ShoreTension Trials and Application to Cruise Ships in Port of Geraldton

Prepared for:

Mid West Ports Authority

20th October 2016

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EXECUTIVE SUMMARY

A trial of ShoreTension hydraulic damping units was done at the Port of Geraldton during May-June 2016, followed by desktop modelling to scale the results to different ships and berths. General conclusions on the application of the ShoreTension system to cruise ships in Geraldton Harbour are as follows:

1. Using ShoreTension reduced horizontal ship motions by an average of 61% for the berth 6 bulk carrier trials. Similar improvements are expected for cruise ships, which will assist in transferring passengers to and from shore.
2. With standard mooring, cruise ship motions are calculated to exceed PIANC limits through a large part of the year at berths 2,3 and 6. This is considerably improved by using 4 ShoreTension units on each ship.
3. In the long wave conditions experienced at Geraldton, ShoreTension line loads are high and the mooring system must be planned accordingly. Using the present quay bollards may be feasible for bulk carriers and cruise ships if the ShoreTension lines are set up in an appropriate configuration.
4. For cruise ships, the “weak link” in the ShoreTension system is the ship’s bollards, which are typically rated to 30 or 40 tonnes. Line loads must be carefully monitored to ensure that ship bollard ratings are not exceeded.
5. The proposed 20 m breakwater spur is predicted to have no impact on cruise ship accessibility at berths 2,3 and 6. The proposed 65 m breakwater spur is predicted to marginally improve accessibility at berths 2 and 6, with no change at berth 3.
6. Long wave limits have been recommended for cruise ships at berths 2,3 and 6, as shown in the Tables A & B. These should be periodically reviewed using port experience if the ShoreTension system is implemented.

	Ship LOA	Long wave limits					
		Present situation	65 m BW	2 x ST	65 m BW + 2 x ST	4 x ST	65 m BW + 4 x ST
Berth 6	**175-185m**	11 cm	12 cm	15 cm	17 cm	29 cm	32 cm
Berth 6	**215-225m**	7 cm	8 cm	10 cm	11 cm	20 cm	22 cm
Berth 2	**175-185m**	4 cm	4 cm	7 cm	8 cm	13 cm	14 cm
Berth 2	**215-225m**	3 cm	3 cm	4 cm	4 cm	8 cm	9 cm
Berth 2	**255-265m**	2 cm	2 cm	4 cm	4 cm	7 cm	8 cm
Berth 3	**175-185m**	8 cm	8 cm	11 cm	11 cm	23 cm	23 cm
Berth 3	**215-225m**	5 cm	5 cm	8 cm	8 cm	15 cm	15 cm
Berth 3	**255-265m**	4 cm	4 cm	6 cm	6 cm	12 cm	12 cm

Table A: Calculated long wave limits for cruise ships, based on PIANC motion limits and ShoreTension line load limits, assuming 40 tonne ship bollards. BW=breakwater, ST=ShoreTension.

	Ship LOA	Downtime days (2 hours / day above threshold) per year					
		Present situation	65 m BW	2 x ST	65 m BW + 2 x ST	4 x ST	65 m BW + 4 x ST
Berth 6	**175-185m**	37	29	13	8	0	0
Berth 6	**215-225m**	92	76	48	37	3	2
Berth 2	**175-185m**	199	199	92	76	21	16
Berth 2	**215-225m**	263	263	199	199	76	64
Berth 2	**255-265m**	329	329	199	199	92	76
Berth 3	**175-185m**	76	76	37	37	2	2
Berth 3	**215-225m**	152	152	76	76	13	13
Berth 3	**255-265m**	199	199	120	120	29	29

Table B: Annual number of downtime days for all cases in Table A

Contents

PART I – SHIP MOTION TRIALS

Figure 1: Bow GNSS receiver on Alam Setia during ShoreTension trials

1 DETAILS OF SHIP MOTION TRIALS

The ship motion measurements were all done at Geraldton Berth 6, where a ShoreTension unit was positioned on the berth near the bow, and another near the stern.

1.1 Ships and measurement dates

Measurements were made on three ships, on the following dates:

- KS Flora, 2nd June 2016
- Alam Setia, 3rd June 2016
- Densa Falcon, 4th June 2016

Photos of each ship at the berth are shown in Figure 2 to Figure 4.

Figure 2: KS Flora

Figure 3: Alam Setia

Figure 4: Densa Falcon

Ship dimensions are shown in Table 1.

	Length overall (m)	Beam (m)	Arrival draft forward / aft (m)	Departure draft forward / aft (m)
KS Flora	176.9	30.0	7.38 / 8.14	8.39 / 8.57
Alam Setia	176.5	28.8	9.88 / 10.40	8.83 / 10.10
Densa Falcon	187.0	27.8	10.10 / 10.60	8.47 / 9.38

Table 1: Ship dimensions

1.2 Ship motion measurement equipment

Ship motions were measured using JAVAD Triumph-1 and Triumph-2 GNSS receivers. Four receivers were used for each set of measurements, with one in each of the following locations:

- Base station fixed to pilot jetty
- Roving receiver fixed to ship bow
- Roving receiver fixed to port bridge wing
- Roving receiver fixed to starboard bridge wing

An example setup is shown in Figure 5.

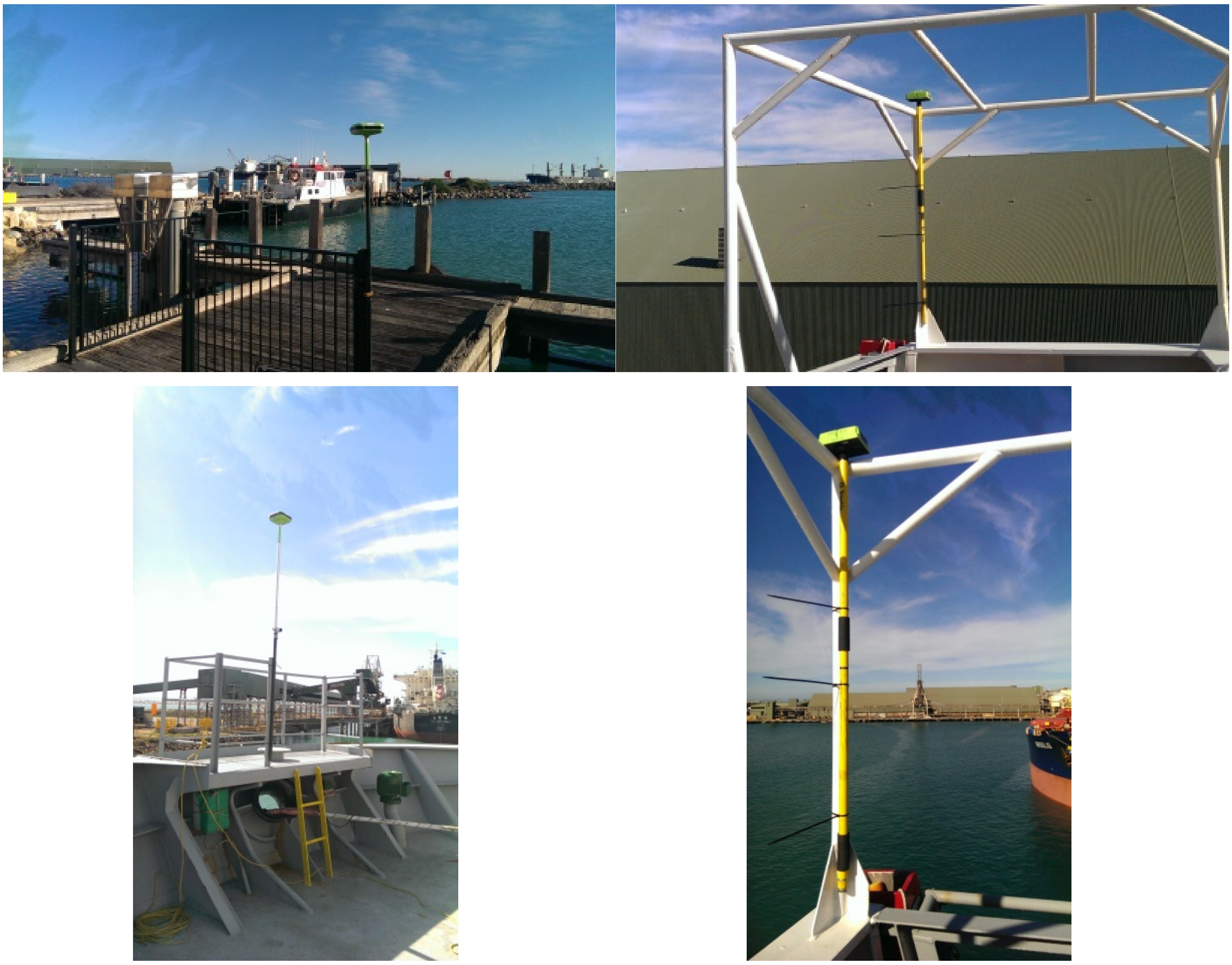

Figure 5: Typical GNSS receiver setup – Alam Setia. (Clockwise from top left) base station, port bridge wing, starboard bridge wing, bow

1.3 Data processing

The JAVAD receivers are amongst world's-best accuracy for post-processing with a nearby fixed base station. Stated accuracy is as shown below.

	Stated accuracy (general)	Stated accuracy (Geraldton trials)
Horizontal	10 mm + 1 ppm x (Baseline length)	11 mm
Vertical	15 mm + 1 ppm x (Baseline length)	16 mm

Table 2: Accuracy of JAVAD GNSS receivers

All data was post-processed and the raw GNSS results for each receiver combined to give the 6-dof motions of the ship as follows:

- Ship surge (fore-and-aft movement, positive forward)
- Bow sway (positive toward the wall)
- Stern sway (positive toward the wall)
- Bow heave (positive upwards)
- Stern heave (positive upwards)
- Roll (positive to starboard)

The first three motions represent the *horizontal* motions of the ship, while the next three motions represent the *vertical* motions of the ship.

The data was found to be clean for all of the measurements, with no data sections needing excluding. All results presented in Appendix A are mean-subtracted.

1.4 Environmental conditions

Forecast long wave conditions over the ship motion measurement period are shown in Figure 6.

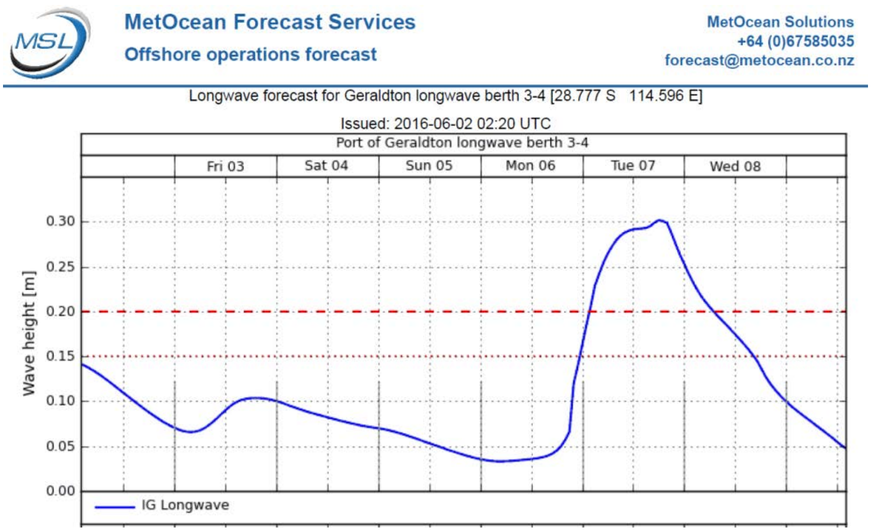

Figure 6: Forecast long wave conditions over the ship motion measurement period

The longwave limit for allowing ships over 100m at Berth 6 is 12 cm, so the berth was only just allowed to be used over the measurement period 2-4 June.

Measured long wave conditions (berth 3/4 significant wave height, 25-120s period) during the ship motion trials were provided by Tremarfon Pty Ltd and are shown in Appendix A.

Forecast wind, sea and swell conditions outside the harbour are shown in Figure 7.

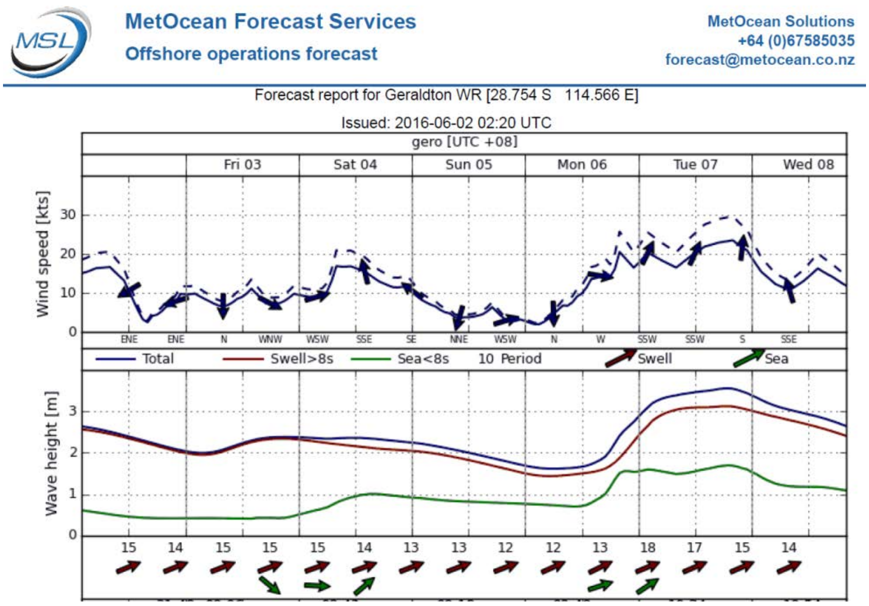

Figure 7: Forecast wind and swell conditions over the measurement period

1.5 ShoreTension data

The ShoreTension units can continuously measure line tension and ram extension. Results for the berth 6 trials were provided by ShoreTension and are shown in Appendix B.

2 MEASURED SHIP MOTION RESULTS

2.1 Individual measurement results

Example 10 minute snapshots of motion data for ShoreTension on or off are shown in Figure 8 and Figure 9. These show the greatly reduced horizontal motions when the ShoreTension system is used.

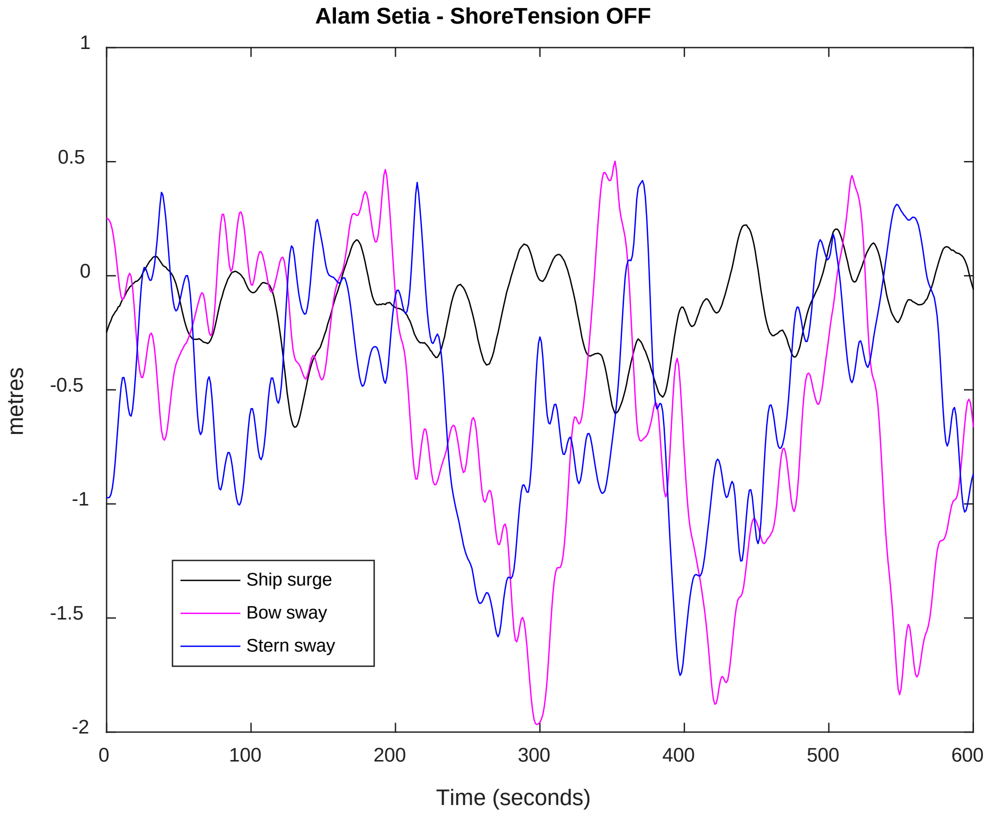

Figure 8: 10-minute snapshot, starting 14:30, of measured horizontal ship motions for Alam Setia with ShoreTension off

Figure 9: 10-minute snapshot, starting 15:30, of measured horizontal ship motions for Alam Setia with ShoreTension on

Graphical results of all ship motions are shown in Appendix A.

Root-Mean-Square (RMS) results for each ship with and without the ShoreTension units operating are shown in Table 3 to Table 5. The RMS motion is approximately half of the Single-Significant Amplitude (SSA), which is the average of the 1/3-highest motion amplitudes. For example, a ship surge RMS of 0.20m corresponds to a SSA of approximately 0.40m.

Time (WST)	13:46-14:51	14:51-16:26	16:26-17:02	17:02-18:00
ShoreTension	Off	On	Off	On
RMS ship surge	0.111m	0.068m	0.103m	0.065m
RMS bow sway	0.404m	0.088m	0.366m	0.103m
RMS stern sway	0.343m	0.135m	0.334m	0.132m
RMS bow heave	0.052m	0.052m	0.043m	0.044m
RMS stern heave	0.065m	0.058m	0.053m	0.049m
RMS roll	0.092º	0.110º	0.080º	0.110º

Table 3: Measured RMS motions for KS Flora with or without ShoreTension units operating

Time (WST)	11:16 – 14:08	14:08 – 14:42	14:42 – 15:57
ShoreTension	On	Off	On
RMS ship surge	0.125m	0.231m	0.135m
RMS bow sway	0.138m	0.638m	0.201m
RMS stern sway	0.112m	0.481m	0.129m
RMS bow heave	0.103m	0.079m	0.068m
RMS stern heave	0.098m	0.078m	0.061m
RMS roll	0.117º	0.145º	0.161º

Table 4: Measured RMS motions for Alam Setia with or without ShoreTension units operating

Time (WST)	12:37 – 13:33	13:33 – 18:10
ShoreTension	Off	On
RMS ship surge	0.222m	0.089m
RMS bow sway	0.522m	0.104m
RMS stern sway	0.301m	0.092m
RMS bow heave	0.074m	0.110m
RMS stern heave	0.076m	0.109m
RMS roll	0.159º	0.148º

Table 5: Measured RMS motions for Densa Falcon with or without ShoreTension units operating

2.2 Overall results

In order to show an overall comparison of each ship with and without the ShoreTension units operating, we can calculate the overall RMS motions in each case. These are shown in Table 6 to Table 8, together with the average long wave height in each case.

	ShoreTension Off	ShoreTension On
Ship surge RMS	0.108m	0.067m
Bow sway RMS	0.391m	0.093m
Stern sway RMS	0.340m	0.134m
Bow heave RMS	0.048m	0.049m
Stern heave RMS	0.060m	0.054m
Roll RMS	0.088°	0.110°
Long wave average height	0.079m	0.070m

Table 6: Overall measured motions for KS Flora with or without ShoreTension units operating

	ShoreTension Off	ShoreTension On
Ship surge RMS	0.231m	0.128m
Bow sway RMS	0.638m	0.157m
Stern sway RMS	0.481m	0.117m
Bow heave RMS	0.079m	0.092m
Stern heave RMS	0.078m	0.087m
Roll RMS	0.145°	0.130°
Long wave average height	0.110m	0.093m

Table 7: Overall measured motions for Alam Setia with or without ShoreTension units operating

	ShoreTension Off	ShoreTension On
Ship surge RMS	0.222m	0.089m
Bow sway RMS	0.522m	0.104m
Stern sway RMS	0.301m	0.092m
Bow heave RMS	0.074m	0.110m
Stern heave RMS	0.076m	0.109m
Roll RMS	0.159°	0.148°
Long wave average height	0.093m	0.097m

Table 8: Overall measured motions for Densa Falcon with or without ShoreTension units operating

2.3 Comparison ShoreTension on/off

Since ship motions are expected to be approximately linear with long wave height, we can correct for the changing long wave conditions by dividing the measured RMS motions by the measured long wave height. These scaled motions are compared for the case ShoreTension on/off in Table 9.

	KS Flora	Alam Setia	Densa Falcon
Ship surge	Reduced by 30%	Reduced by 35%	Reduced by 62%
Bow sway	Reduced by 73%	Reduced by 71%	Reduced by 81%
Stern sway	Reduced by 56%	Reduced by 71%	Reduced by 71%
Bow heave	Increased by 14%	Increased by 39%	Increased by 44%
Stern heave	Increased by 2%	Increased by 31%	Increased by 36%
Roll	Increased by 41%	Increased by 6%	Reduced by 11%

Table 9: Change in RMS motion with ShoreTension on, as compared to ShoreTension off. Results have been corrected for changing long wave conditions.

3 MEASURED SHIP MOTIONS DISCUSSION

3.1 Long wave conditions

As shown in Appendix A, measured long wave conditions at berth 3/4 were 0.07 – 0.09m during the KS Flora trials, 0.07 – 0.11m during the Alam Setia trials, and 0.08 – 0.11m during the Densa Falcon trials. Because the long wave conditions were changing slowly, and the ShoreTension comparisons were done close together for each ship, the average long wave height when the ShoreTension units were on or off was within 15% (see Table 6 to Table 8).

3.2 Horizontal motions

Without the ShoreTension units operating, measured horizontal motions (surge, bow sway and stern sway) are quite large. The maximum RMS motion was 0.638m bow sway for Alam Setia (see Table 7). The maximum excursion from the mean position was 2.2m bow sway for Alam Setia (see Appendix A).

Since mooring lines are closer to horizontal than vertical, and horizontal motions are larger than vertical motions (without ShoreTension), the main effect on mooring line loads is from horizontal motions. Without ShoreTension operating, the measured horizontal motions would have caused large mooring line loads.

With ShoreTension operating, horizontal motions are all decreased by 30 – 81%, after correcting for the changing long wave conditions (see Table 9). If we average the reductions in ship surge, bow sway and stern sway for all ships from Table 9, we find that horizontal motions were reduced by an average of 61% when using 2 ShoreTension units, as compared to a traditional mooring arrangement. This is a massive reduction in horizontal motions.

3.3 Vertical motions

Bow heave and stern heave are generally small, being in the order of 0.1m RMS. Bow heave and stern heave are generally increased when the ShoreTension units are operating, by 2 – 44% after correcting for changing long wave conditions (see Table 9). This is probably because the ShoreTension lines are at a large angle to the horizontal (see Figure 2). Loads in the ShoreTension line produce additional vertical forces on the bow and stern.

Roll is generally small, in the order of 0.1º RMS. Roll is fairly similar with or without the ShoreTension units operating (see Table 6 to Table 8). Because the ShoreTension line attaches high up on the bow or stern (see Figure 2), loads in the line produce a roll moment on the ship. Counteracting this is the increased roll damping from fender friction, caused by the high tension in the ShoreTension lines.

4 MEASURED LOADS

4.1 ShoreTension line loads

The ShoreTension system is designed for a maximum line tension of 60 tonnes, but is rated up to 120 tonnes.

Appendix B shows measured ShoreTension line tension and extension during the berth 6 bulk carrier trials. The tension was set to 35 tonnes for these trials. We see that the line tension typically oscillates between 15 and 35 tonnes. Approximate maximum line tensions are shown in Table 10.

	Bow ShoreTension unit	**Stern ShoreTension unit**
KS Flora	42 tonnes	44 tonnes
Alam Setia	52 tonnes	42 tonnes
Densa Falcon	46 tonnes	52 tonnes

Table 10: Approximate maximum line tensions during ShoreTension trials

A close-up of the Alam Setia bow unit data around the time of the measured maximum tension (52 tonnes at 13:18 on 3rd June) is shown in Figure 10. This is the highest tension measured during the ship motion trials.

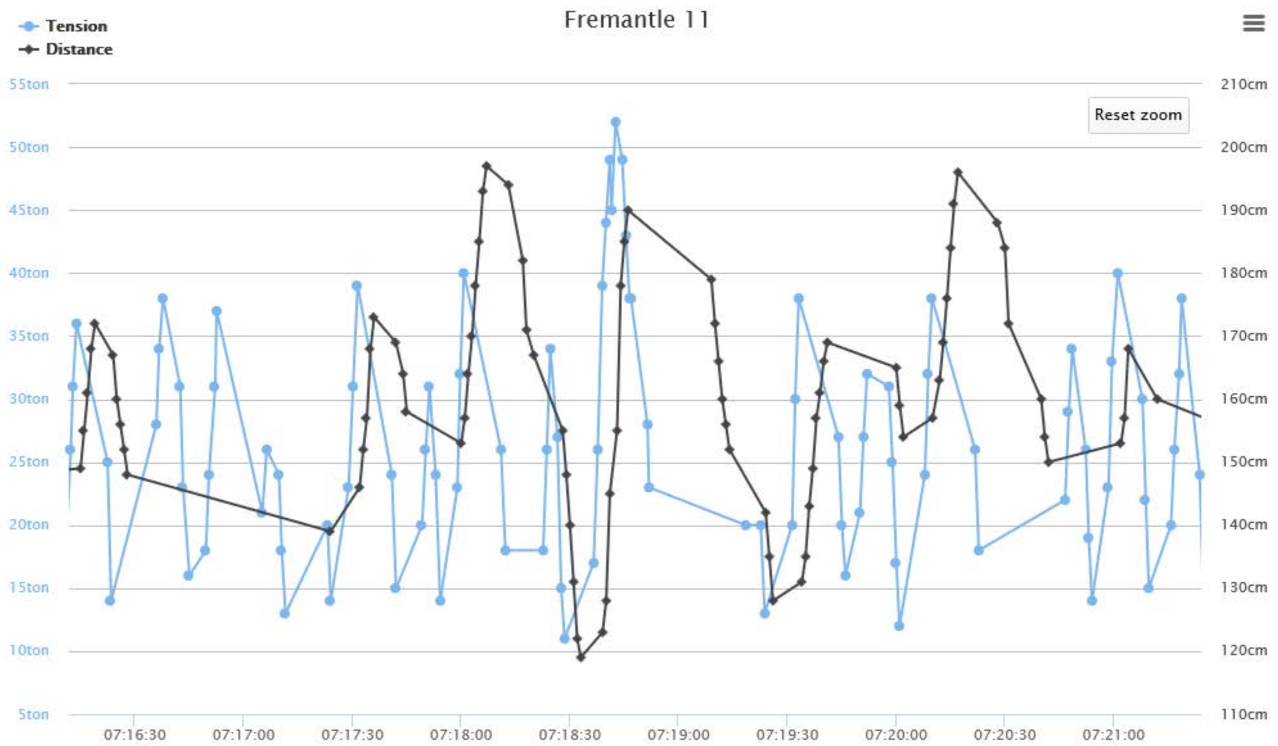

Figure 10: Measured ram extension and line tension for bow ShoreTension unit, at time of peak line load (52 tonnes) measured during Alam Setia trials on 3 June. Time is Netherlands time (add 6 hours for WA time). Graph provided by ShoreTension.

A higher tension of 55 tonnes was measured on the stern unit for Densa Falcon at 03:57 on 4th June, before ship motions were being measured. This peak load is shown in Figure 11.

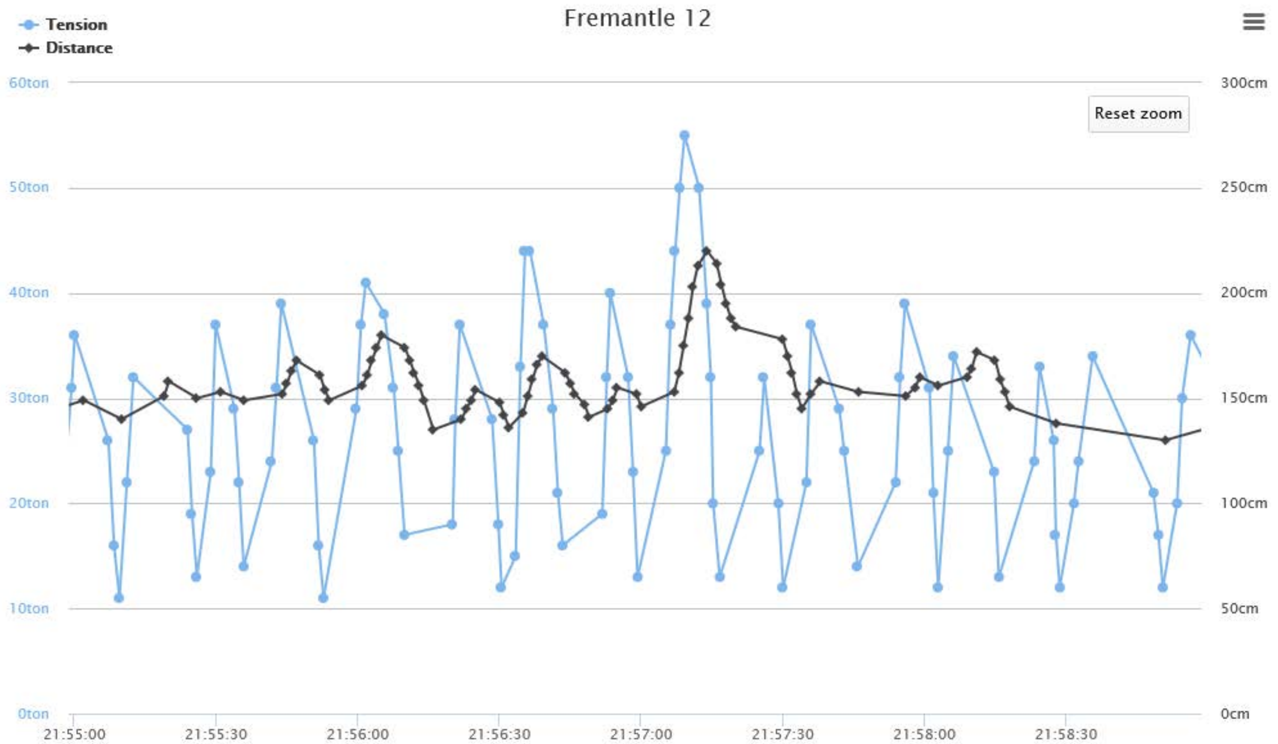

Figure 11: Measured ram extension and line tension for stern ShoreTension unit, at time of peak line load (55 tonnes) measured during Densa Falcon trials on 4 June. Time is Netherlands time (add 6 hours for WA time). Graph provided by ShoreTension.

The peak loads in the ShoreTension line appear to be influenced by the short-period motions of the ship (see Figure 10 and Figure 11). We see that line tension oscillates at a period of around 15 seconds, which correlates with sway, yaw, heave, roll and pitch of the ship caused by swell. The ram extension oscillates at the swell period (around 15 seconds) and also at a period of around 45 seconds, which correlates with surge, sway and yaw of the ship caused by long-period waves[8].

4.2 Quay bollard and ship bollard loads

The quay bollards used in the trials are rated to 75 tonnes. Bulk carrier bollards typically are rated to around 65 tonnes.

As shown in the photographs in Figure 3 and Figure 18, the ShoreTension line is turned back through a sheave block to the ShoreTension unit. Estimated bollard loads at the time of the peak line load during the Alam Setia trials are illustrated in Figure 12.

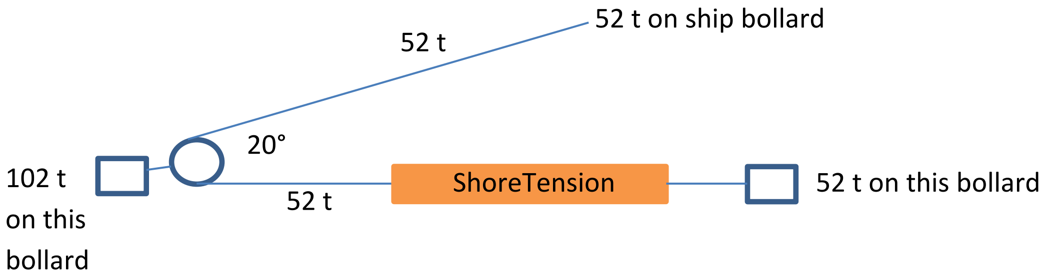

Figure 12: Bollard loads caused by 52 tonne ShoreTension line load during Alam Setia trials

Figure 12 shows that the quay bollard attached to the sheave block at the bow of Alam Setia may have been heavily overloaded (102 tonnes) during the trials. Similar conclusions can be drawn for all bow and stern quay bollards holding ShoreTension sheave blocks during the trials, as all bow and stern ShoreTension lines were doubled back (see Figure 2 to Figure 4) and all experienced loads of 42 – 52 tonnes (see Table 10). Therefore it is likely that each of these bollards experienced loads of 90-100 tonnes during the trials.

4.3 Recommendations

In order to minimize loads on the quay bollard holding the ShoreTension sheave block, the line angle shown in Figure 12 should be increased. However, ShoreTension recommend a maximum line angle of around 120°, as shown in Figure 13. This is to keep the line from coming off the sheave, and to keep the sheave block from impacting the quay, when the tension decreases.

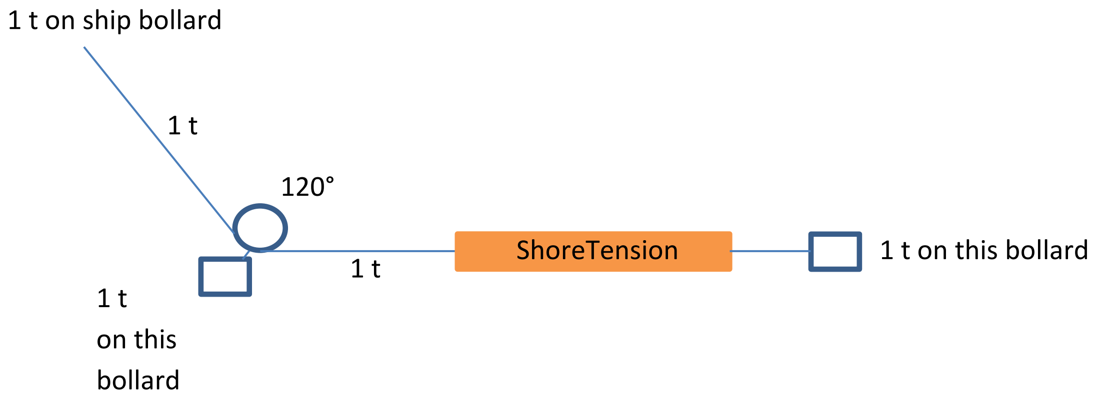

Figure 13: 120° line angle through ShoreTension sheave block. At this angle the loads on both quay bollards are the same.

Load multipliers from line tension to quay bollard load for various line angles are shown in Table 11. We see that a line angle of around 120° seems a good angle to aim for, as this equalizes the loads on both quay bollards.

Line angle	**Multiplier from line load to quay bollard load**
120°	1.00
110°	1.15
100°	1.29
90°	1.41
80°	1.53
70°	1.64
60°	1.73
50°	1.81
40°	1.88
30°	1.93
20°	1.97

Table 11: Multipliers from ShoreTension line load, to load on quay bollard holding ShoreTension pulley, for various line angles

4.4 Berth 2 and 3 measured loads

Early trials of the ShoreTension units were undertaken at berths 2 and 3, as shown in Figure 14, Figure 15, Table 12 and Table 13. No motions data was measured for these trials, although video footage is available. Measured loads were provided by ShoreTension.

Figure 14: United Jalua ShoreTension trials at berth 3. Photo MWPA

	ShoreTension unit 9	ShoreTension unit 10	ShoreTension unit 11	ShoreTension unit 12
Measurement start (WST)	24 May 12:00	24 May 11:00	24 May 18:00	24 May 19:00
Measurement end	25 May 21:00	26 May 10:00	26 May 10:00	26 May 10:00
Position	Breast line (fwd / aft?)	Breast line	Forward spring	Aft spring
Estimated line angle through sheave block	60°	60°	20°	40°
Pre-set tension	47.5 tonnes	47.5 tonnes	?	?
Peak line tension during normal operation	50 tonnes	55 tonnes	46 tonnes	55 tonnes
Peak tension time	25 May 08:00	25 May 14:00	25 May 10:00	25 May 14:00
Estimated peak load on sheave block quay bollard (75 tonne rating)	87 tonnes	95 tonnes	91 tonnes	103 tonnes
Maximum long wave height during trials	14 cm at 25 May 18:00			

Table 12: ShoreTension line load measurements for United Jalua at berth 3

United Jalua was able to stay alongside berth 3 with long wave heights of up to 14 cm, which is close to the normal 15 cm limit for this berth. Video footage showed a marked reduction in horizontal motions when the ShoreTension units were operational. However, it is calculated that all 75 tonne quay bollards holding the ShoreTension sheave blocks would have been overloaded during the trials (see Table 12).

Figure 15: Bison Express ShoreTension trials at berth 2. Photo MWPA

	ShoreTension unit 11	**ShoreTension unit 12**
Measurement start (WST)	27 May 11:00	27 May 12:00
Measurement end	27 May 23:30	27 May 23:30
Position	Forward breast	Aft breast
Estimated line angle through sheave block	120°	120°
Pre-set tension	17 tonnes	19 tonnes
Peak line tension during normal operation	27 tonnes	32 tonnes
Peak tension time	27 May 19:00	27 May 19:00
Estimated peak load on sheave block quay bollard (75 tonne rating)	27 tonnes	32 tonnes
Maximum long wave height during trials	7 cm at 27 May 18:00	

Table 13: ShoreTension line load measurements for Bison Express at berth 2

Bison Express was able to stay alongside berth 2 with long wave heights up to 7 cm, which is above the normal limit of 5 cm for this berth. The Master and pilot were very satisfied with the ship's movement while alongside. With the ShoreTension lines at large angles (see Figure 15), the loads on the quay bollards were also satisfactory. It should also be checked how the measured 32 tonne line load compares to the ship bollard strength in this case.

PART II – APPLICATION TO CRUISE SHIPS

5 BACKGROUND

Cruise ships normally anchor outside the harbour and transfer to the Batavia marina, however the anchorage can be uncomfortable in large swell. Small, older cruise ships regularly moored at berth 6 until around 2013. Pacific Sun (223m) has previously moored at berth 6 (Figure 16), while Sun Princess (261m) has previously moored at berth 2. Radiance of the Seas (293m) typically remains on station inside the harbour using dynamic positioning.

Figure 16: Pacific Sun (223m) moored at Geraldton berth 6. Photo MWPA.

This report assesses the feasibility of mooring cruise ships at berths 2,3 and 6 under ShoreTension, based on the prevailing long wave conditions.

6 SAFETY CRITERIA

6.1 Present harbour long wave limits

Geraldton harbour is subject to long-period swell, and has a fairly rectangular shape and reflective quay walls, which leads to “seiching”, or long wave amplification, inside the harbour. Long, low amplitude waves slosh N-S and E-W across the harbour, causing ships to have large horizontal motions and occasionally break mooring lines. For this reason, limits on the allowable long wave height have been developed, and each berth is evacuated once this limit is reached. Present harbour limits on the forecast or measured 25-120s long wave height at berth 3/4 are shown in Table 14.

Berth	Berth 3/4, 25-120s long wave H_S limit
2	5 cm
6 (vessels < 100m)	10 cm
4,5,6 (vessels > 100m)	12 cm
3	15 cm

Table 14: Present harbour limits, without ShoreTension system

The present harbour limits given in Table 14 are site-specific and are based on experience at the port, but they are primarily designed for bulk carriers rather than cruise ships.

6.2 PIANC guidelines for passenger transfers

The new PIANC guidelines for cruise terminals [1] do not give safe limits for passenger transfers ashore, possibly because of the large variety of gangways in use around the world. As shown in Figure 16, gangways used at Geraldton are of the side ramp / roller type. PIANC recommended motion limits for passenger transfers using this type of ramp are given in [2], and reproduced in Table 15. While these guidelines were originally developed for ferries, they have also been recommended for cruise ships, see e.g. [3].

Motion	Peak-to-peak limit
Surge (fore-aft movement)	0.60m
Sway	0.60m
Heave	0.60m
Roll	2.0°
Pitch	1.0°
Yaw	1.0°

Table 15: PIANC recommended limits for safe transfer of passengers from side ramps on rollers [2]

6.3 Load limits for ShoreTension lines, quay bollards and ship bollards

As seen in Section 4, large ShoreTension line loads were experienced during the berth 6 bulk carrier trials. The mooring arrangement will need to be modified in future to achieve satisfactory quay bollard loading.

Bulk carrier bollards typically are rated to around 65 tonnes. Cruise ship bollards have a lower rating. Dawn Princess (see Table 16) has a safe working load of 40 tonnes on its bollards. Smaller cruise ships may have lower ratings, e.g. 30 tonnes.

Therefore assuming that ShoreTension pulleys are oriented as recommended in Section 4.3, the “weak link” in the ShoreTension system will be the cruise ship bollard strength. Loads in the ShoreTension line will need to be kept beneath the rated load of the cruise ship bollards (e.g. 40 or 30 tonnes, depending on the ship).

7 DEVELOPING SAFETY CRITERIA FOR CRUISE SHIPS AT BERTHS 2,3 AND 6

For most cruise terminals around the world, wind loading on cruise ships is the principal mooring safety criterion, with quay bollards of 150-200 tonne rating often needed to take the largest cruise ships [1]. Geraldton harbour is well protected from wind, so wind loading is normally not critical, although it should still form part of the final mooring safety plan. The wave-induced motions of a cruise ship and the safety of transferring passengers, many of whom are elderly and/or wearing minimal footwear (see Figure 17), will normally be more critical than wind loading at the Port of Geraldton.

Figure 17: Passengers boarding Pacific Sun, moored at Geraldton berth 6. Note scraping of ramp on concrete due to ship movement, and passenger footwear. Photo MWPA.

7.1 Method options

Here we aim to develop initial long wave limits for cruise ships at berths 2,3 and 6, with either 2 or 4 ShoreTension units operating. Two methods were considered for doing this:

Method 1 – full harbour and ship simulation

This method is often used for assessing moored ship motions in harbours, see e.g. [4]. It consists of the following parts:

1. Collation of offshore historical wave spectra, wave propagation modelling into the harbour, and harbour oscillation analysis to determine surface elevations and flow velocities in the harbour
2. Time-domain radiation / diffraction ship motion analysis, including effect of mooring lines (or ShoreTension system) and fenders

MetOcean Solutions is experienced in Part 1 for Geraldton Harbour. CMST and Perth Hydro are experienced in Part 2 for “open” harbours, where the wave field is unidirectional. However, due to the confined nature of Geraldton harbour, standard radiation / diffraction methods cannot be used and new methods are needed, which would require significant time to develop. Such codes are in use at Royal Haskoning DHV, who have experience with modelling the ShoreTension system. Due to the large number of steps in this process, each with its own assumptions and simplifications, there is significant potential for error in the final results of a full harbour and ship simulation.

Method 2 – scaling of measured results for bulk carriers

We already have good data on ship motions and ShoreTension loads and extensions for three ships in the specific environmental conditions of Geraldton harbour. These results can be used to assess cruise ships at berths 2,3,6, using appropriate scaling of the measured data. This is the method used in this report. An error analysis and confidence limits using the method are described in Section 10.

7.2 Comparison between bulk carriers and cruise ships

Principal dimensions of the bulk carriers used in the ShoreTension trials, and the representative cruise ships chosen for analysis here, are shown in Table 16.

Ship name	Type	Length overall	Length waterline (approx.)	Beam	Representative draft	Representative displacement
KS Flora	Bulk carrier	176.9m	172m	30.0m	8.1m	34,000t
Alam Setia	Bulk carrier	176.5m	171m	28.8m	9.8m	39,000t
Densa Falcon	Bulk carrier	187.0m	181m	27.8m	9.6m	39,000t
Astor	Cruise ship	176.5m	158m	22.6m	6.15m	14,000t
Pacific Eden	Cruise ship	219.4m	193m	30.8m	7.50m	30,000t
Dawn Princess	Cruise ship	261.3m	231m	32.3m	8.12m	40,000t

Table 16: Principal dimensions of bulk carriers used in ShoreTension trials, and cruise ships planned for the port

Cruise ships may be classified according to length, with Astor representative of a 175-185m ship (“180m cruise ship”), Pacific Eden representative of a 215-225m ship (“220m cruise ship”), and Dawn Princess representative of a 255-265m ship (“260m cruise ship”).

The 260m cruise ship has similar displacement to the bulk carriers, while the 220m and 180m cruise ships are of lighter displacement.

8 HARBOUR LIMITS BASED ON PIANC GUIDELINES AND TRIALS RESULTS

8.1 Equivalent limiting long wave conditions for bulk carriers

The measured bulk carrier motions described in Part I have been compared with the PIANC limits (Table 15), as shown in Appendix C. The first 5 minutes of data with ShoreTension operational were excluded in each case. All maximum measured motions were for Alam Setia. We see that heave, pitch and yaw easily pass the PIANC criteria, which is also expected to be the case for cruise ships. Therefore surge, sway and roll are the critical motion criteria for cruise ships according to the PIANC guidelines.

Scaling the bulk carrier measurements against the maximum long wave height of 11 cm during the Alam Setia trials gives the corresponding long wave limits shown in Table 17. In this report, all quoted "long wave heights" refer to the 25-120s significant long wave height at berth 3/4, as currently used by the port for measurements and forecasts.

	Maximum measured motion	Maximum long wave height during measurements	PIANC motion limit	Scaled long wave limit
Surge	0.83m	11 cm	0.60m	8.0 cm
Sway	0.56m	11 cm	0.60m	11.8 cm
Roll	1.38°	11 cm	2.0°	15.9 cm

Table 17: Equivalent limiting long wave conditions for bulk carriers at berth 6, using PIANC criteria for passenger vessels. These are an intermediate step to developing the cruise ship guidelines.

8.2 Scaling bulk carrier surge and sway

We start with the general equation of uncoupled ship motions:

$$(m + a)\ddot{x} + b\dot{x} + kx = F sin(\omega t) \qquad \text{(Equation 1)}$$

Here x is the motion displacement (surge or sway in this instance), $\dot{x}$ is velocity and $\ddot{x}$ is acceleration. m is the ship's mass, a is the hydrodynamic added mass, b is the linearized damping coefficient, k is the linearized restoring coefficient, F is the wave loading force amplitude and ω is the wave frequency.

The solution of this equation for the motion amplitude X is [5]:

$$X = \frac{F/k}{\sqrt{\left(1-\frac{\omega^2}{\omega_n^2}\right)^2 + \frac{b^2}{k(m+a)}\frac{\omega^2}{\omega_n^2}}} \qquad \text{(Equation 2)}$$

At the resonance frequency $\omega = \omega_n = \sqrt{k/(m+a)}$

$$X = \frac{F\sqrt{m+a}}{b\sqrt{k}} \qquad \text{(Equation 3)}$$

We see that the motion amplitude is principally governed by:

- The size of the wave loads acting on the ship
- The size of the restoring force acting on the ship

- How close the wave frequency is to the ship's natural frequency
- The amount of damping (especially near resonance)

The ShoreTension units govern the restoring force and damping for surge and sway motions. With 2 ShoreTension units operating, as for the bulk carrier trials, we expect that the motion amplitudes will be similar if the wave loading force is similar. This assumes that the cruise ships' displacement is similar to the bulk carrier displacement, which is the case here for the 220m and 260m cruise ships (see Table 16), though will be less accurate for the 180m cruise ships.

For surge, the wave loading scales with (beam).(draft).(long wave height). For sway, the wave loading scales with (waterline length).(draft).(long wave height). By scaling the surge and sway loads in this way, corresponding long wave limits for cruise ships can be suggested, as shown in Table 18. Long wave limits for Alam Setia are obtained from Table 17.

	Waterline length (m)	Beam (m)	Draft (m)	Long wave limit for surge (cm)	Long wave limit for sway (cm)
Alam Setia	171	28.8	9.8	8.0	11.8
Astor	158	22.6	6.15	16.2	20.4
Pacific Eden	193	30.8	7.5	9.8	13.7
Dawn Princess	231	32.3	8.12	8.6	10.5

Table 18: Scaling long wave limits from measured surge and sway results for bulk carriers at berth 6, to cruise ships at berth 6.

8.3 Scaling bulk carrier roll

Analysis of the measured bulk carrier motions under ShoreTension shows that most roll energy occurs near the ship's natural roll period. The natural roll period may be estimated [6] based on the ship's beam and GM_f (transverse GM, corrected for free surface effect), and is shown in Table 19.

To extrapolate the measured bulk carrier roll data to cruise ships, we start with the general equation of uncoupled roll motions:

$$(I + a)\ddot{\phi} + b\dot{\phi} + k\phi = M\sin(\omega t) \qquad \text{(Equation 4)}$$

Here ϕ is the roll angle, $\dot{\phi}$ is roll velocity and $\ddot{\phi}$ is roll acceleration. I is the ship's roll inertia, a is the hydrodynamic added inertia, b is the linearized damping coefficient, k is the linearized restoring coefficient, M is the wave-induced moment amplitude and ω is the wave frequency.

The solution of this equation for the roll amplitude Φ is [5]:

$$\Phi = \frac{M/_k}{\sqrt{\left(1-\frac{\omega^2}{\omega_n^2}\right)^2 + \frac{b^2}{k(I+a)}\frac{\omega^2}{\omega_n^2}}}$$ (Equation 5)

At the resonance frequency $\omega = \omega_n = \sqrt{k/_{(I+a)}}$

$$\Phi = \frac{M\sqrt{I+a}}{b\sqrt{k}}$$ (Equation 6)

Expanding Equation 6, using e.g. the expressions in [7], and noting that the roll damping from fender friction is proportional to the beam, shows that resonant roll scales according to

$$\Phi \sim \frac{LBH}{\sqrt{GM_f}}$$ (Equation 7)

Here L is the waterline length, B is the beam, and H is the long wave height which is assumed to scale with swell significant wave height within the harbour. When ShoreTension is operational, the principal roll restoring moment is assumed to be from the hydrostatic righting moment, while the principal roll damping moment is assumed to be from fender friction.

As shown in Table 19, resonant roll periods for the bulk carrier and cruise ships occur in the range of *swell* periods under 25s. We assume that swell in the harbour is fairly broad-band [8], so that resonant roll can be scaled between different ships according to Equation 7. This gives the scaled long wave limits shown in Table 19.

	Displacement (tonnes)	Waterline length (m)	Beam (m)	GM_f (m) aprox.	Natural roll period (s)	Long wave limit for roll (cm)	Roll motion (°)
Alam Setia	39000	171	28.8	3.0	13	15.9	2.0
Astor	14000	158	22.6	1.7	14	16.5	2.0
Pacific Eden	30000	193	30.8	1.7	19	9.9	2.0
Dawn Princess	40000	231	32.3	1.7	20	7.9	2.0

Table 19: Scaling long wave limits from measured roll results for bulk carriers at berth 6, to cruise ships at berth 6.

8.4 Long wave limits for ShoreTension lines, quay bollards and ship bollards

As discussed in Section 6.3, cruise ship bollards are expected to be the “weak link” in the ShoreTension system, once the system is arranged to minimize quay bollard loads. We shall use a ship bollard rating of 40 tonnes, as advised for Dawn Princess, and 40 tonnes or 30 tonnes for the smaller cruise ships.

Also as discussed in Section 6.3, for Alam Setia at berth 6 in a long wave height of 11 cm, ShoreTension line tensions reached 52 tonnes. We shall scale the peak loads linearly, as done in Table 17 for motions. This is quite a simplification, as the peak load is also affected by the pre-set tension and other settings in the ShoreTension units. This corresponds to a long wave height of 8.5 cm for 40 tonnes load, or 6.3 cm for 30 tonnes load.

Long wave heights for corresponding line tensions of the cruise ships may be estimated by scaling the wave loads as done in Section 8.2. Results are shown in Table 20.

	Waterline length (m)	Beam (m)	Draft (m)	Surge long wave limit (cm) 40 t bollards	Surge long wave limit (cm) 30 t bollards	Sway long wave limit (cm) 40 t bollards	Sway long wave limit (cm) 30 t bollards
Alam Setia	171	28.8	9.8	8.5	6.3	8.5	6.3
Astor	158	22.6	6.15	17.3	12.8	14.7	10.9
Pacific Eden	193	30.8	7.5	10.4	7.7	9.8	7.3
Dawn Princess	231	32.3	8.12	9.1	-	7.6	-

Table 20: Scaling line tension long wave limit from Alam Setia trials at berth 6, to cruise ships at berth 6.

8.5 Overall long wave limits

The overall long wave limits for cruise ships at berth 6 may be found from taking the minimum values from the surge and sway results (values in bold) in Table 18, roll results in Table 19 and line tension results in Table 20. These are shown in Table 21.

Ship	Long wave limit	
	40 t ship bollards	30 t ship bollards
Astor	14.7 cm	10.9 cm
Pacific Eden	9.8 cm	7.3 cm
Dawn Princess	7.6 cm	-

Table 21: Calculated long wave limits for cruise ships at berth 6, with 2 ShoreTension units operating, according to PIANC guidelines. Dawn Princess results are shaded, as she is too long for berth 6.

We note that ship surge (fore-and-aft), ship roll and ship bollard strength may all be limiting criteria for cruise ships when using the PIANC guidelines.

To extend the results to berth 2, we use the long wave modelling presented in [9, Table 2], which shows that long wave heights are 2.45 times larger at berth 2 than berth 6 and swell wave heights are 1.6 times larger. This reduces the surge and sway results in Table 18 by a factor of 2.45, as these are primarily affected by long waves. The roll results in Table 19 and peak line tension results in Table 20 are reduced by a factor of 1.6, as these are primarily affected by swell. Limiting values are shown in Table 22.

Ship	Long wave limit	
	40 t ship bollards	30 t ship bollards
Astor	6.6 cm	6.6 cm
Pacific Eden	4.0 cm	4.0 cm
Dawn Princess	3.5 cm	-

Table 22: Calculated long wave limits for cruise ships at berth 2, with 2 ShoreTension units operating, according to PIANC guidelines

To extend the results to berth 3, we also use the long wave modelling presented in [9, Table 2], showing that long wave heights are 1.29 times larger at berth 3 than berth 6, and assume that a similar ratio holds for swell heights. This reduces the results in Table 21 by a factor of 1.29, giving the results shown in Table 23.

Ship	Long wave limit	
	40 t ship bollards	30 t ship bollards
Astor	11.4 cm	8.4 cm
Pacific Eden	7.6 cm	5.7 cm
Dawn Princess	5.9 cm	-

Table 23: Calculated long wave limits for cruise ships at berth 3, with 2 ShoreTension units operating, according to PIANC guidelines

A complication is that berth 3 has a dolphin-type fendering system, with low-friction fenders as shown in Figure 18 and Table 24.

Figure 18: United Jalua at berth 3, showing low-friction facing on fenders

	Fender type	Fender model	Low-friction facing	Typical friction coefficient
Berth 2	Arch	HS Chemical NV1000H	No	1
Berth 3	Cone	Fentek SCN1200	Yes	0.2
Berth 6	Arch	Bridgestone Dyna Arch DA-600H	No	1

Table 24: Fender types at berths 2,3 and 6, as advised by MWPA

Therefore we may expect that roll motions at berth 3 may be larger than calculated here, and may exceed the PIANC guidelines at the limits prescribed. The effect cannot be modelled in a straightforward manner, as ship rolling involves friction due to fender compression by the wall-sided ship, as well as sliding friction past the fenders, and the relative proportions of each are unknown.

For the case where 4 ShoreTension units are operating instead of 2, the ship surge and sway restoring forces and damping are approximately doubled. This allows a doubling of the ship surge and sway wave loads, following the same scaling as before. The proportionally lower ship displacement (relative to the wave loads) allows this to be a conservative estimate, in a similar way to the bulk carrier / cruise ship comparison.

The amount of roll damping from fender friction is also approximately doubled when going from 2 to 4 ShoreTension units. According to Equation 7, this will allow a doubling of the long wave height for the same roll angle.

Therefore the allowable long wave limits may be doubled in the case of using 4 ShoreTension units instead of 2. The resulting limits are shown in Table 25, together with the results from Table 21, Table 22 and Table 23, rounded to the nearest centimetre.

	Ship overall length	40 t ship bollards		30 t ship bollards	
		2 x ST	4 x ST	2 x ST	4 x ST
Berth 6	**175-185m**	15 cm	29 cm	11 cm	22 cm
Berth 6	**215-225m**	10 cm	20 cm	7 cm	15 cm
Berth 2	**175-185m**	7 cm	13 cm	7 cm	13 cm
Berth 2	**215-225m**	4 cm	8 cm	4 cm	8 cm
Berth 2	**255-265m**	4 cm	7 cm	-	-
Berth 3	**175-185m**	11 cm	23 cm	8 cm	17 cm
Berth 3	**215-225m**	8 cm	15 cm	6 cm	11 cm
Berth 3	**255-265m**	6 cm	12 cm	-	-

Table 25: Calculated long wave limits for cruise ships, based on PIANC motion limits and ShoreTension line load limits

An idea has been put forward by MWPA to use a bridle on the ShoreTension line, attached to two of the ship's bollards, to halve the ship bollard loads. For ships with 30 tonne bollards, this would raise the long wave limits to the 40 tonne values in Table 25. For ships with 40 tonne bollards, there would be no change to the limits, as these are also governed by the PIANC motion limits.

9 BERTH 3 LIMITS USING UNITED JALUA DATA

We can scale the United Jalua berth 3 measured line load data (Table 12) as a check on the long wave limits given in Table 25. For United Jalua, the peak line tension was 55 tonnes with a long wave height of 14 cm. This is scaled to a long wave height of 10.2 cm for 40 tonne ship bollards, or 7.6 cm for 30 tonne ship bollards. Scaling the wave loads to cruise ship dimensions is shown in Table 26.

	Waterline length (m)	Beam (m)	Draft (m)	Surge long wave limit (cm) 40 t bollards	Surge long wave limit (cm) 30 t bollards	Sway long wave limit (cm) 40 t bollards	Sway long wave limit (cm) 30 t bollards
United Jalua	185	32.3	11.4	10.2	7.6	10.2	7.6
Astor	158	22.6	6.15	26.9	20.2	**22.1**	**16.6**
Pacific Eden	193	30.8	7.5	16.2	12.2	**14.8**	**11.1**
Dawn Princess	231	32.3	8.12	14.3	-	**11.4**	-

Table 26: Scaling line tension long wave limit from United Jalua trials at berth 3, to cruise ships at berth 3. Results are for 4 ShoreTension units operating.

We see that the scaled United Jalua long wave heights (results shown in bold in Table 26) are very similar to the limits given in Table 25.

10 CONFIDENCE LIMITS

The predicted long wave limits given in this report are best estimates based on the available information. They should be periodically reviewed and adjusted using practical experience if the ShoreTension system is implemented.

At the pre-purchase stage for the ShoreTension system, it is also important to understand the confidence limits of the results. There are several steps in the modelling process, each with its own associated error, as shown in Table 27.

Modelling step	Confidence	Risks
Analysis of measured ship motions and loads for bulk carriers at berth 6	High	• Data errors
Scaling motions and loads to cruise ships at berth 6	Moderate	• Linearity with long wave height • Unusual behaviour of cruise ships that has not been accounted for
Scaling from 2 to 4 ShoreTension units	Moderate	• Differing ShoreTension unit arrangement, e.g. breast and spring lines • Effect of pre-set tension
Scaling motions and loads to cruise ships at berths 2 and 3	Moderate	• Linearity with long wave height • Unusual long wave properties (wavelength, currents etc.) that have not been accounted for • Different fendering and mooring line lengths

Table 27: Confidence in each modelling step

This project starts with harbour-specific high-quality measured motions and loads data, which is rare for a numerical modelling project, however the scaling to cruise ships and other berths entails a moderate degree of confidence. Overall it is estimated that the long wave limits should lie within ±20% of the predictions given here. As an example, Table 25 states that for 260m cruise ships at berth 3 with 4 ShoreTension units, the long wave limit is 12 cm. This means that once the ShoreTension system is implemented, the upper limit of safe functioning of the ShoreTension system with respect to PIANC motion limits and line loads, has a best estimate of 12 cm and should lie between 10 cm and 14 cm.

11 LONG WAVE LIMITS FOR CRUISE SHIPS – STANDARD MOORING

11.1 Long wave limits by equating wave loads

Here we calculate long wave limits for cruise ships using standard mooring, based on PIANC motion criteria. The limits are found by scaling the measured bulk carrier motions and loads, as done in Section 8 for the ShoreTension results. Ship mooring line stiffness and its effect on ship surge and sway resonance is not included in this analysis, as this cannot be considered without detailed mooring line information for the bulk carriers and cruise ships being modelled.

Measured motions data for bulk carriers with standard mooring lines (without ShoreTension operational) are shown in Appendix D. We shall use the Alam Setia data for further analysis, to enable comparisons with Section 8. Equivalent long wave limits are shown in Table 28.

	Maximum measured motion	Maximum long wave height during measurements	PIANC motion limit	Scaled long wave limit
Surge	1.25m	11 cm	0.60m	5.3 cm
Sway	0.90m	11 cm	0.60m	7.3 cm
Roll	1.19°	11 cm	2.0°	18.5 cm

Table 28: Equivalent limiting long wave conditions for Alam Setia at berth 6 with standard mooring, using PIANC criteria for passenger vessels. These are an intermediate step to developing the cruise ship guidelines.

We see that with standard mooring, horizontal ship motions (ship surge and sway) are the critical motion components. We now scale the long wave loads as shown in Table 29.

	Waterline length (m)	Beam (m)	Draft (m)	Long wave limit for surge (cm)	Long wave limit for sway (cm)
Alam Setia	171	28.8	9.8	5.3	7.3
Astor	158	22.6	6.15	10.8	12.6
Pacific Eden	193	30.8	7.5	6.5	8.5
Dawn Princess	231	32.3	8.12	5.7	6.5

Table 29: Scaling long wave limits from measured surge and sway results for Alam Setia at berth 6 with standard mooring, to cruise ships at berth 6.

For berths 2 and 3, we use the long wave scaling as done in Section 8. Results for berths 2,3 and 6 are shown in Table 30.

	Ship overall length	**Long wave limit**
Berth 6	**175-185m**	11 cm
Berth 6	**215-225m**	7 cm
Berth 2	**175-185m**	4 cm
Berth 2	**215-225m**	3 cm
Berth 2	**255-265m**	2 cm
Berth 3	**175-185m**	8 cm
Berth 3	**215-225m**	5 cm
Berth 3	**255-265m**	4 cm

Table 30: Calculated long wave limits for cruise ships with standard mooring, based on PIANC guidelines.

Because of the large horizontal ship motions with standard mooring in Geraldton, the long wave limits for cruise ships according to the PIANC guidelines are very restrictive without ShoreTension.

12 EFFECT OF POSSIBLE BREAKWATER MODIFICATIONS

MetOcean Solutions have undertaken wave propagation modelling[10] for two alternative breakwater modifications, consisting of either a 20 m or 65 m breakwater as shown in Figure 19.

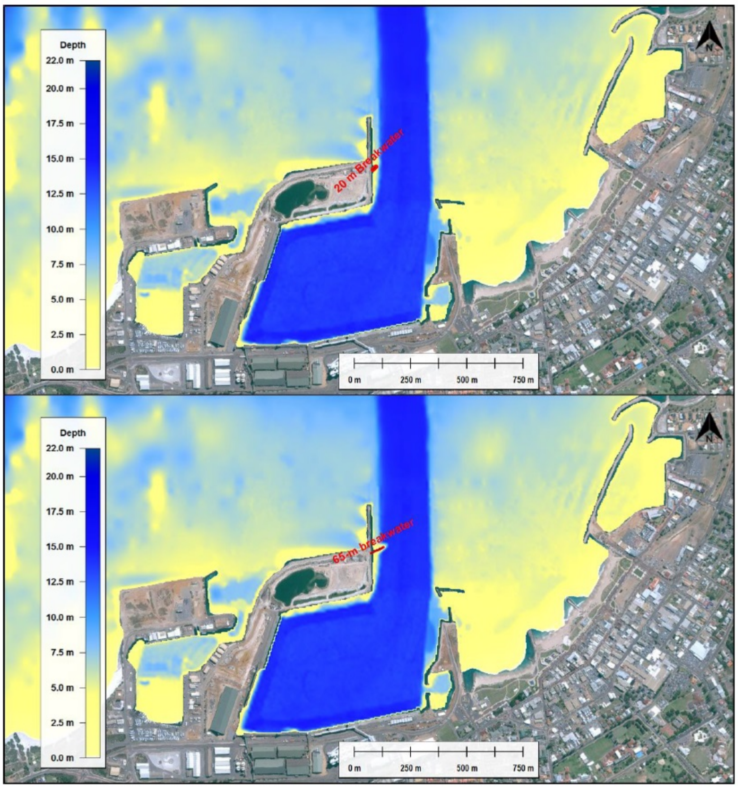

Figure 19: Concept breakwater modifications (from [10, Figure 2.1])

The effect of each is summarized in Table 31.

	20 m breakwater @ 45°	65 m breakwater @ 60°
Berth 2	0 %	-8.3 %
Berth 3	0 %	0 %
Berth 4	-3.1 %	-12.8 %
Berth 5	0 %	-7.7 %
Berth 6	-0.7 %	-11.8 %
Berth 7	-2.7 %	-2.7 %

Table 31: Modelled change in long wave height due to breakwater modifications (from [10, Tables 4.1,4.2])

We see that the 20 m breakwater is not expected to give any significant improvement in long wave conditions at berths 2,3 or 6.

The 65 m breakwater is not expected to give any improvement in long wave conditions at berth 3. At berths 2 and 6, the long wave height is expected to reduce by 8.3% and 11.8% respectively. The increased accessibility is equivalent to a 8.3% or 11.8% increase in the allowable long wave height with the present harbour layout. Results are shown in Table 32 and Table 33, compared to the present breakwater case from Table 25 and Table 30.

	Ship LOA	Long wave limits					
		Present situation	65 m BW	2 x ST	65 m BW + 2 x ST	4 x ST	65 m BW + 4 x ST
Berth 6	**175-185m**	11 cm	12 cm	15 cm	17 cm	29 cm	32 cm
Berth 6	**215-225m**	7 cm	8 cm	10 cm	11 cm	20 cm	22 cm
Berth 2	**175-185m**	4 cm	4 cm	7 cm	8 cm	13 cm	14 cm
Berth 2	**215-225m**	3 cm	3 cm	4 cm	4 cm	8 cm	9 cm
Berth 2	**255-265m**	2 cm	2 cm	4 cm	4 cm	7 cm	8 cm
Berth 3	**175-185m**	8 cm	8 cm	11 cm	11 cm	23 cm	23 cm
Berth 3	**215-225m**	5 cm	5 cm	8 cm	8 cm	15 cm	15 cm
Berth 3	**255-265m**	4 cm	4 cm	6 cm	6 cm	12 cm	12 cm

Table 32: Long wave limits for existing breakwater and equivalent long wave limits for modified breakwater. All assuming 40 tonne ship bollards. BW=breakwater, ST=ShoreTension

	Ship LOA	Downtime days (2 hours / day above threshold) per year					
		Present situation	65 m BW	2 x ST	65 m BW + 2 x ST	4 x ST	65 m BW + 4 x ST
Berth 6	**175-185m**	37	29	13	8	0	0
Berth 6	**215-225m**	92	76	48	37	3	2
Berth 2	**175-185m**	199	199	92	76	21	16
Berth 2	**215-225m**	263	263	199	199	76	64
Berth 2	**255-265m**	329	329	199	199	92	76
Berth 3	**175-185m**	76	76	37	37	2	2
Berth 3	**215-225m**	152	152	76	76	13	13
Berth 3	**255-265m**	199	199	120	120	29	29

Table 33: Annual number of downtime days for all cases. Downtime definitions are given in Appendix E. All assuming 40 tonne ship bollards. BW=breakwater, ST=ShoreTension

13 FUTURE WORK

Other work that could be done as needed, following on from the present work, includes:

13.1 Wind load effects on ShoreTension line tensions for cruise ships

Cruise ships have a large above-water profile area (see Appendix F), so are particularly susceptible to wind loads. Geraldton Harbour is quite well sheltered from wind by the surrounding storage sheds; nevertheless, wind loads on cruise ships moored at berth 6 in a very strong westerly wind, or moored at berth 2 or 3 in a very strong south-westerly wind, may exceed the ShoreTension limits or quay bollard limits. Calculation of these wind loads for cruise ships can be done, including the sheltering effect of storage sheds located around the harbour.

13.2 Calculation of long wave limits for bulk carriers under ShoreTension

The existing full-scale trials data for bulk carriers under ShoreTension can be extrapolated to other berths and bulk carrier sizes, as done in this report for cruise ships. This could be used to recommend long wave limits for bulk carriers at each berth under ShoreTension, based on PIANC recommended motion limits for cargo loading, and safe functioning of the ShoreTension system.

14 REFERENCES

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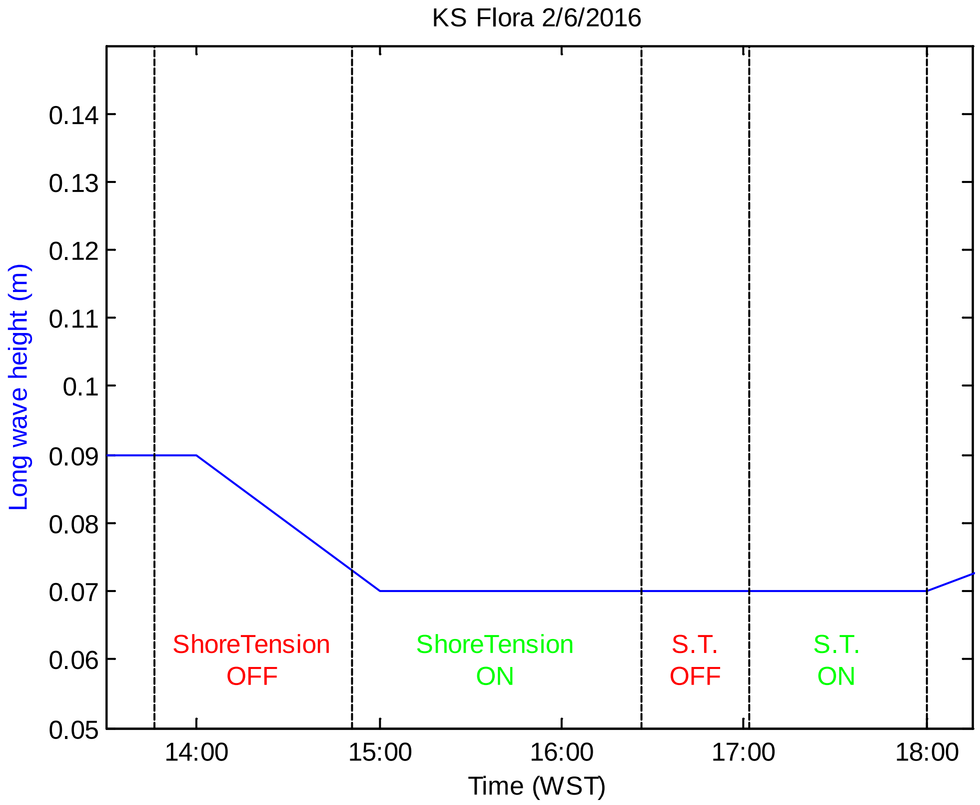
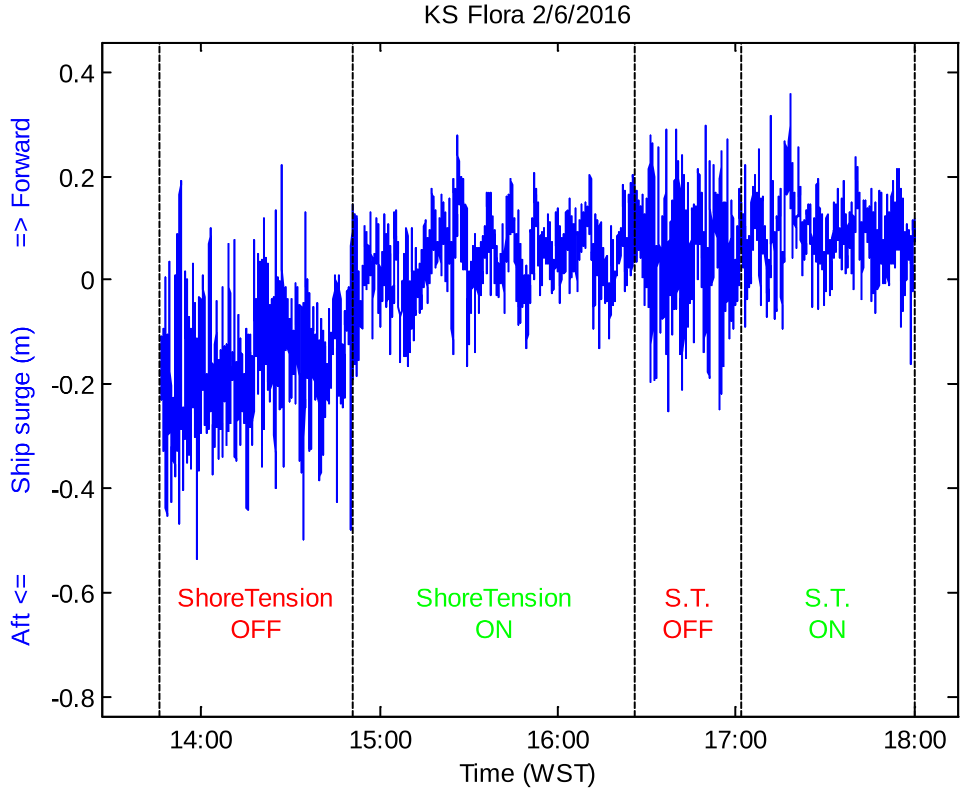
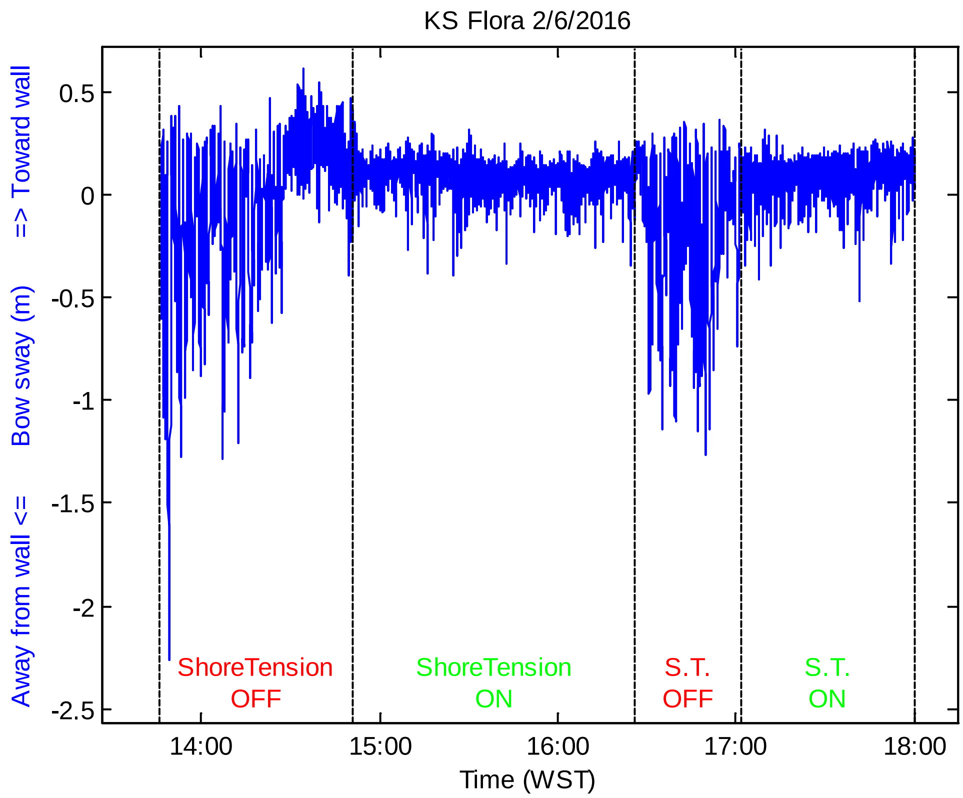
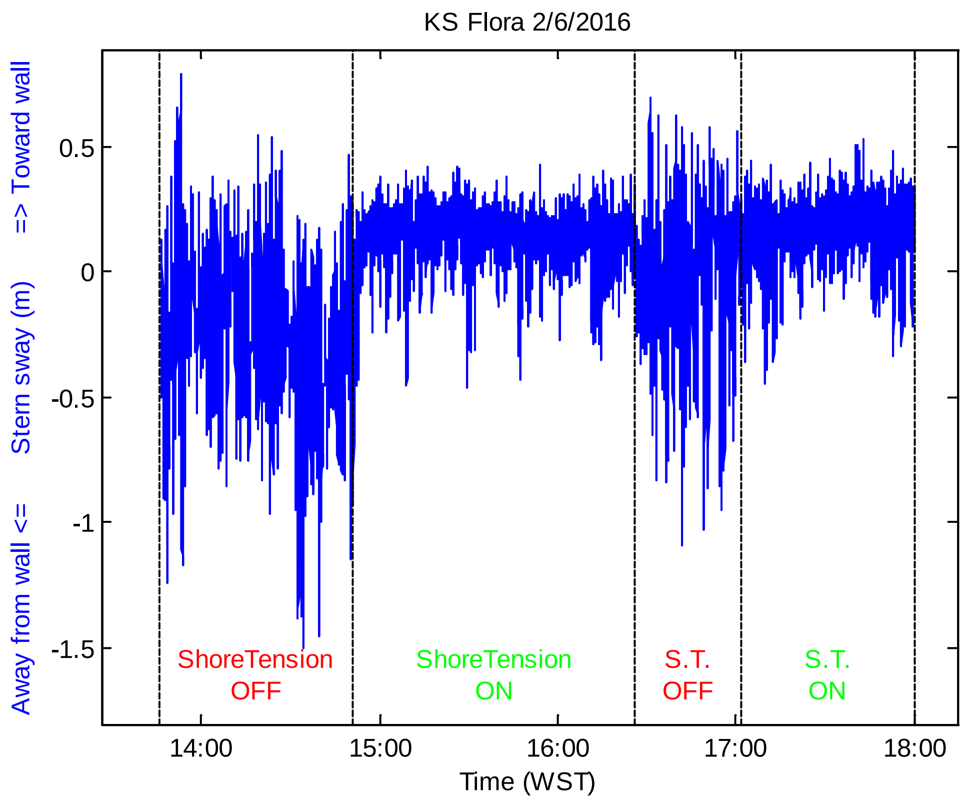
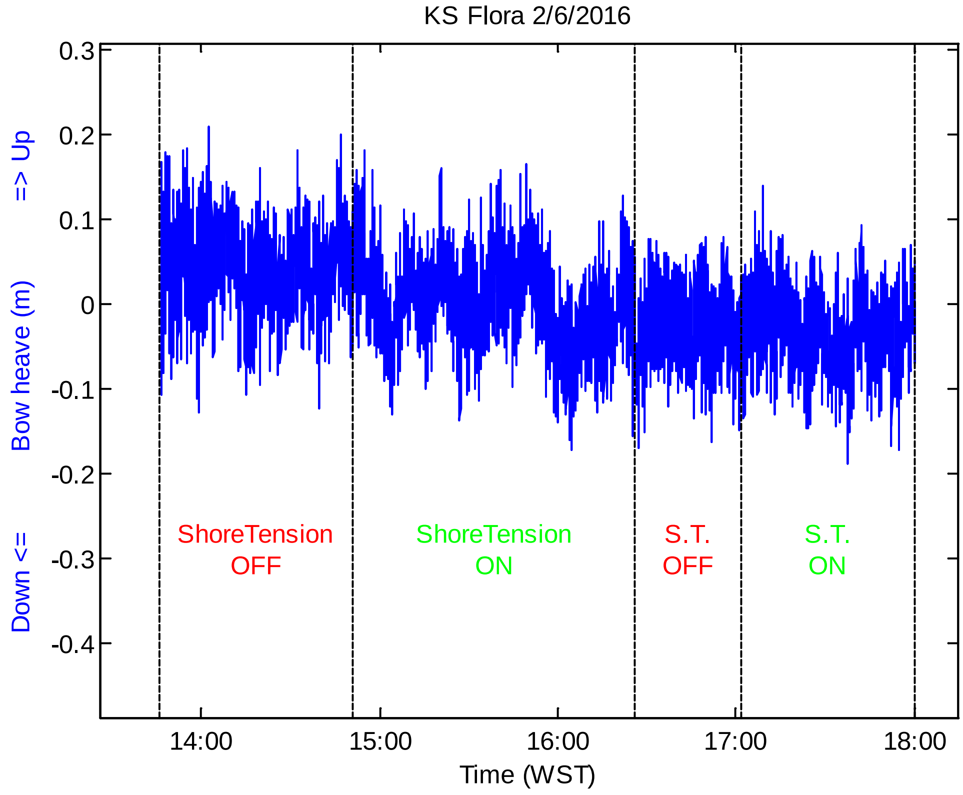
APPENDIX A – GRAPHICAL MEASURED MOTIONS

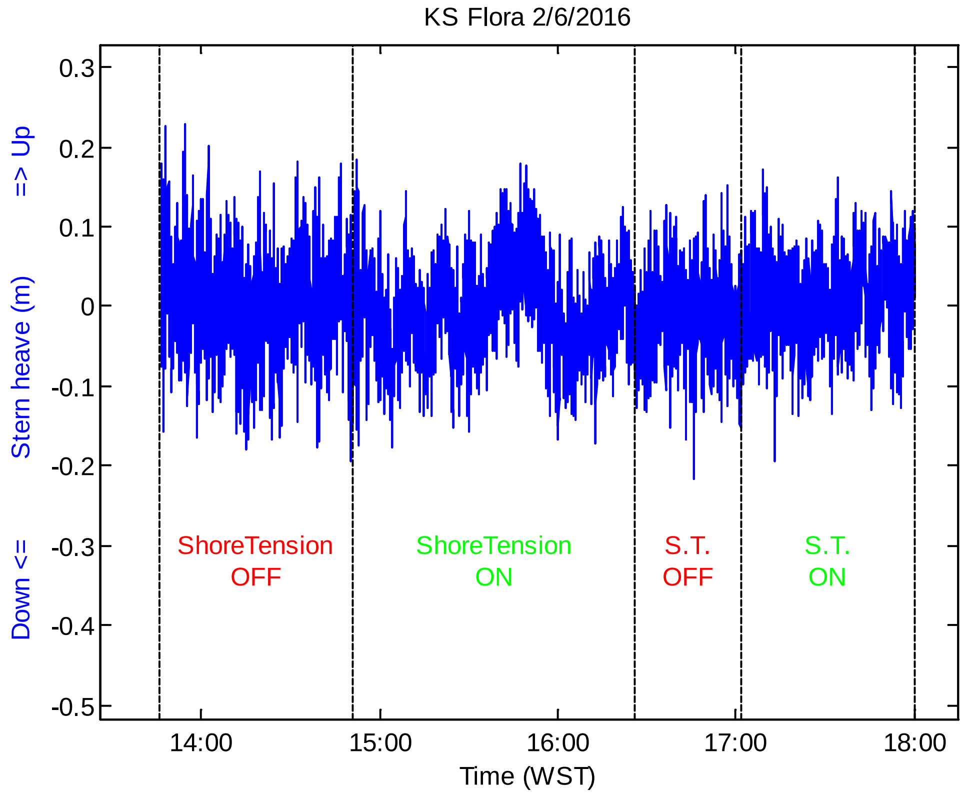


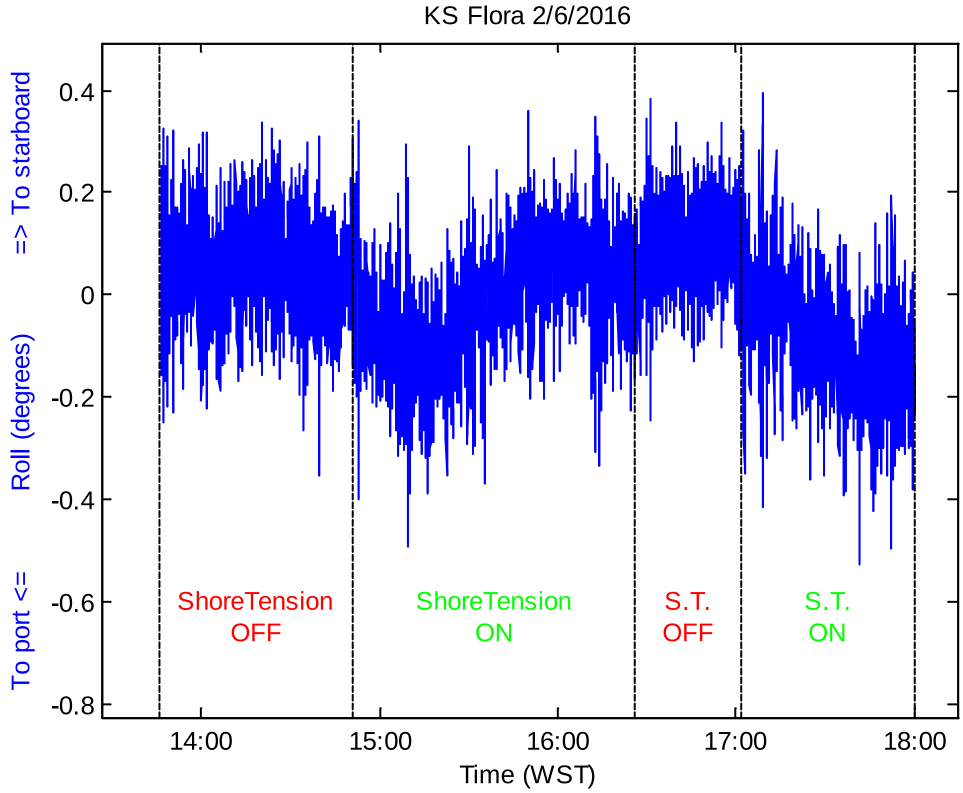


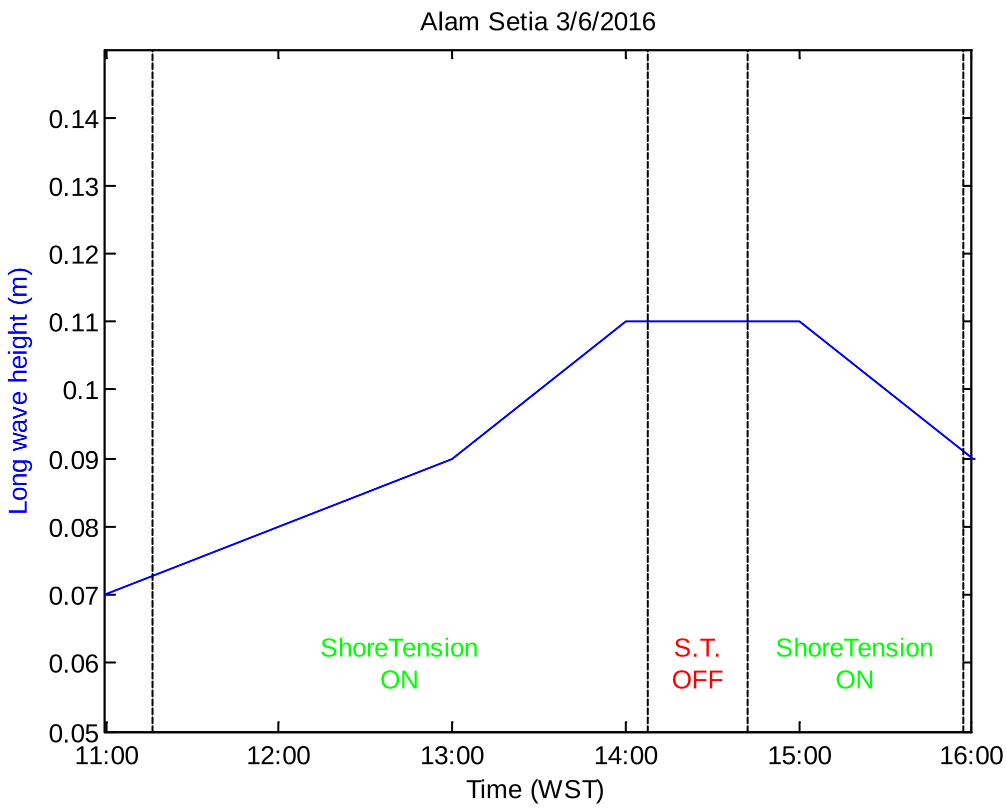

KS Flora 2/6/2016
Away from wall <= Bow sway (m) => Toward wall
0.5
0
-0.5
-1
-1.5
-2
-2.5
ShoreTension OFF
ShoreTension ON
S.T. OFF
S.T. ON
14:00
15:00
16:00
17:00
18:00
Time (WST)

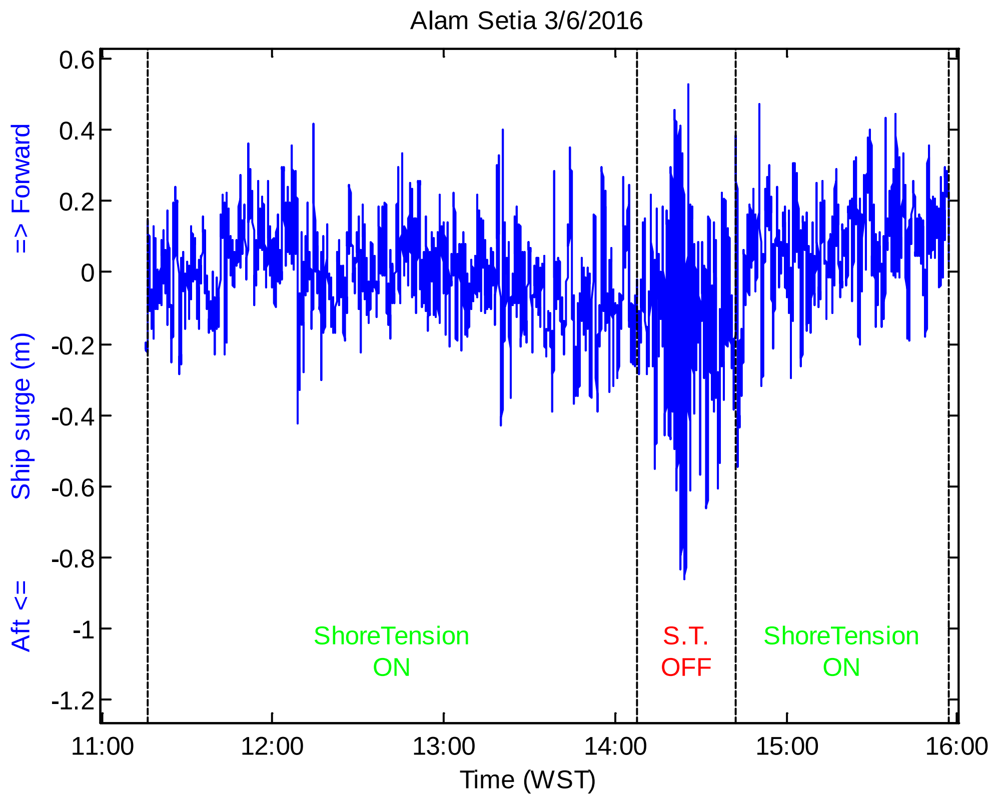

KS Flora 2/6/2016
Away from wall <= Stern sway (m) => Toward wall
0.5
0
-0.5
-1
-1.5
ShoreTension OFF
ShoreTension ON
S.T. OFF
S.T. ON
14:00
15:00
16:00
17:00
18:00
Time (WST)

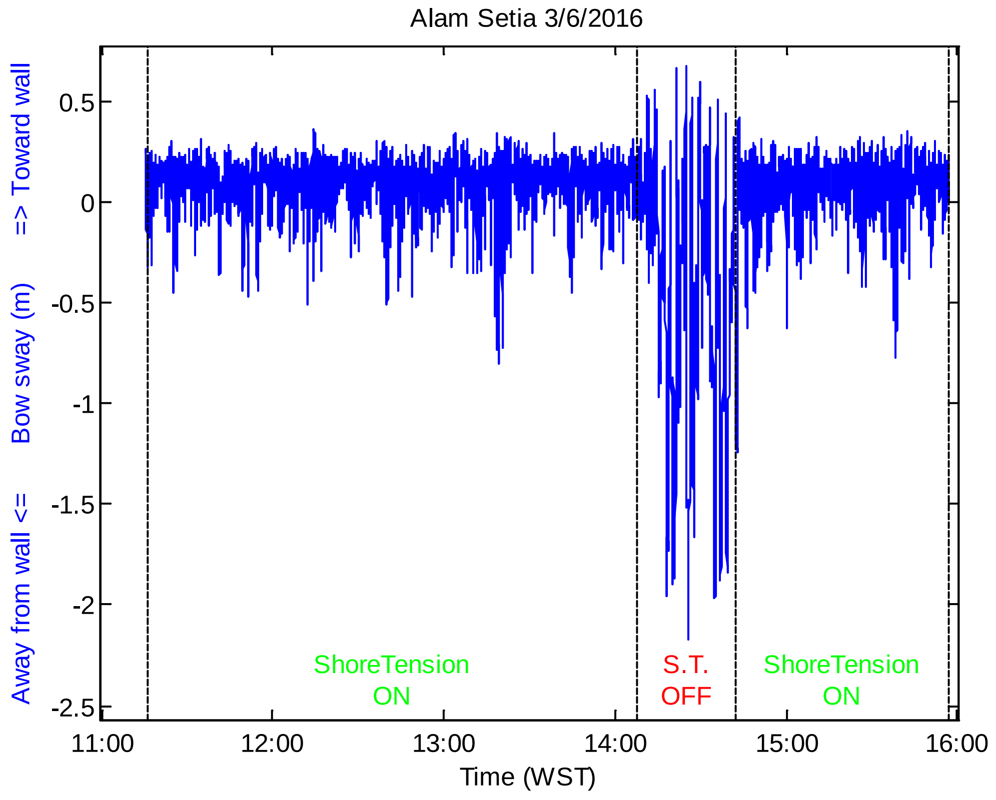

KS Flora 2/6/2016
Down <= Bow heave (m) => Up
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
ShoreTension OFF
ShoreTension ON
S.T. OFF
S.T. ON
14:00
15:00
16:00
17:00
18:00
Time (WST)

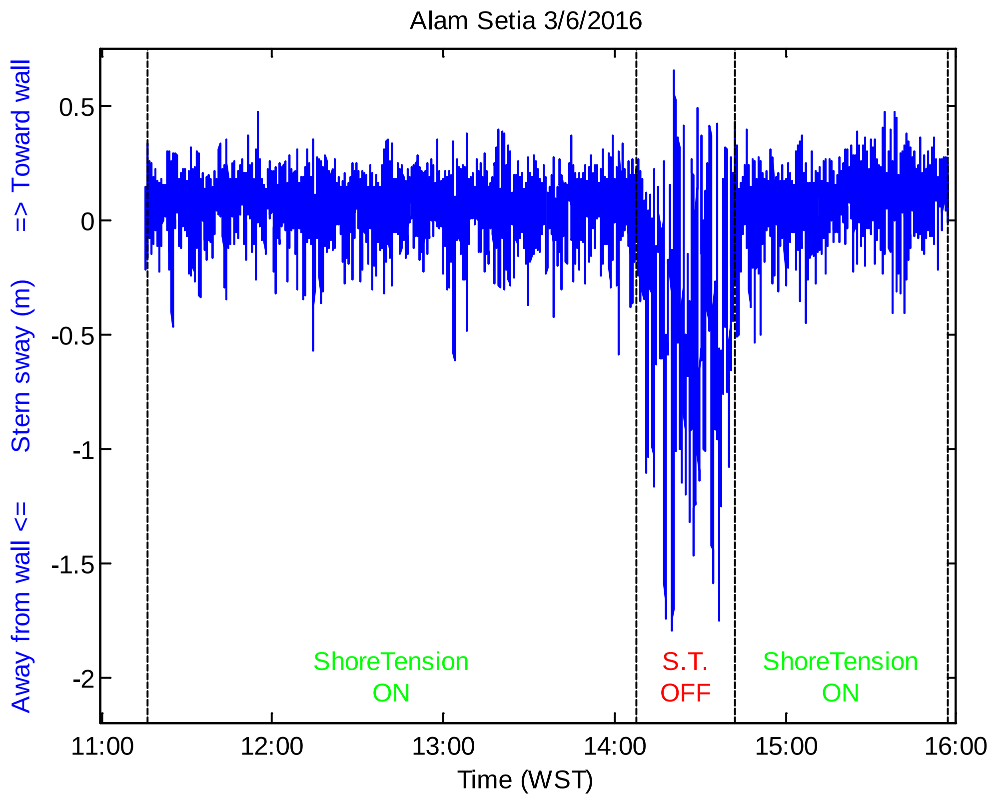

KS Flora 2/6/2016
Down <= Stern heave (m) => Up
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
ShoreTension OFF
ShoreTension ON
S.T. OFF
S.T. ON
14:00
15:00
16:00
17:00
18:00
Time (WST)

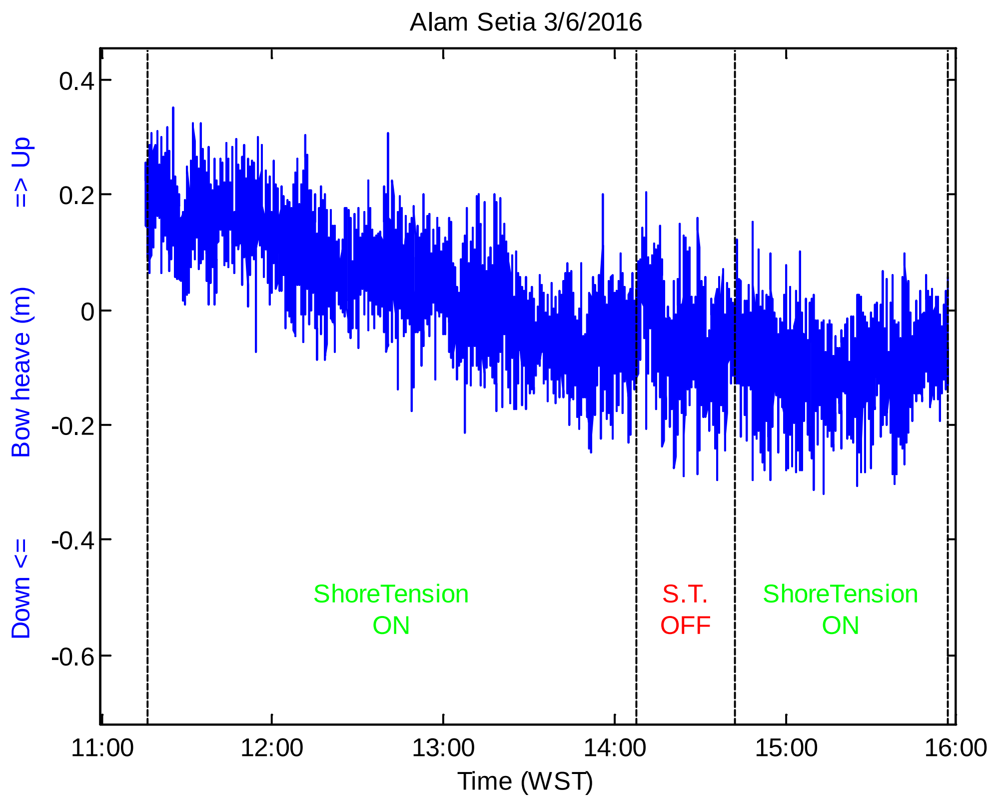

KS Flora 2/6/2016
=> To starboard
Roll (degrees)
To port <=
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
ShoreTension OFF
ShoreTension ON
S.T. OFF
S.T. ON
14:00
15:00
16:00
17:00
18:00
Time (WST)

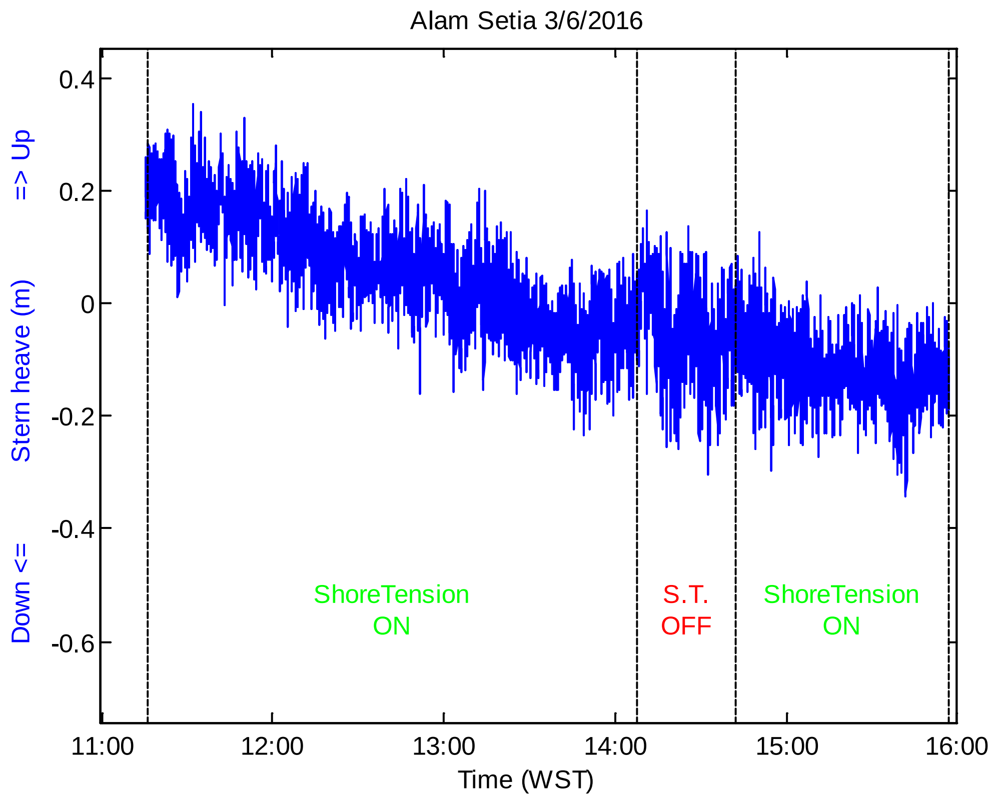

Alam Setia 3/6/2016
Long wave height (m)
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
ShoreTension ON
S.T. OFF
ShoreTension ON
11:00
12:00
13:00
14:00
15:00
16:00
Time (WST)

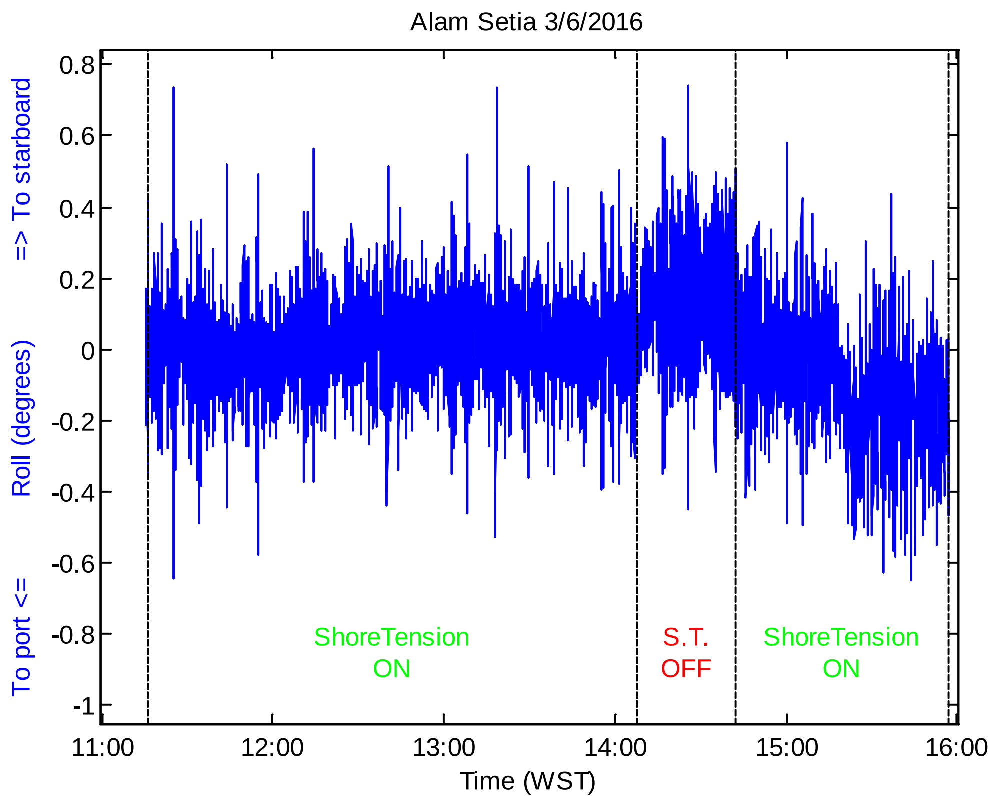

Alam Setia 3/6/2016
Aft <= Ship surge (m) => Forward
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
ShoreTension ON
S.T. OFF
ShoreTension ON
11:00
12:00
13:00
14:00
15:00
16:00
Time (WST)

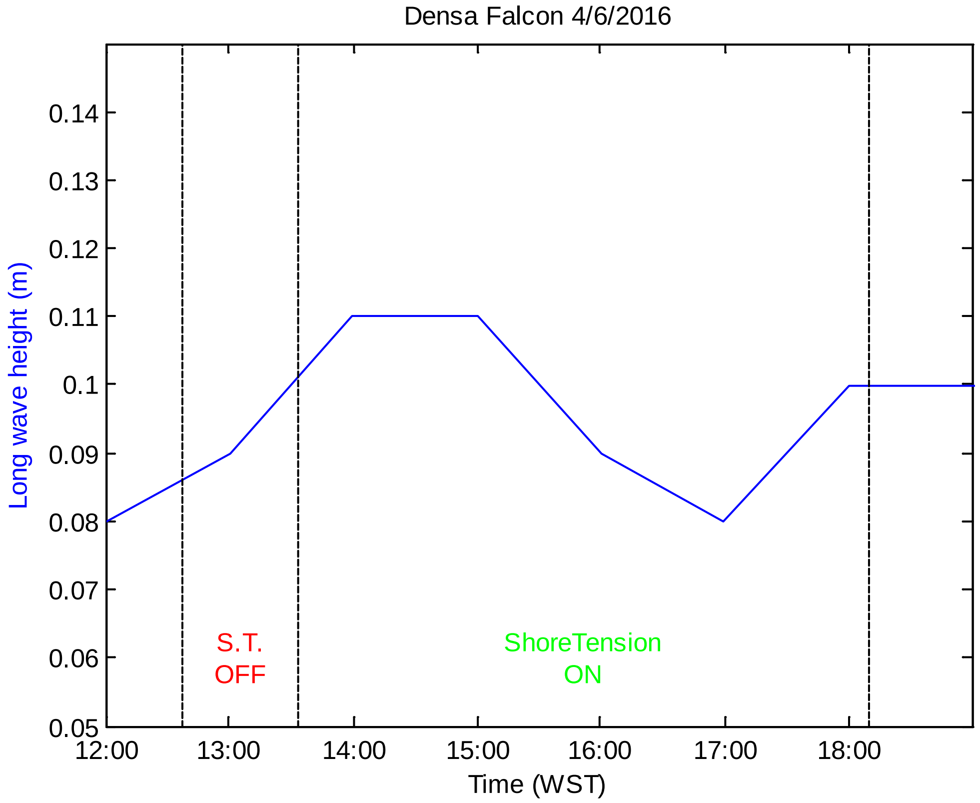

Alam Setia 3/6/2016
Away from wall <= Bow sway (m) => Toward wall
0.5
0
-0.5
-1
-1.5
-2
-2.5
ShoreTension ON
S.T. OFF
ShoreTension ON
11:00
12:00
13:00
14:00
15:00
16:00
Time (WST)

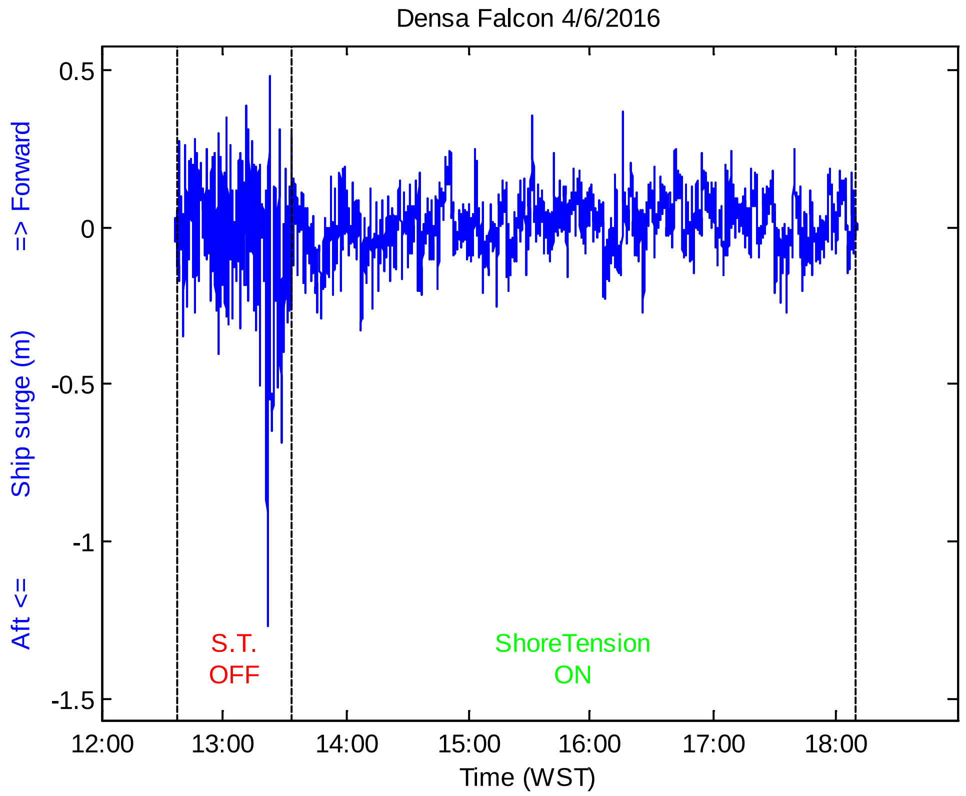

Alam Setia 3/6/2016
=> Toward wall
Stern sway (m)
Away from wall <=
0.5
0
-0.5
-1
-1.5
-2
ShoreTension
ON
S.T.
OFF
ShoreTension
ON
11:00
12:00
13:00
14:00
15:00
16:00
Time (WST)

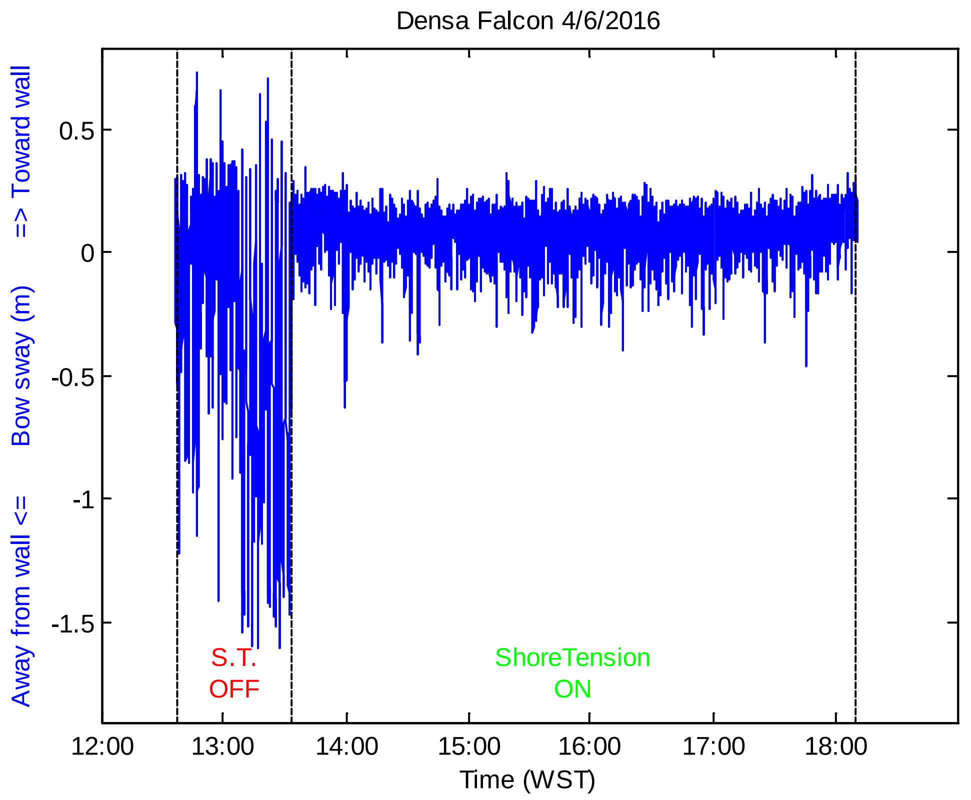

Alam Setia 3/6/2016
=> Up
Bow heave (m)
Down <=
0.4
0.2
0
-0.2
-0.4
-0.6
ShoreTension
ON
S.T.
OFF
ShoreTension
ON
11:00
12:00
13:00
14:00
15:00
16:00
Time (WST)

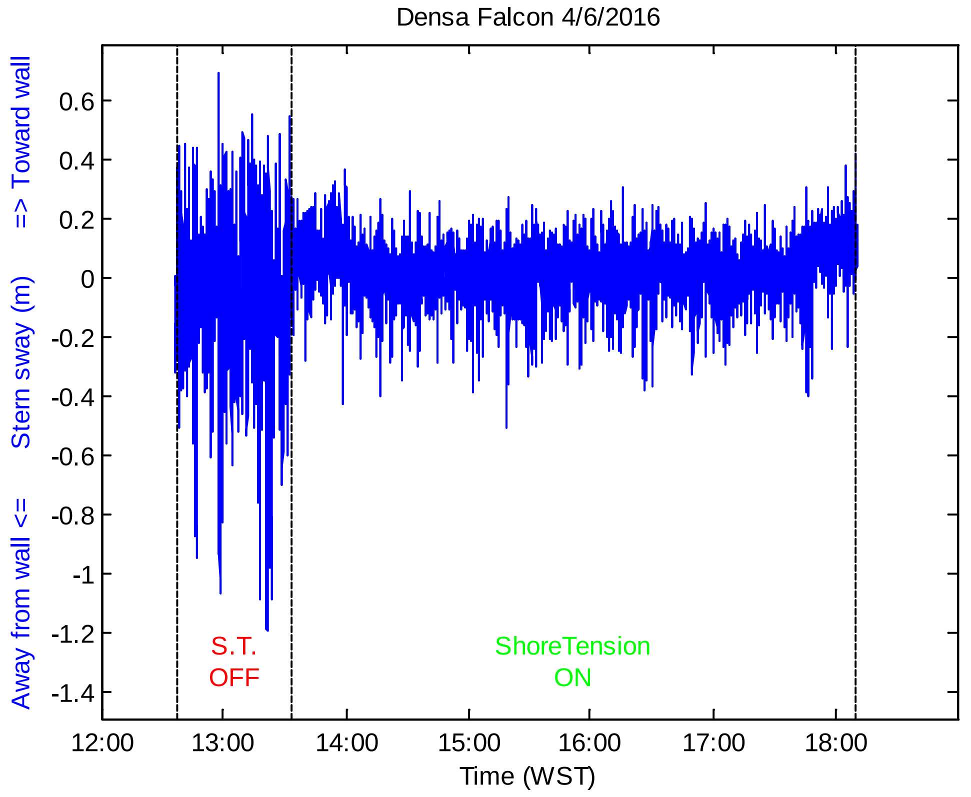

Alam Setia 3/6/2016
0.4
0.2
0
-0.2
-0.4
-0.6
Down <= Stern heave (m) => Up
ShoreTension ON
S.T. OFF
ShoreTension ON
11:00
12:00
13:00
14:00
15:00
16:00
Time (WST)

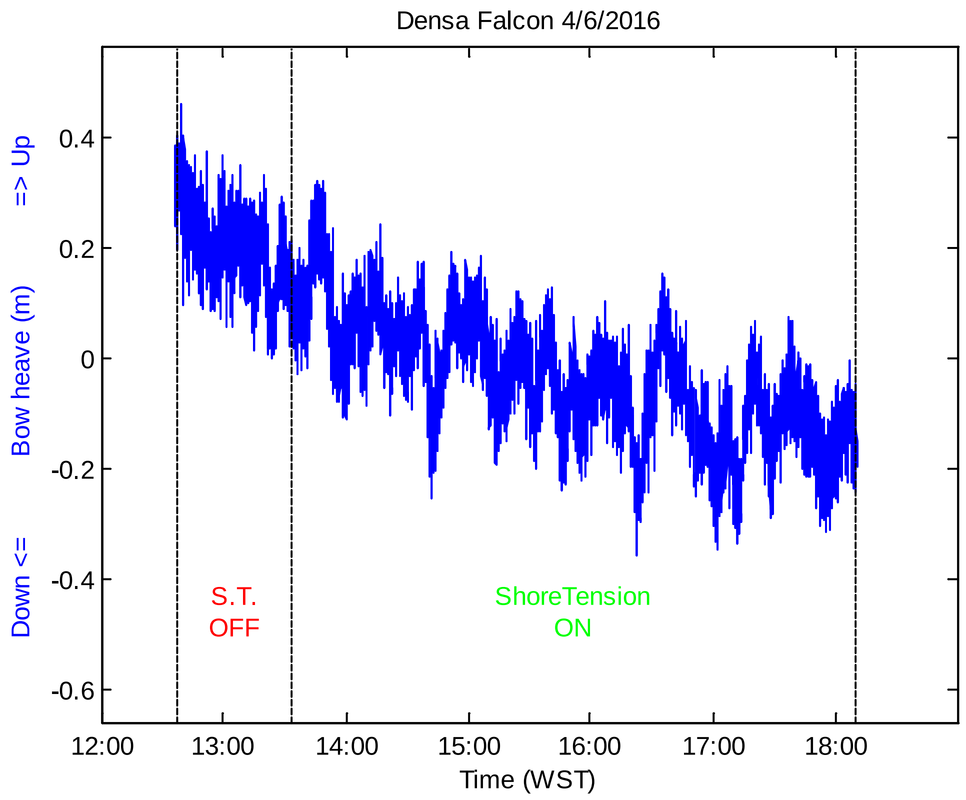

Alam Setia 3/6/2016
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
To port <= Roll (degrees) => To starboard
ShoreTension ON
S.T. OFF
ShoreTension ON
11:00
12:00
13:00
14:00
15:00
16:00
Time (WST)

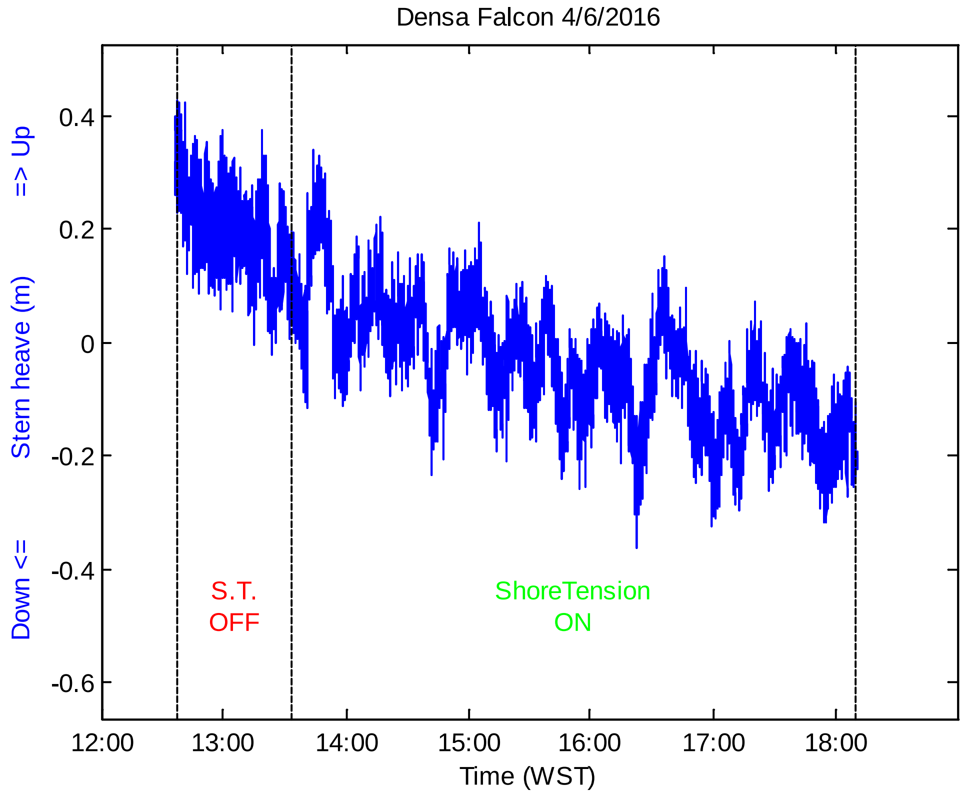

Densa Falcon 4/6/2016
Long wave height (m)
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Time (WST)
S.T.
OFF
ShoreTension
ON

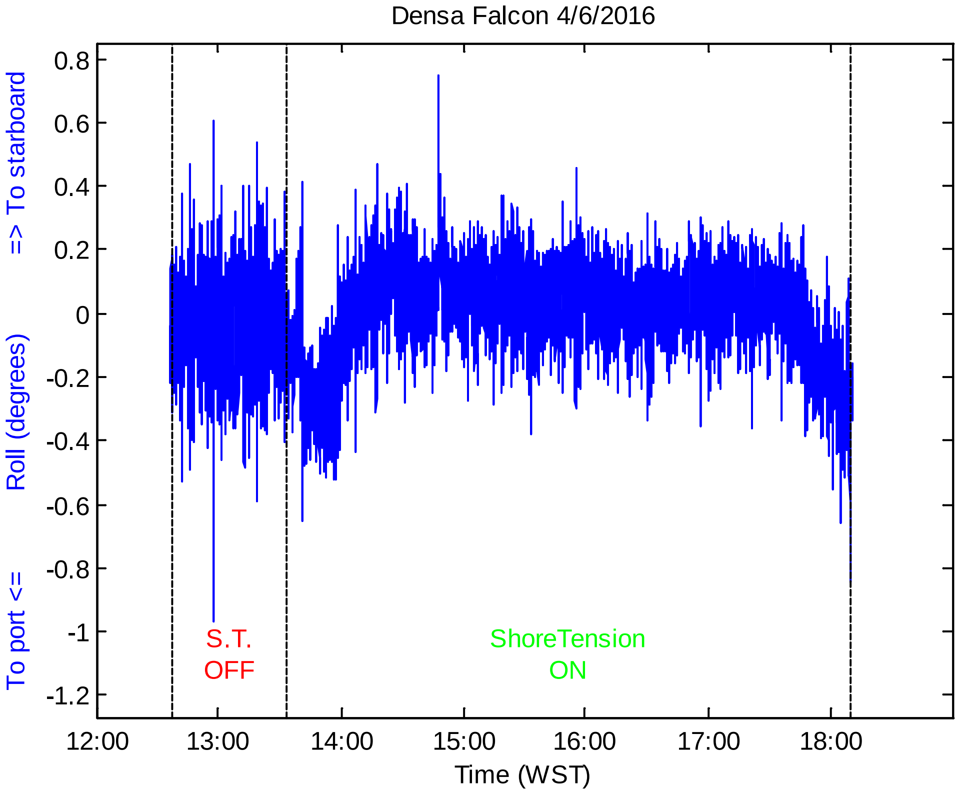

Densa Falcon 4/6/2016
Aft <= Ship surge (m) => Forward
0.5
0
-0.5
-1
-1.5
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Time (WST)
S.T.
OFF
ShoreTension
ON


Densa Falcon 4/6/2016
Away from wall <=   Bow sway (m)   => Toward wall
0.5
0
-0.5
-1
-1.5
S.T.
OFF
ShoreTension
ON
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Time (WST)

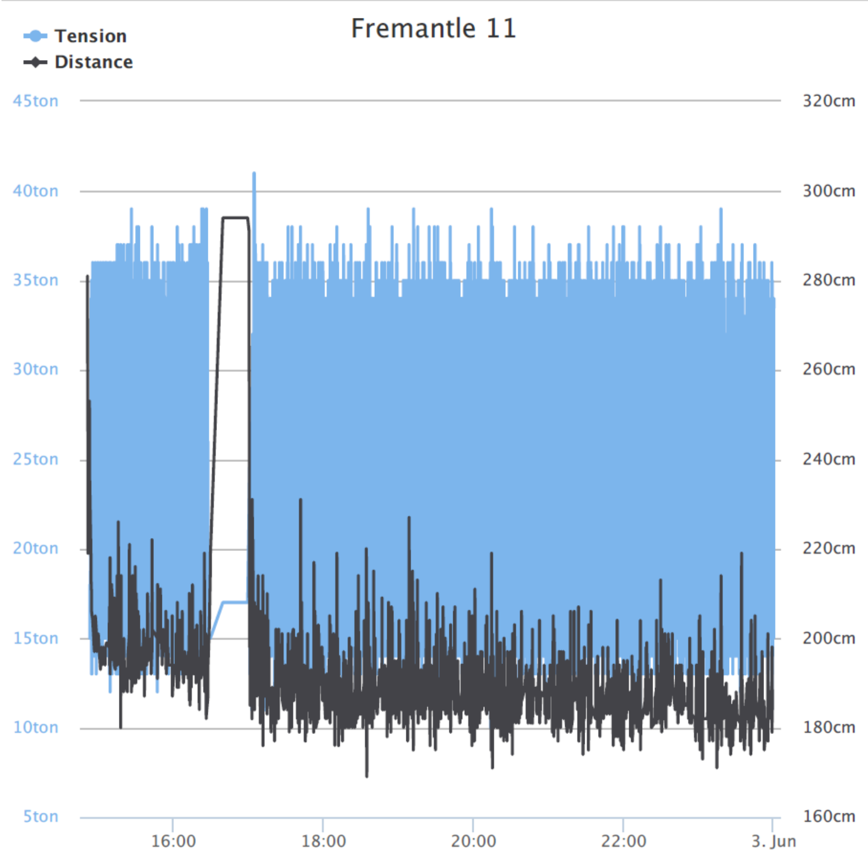

Densa Falcon 4/6/2016
Away from wall <=   Stern sway (m)   => Toward wall
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
S.T.
OFF
ShoreTension
ON
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Time (WST)


Densa Falcon 4/6/2016
Down <= Bow heave (m) => Up
0.4
0.2
0
-0.2
-0.4
-0.6
S.T.
OFF
ShoreTension
ON
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Time (WST)

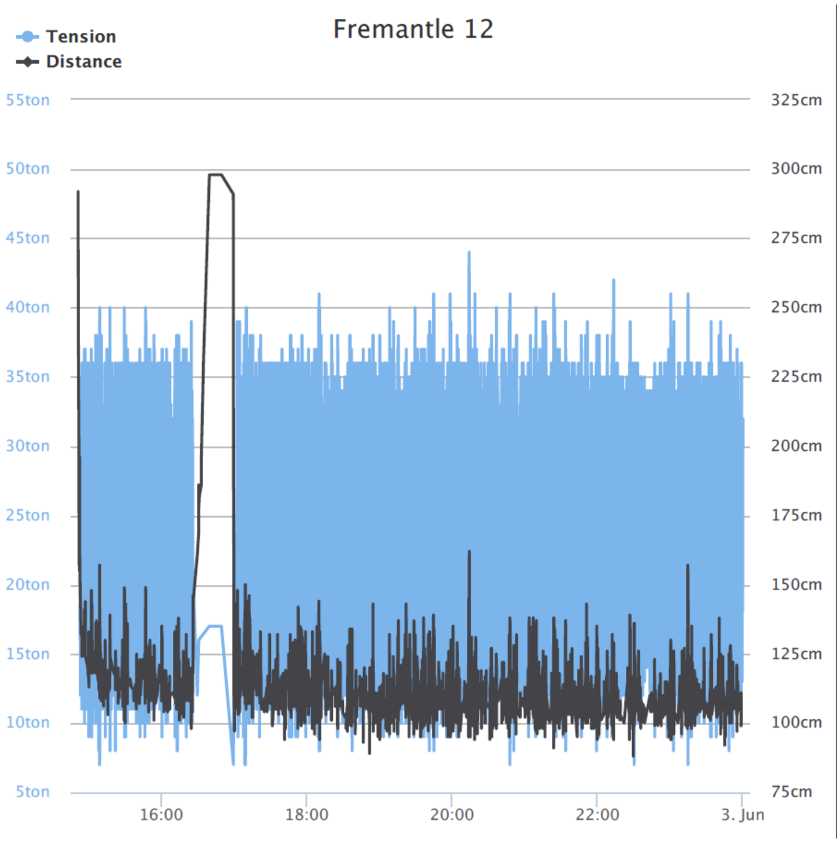

Densa Falcon 4/6/2016
Down <= Stern heave (m) => Up
0.4
0.2
0
-0.2
-0.4
-0.6
S.T.
OFF
ShoreTension
ON
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Time (WST)


Densa Falcon 4/6/2016
To port <= Roll (degrees) => To starboard
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
S.T. OFF
ShoreTension ON
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Time (WST)

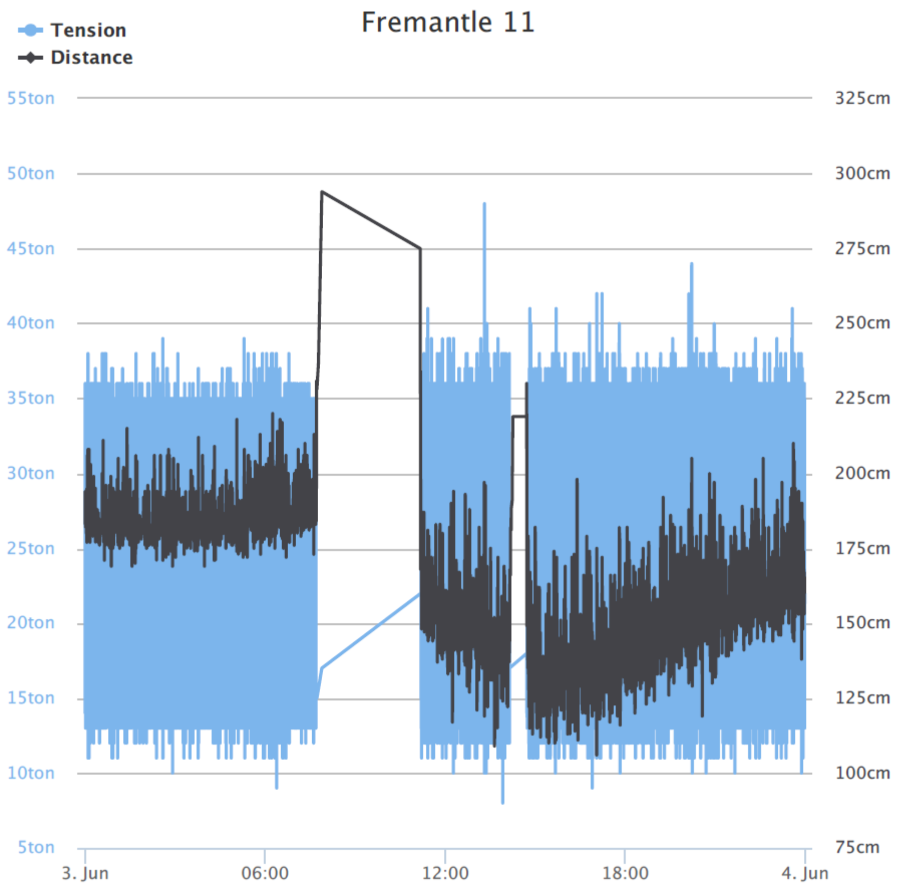
APPENDIX B – MEASURED SHORETENSION RESULTS – BERTH 6



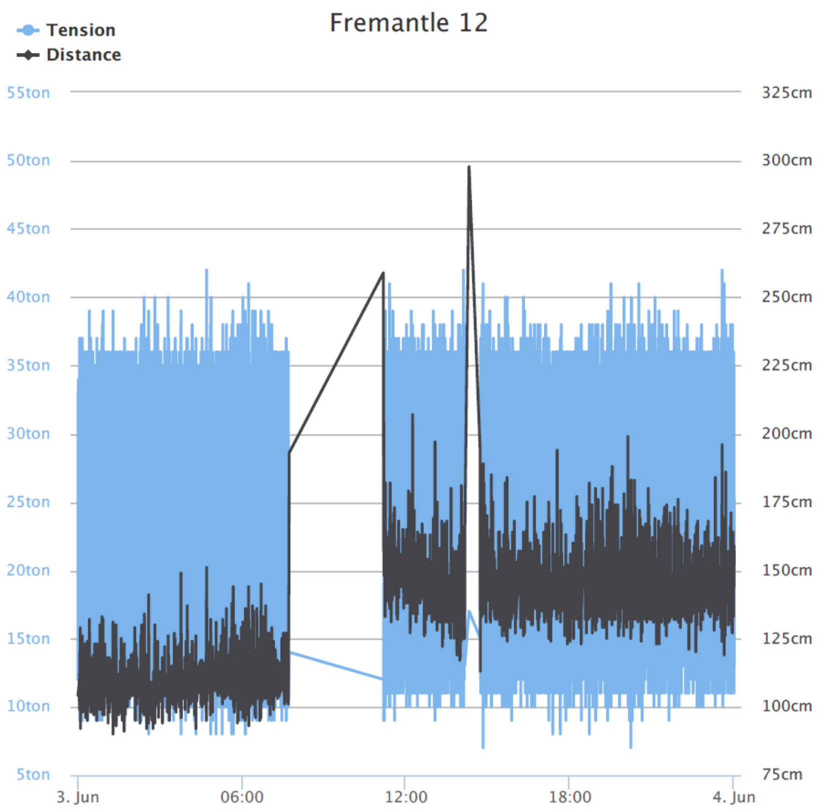
Bow ShoreTension unit line tension and ram extension for KS Flora on 2nd June



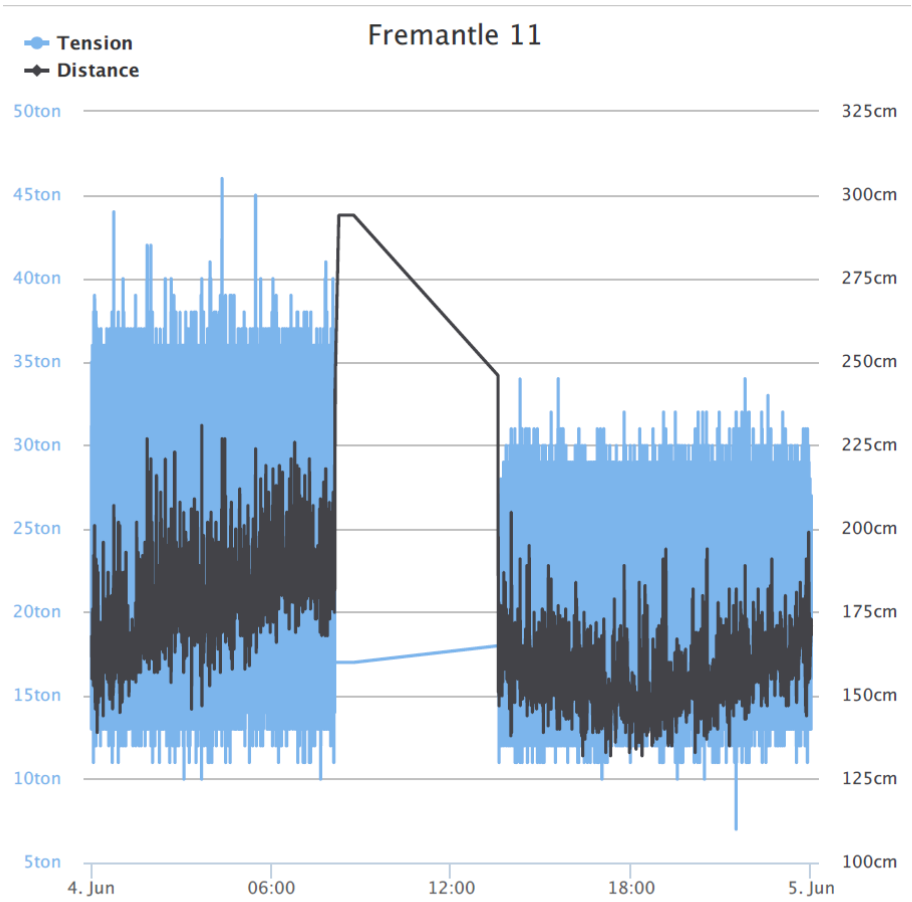
Stern ShoreTension unit line tension and ram extension for KS Flora on 2nd June



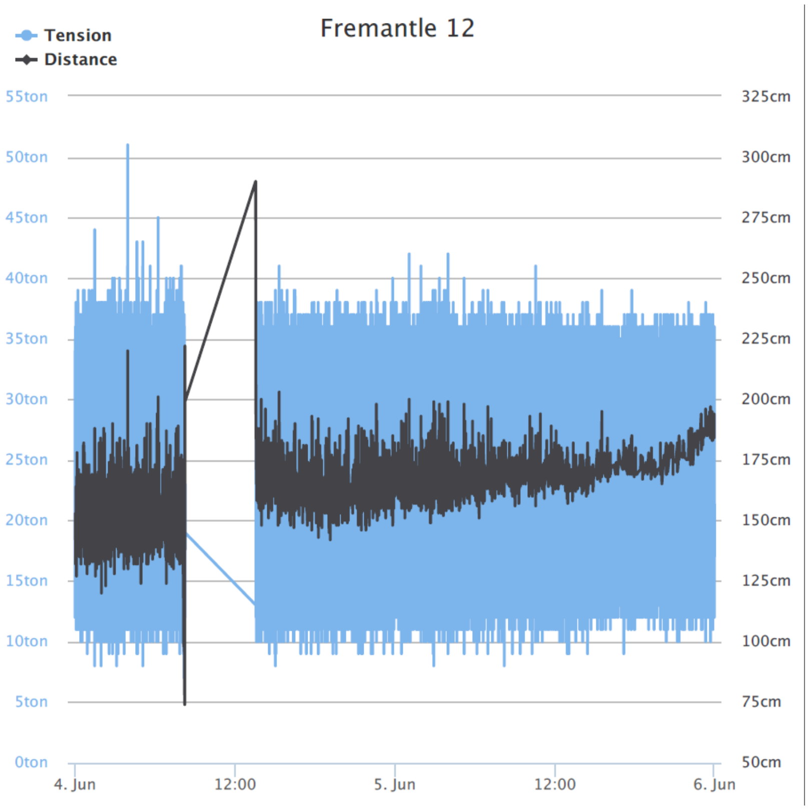
Bow ShoreTension unit line tension and ram extension for Alam Setia on 3rd June



Stern ShoreTension unit line tension and ram extension for Alam Setia on 3rd June

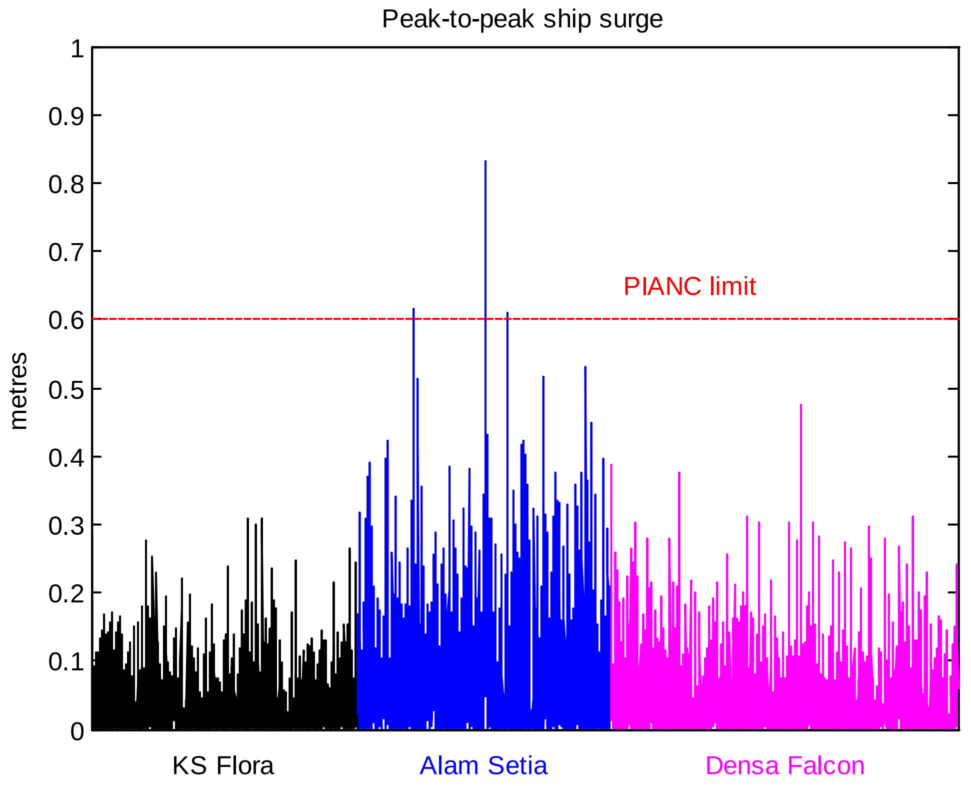


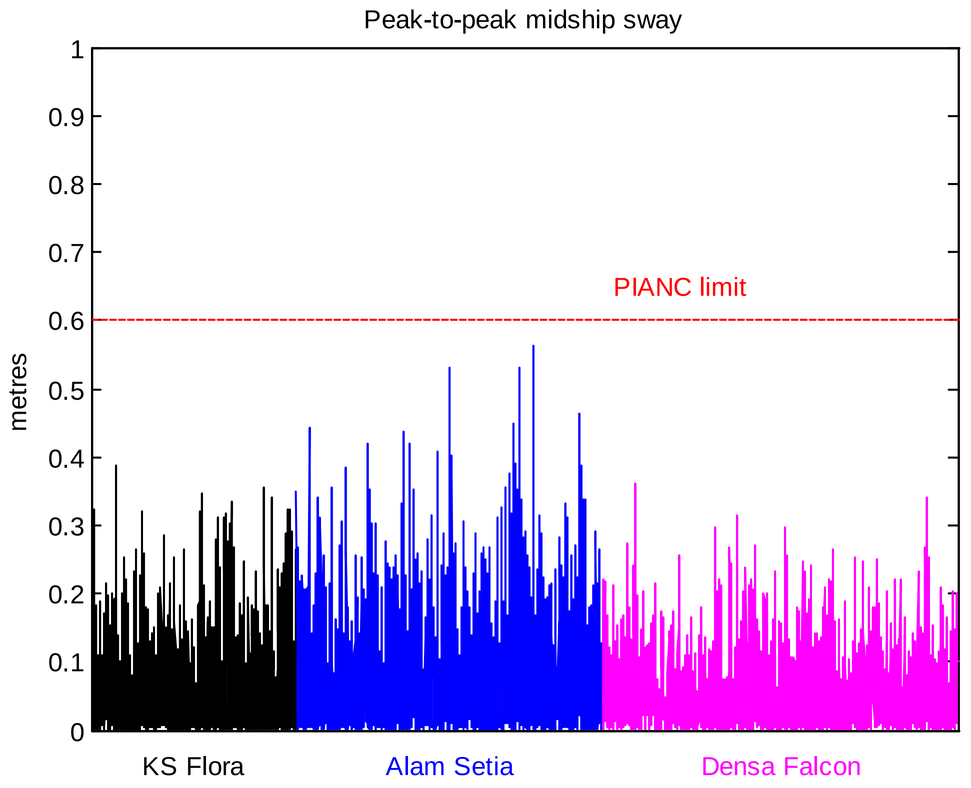
Bow ShoreTension unit line tension and ram extension for Densa Falcon on 4th June

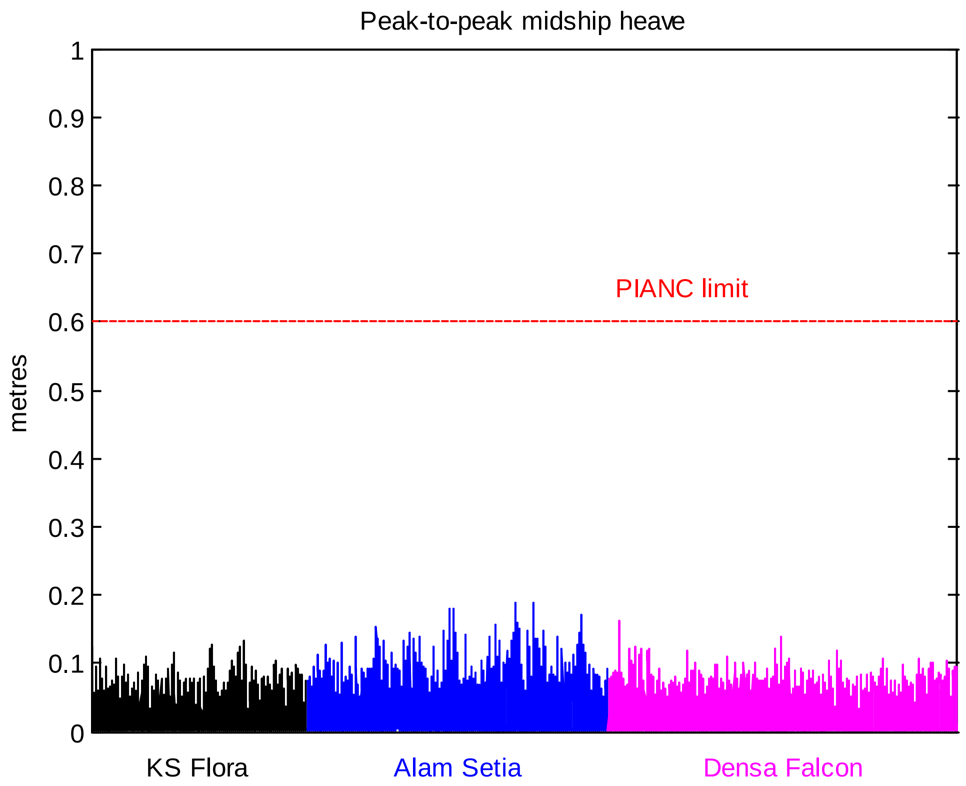


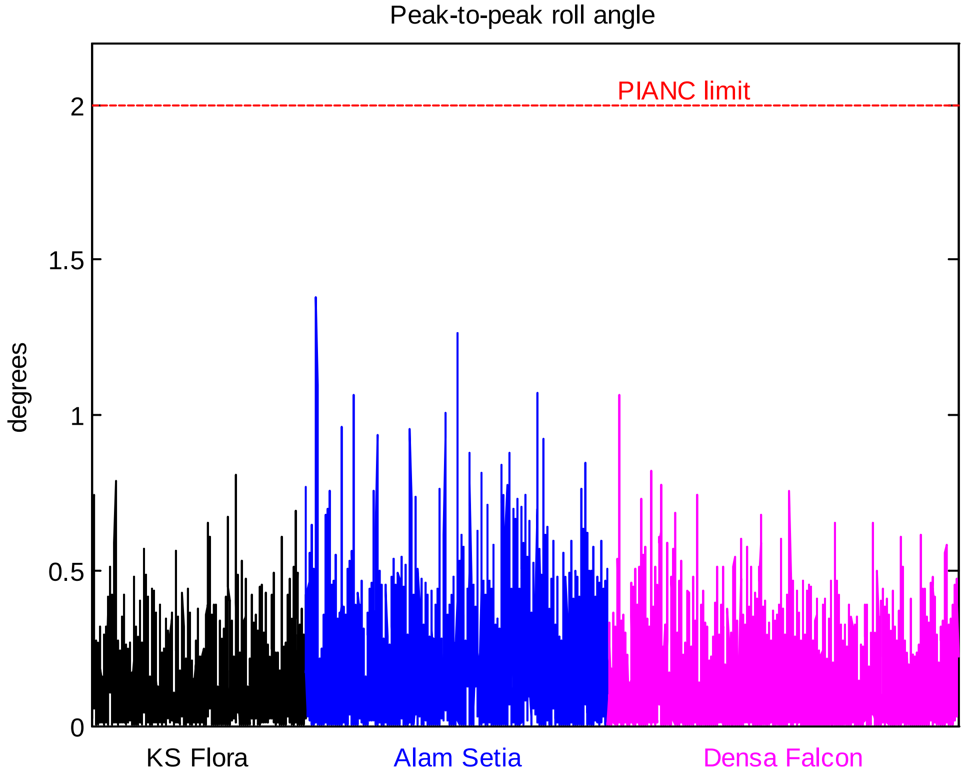
Stern ShoreTension unit line tension and ram extension for Densa Falcon on 4th June

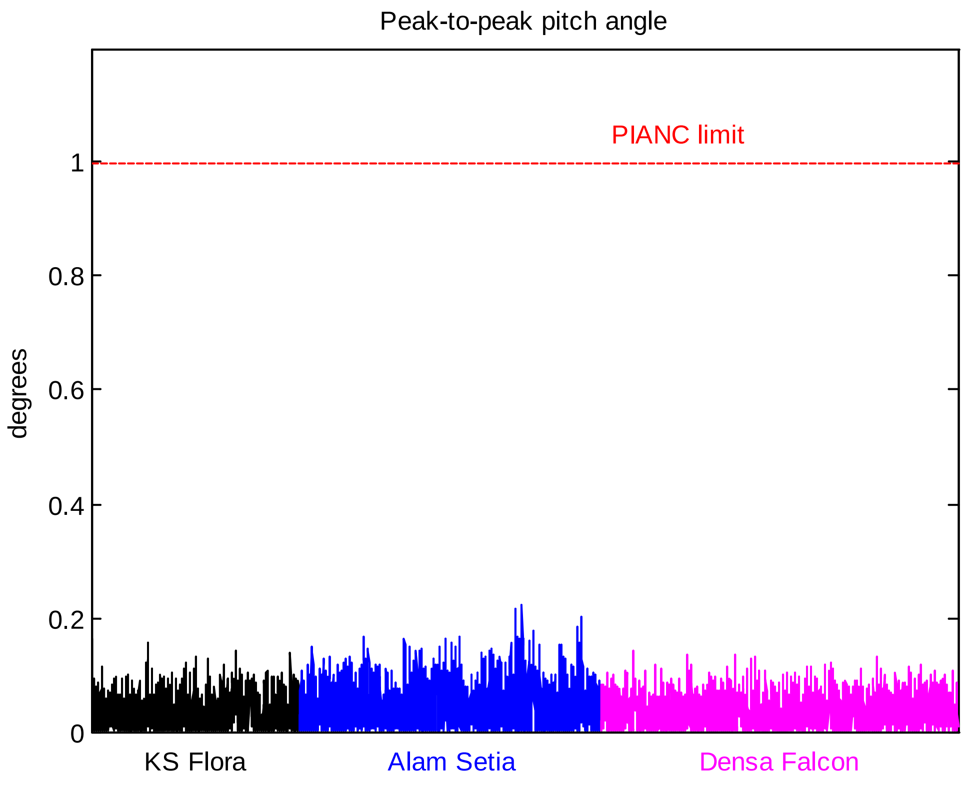
APPENDIX C – MEASURED BULK CARRIER MOTIONS WITH SHORETENSION – BERTH 6

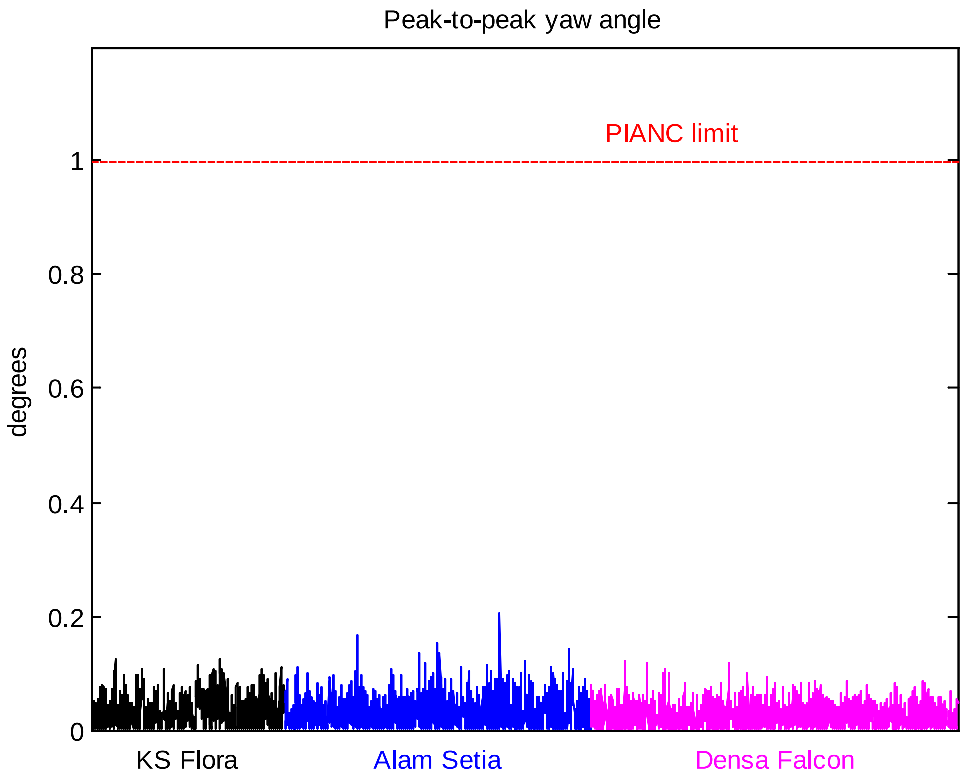




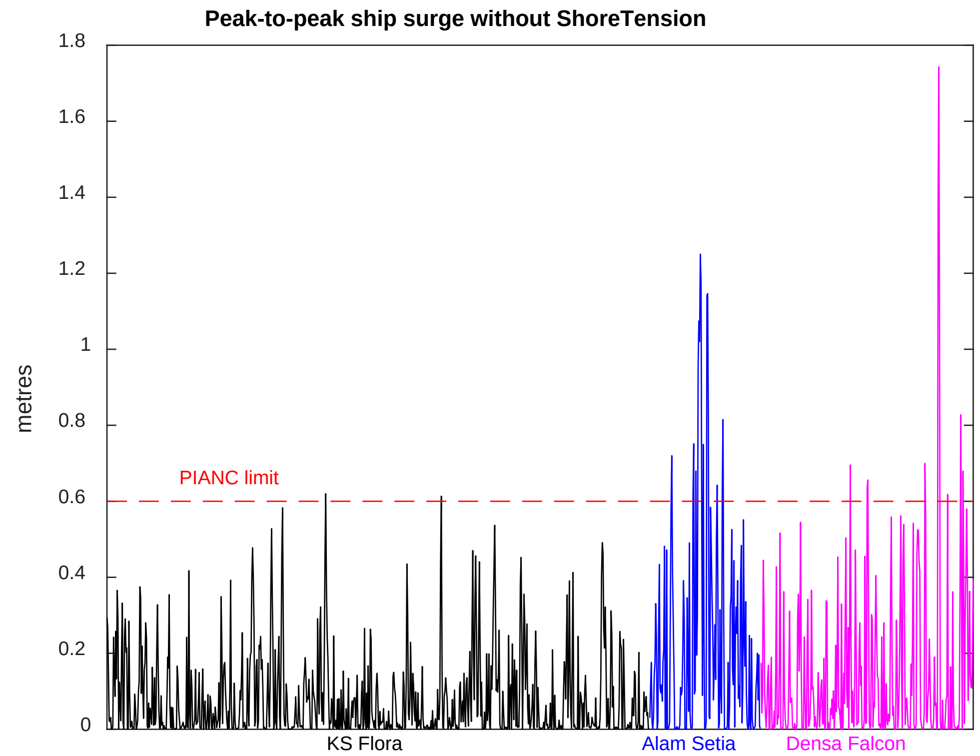

Peak-to-peak midship heave
metres
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
PIANC limit
KS Flora
Alam Setia
Densa Falcon

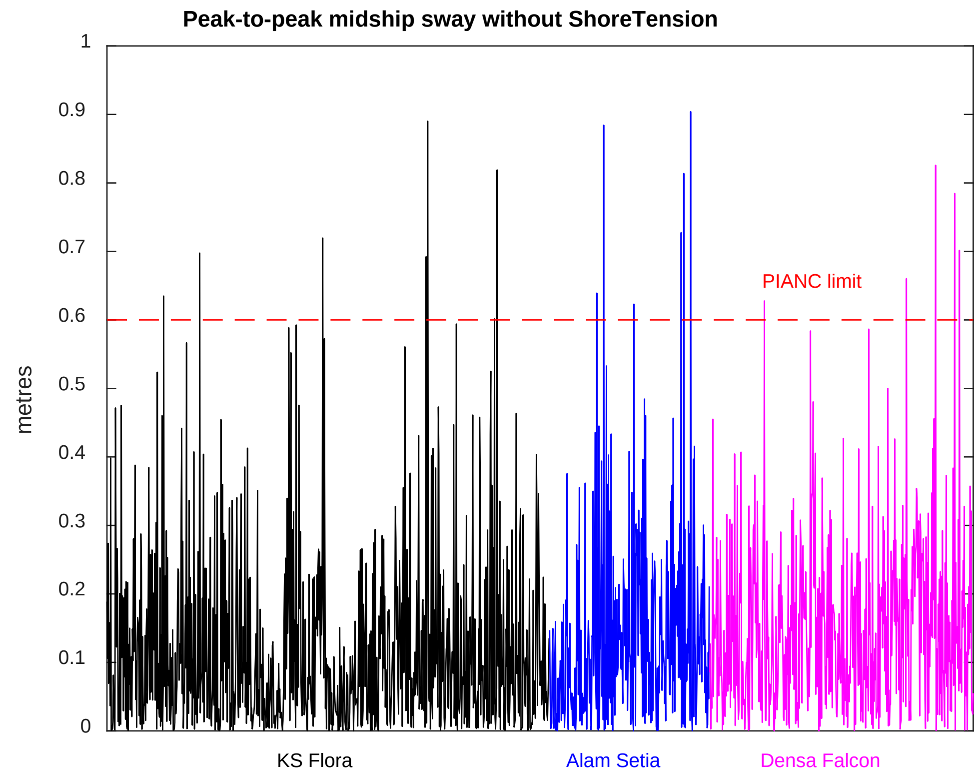

Peak-to-peak roll angle
degrees
2
1.5
1
0.5
0
PIANC limit
KS Flora
Alam Setia
Densa Falcon

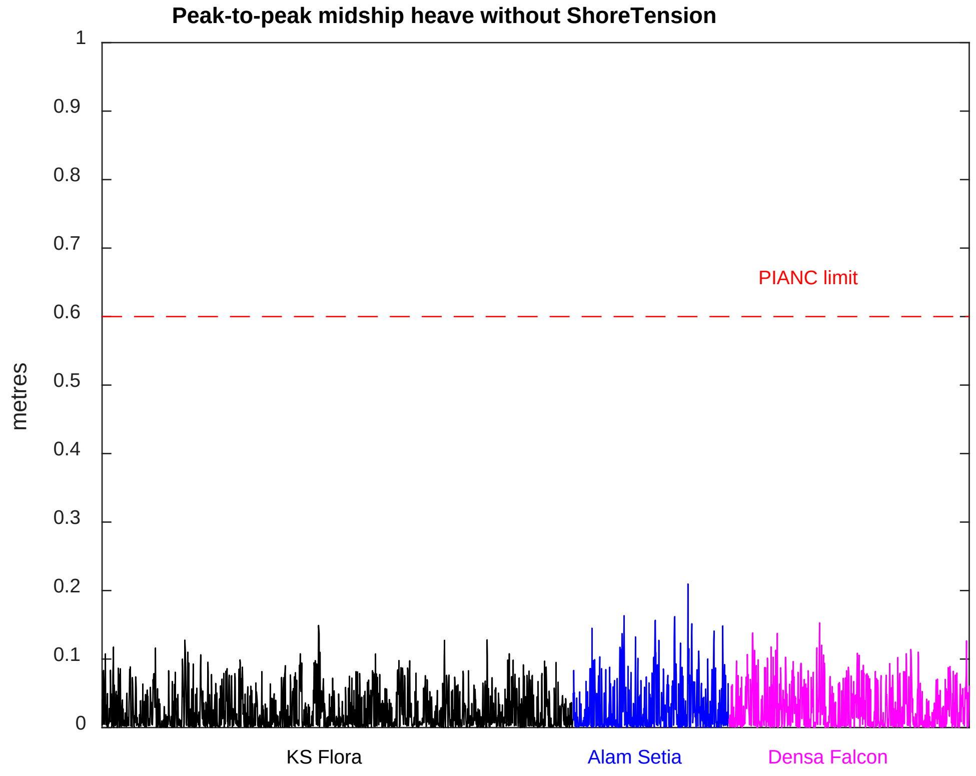

Peak-to-peak pitch angle
PIANC limit
degrees
1
0.8
0.6
0.4
0.2
0
KS Flora
Alam Setia
Densa Falcon

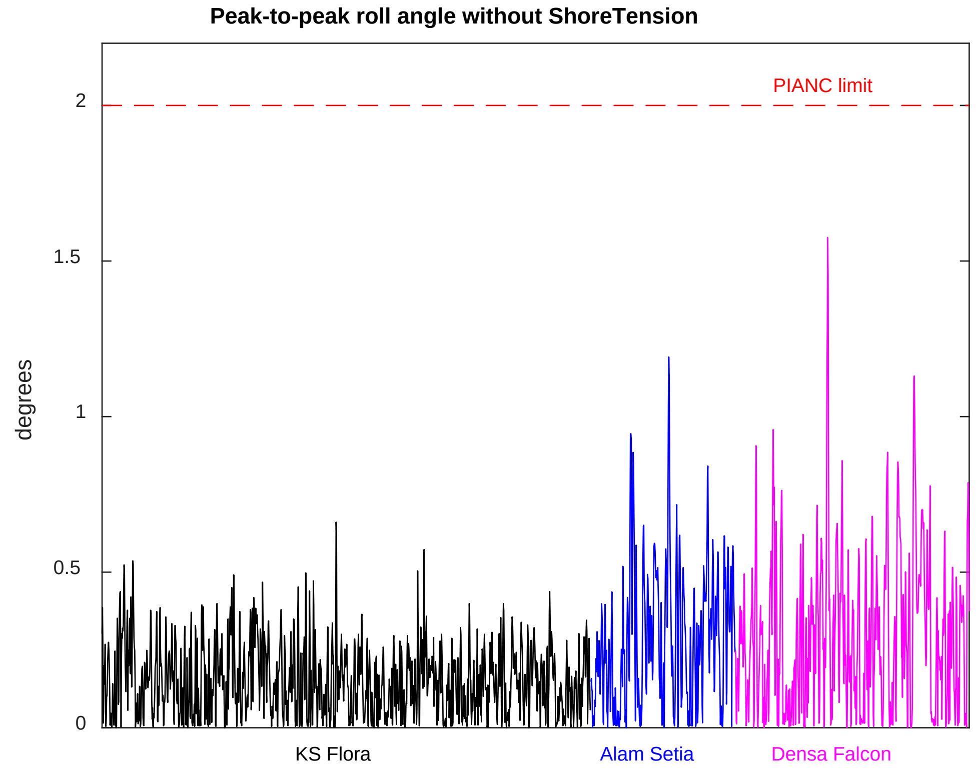

Peak-to-peak yaw angle
PIANC limit
degrees
1
0.8
0.6
0.4
0.2
0
KS Flora
Alam Setia
Densa Falcon

APPENDIX D – MEASURED BULK CARRIER MOTIONS WITHOUT SHORETENSION – BERTH 6






Peak-to-peak midship heave without ShoreTension
metres
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
PIANC limit
KS Flora
Alam Setia
Densa Falcon


Peak-to-peak roll angle without ShoreTension
degrees
2
1.5
1
0.5
0
PIANC limit
KS Flora
Alam Setia
Densa Falcon

APPENDIX E – ANNUAL DOWNTIME FOR EACH LONG WAVE LIMIT

This table shows the port's annual downtime for a given long wave limit, based on measured 25-120s significant long wave heights over the 6-year period 1 June 2010 – 1 August 2016. Raw data was supplied by Tremarfon Pty Ltd.

The "hourly annual downtime" is the percentage of hours in a year when the measured long waves are above the limit. The number of "annual days downtime" is the number of days per year when the long waves are above the limit for 2 hours or more in the day. This would normally mean that a cruise ship is unable to moor in the harbour that day.

As an example, a long wave height limit of 12 cm is exceeded 7.0% of the time, and there would be 29 days in an average year when a cruise ship would be unable to moor in the harbour using this limit.

Berth 3/4 long wave limit (cm)	Hourly annual downtime (percent)	Annual days downtime		Berth 3/4 long wave limit (cm)	Hourly annual downtime (percent)	Annual days downtime
1	98.2	363		21	0.96	2
2	86.1	329		22	0.76	2
3	66.6	263		23	0.62	2
4	48.8	199		24	0.46	2
5	36.2	152		25	0.32	2
6	27.0	120		26	0.22	1
7	20.5	92		27	0.14	1
8	16.1	76		28	0.09	0
9	13.0	64		29	0.06	0
10	10.6	48		30	0.04	0
11	8.6	37		31	0.03	0
12	7.0	29		32	0.02	0
13	5.7	21		33	0.01	0
14	4.7	16		34	0.006	0
15	3.8	13		35	0.006	0
16	3.2	11		36	0.006	0
17	2.6	8		37	0.004	0
18	2.0	5		38	0.004	0
19	1.6	4		39	0.002	0
20	1.3	3		40	0.000	0

APPENDIX F – CRUISE SHIP PROFILE VIEWS

From information supplied by MWPA.

(top) Astor; (middle) Pacific Eden; (bottom) Dawn Princess