

Conceptual Study for IFREMER of a Mooring for Deep Sea Observatories Including Numerical Simulations



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1. Introduction

This study analyzes the conceptual design of an s-tether moored buoy system suitable for oceanographic observations that require an electrical connection to the seafloor. The overall design is based on a mooring system that MBARI has tested extensively and has deployed for two science experiments in the eastern Pacific for periods of up to 18 months. Prior to selecting the s-tether configuration for the MBARI moorings, MBARI and WHOI performed a comparative analysis between the s-tether design and a design configuration that incorporated a subsurface float at various depths. The results showed that the subsurface float increased the mooring complexity and resulted in the concentration of bending fatigue at the subsurface float without resulting in a significant advantage in the reduction of peak cable loads. Additional modeling results have agreed with this result¹. For this reason an intermediate subsurface float design has not been considered further in this study and the analysis is directed at the optimization of the s-tether mooring design shown as the **Concept Design** in figure 1. This mooring system is similar to previously fielded successful designs and has been modified for the Azores region.

In order to complete a workable mooring design for the Azores region of the Atlantic Ocean a numerical simulation of the mechanical mooring system, the Concept Design model, was forced using the wind, wave and ocean current environmental data for the location. The design criteria used are intended to minimize the maximum tensile loads the system experiences and to minimize the bending stress above the floated cable section. MBARI's experience with s-tether moorings has shown that the limiting factor in deployment duration is fatigue damage to the riser cable caused by low tension bending, therefore considerable study was directed at conditions and configurations that effect cable bending. As part of this conceptual study we also predict the peak loads experienced by the mooring cable during an anchor-last deployment and make recommendations for equipment and procedures for field deployment and recovery of the system.

2. The Baseline Mooring Configuration

As a starting point for the static and dynamic numerical simulation studies, a baseline mooring configuration, the Concept Design model, was created that conforms to the best practices that have been developed through direct experience and the post deployment analysis of the results of five separate field trials of ocean observatory type moorings with electrical and optical connections to the seafloor through the anchor, (or riser) cable. The major elements of the Concept Design mooring system and the overall configuration are shown in figure 1 and are described in detail in this section. The system as illustrated was used for the numerical model and simulations except as noted in the detail descriptions of the individual components.

Not To Scale

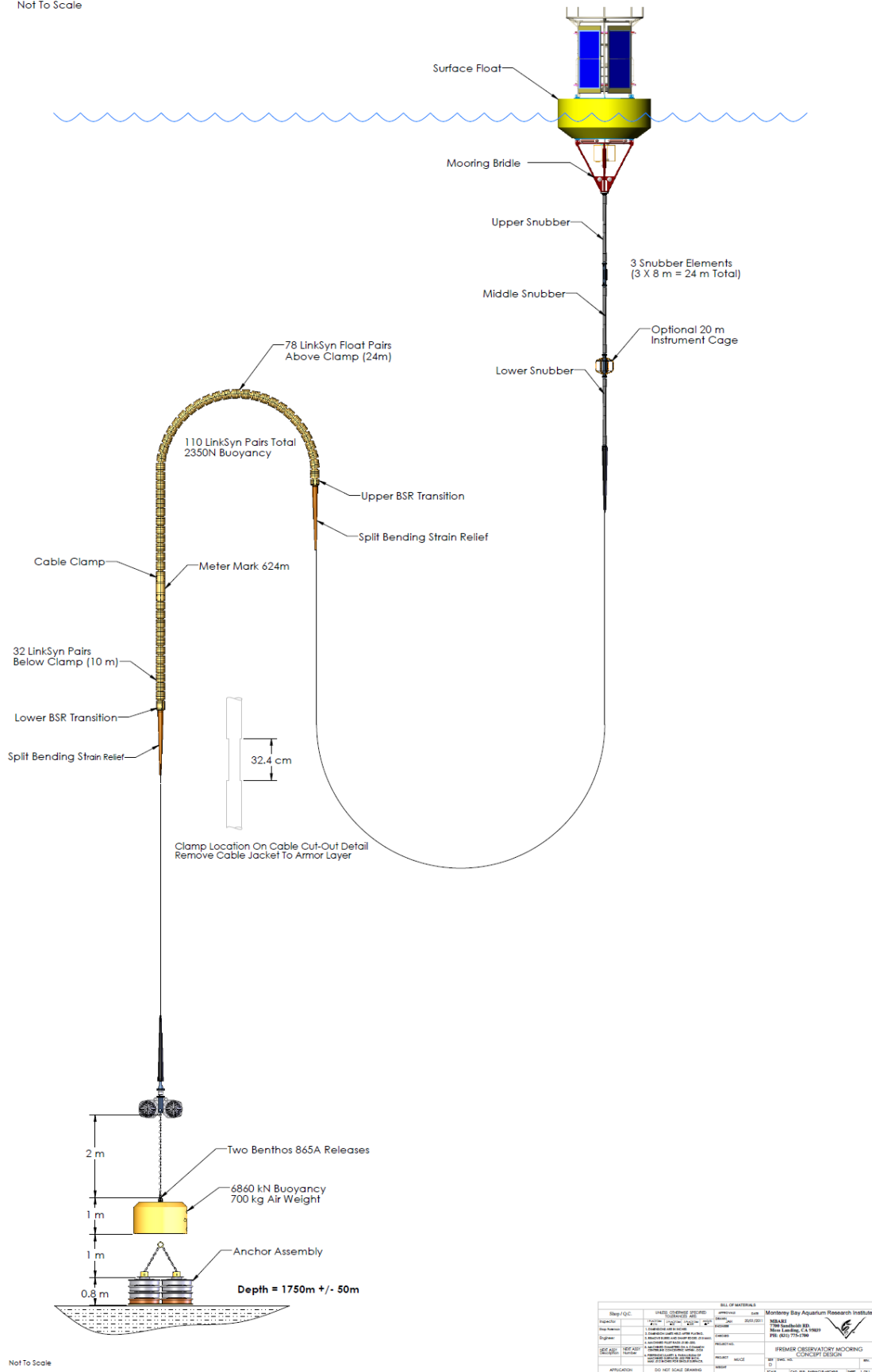


Figure 1. The Concept Design mooring model used as the baseline for the static and dynamic numerical simulations.

2.1. Surface Float

The surface float consists of a buoy constructed of Surlyn® foam². This is a standard material for oceanographic buoys that can be readily modified to a variety of shapes, is relatively low cost and is very resistant to field abuse. The standard density of the material used for this analysis is 84 kg per cubic meter. One disadvantage of the material is that hydrostatic pressure will collapse the foam if the buoy becomes submerged below the surface more than 8 meters, resulting in loss of buoyancy. For this reason the surface float must have enough buoyancy to remain on the surface under all sea conditions. The material properties of the surface float are shown in the table below. The model simulations include the total buoy weight, and a payload of 1160kg for structural support, the power system, instrumentation, etc.

Buoy Properties	Floatation Only	Total Buoy
Material	DuPont Surlyn® or Exxon IOTEK® closed cell foam	
Material density, kg./m ³	84.1	
Volume, m ³ (includes volume loss of center instrument well)	3.74E+00	
Total mass, kg	314	1473
Sw (sq.m), surface area for wind		3.25
h (m) height	1.12	
d (m), diameter	2.340	
Cdt, tangential drag coefficient	1.0	
Cdn, normal drag coefficient	1.0	
Cdw, wind drag coefficient		0.54

Table 1. Buoy surface float properties.

2.2. Load Cell

A load cell for measuring the tension loads on the system below the buoy bridle is included in the buoy mass properties. The load cell is located between the bolt flange on the mooring bridle and the bolt flange of the upper Snubber. The load cell is not strictly required but is very useful for validating the model results during the actual deployment. The load cell has a working range of 0-44.5 kN tension. The effect of the load cell mass on the numerical simulation is not significant.

2.3. Snubber Section

An important element of the mooring system is the Snubber, which provides the transition between the surface mooring bridle and the riser cable. The Snubber has two functions, providing axial compliance to absorb surface wave energy by acting like a spring, and acting as a robust bending element below the buoy so that buoy rocking motions do not concentrate at the cable to buoy interface.

The axial compliance is necessary to reduce the peak loads in the riser cable as the buoy follows surface waves. In a traditional buoy system design, the nylon anchor cable can stretch under load, (normally up to 10%³) and provide compliance in the system. Anchor (riser) cables that include optical and/or electrical elements in their construction cannot stretch more than about 0.6% without risking failure of the copper or glass elements. Therefore the strength members in these cables are low

stretch, high modulus fibers and additional compliance should be included in the mooring system design to lower the peak loads.

In the illustration in figure 1, three Snubber sections are used below the buoy to provide compliance, each section is 8 meters in length and bolted to the adjacent Snubber with a steel connecting tube for a total working Snubber length of 24 meters. In the numerical simulation the Snubber connecting tubes are not included in the model and the total length of the Snubber was varied from the no Snubber condition to a 56 meter total Snubber length. The mass of the tubes would not have a significant effect on the dynamic loads.

The elastic properties of the specific Snubber design used in the MBARI mooring system have been well characterized by measuring the displacement of Snubber sections under increasing tension. From this data a regression analysis has produced an equation describing the non-linear stress-strain relationship. For the 8 meter sections in the Concept Design model the curve has been shown to approximate $6500(e^{(4.5 \times \text{strain})} - 1)$, as shown in figure 2. This relationship has been included in the material properties of the Snubber used in the numerical simulation.

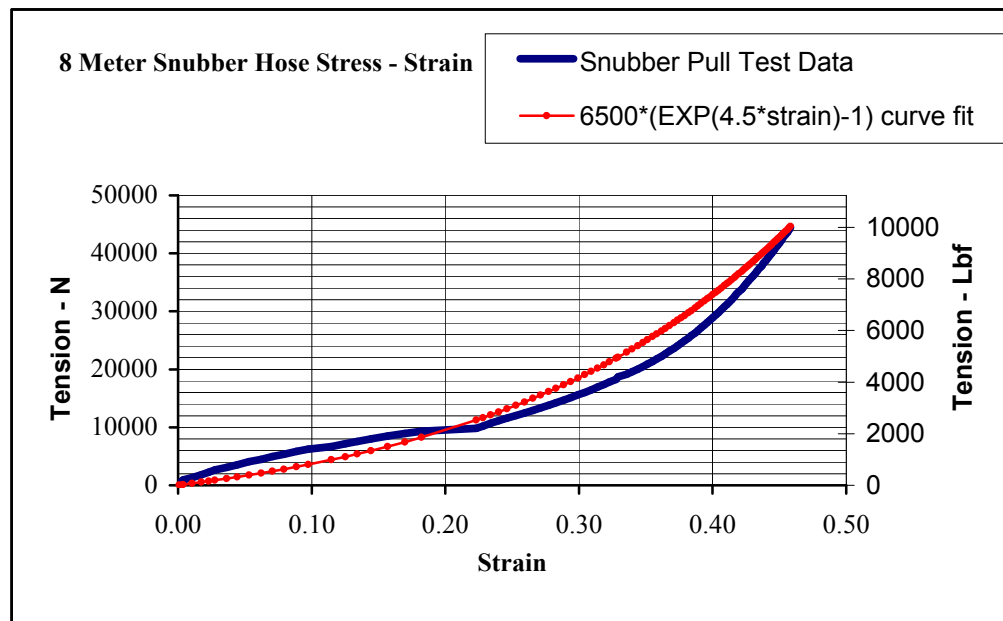


Figure 2. Tension characteristics of the Snubber Elements.

2.4. Electro-Mechanical Cable

The cable material properties used in the Concept Design model are equivalent to JDR Cable Systems PN 010 A 099 Rev. 1B. The cable construction includes an upper section with extra stainless steel braid and polyethylene jacket layer over the core cable for additional fish bite protection. The upper section outside diameter is 34mm, weight in air is 1170 kg/km, the weight in ocean 210 kg/km. The lower section is continuous with the upper section but does not include the extra jacket layers. The lower section outside diameter is 28mm, weight in air is 700 kg/km, the weight in ocean 65 kg/km. The breaking strength of both sections is 245 kN and the maximum working load is 27 kN. The minimum dynamic bend radius of the cable is specified as 500mm. In the numerical simulation the upper section of cable extends to just below the 400 meters point above the anchor and the balance of the cable to the anchor is modeled as lower section cable. It is feasible to extend the upper section cable profile to the seafloor for additional cable protection. This would increase the lower cable weight, possibly requiring additional cable floats. The axial stiffness and other cable

material properties that are used in the Concept Design model are shown in table 3. As in the case of the Snubber, the material properties used in the Concept Design model are derived from actual test data. The plot in figure 3 illustrates the fit of the riser cable EA value in the Concept Design model with the actual pull test data from a riser cable sample.

Riser Cable Properties	Upper fishbite protected section	Lower section
EA (N), Axial stiffness	6.70E+06	6.70E+06
EI (Nm ²), bending stiffness	10.0	1.0
GJ (Nm ²)	0.3	0.1
m (kg/m), mass/length	1.170	0.70
am (kg/m), added mass/length	0.5526	0.50
wet weight/length (N/m)	0.28 X 9.81	0.110 X 9.81
d (m), diameter	0.034	0.028
Cdt, tangential drag coefficient	0.010	0.010
Cdn, normal drag coefficient	1.50	1.50

Table 2. Riser cable material properties.

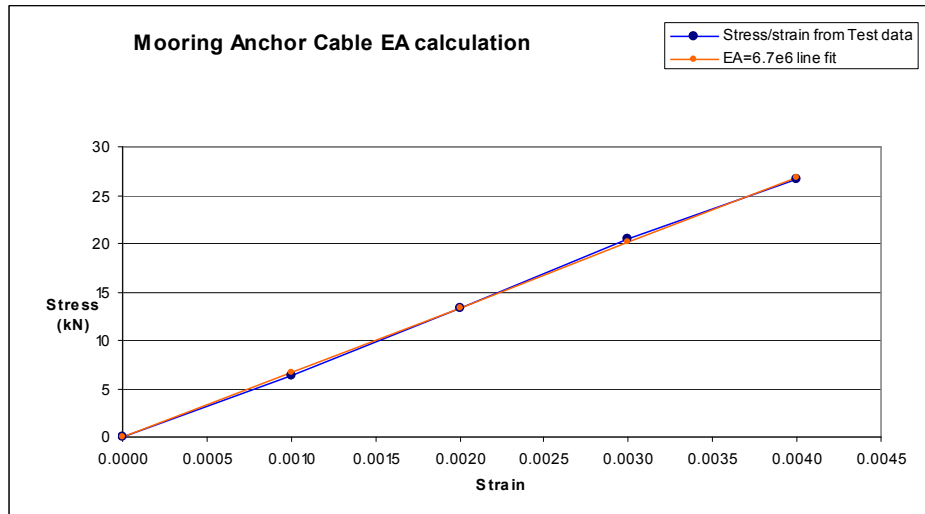


Figure 3. Line fit of anchor cable stress/strain properties used in the mooring numerical simulation.

2.5. Cable Floats and Cable Clamp

To prevent the electro-mechanical riser cable from contacting the seafloor during environmental conditions where there is minimal current forcing and the riser cable is slack, and to force the inverse catenary shape required for allowing wave motion compliance, buoyant floatation elements are clamped around the cable. These floats are manufactured by Trelleborg AB and are known by the trade name "LinkSyn"⁴. The floats lock together and form a bend restrictor that enforces a minimum bend radius on the Riser Cable of one meter. The inner profile of the floats is a custom design for MBARI that provides a smooth curving surface for the Riser Cable. Note that the stock

floats do not necessarily have the smooth inner curve necessary for preventing cable damage under all conditions. The buoyancy of each float pair (two halves) is 5.2 lbs. in seawater. A total of 144 float pairs are used in the Concept Design model used for the simulation.



Figure 4. The cable clamp grips tightly around a relief cut into the cable jacket. The white plastic adapter locks with the cable floats at each end of the clamp assembly.



Figure 5. Cable floats before assembly of the two halves illustrating the interlocking design that limits the riser cable bend radius.

To hold the floats in vertical position, a cable clamp that tightly grips the Riser Cable is placed about 1/3 of the distance up the floated section. The detail design of the cable clamp is important to ensure the clamp – and the floats – do not slip up the cable due to drag forces during mooring deployment. In event the most compact cable constructions, the riser cable diameter is reduced significantly under hydrostatic pressure during initial deployment, therefore to ensure the clamp is locked in place, a section of the riser cable polyethylene outer jacket is removed to form a receptacle to receive the cable clamp and the clamp itself is designed to make up some of the diameter as the cable compresses. The individual cable floats are locked into the clamp forming one continuous buoyancy assembly. At the lower and upper ends of

the cable float assembly there are transition adapters that mate the floats to the cable bending strain reliefs. The Concept Design model incorporates the wet weight (buoyancy), mass and size of the cable float section but does not include the minimum bend radius lock-up feature of the cable floats.

2.6. Bending Strain Reliefs

To provide a smooth bending transition in locations where the Riser Cable is terminated and at each end of the cable float section, bending strain reliefs are used. The stiffness profile of the bending stiffeners is calculated to hold the minimum design bending radius of the Riser Cable under all conditions. The bending reliefs at the cable termination locations are assembled on the cable at the time of the cable termination. The bending strain reliefs at each end of the cable float are a split design that is fastened over the cable with bolts that allow installation at the time of mooring deployment. As is the case for the cable floats, the detail design and manufacture to MBARI specifications of the bending strain reliefs is performed by Trelleborg AB. The Concept Design model incorporates the wet weight, mass and size of the bending strain reliefs but does not include the controlled bend radius feature of the strain relief design (see also Recommendations for Additional Study, sec. 7.2).

2.7. The Anchor Float

The purpose of the anchor float is to provide enough buoyancy to allow the anchor end of the riser cable to float to the surface when the mooring is released from the anchor. This allows servicing of the lower end of the mooring string and re-anchoring the mooring without requiring recovery of the whole mooring string, including the surface float. An example of when this operations might be necessary is if damage occurs to the connector or instruments at the anchor end of the system during deployment or operation. The anchor float also allows an anchor-end recovery option when the entire assembly is recovered. The anchor float is constructed of syntactic foam suitable for the depth of the mooring and the volume is calculated to provide sufficient buoyancy to bring the end of the cable to the surface. In the illustration in figure 1, the Concept Design specifies the anchor float mass as 700kg and wet weight (buoyancy) as 6860 N. The optimum specifications should be closer to mass 998kg and wet weight (buoyancy) of 4004 N. In the detail design the anchor float should be calculated based on the final cable and cable float properties to bring the anchor end of the mooring to the surface upon release.



Figure 6. The anchor float and anchor. After launch the anchor float separates from the anchor.

2.8. Anchor

The anchor must be sized to not drag during peak load conditions. The recommended anchor weight is calculated from the dynamic load analysis for the 25 year return period storm case that shows a maximum tension at the anchor of 33.75 kN (7587 lbs.). For a soft bottom condition the minimum recommended anchor mass is approximately 3500 kg (7700lbs.) in water. The Concept Design model uses an anchor mass of 4026kg in air and a “wet” weight of 34.3kN for simulations of the mooring deployment

3. Environmental Conditions

3.1. Introduction

The environmental conditions used as inputs to the dynamic simulation of mooring performance are described in this section. Hindcast data derived predictions of the wind speeds and wave conditions for the site location were obtained from Oceanweather Inc.⁵. The ocean site for which the data was derived is west of the Azores Islands, 37.29° N, 32.28° W, at the approximate location of the Lucky Strike complex. Four separate sets of conditions are modeled; the slack condition when conditions are at a minimum, the 50%, 70%, 90% annual non-exceedance, and the “design condition” which is the 95% non-exceedance condition in the worst month (February), and survival conditions which are defined as the 25 return period condition. On an annual basis, the design condition equates to a 98% to 99% non-exceedance, or a condition that is only exceeded 1-2% of the year. For the mooring Concept Design model the 25 year condition is considered the maximum condition for survival, however in this study, in a few cases, the 50 year condition is included for comparison.

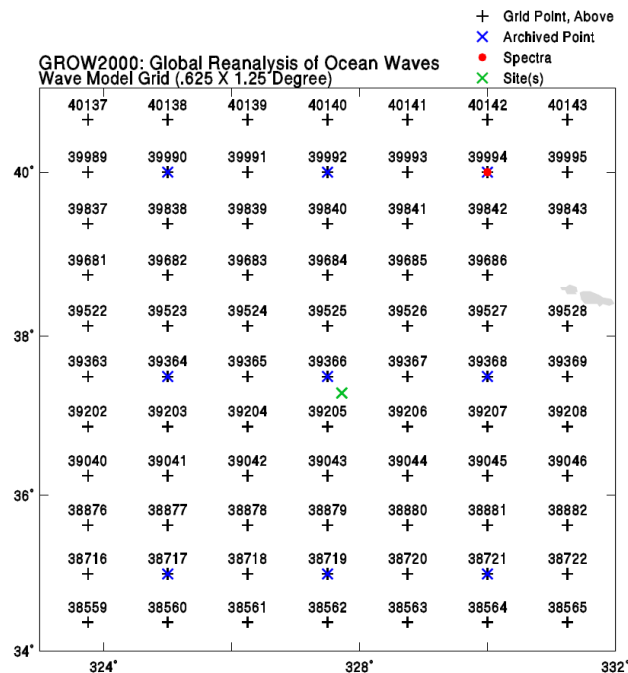


Figure 7. Location map showing grid point 39366 which was the point location of the wind and wave condition hindcast data. The proposed buoy location is marked with a green cross.

3.2. Wind speeds

The wind speed data derived from the Hindcast is 10m height, 1 hour mean values. This data is converted into 1 minute mean values using a factor of 1.11 x the 1 hour mean⁶. Wind loading on the buoy structure is not a significant factor effecting cable loads and the buoy dynamics are dominated by ocean current and wave forcing. This is consistent with the surface area of the cable exposed to sea effects versus the surface area of the buoy exposed to wind effects.

Wind Speed Condition at Lucky Strike Site	Wind Speed at 10 m (m/s), 1 hour mean	Wind Speed at 10 m , 1 min. gust
Slack	0	0.0
<50% Exceedance	6.55	7.3
<70% Exceedance	8.49	9.4
<90% Exceedance	11.66	12.9
Design (<95%)*	15.43	17.1
Survival 25 Year event	25.05	27.8
Survival 50 Year event	26.22	29.1

* Used February data (worst case)

Table 3. Wind forcing conditions.

3.3. Current profiles

Historical ocean current data for the specific location was not available for the site except for during a few short measurement periods at depth and broad area satellite data for the surface. In order to estimate the current profile at the site, satellite derived ocean surface current fields for the region were examined that covered the period 1994-2010⁷. The worst case of this data of approximately 70cm/second was used as the survival surface current condition. For the subsea currents a profile was generated from the surface values to a maximum near bottom value of 30cm/second. The bottom value is the actual extreme value measured at a nearby site in a one year period using in situ instrumentation⁸. The ocean current values for the 50%, 70% and 90% conditions were interpolated from the design condition in direct relation to the wind speed values.

Water Column Current Profile						
Water Depth, meters	Current Speed(m/s)					
	Slack Condition	Interpolated using Wind Data			Design Condition 95% Non-Exceedance	Survival Condition 25 Year Storm
		50% Non-Exceedance	70% Non-Exceedance	90% Non-Exceedance		
0	0.1	0.17	0.22	0.31	0.35	0.7
50	0.08	0.13	0.17	0.24	0.27	0.55
100	0.07	0.10	0.13	0.18	0.2	0.4
150	0.06	0.08	0.11	0.15	0.17	0.35
200	0.05	0.07	0.10	0.13	0.15	0.3
500	0.02	0.02	0.03	0.04	0.05	0.1
1000	0.01	0.02	0.03	0.04	0.05	0.1
1500	0.01	0.05	0.06	0.09	0.1	0.15
1750	0.01	0.07	0.10	0.13	0.15	0.3

Table 4. Ocean current forcing conditions.

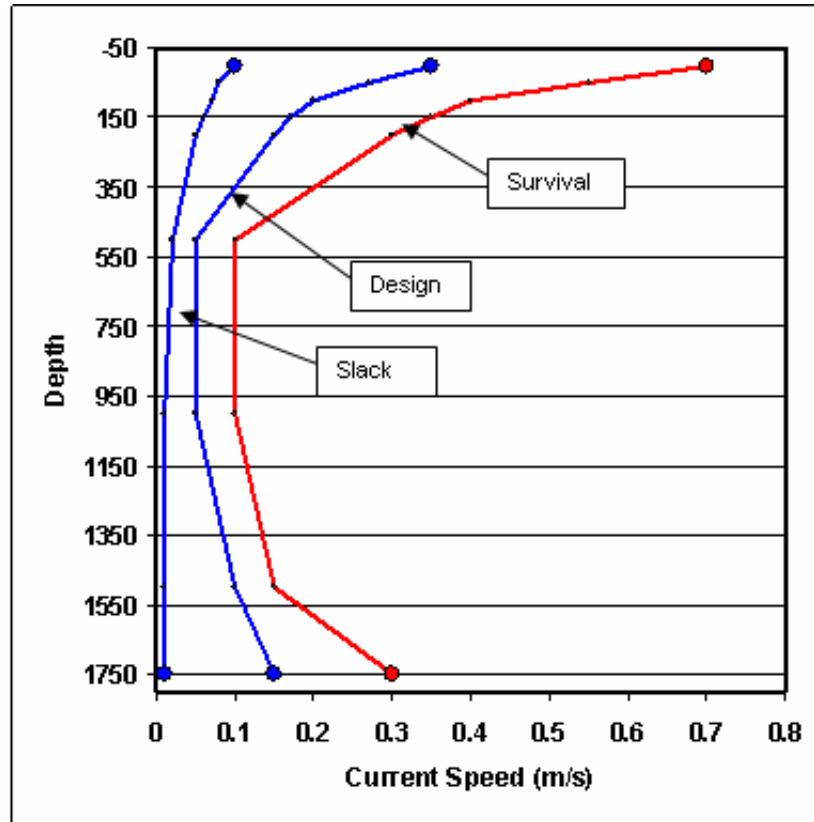


Figure 8. The Subsea current profiles used in the mooring dynamics model.

3.4. Wave conditions

The wave height data derived from the Hindcast includes significant wave height (the average height of the 1/3 highest waves, H_s), and the peak wave period (TP). Oceanweather used wind field data, satellite altimeter data and direct observations to hindcast H_s and period pairs. The H_s and period pairs were subjected to a regression analysis to develop the equation $TP = 6.5819 \cdot H_s^{0.3825}$. From the significant wave height value and the peak period TP equation a modified Pierson-Moskowitz spectrum of wave energy is used for the dynamic simulation.

Wave Height Condition at Lucky Strike Site	Significant Wave Height (H_s , meters)	Peak Wave Period (TP)
Slack	0	0
<50% Exceedance	2.12	8.77
<70% Exceedance	2.96	9.97
<90% Exceedance	4.56	11.76
<95% Exceedance	5.4	12.55
Design (<95%)*	6.94	13.8
Survival 25 Year event	12.35	17.22
Survival 50 Year event	13.04	17.58

* Used February data (worst case)

Table 5. Wave forcing conditions.

4. Static and Dynamic Simulation Results

4.1. Introduction

A numerical model of the Concept Design has been constructed using the WHOI *CABLE* software program⁹. The mooring system is characterized by specifying the physical properties of each element and section of the mooring system; axial and bending stiffness specification, mass, axial and normal drag coefficient, axial and normal added-mass coefficient, length and diameter. Where possible the properties of each element are determined by direct measurement. The ocean depth used for modeling purposes is 1750 meters.

The WHOI *CABLE* software performs a time-dependent simulation of the mooring behavior by solving the cable-dynamics equations in the time domain. The cable-dynamics equations are the equations of motion of the cable that includes cable mass, cable axial and torsional stiffness, and cable added-mass and drag through the water. Boundary conditions are applied at the ends of the cable that represent a fixed anchor end and a floating buoy. The cable and components between the float and anchor are divided into 6036 discrete "nodes" and the numerical equations solved for each node for each time-step. The hydrodynamics of the floating buoy are not included but instead it is assumed that the buoy is a wave-follower in heave. Due to their relatively small size, typical oceanographic buoys have hydrodynamic characteristics that makes this a suitable assumption.

The numerical simulation initially uses the material properties of the Concept Design and the wind and ocean current fields to calculate a static configuration. Following this step the wave field is ramped up to the full value over a period of thirty seconds for the dynamic conditions. The time step for the numerical computations to solve for positions and tensions for this study are 0.02 seconds and the duration of the entire simulation run is 600 seconds (10 minutes). The results of the computations are saved every 0.2 seconds, resulting in a time record of 3000 time steps representing 600 seconds duration for the dynamic solution. The deployment simulation used 0.1 second calculation intervals saved at 0.5 second intervals.

4.2. Summary of the simulation results.

The most significant elements effecting mooring system performance are the length of the Snubber section, the scope of the riser cable and to a less extent the amount of cable float buoyancy and the riser cable weight. The use of a Snubber to reduce the peak tensions caused by wave motion is recommended. Increasing the Snubber length beyond 8 meters reduces the maximum tensions and decreases the number of tension cycles at high amplitudes. It also dramatically reduces negative values and low amplitude cycles around zero kN tension. The ideal Snubber length is probably 40-50 meters, but this length may be difficult to deploy. Field experience has shown that cable failures are more likely to be caused by bending cycling and not tension cycling so allowing higher tension loads with less Snubber length is a reasonable trade-off with the need to make the deployment and recovery operations less difficult.

Increasing the mooring scope changes the configuration and causes a significant reduction in bending cycles at a given environmental forcing. The ocean current is the environmental agent most forcing the mooring configuration. The mooring scope, the cable floatation and the cable weight can all be optimized to reduce bending cycles in the majority of conditions if the local currents are well characterized.

4.3. The static model

The static results shown here illustrate the configuration and tension in the mooring Concept Design model under the range of environmental conditions due to the forcing of the wind and currents with no wave forcing. These results become the mean values about which the dynamic forces oscillate due to time-dependent wave forcing. Figure 9 illustrates the position of the mooring elements under the simulated environmental forcing in the static condition with a 1.25 mooring scope. The series of interlocking cable floats placed around the cable at 600 meters above the anchor forces the mooring into an "S" shape at low ocean currents and higher currents cause the mooring to move further from the anchor position horizontally. The corresponding static tensions along the mooring string for the simulated environmental conditions are illustrated in the plot shown in figure 10. The static (and mean dynamic) tensions at the anchor also include the buoyancy of the anchor float as shown in the figure as the sharp rise in tensions at the zero distance position. The float properties included in the Concept Design model and the simulation provide about 2.8kN more buoyancy than is necessary for floating the cable to the surface. The buoyancy of this float could likely be reduced in the detail design, reducing the peak and mean anchor loads.

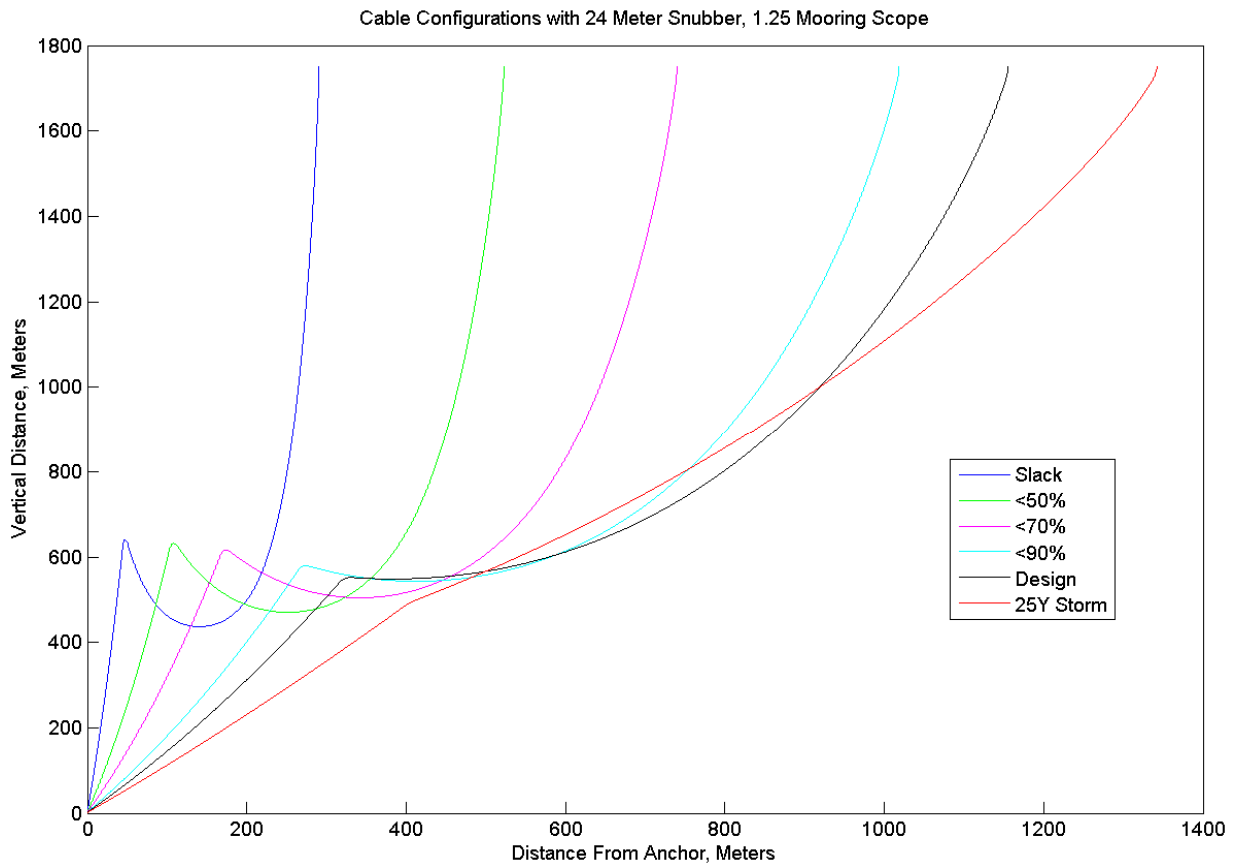


Figure 9. The mooring cable configuration under different environmental forcing conditions.

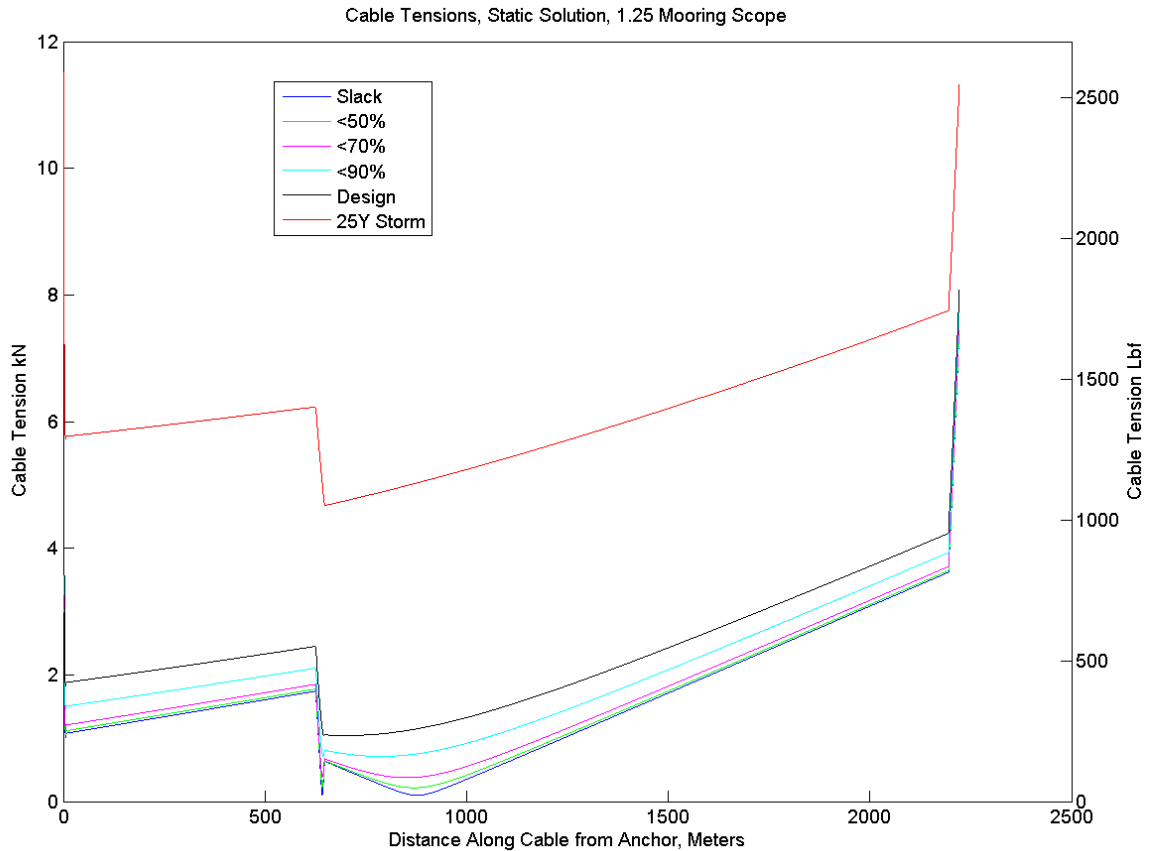


Figure 10. Static tensions along the mooring Riser Cable.

4.4. The Dynamic simulation

The dynamic simulation adds the effects of waves on the Concept Design model and as a result the tensions in the cable at any point vary with time. Table 6 shows the tensions directly below the buoy, just above the cable floats and at the mooring anchor in the simulated environmental conditions. These values include the mean and maximum expected cable tensions. Maximum tensions are computed as the mean tension plus four times the standard deviation of the tension signal during the 10 minute (600 seconds) simulation. Note that tensions described as in the cable are taken at the terminations or transition points in the riser cable. Tensions at the anchor are taken below the anchor float at the anchor shackle and are higher.

Mooring Dynamic Tensions in kN Scope 1.25							
Note: max = 4σ + mean		Below Surface Float		Above Cable Floats		At Anchor	
		Mean	Maximum	Mean	Maximum	Mean	Maximum
24 meter Snubber	Slack (no waves)	7.5	7.5	0.6	0.6	8.1	8.1
	Design	8.3	18.2	1.3	6.1	8.7	12.9
	25 Year Survival	14.4	31.6	7.3	26.9	14.5	33.8
	50 Year Survival	14.7	33.0	7.6	28.3	14.7	35.1

Table 6. Summary table of dynamic loads for 24 meter Snubber and scope 1.25.

Mooring Riser Cable Dynamic Tensions in kN							
Note: max = 4σ + mean		Below Surface Float			Below Snubber		
		Mean	σ	Maximum	Mean	σ	Maximum
No Snubber Scope 1.25	Slack (no waves)	4.0	0.0	4.0	-	-	-
	Design	4.7	2.8	16.0	-	-	-
	25 Year Survival	9.1	5.8	32.3	-	-	-
	50 Year Survival	9.3	6.1	33.8	-	-	-
8m Snubber Scope 1.25	Slack (no waves)	5.2	0.0	5.2	4.0	0.0	4.0
	Design	6.0	3.0	17.8	4.8	2.8	16.1
	25 Year Survival	11.2	5.7	33.9	10.1	5.7	33.0
	50 Year Survival	11.5	6.0	35.7	10.3	6.1	34.7
16m Snubber Scope 1.25	Slack (no waves)	6.3	0.0	6.3	4.0	0.0	4.0
	Design	7.1	2.7	17.8	4.8	2.5	14.9
	25 Year Survival	13.1	5.0	33.2	10.8	5.1	31.3
	50 Year Survival	13.3	5.2	34.2	11.0	5.3	32.3
24m Snubber Scope 1.25	Slack (no waves)	7.5	0.0	7.5	4.0	0.0	4.0
	Design	8.3	2.5	18.2	4.8	2.3	14.1
	25 Year Survival	14.4	4.3	31.6	11.0	4.5	28.9
	50 Year Survival	14.7	4.6	33.0	11.3	4.8	30.3
24m Snubber Scope 1.36	Slack (no waves)	7.8	0.0	7.8	4.2	0.0	4.2
	Design	8.4	2.7	19.1	4.9	2.5	14.8
	25 Year Survival	13.1	4.7	32.1	9.7	4.8	28.7
32m Snubber Scope 1.25	Slack (no waves)	8.7	0.0	8.7	4.0	0.0	4.0
	Design	9.5	2.3	18.8	4.9	2.2	13.6
	25 Year Survival	15.6	3.9	31.2	11.1	4.1	27.5
	50 Year Survival	16.0	4.2	32.6	11.5	4.4	29.0
40m Snubber Scope 1.25	Slack (no waves)	9.8	0.0	9.8	4.0	0.0	4.0
	Design	10.8	2.2	19.5	5.0	2.1	13.4
	25 Year Survival	16.1	3.3	29.3	10.4	3.6	24.7
	50 Year Survival	15.9	3.4	29.6	10.3	3.7	24.9
48m Snubber Scope 1.25	Slack (no waves)	11.0	0.0	11.0	4.0	0.0	4.0
	Design	12.0	2.1	20.4	5.0	2.0	13.1
	25 Year Survival	17.0	2.9	28.5	10.3	3.2	23.1
	50 Year Survival	17.5	3.1	30.0	10.7	3.5	24.6
56m Snubber Scope 1.25	Slack (no waves)	12.1	0.0	12.1	3.9	0.0	3.9
	Design	13.2	2.0	21.3	5.1	1.9	12.8
	25 Year Survival	18.3	2.6	28.7	10.5	3.0	22.6
	50 Year Survival	18.3	2.7	29.1	10.5	3.2	23.2

Table 7. Table of maximum dynamic tensions for multiple configurations.

Dynamic mooring simulations were run for most configuration conditions using the environmental values of the 50%, 70%, 90% non-exceedances, and for all cases, the design and 25 year conditions. A limited number of simulations were also run for the 50 year storm condition for comparison. Most simulations used a mooring scope of 1.25, however a series of comparative runs were conducted with a scope of 1.36. The

detailed results of the numerical simulations for mean and maximum loads for different configurations are shown in table 7. Note that some of the maximum tension values are slightly greater than the specified 27kN working load of the Concept Design riser cable. The time series plots of tension for the baseline Concept Design are shown in figures 11 to 14 below.

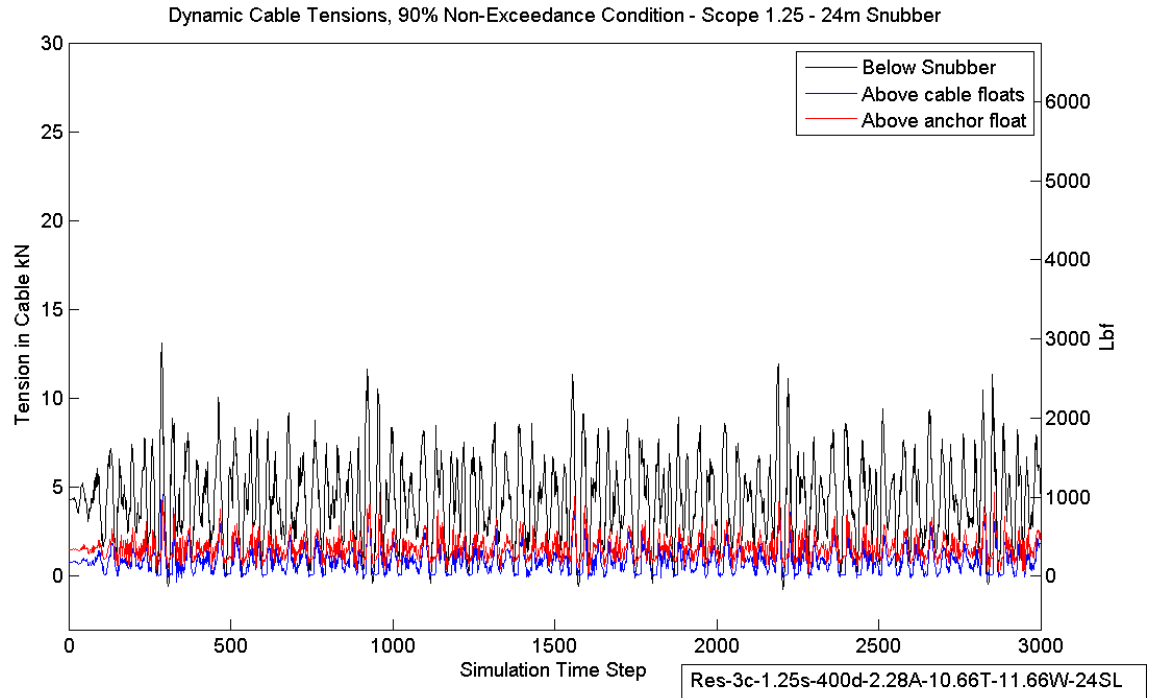


Figure 11. Dynamic tensions in the riser cable for the <90% exceedance condition. The text in the lower right is the source data filename. 3000 time steps represents 600 seconds of simulation time recorded every 0.2 seconds.

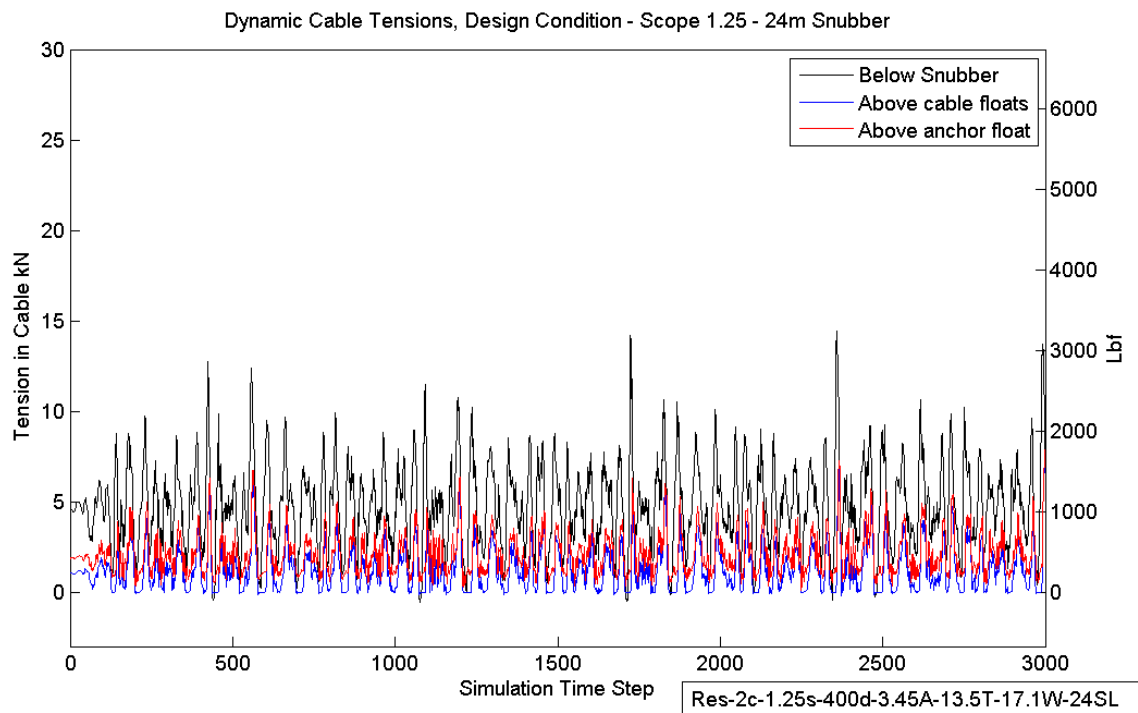


Figure 12. Dynamic tensions in the riser cable for the design condition.

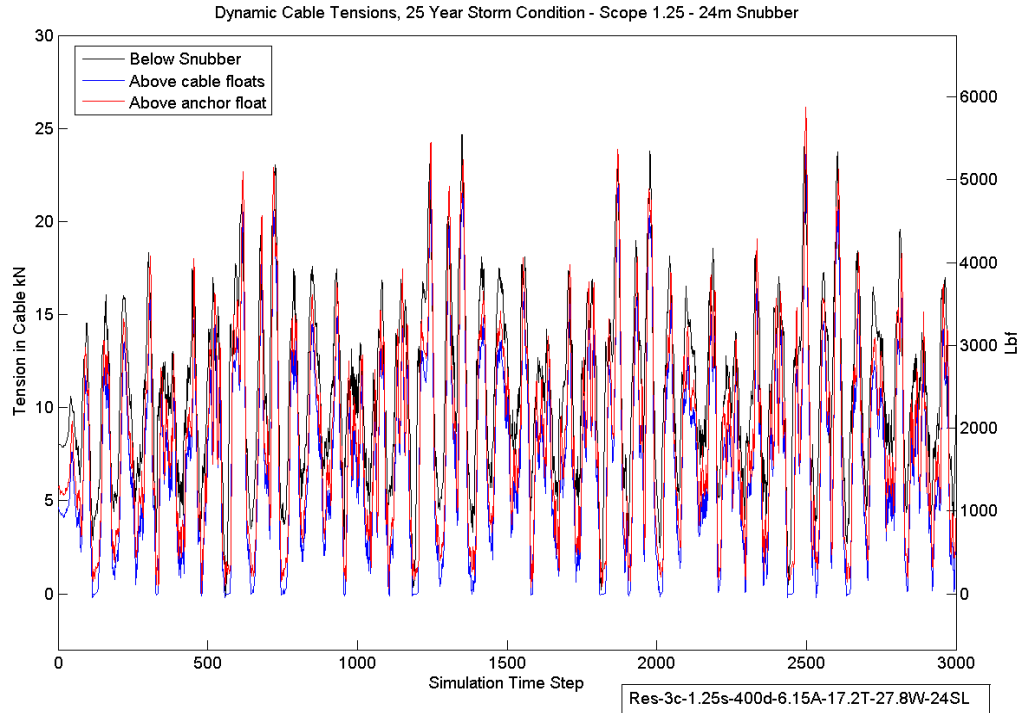


Figure 13. Dynamic tensions in the riser cable for the 25 year storm condition.

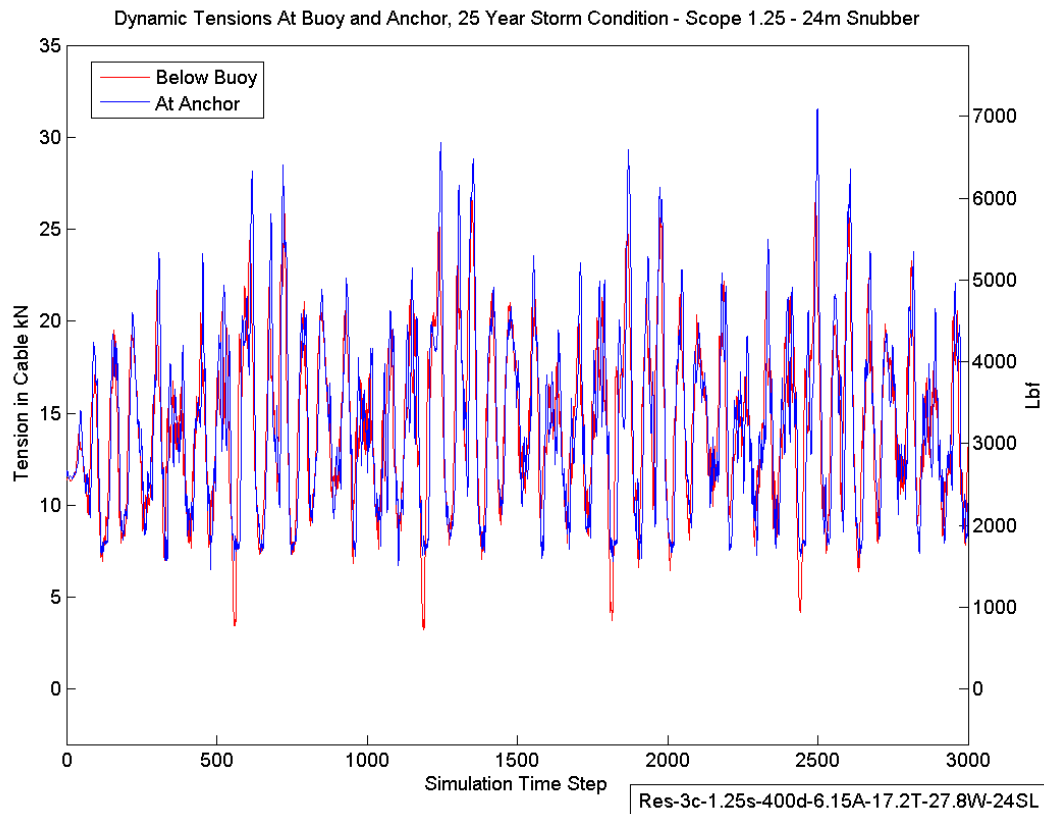


Figure 14. Dynamic tensions below the surface buoy and at the anchor for the 25 year storm condition. These higher tensions include the loads of the Snubber mass and the anchor float buoyancy (which are not seen by the cable).

5. Mooring design sensitivity analysis and design optimization.

5.1. Optimization of the Snubber length.

As the baseline condition for the numerical simulation a Snubber length of 24 meters was selected. This length has been shown to both have a significant effect on reducing peak loads while remaining short enough to be field deployable without specialized equipment such as a dedicated winch. To test the effect of different Snubber lengths in the Concept Design model, simulations were run for Concept Design models that ranged from a no Snubber below the buoy to a 56 meter Snubber length below the buoy in 8 meter Snubber length increments. Figure 15 plots the results of the changes in Snubber lengths on the maximum loads at the base of the buoy (buoy-Snubber junction) and at the base of the Snubber (the Snubber-cable junction). It can be seen that as the Snubber length increases, the peak tensions in the cable decrease. One exception is the 8 meter Snubber length where the tensions actually increase. In the design environmental condition the maximum tensions below the buoy can be seen to increase as the Snubber lengthens as a result of the mean tension increasing due to the static weight of the Snubber. Simultaneously as the Snubber length increases, the standard deviation of tensions (dynamic tensions) are reduced due to the energy absorbing qualities of the Snubber and below the Snubber the maximum tensions in the cable riser are decreased. In the 25 year storm survival condition, as the Snubber lengthens the maximum loads are more influenced by the significant reduction in dynamic loads and the maximum tensions are decreased both at the buoy and below the Snubber in the cable. From the simulation data it is clear that after 8 meters, longer Snubber lengths result in reduced peak loads. Previous work has shown that the optimal Snubber length is reached when the increase in mean tension becomes greater than four times the reduction in the standard deviation of tension resulting from the greater Snubber length¹.

In addition to changing the total length, the stress strain curve of the Snubber can also be modified by changing the material properties of the Snubber, however for the Concept Design model and simulations presented here we chose to only change the Snubber length. This is for two reasons; 1) The design used in the simulation can be manufactured reliably and has been well characterized and field tested. 2) Changing the overall Snubber length is a good approximation for changing the stress-strain curve for an individual fixed length element. See also the recommendations for additional study in section 7 for more discussion on the feasibility of modifying the Snubber construction to produce a more elastic stress-strain curve.

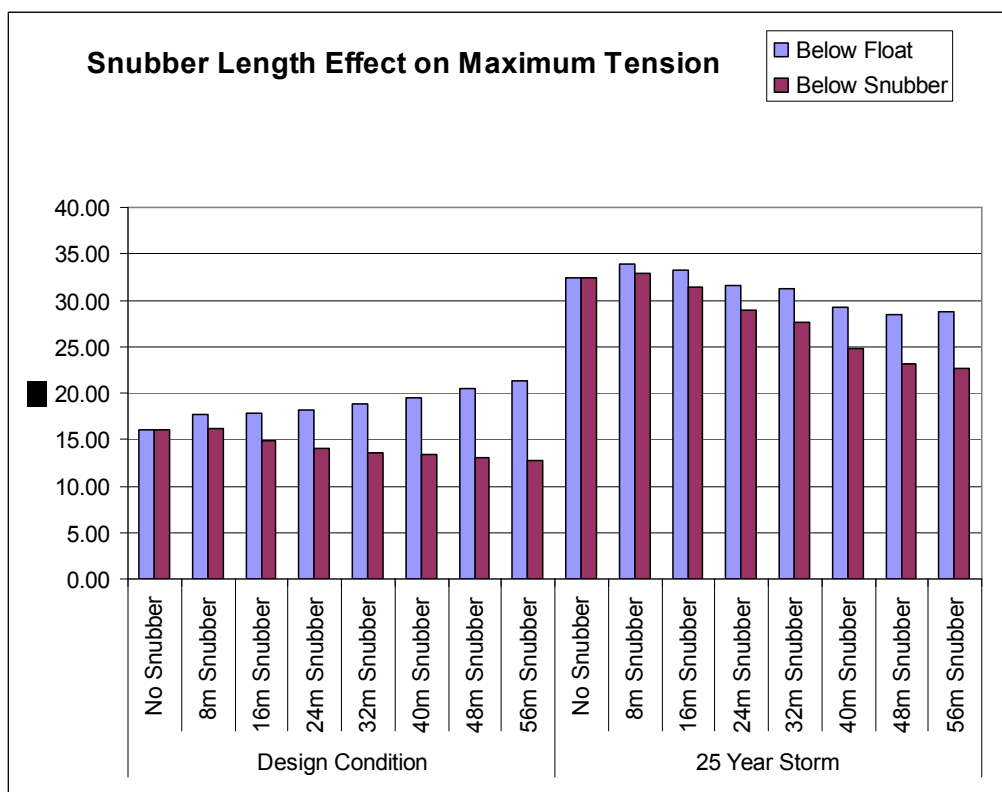


Figure 15. The effect of Snubber length on mooring maximum tension.

Mooring Riser Cable Maximum Dynamic Tensions					
		Below Surface Float		Below Snubber	
		Lbs	kN	Lbs	kN
Design Condition	No Snubber	3599	16.01	3599	16.01
	8m Snubber	3992	17.76	3626	16.13
	16m Snubber	4009	17.83	3349	14.89
	24m Snubber	4090	18.19	3176	14.13
	32m Snubber	4218	18.76	3054	13.59
	40m Snubber	4384	19.50	3002	13.35
	48m Snubber	4590	20.41	2954	13.14
	56m Snubber	4786	21.29	2878	12.80
25 Year Storm	No Snubber	7266	32.32	7266	32.32
	8m Snubber	7629	33.94	7411	32.97
	16m Snubber	7470	33.22	7044	31.33
	24m Snubber	7106	31.61	6494	28.88
	32m Snubber	7009	31.18	6191	27.54
	40m Snubber	6576	29.25	5557	24.72
	48m Snubber	6406	28.49	5192	23.09
	56m Snubber	6459	28.73	5089	22.64

Table 8. Maximum dynamic tensions from simulation of different Snubber lengths.

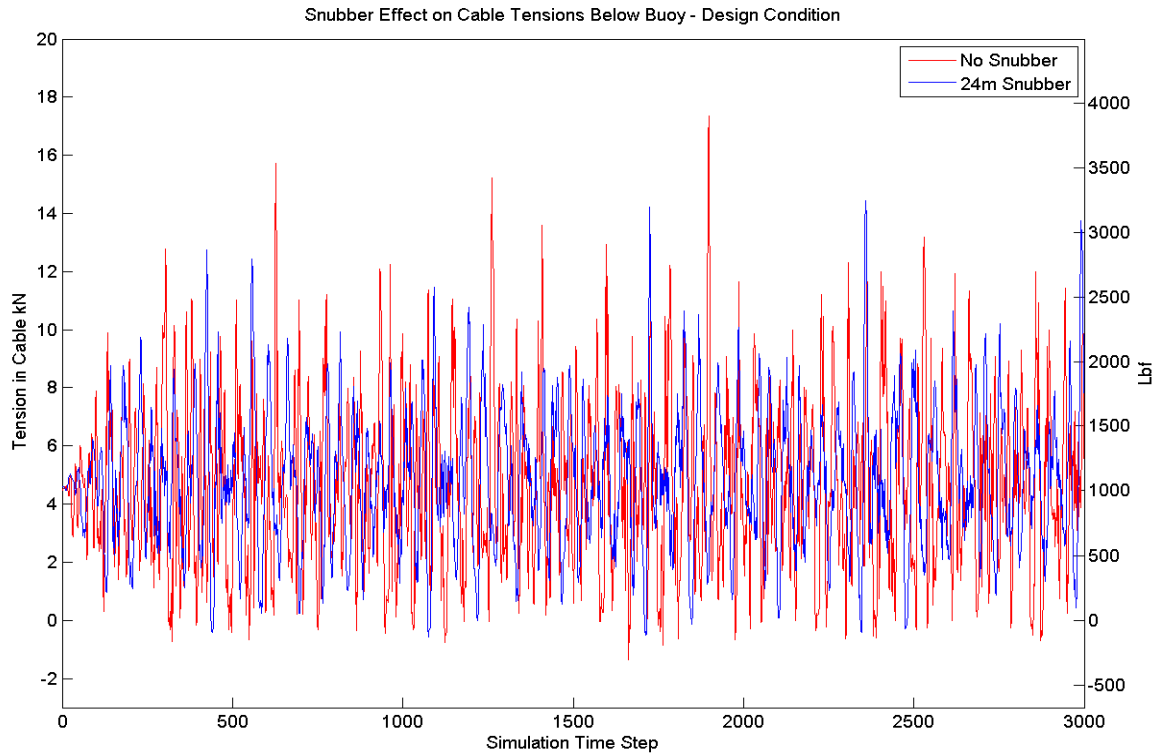


Figure 16. Comparison of cable tension with 24 meter Snubber and no Snubber in the design condition. 3000 time steps represents 600 seconds of simulation time recorded every 0.2 seconds.

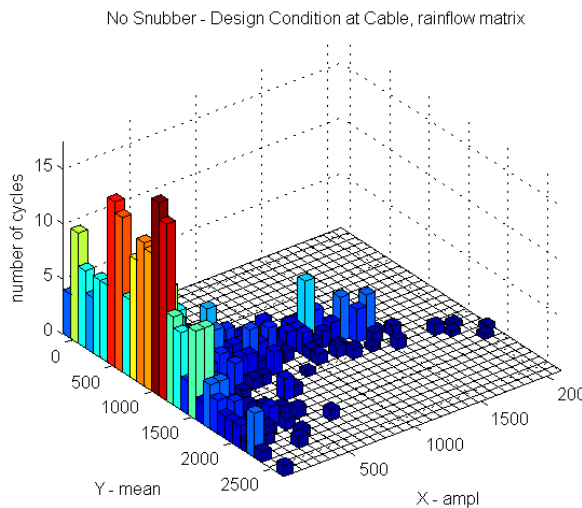


Figure 17. No Snubber (xy in lbf)

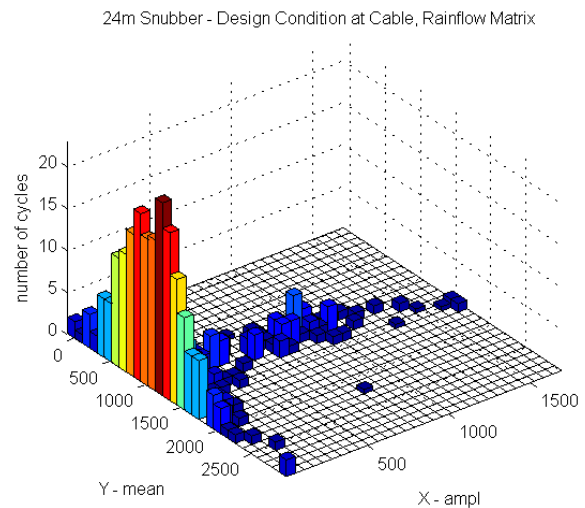


Figure 18. 24m Snubber (xy in lbf)

The time series of the dynamic tensions at the upper termination of the mooring cable are plotted for the design condition in figure 16 for the no Snubber and 24 meter Snubber conditions. A rainflow analysis of the wave forced tension cycles results in a matrix plot (see section 5.2 for details of rainflow cycle counting) of the number of cycle occurrences, cycle amplitudes and cycle mean values. Comparing the 24 meter Snubber plot in figure 18 with the no Snubber plot in figure 17 shows that the Snubber reduces the peak tension value and significantly lowers the number of cycles

at higher amplitudes. An additional effect of the Snubber is that the number of cycles with a mean near or below 0 kN is reduced and the number of cycles that extend below 0 tension is reduced. When the tension in the cable approaches 0 or negative values there is concern that “snap loading” of the cable below the mooring could occur and cause premature cable failure.

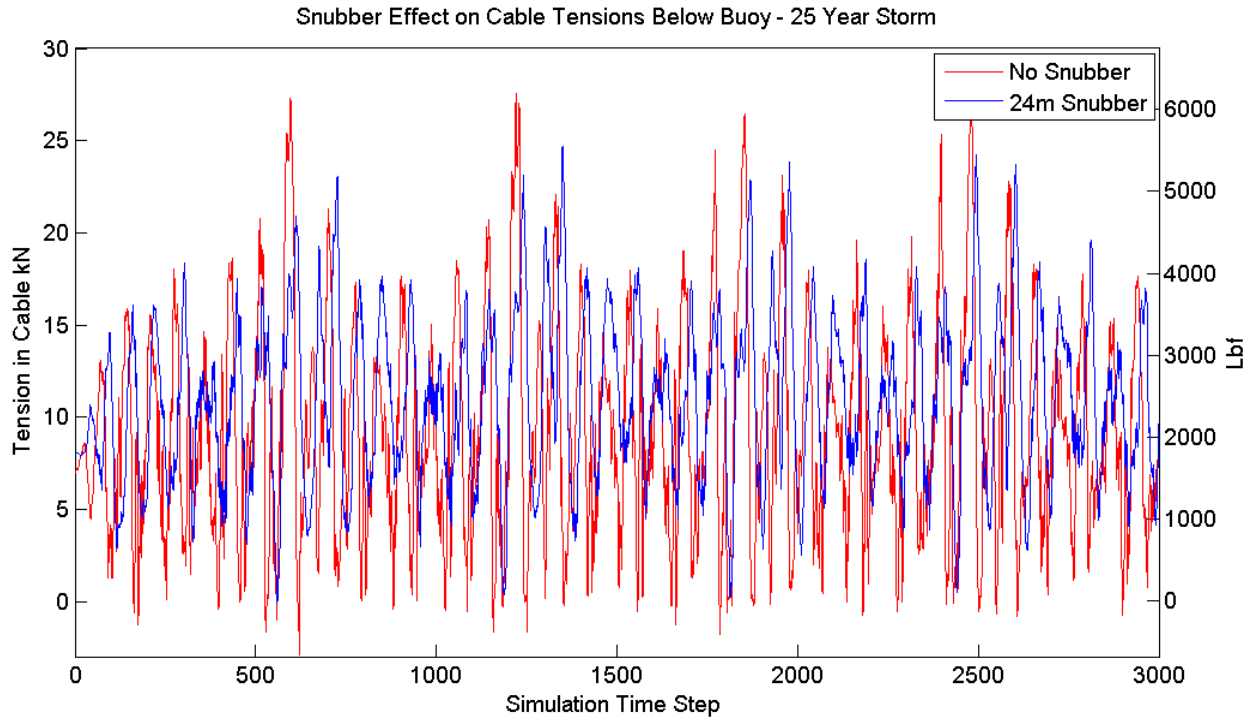


Figure 19. Comparison of cable tension with 24 meter Snubber and no Snubber in the 25 year storm condition.

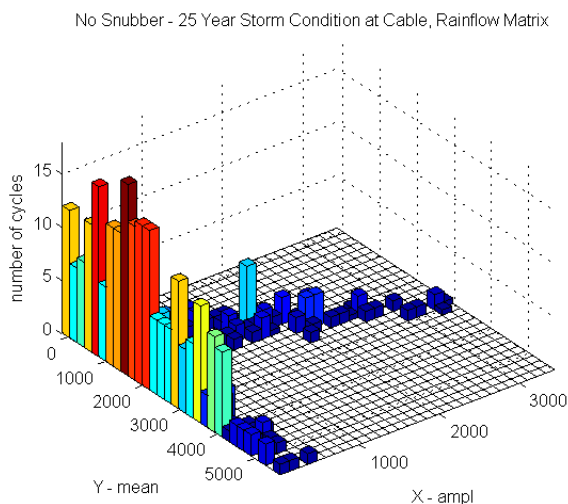


Figure 20. No Snubber (xy in lbf).

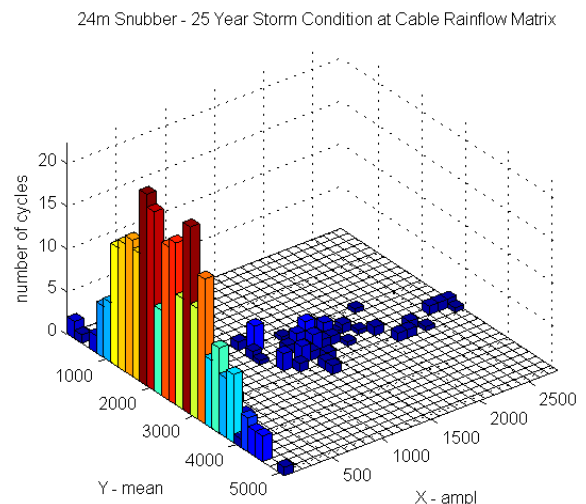


Figure 21. 24m Snubber (xy in lbf).

The times series of the dynamic tensions at the upper cable termination for the 25 year storm condition are plotted in figure 19 and the rainflow tension cycle plots for this condition are shown in figures 20 and 21. Note that in these conditions the Snubber also reduces the peak tension value and significantly lowers the number of cycles at higher amplitudes. In the 25 year storm condition the effect of the Snubber

reducing the number of cycles with a mean near or below 0 kN is more pronounced and cycles that extend below 0 kN tension are not present. The ability of the Snubber to reduce peak loads and prevent 0 kN load excursions continues to improve as the Snubber length increases as is shown in figures 22, 23 and 24 which illustrate the comparative results from the simulation comparing the results with Concept Design models incorporating 40 m and 56m Snubbers .

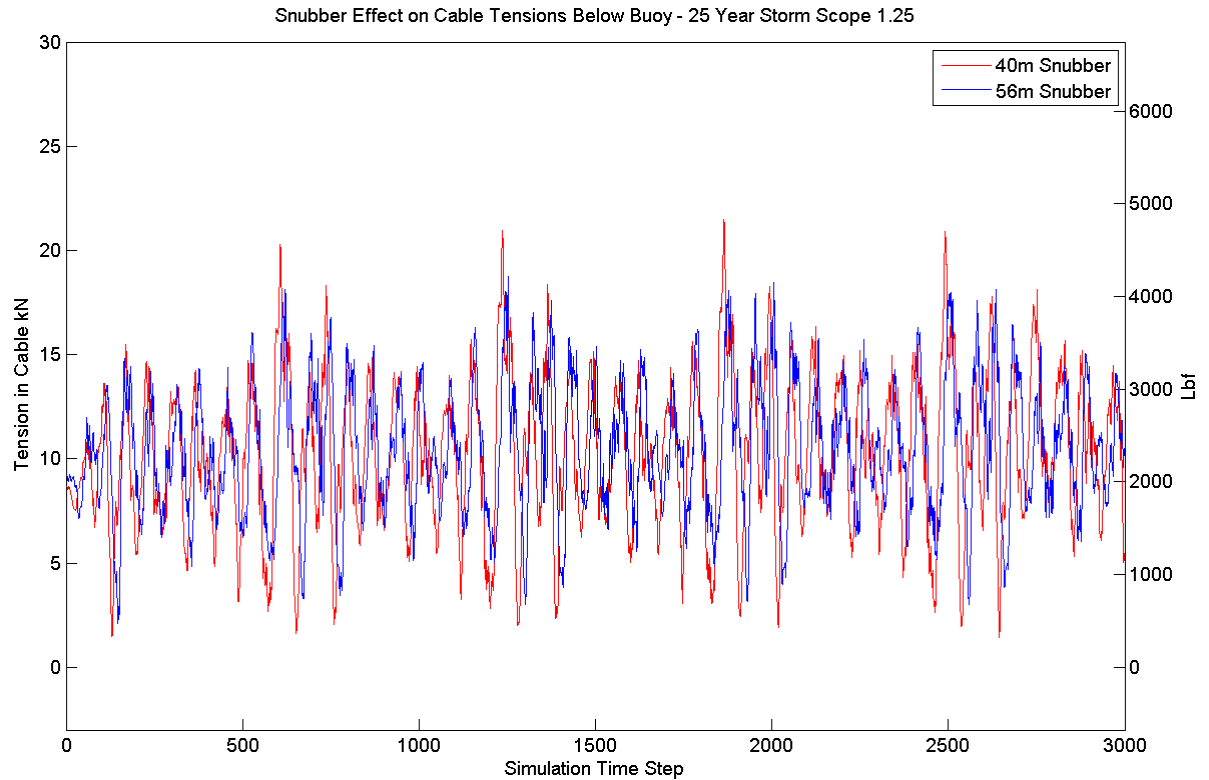


Figure 22. . Comparison of cable tension with 40 meter Snubber and 56m Snubber in the 25 year storm condition.

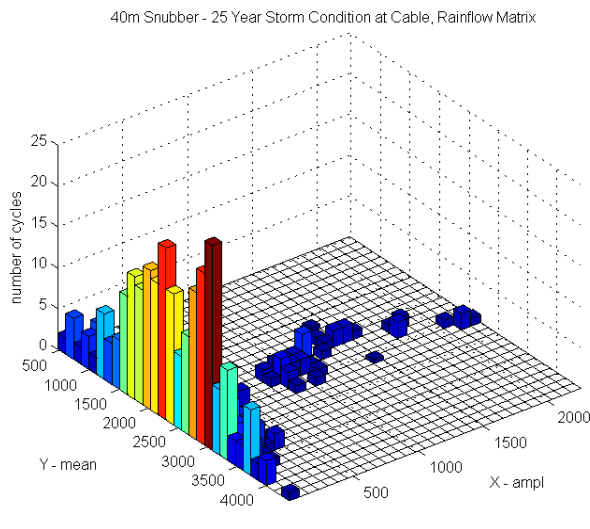


Figure 23. 40m Snubber (xy in lb).

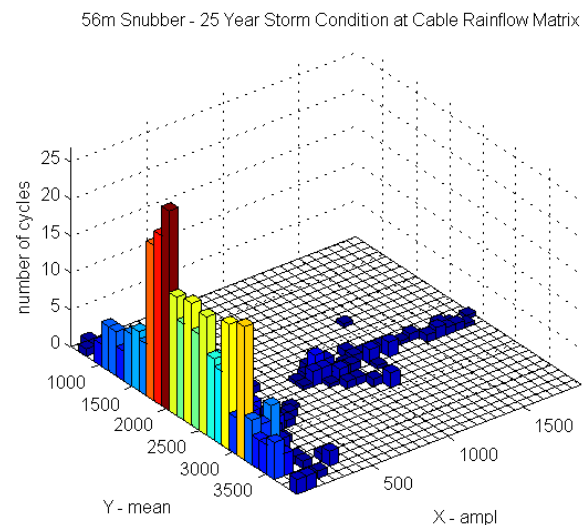


Figure 24. 56m Snubber (xy in lbf).

The plot in figure 25 is a more detailed view of a section of the time history of the 25 year storm forcing conditions. It clearly illustrates how longer Snubbers provide compliance for wave motions, reducing the peak loads and decreasing the load excursions around the mean tension value. The longer Snubber lengths also significantly reduce the number of load excursions below zero tension.

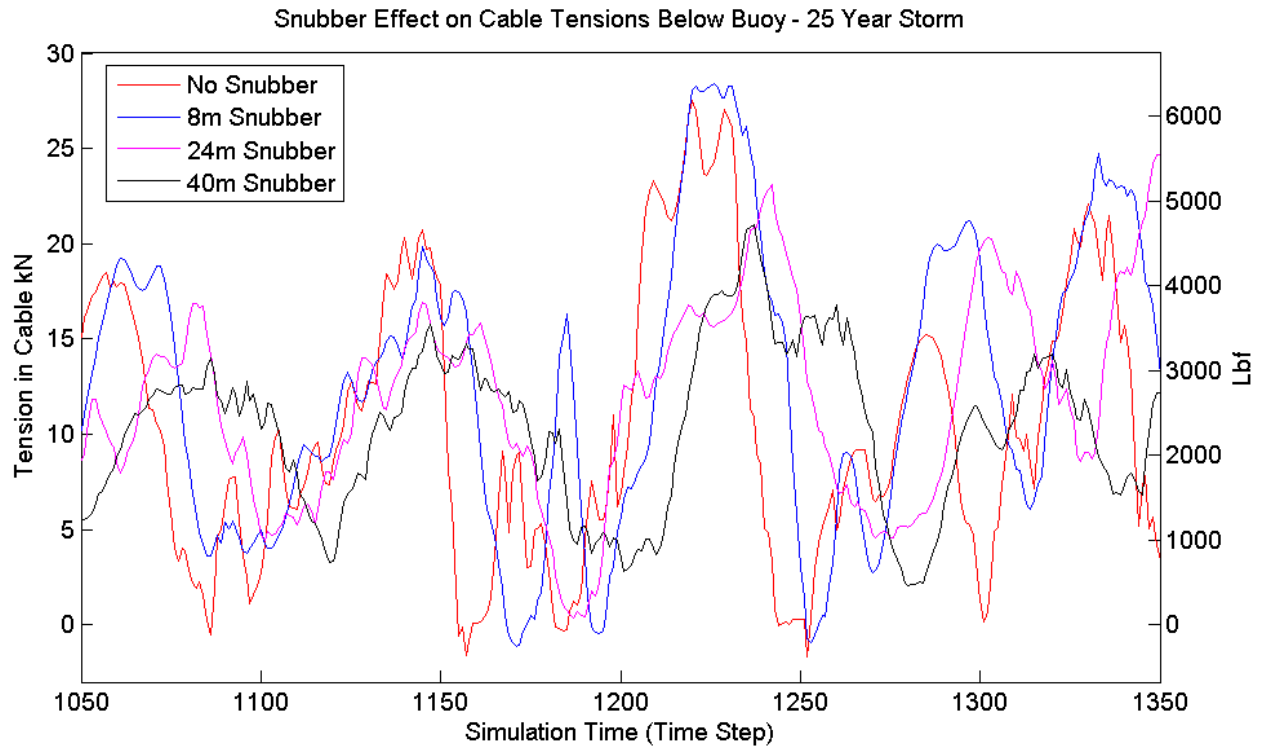


Figure 25. High resolution plot illustrating the comparative response to wave motion with sample of different length Snubbers.

5.2. Cable bending Analysis

MBARI's experience with mooring systems of this type has shown that the riser cable is subject to fatigue damage caused by fiber compression during low tension bending. The accumulation of low tension bending cycles is one of the significant limiting factors in the mooring system lifetime. Unpredicted bending fatigue in the riser cable could also cause a line break before the planned service life of the mooring. Testing of mooring riser cables recovered after 18 months of service with configurations very similar to the design configuration used in this concept study has shown that the area of the cable that weakens most significantly during the course of a mooring deployment is located at the upper end of the cable float section, as shown in figure 26. All other areas of the cable have shown a minimal loss of strength over the deployment durations. For these reasons, the bending analysis will concentrate on this section of the cable.

The riser cable and floated cable section are only constrained by the effects of mass and hydrodynamic drag on the components. For these reasons, bending in the cable occurs mostly under very low tensions and higher tensions pull the cable and floated section straight. The relationship between cable tension and cable bend angle can be seen in figure 27. When the cable tensions are high, the bend angles are low and the most severe bending occurs at almost zero tension.

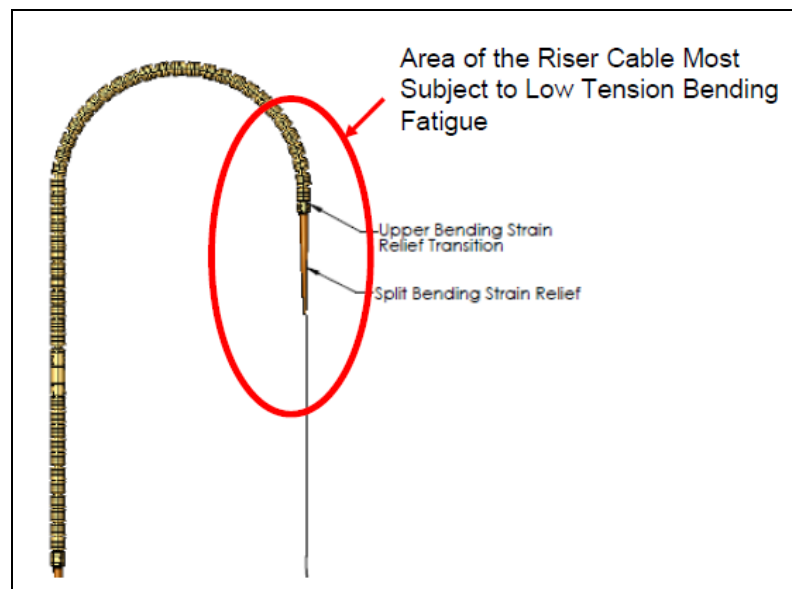


Figure 26. Detail of the riser cable in the area of the cable floats.

The method used to examine bending along the cable in detail has been to use the output data from the simulations to calculate the bend in the cable per meter under the range of environmental conditions modeled. Figure 28 plots an example of the bend per meter calculation under slack conditions. When the bend per meter value is positive, the actual cable bend is downward. The large positive value reaching 60 degrees per meter is the bend in the floated section arcing downward. The cable is then straight until the dip to negative values indicates a very gentle bend upward which is in the large radius lower section of the large catenary bend. This condition can be considered to be a very good environment for the cable. In a real mooring, the floated section containing the 60° bend has a constrained minimum bend radius due to the float lockup. It should be noted that the lockup at minimum radius of the floated section is not captured in the Concept Design model and that the degree of positive

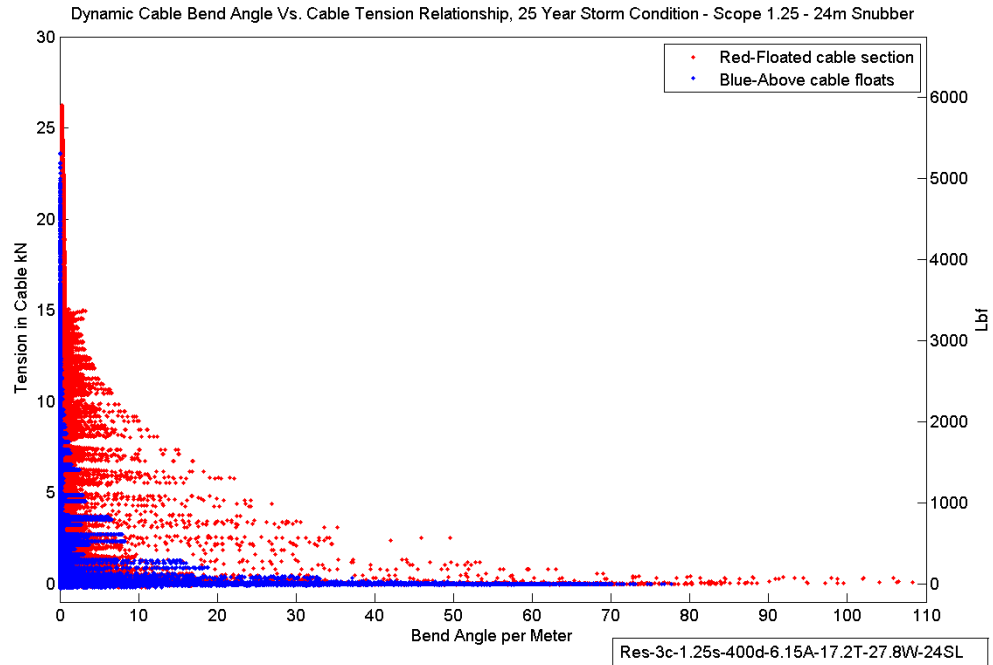


Figure 27. The relationship between cable tension and bend angle per meter for the cable in and above the floated section.

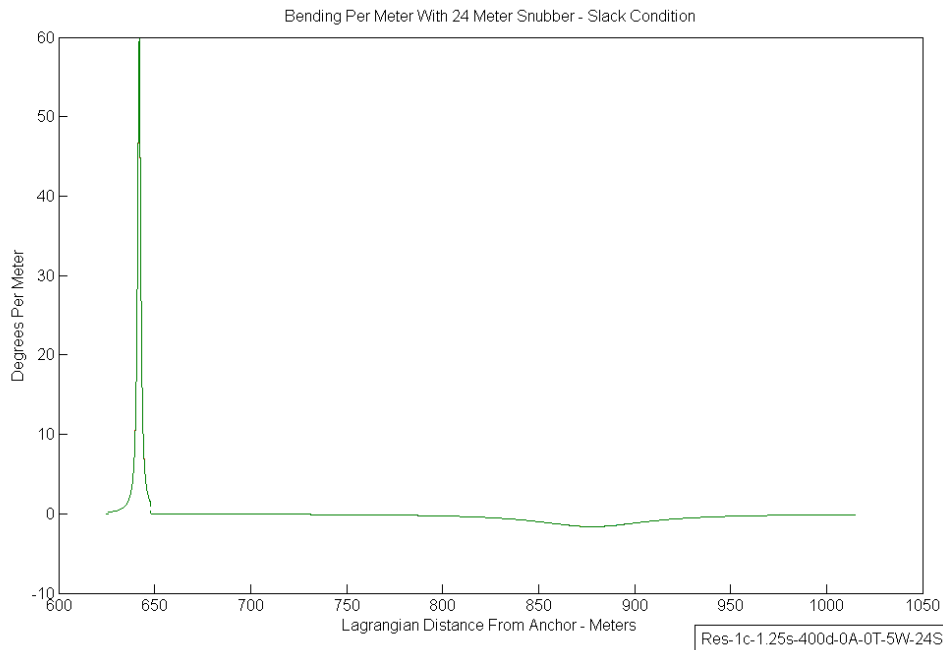


Figure 28. Cable bending along the middle (catenary) section of the cable length in the slack condition (see figure 9 for the actual position of the cable to help interpret this graph).

bending angles shown in the simulation results in figure 28 for the floated section are the results of the cable stiffness and tension relationship only. It is a coincidence that the 60 degrees per meter bend in the simulation corresponds exactly to the cable float lock-up point which is also 60 degrees per meter. Figure 29 shows a similar plot for the bend per meter values for the 90% non-exceedance condition in the dynamic

simulation. The cable area just after the floated section (at the 650 meter point on the x axis) now shows negative bending values. The bends here are not very severe but show that in some waves the catenary loop has been pulled straight and that upward deflection of the cable is now starting to take place in this section of cable. The line colors of the plot represent the bend per meter results for each of the 3000 time step records that were saved during the simulation, each line plotted by cycling through the color table. Further to the right in the plot, the multiple areas of localized bending in the riser cable appear to be gentle s-bends formed in the cable when the buoy drops faster than the mass of the cable can accelerate downward.

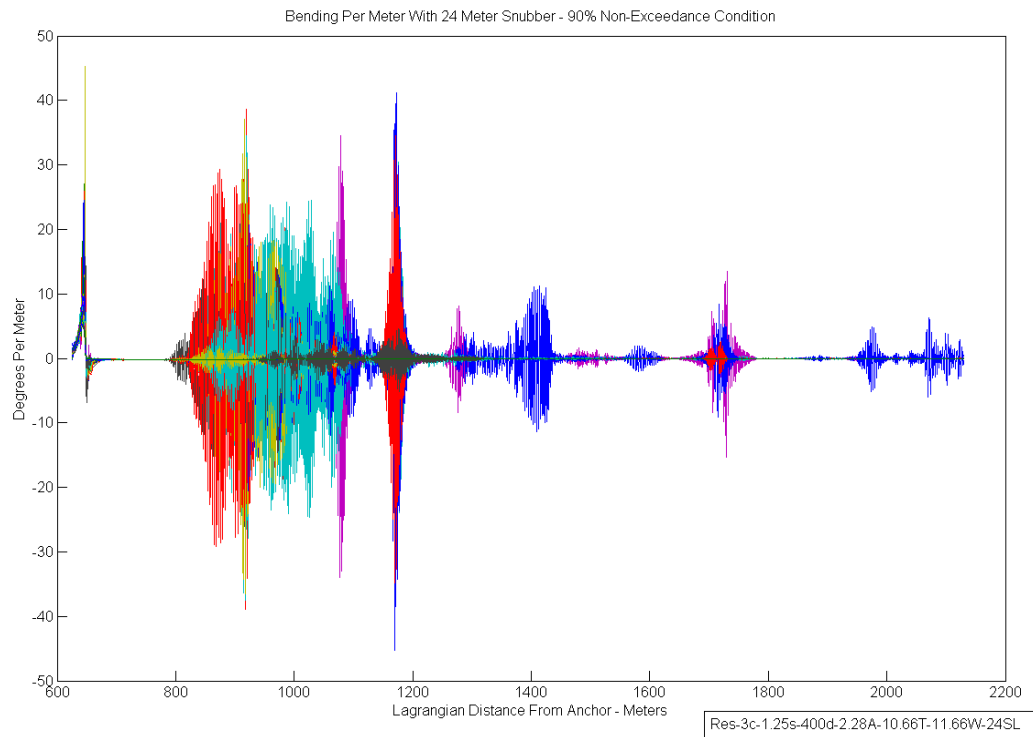


Figure 29. Cable bending for the 90% non-exceedance condition.

These multiple bends may also be artifacts of the numerical simulation and not actually exist in the real case. For example if the cable model values for transverse and tangential drag are slightly higher than the actual values it could produce this effect. If these bends are also occurring in actual moorings then they seem to be of little consequence. After several lengthy field trials no weakness has been detected in this section of the riser cable. In comparison, the cable area around the 650 meter point has consistently been shown to suffer from bending fatigue damage and this analysis will concentrate in this area.

In figure 30 the same data as figure 29 is shown in more detail, restricted to only the area of interest in the region of the transition from the cable floats to the unsupported cable in the position from 620 to 670 meters above the anchor. The plot shows the cumulative results the bend per meter results for each of the 3000 time step records that were saved during the simulation, each line plotted by cycling through the color table. Note that the area of greatest positive signal (downward bending) is occurring very close to the transition point from the floated cable to the non-floated cable whereas in figure 28 the cable bend at the transition was very low as the cable was tending straight down. See also the mooring configuration in the slack and 90% conditions in figure 9.

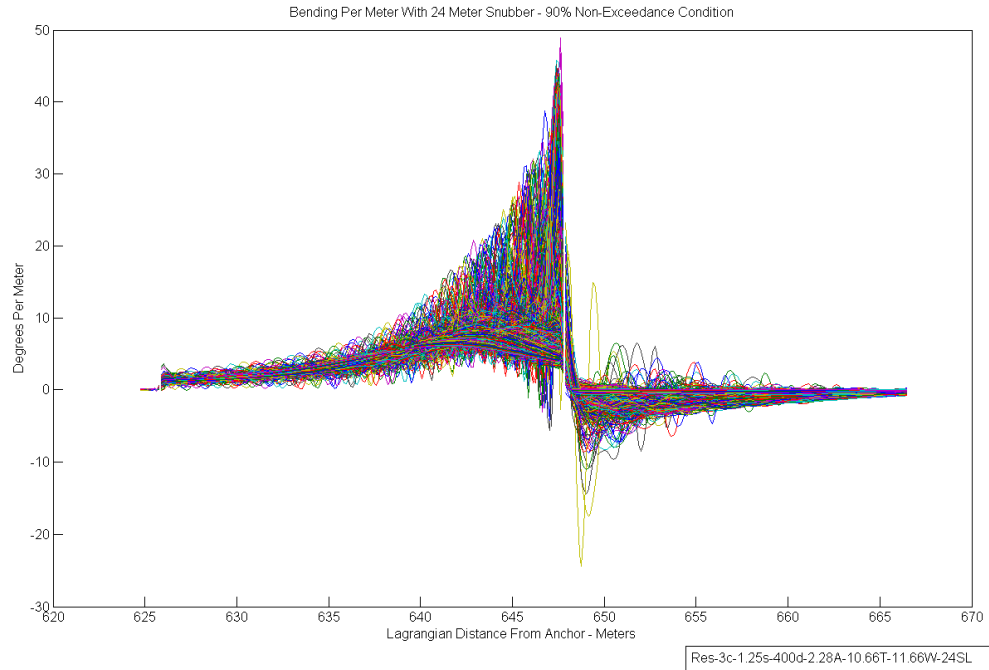


Figure 30. Smaller scale plot of the cable bending per meter in the area at the end of the floated cable section. The vertical line of no data at the 648 meter point is the junction of the floated cable segment with the unfloated cable.

In order to understand the significance of the bending at a particular location in the riser cable we can look at the bending history at a specific node in the time domain. This is illustrated in figure 31 which shows the time history of bending at node 198, which corresponds exactly to the position 649 meters up the cable that is shown in figure 30, a location in the cable immediately after the cable floats. Figure 30 shows that this location has a significant degree of bending per meter. The time history of the data at this location is shown in figure 31 and illustrates that the majority of the time the cable is nearly straight or bending to negative bend per meter values, indicating that the cable is bending upward, but that the peak amplitude of the bends are relatively small.

To quantify the number of bend cycles of a given magnitude at this node we can perform a rainflow counting exercise on the bending excursions captured in the time history data. Rainflow counting is a method used in the analysis of stress caused by random loadings¹⁰. Each cycle of a time history record is counted and binned with cycles of similar magnitude. In this case we apply the rainflow counting method to bending stress analysis. The rainflow calculation of a time series can be performed using a readily available Matlab algorithm¹¹. The result of the rainflow analysis is a histogram of the bending cycle amplitudes and mean values as shown in figures 32 and 33. It is important to note that the amplitude shown in the rainflow analysis plots is half the peak to peak value of a given bending cycle, i.e. a bend per meter cycle value from 0 to 40° in figure 31 is shown in the rainflow histogram in figure 32 as having an amplitude of 20°. Examination of figure 32 shows that numerous small amplitude bends occur but that relatively few bends occur at larger amplitudes. The minimum bend radius of the Concept Design model cable is 0.5 meters, which corresponds to a bend angle of 115 degrees per meter in the time history plots. In the rainflow plots this would represent 57 degrees per meter. Repetitive bend angles approaching these values will likely cause significant cable fatigue damage over time.

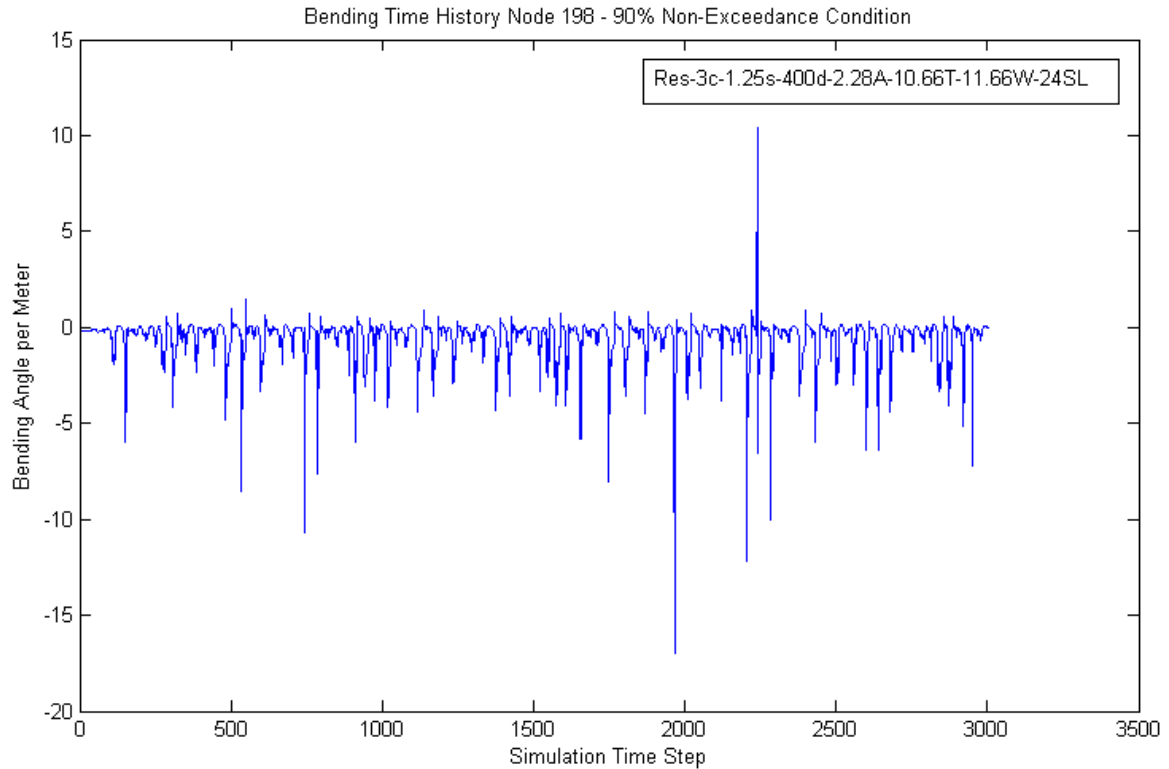


Figure 31. The time history of bending at node 198 in the 90% non-exceedance condition, which corresponds to the 649 meter point of figure 12. 3000 time steps represents 600 seconds of simulation time recorded every 0.2 seconds.

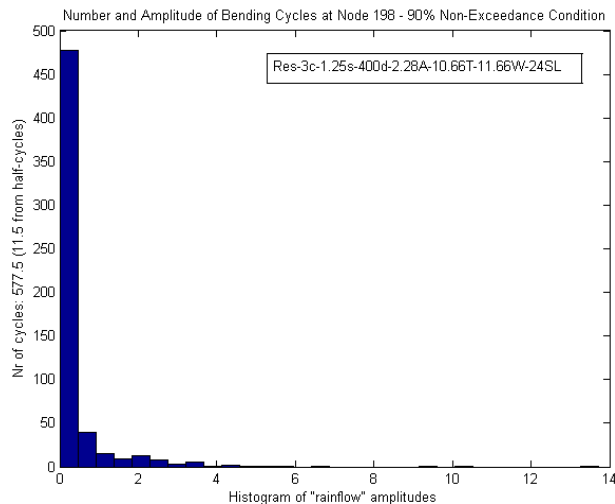


Figure 32. Histogram of the bending cycle amplitudes and the number of cycles at each amplitude of the node 198 time history shown in figure 15.

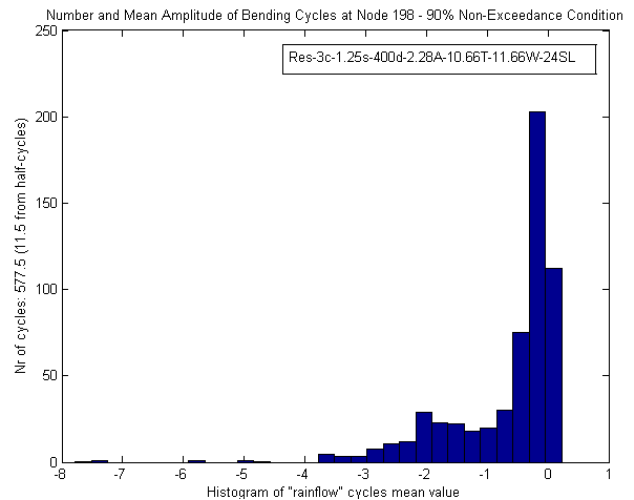


Figure 33. Histogram of the bending cycles mean values and the number of cycles at each mean of the node 198 time history shown in figure 15.

The histogram plot in figure 33 shows the mean values of each bending cycle and the number of occurrences at each mean value. Note that all of the cycle values are zero degrees or negative, indicating that the cable bending is predominately through the

neutral axis or upwards. Figure 34 combines the amplitude, mean and number of bend cycle data into a single matrix plot. It clearly illustrates that most of the bending cycles are of low amplitude, the higher amplitude cycles predominately have mean values that are negative (cable bending upward) and the mean values of each cycle are of similar absolute value as the bend cycle amplitudes meaning the cable is flexing in one direction at this location and not back and forth through 0 degrees. For example, the cycle with a mean value of -6 degrees has an amplitude of about 6 degrees so the bend cycle was approximately from zero degrees to -12 degrees (remember that the amplitude is $\frac{1}{2}$ the cycle peak to peak value). There are a few exceptions to this observation and they can be seen both in the time series plot in figure 31 and as the outlying points in the rainflow matrix plot in figure 34.

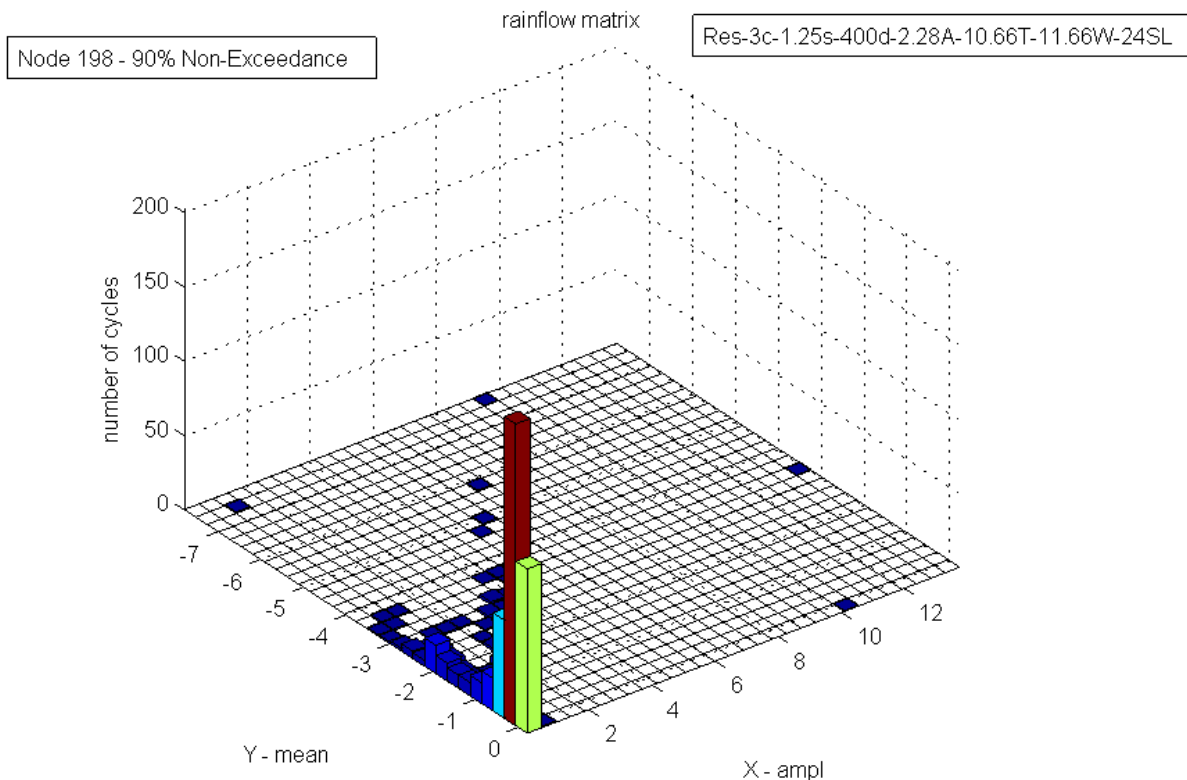


Figure 34. Rainflow matrix of bending cycle amplitudes and mean values for the 90% condition.

If we now examine the simulation data for the design condition at the same location in the cable we find that the number of bending cycles at higher peak amplitudes is much greater. This is shown in the time series plot in figure 35. The corresponding rainflow counting matrix plot in figure 36 clearly shows that most of the high amplitude bend cycles occur with a mean value near zero, meaning that the cable is flexing back and forth through neutral or zero degrees. This is considered the most damaging condition for the cable as the fiber strength elements in the cable are alternately cycled in tension and compression by the cable bend. The overall mooring configuration in the design condition can be examined by referring back to figure 9.

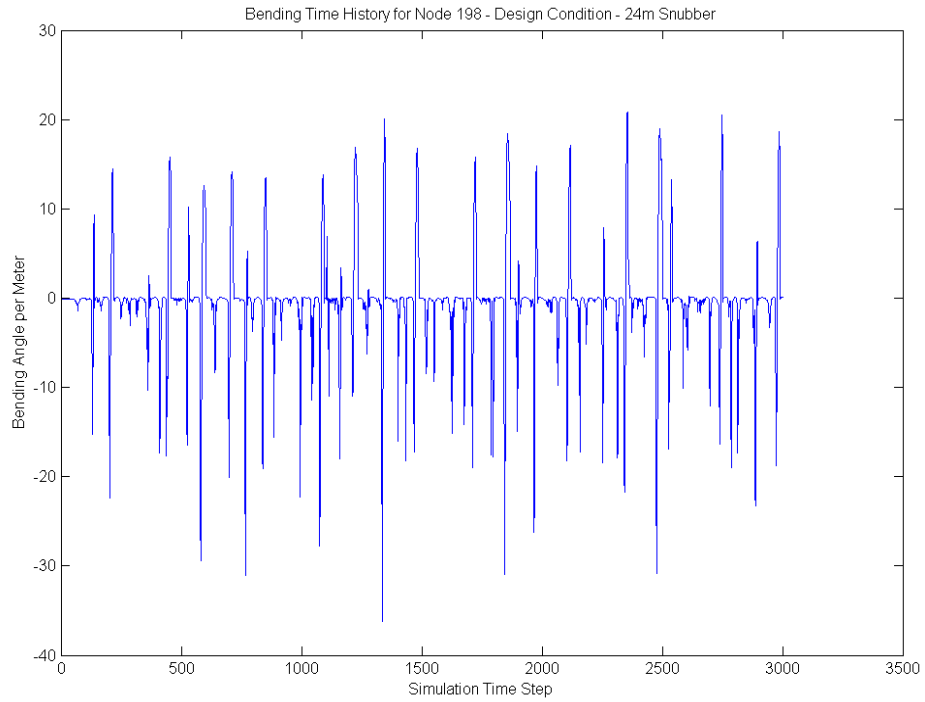


Figure 35. The time history of bending per meter at node 198 in the design condition with a 1.25 scope.

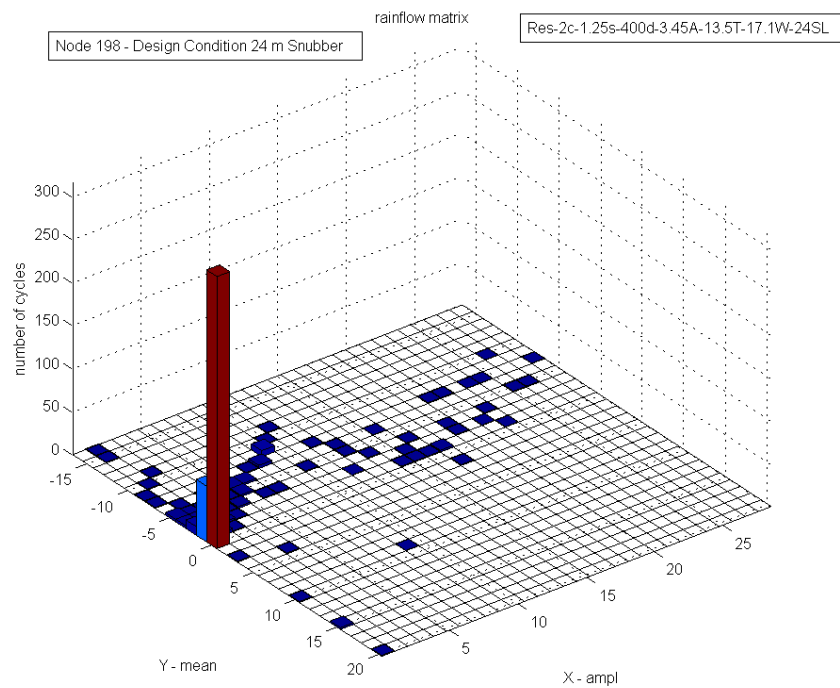


Figure 36. Rainflow matrix of bending cycle amplitudes and mean values for the design condition.

The time series plot in figure 37 for the 25 year storm condition shows very interesting results. The cable is straight in this location much more than in previous conditions, however there are periodic bends upward (negative values on the plot) of great magnitude. There are also downward cable bends periodically (positive values), as the catenary tries to resume it's relaxed shape. These downward cable bends are no greater in magnitude than in the design case. The rainflow plot in figure 38 also shows that most bends are upwards (negative values) but also that the high amplitude bend cycles have mean values closer to zero, showing that the cable is bending thru zero degrees.

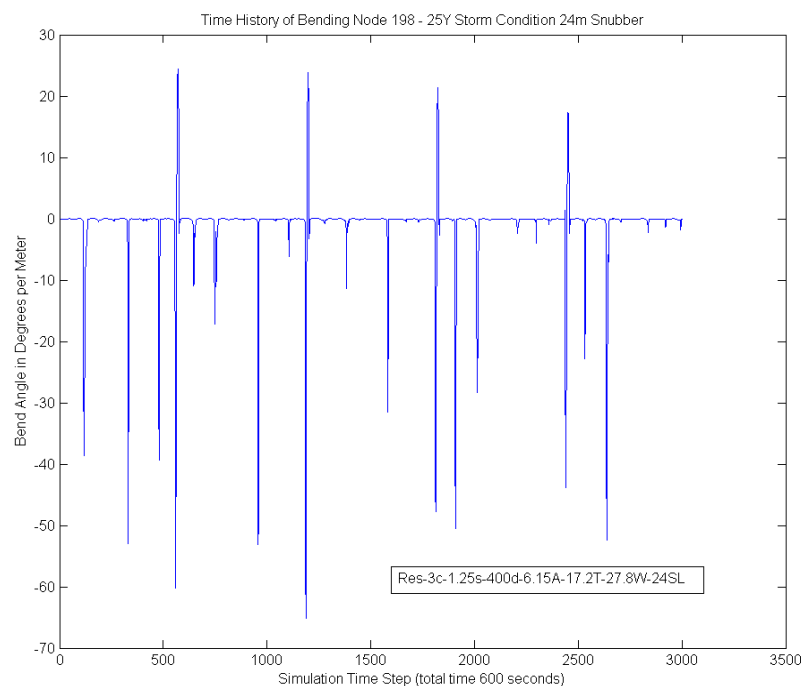


Figure 37. The time history of bending per meter at node 198 in the 25 year storm condition.

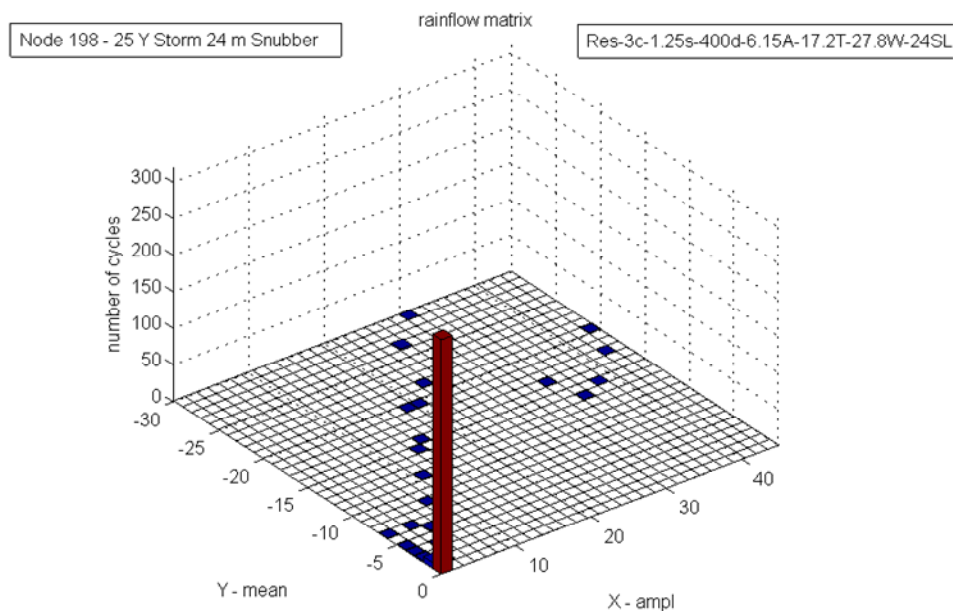


Figure 38. Rainflow matrix of bending cycle amplitudes and mean values for the 25 year storm condition.

5.2.1.Changes in mooring configuration that effect the bending number of cable bending cycles.

5.2.1.1. Mooring riser cable scope effect on bending.

From the simulation data it appears that the bending environment for the cable at the end of the floated cable section only becomes severe when ocean current conditions force the mooring to near the edge of the watch circle. In the simulation with the Concept Design this condition started to occur after the <90% exceedance condition and became very pronounced in the design condition. Under these conditions the wave motion absorbing catenary has been decreased to where the repetitive bending of the cable due to wave motion has moved down to the transition point between the floated cable section and the non-floated cable. With each wave cycle the cable alternately is pulled straight and then begins to re-form the catenary configuration. For a given ocean current condition the catenary shape can be changed by changing the properties of the cable floats and the cable itself. By increasing the weight of the cable it allows a catenary shape to remain under higher current forcing conditions. Another approach is to increase the mooring scope, which increases the cable weight and stiffens the catenary.

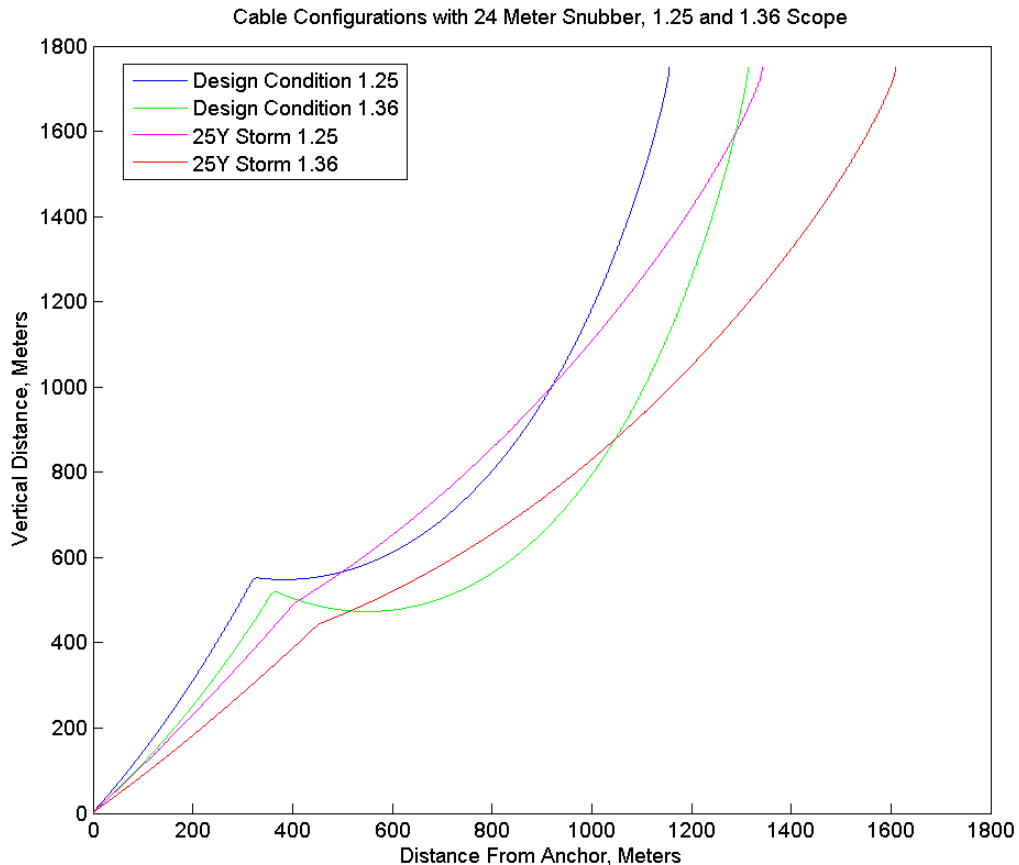


Figure 39. The comparison of the mooring configuration with cable scopes of 1.25 and 1.36.

To test this condition the mooring scope was increased to 1.36 which increased the anchor cable length by 192.5 meters. Figure 39 compares the resulting cable configurations. Note that the configuration of the cable in the design condition with a scope of 1.36 compares well with the configuration of the cable in the <90%

configuration in figure 9 where the scope was 1.25. Also, as shown in table 7, the maximum dynamic loads did not increase significantly with additional scope. The bending time history plot in figure 40 and the rainflow matrix plot in figure 41 confirm that with the mooring scope increase to 1.36 the bending cycles in the design condition are reduced to a value similar to the <90% condition and 1.25 scope. The simulation shows that increasing the mooring scope to 1.36 places much less bending stress on the cable in the design condition.

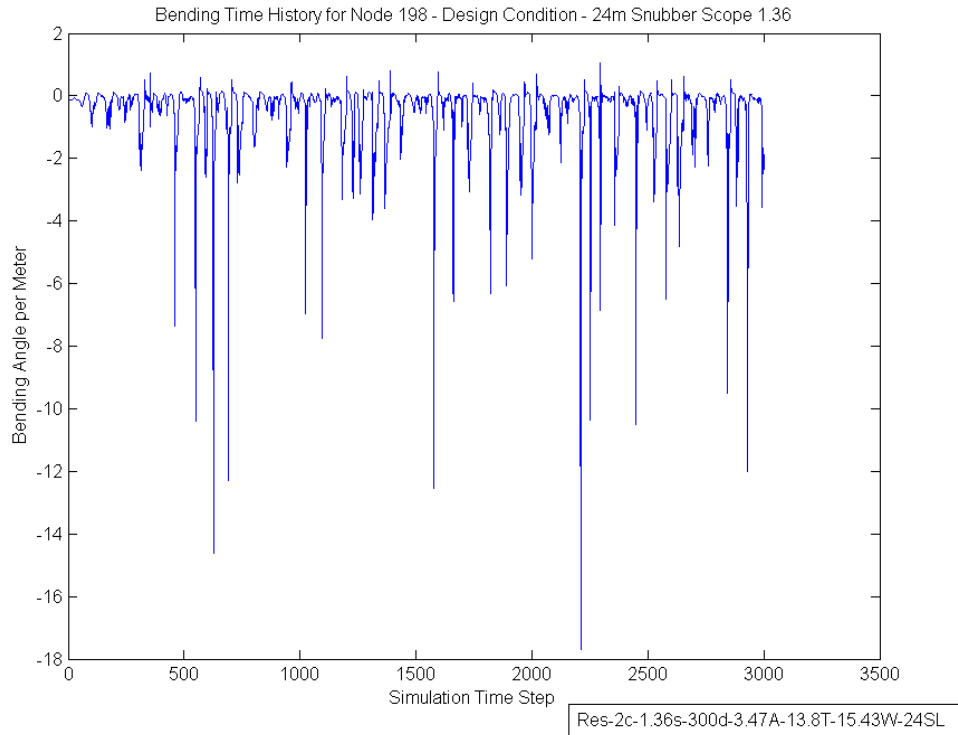


Figure 40. The time history of bending per meter at node 198 in the design condition with a 1.36 scope.

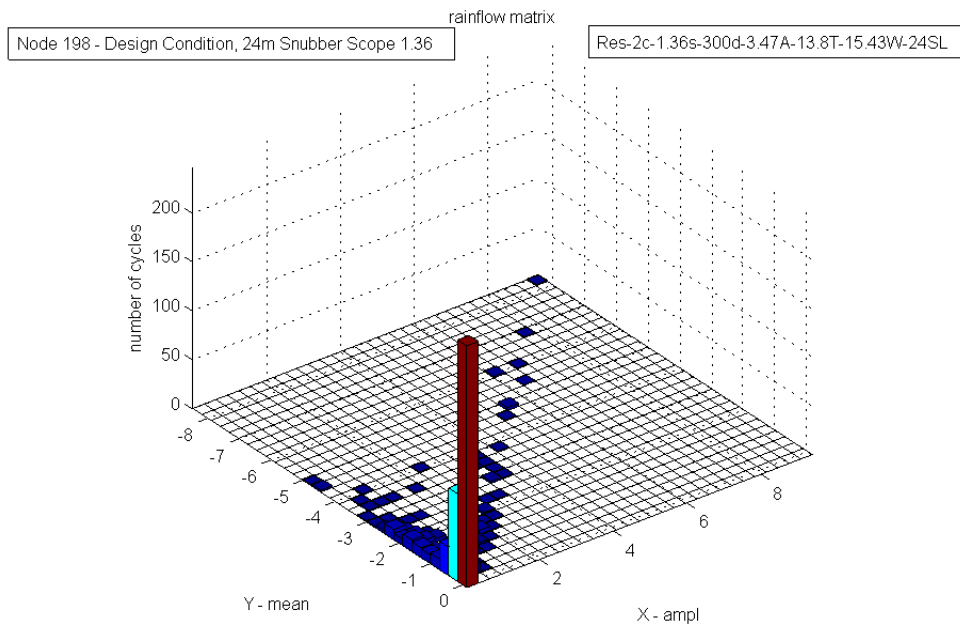


Figure 41. Rainflow matrix of bending cycle amplitudes and mean values for the design condition and 1.36 mooring scope.

5.2.1.2. Snubber length effect on bending.

In a second test on the effects of changing the mooring configuration on bending stress the Snubber length was increased from 24 to 56 meters while the scope remained at 1.25. Increasing the Snubber length resulted in only a minor effect on the bending environment. In figure 42 the time history shows that in the design condition the number of bending cycles at node 198 was slightly reduced with the 56 meter Snubber when compared to the results with a 24 meter Snubber as shown in figure 35. Mostly likely this is the result of the longer Snubber absorbing more of the energy from the smaller waves. There was also a mean shift resulting in fewer bends with a mean near zero degrees where the cable is flexing through neutral. The magnitude of the bends actually increased slightly with the longer Snubber. Overall the increase in Snubber length did not result in a significant reduction in the number of bend cycles or bend amplitudes in the design condition.

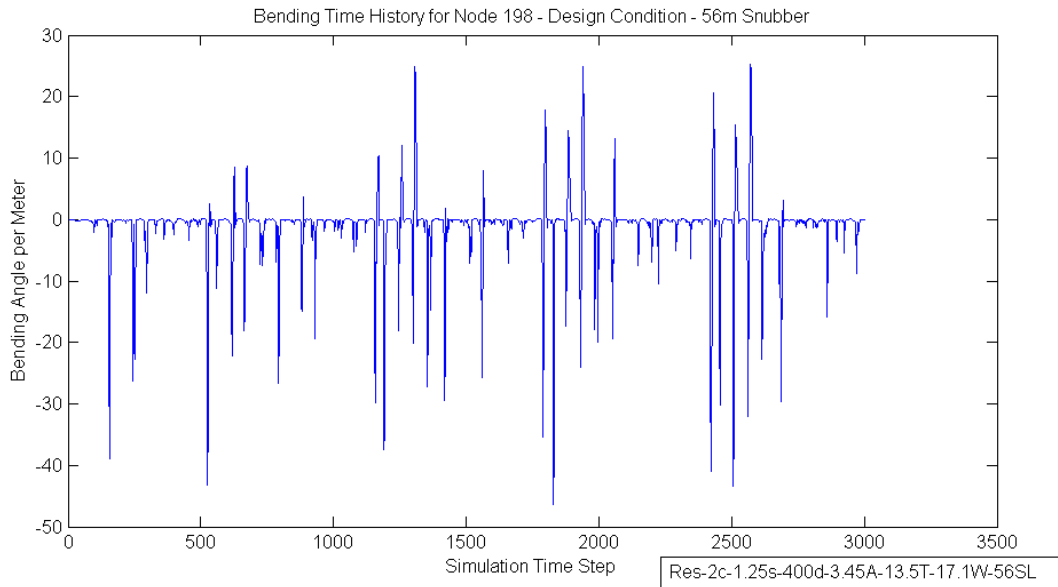


Figure 42. The time history of bending per meter at node 198 in the design condition with a 1.25 scope and 56 meter Snubber.

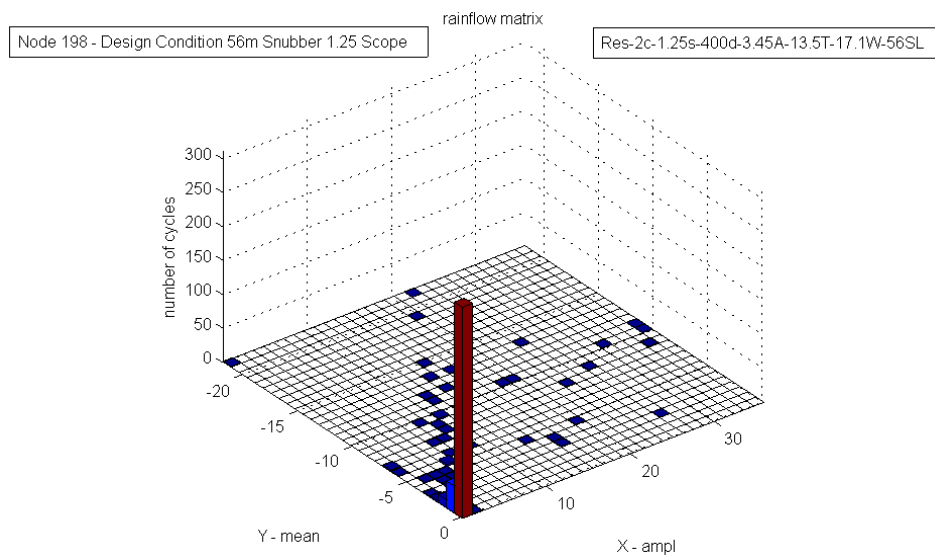


Figure 43. Rainflow matrix of bending per meter at node 198 in the design condition with a 1.25 scope and 56 meter Snubber

5.2.2. Conclusion of the bending analysis.

The analysis of the bending data shows the under the environmental forcing conditions corresponding to the 50%, 70% and 90% non-exceedance values, very little damaging flexing of the mooring riser cable occurs. In conditions that exceed these values the configuration of the mooring allows the repetitive cable movement from wave motions to concentrate bending in the cable region where the cable floats end and the non-floated cable begins. In the Concept Design model this floated to non-floated cable transition point occurs at a cable length of 948 meters from the anchor.

In the simulation runs of this study, the effect of current, waves and wind for a given environmental condition are not modeled separately, however the mooring position in the watch circle is mostly driven by current forcing. The result of this is that the conditions that are damaging to the mooring cable may occur in conditions where the currents are high and force the mooring near to the edge of the watch circle, however the wind and wave conditions may not be as severe as the conditions simulated. See also the recommendations for additional study in section 7 for more discussion on optimizing the mooring design for the ocean current conditions at the study site.

5.2.3. Optimization of total cable float buoyancy.

The optimization of the total cable float buoyancy should be performed as an optimization step in the final design based on predictions of the yearly distribution of current forcing. The objective is to minimize cable bending over the greatest range of predicted conditions. See the recommendations in section 7.3.

5.2.4. Optimization of the location of the cable floats

Due to time limitations simulation runs were not conducted to optimize the location of the cable floats. Previous work has shown that the vertical location has a minimal effect on the mooring dynamics. The function of the cable floats is to prevent the excess cable from the catenary from contacting the seafloor. The closer to the anchor end of the riser cable the floats are placed the less buoyancy is needed. In order to facilitate ROV access to the seafloor area near the mooring anchor the floats and catenary bend are placed approximately 600 meters up the cable in the Concept Design model.

6. Installation Methods

6.1. Ship Winch Requirements

The deployment of the mooring system described in this Concept Design will require an oceanographic winch system of sufficient capacity to store the total length and type of cable specified for the system. The drum core diameter and any fairleads or sheaves used for the Riser Cable must be sized to meet the minimum bend radius specification of the cable. The cable must be wound on the drum in a direction consistent with the construction of the cables outer wrap, either a left-hand or right-hand lay. The line pull requirements for the winch system are that it can, at a minimum, retrieve the weight of the length of the riser cable not supported directly by the cable and anchor floats.

6.2. Deployment simulation

It is recommended that an anchor last free fall deployment method be used. This method eliminates the uncontrolled dynamic loads associated with gradual anchor

lowering from a vessel and is safer for deck personnel. The positioning accuracy of the anchor location expected with this method is approximately 1% of water depth or better. The Concept Design model was used in an anchor last deployment simulation with a numerical solution calculated on 0.1 second intervals. The position of the mooring was saved every 5 seconds of simulation time. The anchor contacted the seafloor 735 seconds (12 minutes 16 seconds) after launch at a point (setback) 260 meters from the launch position. The successive positions of the mooring system as the anchor free-falls to the seafloor are shown in figure 44. The time history of the riser cable tension loads at the base of the Snubber and above the anchor float are shown in figure 45. The maximum tension loads on the riser cable are within the specified working range of the riser cable.

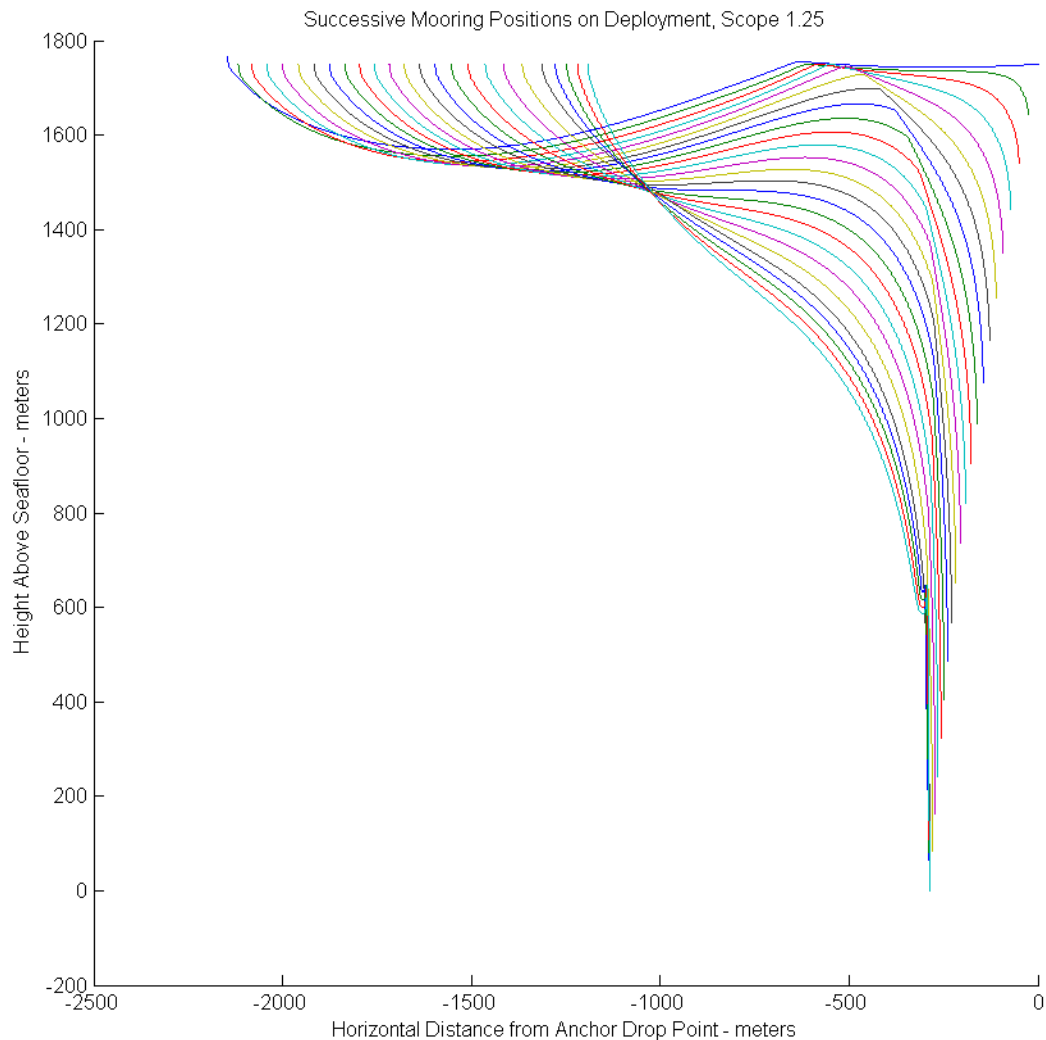


Figure 44. Successive mooring positions during deployment simulation.

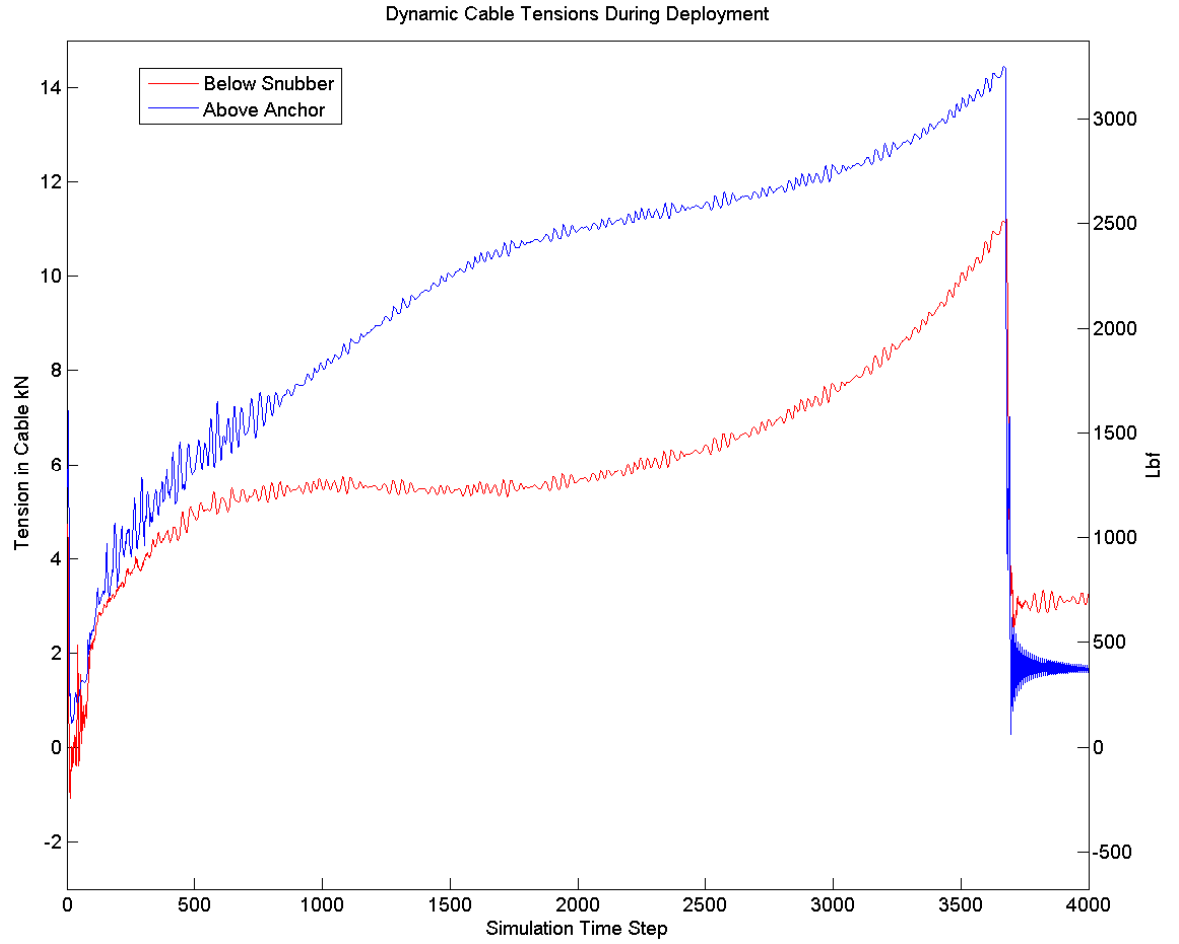


Figure 45. Tensions in the riser cable below the Snubber and above the anchor during the deployment simulation. The recorded simulation time step is five seconds, so 4000 time steps represents a duration of 800 seconds.

7. Recommendations for Additional Study

7.1. Riser cable materials

As described in the “Optimization for bending” section above, previous work has determined that the limiting factor in the service life of the riser cable is weakening in the section at the transition from the cable floats to the upper section of the cable. The fatigue mechanism is most probably repeated bending under low cable tension causing fiber compression and kink band formation. An area for further study is to seek improvements in the Riser Cable survivability by investigating methods of improving the tolerance for low tension bending by investigating materials and construction methods which may be more tolerant of low tension bending fatigue. The best cable material to date for low tension bending fatigue life has been found to be Liquid Crystal Aromatic Polyester (LCAP), known by the trade name Vectran®, however there are other synthetic fibers with the potential to improve fatigue life such as High Modulus Polyethylene (HMP)(trade names Dyneema®, Spectra® and Certran®) and possibly Dyneema®/Vectran® blends. The successful design of an improved Riser Cable incorporating HMP fibers depends on the effect of the integrated load history on the fibers long term creep properties. Laboratory and field testing of the cable would be required to verify that the bending fatigue life improved and that the long term creep did not exceed a value that can be tolerated by the electrical conductors.

7.2. Refine model to improve representation of the floated cable section and associated bending strain relief.

The Concept Design model does not include the property of the cable floats to lock up at 60 degrees of bend per meter and does not include the graduated bending strain relief that transitions the cable from the floated section to the unmodified cable. Previous experience has shown that the area of this transition is most prone to fatigue damage from repeated cable bending and is the limiting factor in the mooring system lifetime. Increasing the resolution of the Concept Design model in this critical area of the mooring riser cable may facilitate tuning the configuration of the mooring system to minimize fatigue bending.

7.3. Use previous mooring position records and hindcast bulk current fields to develop a profile of the predicted mooring position in the watch circle.

The factor most influencing the degree of fatigue bending above the floated cable section is the position of the surface mooring in relation to the anchor – the position in the watch circle - , and the mooring position is driven primarily by the forcing of ocean current on the riser cable. If the bulk ocean current can be reliably predicted then the Concept Design and simulation can be used to optimize the factors that influence the degree of bending in a given current condition and to minimize the number of high amplitude bend cycles over the greatest possible range of current conditions predicted.

It may be possible to use location data from previous mooring deployments with a model of the mooring system deployed to simulate and subsequently hindcast the bulk ocean current conditions. This information could then be used to optimize the riser cable weight, the cable float buoyancy and the mooring cable scope, to minimize cable bending and maximize cable life in a new mooring design specifically for the target location.

7.4. Consider designing a Snubber with a softer EA curve to allow a shorter length to be used.

The Snubber used in the Concept Design model is a design that has been well characterized in laboratory load tests and endurance tested in the field. The design has been fabricated numerous times by a commercial manufacturer with very consistent results. The Snubber hose design is relatively stiff compared to other similar designs that have been built for other buoy applications. For example the Snubber in the concept design model has a strain of 0.33 at the Snubber nominal working load (stress) of 20kN (see figure 2). Snubbers have been developed that have strains reaching 1.0 at the design working load or 100% stretch¹². The use of a softer Snubber would allow a shorter total Snubber section length with the same benefits in reducing peak cable loads. The original design of the Snubber hose was performed at WHOI, however the basic design principles are in the public domain and can be replicated for new designs. A new design would have to be thoroughly tested to ensure that is performed to the same level of reliability.

7.5. Develop an SN curve based on bending severity for cable and use to predict field lifetime.

It is possible to test cable designs by performing a measurement of the number of stress cycles to break under different degrees of low tension bending. Ideally the conditions should approximate the tension and bend angle relationship shown in figure 27. Using the cycle counts from rainflow analysis it may then be possible to estimate the service life of the riser cable under predicted field conditions.

7.6. Mooring release system.

The use of high modulus riser cable results in higher cyclic loads in the mooring release system and ground tackle than with traditional moorings with nylon cables. MBARI has had several instances of mooring releases failing due to fatigue failure of the release attachment point or wear-through of the release jaws. The mooring release system must be carefully designed to ensure it is capable of sustaining the required loads for the duration of the intended deployment.

7.7. Perform a detailed mooring design.

Based on the results of the concept study and the additional work described above, a detailed design should be completed that results in final specifications for the buoy payload, surface float volume, riser cable design, mooring scope, cable floatation, Snubber EA profile and length, anchor float buoyancy and anchor weight. The mooring Concept Design model used for this simulation represents a workable design, however for the best performance at least one more optimization cycle should be completed.

8. Appendix

8.1. Cable run input files

```
#include "Lower_Cable.spec"

Problem Description
  title = "MOOS Mooring"
  type = surface

Analysis Parameters
  static-outer-iterations = 1000
  static-iterations      = 10000
  static-relaxation       = 0.1
  static-tolerance       = 0.01
  static-outer-tolerance = 0.01
  static-outer-relaxation = 0.99

  duration                = 600
  time-step               = 0.02
  dynamic-tolerance       = 1e-6
  dynamic-relaxation      = 1
  dynamic-iterations      = 20
  dynamic-integration     = temporal
  ramp-time               = 30.0

Environment
  rho                    = 1025
  gravity                = 9.81
  x-current              = (0.0, CURR_0) (50, CURR_50) (100, CURR_100) (150, CURR_150) (200, CURR_200)
(500, CURR_500)
                        (1000, CURR_1000) (1500, CURR_1500) (1750, CURR_1750)
/*(x-current            = (0.0, CFACT*0.7) (50.0, CFACT*0.63) (100, CFACT*0.56) (150, CFACT*0.50)
(200, CFACT*0.50)
                        (250, CFACT*0.45) (300, CFACT*0.25) (WATER_DEPTH, CFACT*0.1163) */

  x-wind                 = WIND /* design wind */
  depth                  = WATER_DEPTH
  input-type             = random
  forcing-method          = wave-follower
  x-wave = (AMP,PER,0.0)
  bottom-stiffness       = 750.0
  bottom-damping         = 0.5

Buoys
  buoy_LB                type = cylinder
                        d = 2.34
                        h = 1.12          m = 1473          Sw = 3.25
                        Cdn = 1           Cdt = 1           Cdw = 0.54

Anchors
  clump                  color = red
                        m = 4026 /* 8858 lbm */
                        wet = 34300
                        d = 0.96*1.8 /* Diameter adjusted to reflect double config */
                        Cdn = 1.0
                        Cdt = 1.0

Connectors
  coupling               m = 13.35
                        wet = 113.4
                        Cdn = 0.001
                        d = 0.001

  coupling2              m = 0.01
                        wet = 0.01
                        Cdn = 0.0001
                        d = 0.0001

  bot_footballs d = 0.5771 /*This represents 4 footballs bunched right at bottom */
                        m = 4*37.9
```

```

        am = 31.84
        wet = -21.9*9.81*4
        Cdn = 1.0
        Cdt = 0.2

lg_football  d = 0.5771
              m = 37.9
              am = 31.84
              wet = -21.9*9.81
              Cdn = 1.0
              Cdt = 0.2

sm_football  d = 0.4545
              m = 18.52
              am = 14.84
              wet = -11.29*9.81
              Cdn = 1.0
              Cdt = 0.2

TerminationFloats
  d = .7
  m = 500/2.2
  wet = -250*9.81/2.2
  Cdn = 2.0
  Cdt = 2.0

Materials

chain_1_2    EA = 5.5e7      EI = 0.5      GJ = 0.1
              m = 6.2        am = 0.584     wet = 38.1
              d = 0.0265     Cdt = 0.01    Cdn = 0.55

Lower_cable  EA = 6.7e6      EI = 1.0      GJ = 0.1
              m = 0.700      am = 0.5      wet = .110*9.81
              d = .028       Cdt = 0.005     Cdn = 1.5
/* Changed Cdt to .005 from .01 based on research*/

Upper_cable  EA = 6.7e6      EI = 10.0     GJ = 0.3
              m = 1.17       am = 0.5526    wet = 0.28*9.81
              d = 0.034      Cdt = 0.005     Cdn = 1.5
/* Changed Cdt to .005 from .01 based on research*/

Unstiffened_Upper_cable EA = 6.7e6      EI = 5.0      GJ = 0.3
              m = 0.9        am = 0.5526    wet = 0.1*9.81
              d = 0.034      Cdt = 0.01     Cdn = 1.5

Floated_cable EA = 6.7e6      EI = 3.0      GJ = 0.3
              m = FC_MASS
              d = FC_DIAM    Cdt = 0.1      Cdn = 1.5

snubber      type = nonlinear /*added type = to model as nonlinear EA curve*/
              EA = 3.13e4    EI = 1000     GJ = 500
              m = 27.8       am = 14.33     wet = 145.4
              d = 0.1334     Cdt = 0.01     Cdn = 1.5
              bt = 2.5 /*estimated value for neoprene rubber*/
/* Changed snubber m and wet based on new calculation*/
/* New Snubber material property values based on pull test*/
              T = 6500*(exp(4.5*e)-1)
              Te = 29250*exp(4.5*e)
              Tee = 1.31625e5*exp(4.5*e)

/* 5.625" OD 5.25" ID diam 316L stainless pipe, mass adjusted for flanges on ends, so useful for ~1m
sections only*/
SS_Pipe
  EA = 4.0e8      EI = 1000      GJ = 1000
  m = 21.0        wet = 62
  d = 0.143       Cdt = 0.01     Cdn = 1.5

/* 5.625" OD 5.25" ID diam 316L stainless pipe, mass adjusted for flanges on ends, so useful for ~1m
sections only*/
SS_PipeBetweenSnubbers
  EA = 4.0e8      EI = 1000      GJ = 1000

```

```

        m = 38.0                wet = 0.8742*38.0*9.81
        d = 0.143                Cdt = 0.01                Cdn = 1.5

    BendingStrainRelief  EA = 6.7e6  EI = 10.0            GJ = 0.3
/* Length = 1.8 */      m = 23/1.8    wet = 7*9.81/1.8
                        d = 0.12        Cdt = 0.1          Cdn = 1.5

    AcousticRelease      EA = 1.0e9  EI = 1.0e7  GJ = 1.0
/* Length = .91 */      m = 35/.91    wet = 9.8*(35-9)/.91
                        d = 0.127      Cdt = .5        Cdn = 3.0

    FloatedDoubleRelease EA = 1.0e9  EI = 1.0e7  GJ = 1.0
/* Length = 1.0 */      m = 700        wet = -700*9.8
                        d = 1           Cdt = 1.0        Cdn = 1.0

    LowerLoadCell        EA = 1.0e8  EI = 1.0e7  GJ = 1000.0
/* Length = .19m */     m = 4/.19      wet = 4*.87*9.81/.19
                        d = 0.05        Cdt = 0.1          Cdn = 1.5

    Upper_Termination    EA = 1.0e9  EI = 1.0e7  GJ = 1000.0
/* Length = .5m */      m = 61         wet = 525
                        d = 0.143      Cdt = 0.5          Cdn = 1.75

    Lower_Termination     EA = 1.0e9  EI = 1.0e7  GJ = 1000.0
/* Length = .84m */     m = 50/.84      wet = 0
                        d = .35         Cdt = 0.5          Cdn = 1.75

Layout
    terminal = {
        anchor = clump
#ifdef DEPLOY
        x-speed = 2.0*0.514
#endif
    }

    segment = { /* 1.5 meters of chain approximates bridle */
        length = 1.5
        material = chain_1_2
        nodes = (6, 1.0)
    }

    segment = {
        length = 1.0
        material = FloatedDoubleRelease
        nodes = (3, 1.0)
    }

    segment = {
        length = 2
        material = chain_1_2
        nodes = (3, 1.0)
    }

    segment = {
        length = .84
        material = Lower_Termination
        nodes = (3, 1.0)
    }

    segment = {
        length = 1.8
        material = BendingStrainRelief
        nodes = (6, 1.0)
    }

    segment = {
        material = Lower_cable
        length = LCB_LENGTH
        nodes = LCB_NODE_SPEC
    }

    segment = {

```

```

        material = Floated_cable
        length = FC_LENGTH
        nodes = FC_NODE_SPEC
    }

segment = {
    /* this is the upper cable */
    length = UC_LENGTH
    material = Upper_cable
    nodes = UC_NODE_SPEC
}

segment = {
    length = 1.8
    material = BendingStrainRelief
    nodes = (6, 1.0)
}

segment = {
    Length = .5
    Material = Upper_Termination
    nodes = (3, 1.0)
}

segment = {
    length = 1
    material = SS_Pipe
    nodes = (4,1.0)
}

segment = {
    length = SNUB_LENGTH
    material = snubber
    nodes = SNUB_NODE_SPEC
}

terminal = {
    buoy = buoy_LB
}

End

```


9. References

-
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- ⁴ Trelleborg Offshore, 114 rue Saint Lazare - BP20609, 60476 - Compiègne cedex 2, France, Tel: +33 (0)3 44 23 03 50. <http://www.trelleborg.com/en/offshore/Home/>
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