LIFE Recreation ReMEDIES Advanced Mooring Systems Modelling

Project Summary Report

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J. Stone - Morek Engineering Ltd

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Further information

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This work would not have been possible without the interaction and contributions of several key individuals and organisations – Andrew Jones QHM Plymouth, Vicki Spooner of Falmouth Harbour Commission, Stephen Treby of Natural England (Solent / Isle of Wight), Alan Kavanagh of Natural England (Essex), Dale Clark Harbour Master St. Marys, Isles of Scilly.

Also input from Hazelett Marine, Seaflex and Mark Parry of Ocean Conservation trust (Stirling mooring).

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Working in partnership with:

Executive summary

This work, commissioned by Natural England through the Life Recreation ReMEDIES (Reducing and Mitigating Erosion and Disturbance Impacts affEcting the Seabed) project has investigated the performance of a range of Advanced Mooring Systems. The mooring systems have been compared to a baseline block and chain catenary system. The main objective of the AMS systems is to reduce the interaction between the mooring and the sensitive seafloor ecosystem of UK harbours and estuaries. This work is presented in two sections, the first shows the results of stakeholder engagement with the Life ReMEDIES site leads and regional representatives. This has enabled the derivation of suitable environmental input parameters for the numerical modelling. The second stage involves the direct simulation of the performance of AMS systems with the offshore dynamics simulation software Orcaflex. The conclusions of this study further support the advancement of AMS systems as a means of protecting seabed habitats. However, it is clear that further optimisation is necessary to develop a clear design guideline for specific vessel and depths combinations.

This report will be of interest to marine managers including harbour authorities as well as individual mooring users and owners.

Advanced Mooring Systems
MOR-039-RPT-001

Project Summary Report

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Rev.	Date	Description	Prepared By	Checked By	Approved
01	24/03/2021	First Draft	JS	JM	BC
02	28/04/2021	First issue	JS	BC	BC
03	25/05/2021	Second issue following review	JS	BC	BC

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This report was produced by Morek Engineering and commissioned by Natural England. Morek (Maritime in Cornish) is a consultancy combining naval architecture and marine engineering skills to offer high quality, detailed technical services to all aspects of the blue economy. Involvement in Advanced Mooring Systems (AMS) aligns with Morek's vision of using engineering skills to both reduce the harmful exploitation and increase the sustainable use of the seas. Whilst the scale and specific application to boating in the leisure industry is relatively new to Morek, this work has benefited from their extensive track record in larger marine renewables (including wave, tide and offshore wind energy) and in particular their use of marine dynamics software, Orcaflex. Morek are looking forward to further their involvement in AMS deployment and would be happy to hear from interested parties (info@morek.co.uk)

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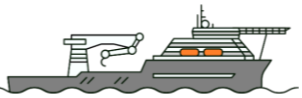

1. EXECUTIVE SUMMARY

This work, commissioned by Natural England through the Life ReMEDIES project has investigated the performance of a range of Advanced Mooring Systems. The mooring systems have been compared to a baseline block and chain catenary system. The main objective of the AMS systems is to reduce the interaction between the mooring and the sensitive seafloor ecosystem of UK harbours and estuaries.

This work is presented in two sections, the first shows the results of stakeholder engagement with the Life ReMEDIES site leads and regional representatives. This has enabled the derivation of suitable environmental input parameters for the numerical modelling. The second stage involves the direct simulation of the performance of AMS systems with the offshore dynamics simulation software Orcaflex.

The conclusions of this study further support the advancement of AMS systems as a means of protecting seabed habitats. However, it is clear that further optimisation is necessary to develop a clear design guideline for specific vessel and depths combinations.

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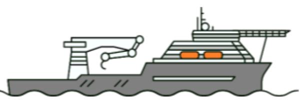

3. INTRODUCTION

Seagrass is a flowering plant that forms a lush underwater meadow on the seabed. It's populations are decreasing and are a UK habitat of principal importance.

Seagrass beds:

- support a diverse ecosystem which provide food and shelter for fish and other animals, from tiny invertebrates to marine mammals and waterfowl.
- are spawning, nursery and refuge areas for fish, including commercially- important plaice.
- stabilise the sediment with their roots.
- absorb nutrients and clean the surrounding seawater.

Mass deployment of traditional (block and chain) swing mooring systems for recreational craft in shallow water causes decline of such vital habitats. This is due to the scouring of the seabed when in contact with ground chain. The impact of this could be hugely reduced by employing the use of Advanced Mooring Systems (AMS) which minimise components contacting the seabed.

The main objective of this work is to model the behaviour of AMS for small to mid-size recreational craft, allowing assessment of vessel motions and loads. The aim is to identify the most suitable alternative to the traditional block and chain moorings.

This work is being conducted as part of the "Life Recreation ReMEDIES" project which is focused on the protection of seagrass and Maerl habitats across the south of the UK. The project has regional activities in the following locations which will be used in the study:

- Isles of Scilly (IOS)
- Falmouth
- Plymouth
- Solent
- Essex

The work follows a similar piece of work for Tevi [1], who have agreed to make the input data, numerical models and conclusions available to this project. It is not the intention to simply repeat the original scope but instead to take learning and recommendations to further develop the knowledge and understanding of AMS through numerical simulation.

This report summarises modelling undertaken to compare the performance of three types of AMS against a traditional block and chain mooring. OrcaFlex marine dynamics software has

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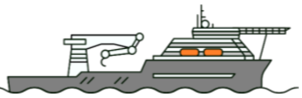
[1] Tevi and Morek; "Modelling of Advanced Mooring Systems in Cornish Harbours"; Spring 2021



been used to simulate the response of typical recreational vessels moored with three configurations of AMS. These simulations account for the environmental conditions expected at Life ReMEDIES project sites.

3.1. Learning from Previous Work

Prior to the commissioning of this study a similar study has been executed under the Tevi program. The work focused on the application of AMS to Cornish waters. This fresh study aims to complement the findings of the Tevi work, advancing learnings from this previous scope. The following section outlines the key learning points from the Tevi work:

- Many near shore sites that use frape moorings tend to dry out. The AMS considered are not suitable for this arrangement so these sites were excluded.
- The majority of charted water depths for AMS sites were in the range of 3-5m with c.6m tidal range. The hazelett system was unable to cope with this large tidal variation relative the small water depths and was hence excluded from the dynamic analysis.
- The maximum significant wave height used was 1m although this provided very high cleat loads in some cases, and may be conservative for summer deployments, particularly as in sites that experience such conditions, the owners would tend to remove vessels from their moorings. The environmental load cases will be revisited and expanded for this study to provide a wider range of operating conditions.
- The majority of vessels from the stakeholder survey were in the length range 5-10m, which resulted in selection of 10-12m vessels for the modelling. An additional smaller vessel class will be included in this study.

4. INPUT DATA

4.1. Stakeholder survey

To assess the performance of the AMS it was first necessary to characterise the likely regional considerations to their site-specific deployment. This involved collating input data from representatives across the range of sites include in the Life ReMEDIES project. To achieve this a basic baseline survey was generated and undertaken in the form of direct correspondence with local representatives. The main objectives of the survey were to.

- determine the status of existing small boat moorings.
- gain relevant input environmental conditions; and
- to gauge interest in deployment of AMS.

All the authorities and marinas that were contacted provided valuable input into the study. General survey feedback is shown below, and more detailed feedback on environmental conditions, vessel sizes and mooring types follows throughout the report in Sections 5.1, 6.1 and 7.1.

General feedback

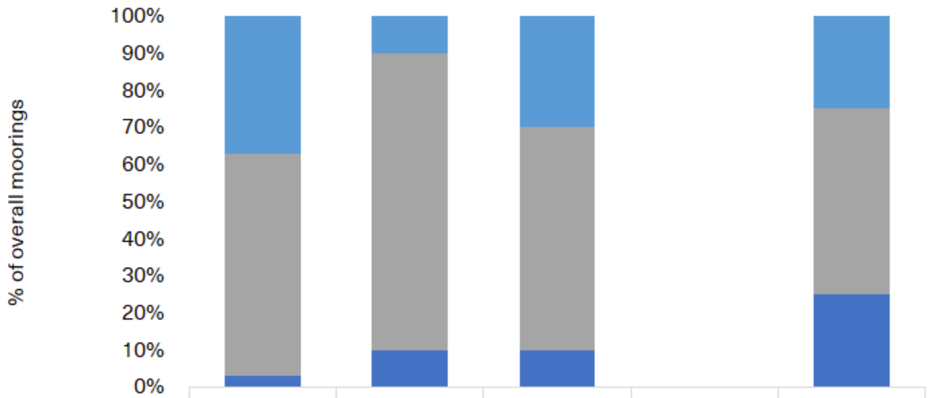
Feedback from harbours showed that charted depths were generally in the range 0m to 5m with peak tidal range of around 6m. The wave climates were also similar throughout with summer wave heights in the region 0.5m – 2m and annual wave heights 0.5 to 2.5m. Most harbours did not report on previous experience of using AMS however Yarmouth stated that the length of multiplait rope, acting as the bottom fixing on the Seaflex system, was at risk of chaffing and as such they find it unsatisfactory and would not wish to place a customer's vessel on the mooring.

It is noted that MCS (Marine Conservation Society) and NMA (National Marine Aquarium) have already conducted some practical trials at the Cawsand bay project site. This work has been conducted within the ReMEDIES project; however, at the time of writing no direct detailed feedback has been available.

5. VESSELS

5.1. Vessel Sizes

Figure 1 shows the relative ratios of vessel length at the harbours. Plymouth, as expected with access to deeper waters, has the largest proportion of over 10m vessels. In general, most vessels throughout are in the range 5 – 10m. No response for the Essex site was provided.



	Plymouth	Falmouth	Isle of White / Solent	Essex	Isles of Scilly
■ Vessels 10m+	37%	10%	30%	0%	25%
■ Vessels 5 - 10m	60%	80%	60%	0%	50%
■ Vessels 0 - 5m	3%	10%	10%	0%	25%

Figure 1: Percentage of vessel sizes

The feedback from the harbours in Figure 1 shows that it is worth considering a smaller vessel class than those previously considered in the precursor Tevi Study. As such an additional, smaller displacement vessel has been considered for both the motor launch and sailing vessel selected for the previous work. Further details of the original selection of vessel can be accessed in the Tevi
'Seagrass Protection and Advanced Moorings' report (2021)

The original larger two vessels are unchanged from previous work; the smaller vessels are in turn scaled from these.

- Motor Launch –
  - 10.2m (33ft) cabin cruiser, with a draught of 0.8m and displacement of 10te
  - 5.1m (17ft) cabin cruiser, with a draught of 0.4m and displacement of 1.25te
- Sailing Vessel –
  - 12m (40ft) yacht, with a draught of 2m and displacement of 6te
  - 6m (40ft) yacht, with a draught of 1m and displacement of 0.75te

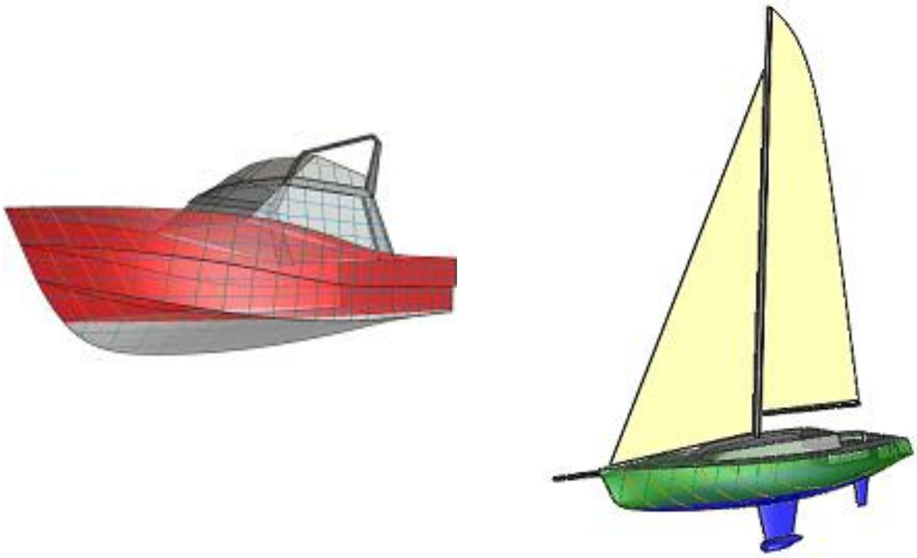


Figure 2: Images of selected vessels (extracts from the software package DelftShip). On the left is a graphic of a motor launch and on the right is a graphic of a sailing vessel. ©DelftShip. Reproduced with permission.

5.2. Hydrodynamic modelling

Similarly, to the precursor Tevi report the additional vessels have been assessed to develop hydrodynamic representations as required in the numerical modelling. The vessel response was characterised in two ways:

- Diffraction analysis to define the vessel response to 1st and 2nd order wave loading.
- Morrison's drag coefficients to define the vessel response to current and wind drag.

Panel meshes for the smaller vessels were generated in Rhino 3D, with mass and inertia properties also scaled from the original larger vessels. The diffraction analysis was performed in Orcina's OrcaWave software, which interfaces directly with OrcaFlex, reducing the uncertainty typical of importing this type of data into OrcaFlex. Figure 3 shows the 4 vessels considered in this study.

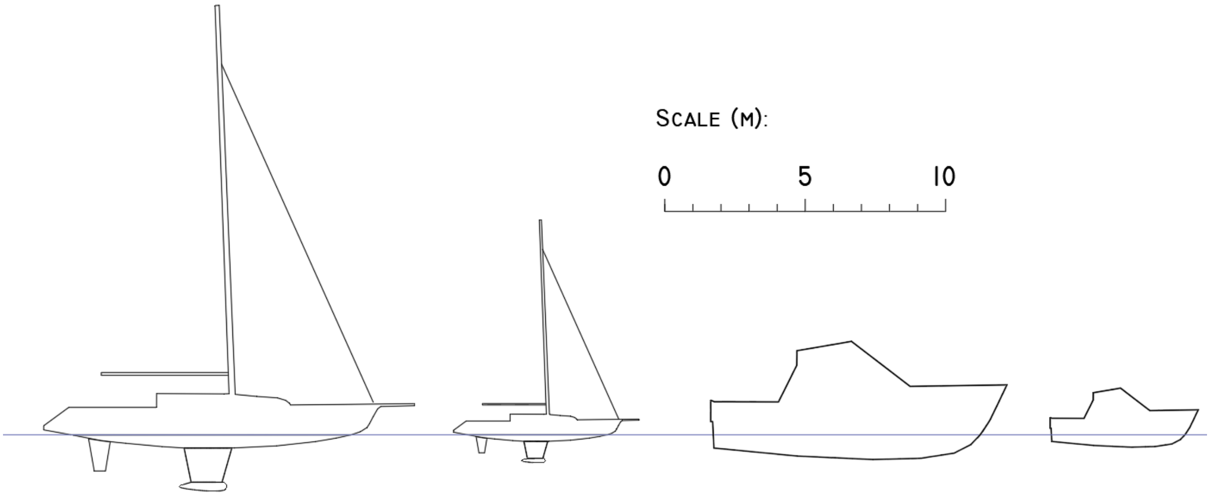


Figure 3: Vessel outlines for Large and small versions of the vessels (RHS -Sailing Yacht and LHS-Motor Launch)

The output of this analyis is a hydrodynamic database, consisting of hydrodynamic added mass and damping matrices, load RAOs (Response Amplitude Operators), displacement RAOs and Quadratic transfer functions, all of which are required to characterize the effect of the wave climate on the vessel.

Note that for the purpose of this study, no validation has been conducted on this analysis as it was not possible within the scope and budget. It would be recommended to vaildate the response models against tank test or full scale data.

6. MOORING

6.1. Existing moorings

There are three main types of moorings currently seen across the surveyed harbours. These include: Block and chain moorings, frape moorings and Trot moorings, as shown in Table 1.

Location	Existing mooring types	Number of moorings
Plymouth	Mainly block and chain, some AMS (for ReMEDIES project)	2500 Block and chain 45 licenses for AMS
Falmouth	Block and chain, Some trot	600 Block and chain 36 Trot
Isle of White / Solent	Block and Chain, Pontoon, Quay wall, Some trot	166 block and chain Unclear on others
Essex	Limited response but many sites suitable for a range of moorings	N/A
Isles of Scilly	All block and chain	216

Table 1: Existing moorings summary

The following sections describes these mooring types and the technical details of how they are configured across the sites.

Block and Chain (baseline)

The most common mooring arrangement used in the harbours assessed in this study is a block and chain, as shown in Figure 4, also known as a “swing mooring”. This arrangement uses a concrete or granite block as a gravity anchor with a chain catenary connected to a surface buoy. The catenary chain has two functions:

- To produce a spring effect, meaning the mooring arrangement can tolerate the difference in water depth between low and high tides, and provide a stiffness to the mooring keeping the moored vessel within a given range around the anchor point.
- To reduce any uplift of the mooring block. As such, the chain rests on the seabed after leaving the block, its weight ensures that the concrete block is only ever subject to horizontal loading. The single point attachment allows the vessel to weathervane, typically with the tidal flow direction but can be dominated by strong wind, especially for shallow draft vessels. This action causes the portion of chain in contact with the seabed to scour as it drags along the seabed with the changing loads on the moored vessel, invariably this occurs with every tidal cycle.

The block and chain will be used as a point of comparison for the analysis and will be known as the 'baseline'.

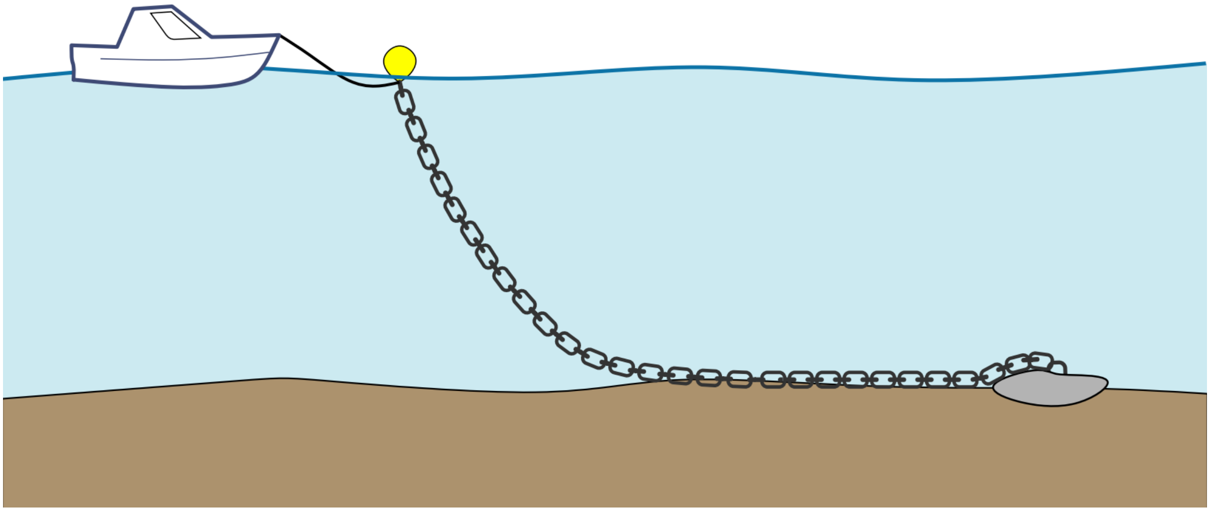


Figure 4: Block and chain mooring arrangement.

For example, at St. Mary's, a typical block and chain will be constructed as follows.

Anchor	-	200kg gravity anchor
Riser	-	7.5m x 16mm riser chain
Surface buoy	-	600mm diameter hard buoy
Rode to Vessel	-	Vessel owner supplied.

Trot Mooring

A trot mooring differs from a swing mooring in that instead of using a heavy ground anchor a heavy ground chain is laid between two granite blocks, this allows two chain risers per vessel to provide fore and aft connection points, this ensures moored vessels maintain station and heading throughout the tide and are typically used for larger vessels and preferred in constrained waterways with current.

The swing type aspect of the Trot mooring the interaction with the seabed is limited, there is much less scope for the heavy ground chain to move if laid straight and with large gravity anchors on either side. The Trot has not been specifically considered in this study.

Frape Mooring

Frape moorings are used to connect smaller vessels to shore based anchors and as such are in shallow water and tend to dry out. They are more suited to tenders and small motor craft. They also typically have little or no interaction with the seabed other than the direct axial running of the line when the vessel is pulled to shore or sent back to moor. As a result, they have not been considered in this study.

Pontoon / Quay Wall Mooring

As the name suggests pontoon and quay wall moorings are dedicated connections to fixed structures in a marina and as such have no or minimal interaction with the seabed, however AMS components may be used on floating pontoons as a method to cope with tidal variation. These types of moorings have not been considered in this study.

6.2. Advanced Mooring Systems (AMS)

This section outlines the AMS considered in the scope of this study, the technical details of the mooring components were provided by the suppliers.

Hazelett

The Hazelett Conservation elastic mooring system is a commercially available product manufactured and supplied by the American firm Hazelett Marine. The Hazelett system uses an elastic rode component to provide a spring between the surface buoy and anchor (Figure 5). Although a spar is pictured in the marketing material, discussions with Hazelett have concluded that a traditional hippo type buoy (same as baseline) or Norfloat would be more appropriate for the conditions in this study.

The surface line (for vessel connection) can be equivalent to that used in a typical block and chain mooring, with the length specified by the boat owner or marina.

Traditional gravity anchors can be used, with the overall mooring loads expected to be less than a catenary mooring. The preference is however, for Screw/Helical pile anchors, for two reasons: firstly, they have minimal impact on the seabed due to the small amount of interaction; and secondly, they are more suited to vertical loading, whereas a gravity anchor gains an advantage through the friction on the seabed.

During technical discussions Hazelett have indicated that a large tidal variation in shallow water depth would result in a situation where the downline could be close to or at the water surface at low tide. Ultimately this results in mooring components exposed to passing vessel propellers, which poses unacceptable risk. As all the sites in this study possess this trait, the Hazelett system has been excluded from the analysis.

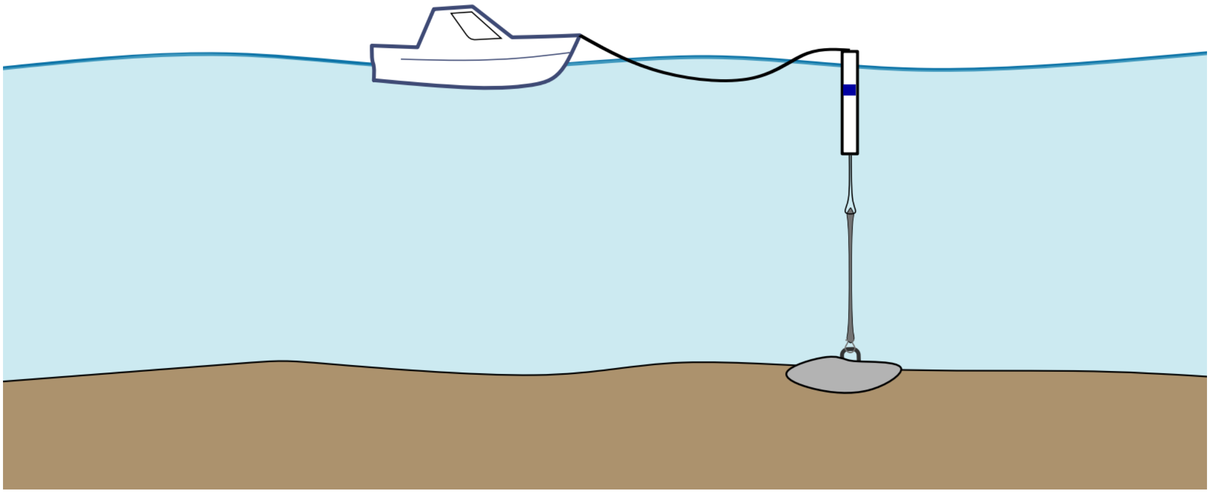


Figure 5: Hazelett mooring arrangement

Seaflex

Seaflex is a Swedish supplier of the similarly named product Seaflex AMS. The main part is a reinforced homogeneous rubber hawser. The system also includes a specific buoy type. The buoy incorporates a stiff arm at the top for connecting the surface line and at the bottom where a short sling joins to the top of the elastic rode. A length of synthetic line connects the rode to the anchor (Figure 6). The arrangement differs to that of the Hazelett in that the elastic rode is closer to the surface, whereas in the Hazelett system the rode is connected directly to the anchor. The Seaflex rode has novel elastomeric qualities, captured in modelling but not presented due to commercial sensitivity.

The surface line (for vessel connection) can be equivalent to that used in a typical block and chain mooring, with the length specified by the boat owner or marina.

It is possible to use either traditional gravity anchors or screw type anchors with the Seaflex arrangement, with preference to the helical screw due to the lack of interaction with the surrounding seabed.

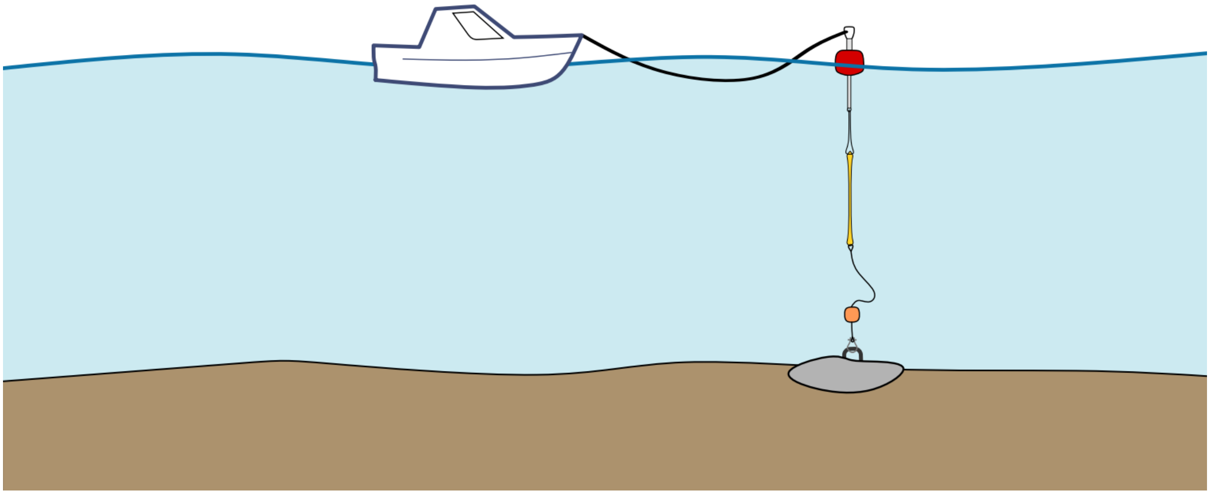


Figure 6: Seaflex mooring arrangement

Stirling

The Stirling system provides the least change from the baseline in terms of construct. The rode itself is plain chain however rather than acting as a typical catenary with a section of ground chain, a series of small buoys or floats are attached along the length, keeping the chain suspended in the water column (Figure 7). In this instance, the buoyant properties replace the effect of the mass of chain in the plain catenary, but still providing similar a spring effect but without interaction with the seabed.

As with the other AMS systems, the surface line (for vessel connection) can be equivalent to that used in a typical block and chain mooring, with the length driven by the boat owner or marina. Also, either traditional gravity anchors or helical screw anchors can be used.

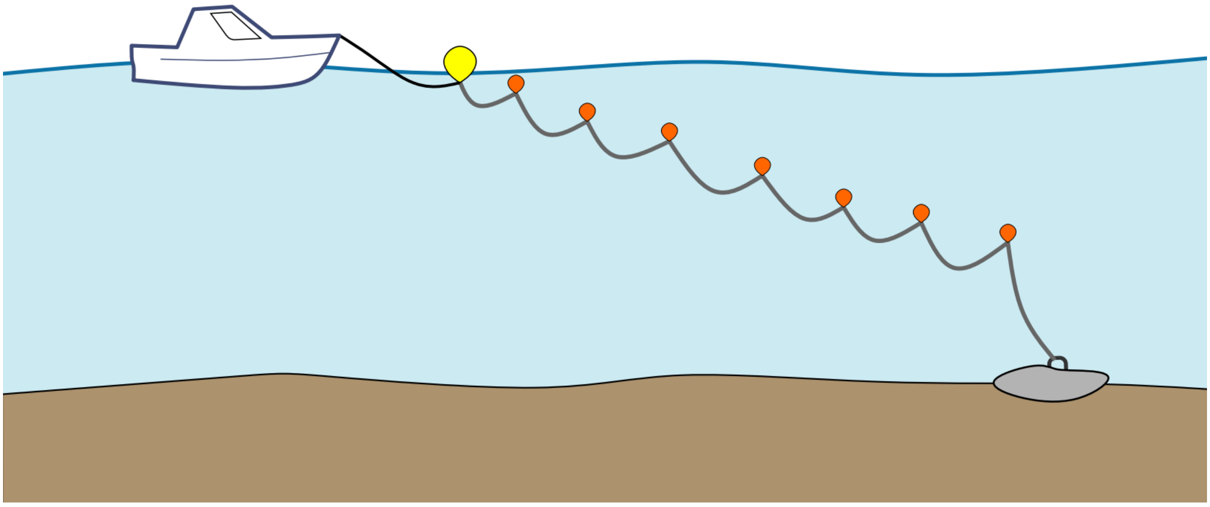


Figure 7: Stirling mooring arrangement

7. ENVIRONMENTAL DATA

7.1. Environmental baseline data

Table 2 summarises environmental data for the harbours gathered via stakeholder surveys.

	Plymouth	Falmouth	Isle of White / Solent	Essex	Isles of Scilly
Depths	1 to 5m	0.5 to 5.6m	0.5 to 2.8m	0 to 7m	0 to 2.8m
Tidal range	5.5	6	3.5	5.9	6
Sheltered Wind direction	N, W, SW	All except E	W, SW, E, SE	W	NE, SW
Exposed Wind direction	SE	E	NW, NE	E	W, N
Significant Tidal current	0.5	0.5	2	0.5	0.25
Principle ebb and flow directions	S (Ebb) N (Flood)	SE (Ebb) NW (Flood)	N (Ebb) S (Flood)	E (Ebb) W (Flood)	W (Ebb) E (Flood)
Summer Wave height	0.5	Unknown	0.9	0.75	2
Summer Wave period	10	Unknown	6	Unknown	5
Annual Extreme Wave Height	1.5	Unknown	1.5	0.5	2.5
Annual Wave period	8	Unknown	6	Unknown	5
Most common Wave direction	W	E	W	W, E	W

Table 2: Feedback from stakeholder engagement

7.2. Environmental modelling parameters

The environmental data used in the simulations has been derived to reflect the responses from harbours and marinas. Across the five sites considered, the water depths and extreme tidal ranges will be used. Two sets of load cases have been derived for the purpose of this study.

- **Benign** – The benign case represents a realistic seasonal maximum (termed the 'benign'), this load case represents the most likely conditions for a pleasure craft sat at a mooring throughout the summer boating season (May to September).
- **Energetic** – The energetic load case is a more extreme scenario, more likely to represent the likely peak loads for a permanently moored vessel experiencing all four seasons. This case will provide a more conservative set of load cases and help to understand the limits of the mooring systems.

It is important to note that these conditions are deemed representative, they are not a result of detailed oceanographic simulation or data collection and as such should be approached with due caution.

Tidal Elevation

The charted depths suitable for swing moorings across the four sites range from 3m to 5m, with a tidal range of +6m. This has been distilled into two base cases for water depth, each with two variations of tidal range, these will be applied across benign and energetic load cases.

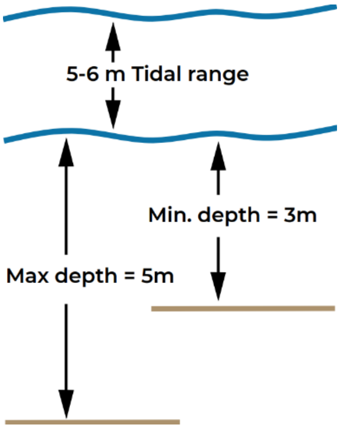


Figure 8: Tidal elevation and range

Surface Current Speed

The maximum surface current speed expected on any of the sites is 0.5m/s (c.1kt), which will be selected for the energetic load cases whereas the benign load cases will consider a current speed of 0.1m/s (c.0.2kt).

Wind

The energetic wind climate is classed as a beaufort force 7-8 or near gale to gale (see Appendix A – Beaufort Scale), with a sustained wind speed of 18.5m/s (c.37kt). The benign wind climate will be defined as a beaufort force 3 or a gentle breeze, with a sustained wind speed of 5m/s (c.10kt).

Wave

A range of wave conditions have been assessed, for both the benign and energetic load case sets three wave heights have been assessed. These heights have been paired with wave periods derived from wave steepness values of 1/60 and 1/50 respectively. Figure 9 shows all Hs Tp combinations for both load case sets as stated below;

- Benign load cases: Hs = 0.25m, 0.5m and 0.75m (1/60 steepness)
- Energetic load cases: Hs = 0.75m, 1.0m and 1.25m (1/50 steepness)

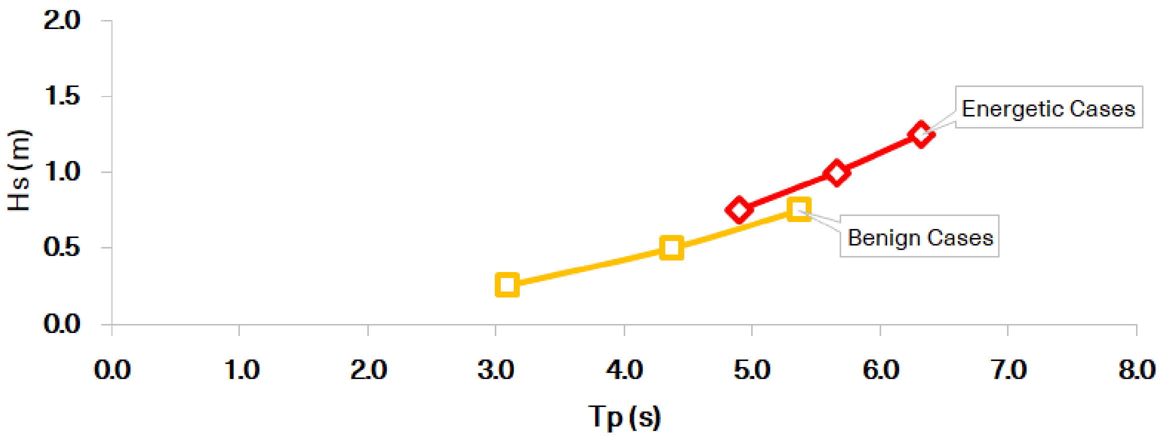


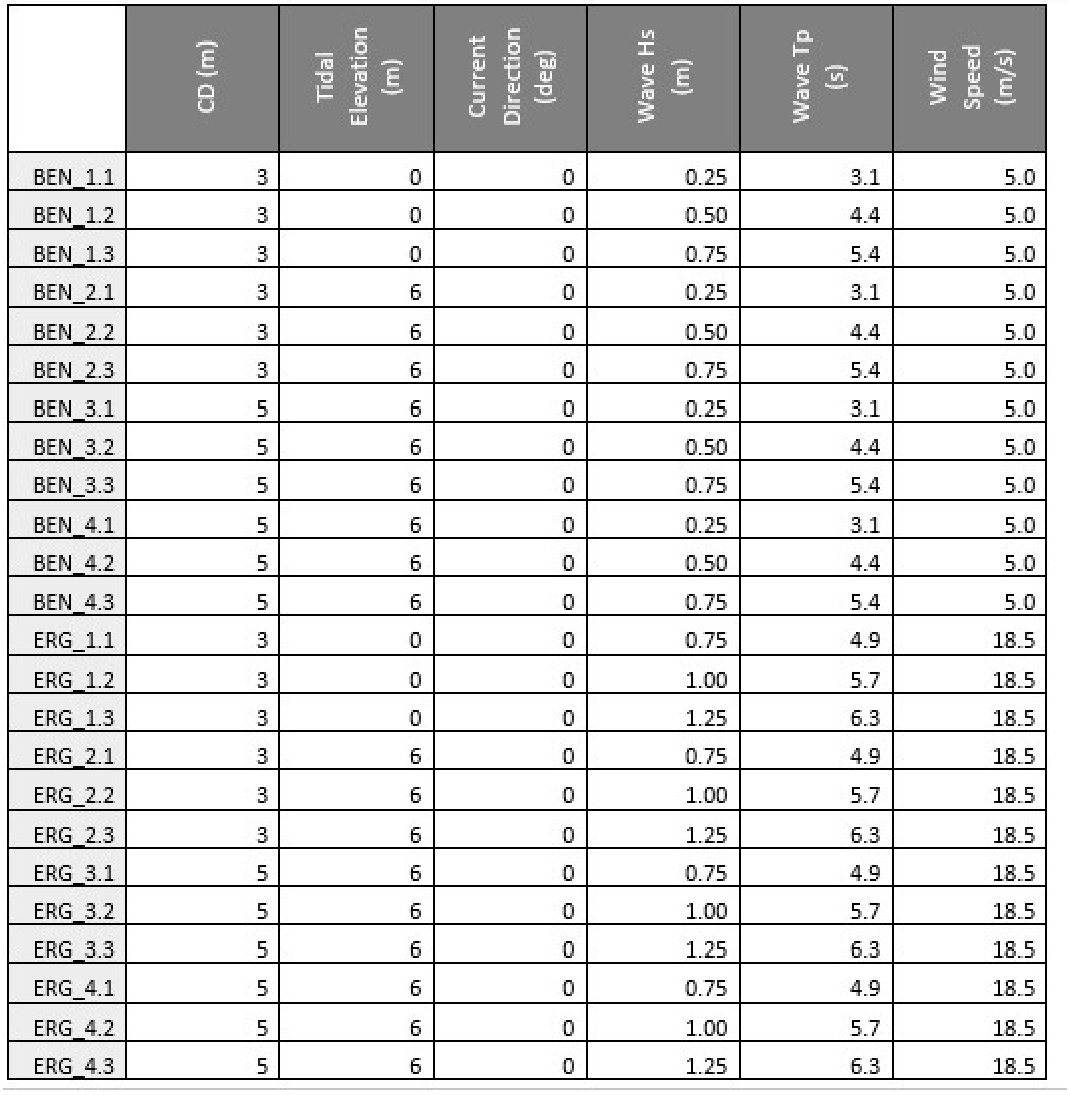
Figure 9: Sea states

Load cases

The following load case table shows a concise summary of representative environmental conditions for the assessment of the AMS systems. The load cases cover combinations of the following;

- 2 Charted depth cases (3 and 5m)
- 2 tidal range scenarios (0 and +6m)
- 1 set of current and wind strengths, remaining static throughout.
- 3 Significant wave heights with corresponding wave periods

These variables generate a total of 24 individual load cases to be used in the analysis, as shown in Table 3.



	CD (m)	Tidal Elevation (m)	Current Direction (deg)	Wave Hs (m)	Wave Tp (s)	Wind Speed (m/s)
BEN_1.1	3	0	0	0.25	3.1	5.0
BEN_1.2	3	0	0	0.50	4.4	5.0
BEN_1.3	3	0	0	0.75	5.4	5.0
BEN_2.1	3	6	0	0.25	3.1	5.0
BEN_2.2	3	6	0	0.50	4.4	5.0
BEN_2.3	3	6	0	0.75	5.4	5.0
BEN_3.1	5	6	0	0.25	3.1	5.0
BEN_3.2	5	6	0	0.50	4.4	5.0
BEN_3.3	5	6	0	0.75	5.4	5.0
BEN_4.1	5	6	0	0.25	3.1	5.0
BEN_4.2	5	6	0	0.50	4.4	5.0
BEN_4.3	5	6	0	0.75	5.4	5.0
ERG_1.1	3	0	0	0.75	4.9	18.5
ERG_1.2	3	0	0	1.00	5.7	18.5
ERG_1.3	3	0	0	1.25	6.3	18.5
ERG_2.1	3	6	0	0.75	4.9	18.5
ERG_2.2	3	6	0	1.00	5.7	18.5
ERG_2.3	3	6	0	1.25	6.3	18.5
ERG_3.1	5	6	0	0.75	4.9	18.5
ERG_3.2	5	6	0	1.00	5.7	18.5
ERG_3.3	5	6	0	1.25	6.3	18.5
ERG_4.1	5	6	0	0.75	4.9	18.5
ERG_4.2	5	6	0	1.00	5.7	18.5
ERG_4.3	5	6	0	1.25	6.3	18.5

Table 3: Load cases for dynamic analysis

8. SIMULATION

The numerical modelling has been undertaken with the marine dynamics software Orcaflex, the world's leading package for the dynamic analysis of offshore marine systems, regularly used for the design and analysis of moorings.

Models were generated for each of the AMS arrangements in the OrcaFlex user interface, capturing the following attributes of the systems:

- Vessel response characteristics: from the diffraction analysis detailed above.
- Behaviour of the buoys: hydrostatics and hydrodynamics.
- Behaviour of the chain and synthetic lines: structural stiffness and hydrodynamics.
- The anchor is assumed as fixed, with the end of the line attached to a point on the seabed, the loads will be reported for consideration of anchoring technologies.

The dynamic simulations were run for 3600seconds (60 minutes). The following environmental conditions were applied:

- Tidal current and wind: applied as a constant static load on the vessel and mooring components.
- Wave conditions: Pierson Moskovitz wave spectra with peak shape parameter, γ = 1, the same seed has been used for each environmental case throughout, resulting in identical wave trains for each mooring arrangement.

8.1. Baseline

The baseline model has been setup with a varying length of catenary chain for each charted depth. The catenary accommodates the tidal variation and allows for a small amount of chain to always be in contact with the seabed, even at the deepest condition. The ground chain ensures this type of system only applies horizontal loading to the anchor itself. Exact details of the specific lengths were not provided by individual harbours, as such a suitable configuration has been designed to suit the range of depths in this study. The arrangement uses the mooring components shown in Table 4 and illustrated in Figure 10.

Item	Description	Type	Diameter (mm)	Length (m)
1.	Catenary chain	Studlink chain	30	Varies
2.	Surface buoy	Norfloat or similar	800	-
3.	Surface line	Nylon multistrand	40	4

Table 4: Mooring component Bill of Materials (BOM) - Baseline

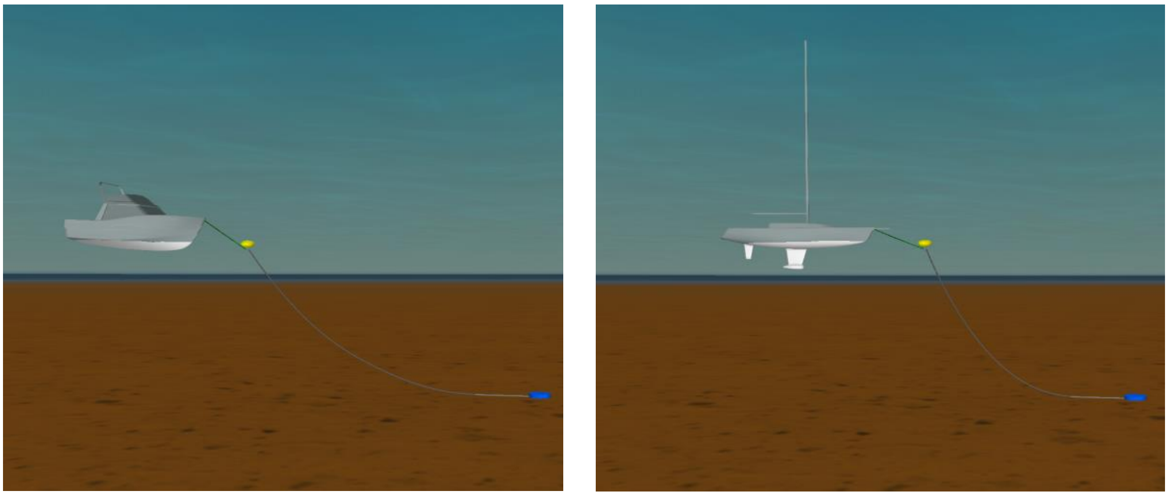


Figure 10: OrcaFlex model setup (left: motor launch, right: sailing vessel) – Baseline

8.2. Seaflex

The Seaflex model has been setup with a 2-hawser bypass system, like the Hazelett system although provided as a single product. The hawser is connected to the bottom of the buoy (via a short sling) unlike the Hazelett system which connects directly to the anchor. A small float is attached approximately halfway down the riser, allowing the system to accommodate the tidal variation. The arrangement uses the mooring components shown in Table 5 and illustrated in Figure 11.

Item	Description	Type	Diameter (mm)	Length (m)
1.	Riser section	Nylon multistrand	40	Varies
2.	Submerged float	9.8L trawl float	-	-
3.	Elastic rode	Seaflex product	-	2
4.	Sling	Nylon multistrand	40	0.5
5.	Surface buoy	Seaflex product	600	-
6.	Surface line	Nylon multistrand	40	4

Table 5: Mooring component Bill of Materials – Seaflex

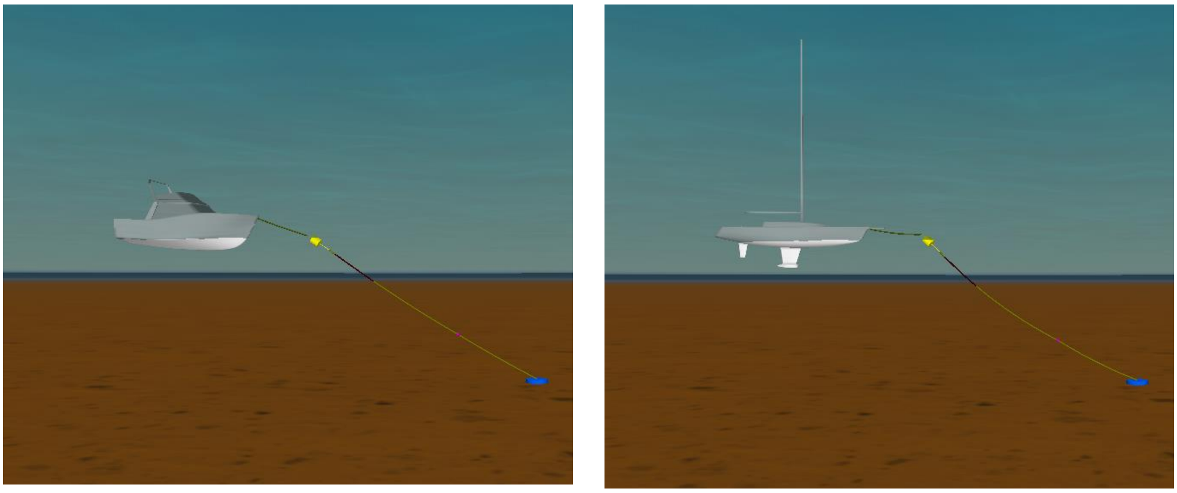


Figure 11: OrcaFlex model setup (left: motor launch, right: sailing vessel) - Seaflex

8.3. Stirling

The Stirling model has been setup with a varying length of catenary chain for each charted depth, which is lighter than that of the baseline, and incorporates small trawl floats attached along its length. The arrangement uses the mooring components shown in Table 6 and illustrated in Figure 12.

Item	Description	Type	Diameter (mm)	Length (m)
1.	Riser chain	Studlink chain	20	Varies
2.	In line buoyancy	Trawl floats	280	-
3.	Surface buoy	Norfloat or similar	700	-
4.	Surface line	Nylon multistrand	40	4

Table 6: Mooring component Bill of Materials - Stirling

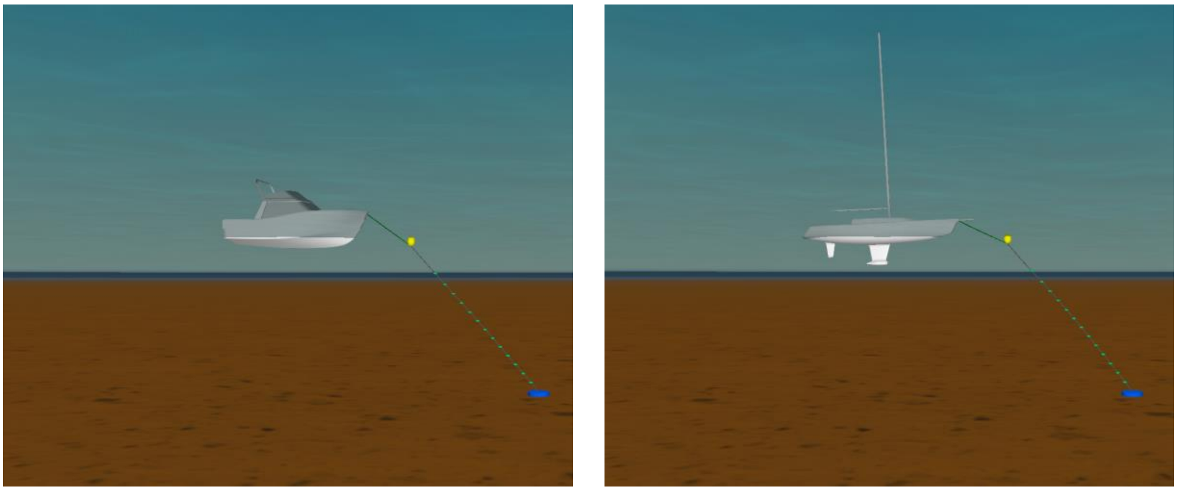


Figure 12: OrcaFlex model setup (left: motor launch, right: sailing vessel) – baseline

9. RESULTS

This section outlines the results from the dynamic analysis. The results have been reported as per each charted water depth, representing the range of harbours considered in this study.

9.1. Water Depth = 3m

This water depth represents the shallower moorings at Plymouth, Falmouth and Essex as well as the deeper moorings at Isle of Wight, Solent and Isles of Scilly.

Mooring Stiffness

The following plots show the tension in the surface line each of the mooring arrangements with respect to excursion from the anchor point. The stiffness of the system is noted as the gradient of these curves. Figure 13 shows the stiffness of the Stirling and baseline are similar, showing a similar increase in force for a given extension. The Seaflex system shows a greater extension for a given force, hence a lower overall stiffness.

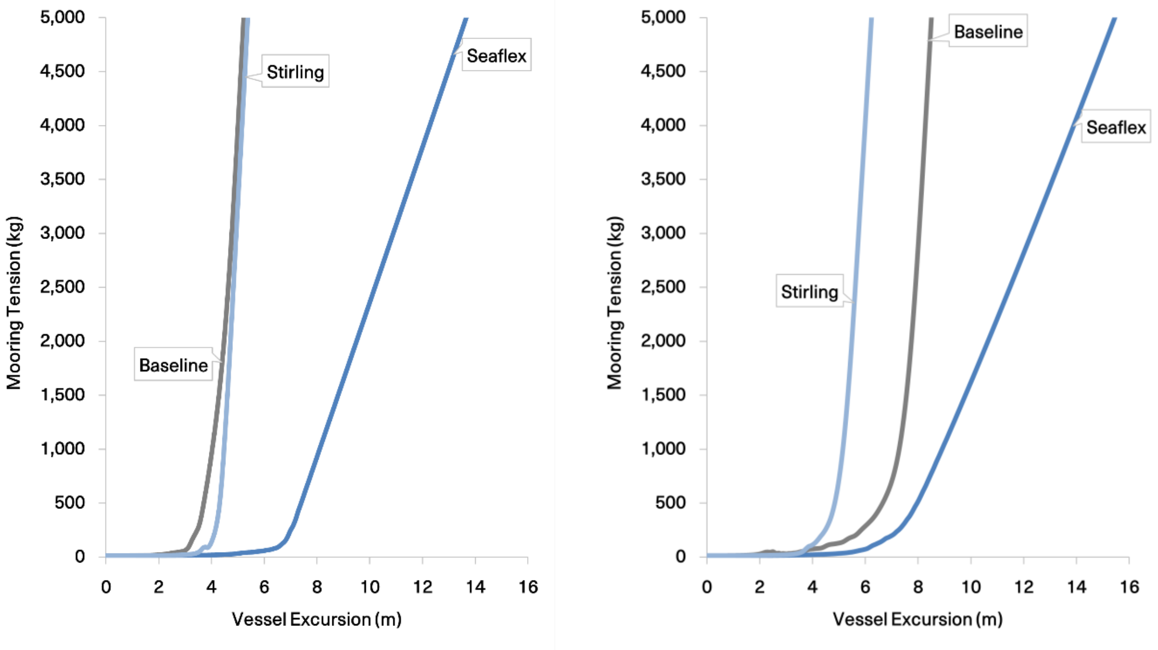


Figure 13: Mooring stiffness plots (left: 3m depth, right: +6m tidal elevation)

Excursions

The graph below shows the maximum horizontal excursion of the vessels when connected to the AMS at the low tide condition (providing greater excursions than the high tide condition). As stated above it is accepted that the baseline catenary chain length is unknown, so this comparison must be treated with caution, however there will be saving in watch circle as there is no requirement for ground chain for any of the AMS.

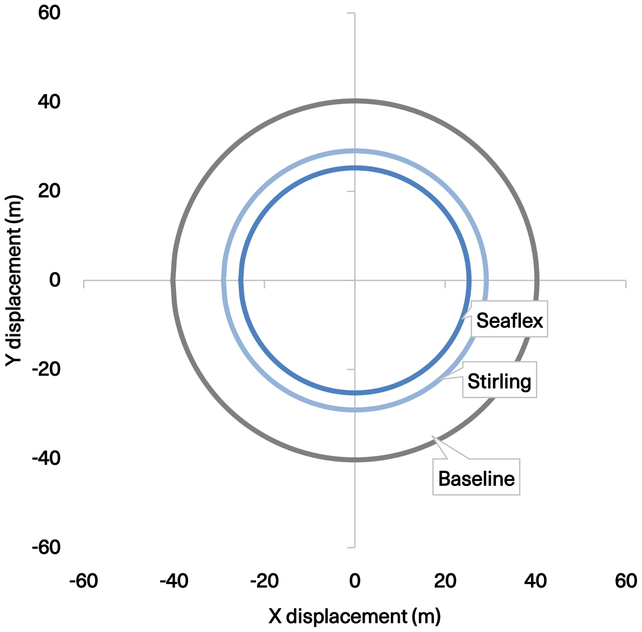


Figure 14: Max vessel excursion, depth = 3m, benign load cases

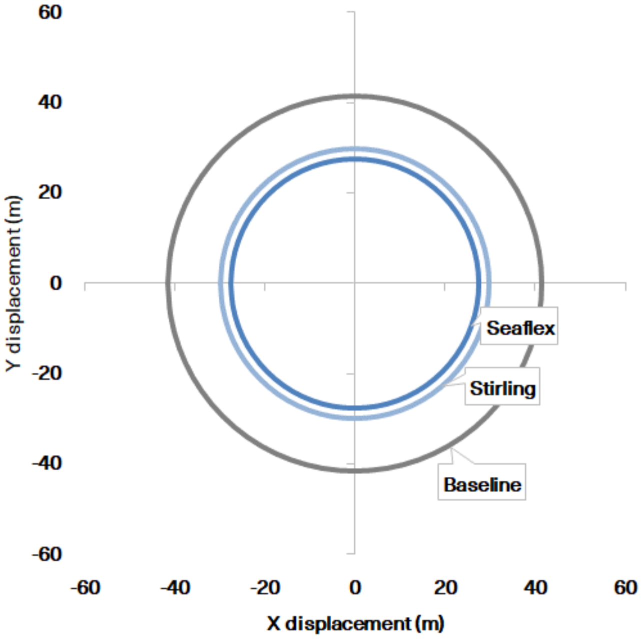
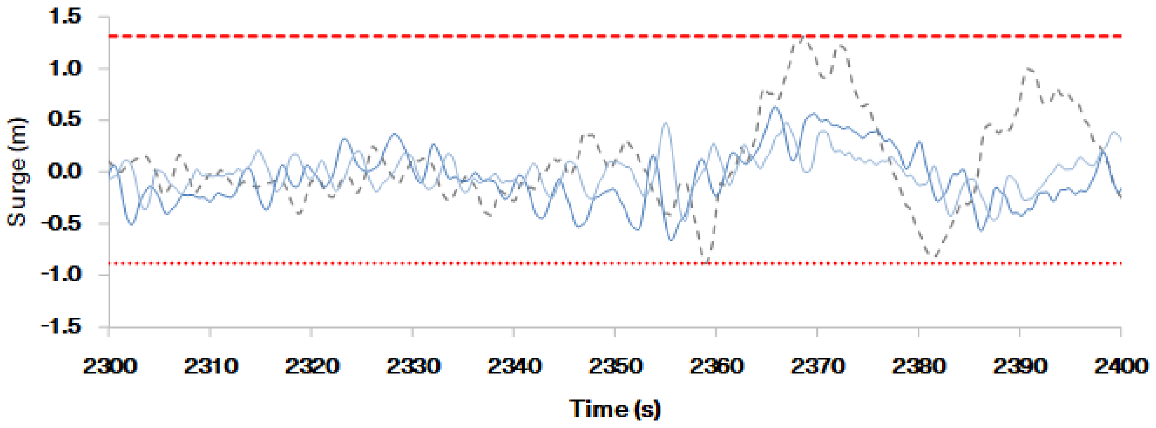
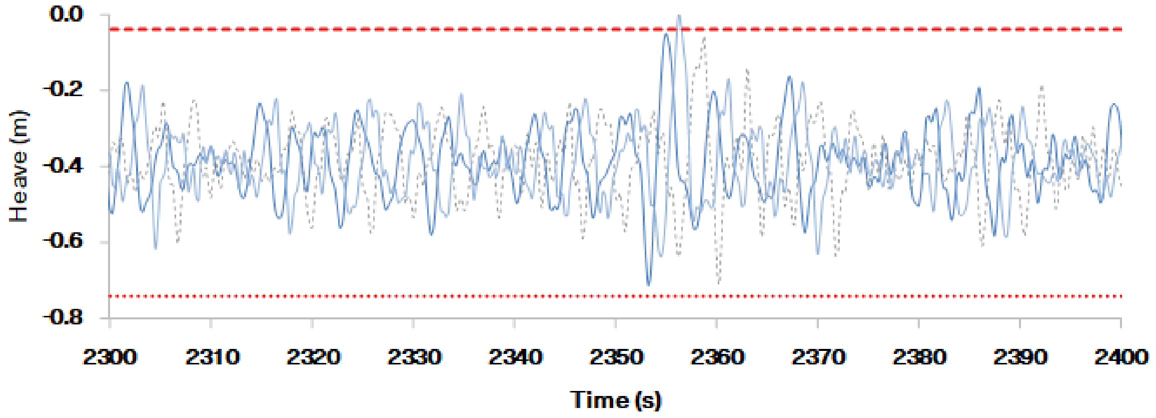


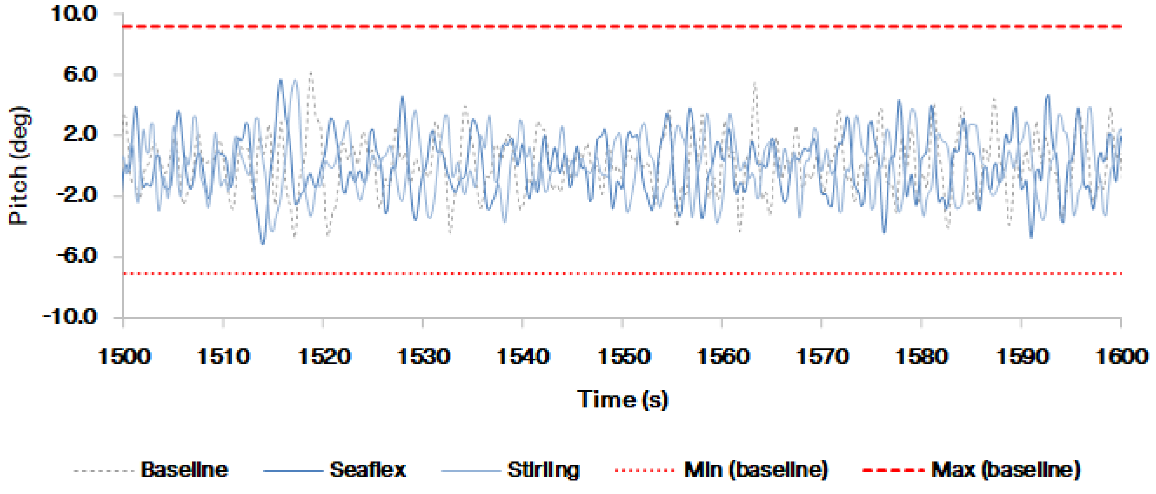
Figure 15: Max vessel excursion, depth = 3m, energetic load cases

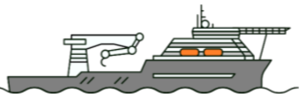
Vessel Motions

In general, the response of the vessel when connected to the AMS was very similar to that of the baseline. The plots below show a snapshot of time from the 5m motor launch at 3m water depth with Hs=0.5m and Tp=4.4s, a case that is anticipated occur frequently. The heave and pitch show good correlation between the AMS and the baseline, there are some events when the baseline system shows slightly greater surge response.









Mooring Loads

The anchor tensions are reported as the resultant load acting in line with the mooring leg at both the anchor and cleat end of each mooring. The precision of these loads should be treated with caution, without the opportunity to validate vessel hydrodynamic characteristics it is only possible to use this output as representative in the sense of absolute values. The output is however a suitable comparator between the three systems.

Benign Load Cases -

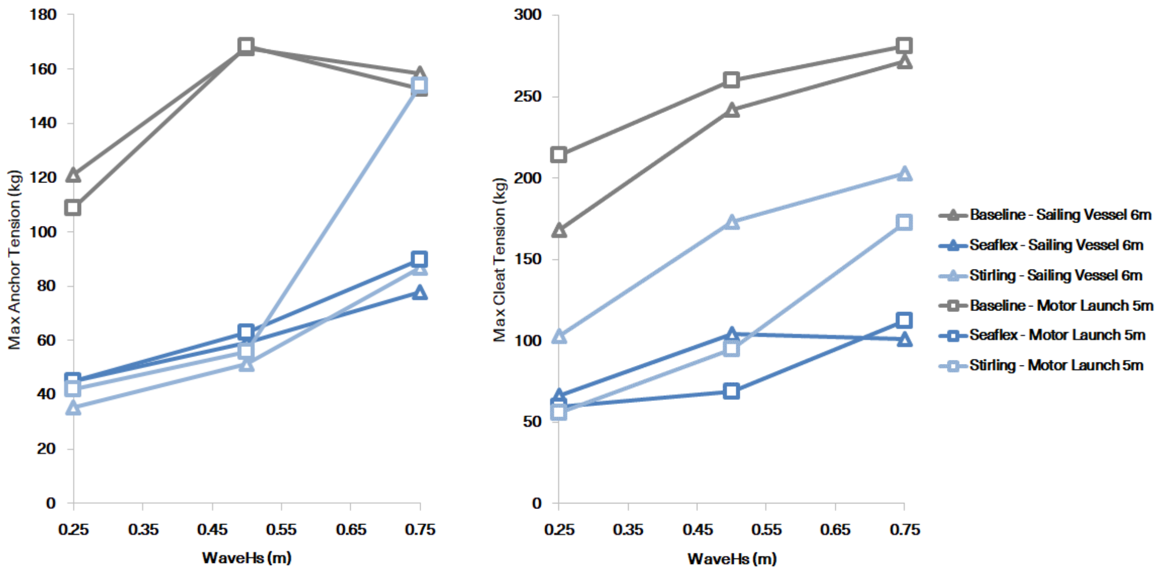


Figure 16: Mooring loads for the smaller vessels, d=3m (left = anchor tensions, right = cleat tensions)

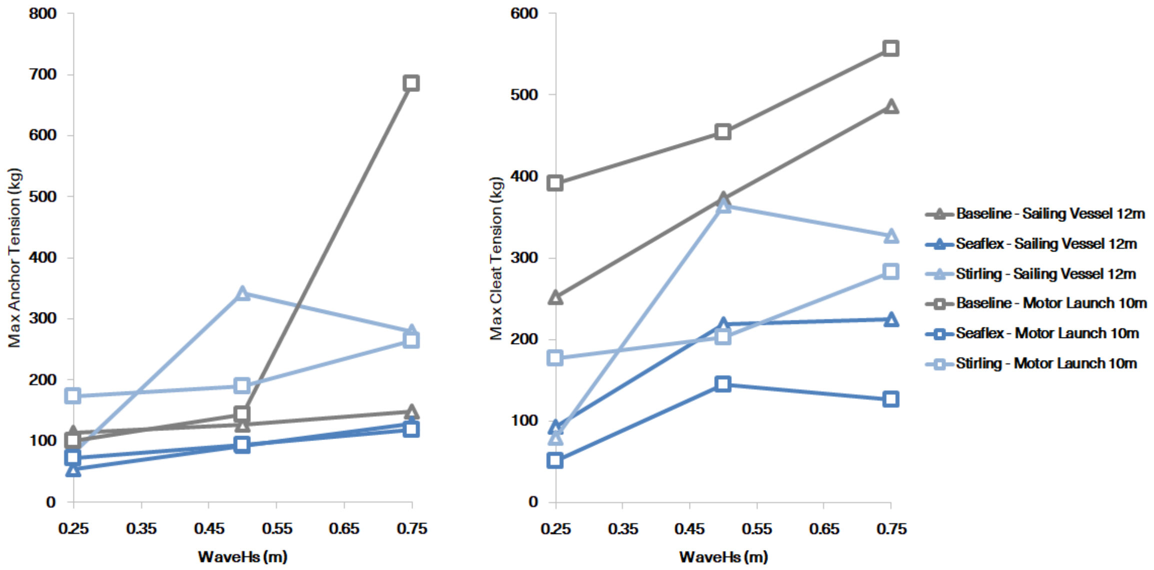


Figure 17: Mooring loads for the larger vessels, d=3m (left = anchor tensions, right = cleat tensions)

Shallow water benign cases both AMS produced lower peak loads than the baseline, except for the larger vessel anchor tension in smaller sea states.

Cleat tensions were in the order of magnitude of 50-250 kg and greatest for the baseline system.

Anchor tensions approximately similar for the AMS systems (peak 80kg) and approximately double for the baseline catenary (peak 160kg)

The cleat loads were approximately double for the larger displacement vessel, showing a similar relationship for each mooring system, the baseline exhibiting the highest peak loads.

The anchor loads show slight differences for the larger displacement vessel, the chain system still shows the highest peak value (700kg) however the Stirling system also shows a high peak in the intermediate wave height (300kg).

When compared to the motor yacht the sailing vessel tends to demonstrate higher overall loads for the Stirling system, conversely the sailing vessel shows lower loads for the chain baseline.

Energetic Load Cases -

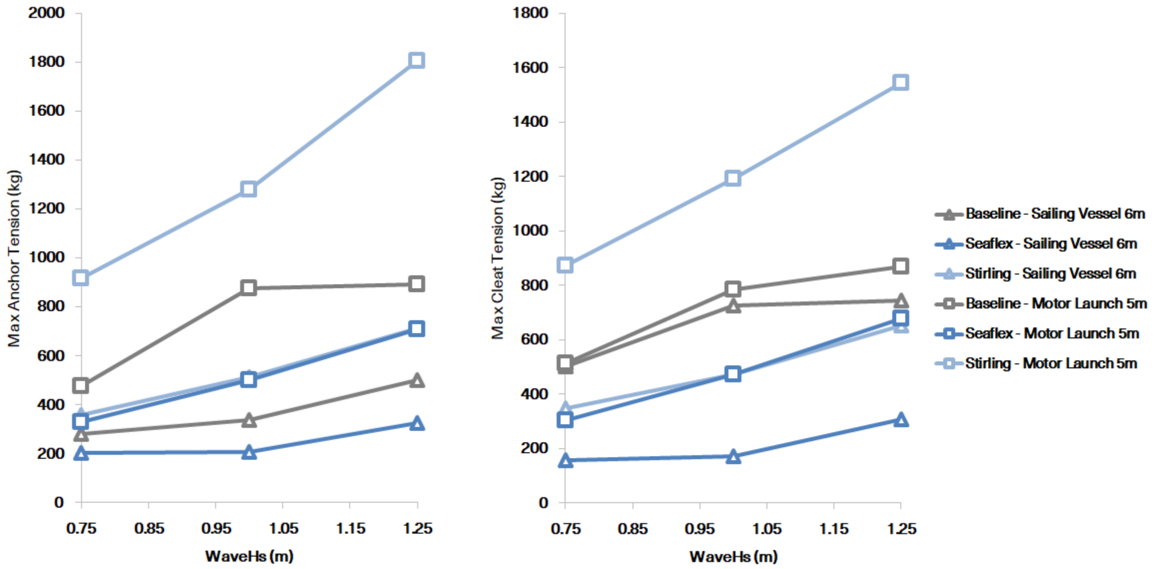


Figure 18: Mooring loads for the smaller vessels, d=3m (left = anchor tensions, right = cleat tensions)

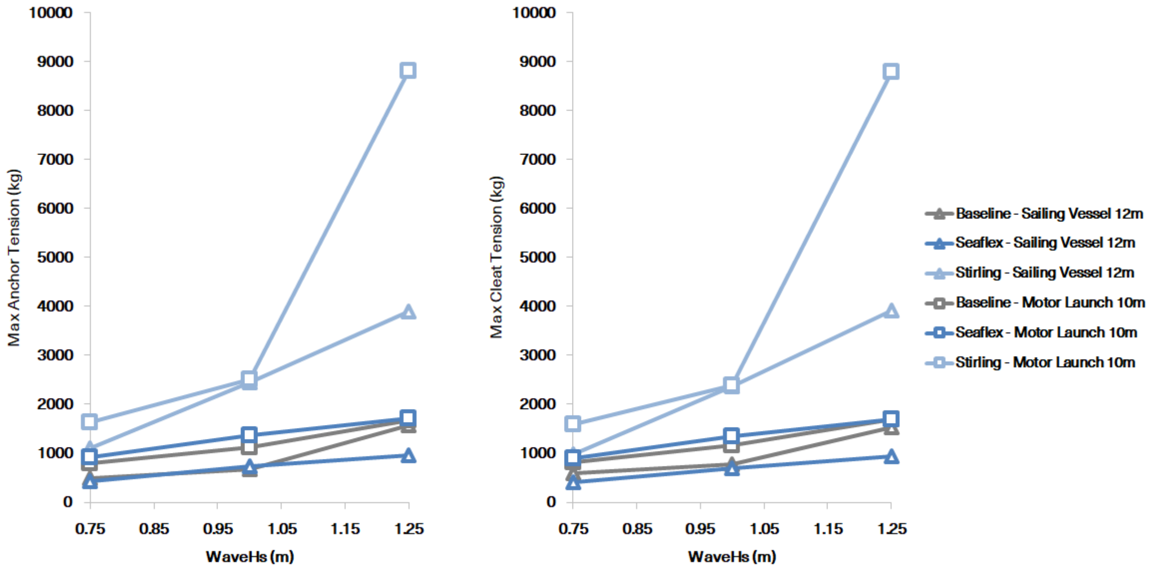


Figure 19: Mooring loads for the larger vessels, d=3m (left = anchor tensions, right = cleat tensions)

The peak tension values for the energetic simulations are significantly higher (as expected) than the benign cases. The Stirling system with the motor launch consistently produces the highest peak loads at both anchor and cleat for both vessel sizes. The Seaflex system with the sailing vessel offers the lowest peak tensions with the sailing vessel over both vessel sizes.

9.2. Water Depth = 5m

This water depth represents the deeper moorings at Plymouth, Falmouth and Essex. The results are presented in the same format as those of the 3m depth, against vessel size and load case energy levels.

Mooring Stiffness

As seen in the shallow water depths the stiffness of the Stirling and baseline catenary are similar, with the Seaflex again showing a lower gradient and higher overall excursion for a given force. The deeper water scenario provides less overall tension from the Stirling system but equivalent stiffness values.

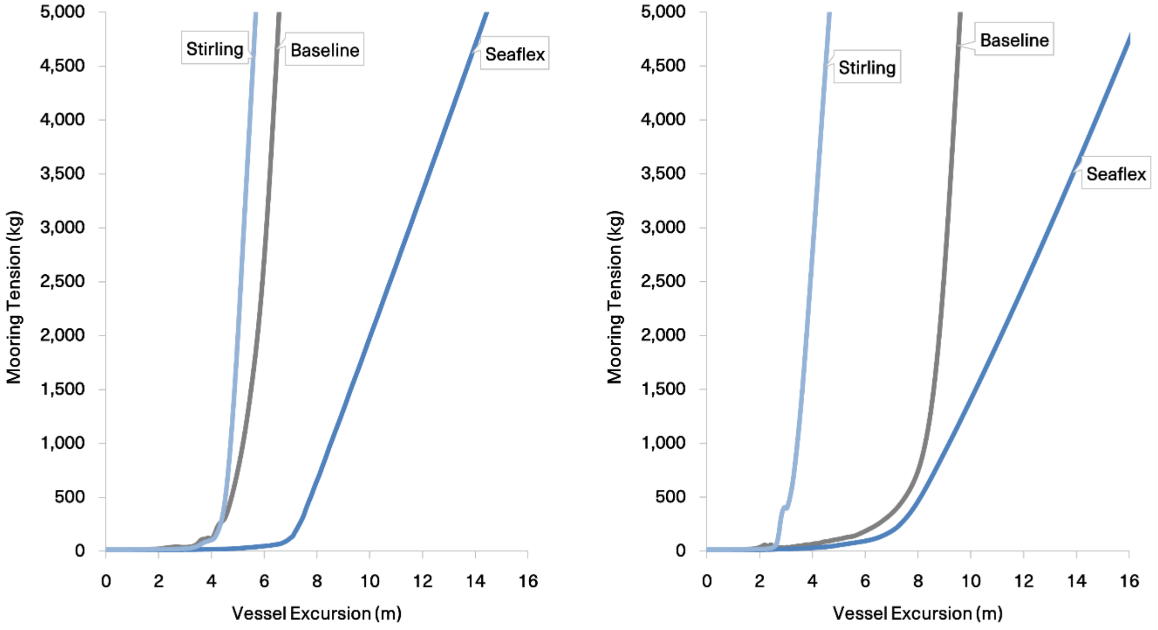


Figure 20: Mooring stiffness plots (left: 5m depth, right: +6m tidal elevation)

Excursions

The graph below shows the maximum horizontal excursion of the vessels when connected to the AMS at the low tide condition (providing greater excursions than the high tide condition). As stated above it is accepted that the baseline catenary chain length is unknown, so this comparison must be treated with caution, however there is a clear saving in watch circle as there is no requirement for ground chain for any of the AMS.

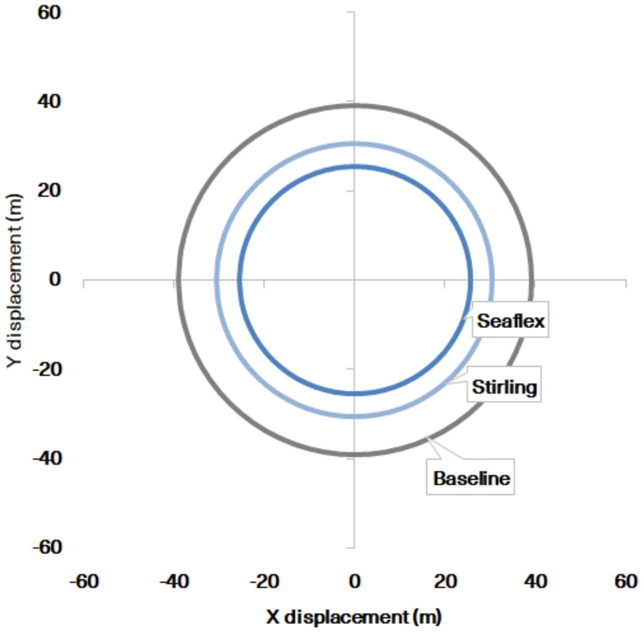


Figure 21: Max vessel excursion, depth = 5m, benign load cases

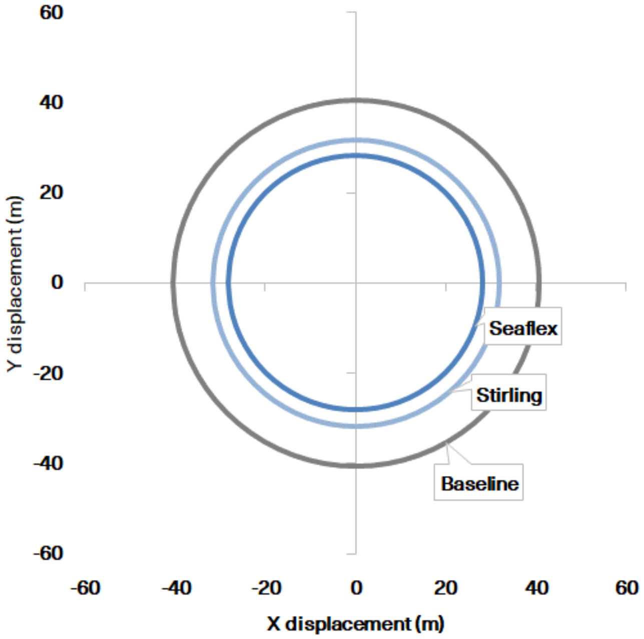


Figure 22: Max vessel excursion, depth = 5m, energetic load cases

Vessel Motions

Like the lower depth simulations, the overall response of the AMS systems is similar to that of the baseline. The plots below show a snapshot of time from the 12m sailing vessel at 5m water depth with Hs=0.25m and Tp=3.1s, a case that is anticipated occur frequently. The amplitude of the motions shows good correlation between the AMS and the baseline, although they are generally out of phase.

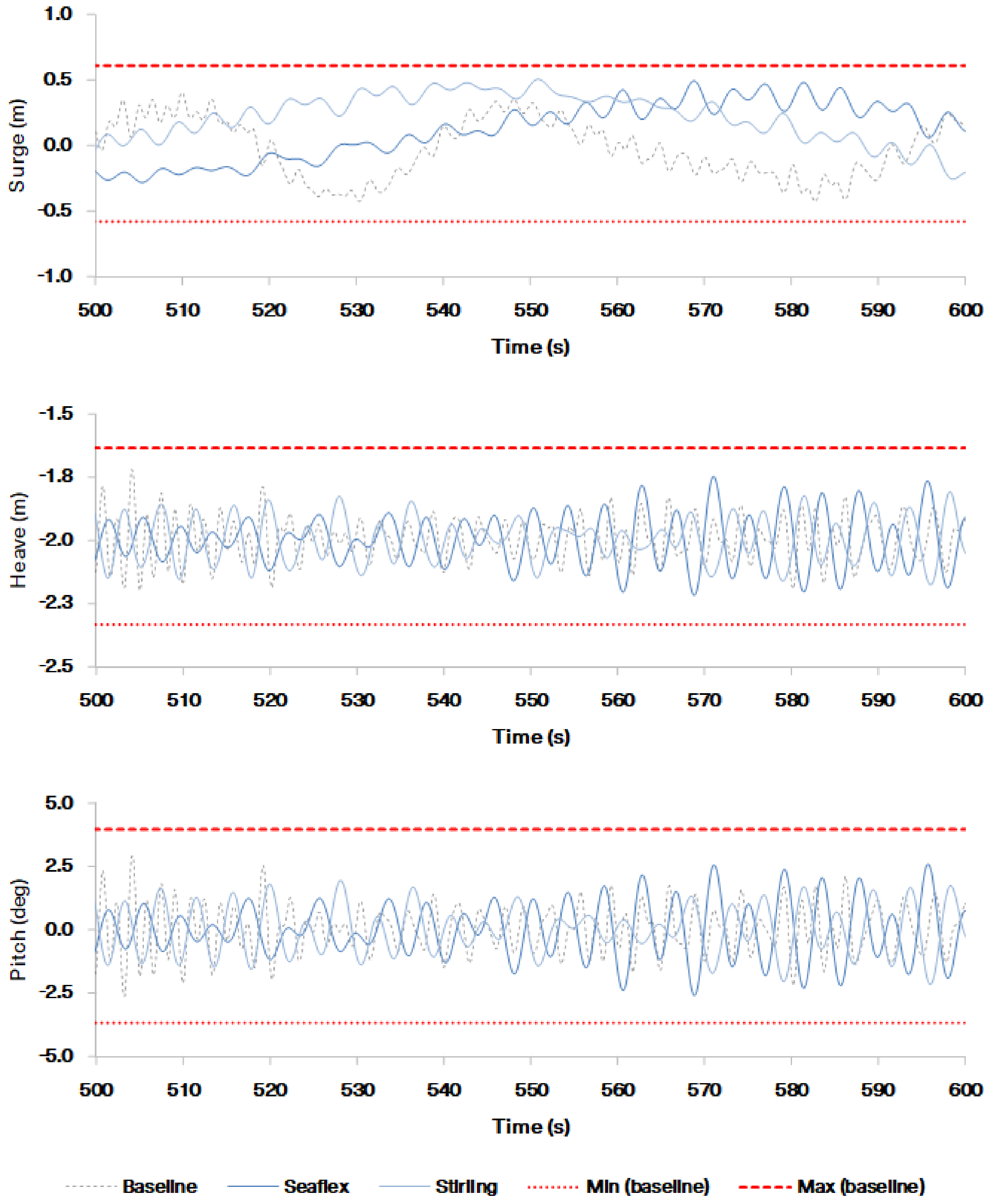


Figure 23: Time-history vessel motions (top: surge, middle: heave, bottom: pitch)

Mooring Loads

The following figures show the overall peak loads outputs from the simulations, presented in the same format as the lower depth load sets.

Benign Load Cases -

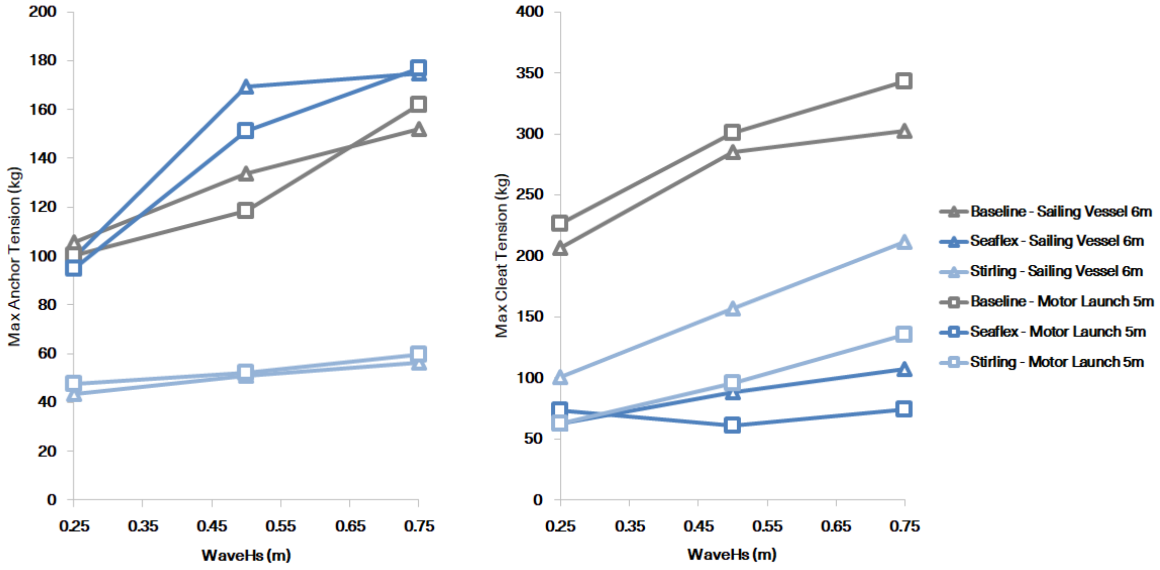


Figure 24: Mooring loads for the smaller vessels, d=5m (left = anchor tensions, right = cleat tensions)

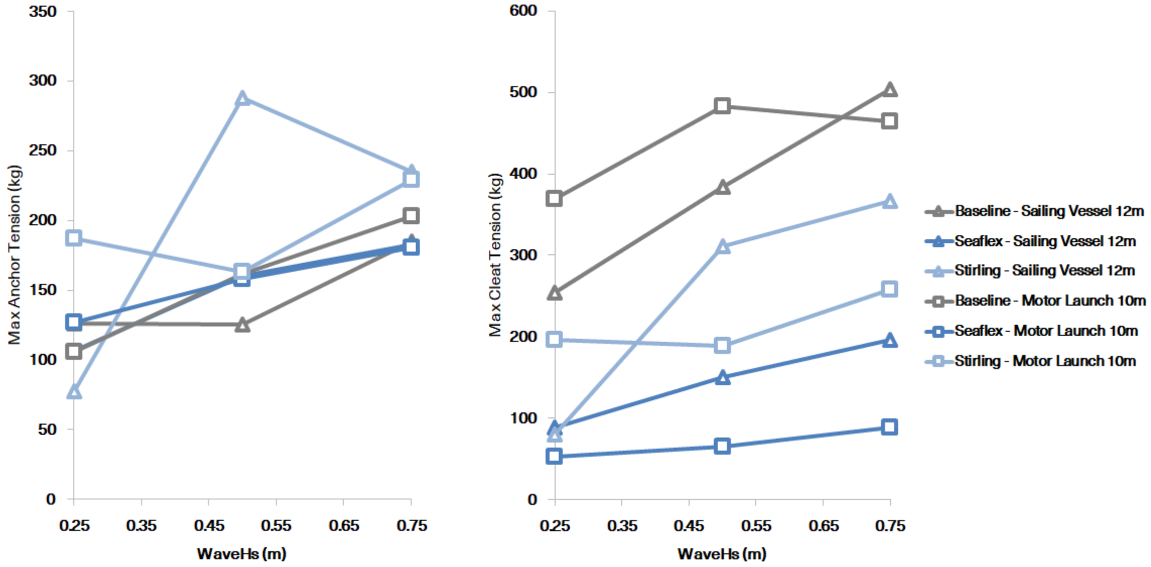


Figure 25: Mooring loads for the larger vessels, d=5m (left = anchor tensions, right = cleat tensions)

The AMS systems show a significant reduction in overall cleat tension across all simulations for the smaller vessel, the Seaflex system appears to produce the lowest loads, with least overall variation across the range of wave heights.

The cleat relationships are broadly matched with the larger vessel, again with the baseline generating the largest peak load and the Seaflex resulting in the lowest peak loads.

The anchor tensions appear to be broadly similar for the Seaflex and the chain catenary, the Stirling system shows lower overall anchor loads.

The anchor loads are less clear with the larger vessel simulations, these show the Stirling mooring to provide the largest loads. There is not a clear distinction between the baseline and Seaflex systems.

Energetic Load Cases -

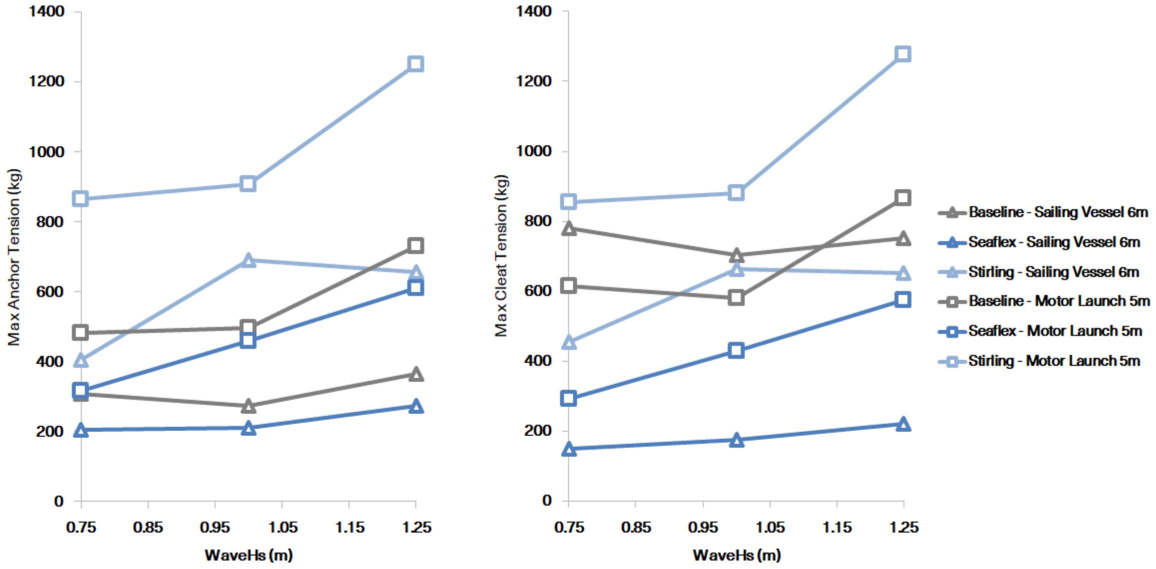


Figure 26: Mooring loads for the smaller vessels, d=5m (left = anchor tensions, right = cleat tensions)

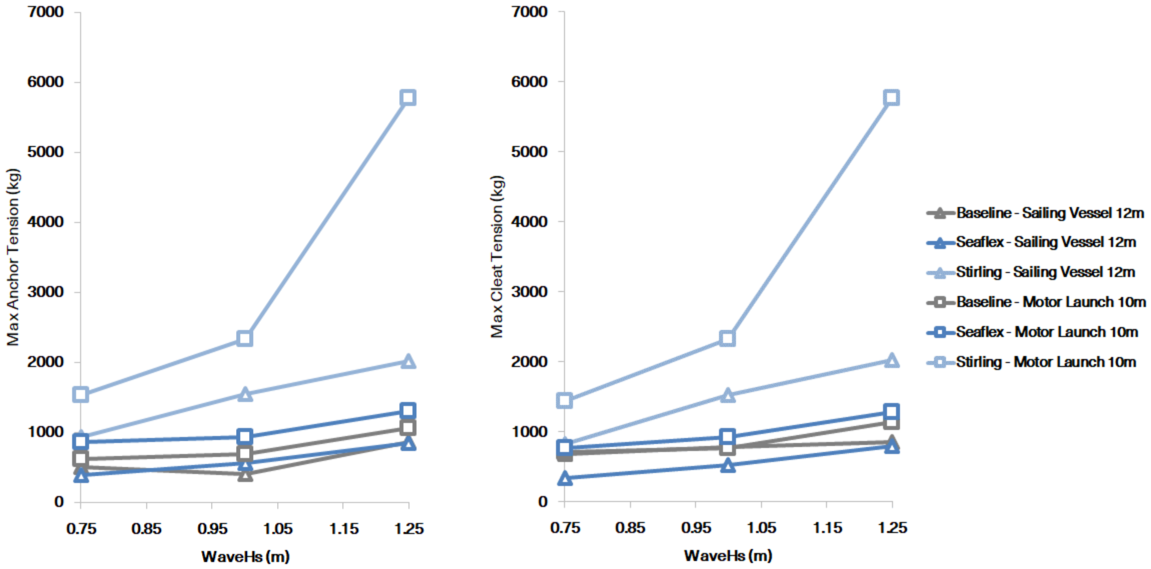


Figure 27: Mooring loads for the larger vessels, d=5m (left = anchor tensions, right = cleat tensions)

The energetic load cases show that for both the small and large vessel simulations the Stirling mooring provides the highest cleat and anchor loads at the deeper water depth. Peak loads for the larger motor vessel around 6 tonnes, compared to the Seaflex and baseline which are around 1 tonne at both cleat and anchor. The smaller motor vessel on the Stirling system shows 1.2 tonne loads at cleat and anchor.

The Seaflex system performs well for both the vessel sizes, showing a larger advantage in peak loads for the smaller vessel.

10. FINDINGS

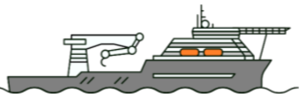
The general findings from the work show that there are significant opportunities for the proposed AMS systems to match and exceed the performance of the baseline chain catenary systems. The AMS systems show the capability of providing equivalent or in some cases reduced overall peak loads at a reduced excursion.

As with mooring designs of larger offshore systems there is a significant difference in the function of the systems when comparing the benign operating conditions with those of the extreme event or energetic conditions. This challenges the designer to accommodate the demands of the extreme conditions whilst maintaining a modest component specification.

A key observation from the study is that there is no clear front runner, both the Stirling and Seaflex systems have their advantages and disadvantages over the Baseline. Both systems provide smaller excursions resulting in the potential for increased packing density, and there is no significant difference in the vessel motions. However, when considering the cleat and anchor tensions it is difficult to distinguish a favourable mooring spread, this varies dependant on water depth, vessel size and operating regime (i.e. benign and energetic). The limitations of this study are such that a relatively small number of permutations of variables were considered, a more detailed assessment may provide a suitable data set to draw a conclusion with greater confidence.

All the sites considered in the study contained mooring locations that were represented by the 3m water depth. At these sites, the benign cases provided anchor and cleat loads of less than 1tonne and the energetic generally up to around 2tonne apart from some extreme cases. Plymouth, Falmouth and Essex contain deeper mooring locations which are represented by the 5m water depth. At this depth the anchor and cleat loads for the benign cases are all below 0.5tonne whereas the energetic cases are generally below 2tonne, again with some extreme cases providing much greater values.

Stirling system –
The Stirling system seems consistent in the capability to efficiently moor both vessels in the benign conditions with the lowest peak loads. However, the system has difficulty in maintaining this performance in the energetic sea states. The Stirling produced the largest cleat loads for both depths during these energetic simulations. It is suggested that the system might benefit from further refinement. An optimisation of the position and size of the buoyancy would be beneficial. It is expected that a graduation of overall buoyancy along the mooring line might be beneficial in creating more favourable stiffness characteristics for the two operating regimes.



Seaflex –
The Seaflex system has performed well in most simulations. It appears that the specific arrangement modelled in this work shows a better overall performance when mooring the larger of the two vessels. It is suggested that the smaller vessel mooring might benefit from re-sizing of the elastic rode and could provide gains in overall cleat and anchor load reduction.

11. RECOMMENDATIONS

One clear output from this and previous work is that there is a requirement for further work to optimise the AMS systems, whilst this study has shown promise for the technical merits of the AMS a direct and prescriptive set of guidelines is required to specify the exact arrangement of the AMS systems.

The overall absolute values of loads in this work appear to be slightly conservative, to determine more precise values a field trial campaign is recommended. Such a study would focus on the validation of the hydrodynamic assumptions of the input vessels, monitoring of the onset environmental conditions and also direct instrumentation of the mooring system.

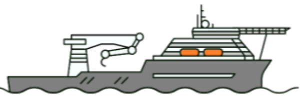
12. ABBREVIATIONS

Acronym	Definition
ABC	Helical pile supplier
AMS	Advanced Mooring System
BOM	Bill of Materials
ERDF	European Regional Development Fund
IOS	Isles of Scilly
IOW	Isle of Wight
LCB	Longitudinal Centre of Buoyancy
LHS	Left Hand Side
MCS	Marine Conservation Society
NMA	National Marine Aquarium
QHM	Queen's Harbour Master
RHS	Right Hand Side
RPT	Report
TBC	To Be Confirmed
VCB	Vertical Centre of Buoyancy
VCG	Vertical Centre of Gravity

Appendix A – Beaufort Scale

Beaufort wind scale	Mean Wind Speed (knots)	Mean Wind Speed (m/s)	Limits of wind speed (knots)	Limits of wind speed (m/s)	Wind descriptive terms	Probable wave height (m)	Probable max wave height (m)	Seastate	Sea descriptive terms
0	0	0	<1	<1	Calm	-	-	0	Calm (glassy)
1	2	1	1-3	1-2	Light air	0.1	0.1	1	Calm (rippled)
2	5	3	4-6	2-3	Light breeze	0.2	0.3	2	Smooth (wavelets)
3	9	5	7-10	4-5	Gentle breeze	0.6	1	3	Slight
4	13	7	11-16	6-8	Moderate breeze	1	1.5	3-4	Slight - Moderate
5	19	10	17-21	9-11	Fresh breeze	2	2.5	4	Moderate
6	24	12	22-27	11-14	Strong breeze	3	4	5	Rough
7	30	15	28-33	14-17	Near gale	4	5.5	5-6	Rough-Very rough
8	37	19	34-40	17-21	Gale	5.5	7.5	6-7	Very rough - High
9	44	23	41-47	21-24	Strong gale	7	10	7	High
10	52	27	48-55	25-28	Storm	9	12.5	8	Very High
11	60	31	56-63	29-32	Violent storm	11.5	16	8	Very High
12	-		64+	33+	Hurricane	14+	-	9	

Table 7: Beaufort scale

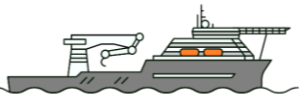


Appendix B – Reference vessel details

The table below shows a breakdown of the vessel input parameters used in the analysis.

Parameter	**Description**	**Motor Launch 10.2m**	**Motor Launch 5.1m**	**Sailing yacht 12m**	**Sailing yacht 6m**	**Units**
Length	Length (Overall)	10.2	5.1	12	6	m
Beam	Molded Beam	4.22	2.11	3.375	1.69	m
Draft	Baseline to waterline vertical length	0.8	0.4	2	1	m
Cb	Block Coefficient	0.3398	0.3398	0.103	0.103	n.d
Δ Displacement	Mass displacement	10.09	1.26	6.037	0.75	tonne

Table 8: Vessel input parameters



Appendix C – Vessel RAOs

The below show the displacement RAOs (at 0deg wave heading) for each vessel.

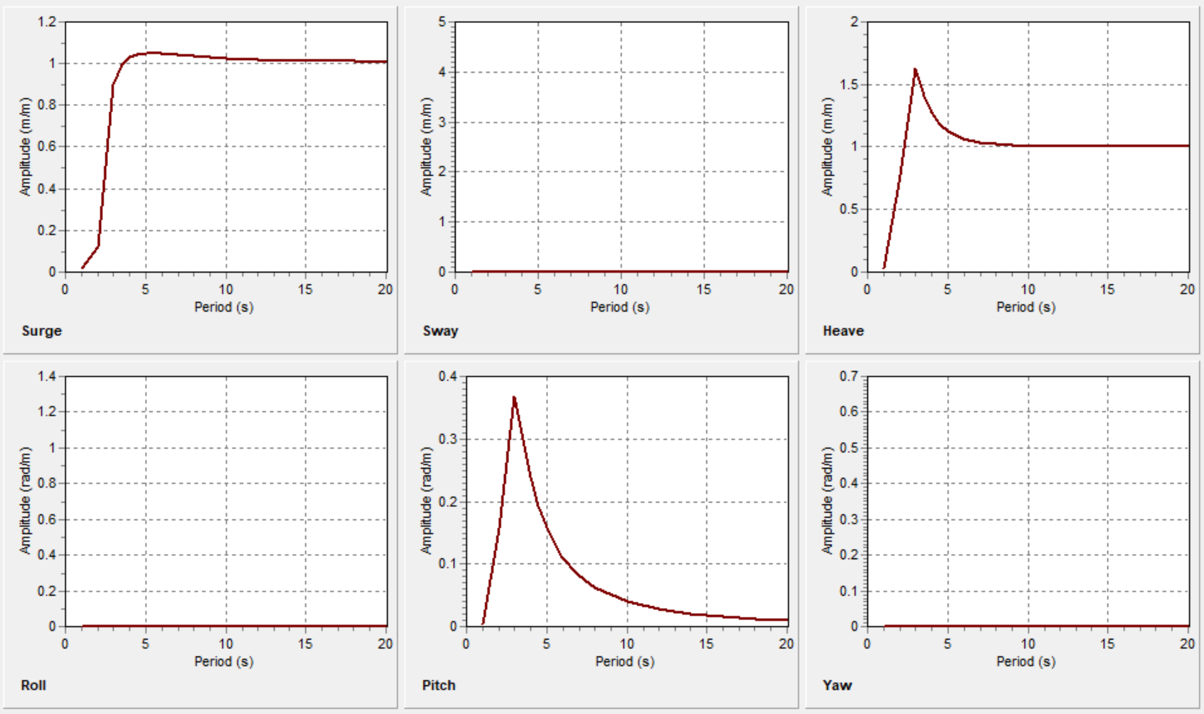


Figure 28: Motor launch displacement RAOs at 0deg

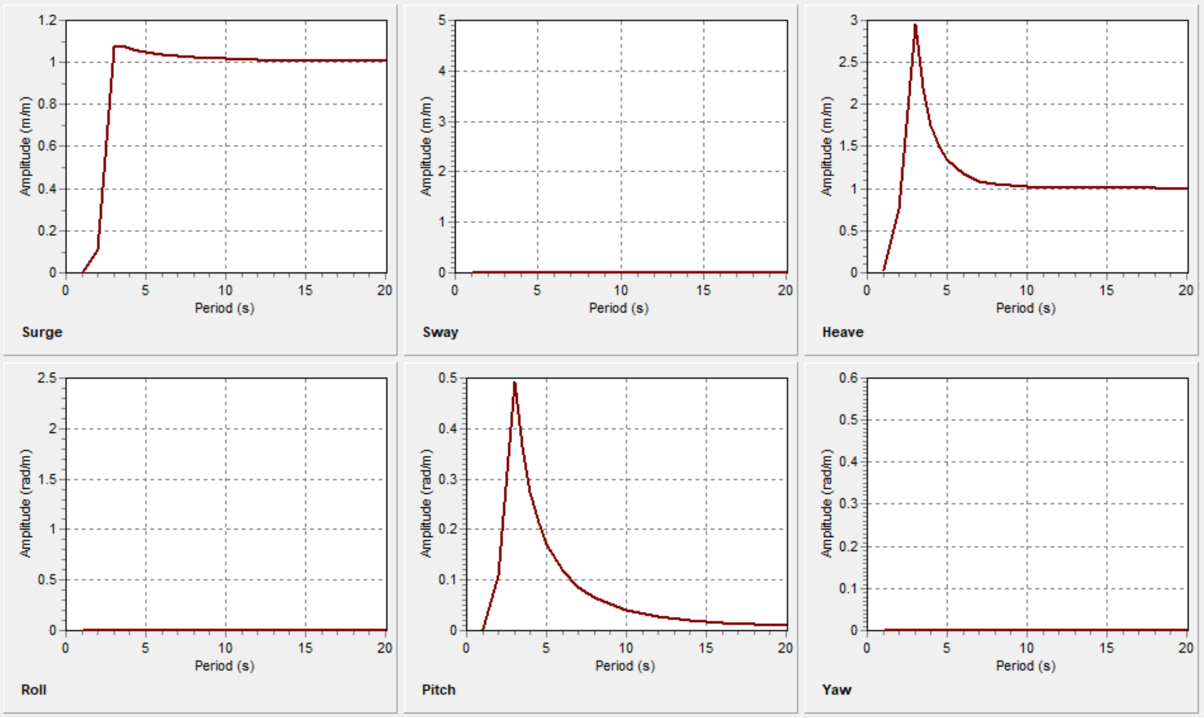
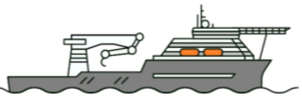


Figure 29: Sailing yacht displacement RAOs at 0deg



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