HMS WARRIOR Mooring System

Author: Tom Smith

Checked: Cathy Ingram

Certified: Tim Lear/Will Giles

Approved: Cathy Ingram

Agenda

- **Inspection and Maintenance plan**
- **Dynamic Analysis**
  - Determination of conditions
  - Setup of analysis
  - Analysis at high tides
  - Analysis at low tides
  - Impact of a line breaking
  - Impact of passing vessels
- **Conclusions**

Inspection and Maintenance Plan

- **Inspection and maintenance plan issued separately – BMT ref DSL/38651/00682.**
- **The document describes the current arrangement and recommendations for an initial survey and on-going surveys.**
- **The survey regime has been developed to provide understanding of the condition of the current system and a programme to maintain the system in an acceptable condition.**
- **In summary the proposed regime covers:**
  - An initial Material State Survey to determine the condition of the current system. Two proposals have been made:
    1. A divers survey, where divers visually inspect the full system, including the chain and anchor beyond the 20 t sinkers;
    2. Remove and replace two lines including cables, anchors and sinkers, allowing for a thorough examination of those lengths which can be used as an indication of the condition of the remaining system.
  - Daily visual checks of inboard cables and securing arrangements as part of Ship's rounds to look for any obvious damage or deflection;
  - Monthly (or following heavy weather) examinations of inboard cables and securing arrangements including surrounding structure. This is to include checking for loose fittings and corrosion/plate thinning. Formal records of these examinations should be maintained;
  - Annual survey to include internal examination of the propeller well, the use of divers to inspect the submerged system and inspection of the system between the hawse pipes and the low water mark. Formal records of these surveys should be maintained and referenced to determine degradation of the system between surveys and to inform future maintenance and survey requirements. If required, a line-by-line rolling replacement plan should be derived.

Dynamic Analysis

Wave definition

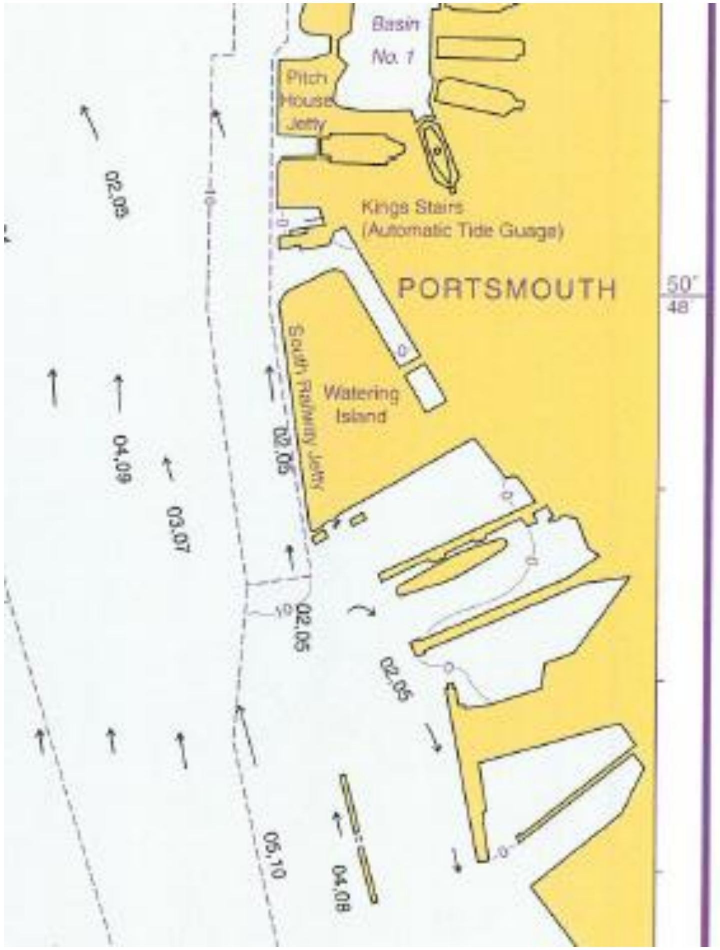
- Wave heights available at the two locations shown from Portsmouth City Council.
- Available for periods from 1 to 200 years.
- "Typical" waves are larger north of Warrior.
- Storm conditions give larger waves south of Warrior.
- The wave height at Warrior has been taken as the average of these two values.
- Wave periods are also based on the information available from Portsmouth City Council.

	Wave height (m)	Wave period (s)
Typical	0.39	3.08
50 year	0.54	3.65
75 year	0.56	3.71
100 year	0.57	3.75

Dynamic Analysis

Tidal Conditions

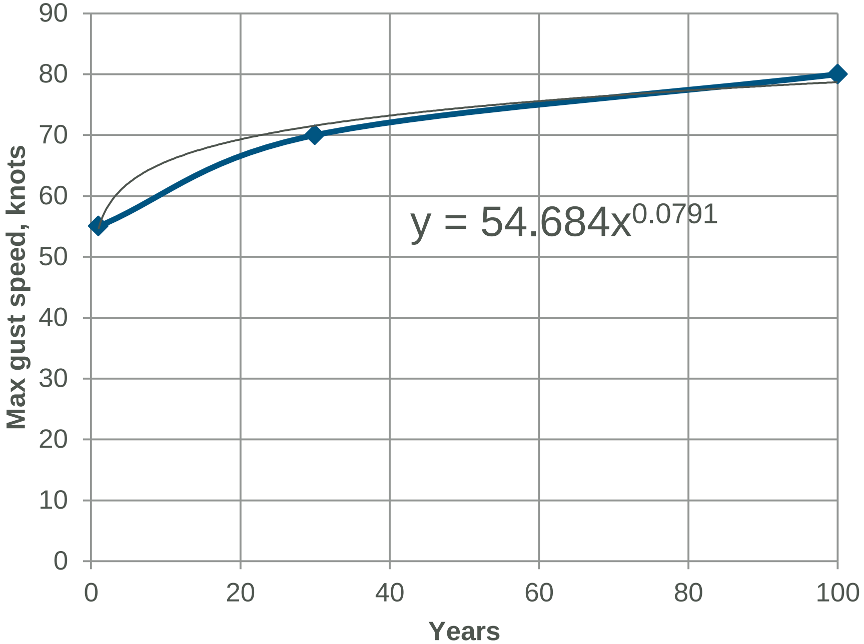
- The Admiralty Tidal Atlas shows current circulating onto the port beam of Warrior.
- The Atlas indicates a mean current of 0.5 knots (spring rate) in this area.
- The 1983 Mooring Report captured speeds of up to 0.6 knots.
- Therefore, a current of 0.6 knots on the port beam has been considered. While wind and waves have been considered from all directions, the current in this area is principally on the port beam so has only been considered from this direction. The Admiralty Tidal Atlas shows it is unlikely that any significant current will develop in other directions.
- A spring tidal range of 4m has been used to capture a realistic yet large variation in water depth.
- Based on the GA of the dredged berth provided, it is understood that the berth was dredged to 8m depth. This has been assumed as the low water depth.



Dynamic Analysis

Wind Speeds

- The average wind speed in Portsmouth is approximately 10.5 knots.
- The highest wind gust recorded in the area is 76 knots (ref previous mooring report).
- Based on this, the maximum wind speed considered is 80 knots.
- 30 years data has been considered from historical data from Southampton and Portsmouth. This covers 10 years (from previous mooring report) for Lee-On-Solent and 20 years (available online) for Southampton.
- Over 30 years the maximum gust recorded was 70 knots.
- Average maximum gust for any given year is 55 knots.
- Based on this, a power law was used to determine wind speeds for 50 and 75 year storm conditions.



No of years	Wind speed (knots)
Typical	10.5
50	75
75	77
100	80

Dynamic Analysis

Windage

- The windage profile areas were based on the original mooring report.
- Drag coefficients were derived from analysis undertaken for the design of dynamic positioning systems.
- The previous report used a single drag coefficient (1.3) applied to the entire area and gave a resultant force of 1559 kN with an 80 knot wind.
- The table below gives the forces for each component of the wind profile.

		Beam Winds		Head/following winds	
Component	**Drag Coefficient**	**Longitudinal area (m2)**	**Force (kN)**	**Lateral area (m2)**	**Force (kN)**
Hull side	1	848	883	124	129
Funnels	0.5	18	9	18	9
Masts	1.5	92	144	92	144
Spars	1.5	115	179	115	179
Bowsprit	1.5	26	41	26	41
Crosstrees	1.5	8	13	8	13
Rigging	1.5	92	144	92	144
		Total beam wind force (kN)	**1413**	**Total head wind force (kN)**	**659**

- Analysis in an 80 knot wind therefore uses 1413 kN (beam wind) and 659 kN (head and following wind)

Dynamic Analysis

Load transmitted beyond 20t sinkers

- Load will be transmitted beyond the 20t sinkers if the sinkers move on the seabed (or if the sinkers lift off the seabed – see later slides).
- The loads required to move the 20t sinkers will depend on the seabed conditions, including the nature of the seabed and the sinkers are buried.
- The key is to estimate the coefficient of friction between the seabed and the sinker. The coefficient of friction dictates the force required to pull/push an object on a surface

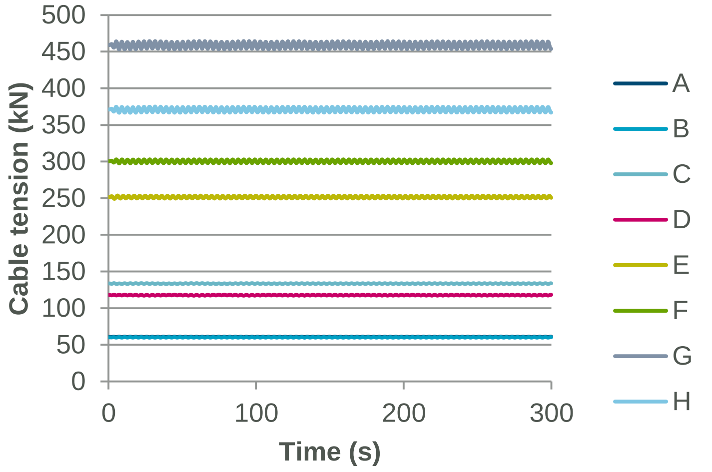
$$Force = Frictional\ coefficient \times mass \times gravity$$

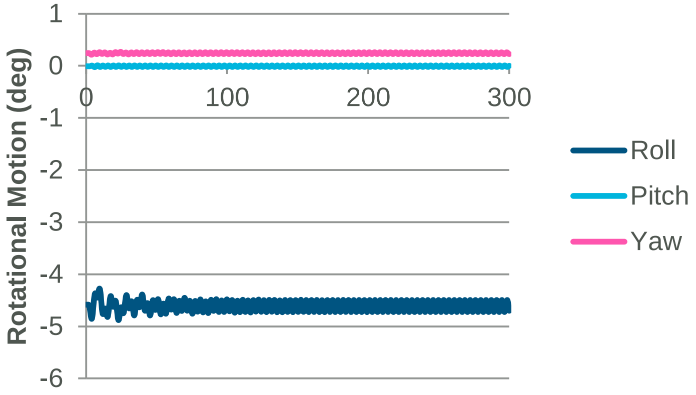
  Where mass/gravity are adjusted to take into account buoyancy and vertical load from the lines.
- A typical coefficient of friction between soil and concrete is 0.5. Given some sinkers are likely to be partially buried in mud, the coefficient of friction may be higher. This is taken into account in the analysis discussed later in this presentation.
- While it is possible to give estimates of the loads transmitted beyond the 20t sinkers using this methodology, the load transmitted will vary considerably based on the condition of the sinkers in the mud. It is not possible to estimate this with any accuracy.

Results

Presentation

- **Analysis has been run with:**
  - Constant wind and current;
  - Regular waves;
  - For a 5 minute time period.
- **In general, wave forces are small compared to wind and current. This results in lines being almost straight with small fluctuations resulting from the passing waves.**
- **Information in this presentation is primarily limited to Root Mean Square (RMS) data to capture mean tensions/motions rather than peaks. RMS allows averages to be calculated from a series of numbers including positive and negative values and allows more meaningful comparison.**
- **Cable tensions are presented in kN. In addition to RMS values, peak tensions are extracted where relevant.**
- **Motions are presented in metres and degrees and show the disturbance from equilibrium. For example, in the lower graph it is not so much the fluctuation of the roll motion that is key, but that the wind and current forces push the ship to almost 5 degrees.**

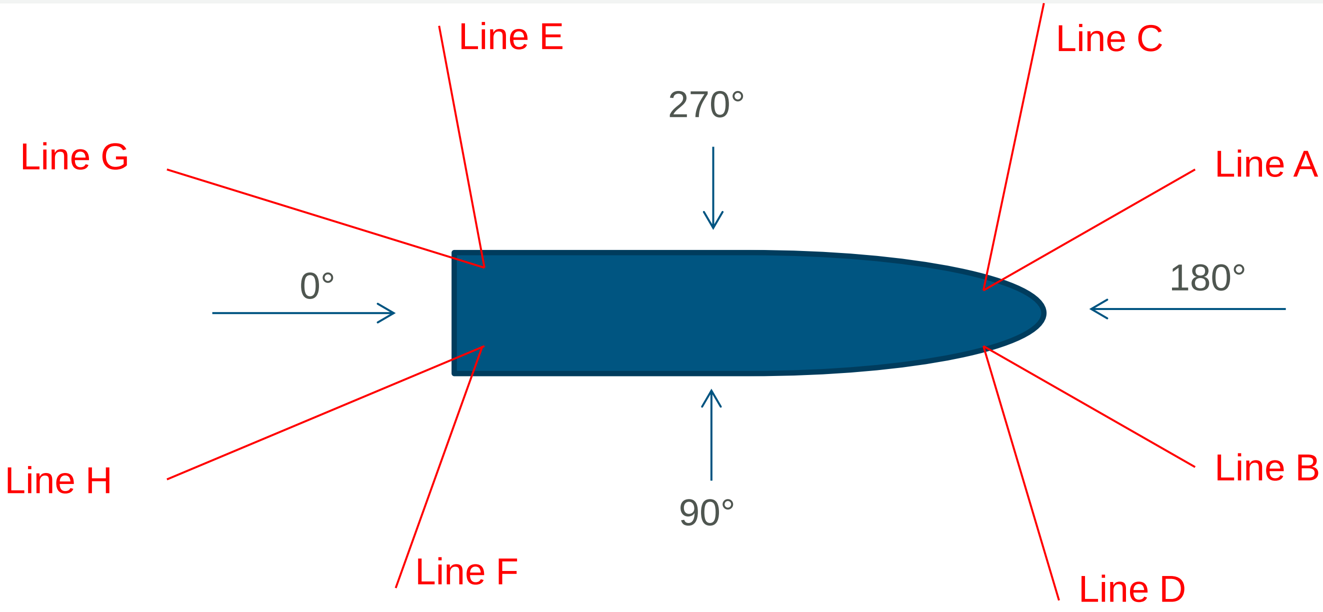




Results

High Water

- At high water, there is tension purposefully built into the mooring system.
- This means that motions are reduced but the forces in the system are at their maximum.
- From discussions and the original mooring report, it is understood that the system was tensioned to have 20t in each line at high water. This has been set up in our model.
- It is assumed that the anchors are fixed and that the strength characteristics (not dimensions) of the original chain are similar to those of the replacement chain



Results

High Water – Tension in breast mooring lines (C, D, E and F), 100 year storm

Radial axis shows cable tension in kN

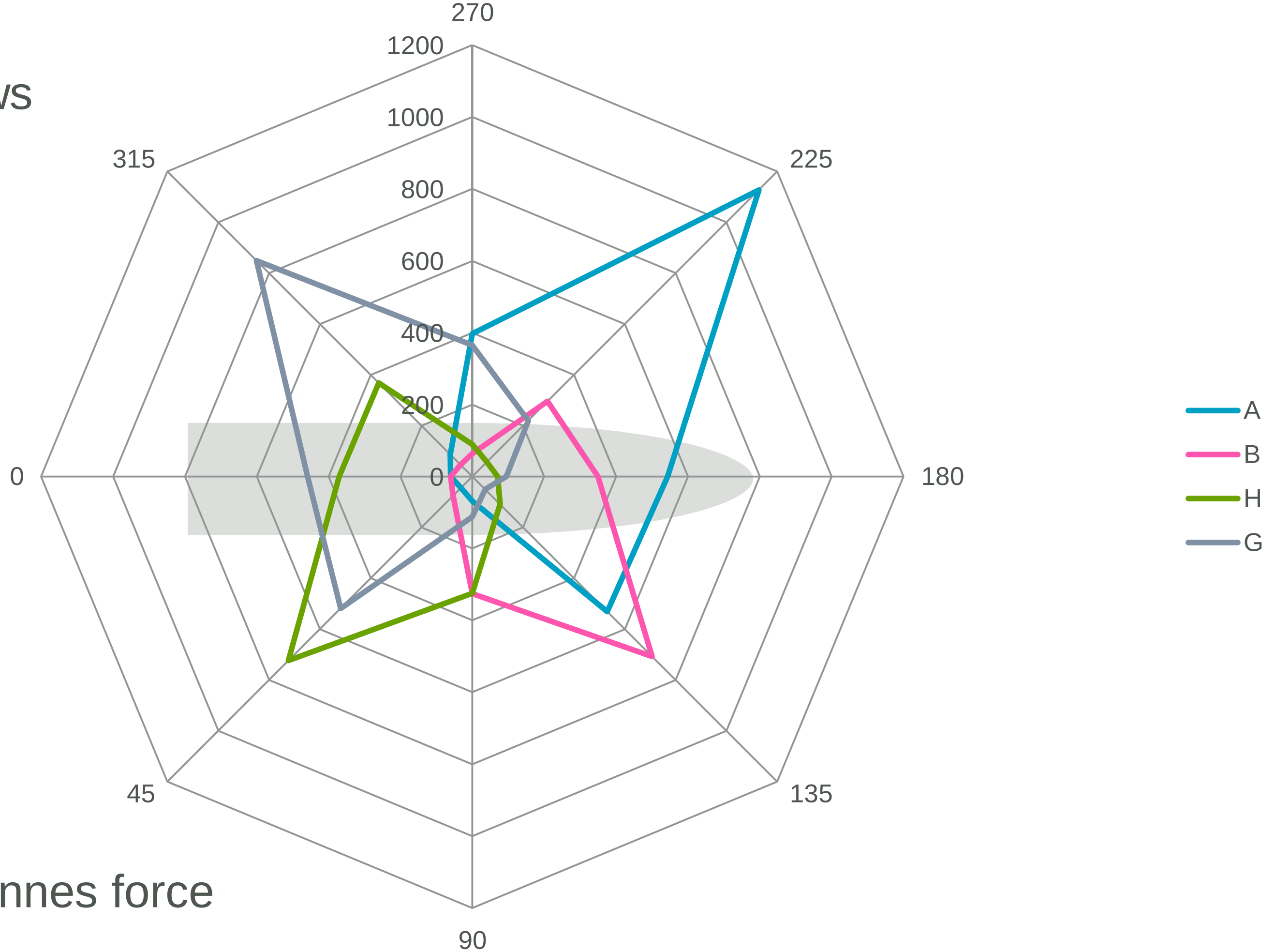
100 kN = 10.2 tonnes force

BMT

Results

High Water – Tension in bow and stern mooring lines (A, B, G and H), 100 year storm

Radial axis shows cable tension in kN

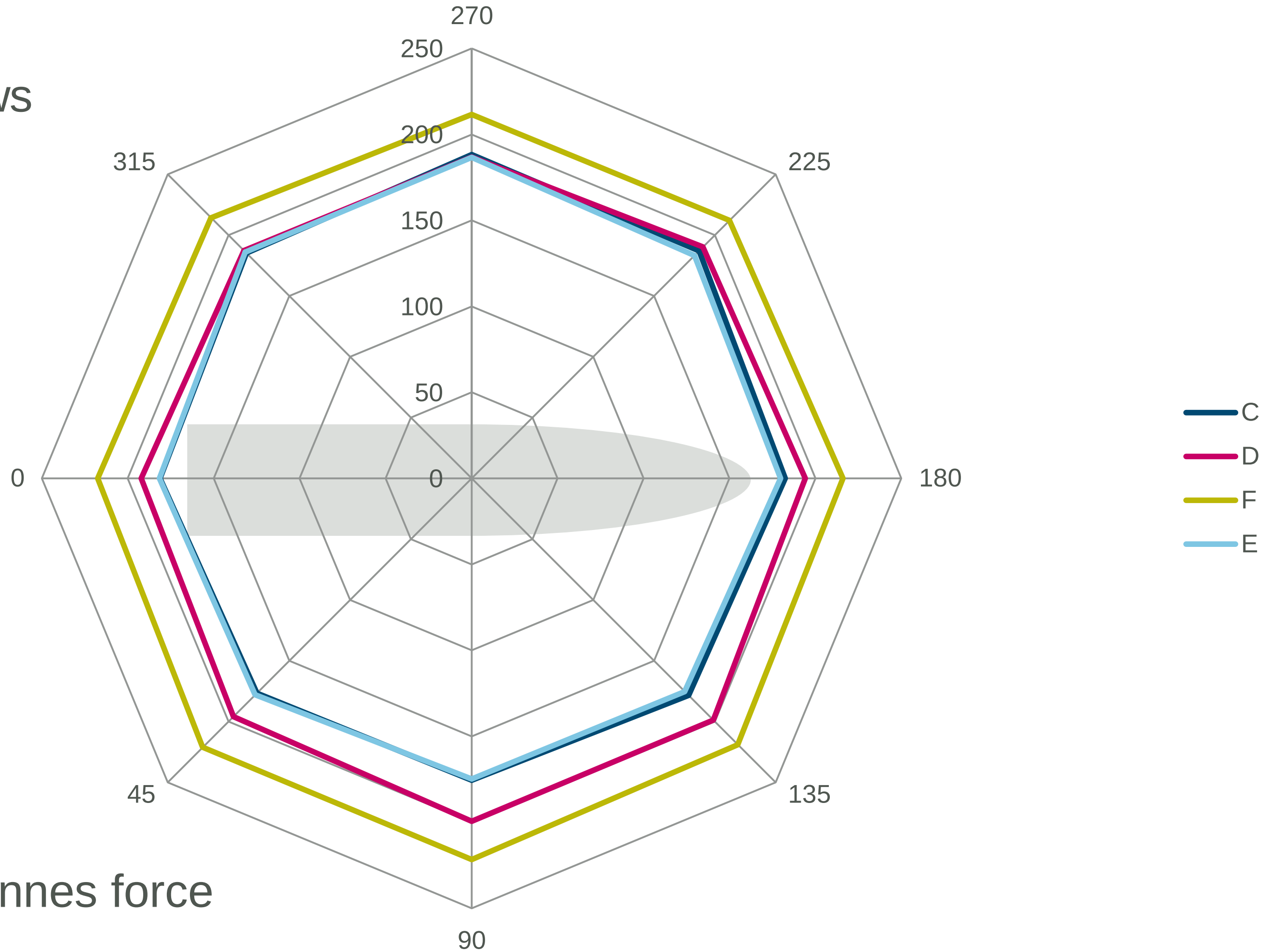


100 kN = 10.2 tonnes force

Results

High Water – Tension in breast mooring lines (C, D, E and F), typical conditions

Radial axis shows cable tension in kN

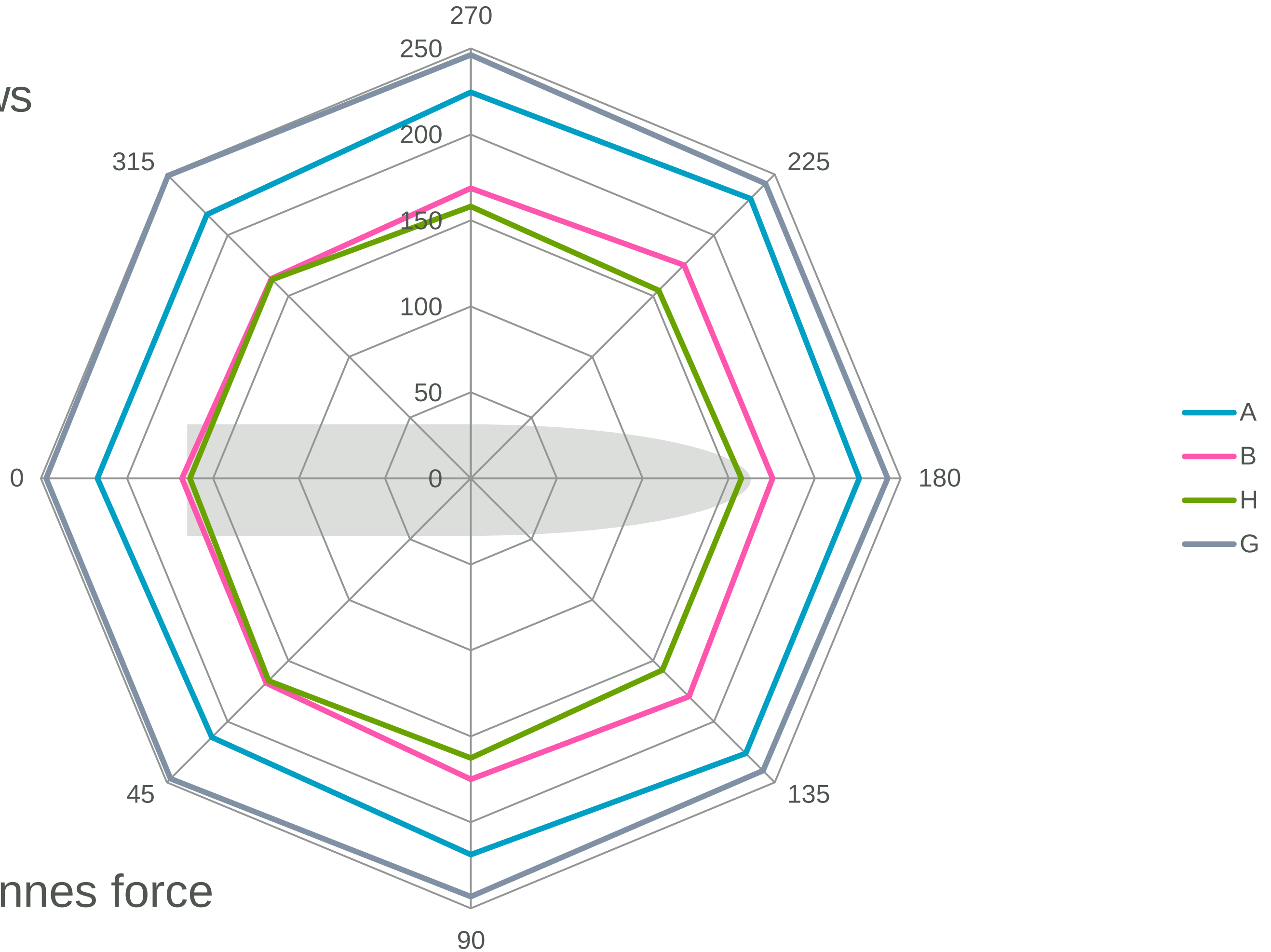


100 kN = 10.2 tonnes force

Results

High Water – Tension in bow and stern mooring lines (A, B, G and H), typical conditions

Radial axis shows cable tension in kN

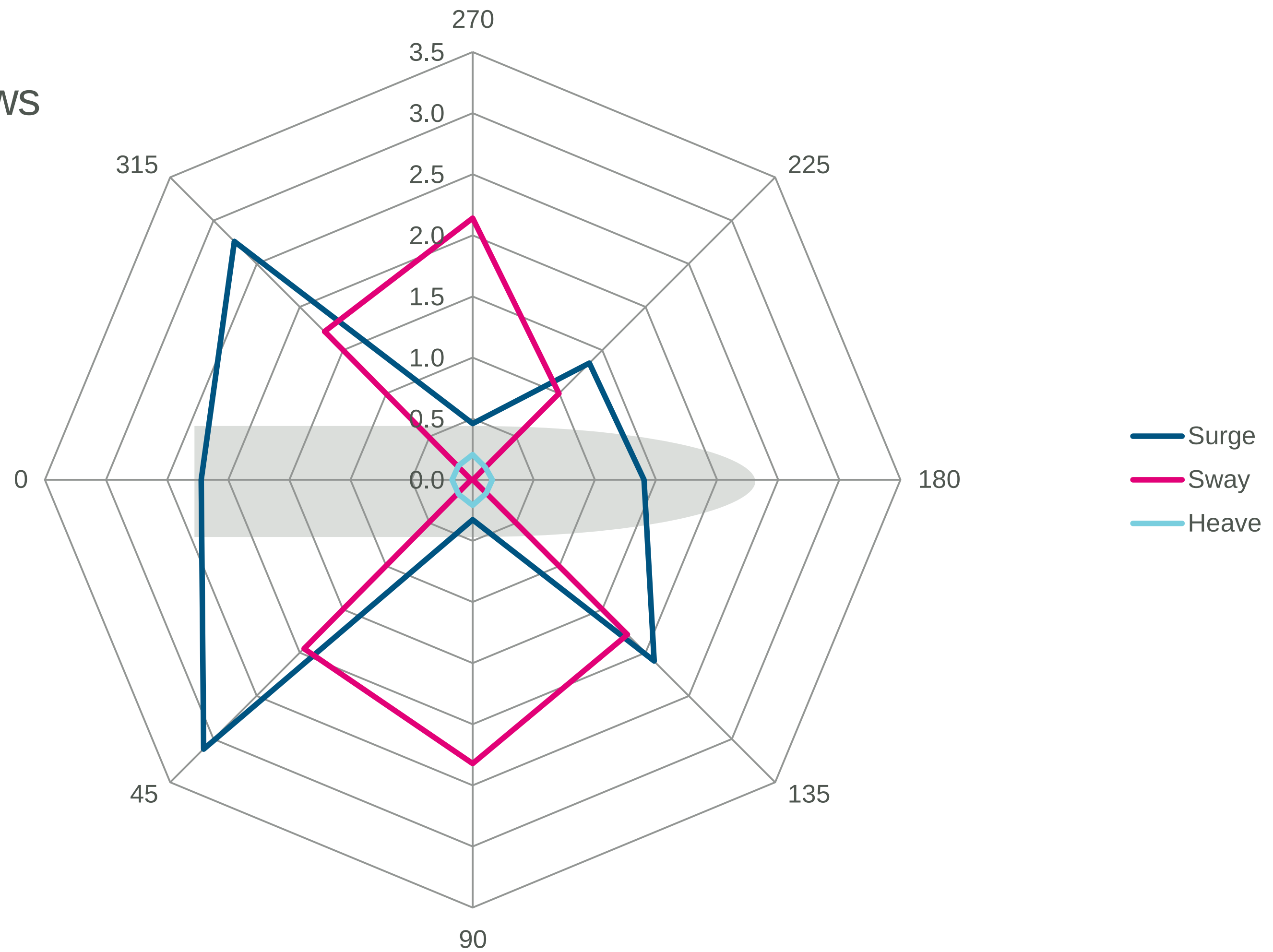


100 kN = 10.2 tonnes force

Results

High Water – Translational motions, 100 year storm

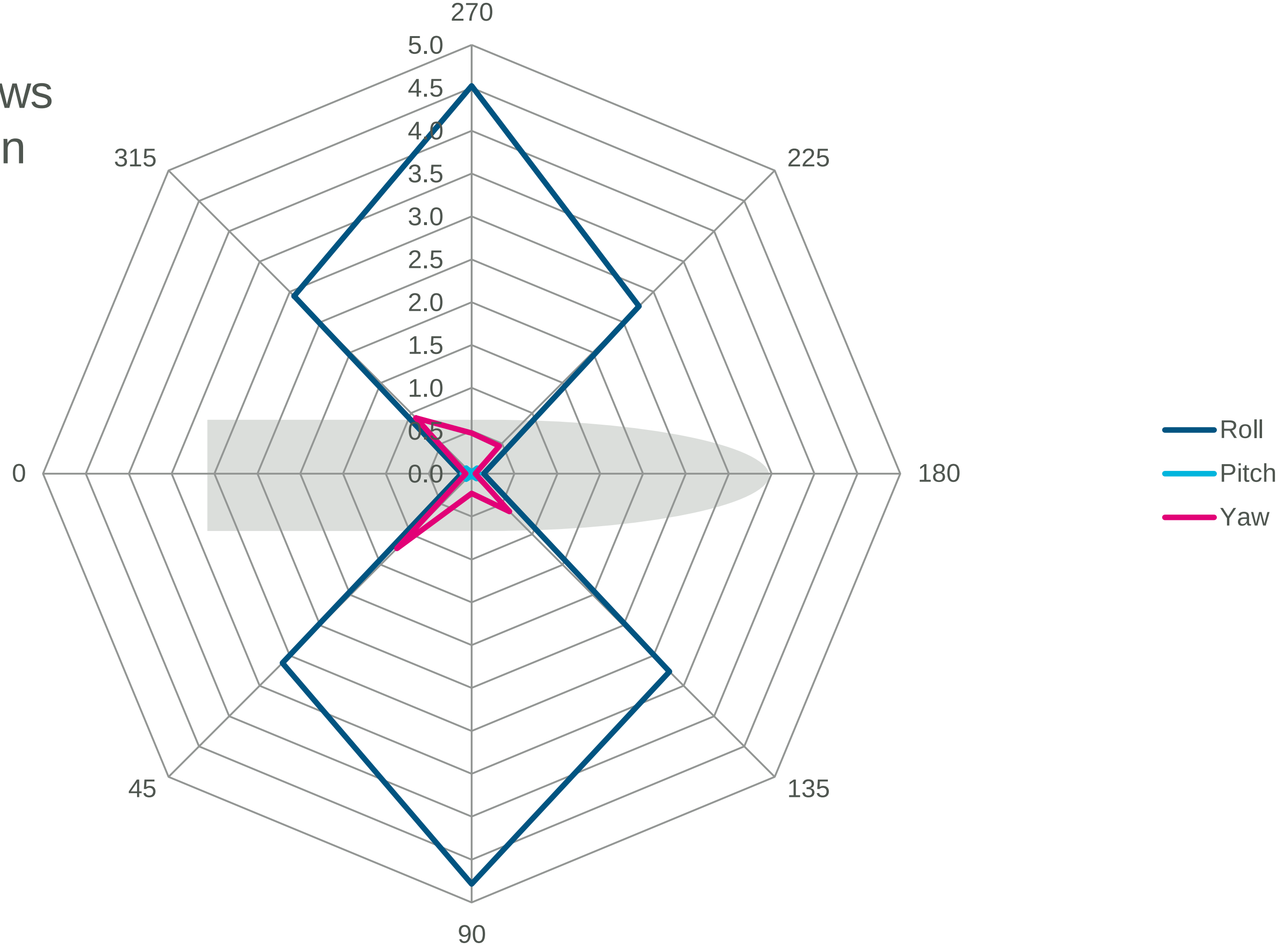
Radial axis shows motion in m



Results

High Water – Rotational motions, 100 year storm

Radial axis shows rotational motion in degrees



Results

High Water - Summary

- The maximum load is seen in line A with 100 year storm conditions coming inline with line A (225 degree heading). In this condition the RMS load is 1127kN and the peak load is 1169kN. Note that it is unlikely that severe weather conditions would come from this heading as this is not the prevailing weather condition HMS WARRIOR is partially sheltered in that direction.
- In a typical environmental condition, it is the pre-tensioning of the lines to 20 tonnes (196kN) which is dominant. Most of the variation in loading of the lines in this condition is due to variation in the pre-tension within the model due to the impact on tension on other lines when a line is tensioned. The maximum tension in any line in this condition is approximately 250kN, 30% of that in the storm condition.
- The 50 year storm condition results in maximum motions very similar to those of the 100 year storm condition. The maximum tension in the mooring line in the 50 year storm condition is 86% of that in the 100 year storm condition.
- The proof-load of the recently replaced chain is 2187kN so there is a margin of 1.9 times between the maximum anticipated load (100 year storm) and the proof-load. However, the safe working load of the fittings on HMS WARRIOR is not known and based on the current condition of some of the fittings will be considerably less than the proof-load of the chain.
- Depending on the wind and wave direction, in a 100 year storm surge motions of up to 3.1m may be experienced, along with sway (transverse translation) of 2.3m and roll of up to 4.8 degrees
- The vertical force on the 20t sinkers is considerable at high water and it is expected that these sinkers will be lifted off the sea bed in moderate winds.
- Loads transmitted beyond the sinkers are discussed on a later slide.

Results

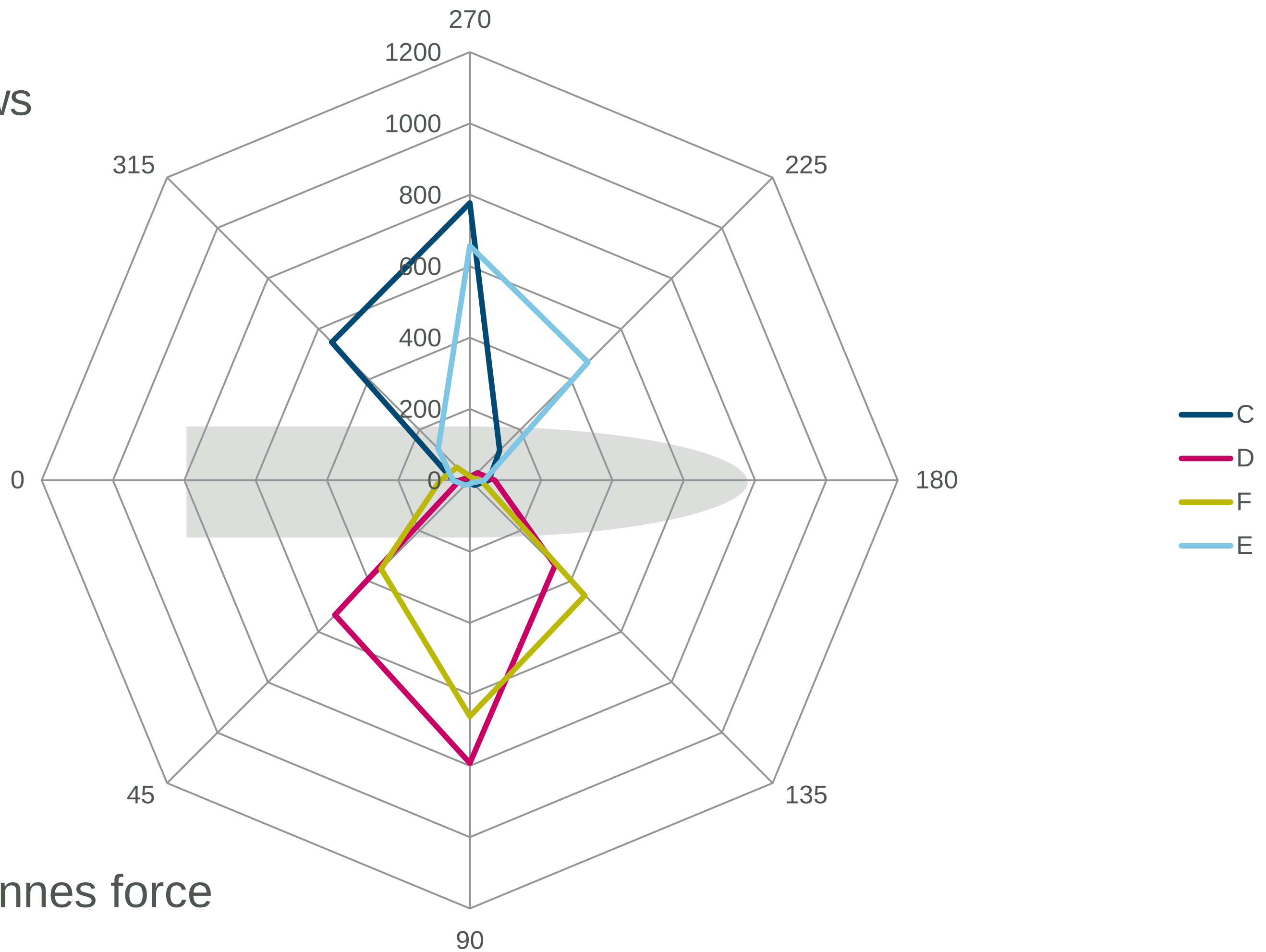
Low Water

- **At low water, the tension in the mooring line decreases significantly in “typical” conditions but peaks above that at high water in individual lines in storm conditions.**
- **With no environmental loads the tension in the lines decreases by a factor of 4.**
  - At high tide, the system was tensioned to 20t per line with no environmental load.
  - At low tide, this becomes an average of about 5t per line with no environmental load.
- **The motions of the ship increase in the low water condition as there is more slack in the system.**

Results

Low Water – Tension in breast mooring lines (C, D, E and F), 100 year storm

Radial axis shows cable tension in kN

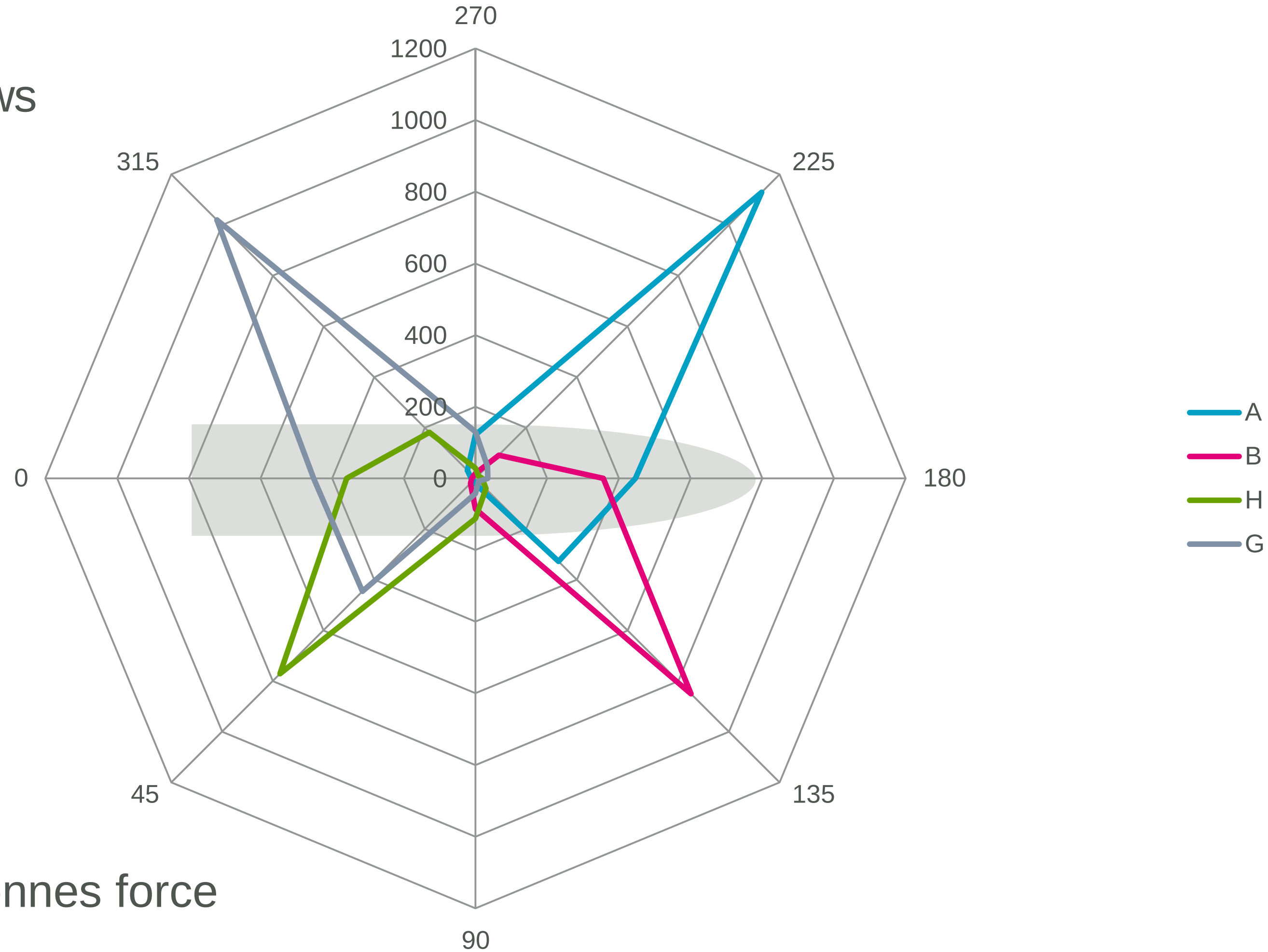


100 kN = 10.2 tonnes force

Results

Low Water – Tension in bow and stern mooring lines (A, B, G and H), 100 year storm

Radial axis shows cable tension in kN

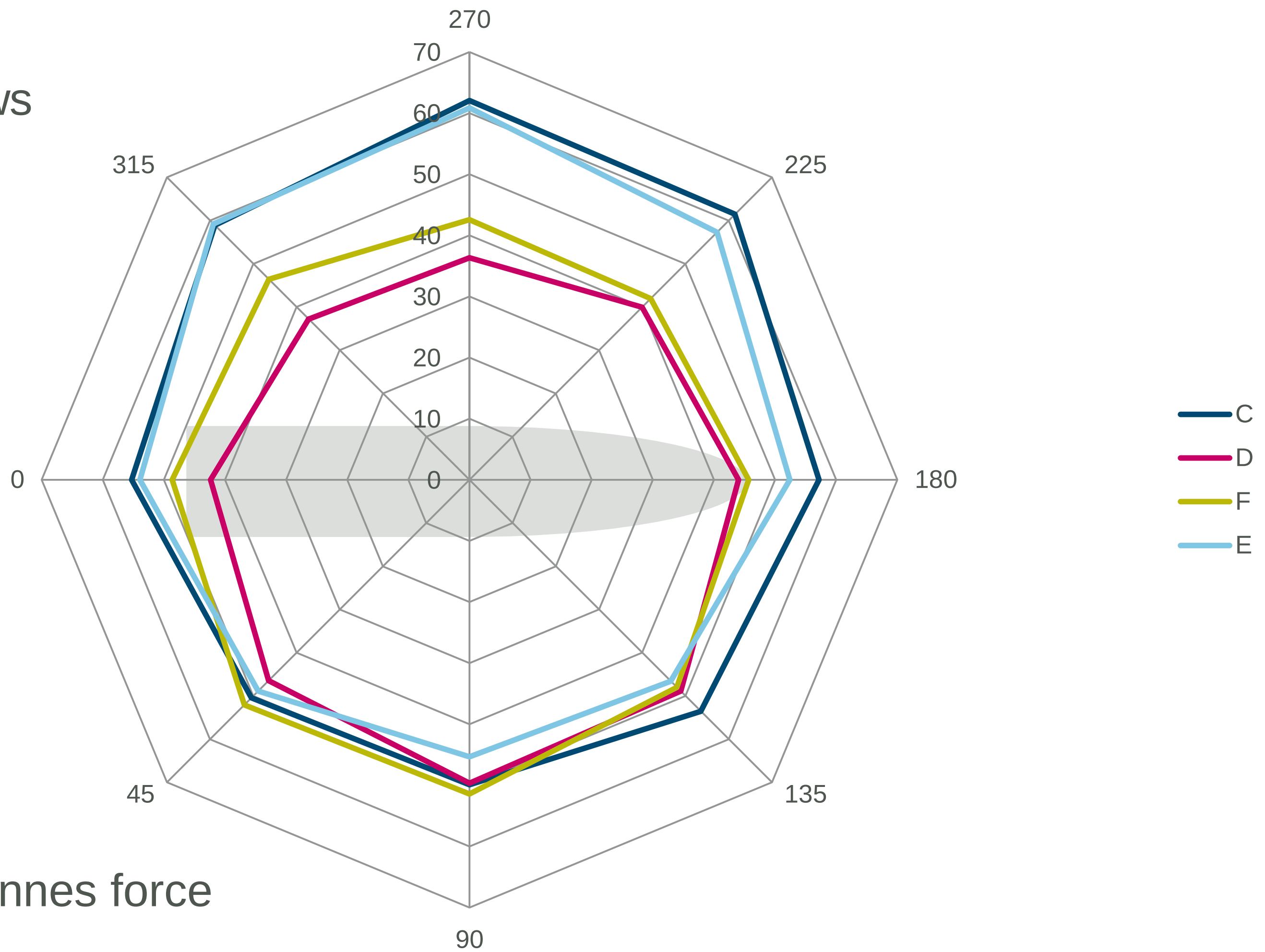


100 kN = 10.2 tonnes force

Results

Low Water – Tension in breast mooring lines (C, D, E and F), typical conditions

Radial axis shows cable tension in kN

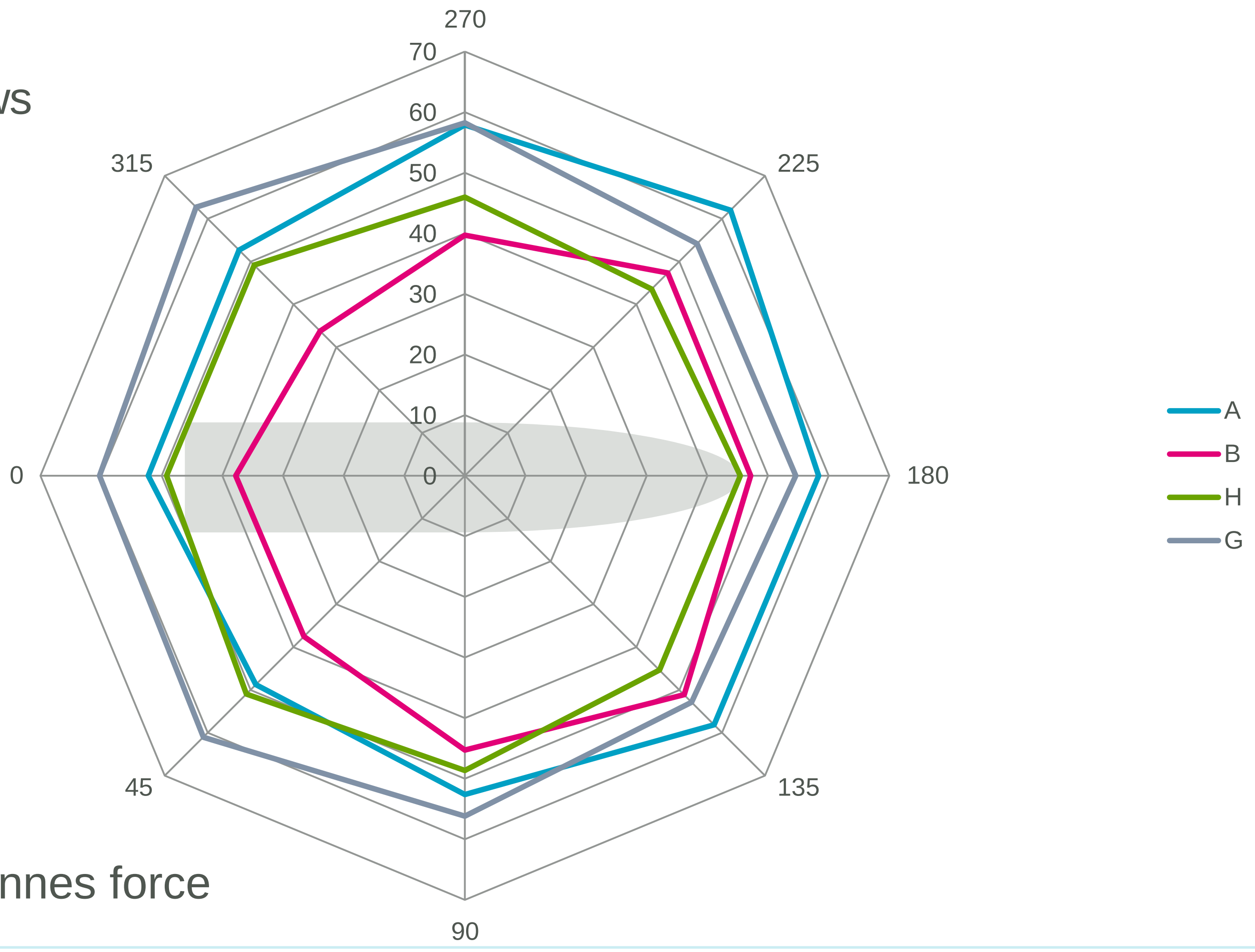


100 kN = 10.2 tonnes force

Results

Low Water – Tension in bow and stern mooring lines (A, B, G and H), typical conditions

Radial axis shows cable tension in kN

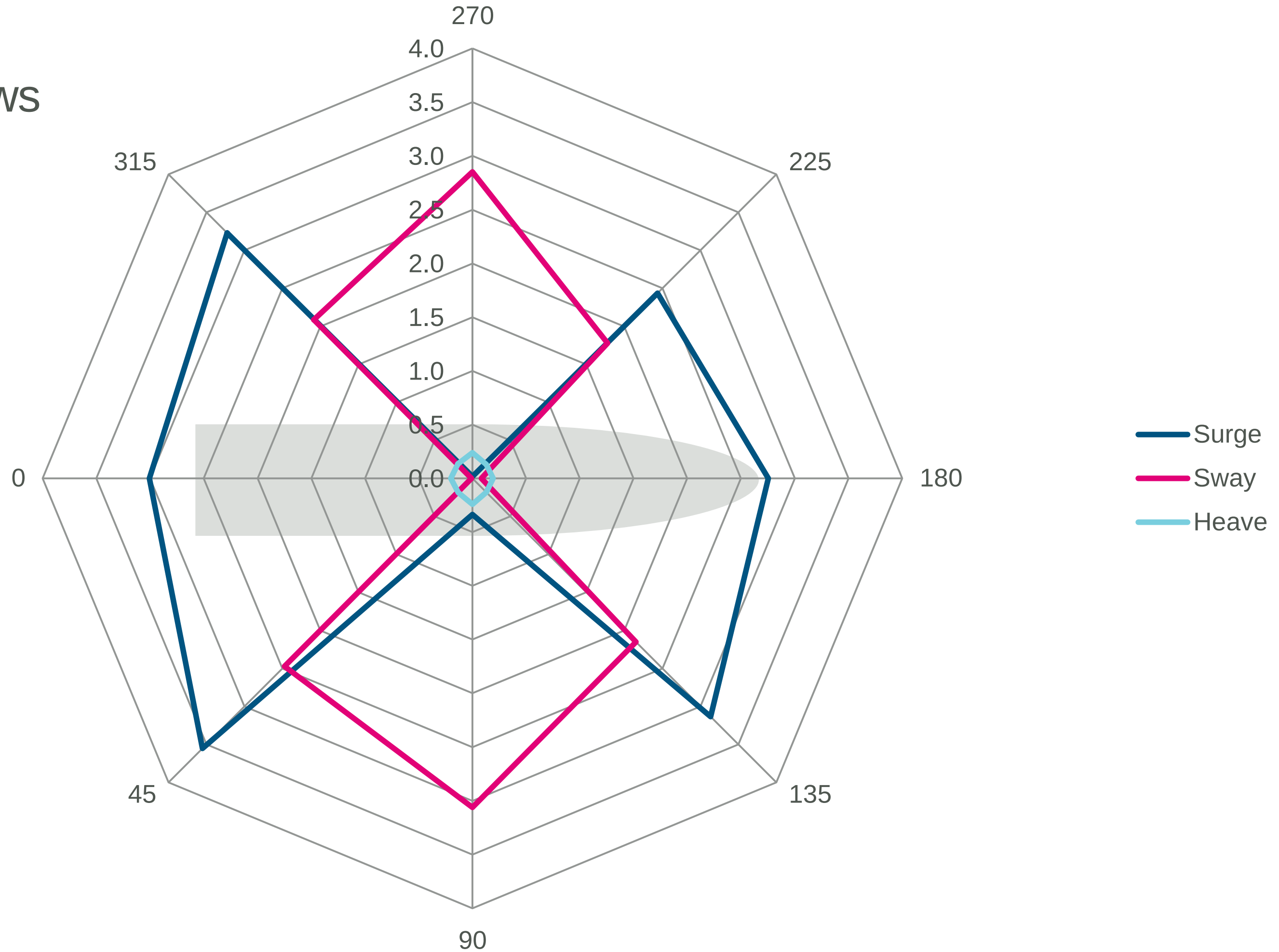


100 kN = 10.2 tonnes force

Results

Low Water – Translational motions, 100 year storm

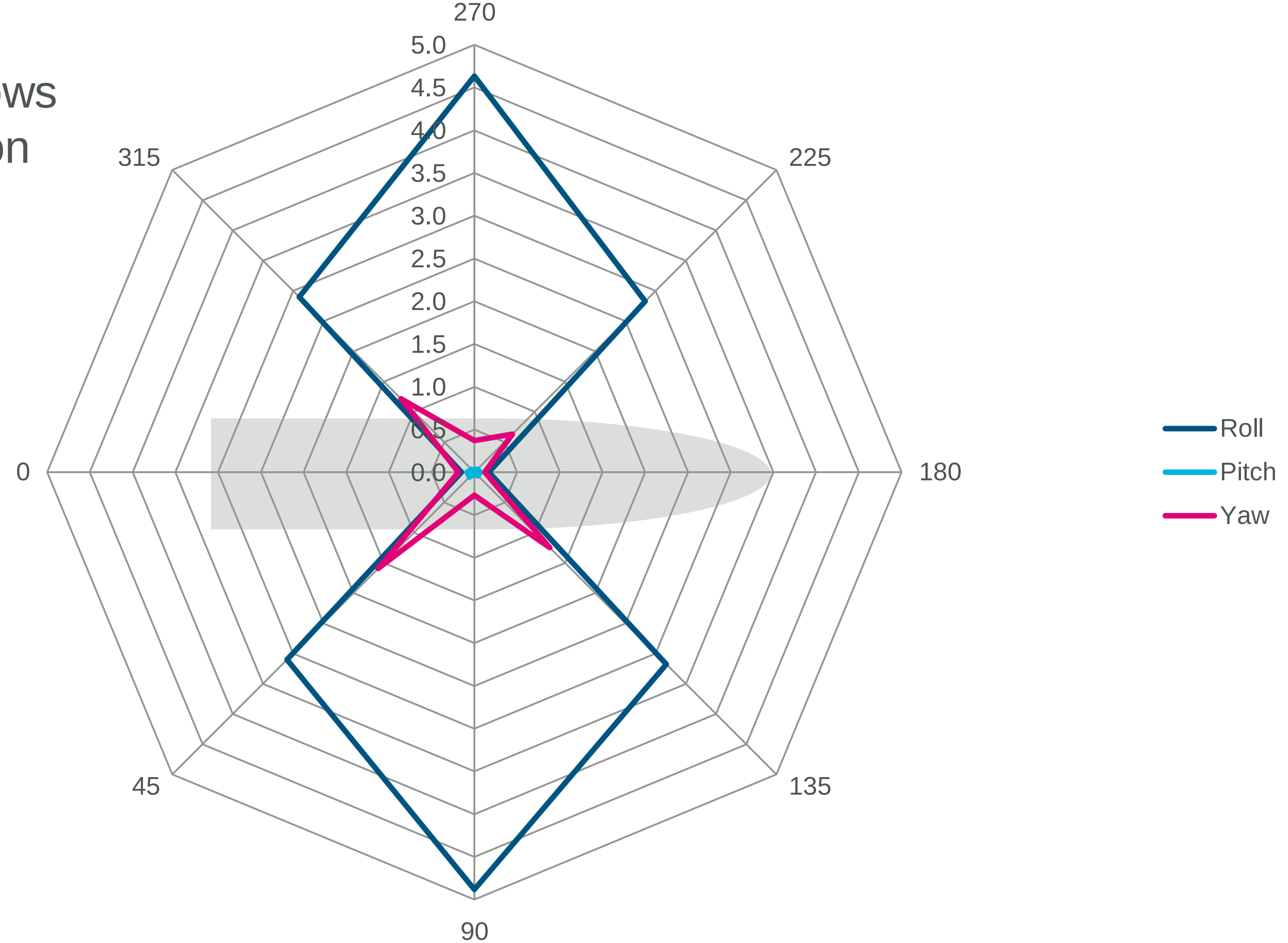
Radial axis shows motion in m



Results

Low Water – Rotational motions, 100 year storm

Radial axis shows rotational motion in degrees



Results

Low Water - Summary

- As for the high water condition, the maximum load is seen in line G with 100 year storm conditions coming inline with line G (315 degree heading). In this condition the RMS load is 1020kN and the peak load is 1048kN.
- In the “typical” condition, the tension in the mooring lines is slight as the change in tide height reduces the tension in the lines. The RMS loads in the lines vary between 34 – 73kN.
- The 50 year storm condition results in maximum motions very similar to those of the 100 year storm condition. The maximum tension in the mooring line in the 50 year storm condition is 97% of that in the 100 year storm condition.
- The proof-load of the recently replaced chain is 2187kN so there is a margin of 2 times between the maximum anticipated load (100 year storm) and the proof-load. However, the safe working load of the fittings on HMS WARRIOR is not known and based on the current condition of some of the fittings will be considerably less than the proof-load of the chain.
- Depending on the wind and wave direction, in a 100 year storm surge motions of up to 3.6m may be experienced, along with sway (transverse translation) of 2.9m and roll of up to 4.9 degrees.

Results

Summary – Intact system in varying environmental conditions

		Max Tension (RMS)	Max Surge	Max Sway	Max Roll
High Water	100 year Storm	1130 kN	3.1m	2.3m	4.8°
	50 year	976 kN	2.9m	2.2m	4.2°
	Typical	249 kN	0.04m	0.09m	0.3°
Low Water	100 year Storm	1020 kN	3.6m	3.1m	4.9°
	50 year	986 kN	3.4m	3.0m	4.3°
	Typical	63kN	0.4m	0.6m	0.3°

Results

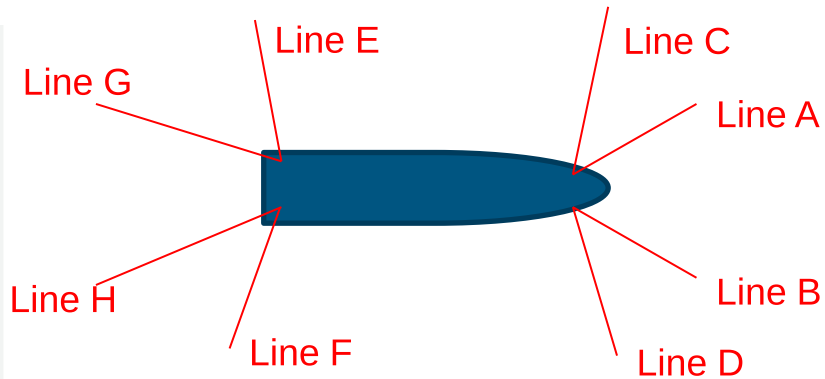
Loads beyond 20t sinkers

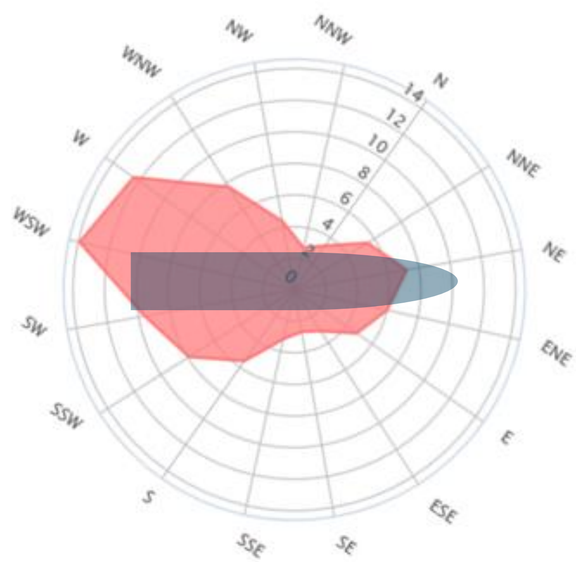
- Analysis has been conducted to determine if loads are transmitted beyond the 20t sinkers. At high and low tides, the forces on the vessel from each of the 8 mooring lines has been determined in benign conditions.
- At low tide, all of the 20t sinkers are resting on the seabed, with very little tension lifting them up. Therefore, the sinkers are resisting only the horizontal component of the tension. The sinkers are concrete and are resting on sand/silt and so there is a high probability that the friction between the sinker and the seabed will prevent load being transmitted down to the anchor.
- Using the method described earlier, a friction coefficient of at least 0.34 is adequate to prevent load from being transmitted. It is anticipated that a coefficient of at least 0.5 will be observed and so load will not be transmitted beyond the sinker.
- However, at high tide, the tension in the mooring lines is much higher. Whilst the 20t sinkers are still likely to be resting on the seabed, most of their weight is taken up by the tension in the cable. Therefore, the horizontal component of the tension will be transmitted beyond the sinker. Based on a 20t cable tension, the average horizontal force on each mooring line in benign conditions will be 16t. It is expected that most of this load will be transmitted beyond the sinkers.
- Therefore, in all weather conditions at high tide, significant loads are transmitted beyond the 20t sinkers.

Results

Failed mooring line

- **Line G selected as the line to assume failed because:**
  - The conditions in which line G is most critical, align with the prevailing environmental conditions;
  - It is a highly loaded line, particularly in the prevailing weather (315° heading drives);
  - It has reasonably high tensions on other surrounding headings.
- **The polar plot shows the % time a given prevailing wind direction is experienced e.g. WSW winds are experienced approximately 14% of the time. This shows that the prevailing weather condition aligns broadly with line G.**
- **The impact of the failure of this line has been considered in the 100 year storm condition and for wind and waves from the stern (0°) to the port beam (270°).**
- **The following slides show how a broken line G, affects the tensions and motions at high and low tide.**





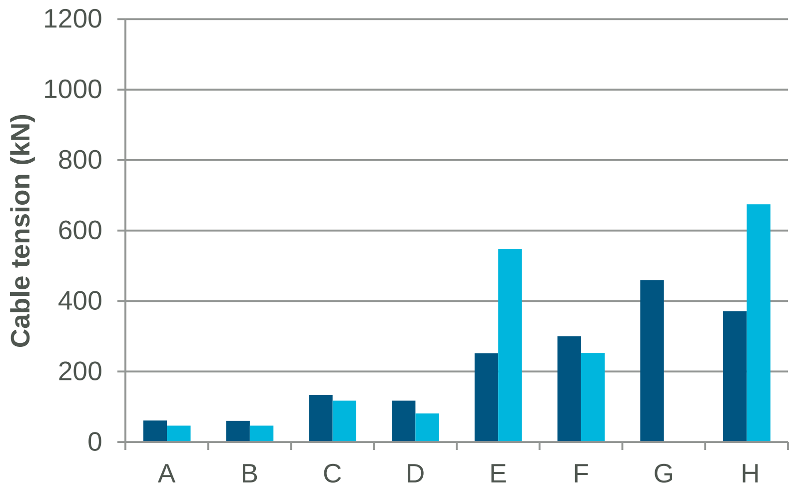
Results

Failed mooring line – High water tension in lines

Loads in lines with intact system

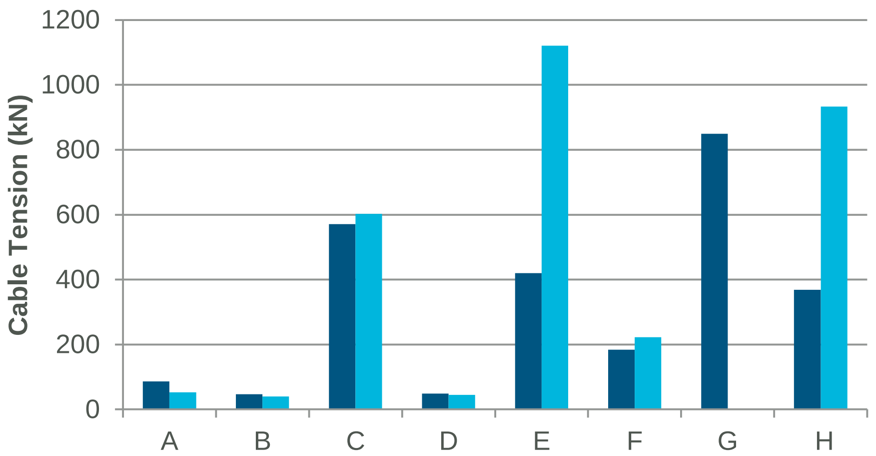
Loads in lines with line G broken

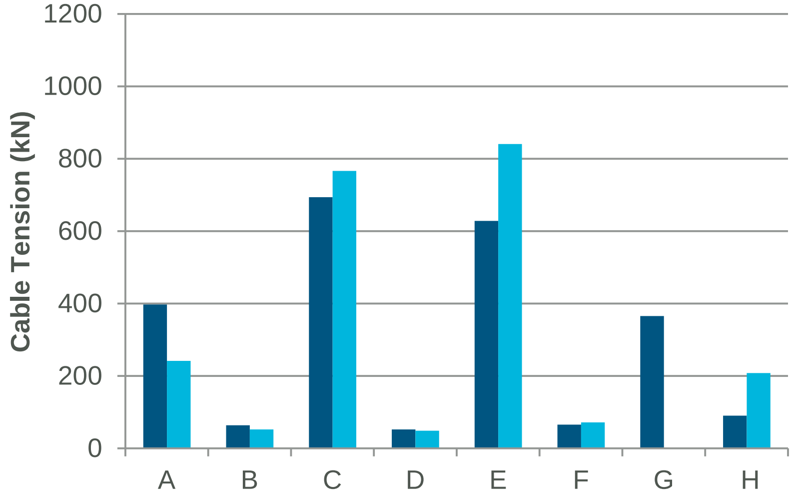
100 kN = 10.2 tonnes force



0° wind/waves – on the stern

315° wind/waves – stern quartering





270° wind/waves – on the port beam

Results

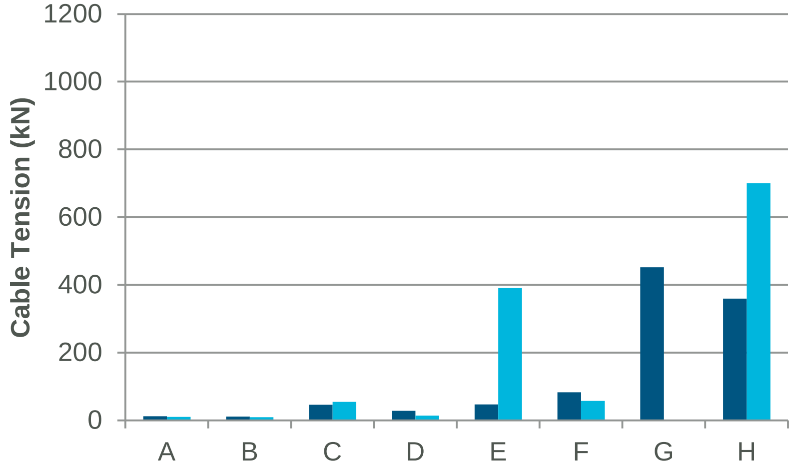
Failed mooring line – Low water tension in lines

Loads in lines with intact system

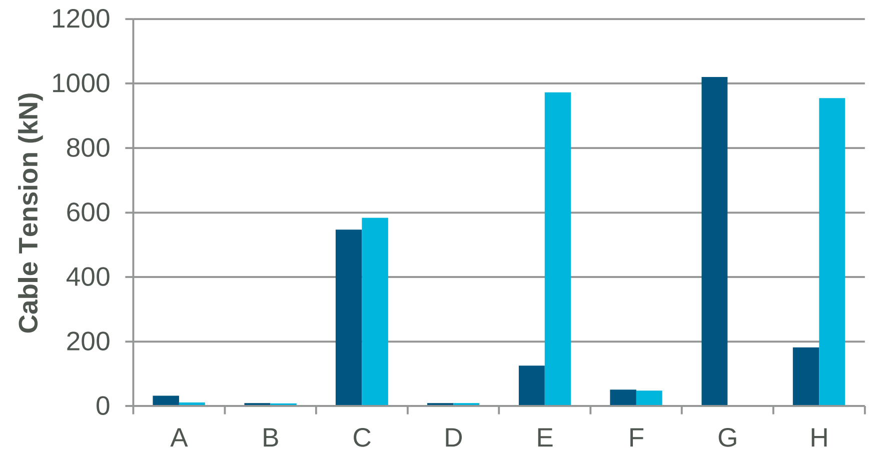
Loads in lines with line G broken

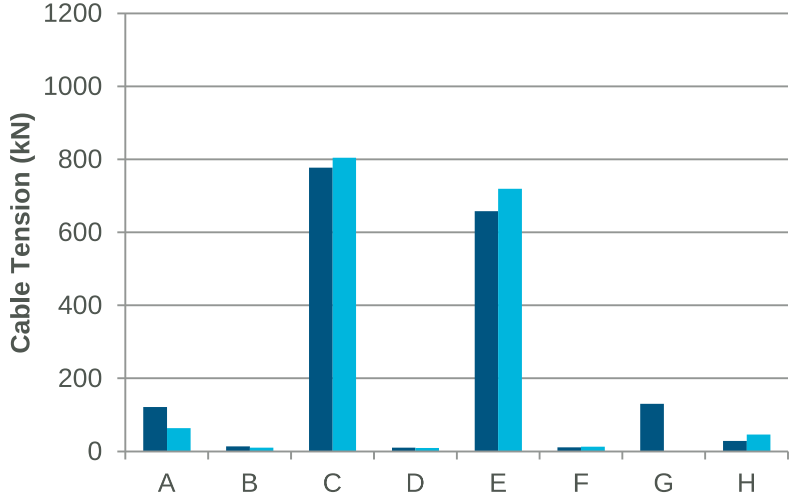
100 kN = 10.2 tonnes force

0° wind/waves – on the stern



315° wind/waves – stern quartering





270° wind/waves – on the port beam

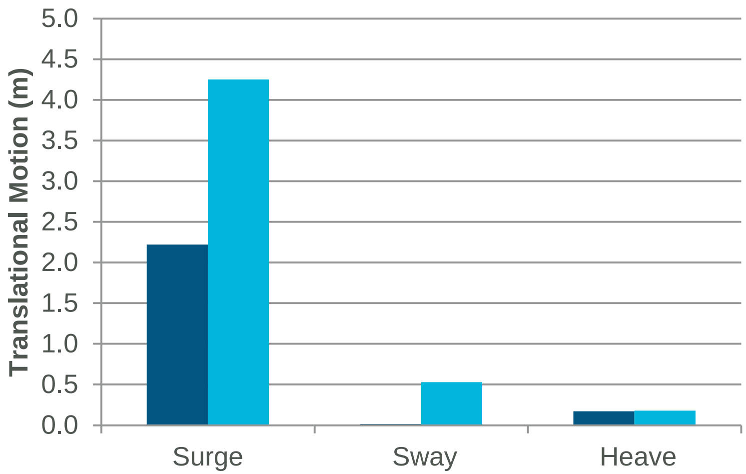
Results

Failed mooring line – High water translational motions

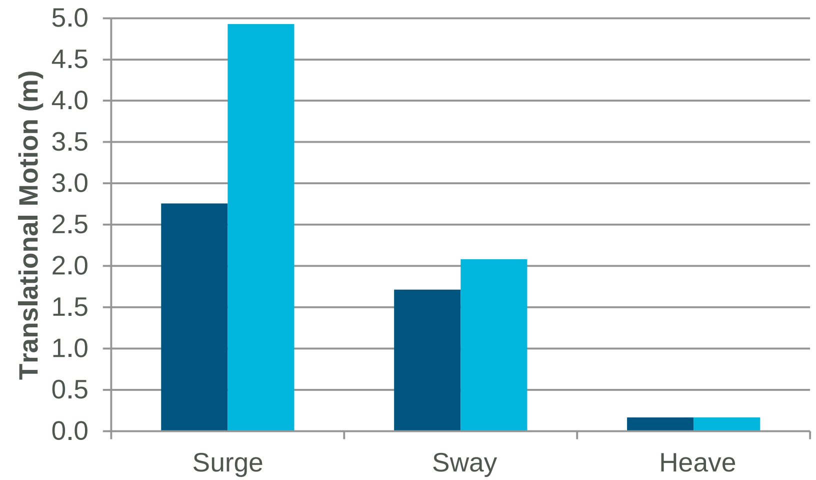
Motions with intact system

Motions with line G broken

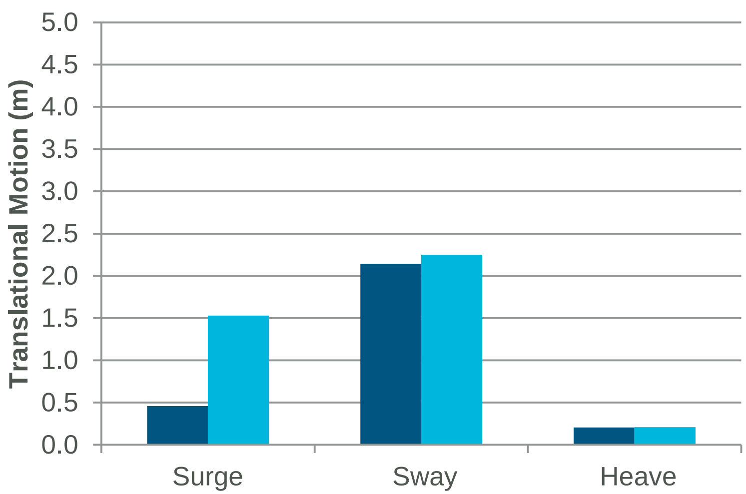
0° wind/waves – on the stern



315° wind/waves – stern quartering



270° wind/waves – on the port beam

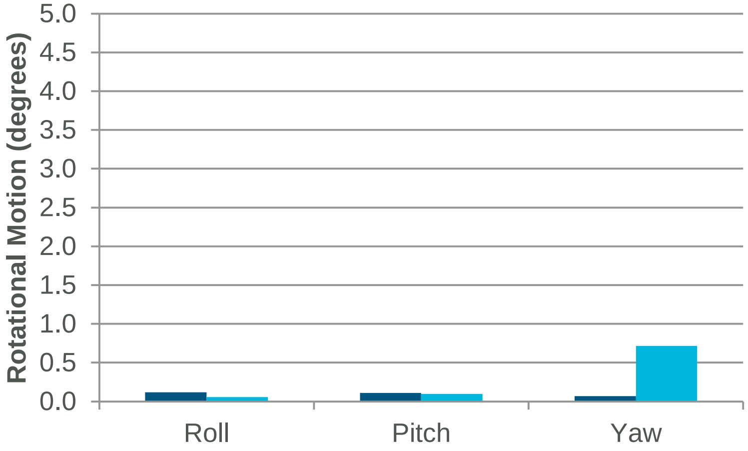


Results

Failed mooring line – High water rotational motions

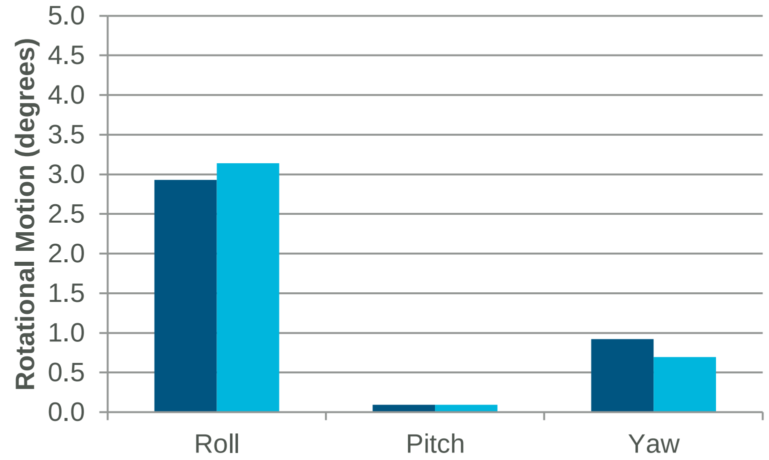
Motions with intact system

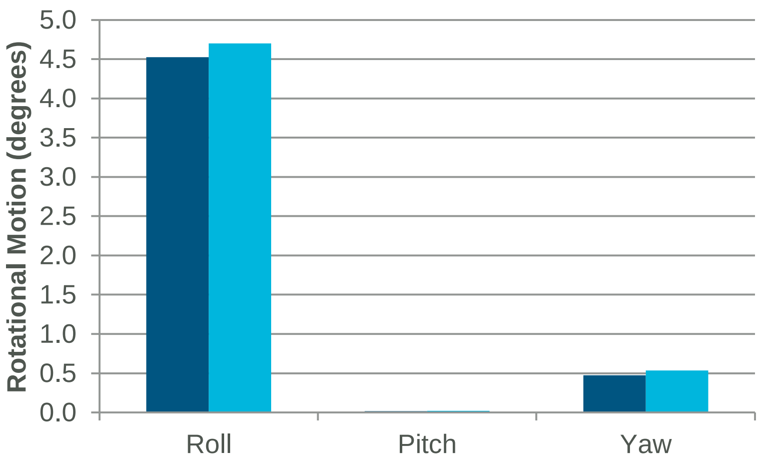
Motions with line G broken



0° wind/waves – on the stern

315° wind/waves – stern quartering





270° wind/waves – on the port beam

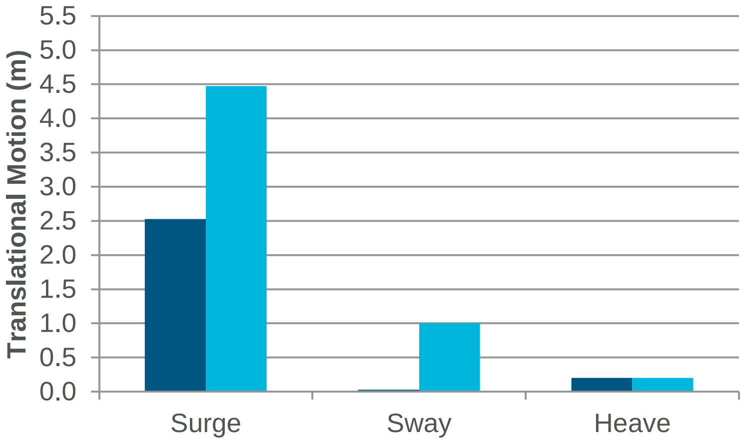
Results

Failed mooring line – Low water translational motions

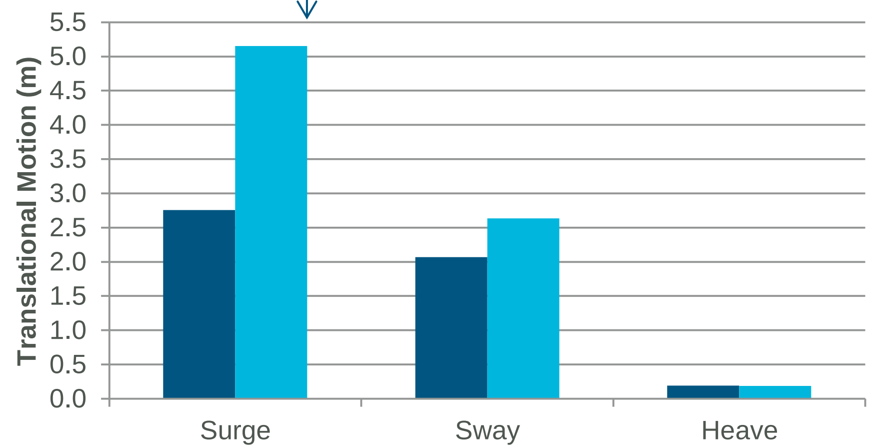
Motions with intact system

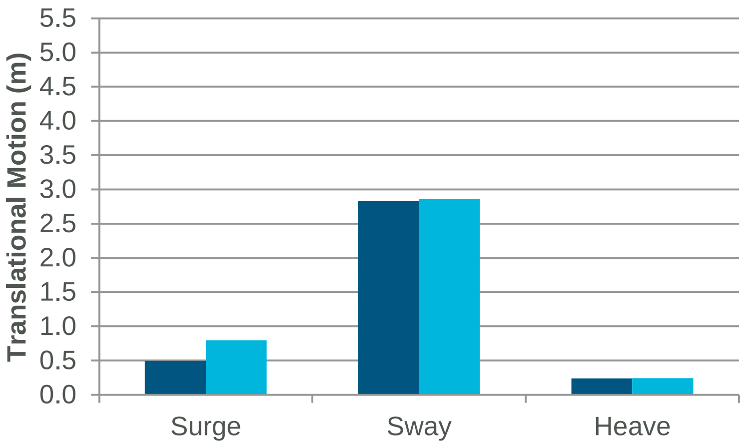
Motions with line G broken

0° wind/waves – on the stern



315° wind/waves – stern quartering





270° wind/waves – on the port beam

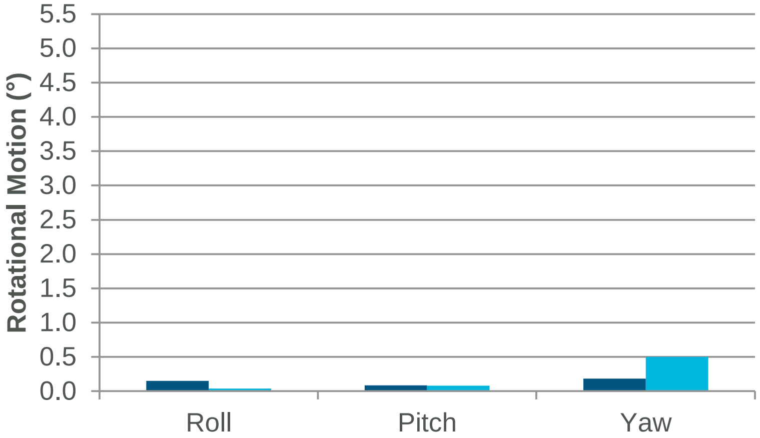
Results

Failed mooring line – Low water rotational motions

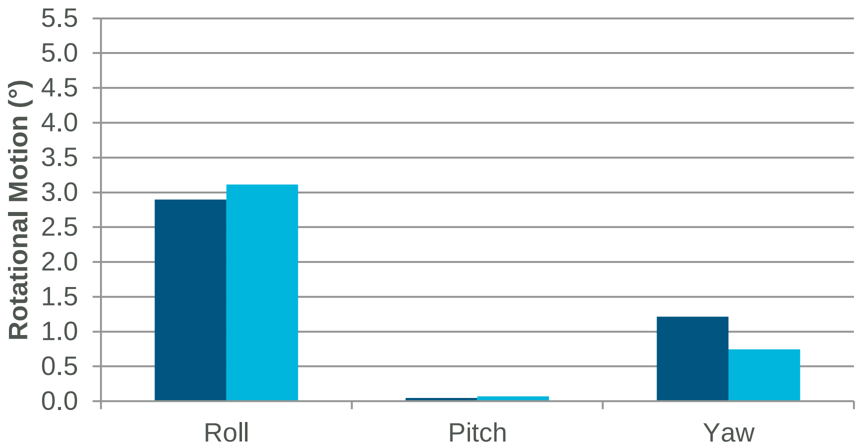
Motions with intact system

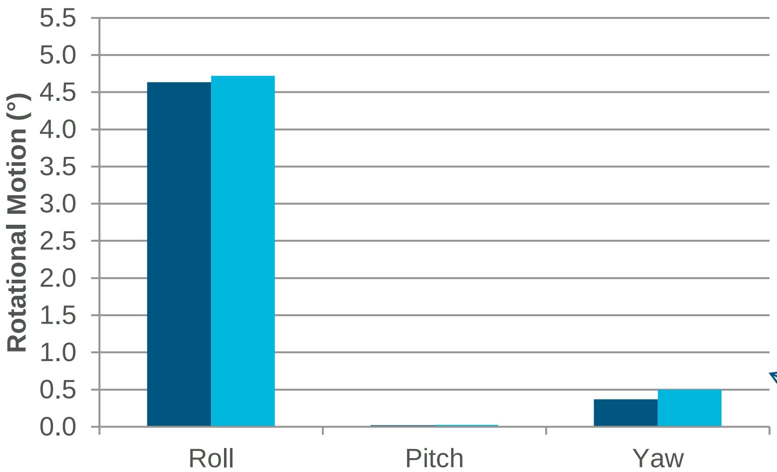
Motions with line G broken

0° wind/waves – on the stern



315° wind/waves – stern quartering





270° wind/waves – on the port beam

Results

Summary – Line G Broken, 100 year storm condition

		Max Tension (RMS)	Max Surge	Max Sway	Max Roll
High Water	Line Broken	1121 kN	4.9m	2.3m	4.7°
	Line Intact	850 kN	3.1m	2.3m	4.8°
Low Water	Line Broken	973 kN	5.6m	2.9m	4.7°
	Line Intact	1020 kN	3.6m	3.1m	4.9°

- **With mooring line G broken, the maximum tension in a line is 1121kN, which gives a safety factor of 1.95 times the proof load of the recently replaced chain (2187 kN).**
- **The translational motions of the ship increase, with a maximum surge motion of 5.6m (compared to 3.6m with the system intact).**
- **Roll motion has not been reported for the high water conditions, as this is only a factor in beam seas, which have not been considered in this part of this study.**
- **At low water, line G is under considerably more strain (1020 kN maximum) than the surrounding lines. With line G broken, the load in the surrounding cables increases significantly, but remains below the maximum load seen in line G (when it is intact).**

Passing Ship Effects

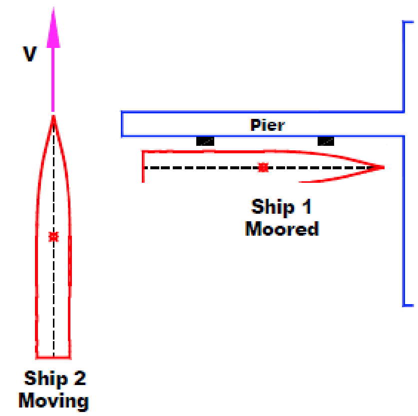
US Navy Historic incidents

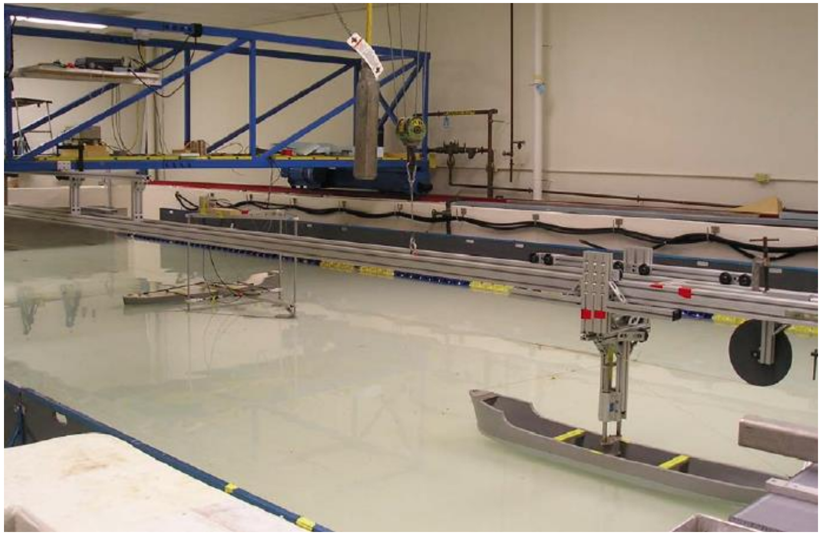
1. Two Iowa Class Battleships moored side by side in Philadelphia Naval Shipyard using a chain and sinker system would surge 3.5 – 4.5m when ships passed. This caused accelerated wear on the mooring system. It is not recorded whether the ships were moored parallel or perpendicular to the passing ships.
2. Two US Naval (Auxiliary) Ships were moored side by side in New Orleans. Large cargo ships passed in the Mississippi caused the ships to move so suddenly that a woman and child visiting the inboard ship were run over and seriously hurt by a 1.4 tonne rolling gangway.
3. While this is less relevant to HMS WARRIOR due to the close proximity of the ships (approx. 20 m), a tanker, the US Jupiter, was moored and unloading fuel when another ship (Buffalo) passed at approximately 4 knots. This was sufficient to break the mooring lines and the discharge hose, causing a fire that resulted in a fatality and the total loss of the ship.
4. QE2 passed approximately 500m from the Norfolk VA beachfront at 15-20 knots. Multiple Naval Ships broke mooring lines and shore cables, brows failed and pier pilings were broken.

Passing Ship Effects

Two Methods Considered

- **First Principles: Understanding the generation of bow waves.**
  - Froude derived a relationship between the velocity of a ship and the wave length of the bow wave it generates.
  - However, the wave lengths generated are such that the linear assumptions applied within AQWA are no longer applicable and the analysis “falls down” predicting very slight surge motions (in the order of 1m surge with a 2m wave).
- **Empirical Methods: Building on model testing.**
  - Because of the risks associated with passing ships, much effort has been spent on understanding these forces.
  - Unfortunately, most work focuses on ships being moored parallel to passing ships with different suction effects due to the different arrangement of the ships.
  - Kriebel (United States Naval Academy) took previous work undertaken and undertook model tests to understand the forces on ships moored perpendicularly and to develop an empirical equation for this force.

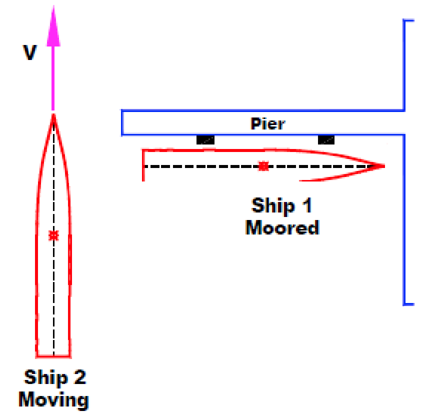


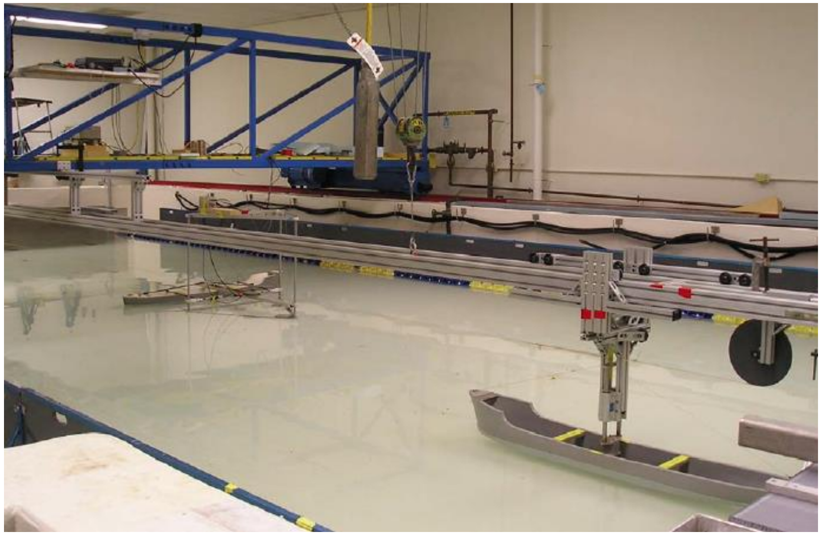


Passing Ship Effects

Kriebels Method

- Kriebel ran 133 model test experiments with variables including passing ship speed, separation distance from passing ship to moored ship and ratio of displacement between passing ship and moored ship.
- He determined empirical relationships for the surge and sway forces on the moored ship and the yaw moment. These vary with time as the ship moves past the moored ship and have been applied in ANSYS AQWA as a time dependant force.
- The ratio of displacements considered in model testing does not reflect the ratio of displacements between HMS WARRIOR and passing ferries. This is thought to have a limited impact on the results .
- Based on some assumed properties of a typical ferry operating from Portsmouth, the forces on HMS WARRIOR have been estimated.
- Only low water has been considered as it is the motions of the ship that are critical, and the tensions that result from restraining these motions.
- 3 speeds of passing vessels were considered: 5, 10 and 15 knots. 10 knots is the speed limit in Portsmouth Harbour.
- No wind/waves/current have been considered.



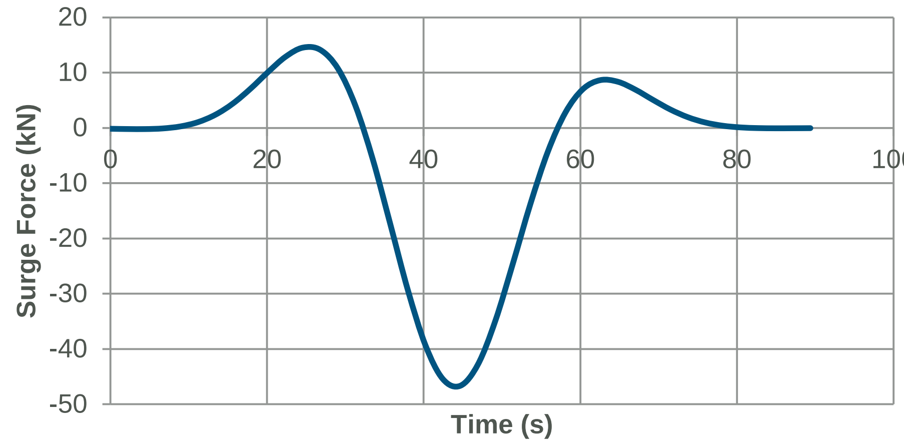


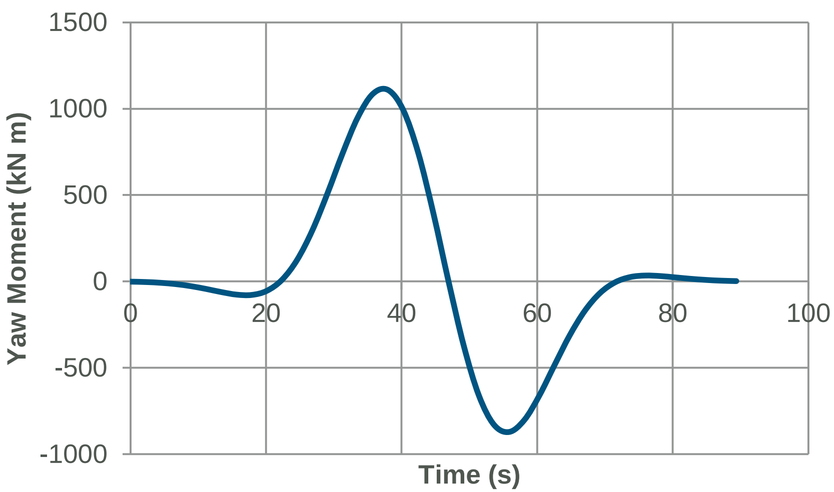
Passing Ship Effects

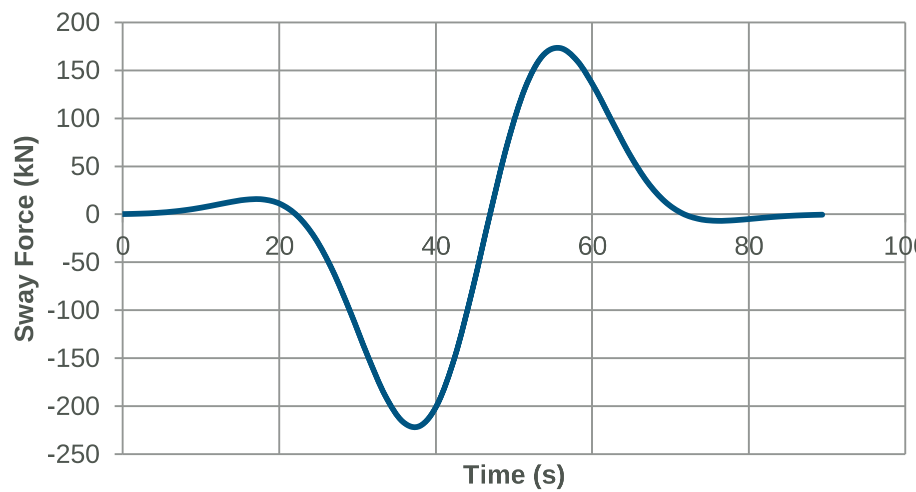
Forces Applied

100 kN = 10.2 tonnes force

- These plots show the forces and moments that result from a ship passing at 300m separation distance at a speed of 10 knots.
- This separation distance and speed are used in the following slides to illustrate the impact of a passing ship.



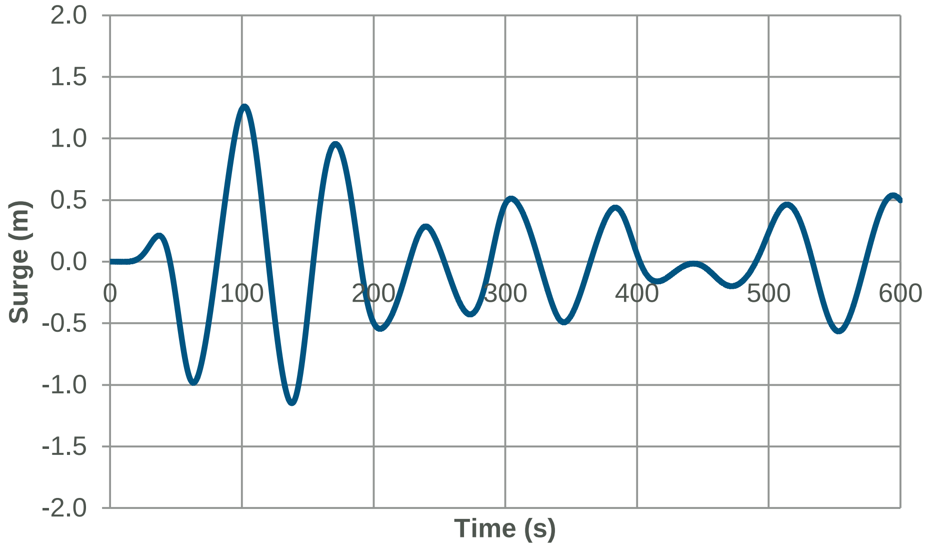


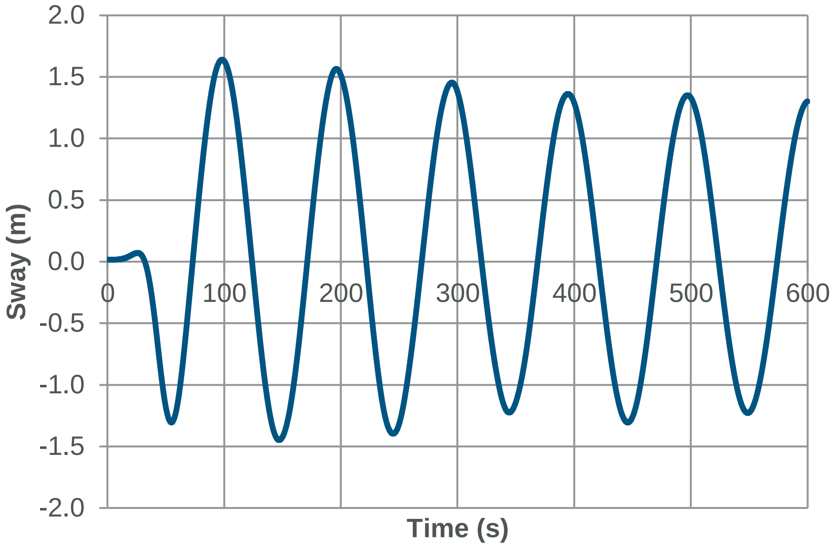


Passing Ship Effects

Forces Applied and Response

- The bow wave initially pushes the HMS WARRIOR forward before suction effects pull her back.
- When the ship is passing the suction force is suddenly reversed causing the ship to surge forward again then the motion oscillates back to equilibrium.
- The sway forces simultaneously cause lateral motions, which gradually decay and increase the load on the mooring system.

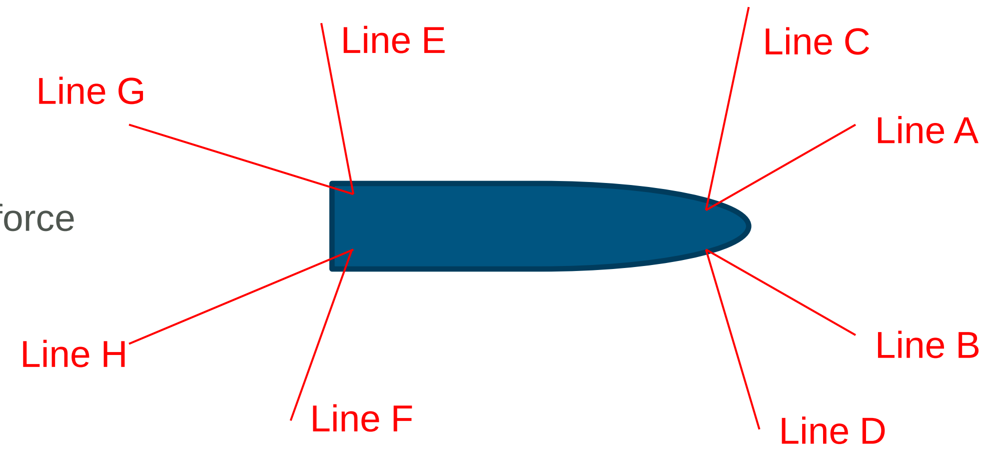


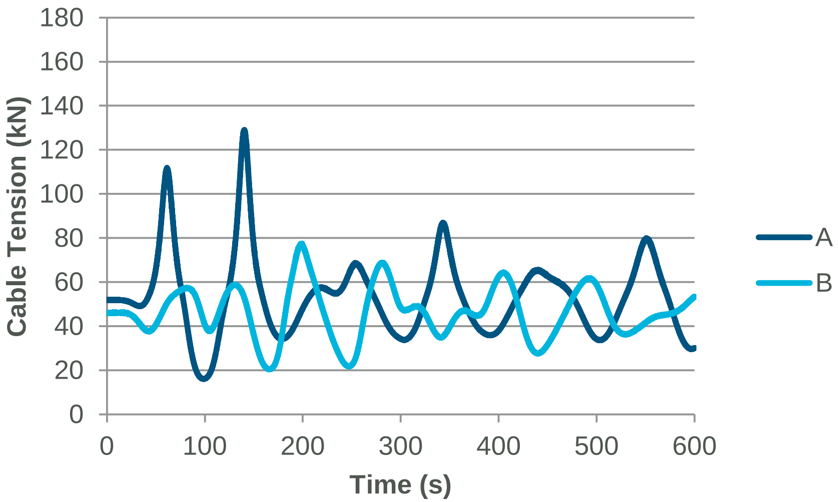


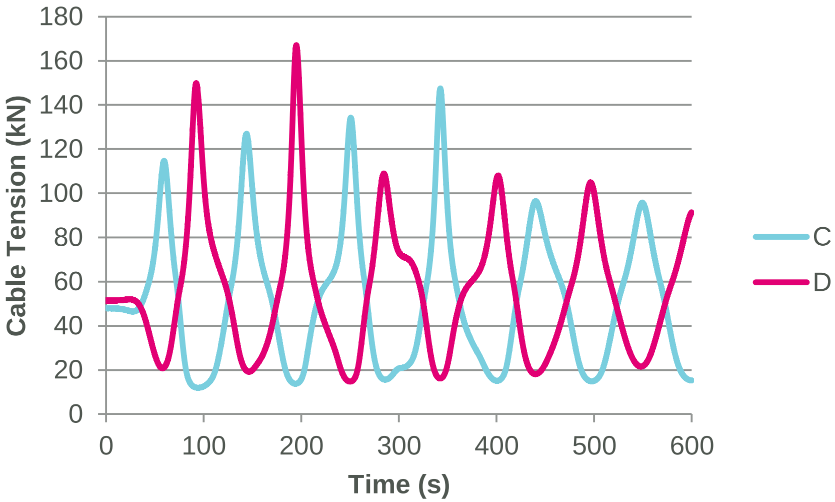
Passing Ship Effects

Cable Tension in the forward mooring lines (A, B, C and D)

100 kN = 10.2 tonnes force



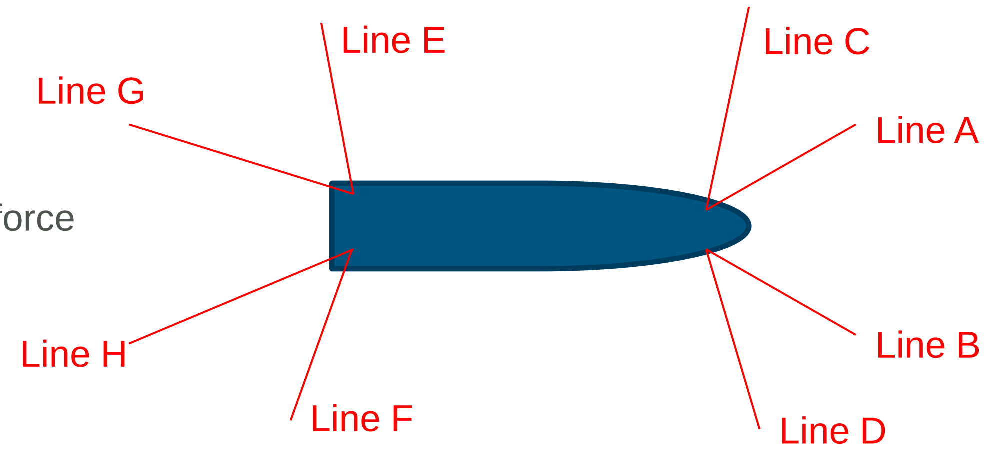


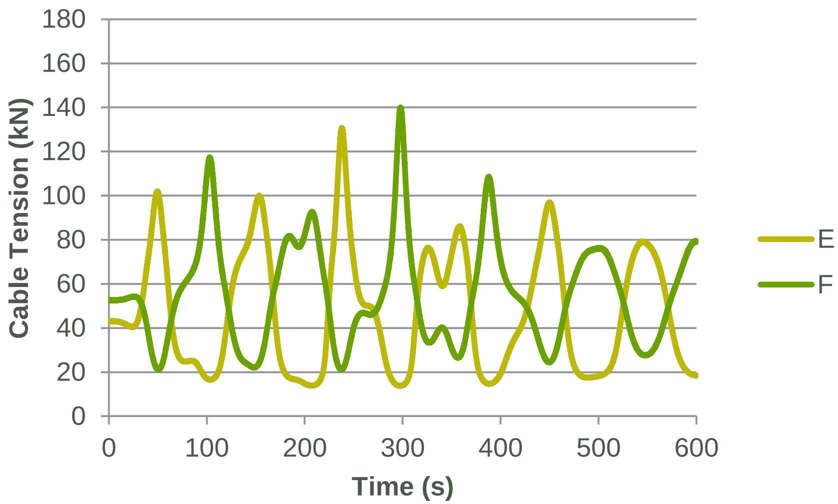


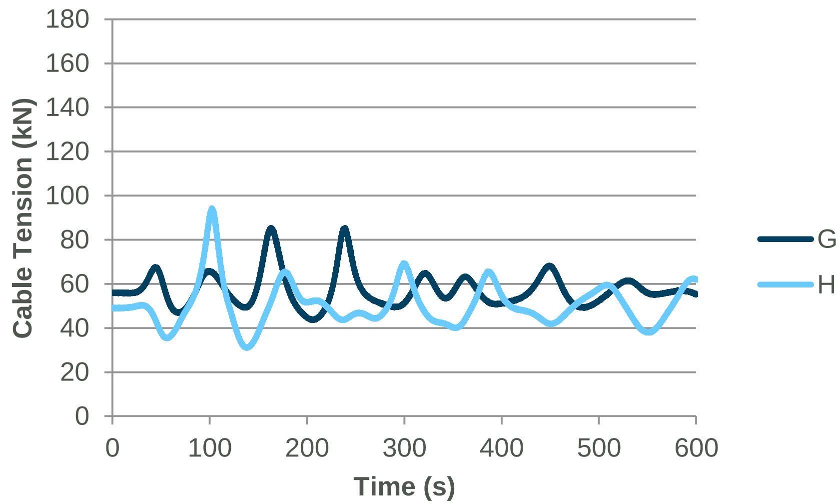
Passing Ship Effects

Cable Tension in the aft mooring lines (E, F, G and H)

100 kN = 10.2 tonnes force

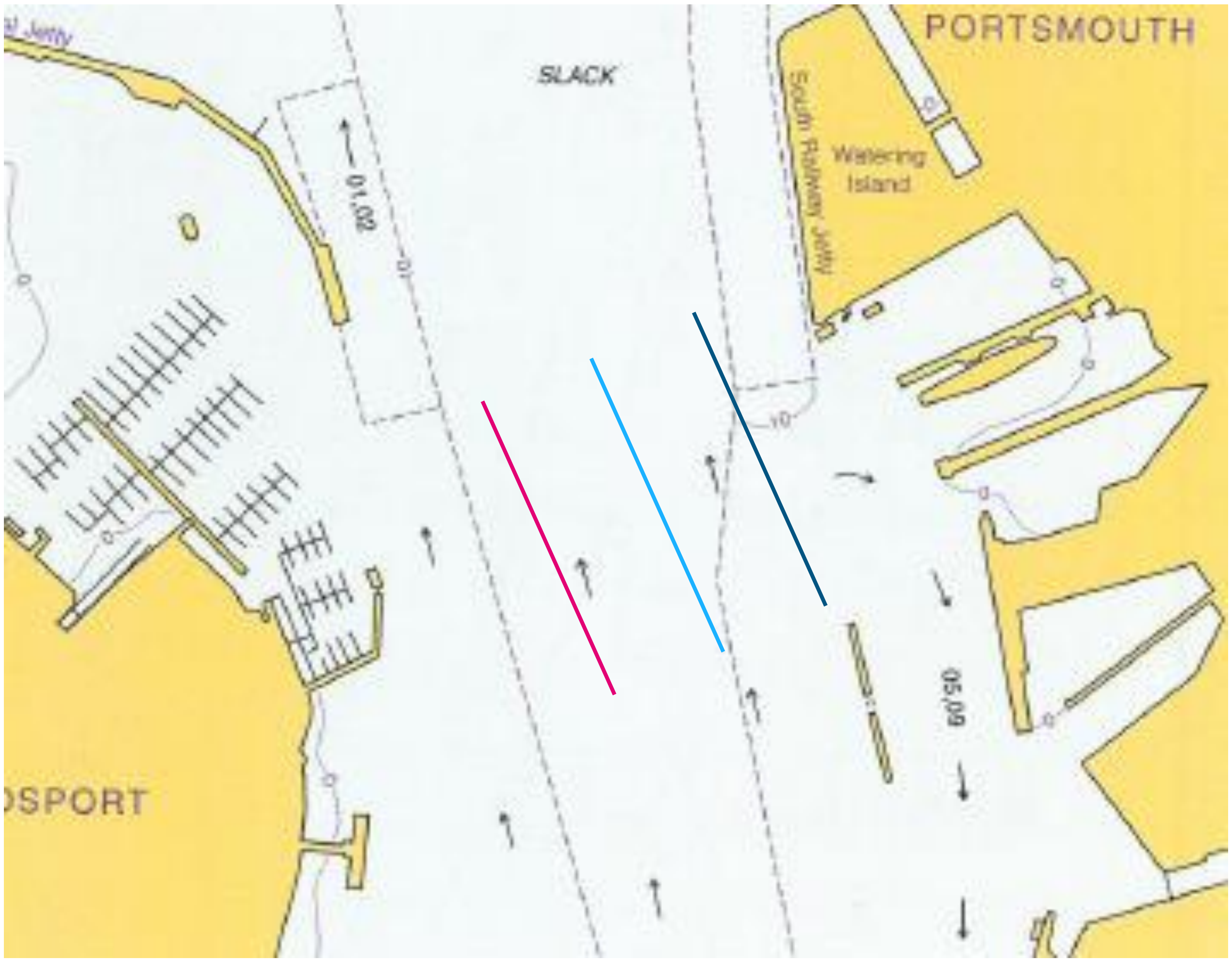






Passing Ship Effects

Separation Distance



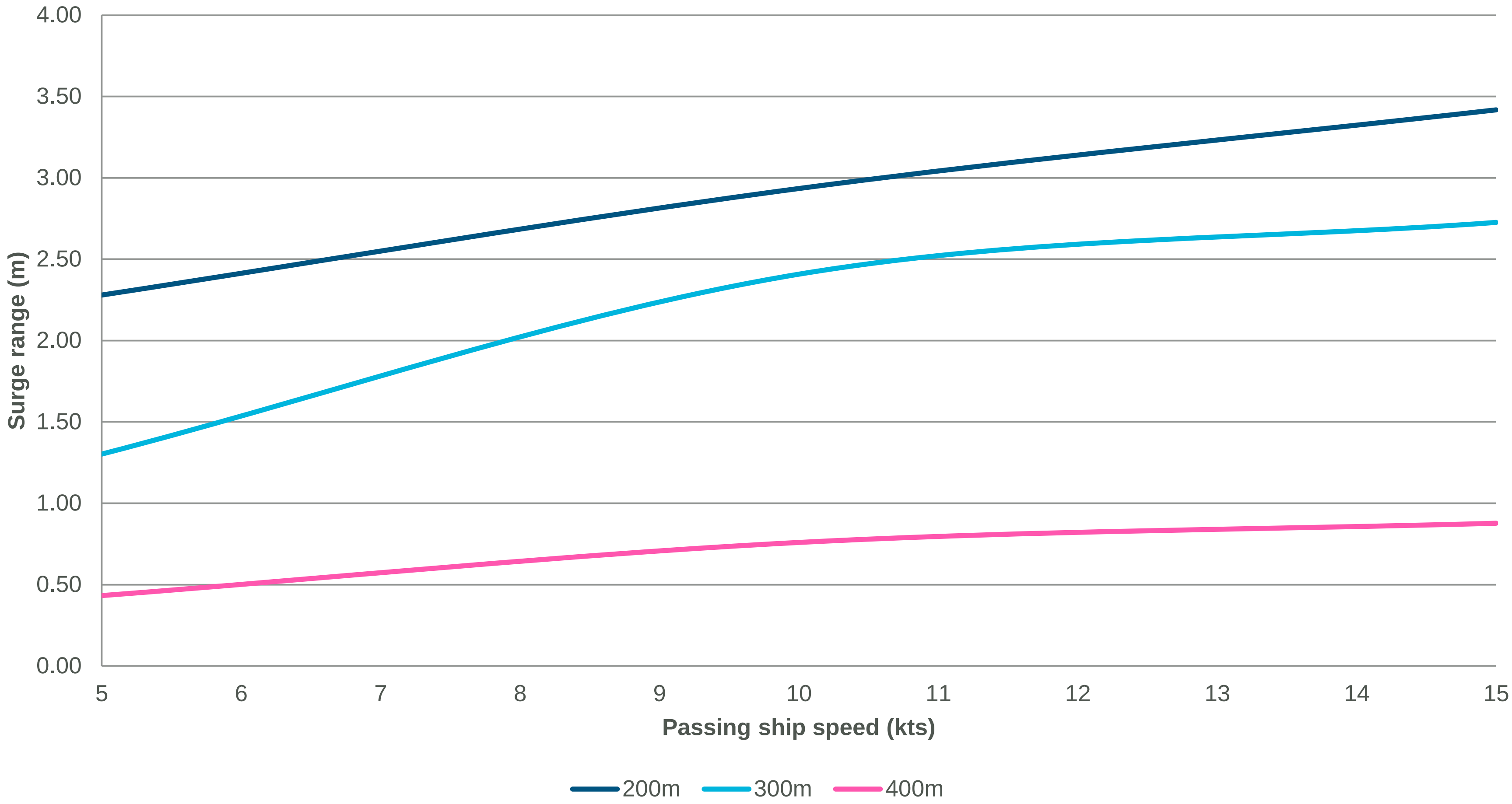
200m

300m

400m

Passing Ship Effects

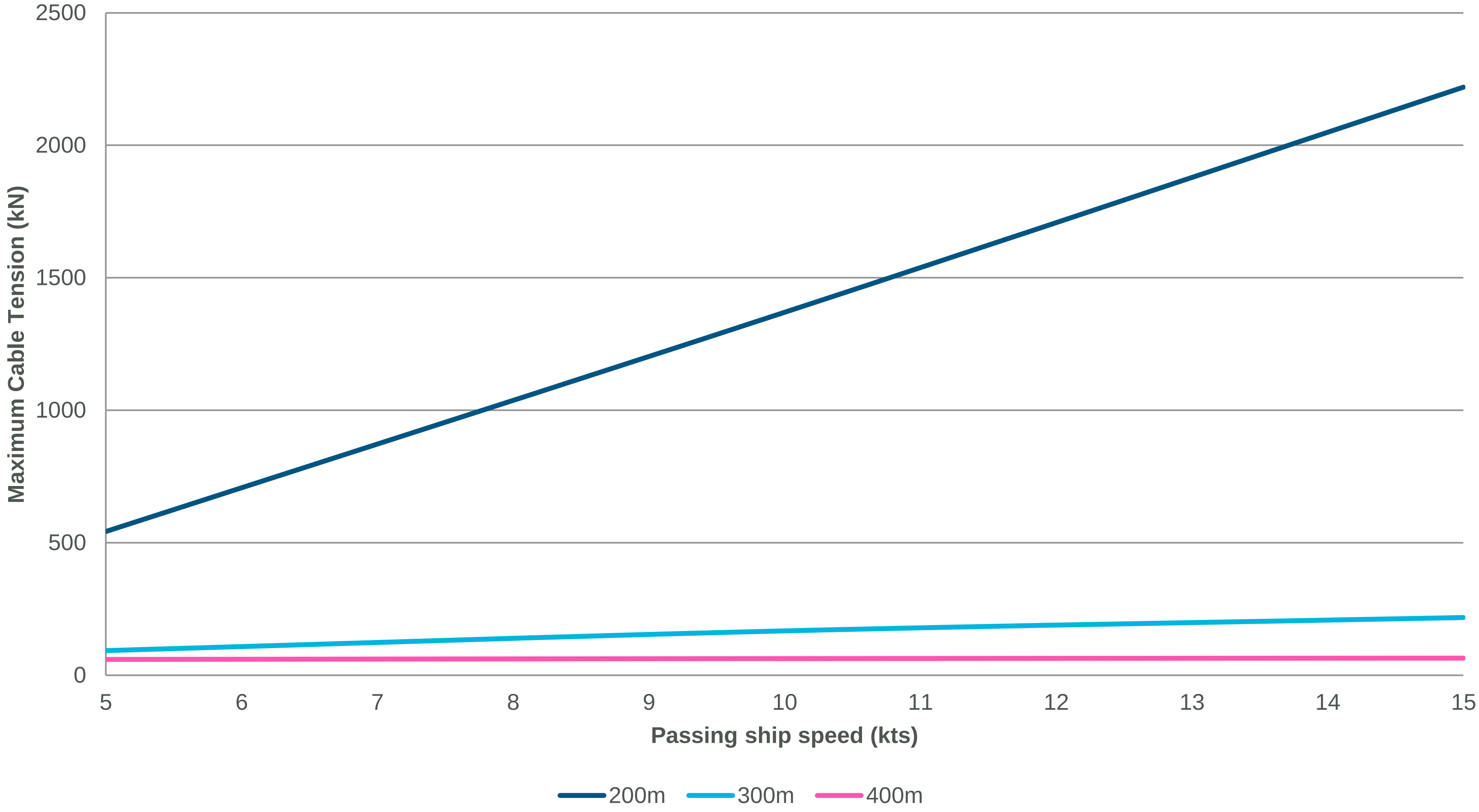
Results – Surge range (the distance between the point furthest forward of equilibrium to the point furthest aft of equilibrium as a result of a passing ship)



Passing Ship Effects

Tensions in mooring lines

100 kN = 10.2 tonnes force



Conclusion

- The mooring system as designed is satisfactory for withstanding the environmental loads on the ship. The survey and maintenance regime issued separately has been developed to allow the design intent of the mooring system to be maintained through life.
- This is true both when the system is intact and when line G (the most heavily loaded line in prevailing weather conditions) is assumed to be broken.
- When the system is intact, there is a 2x factor of safety against the proof load of the replacement line.
- With line G assumed to be failed, the load in the immediately surrounding lines increases. A safety factor of 1.95 remains.
- The condition of the mooring lines beyond the 20 tonne sinkers is not known, however analysis shows that load is transferred beyond the sinkers. Should multiple mooring lines beyond the sinker be degraded such that they are ineffective, the 20Te sinker is not sufficient to hold the ship in place. It is therefore essential that the condition of the whole mooring system is established and maintained.
- Given the age of the vessel, it is likely that the fittings on HMS WARRIOR will be the “weak link” in the current mooring system. A preliminary survey of the mooring arrangements shows that the condition of the propeller well is of particular concern.
- The surge motions of the ship during a storm may be up to 3.6m depending on the condition of the tide and the direction of the wind and waves. The ship may also roll up to 4.9°.
- Ships passing at a distance of 200m from the aft end of HMS WARRIOR result in high tensions in mooring lines. If the ships are travelling at high speeds (14 knots) and passing at a distance of 200m it is possible for the proof load of the line to be exceeded
- In general, the mooring system as designed is considered suitable for the environmental loads imparted. The only concerns identified are regard the degradation of the condition of the mooring system and the impact of vessels passing at high speed and very close to HMS WARRIOR, and could result in motions on the ship, and the brow being knocked off.

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