequency is far removed so dynamic amplification does not occur. The research has highlighted a gap in design guidelines/standards specific to allowable motions of floating pontoons. Although no specific guidelines exist, the paper proposes safe motion limits (what level of motion accelerations might be acceptable) and how to undertake preliminary design in order to minimise motions of floating pontoons. For important pontoon structures physical wave flume testing to measure response motions and accelerations is recommended.

## 7 REFERENCES

BSi, 2000. BS6349-6 Maritime Stuctures — Part 6: Design of Inshore Moorings and Floating Structures. In *Bsi*.

Defence, A.G.D. of, 2016. *2016 Defence White Paper*,

DNV, 2012. *DNV Rules for Classification of Ships Hull Structural Design Ships With Length 100 Metres and Above*,

Freeman, E.L., Cox, R.J. & Splinter, K.D., 2017. Suitable Criteria for Safe Motion Limits of a

Floating Pontoon Relative to the Postural Stability of a Stationary Standing Person. In *Coasts and Ports Conference*. pp. 21–23.

Gaythwaite, J.W., 2016. Design of Marine Facilities. Available at: http://ascelibrary.org/doi/book/10.1061/9780784414309.

NSW Maritime, 2005. *NSW Maritime Engineering Standards and Guidelines for Maritime Structures*, NSW Maritime.

Rosen, D.S., ASCE, M. & Kit, E., 1984. A Simulation Method for Small Craft Harbour Models. *Coastal Engineering*, pp.2985–3000.