

# Mooring arrangement design to minimise berthed ship motions due to a passing ship

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## ABSTRACT

Ships at berth range on their moorings due to forces and moments imparted by passing ships. This can cause large mooring line and fender loads and in extreme cases can result in damage to mooring infrastructure and dangerous situations for crew and passengers. Berthed ship motions also influence loading/unloading procedures and can reduce the efficiency of the berth. Therefore understanding the berthed ship – passing ship interactions is important for the safe and efficient design and operation of ports.

The berthed ship motions are dependent on the form and magnitude of the interaction forces and moments, which are significantly influenced by the bathymetry around the berthed and passing ships. In general, a ship berthed in a narrow channel would experience greater surge force and a lower sway force and yaw moment compared to an equivalent case in a wider channel. Designing the mooring arrangement to minimise the berthed ship motions due to a passing ship is advantageous to increase berth efficiency, reduce loads on mooring infrastructure and increase safety for crew and passengers.

This paper presents interaction forces and moments measured on a berthed ship due to a passing ship from physical scale model experiments conducted at the Australian Maritime College's Model Test Basin facility. Two cases are presented that represent a berthed ship in a wide channel, where bank effects can be considered negligible and in a narrower channel, where bank effects are significant. The results from the model scale experiments were scaled to represent a full scale scenario and used as input to a numerical simulation model to predict the berthed ship motions and mooring loads experienced by a berthed ship due to a passing ship. The simulations were conducted using a generic mooring arrangement. Additional mooring arrangements were tested to quantify the effect of initial mooring line pretension and mooring line configuration on the maximum safe passing ship speed based on selected safety criteria. The results from the numerical simulations demonstrated the advantages of increased pretension and designing the mooring arrangement to suit the bathymetry around the berthed ship.

## NOMENCLATURE

AMC Australian Maritime College

$B$  Beam (m)

$BD$  Bank offset distance (m)

$Fr_h$  Froude depth number ( $Fr_h = U/\sqrt{gh}$ )

$g$  Gravitational constant (9.81 m/s<sup>2</sup>)

$h$	Water depth (m)
$L_B$	Berthed ship length between perpendiculars (m)
$L_C$	Characteristic length ( $L_C = \frac{L_P + L_B}{2}$ ) (m)
$L_{oa}$	Ship length overall (m)
$L_P$	Passing ship length between perpendiculars (m)
MTB	Model Test Basin
$N$	Yaw moment (N)
$N'$	Non-dimensional yaw moment ( $N' = \frac{N}{\rho g \nabla_C L_C F r h^2}$ )
$PD$	Passing ship position ( $PD = \frac{2x}{L_P + L_B}$ )
$S$	Lateral separation, centreline to centreline (m)
$T$	Draft (m)
$U$	Passing ship speed (m/s)
UKC	Under keel clearance
$x$	Longitudinal coordinate of passing ship's midship from berthed ship's midship (m)
$X$	Surge force (N)
$X'$	Non-dimensional surge force ( $X' = \frac{X}{\rho g \nabla_C F r h^2}$ )
$Y$	Sway force (N)
$Y'$	Non-dimensional sway force ( $Y' = \frac{Y}{\rho g \nabla_C F r h^2}$ )
$\rho$	Water density (kg/m <sup>3</sup> )
$\nabla_B$	Berthed ship displacement (m <sup>3</sup> )
$\nabla_C$	Characteristic ship displacement ( $\nabla_C = \frac{\nabla_P + \nabla_B}{2}$ ) (m <sup>3</sup> )
$\nabla_P$	Passing ship displacement (m <sup>3</sup> )

## INTRODUCTION

In addition to restricting berthed ship motions due to environmental loads such as waves, wind and current, the mooring equipment is also required to restrict the berthed ship motion due to passing ship interaction. Excessive berthed ship motions and mooring loads due to ship to ship interaction have resulted in damage to vessels, mooring infrastructure and in extreme cases injury to passengers and crew [15]. Berthed ship motion can also affect loading/unloading procedures which can reduce port efficiency. To combat this many ports have limits on the speed at which vessels can transit a channel in the vicinity of a berthed ship.

In order to predict the effect that passing ship interaction will have on the berthed ship motions and mooring loads, the interaction forces and moments must first be accurately

predicted. Many empirical methods exist to predict the interaction forces and moments on a berthed ship due to a passing ship which include the effects of ship size, passing ship speed, lateral separation and water depth [7, 9 & 21]. Most methods, however, are based on cases without the effects of banks (wide channels or open water). It has been shown that the effect of increased blockage due to banks generally increases the surge force and reduces the sway force and yaw moment imparted on the berthed ship by the passing ship [7, 18, 19 & 20]. Since the form and magnitude of the interaction forces and moments can greatly affect the berthed ship motions [4 & 5] incorporating the bathymetry effects in the interaction force and moment predictions is essential.

This study compares the interaction forces and moments experienced by a berthed ship due to a passing ship in a wide rectangular channel ( $8.25 \times \text{Beam } (B)$  wide channel) to a narrower rectangular channel ( $3.04B$ ). The interaction forces and moments were measured using physical scale model experiments conducted at the Australian Maritime College's (AMC) Model Test Basin (MTB) facility. The experiments were conducted at speeds of Froude depth number ( $Fr_h$ ) 0.25 and below. The measured interaction forces and moments were then scaled to represent a 300m length overall ( $L_{oa}$ ) vessel. The measured interaction forces and moments were used as input, along with a generic mooring arrangement, to the numerical simulation software to predict the berthed ship motions and mooring loads due to the interaction of the passing ship. The berthed ship motions and mooring loads from the wide and narrower channel cases were compared to relevant safety criteria [12 - 14] to determine the maximum safe passing ship speed for the cases presented. Three additional mooring arrangements were analysed to investigate how the maximum passing ship speed is affected by increasing the initial mooring line pretension and changing the distribution of mooring lines but keeping the total number of lines constant.

## **PHYSICAL SCALE MODEL EXPERIMENTS**

A series of physical scale model experiments were conducted at the AMC's MTB to quantify the effect that a laterally restricted channel has on the magnitude and form of the interaction forces and moments experienced by a berthed ship due to a passing ship. It was noticed in previous experiments conducted by the authors [2 – 5] that the towing rig used didn't fully restrict the passing ship in sway as it passed the berthed ship. As a result the lateral separation between the berthed and passing ship changed in the region that the berthed ship was affected by the passing ship. The sway motion of the passing ship was not measured and the effect on the magnitude of the forces and moments is unknown. To correct for this a new towing rig was constructed within the MTB to fully constrain the passing ship in surge, sway and yaw.

### **Ship model details**

MarAd F Series bulk carrier type hull forms [17] were used to represent the berthed and passing ships. The berthed and passing ship models had a length to beam ratio of 5.50, a beam to draft ratio of 3.31 and a block coefficient of 0.85. A body plan of the ship models used in the physical scale model experiments can be seen in Figure 1.

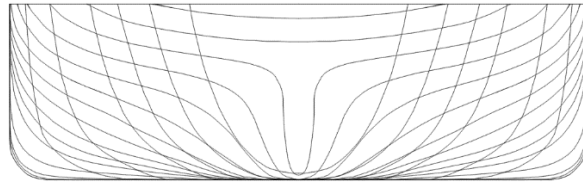


Figure 1 - Body plan of Marad F Series used during the physical scale model experiments.

### Test program

The interaction surge force, sway force and yaw moment on the berthed ship were measured for two different scenarios. A cross sectional schematic of the physical scale model experiments can be seen in Figure 2. A stationary model was used to simulate the berthed ship. The particulars of the lateral separation, water depth and bank distance can be seen in Table 1.

For Condition 1 the vertical surface piercing banks were parallel to the passing ship path, located 6.00m ( $8.25B$ ) from the passing ship model's centerline. For the range of Froude depth numbers tested, with bank offsets of 8 beams or larger, the bank effect is considered negligible [10] and could therefore be considered laterally unrestricted case. Condition 2 was used to simulate a berthed ship – passing ship interaction scenario in a laterally restricted case of a narrow rectangular channel. The vertical surface piercing banks were parallel to the passing ship path, 2.21m ( $3.04B$ ) either side of the passing ship's centerline. The lateral separation between the berthed and passing ship was 1.82m ( $2.50B$ ) for both Condition 1 and 2. The depth to draft ratio for both cases was 1.20.

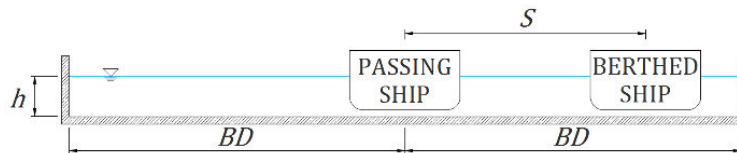


Figure 2 - Cross sectional view of the bathymetry of Conditions 1 and 2.

Table 1 - Lateral separation, water depth and bank offset distances of physical scale model experiments.

	Channel width description	$S$	$h$	$BD$
Condition 1	Wide	$2.50B$	$1.20T$	$8.25B$
Condition 2	Narrow	$2.50B$	$1.20T$	$3.04B$

### Test procedure

The passing ship was accelerated from rest to a predetermined constant speed before reaching the region that affects the berthed ship (2 ship lengths fore and aft of the berthed ship's midship section) [1, 9 & 16]. The constant passing ship speed was maintained until the passing ship's effect on the berthed ship was negligible. The range of speeds analysed were between the  $Fr_h$  of 0.15 to 0.25.

The passing ship speed and the surge force, sway force and yaw moment on the berthed ship were recorded at a sample rate of 200Hz. A fourth order Butterworth low pass filter

was applied to the results with a 0.12Hz cut-off frequency. The cut-off frequency was based on the fastest passing ship speed tested in the current research. At least 30 minutes was allowed between consecutive runs to allow similar initial conditions. A selection of runs was repeated to determine the repeatability and experimental spread of the test results.

### Experimental force and moment results

The interaction force and moment results from the experiments were non-dimensionalised using Equations 1, 2 & 3. The sign convention is given in Figure 3.

$$X' = \frac{X}{\rho g \nabla_C Fr_h^2} \quad (1)$$

$$Y' = \frac{Y}{\rho g \nabla_C Fr_h^2} \quad (2)$$

$$N' = \frac{N}{\rho g \nabla_C L_C Fr_h^2} \quad (3)$$

The non-dimensional surge force, sway force and yaw moment are plotted as functions of passing ship position ( $PD$ ) in Figure 4, which is the non-dimensional offset between the midship sections of the two ships, as given in Equation 4.

$$PD = \frac{2x}{L_P + L_B} \quad (4)$$

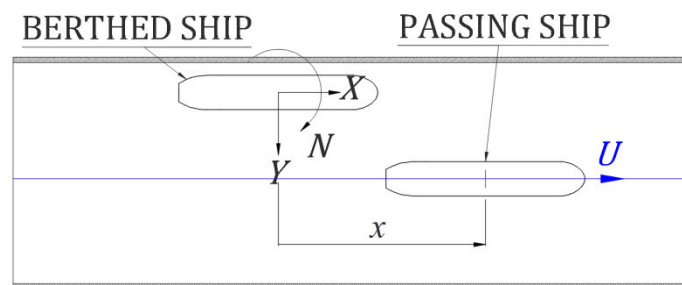


Figure 3 - Sign convention of the forces, moments and motions.

The surge force in the narrower channel ( $3.04B$ ) was much larger than the wider channel ( $8.25B$ ). The peak positive surge force occurs at a greater value of  $PD$  for the narrower channel case. The magnitude of the sway force and yaw moment was reduced by the reduction in the channel width. This is consistent with previous research [7, 15, 18, 19 & 20].

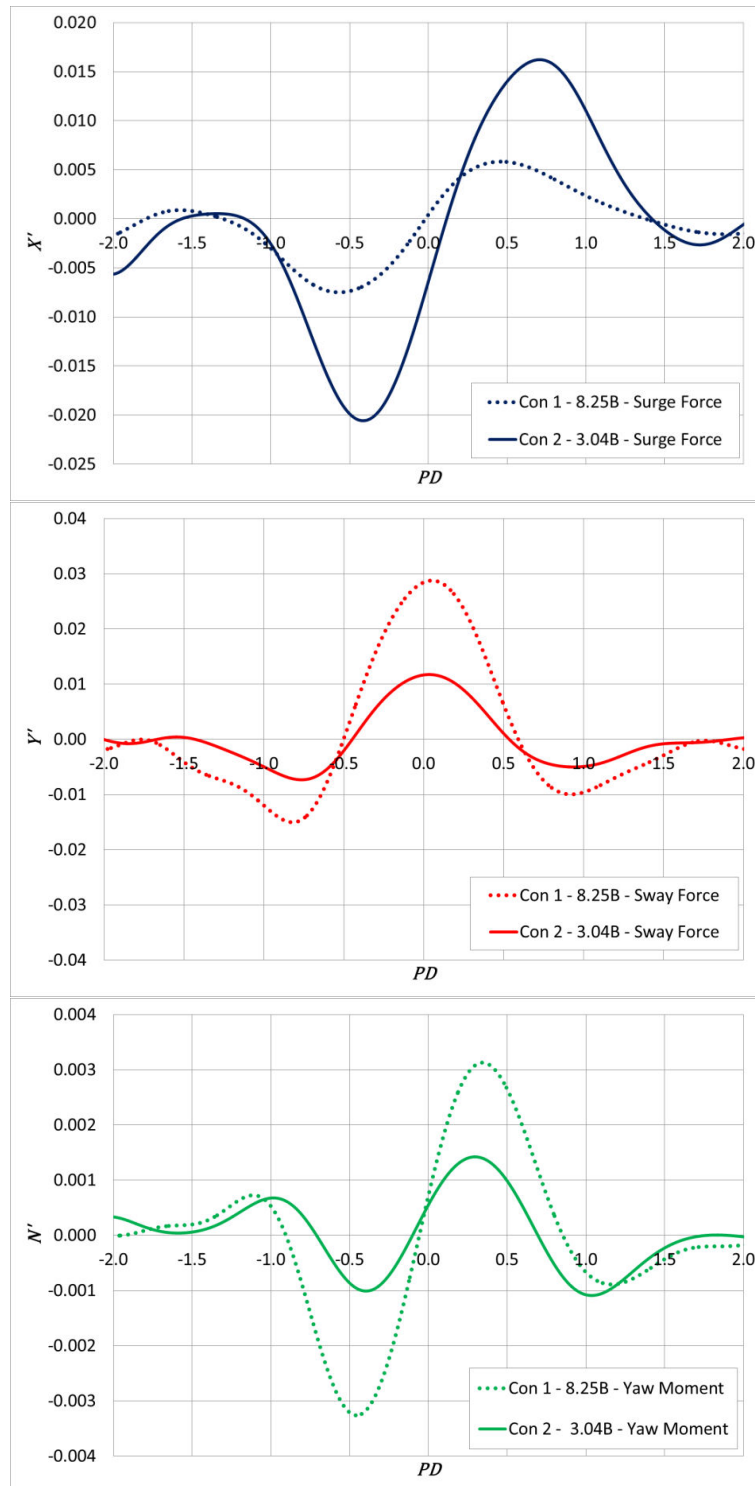


Figure 4 - Interaction surge force, sway force and yaw moment for the wide and narrower channel cases ( $Fr_h = 0.23$ ,  $h = 1.20T$ ,  $S = 2.50$ )

## NUMERICAL SIMULATIONS

The time domain interaction forces and moments measured during the 1:70.1 physical scale model experiments were extrapolated to full scale using Froude scaling laws [11] to represent 300m  $L_{oa}$  bulk carrier berthed and passing ships. The model scale speeds tested represented full scale speeds of 4.0 to 6.6 knots. The full scale peak to peak surge force, sway force and yaw moment from Conditions 1 and 2 can be seen in Figure 5. The general

trend of the peak to peak results shows that the surge force was significantly increased and the sway force and yaw moment was significantly reduced when the channel width was reduced to  $3.04B$ .

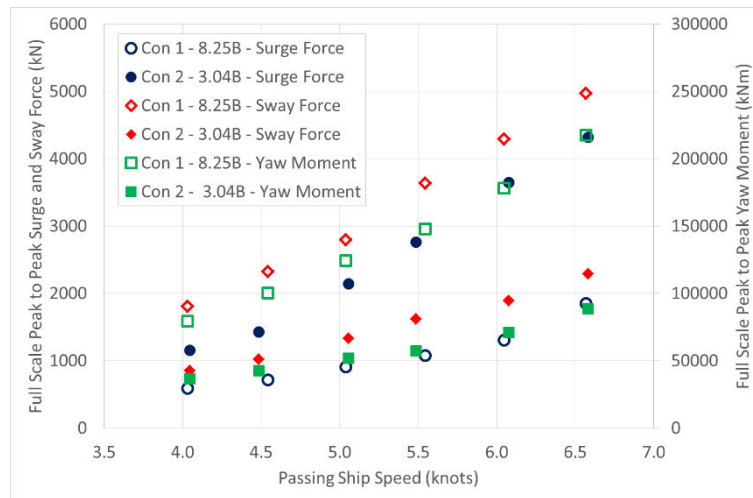


Figure 5 - Peak to peak interaction surge force, sway force and yaw moment for the wide and narrow channel cases ( $F\gamma_h$  0.15 to 0.25,  $h = 1.20T$ ,  $S = 2.50$ ).

The full scale interaction forces and moments were used as input to the time domain numerical simulation software aNyMOOR.TERMSIM [12] along with a generic mooring arrangement to determine the effect of the channel width on the predicted berthed ship motions and mooring loads due to a passing ship. The berthed ship motions and mooring loads were assessed against safe working criteria [12 – 14] to determine the maximum allowable passing ship speeds for Condition 1 and 2. Three additional mooring arrangements were also tested to investigate if the motions and mooring loads could be reduced by increasing the initial pretension and changing the distribution of the mooring lines, whilst keeping the total number of mooring lines constant. A point of interest was to investigate if specific mooring arrangements are more effective for different channel widths. No environmental loads due to wind, waves or current were applied to the berthed ship during the simulations.

### Mooring Arrangement Detail

Four mooring arrangements were tested. A schematic plan view of the mooring layout can be seen in Figure 6. The bollard, fender, and fairlead locations were based on past research conducted by AMC and remained constant for all mooring arrangements tested. Each mooring arrangement tested consisted of 16 mooring lines. The different mooring arrangements were obtained by changing the number of head, breast, spring and stern lines, whilst keeping the total number of mooring lines constant. The mooring lines used in the simulations represented 88.9mm nylon double braid lines [12] with a Minimum Breaking Load (MBL) of 1638kN. Five fenders were modelled for all mooring arrangements tested. The fender properties were based on Bridgestone C3000H cell fenders [12]. A friction coefficient of 0.12 was used to model the fender panel face [8].

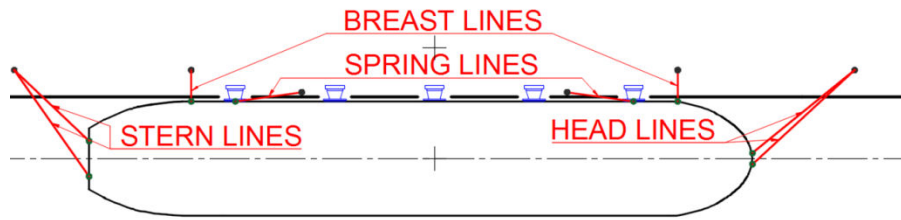


Figure 6 – Schematic of the mooring arrangement.

Details of each mooring arrangement can be seen in Table 2. Mooring Arrangement 1 was used as the base case which all other mooring arrangements were assessed against. Mooring Arrangement 2 was used to assess what effect an increase in initial pretension would have on the predicted motions and mooring loads. For the wider channel case, the sway force and yaw moment is much larger than the narrow case, hence Mooring Arrangement 3 was introduced to establish if the additional breast lines would help reduce the sway motion experienced by the berthed ship. For the narrower channel case the surge force is much larger than the wider channel case, hence Mooring Arrangement 4 was used to assess whether additional spring lines would reduce the predicted surge motion of the berthed ship. It should be noted for Mooring Arrangements 3 and 4 the number of head and stern lines were reduced to accommodate the additional breast and spring lines so the total number of mooring lines remained the same (16 lines in total).

Table 2 – Mooring arrangement particulars used in the numeric simulations.

Mooring Arrangement	1	2	3	4
Description	Generic base case	Increased initial pretension	More breast lines, fewer head and stern lines	More spring lines, fewer head and stern lines
Head Lines	4	4	2	2
Fwd Breast Lines	2	2	4	2
Fwd Spring Lines	2	2	2	4
Aft Spring Lines	2	2	2	4
Aft Breast Lines	2	2	4	2
Stern Lines	4	4	2	2
Initial Pretension	15t	25t	15t	15t

### Safety Criteria

The berthed ship motions were assessed against safety criteria for a bulk carrier loading with conveyor belt loading equipment [14]. The motion criteria used were:

- Maximum peak to peak surge motion of 5.0m



- Maximum zero to peak sway motion (away from fenders) of 2.5m
- Maximum peak to peak yaw motion 3 degrees.

The maximum safe mooring line load allowed was 819kN (50% of the MBL for nylon mooring lines [13]). The maximum allowable fender load was taken as 3924kN [12].

Any numerical simulation run that exceeded the MBL or maximum fender deflection of 1.65m was considered unrealistic as the effect of the broken line or fender could not be accurately modelled and the results were omitted.

### **Berthed Ship Motion and Mooring Load Predictions**

At the start of each simulation, the berthed ship was positioned so that the midship was adjacent to the middle fender and just touching the fender face (no fender deflection occurring), as seen in Figure 6. The pretensions were then applied to each mooring line simultaneously. The berthed ship was then allowed to move to an equilibrium position based on the mooring line pretension and the fender friction and deflection. Sufficient time was allowed to ensure that the berthed ship was stationary before the interaction forces and moments were applied to the berthed ship. The resulting peak to peak and zero to peak motions and maximum mooring and fender loads were obtained from the time domain predictions.

The peak to peak surge and yaw motion and the zero to peak sway motion for the wide and narrow channels for Mooring Arrangement 1 can be seen in Figure 7. The maximum mooring line load for both channel widths with Mooring Arrangement 1 can be seen in Figure 8. The maximum fender load for both channel widths with Mooring Arrangement 1 can be seen in Figure 9. As expected, the predicted peak to peak surge motion for the narrow channel (3.04B channel) was much higher than for the wider channel (8.25B). The zero to peak sway motion and the peak to peak yaw motion was much larger the wider channel case (8.25B).

For the wider channel case (8.25B) the surge motion criteria was exceeded at the passing ship speed of 6.6 knots using Mooring Arrangement 1. The maximum fender load safety criterion was not exceeded. However, the 50% MBL safety criterion was exceeded in the forward breast lines at the passing ship speed of 5.5 knots. Therefore, the maximum safe passing ship speed tested for the wide channel with Mooring Arrangement 1 was 5.0 knots, with the mooring line load being the limiting safety criterion.

For the narrow channel case (3.04B) with Mooring Arrangement 1 the surge motion safety criterion was exceeded at the passing ship speed of 5.5 knots and above. The maximum fender load safety criterion was not exceeded. The maximum mooring line load in the forward and aft spring lines exceeded the 50% MBL safety criterion at the passing ship of 6.1 knots. Hence, the surge motion was the limiting safety criterion for the narrow channel with Mooring Arrangement 1.

For the wide and narrow channels, using Mooring Arrangement 1 the maximum safe passing ship speed tested was 5.0 knots. None of the cases tested resulted in the fender load exceeding the safety criteria.

The maximum safe passing ship speed was determined for both channel widths for each mooring arrangement tested. The maximum safe passing ship speed and limiting safety criteria is presented in Figure 10. For both channel widths, for Mooring Arrangement 1, the maximum safe passing ship speed tested was approximately 5 knots and the limiting criterion was the forward breast line load for the wider channel and the surge motion for the narrow channel (as specified earlier). By increasing the initial pretension from 15t (Mooring Arrangement 1) to 25t (Mooring Arrangement 2) the maximum safe passing ship speed tested was increased to approximately 6 knots for both channel widths. The mooring line loads were the limiting criteria for Mooring Arrangement 2.

For Mooring Arrangement 3 (more breast lines, fewer head and stern lines) the maximum safe passing ship speed tested was increased to 6 knots for the wide channel. However, increasing the number of breast lines and reducing the number of head and stern lines in Mooring Arrangement 3 did not increase the safe passing ship speed for the narrow channel. For Mooring Arrangement 3 the limiting criteria were the surge motion and forward breast line loads for the wide channel and the surge motion for the narrow channel.

Increasing the number of spring lines and reducing the number of head and stern lines (Mooring Arrangement 4) did not increase the maximum safe passing ship speed tested for the wide channel and the forward breast line loads limited the safe passing ship speed. The maximum safe passing ship speed tested for the narrow channel was increased to approximately 6 knots when additional spring lines were added and head and stern lines were removed (Mooring Arrangement 4).

The advantage of increasing the initial mooring line pretension can be seen from the safe maximum passing ship speed tested results. What is also clear is that designing the mooring arrangement around the site specific bathymetry could increase the safe passing ship speed. In order to increase port efficiency, understanding the effects that the bathymetry has on the forces and moments affecting the berthed ship is important and designing mooring infrastructure and procedures.

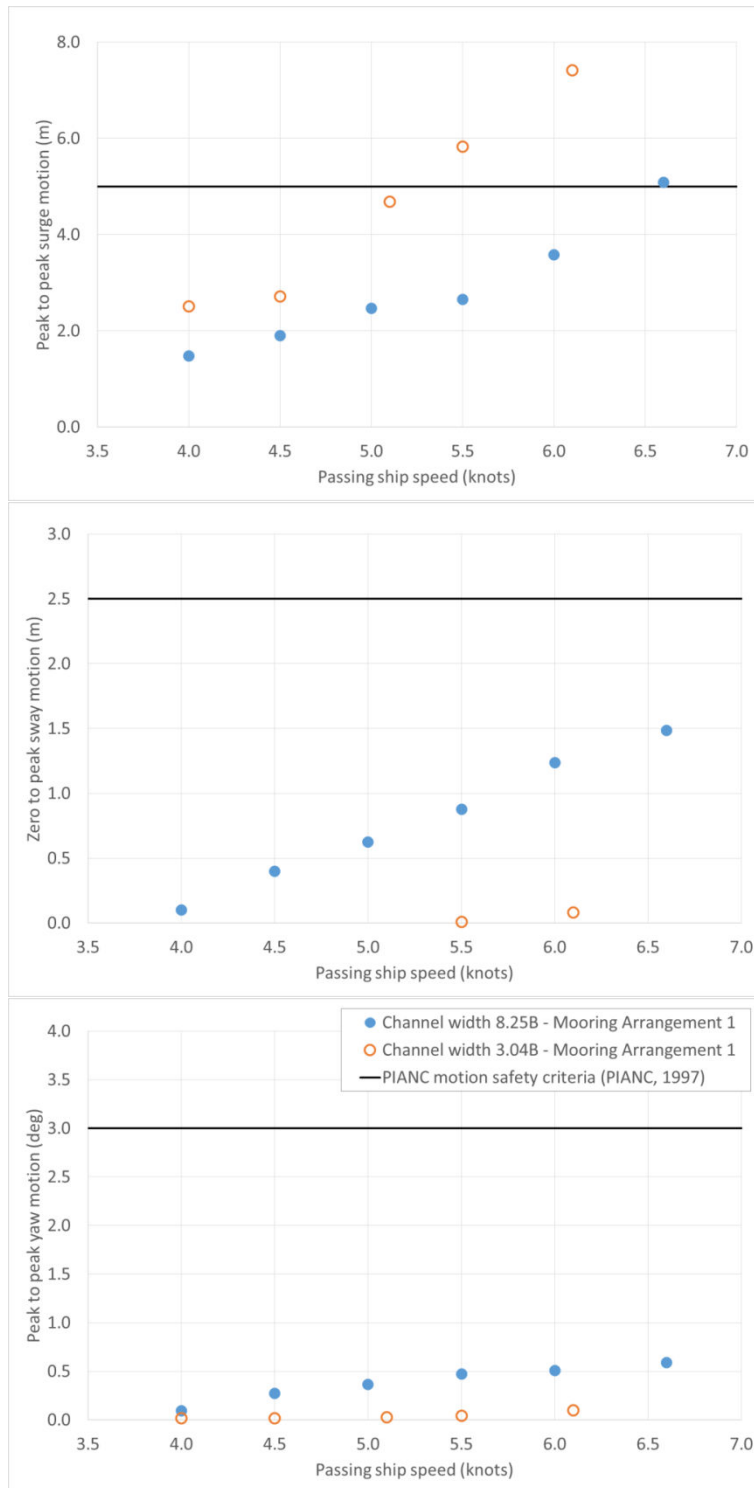


Figure 7 – Predicted peak to peak surge motion, zero to peak sway motion and peak to peak yaw motion for Conditions 1 and 2 with Mooring Arrangement 1.

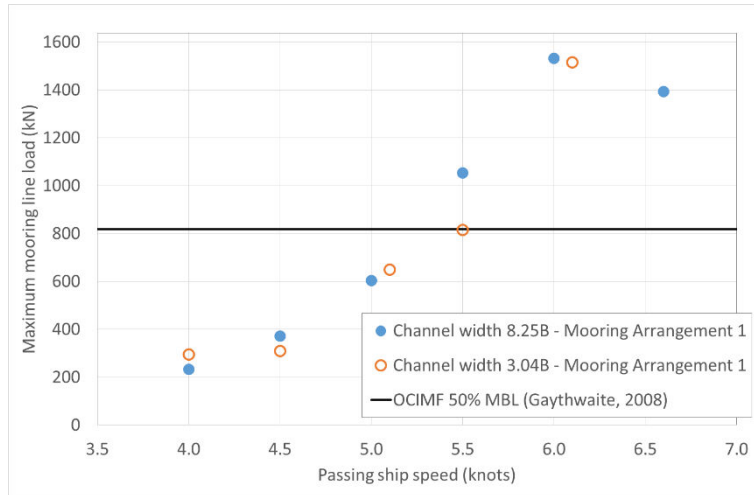


Figure 8 – Predicted maximum mooring line load for Conditions 1 and 2 with Mooring Arrangement 1.

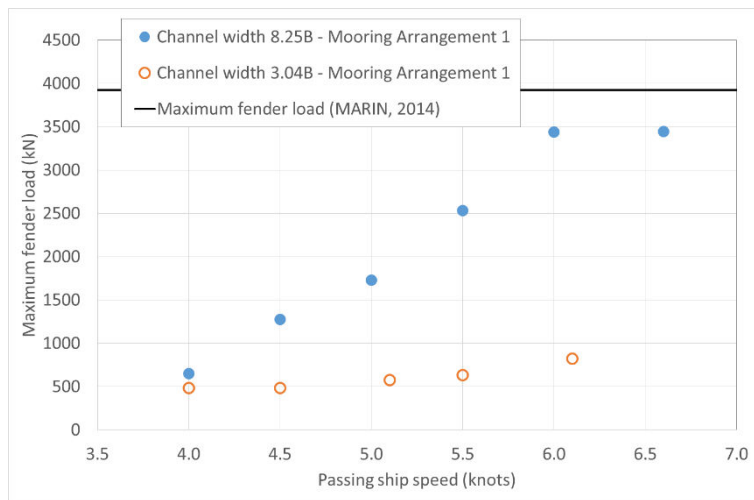


Figure 9 – Predicted maximum fender load for Conditions 1 and 2 with Mooring Arrangement 1.

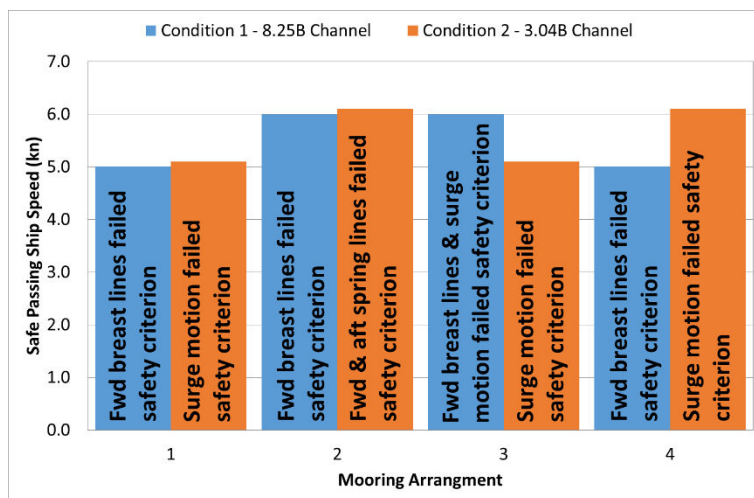


Figure 10 – Maximum safe passing ship speed tested for wide and narrow channel for all mooring arrangements showing the parameters that failed the safety criteria.

## CONCLUDING REMARKS

A series of physical scale model experiments were conducted at AMC's MTB facility to measure the interaction forces and moments experienced by a berthed ship due to a passing ship in a wide and narrow rectangular channel. The interaction forces and moments were scaled to represent 300m  $L_{oa}$  vessels and used as input to a numerical simulation, along with a generic mooring arrangement, to predict the berthed ship motions and mooring loads due to the passing ship in the two channel configurations. The motions and mooring loads were assessed against relevant safety criteria to determine the maximum safe passing ship speed for each channel width. Three additional mooring arrangements were also tested to determine if the maximum safe passing speed could be increased by increasing the initial pretension and changing the distribution of mooring lines, whilst keeping the total number of lines constant.

The additional blockage of the narrow channel increased the magnitude of the surge force and reduced the magnitude of sway force and yaw moment experienced by the berthed ship due to the passing ship.

For the generic base mooring arrangement (Mooring Arrangement 1) the maximum safe passing ship speed was approximately 5 knots. The limiting criteria for the wide channel case (8.25B) was the breast mooring line loads, whereas the limiting criteria for the narrower channel case (3.04B) was the surge motion.

The maximum safe passing ship speed for both the wide and narrow channel cases was increased by increasing the initial pretension. For the wider channel case the safe passing ship speed was increased by the increasing the number of breast lines and reducing the number of head and stern lines to keep the total number of lines constant (Mooring Arrangement 3). However, this did not increase the safe passing ship speed for the narrower channel case.

Increasing the number of spring lines and reducing the number of head and stern lines (Mooring Arrangement 4) did increase the safe passing ship speed for the narrower channel case but did not increase the safe passing ship speed for the wider channel case.

From these results it has been shown that the maximum safe passing ship speed can be increased by designing the mooring arrangement to suit the bathymetry conditions around the berthed ship.

The results presented in this paper are part of a larger research project which aims to develop an empirical method to better predict the interaction forces and moments in restricted waterways. The research will also be used to refine AMC's Full Bridge Simulator to better account for restricted water effects in its mathematical model.

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