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Riser System Selection and Design for a Deepwater FSO in the Gulf of Mexico

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Abstract

The process used to select a riser concept for a deepwater Floating Storage and Offloading system for the Gulf of Mexico is presented. Numerous riser concepts were screened with three taken forward through the more rigorous concept selection process. The three riser configurations were the Steel Lazy Wave Riser, the Single Line Hybrid Riser and the Tension Leg Riser. A system approach was adopted where the turret location, the mooring system and the risers were designed together. The process involved rigorous evaluation to verify both technical and installation feasibility, along with engineering definition sufficient to establish cost estimates. Analysis results for the three risers are presented to demonstrate important design issues that must be investigated to make an informed riser selection.

Introduction

The recent increase in discoveries in deep and ultra-deep water, coupled with fast-paced development schedules for Floating Production Systems, has led to a rapid evolution in the design of risers in terms of their complexity as well as variety. In addition, ship-shaped systems, including both Floating Production, Storage and Offloading systems (FPSOs) and Floating Storage and Offloading systems (FSOs), are often the preferred option for various technical and commercial reasons. Equipped with turrets, they can be highly functional solutions even in harsh environments. However, the motions of ship-shaped systems are typically more severe than the motions of other types of floating facilities due to their heave, roll and pitch motions being in the same frequency range as the wave energy. This further complicates the design of the risers. Consequently, riser systems that may be feasible on a Tension Leg Platform, Spar or semi-submersible–based facility may not always work on an F(P)SO. Particularly in harsher environments, this requires the F(P)SO riser system to have either a more compliant or a de-coupled configuration compared to simple catenary or top-tensioned vertical risers.

A study was performed to assess the technical feasibility and commercial viability of several riser options for a 2-million barrel new-build FSO studied for possible deployment in approximately 1,370 meters water depth in the Gulf of Mexico. Steel Lazy Wave Riser (SLWR), Single Line Hybrid Riser (SLHR) and Tension Leg Riser (TLR) concepts were investigated in detail. To establish technical feasibility, an integrated system approach was adopted where the FSO hull form, turret location, mooring system and riser system were investigated jointly to capture the important interactions between key components.

To assess technical feasibility of the risers, extreme hurricane conditions were investigated to check allowable stresses and compression in the riser and to determine top termination requirements in terms of tension and rotation. Fatigue analyses were also performed. Both wave frequency fatigue and slow drift fatigue were examined along with fatigue due to Vortex Induced Vibration (VIV). The technical assessment confirmed that the three riser concepts are feasible for the conditions specified in the study. Note, however, that the SLWR was close to the fatigue limit while the SLHR and TLR, which de-couple their steel riser segments from the motions of the vessel, exhibited good fatigue performance.

The commercial assessment was made by developing screening-level, total-installed cost estimates for each riser concept, including the cost impact on associated systems such as the turret. For this study, the SLWR was shown to be the most cost-effective system. However, under different parameters, the SLHR or the TLR could be more cost competitive. This depends on many factors such as water depth, number and size of risers, metocean conditions, vessel motions, turret location, turret loading, field layout and footprints, soil conditions, seabed topography and flow assurance requirements. Each of the systems has unique performance, cost and applicability in view of these different influences. Economics usually drives the riser selection, but risk is also important and must be considered in the process.

FSO Particulars

The vessel assumed in this study was a new-build “tanker” with a more or less elliptical bow and a storage capacity of approximately 2 million barrels. The length was 285 meters, the beam was 63 meters and the depth was 30.5 meters with a fully loaded draft of 19.5 meters and ballast draft of 8 meters. Both loaded and ballast conditions were considered in the investigation of riser performance. The tanker was to be turret-moored in deep water (1,370 meters). In order to investigate the important effect of turret location on FSO responses, three different turret locations were evaluated: 0.31L, 0.35L, and 0.4L forward of amidships. The turret was designed to accommodate up to six risers of 406.4 millimeters outer diameter (16-inch OD).

Metocean Conditions

Typical deepwater Gulf of Mexico environmental parameters were used for hurricane conditions, loop/eddy current events, and everyday fatigue sea states. Traditional mooring/riser design recipes for Floating Production Systems in the Gulf of Mexico often rely on the application of 100-year extreme metocean events that assume collinear waves, wind and current. However, the floating facility considered in this study was sensitive to non-collinear conditions as it was turret-moored and weathervaned passively. Consequently, designer sea states that reflect the environment's true non-collinear behavior were selected and used based on recommendations from industry standards and results from long-term response-based analyses performed on similar vessels. These designer sea states are shown in Table 1.

Preliminary Riser Sizing

Preliminary pipe wall thickness was established using API RP 1111 [1]. The pipe material was API 5L X65. Maximum internal operating pressure was taken to be 3447 kiloPascals with a product specific gravity of 0.9. Both the SLWR and the TLR designs assumed the pipe would be installed in a voided condition, with wall thicknesses governed accordingly by collapse due to external pressure. A relatively thick wall was selected for these risers, 19 millimeters (3/4 inch). The SLHR, however, was assumed to be installed flooded and would never be in the empty/vented condition throughout its design life. As a result, its design was not governed by collapse and a thinner wall was selected, 12.7 millimeters (1/2 inch). Further, since this was to be an FSO that received stabilized crude, flow assurance was only a minor concern, and no riser insulation was required. The system still needed to accommodate pigging operations, however.

Global Analysis

A diffraction analysis was performed for both the ballast and fully loaded conditions to generate RAOs for input into the vessel motions program Shipsim [2] and global analysis program SPMsim [3]. SPMsim provides a fully coupled frequency domain analysis of turret moored vessels, mooring and riser systems. Preliminary global analysis of the FSO was performed to:

- Develop a preliminary mooring system.
- Determine vessel motions (in particular, heave at the chain table) for use in selecting an optimum turret location for the three riser options.
- Provide extreme offsets and motions for use in the riser analyses.

Turret Location Selection

For weathervaning and mooring performance, it is desirable to have the turret as far forward of amidships as possible. However, as the turret is moved forward, the heave at the chain table increases and the performance of the riser system degrades. In the end, a compromise location for the turret must be selected in view of these drivers.

Results from other studies such as reference [4] have shown that for turret locations more than 0.3L forward of amidships, the roll response tends to change very little as the turret moves further forward. On the other hand, the heave tends to increase more rapidly as the turret moves more forward. Thus, the primary parameter investigated for selecting the turret location was heave motion at the chain table, as this was also the response that influenced riser performance the most.

Figure 1 shows the single amplitude significant heave motion at the chain table as a function of turret location for the fully loaded vessel. Over the selected range of turret locations, the response increases fairly linearly. Of the three riser systems, the SLWR is the most sensitive to the heave motion as its continuous riser segments are connected directly to the turret. The SLHR and TLR are less sensitive since their steel segments are de-coupled from the vessel. With the SLHR and TLR, only the flexible jumpers between the vessel and the subsurface support buoy are significantly impacted by the heave-induced compression (and also dynamic tension, minimum bending radius, etc.). Preliminary extreme analyses for the three riser concepts were performed for three turret locations in the designer sea state producing the most severe heave response (Crossed 2). Note that for the Crossed 2 condition, the waves are approximately 25 degrees off the bow. The analyses showed that for the location 0.35L forward of amidships (100 meters), all three riser systems were viable. This location was also suitable for efficient passive weathervaning performance of the FSO. Thus this location was selected for performing the detailed mooring and riser analysis.

Mooring System Description

With the turret location selected, a more detailed mooring system design was undertaken. Preliminary riser results from the turret location selection study indicated that for riser strength requirements, the intact offset needed to be less than 10% of water depth and the damaged offset less than 14%. These requirements were primarily for the SLWR. However, as offsets increase, the flexible jumper lengths for the SLHR and TLR must also increase to meet their design requirements.

The mooring system was designed to API RP 2SK [5]. The mooring design selected was a grouped 3x3 semi-taut anchor leg system. This configuration provided large open sectors for the risers to approach the FSO. Each anchor group was spaced at 120 degrees with individual legs spaced at 5 degrees. The anchors were suction embedded piles suitable for vertical loading, i.e. uplift. Table 2 provides a summary of the anchor leg components and properties.

Results from the mooring analysis are presented in Table 3. The fully loaded case controlled the design, thus this loading condition is the only one presented. The table shows results for both intact and damage conditions and for the different designer sea states. In addition, results are shown for environmental directions that result in vessel orientations both “inline” with an anchor leg group and “between” two adjacent anchor leg groups. The “inline” case usually provides the maximum anchor leg loads while the “between” case usually produces the largest offsets (due to the lower mooring stiffness). A 1000-year hurricane condition is also presented to verify that the mooring system will survive such an event in an intact condition.

For the intact mooring system, the 100-year hurricane condition for the Crossed 2 designer sea state controls the design. The maximum offset is 137.5 meters (10% of water depth), and the maximum anchor load is 900 metric tons, which corresponds to a factor of safety of 1.8. Although this exceeds the API RP 2SK requirement of a minimum factor of safety of 1.67, it is considered adequate for the purposes of this study. For the one-line damage condition, the maximum offset is 168.4 meters (12.3% of water depth), and the maximum anchor leg load is 1,186 metric tons, or a safety factor of 1.3 versus the API RP 2SK minimum of 1.25 (again, adequate for this study). For the 1000-year hurricane, the mooring is not expected to fail since the minimum safety factor is 1.3 and the offsets are only slightly higher than the damaged condition at 13% of water depth.

A case was also examined with all six risers of the SLWR system included in the global analysis. This showed that the risers had little impact on the vessel offsets as they have very little lateral stiffness in comparison to the mooring system. The maximum offset with the risers included decreased to 9.6% of water depth versus 10%. Furthermore, the anchor legs alone are fairly heavily damped, thus a small increase in damping from the risers does not change the extreme drift motions dramatically. Note that if more risers were present in the system, these observations would possibly change.

Riser Strength Design

The risers were designed to API RP 2RD [6]. The design of the flexible jumpers for the SLHR and TLR investigated maximum tension, maximum compression and minimum-bending radius and checked these parameters against manufacturer specifications. For a flexible jumper with inside diameter 368.3 millimeters (14.5 inches, to roughly match the inside diameter of the steel portion of the riser for pigging requirements), manufacturer limits for maximum tension, maximum compression, and minimum-bending radius are 218 metric tons, 10 metric tons, and 4.5 meters, respectively. OrcaFlex [7] was used to perform the dynamic analysis of the risers.

Strength checks in extreme storm conditions, including loop current and 1000-year hurricane, were analyzed for different offset cases. The slow drift extreme offset of the FSO was used for each condition, and wave RAOs were used to simulate the wave frequency motions of the vessel around the low-frequency offset. Design cases included accidental conditions (such as a damaged mooring line) as well as the designer sea states. Both ballast and fully loaded draft conditions were investigated.

Along with an inertia coefficient of 2.0, a drag coefficient of 0.7 was used, assuming no strakes. Irrespective of whether or not strakes are needed, the use of a low drag coefficient in the strength design should produce conservative results since the system will have less viscous damping and thus more dynamic response.

Riser Fatigue Design

For the fatigue analysis, a stress concentration factor of 1.1 was assumed, and the DNV “E” S-N curve was used for the cumulative damage calculation. The NPD wind spectrum was used, and the irregular waves in the scatter diagram were modeled using a Jonswap spectrum with a gamma of 1.0. The design life was 30 years, and a safety factor of 10 was used on wave-induced fatigue and 20 on VIV fatigue.

Total fatigue damage due to wave action was computed separately for first and second order motions and then summed to obtain a total damage for each point along the riser. A Rayleigh damage equation was used with estimates of standard deviation of stresses over the length of the riser.

SLWR Description

Examining riser performance in the extreme sea states allowed the SLWR configuration to be optimized. The parameters of interest were maximum effective tension, maximum Von Mises stresses and whether or not compression occurred. By changing the hang-off angle and the location and distribution of buoyancy, the ideal configuration was developed.

Figure 2 shows the SLWR configuration in the near, mean and far positions. The nominal hang-off angle is 10 degrees and the top termination is to a flexible joint. The upper catenary section is 1,550 meters, followed by 450 meters of buoyant section, and 475 meters of lower section to the nominal touchdown point. A foam specific gravity of 0.475 was used, which gave a total foam net buoyancy of 108 metric tons (foam diameter of 805 millimeters). The nominal touchdown point is 1340 meters from the turret hang-off location.

Tension Leg Riser Description

Figure 3 shows TLR [8] system layout. The “H” shaped buoy has a displacement of 2,620 metric tons, providing a net buoyancy of 2,040 metric tons. The buoy is an open bottom design to equalize internal and external pressures. The buoy is located 145 meters below the water surface. The buoy is tethered to the seafloor with four, 76 millimeters diameter, SPR3 sheathed spiral strand tendons. The tendons are secured to the seafloor using suction piles. The buoy is a lateral distance of 220 meters from the turret. The flexible jumpers are 500 meters in length. The steel catenaries depart from the buoy at a 5.5 degrees angle and are 1,400 meters in length with a touchdown point approximately 450 meters from the buoy. The steel catenaries are terminated at the buoy in a stress joint.

Single Line Hybrid Riser Description

Figure 4 shows the SLHR configuration. Buoyancy for each vertical riser is provided by an air can with a displacement of 283 MT and net buoyancy of 227 MT. The air can is 5 meters in diameter and 14 meters long. It is located 145 meters below the water surface. The top tension ratio is 1.8. The riser base is located 200 meters from the FSO center. The flexible jumpers are 400 meters long. The riser loads are resisted at the seafloor with a suction pile. On top of the suction pile is a base consisting of a simple two flowline hub structural arrangement. A center hub is for the riser attachment and the outboard hub is for a flowline inverted U-jumper connection to a Pipeline End Termination (PLET).

Steel Lazy Wave Riser Survival Analysis

Static analyses were performed for the SLWR with the riser filled with air, oil and water. These analyses showed that the when the buoyancy section of the riser is being installed, the riser cannot be installed void as excessive departure angles would occur on the lay vessel.

A sample of the results from the dynamic analyses is provided in Table 4. Figure 5 shows effective tension range along the arc length of the riser. There are no compression loads in the riser and maximum stresses are kept below their allowable limits. Generally, the ballast condition produces slightly greater extremes than the fully loaded. The table also provides information for the flexjoint design. These angle ranges are within the capabilities of typical single-action flexjoint designs.

Steel Lazy Wave Riser Wave Fatigue Analysis

First and second order wave-induced fatigue results for the SLWR are presented in Table 5. Both fully loaded and ballast cases are examined. The ballast case is more sensitive in riser fatigue with approximately half the fatigue life of the fully loaded condition. The ballast case in the cross condition assumes all the waves are incident 20 degrees off the bow. This case was analyzed to check sensitivity to the vessel weathervaning performance and to recognize that the waves will seldom be directly on the bow. For this case, the effect of the non-collinear waves did not have much impact on the minimum fatigue life since the touchdown point controls the design. However, the non-collinear waves noticeably affect the fatigue life at the hang-off point due to the increase in roll response, as the waves become more quartering. Low frequency motions contributed very little to the total damage. Note that this is an FSO, thus very little topside equipment is present to increase wind loading. The same may not hold true for an FPSO.

Figure 6 shows total fatigue along the length of the riser for the ballast condition and collinear waves. Note that the total fatigue life at the top termination, in the buoyancy section and at the touchdown point are approximately the same, indicating a well-optimized riser configuration.

Numerous sensitivity cases for determining minimum fatigue life were investigated. Not all can be presented in this paper due to space limitations. Importantly, none of the cases explored proved to be “showstoppers.” The sensitivity cases addressed soil vertical stiffness, number of sea state bins selected, drag coefficient, flex-joint stiffness, length of elements used in critical regions, vessel heading, vessel draft, slow drift, and riser heading.

Tension Leg Riser Survival Analysis

Table 6 shows the results of the TLR survival analysis. The results show that the steel part of the riser meets all the design requirements. Note the small difference between the maximum and minimum top tension that indicates the riser is fairly well de-coupled from the FSO motions. The hang-off angles, measured from the vertical axis of the buoy, are well within the limits of an acceptable stress joint design. Results for the flexible jumpers are not presented due to space limitations but were also found to be within acceptable limits.

The TLR buoy mooring tendons were also checked. The minimum intact safety factor is 2.80 and the minimum for a damaged tendon condition is 1.31. Should a tendon fail, the buoy will tilt due to the asymmetry of the vertical loads. Should the resulting transient and mean rotations from a failed tendon be determined to be excessive for the risers or the jumpers, an eight-leg mooring could be designed (two tendons at each corner), which will greatly reduce the maximum tilt.

Tension Leg Riser Wave Fatigue Analysis

The minimum fatigue life calculated for the TLR catenary riser is 7800 years. The minimum fatigue life occurs at the touchdown point. This large fatigue life also demonstrates how efficient the TLR system is in de-coupling the catenary risers from the vessel motions.

Single Line Hybrid Riser Survival Analysis

Table 7 presents the results for the SLHR survival analysis. All parameters are kept within acceptable limits except for stresses at the bottom of the riser. Therefore, at the base of the riser, a stress joint would be incorporated which was not accounted for in the model. Angle variations at the base are within the limits for a stress joint. Similar to the TLR, the results show how well the SLHR concept de-couples the vertical steel riser from the FSO motions. Results for the flexible jumpers are not presented but were found to be acceptable, thus no integrity issues exist for the system.

Single Line Hybrid Riser Wave Fatigue Analysis

The minimum wave fatigue life for the SLHR riser was found to be 7860 years. This minimum occurs at the base of the riser. Again, the stress joint was not included, thus the minimum fatigue life would be much better since the first weld could be moved outside the fatigue sensitive zone at the base.

VIV Analysis

The fatigue damage due to VIV was examined for the three risers using the program Shear7 [9]. The SLWR will only be discussed here since it is the more interesting case. A pinned-pinned beam model was assumed with mode shapes imported from a Finite Element Analysis (FEA) program. The currents at the site were represented as eddy conditions for 25% of the year, and for the remaining 75%, background currents were assumed. Bottom currents were included in the current data.

The SLWR had a VIV fatigue life of approximately 15 years assuming initially no strakes. The eddy currents cause 80% of the damage. The minimum fatigue life occurs in the buoyancy section. The case with the 100-year eddy occurring continuously was also explored as a robustness check. In this case, the SLWR had a VIV fatigue life of roughly 130 days.

In order to validate the Shear7 results and obtain a lower limit on the fatigue life, the stress range was calculated by:

$$\sigma = E\,(D/2)\,[\,D \times (A/D) \times Y_n''\,]$$

where E is Young's modulus, D is the diameter, A is the amplitude of oscillation, and Y_n'' is the curvature profile for the n^{th} mode shape obtained from the FEA. The stress range can be found by assuming a reasonable A/D ratio, for example 0.5. This stress is multiplied by two to get a full stress cycle. For each current speed, the corresponding Strouhal number is matched to the mode number to determine what frequency the current is exciting. A minimum fatigue life under continuous exposure is calculated and results of such a study are shown in Figure 7. For a 1 m/s current, the bare riser would have about 20 days of fatigue life. This simple analysis is in line with the Shear7 results and clearly demonstrates the need for strakes on the SLWR.

With the specified safety factor of 10 on wave induced fatigue, 20 on VIV induced fatigue and a service life of 30 years, the VIV induced fatigue life needs to be approximately 1,100 years. Using Shear7, further analyses were conducted to estimate the extent of strakes required. It was determined that approximately 1,000 meters of strakes would be required.

Cost and Installation

All three riser options were determined to be technically feasible, although the SLWR showed a narrow margin in fatigue. Installation procedures were thus developed for the three riser concepts to confirm feasibility and estimate installation cost. The J-lay method was assumed for installing the steel riser sections, and reeling was assumed for installing the flexible jumpers for the TLR and SLHR. Installation procedures detailed in the two referenced DeepStar studies [10 & 11] that investigated the SLWR, hybrid tower, and TLR are similar to what would be used to install these risers, with the exception that the SLHR would not be fabricated at the beach and towed to site like the hybrid tower. The SLHR would be J-lay installed (in as near to vertical as possible) and transferred to a porch on the installation vessel, using the crane. The jumper and air can would then be connected to the gooseneck. While flooding the air can, the riser would be lowered and connected to the subsea connector, upon which the buoyancy tank would be de-ballasted.

The normalized riser costs for procurement, fabrication, installation, engineering and project management are as follows:

SLWR	1.00
SLHR	1.32
TLR	1.38

For the SLWR, a nominal cost impact on the turret was included since it has much greater riser hang-off loads. For this application, the SLWR was the lowest cost option. However, under different parameters, the SLHR or TLR may be more cost competitive. For example, the TLR appears better for deeper water depths, larger diameter risers and high riser count.

Conclusions

This paper presents the process used to select a riser concept for a turret-moored FSO in the Gulf of Mexico. An integrated system approach was adopted since the vessel, turret, and mooring will all impact the design of the risers. It was demonstrated that all three risers were technically feasible with the TLR and SLHR displaying more robust performance in fatigue due to the fact that they effectively de-coupled their steel pipe sections from the FSO motions. All three risers can be installed with little modification to existing equipment. The cost comparison showed that the SLWR had the lowest cost by a significant margin. Further, although the SLWR's fatigue life was shown to approach the limit of acceptability, it is believed that this concept will still be acceptable after a detail design is completed, based on the thorough approach taken in this study to investigate all elements of the system that will impact the design. Numerous sensitivity cases for determining minimum fatigue life were investigated, and none proved the concept to be infeasible.

In order to verify the designer sea states used in this study, a Response-Based Design Approach is required. In addition, since traditional wave scatter diagrams are based on collinear sea states, a new hindcast database of operational sea states is required that can give information about joint directionality of waves, wind and current for use in fatigue analysis. Such a study was completed subsequent to this study [4]. The results for the extreme analysis, where the short-term responses of pitch, roll and chain table heave were fitted to match the 100-year long term response, were found to be very similar to designer sea state, Crossed 2. The primary differences were that the wind-wave relative direction was 55 degrees as opposed to 35, and the wave-current relative direction was 10 degrees as opposed to 15. Note that this sea state often controlled the design of the system in the survival analysis.

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Table 1. Designer Sea States

	100-Year Environment							Units
	Collinear	**Crossed 1**	**Crossed 2**	**Crossed 2b**	**Crossed 3**	**Crossed 4**	**Crossed 5**	
Waves								
Significant Wave Height, Hs	12.2	12.2	12.2	12.2	10.7	10.7	8.9	m
Spectral Peak Period, Tp	14.2	14.2	14.2	14.2	13	13	14.5	sec.
Peakedness Paramater, γ	2.4	2.4	2.4	2.4	2.4	2.4	1.4	
Direction	0	0	0	0	0	0	0	deg.
Wind								
Velocity (1-hour)	36.5	36.5	36.5	36.5	30.9	33.4	26.9	m/s
Wind-Wave Direction	0	(+) 35	(+) 35	(+) 30	(+) 30	0	(+) 95	deg.
Current								
Surface Velocity	1.75	1.75	1.75	1.75	1.29	2.31	0.9	m/s
Current-Wave Direction	0	(-) 15	(+) 15	(+) 45	(-) 90	(-) 45	0	deg.

Table 2. Mooring System Anchor Leg Components

Full Load Draft (19.5 m)

Pretension	297	MT
Fairlead Angle	47	degrees
Anchor Radius	3000	m

Ballast Load Draft (8 m)

Pretension	314	MT
Fairlead Angle	46	degrees

Anchor Leg Component	Nominal Diameter (mm)	Type	Grade	Deployed Length (m)	Dry Weight (kg/m)	Breaking Strength (MT)	Dry Weight/Leg (MT)
Top Chain	140	Studless	R4	20	382	1,796	8
Riser Wire	121	Spiral sh.	SPR3	2,350	77	1,580	181
Ground Chain	140	Studless	R3	1,050	382	1,796	401
				Total Dry Weight/Leg (MT)			**590**

Notes:

1.) *Wear and Corrosion allowance for top chain = 10 mm for 30 year field life*
2.) *Wear and Corrosion allowance for ground chain = 10 mm for 30 year field life*
3.) *Riser wire is sheathed spiral strand (Bridon SPR3); sheath thickness = 11 mm*

Table 3. Summary of Global Analysis Results for Fully Loaded Condition.

Alignment	**Waves Towards**	**Mean Vessel Heading**	**Orientation**	**Mooring**	**Max Tension** (MT)	**Factor of Safety**	**Max Turret Loads**		**Static Offset**		**Mean Offset**		**Max LF Offset**		**Max XY Offset**	
							Fxy (MT)	**Fz** (MT)	**X** (m)	**Y** (m)	**X** (m)	**Y** (m)	**X** (m)	**Y** (m)	**xy** (m)	**%age WD**
100-Year Hurricane																
Collinear	180	0	Inline	Intact	626	2.5	1,113	-3,203	0	0	-42	0	-67	0	67	4.9
	180	0		Damaged	804	2.0	1,150	-2,900	-26	3	-47	4	-76	6	102	7.4
	240	60	Between	Intact	578	2.7	879	-3,157	0	0	-26	-46	-45	-77	89	6.5
	240	60		Damaged	706	2.2	856	-2,814	-26	-3	-34	-56	-55	-92	124	9.1
Crossed 2	160	-44	Inline	Intact	900	1.8	2,000	-3,648	0	0	-59	-3	-116	-5	116	8.5
	160	-44		Damaged	1,260	1.3	2,145	-3,280	-26	0	-69	-3	-130	-7	155	11.3
	100	-104	Between	Intact	783	2.0	1,500	-3,452	0	0	-43	73	-70	118	138	10.0
	100	-104		Damaged	1,000	1.6	1,426	-3,113	-26	0	-50	85	-78	-133	168	12.3
Crossed 2b	170	-35	Inline	Intact	814	1.9	1,747	3,501	0	0	-53	-1	-103	-2	103	7.5
	170	-35		Damaged	1,087	1.5	1,785	-3,175	-26	0	-60	-1	-115	-3	141	10.3
	230	26	Between	Intact	714	2.2	1,279	-3,330	0	0	-36	-64	-63	-111	127	9.3
	230	26		Damaged	899	1.8	1,265	-2,980	13	-22	-43	-74	-71	-123	157	11.4
Crossed 5	200	57	Inline	Intact	697	2.3	1,419	-2,910	0	0	-38	2	-84	5	84	6.1
	200	57		Damaged	919	1.7	1,376	-2,603	-26	0	-43	3	-94	7	121	8.8
	140	-29	Between	Intact	603	2.6	1,165	-2,830	0	0	-23	44	-45	83	94	6.9
	140	-29		Damaged	748	2.1	1,034	-2,496	13	23	-29	51	-52	93	122	8.9
100-Year Loop Current & 10-Year Hurricane																
Crossed 3	220	-2	Inline	Intact	515	3.1	770	-2,790	0	0	-21	-2	-48	-6	49	3.5
	220	-2		Damaged	648	2.4	800	-2,510	-26	0	-23	-3	-54	-7	81	5.9
	155	-67	Between	Intact	511	3.1	622	-2,769	0	0	-12	21	-28	47	55	4.0
	155	-67		Damaged	620	2.5	593	-2,452	-26	2	-15	25	-32	55	81	5.9
Crossed 4	190	-11	Inline	Intact	535	3.0	784	-2,580	0	0	-30	2	-57	3	57	4.2
	190	-11		Damaged	687	2.3	795	-2,310	-26	0	-33	2	-64	4	90	6.6
	250	49	Between	Intact	486	3.3	626	-2,567	0	0	-19	-31	-37	-59	70	5.1
	250	49		Damaged	612	2.6	620	-2,292	-26	-2	-23	-37	-43	-70	99	7.3
1000-year Hurricane																
Collinear	180	0	Inline	Intact	744	2.1	1,627	-3,957	0	0	-57	0	-85	0	85	6.2
	240	60	Between	Intact	701	2.3	1,243	-3,789	0	0	-40	-70	-60	-105	121	8.8
Crossed 2	160	-46	Inline	Intact	1,186	1.3	2,916	-4,254	0	0	-79	1	-138	1	138	10.1
	100	-105	Between	Intact	1,000	1.6	2,280	-4,002	0	0	-60	104	-89	154	178	13.0
Crossed 2b	170	-35	Inline	Intact	1,010	1.6	2,493	-4,226	0	0	-69	2	-122	4	122	8.9
	110	-95	Between	Intact	920	1.7	2,057	-3,956	0	0	-51	89	-79	139	160	11.6

Table 4. SLWR Dynamic Analyses Results

Case				Top Tension		Tension Along the Riser		Fairlead Angle		von Mises Stress
Environment Alignment	Storm	Vessel Offset	Mooring System	Max MT	Min MT	Max MT	Min MT	Max deg	Min deg	Max kN/m^2
Collinear	100 Yr Hurricane	Far	Damaged	313	122	313	15	12.2	0.0	2.1E+05
Collinear	100 Yr Hurricane	Near	Damaged	310	104	310	5	10.1	0.1	2.7E+05
Crossed	100 Yr Hurricane	Far	Damaged	332	119	332	14	16.2	1.5	2.1E+05
Crossed	100 Yr Hurricane	Near	Damaged	299	114	299	7	10.1	0.2	3.0E+05
Crossed	100 Yr Hurricane	Near	Intact	300	114	300	7	9.6	0.2	2.8E+05
Crossed	100 Yr Hurricane	Far	Intact	312	129	312	18	12.8	0.9	2.0E+05
Collinear	1000 Yr Hurricane	Far	Intact	315	119	315	11	16.1	0.3	2.3E+05
Collinear	1000 Yr Hurricane	Near	Intact	309	105	309	3	12.3	0.1	2.9E+05
Crossed 2	1000 Yr Hurricane	Far	Intact	326	121	326	10	18.4	0.4	2.3E+05
Crossed 2	1000 Yr Hurricane	Near	Intact	325	92	325	0	15.9	0.5	3.1E+05
Crossed 2b	1000 Yr Hurricane	Far	Intact	326	120	326	9	18.6	0.5	2.3E+05
Crossed 2b	1000 Yr Hurricane	Near	Intact	307	100	307	2	13.7	0.9	3.0E+05
Crossed 4	100 Yr Loop w/ 10 Yr Hurricane	Far	Damaged	294	144	294	29	5.9	0.7	1.7E+05
Crossed 4	100 Yr Loop w/ 10 Yr Hurricane	Far	Intact	290	143	290	27	6.8	0.6	1.8E+05
Crossed 4	100 Yr Loop w/ 10 Yr Hurricane	Near	Damaged	279	138	280	16	5.3	0.9	2.6E+05
Crossed 4	100 Yr Loop w/ 10 Yr Hurricane	Near	Intact	287	133	287	16	6.0	0.9	2.4E+05

Table 5. Wave Induced Fatigue Analysis Results for SLWR

Parameter	**Unit**	**Analysis Case**		
Draft Condition		Full	Ballast	Ballast
Flexjoint Stiffness	KN-m/deg	30	48	48
Shortest Element	Meters	5	2	2
Environment		collinear	collinear	cross
Offset Direction		far	far	far
WF Damage	1/years	6.59E-04	1.36E-03	1.37E-03
% of total damage		99	98	93
LF Damage	1/years	7.24E-06	2.99E-05	9.73E-05
% of total damage		1	2	7
Total Damage	1/years	6.67E-04	1.39E-03	1.47E-03
Total Life	**years**	**1500**	**718**	**680**
Location		TDP	TDP	TDP

Table 6. Survival Analysis Results for TLR.

Case				Top Tension		Tension Along the Riser		Declination Angle at Buoy		von Mises Stress
Environment Alignment	Storm	Vessel Offset	Mooring System	Max MT	Min MT	Max MT	Min MT	Max deg	Min deg	Max kN/m^2
Collinear	100 Yr Hurricane	Far	Damaged	202	181	202	0	4.4	5.3	3.2E+05
Collinear	100 Yr Hurricane	Near	Damaged	207	187	207	0	5.9	6.7	2.6E+05
Collinear	100 Yr Hurricane	Trans	Damaged	210	182	210	0	5.6	5.7	3.0E+05
Crossed 3	100 Yr Loop w/ 10 yr Hurricane	Near	Damaged	201	191	201	0	5.9	6.2	2.6E+05
Colinear	100 Yr Loop w/ 10 yr Hurricane	Trans	Damaged	196	193	196	0	5.7	5.7	2.7E+05
Crossed	100 Yr Hurricane	Far	Damaged	200	180	200	0	4.0	4.9	3.3E+05
Crossed	100 Yr Hurricane	Near	Damaged	209	185	209	0	6.2	6.8	2.6E+05
Crossed	100 Yr Hurricane	Trans	Damaged	212	177	212	0	5.5	5.7	2.9E+05
Collinear	1000 Yr Hurricane	Far	Intact	200	183	200	0	4.2	5.5	3.1E+05
Collinear	1000 Yr Hurricane	Near	Intact	206	189	206	0	5.6	7.2	2.5E+05
Crossed	1000 Yr Hurricane	Far	Intact	199	181	199	0	3.9	5.1	3.2E+05
Maximum and Minimum Allowable along the Steel Riser			Intact	635	0	635	0	N/A	N/A	**
			Damaged	635	0	635	0	N/A	N/A	**

Table 7. Survival Analysis Results for the SLHR.

Case				Top Tension		Tension Along the Riser		Bottom Tension	Von Mises Stress at Top	Von Mises Stress at Bottom	Top Angle		Bottom Angle	
Environment Alignment	Storm	Vessel Offset	Mooring System	Max MT	Min MT	Max MT	Min MT	Max MT	Max kN/m^2	Max kN/m^2	Max deg	Min deg	Max deg	Min deg
Collinear	100 Yr Hur.	Far	Damaged	213	195	214	81	101	2.2E+05	3.9E+05	1.0	0.4	3.3	2.8
Collinear	100 Yr Hur.	Near	Damaged	213	193	213	80	101	2.5E+05	1.1E+05	1.2	1.1	0.6	0.1
Collinear	100 Yr Loop w/ Hs=3.6m	Far	Damaged	207	202	208	88	95	2.0E+05	5.5E+05	0.8	0.8	5.0	4.8
Collinear	100 Yr Loop w/ Hs=3.6m	Near	Damaged	208	199	208	86	95	2.3E+05	3.2E+05	1.1	1.0	2.7	2.5
Collinear	10 Yr Loop w/ Hs=3.6m	Near	Intact	207	199	208	86	95	2.3E+05	1.9E+05	1.1	1.0	1.3	1.2
Crossed	100 Yr Hur.	Far	Intact	216	194	216	80	104	2.1E+05	4.0E+05	0.9	0.4	3.5	3.1
Crossed	100 Yr Hur.	Near	Intact	213	193	214	79	101	2.5E+05	1.0E+05	1.2	1.1	0.5	0.1
Collinear	1000 Yr Hur.	Near	Intact	219	187	220	74	107	2.6E+05	1.2E+05	1.3	1.1	0.6	0.0
Crossed 2B	1000 Yr Hur.	Far	Intact	228	184	229	70	117	2.1E+05	4.5E+05	1.0	0.2	3.9	3.5
Crossed 2B	1000 Yr Hur.	Near	Intact	220	187	220	74	108	2.5E+05	9.3E+04	1.3	1.1	0.4	0.0
Crossed 3	100 Yr Loop w/ 10 Yr Hur.	Far	Damaged	207	204	207	90	95	2.0E+05	6.1E+05	0.8	0.6	5.6	5.6
Crossed 3	100 Yr Loop w/ 10 Yr Hur.	Far	Intact	207	203	208	89	95	2.0E+05	5.9E+05	0.9	0.6	5.5	5.4
Crossed 3	100 Yr Loop w/ 10 Yr Hur.	Near	Damaged	205	203	206	89	93	2.4E+05	4.2E+05	1.2	0.9	3.6	3.6
Crossed 3	100 Yr Loop w/ 10 Yr Hur.	Near	Intact	205	202	206	89	93	2.4E+05	4.0E+05	1.2	0.9	3.5	3.5
Crossed 4	100 Yr Loop w/ 10 Yr Hur.	Far	Damaged	210	201	211	87	98	2.0E+05	6.5E+05	0.8	0.6	6.0	5.7
Crossed 4	100 Yr Loop w/ 10 Yr Hur.	Near	Damaged	210	198	210	85	97	2.4E+05	4.1E+05	1.3	1.0	3.6	3.4
Maximum and Minimum Allowable Along the Steel Riser			Intact	430	0	430	0	430	3.6E+05	3.6E+05	N/A	N/A	N/A	N/A
			Damaged	430	0	430	0	430	4.5E+05	4.5E+05	N/A	N/A	N/A	N/A

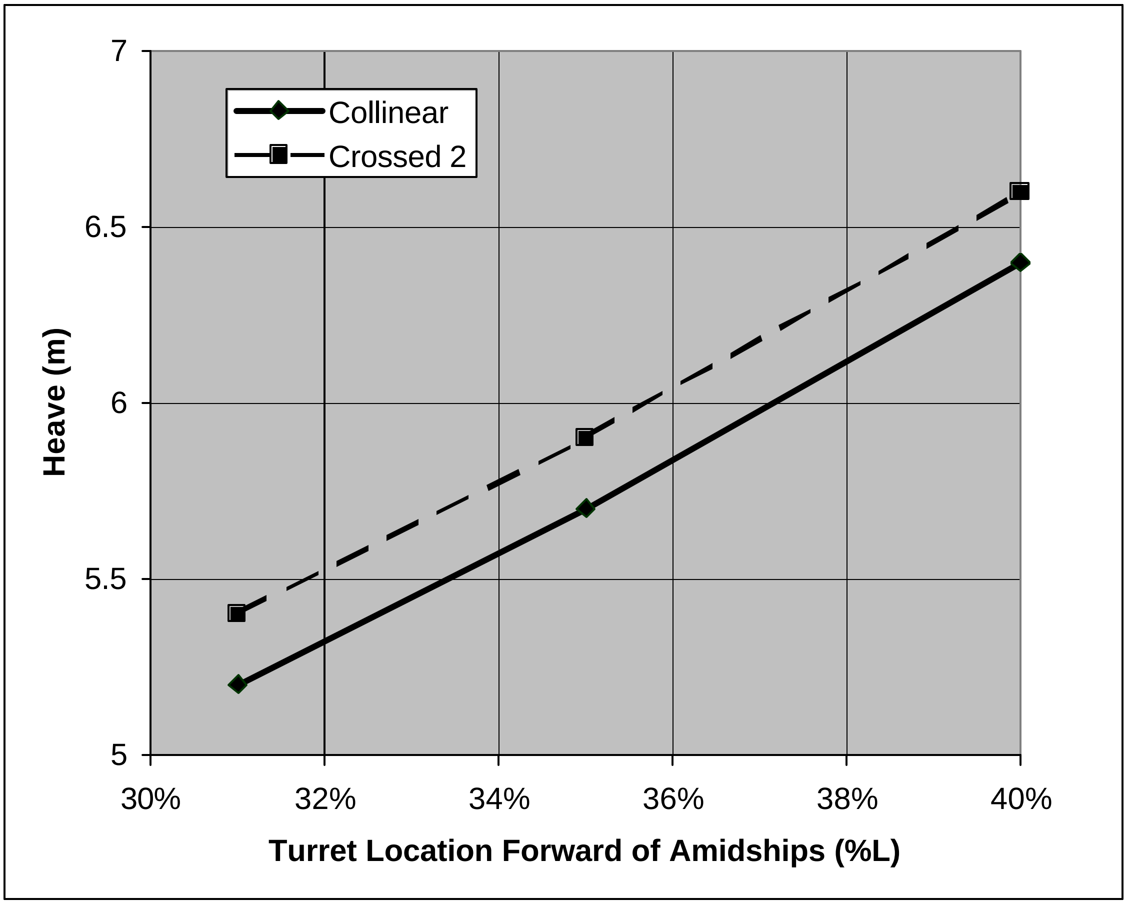

Figure 1. Single Amplitude Heave at Chain Table for Different Turret Locations for Fully Loaded Conditions.

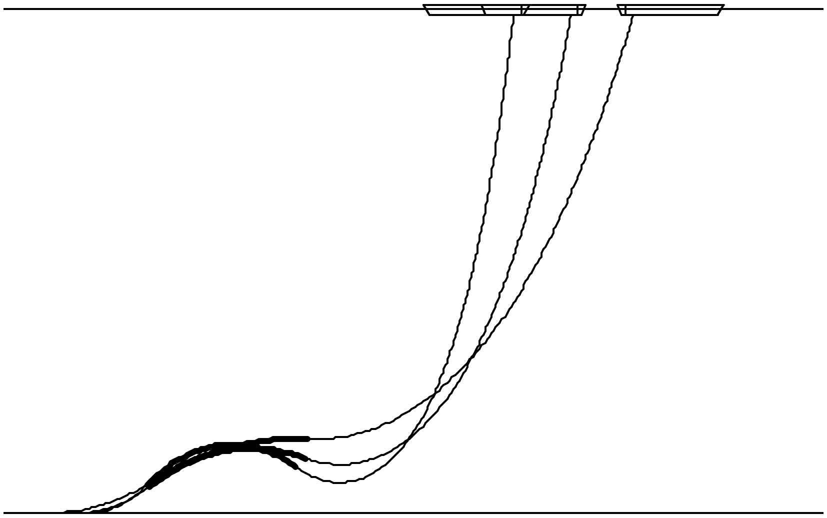

Figure 2. Steel Lazy Wave Riser in Near, Mean and Far Position.

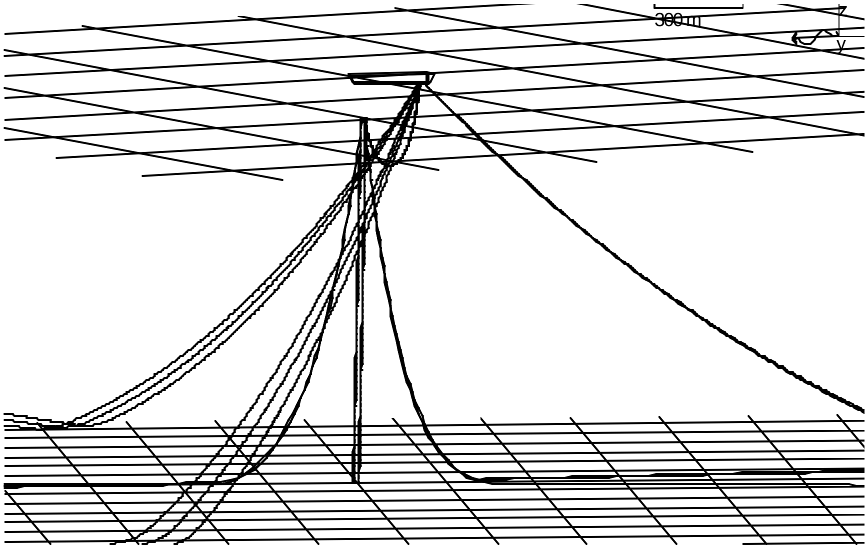

Figure 3. Tension Leg Riser Layout.

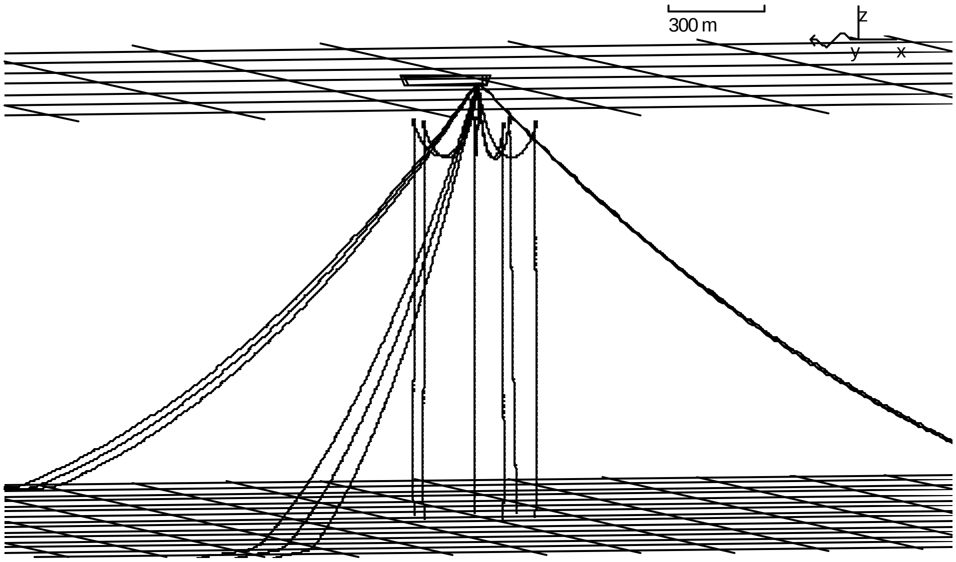

Figure 4. Single Line Hybrid Riser Layout.

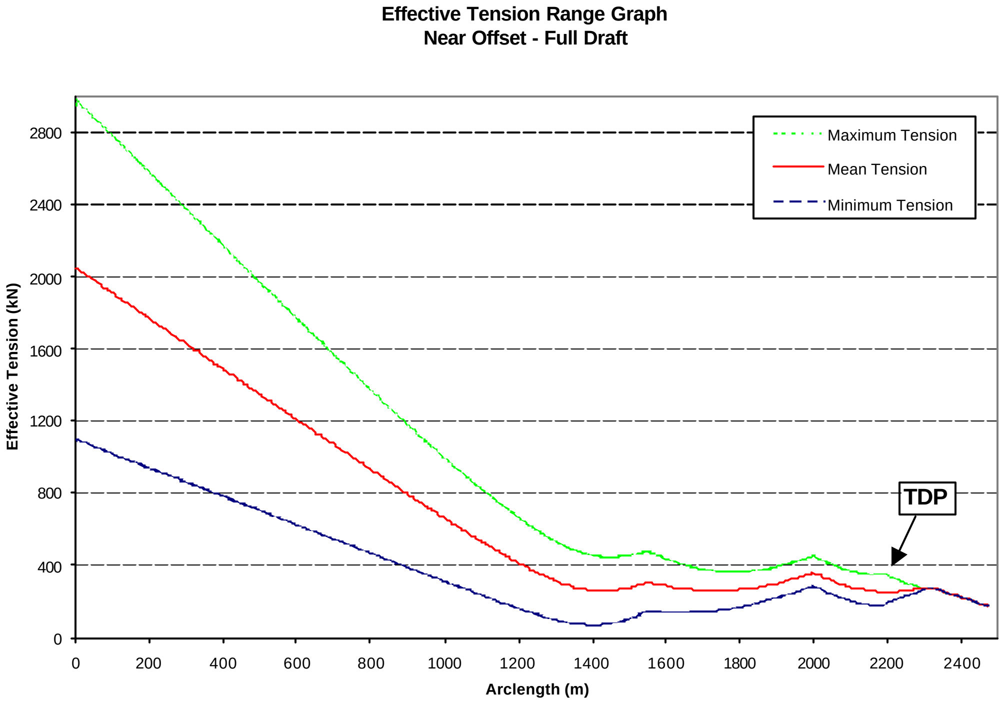

Figure 5. SLWR Effective Tension along Arc Length.

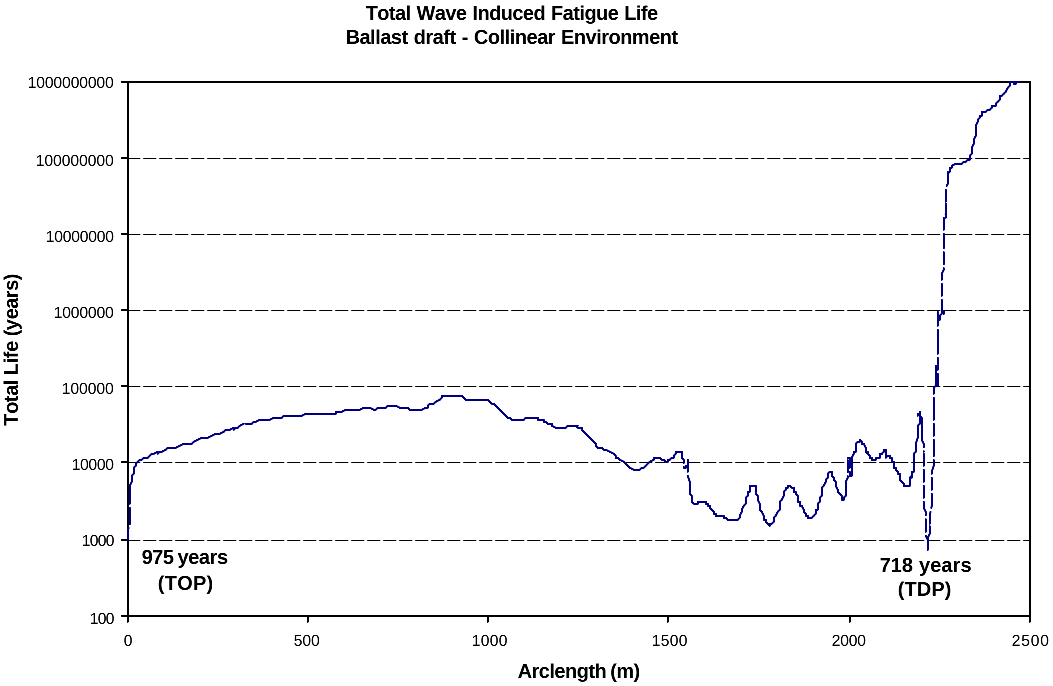

Figure 6. Total Wave Fatigue Life Along the Arc Length of the SLWR for the Ballast, Collinear Condition.

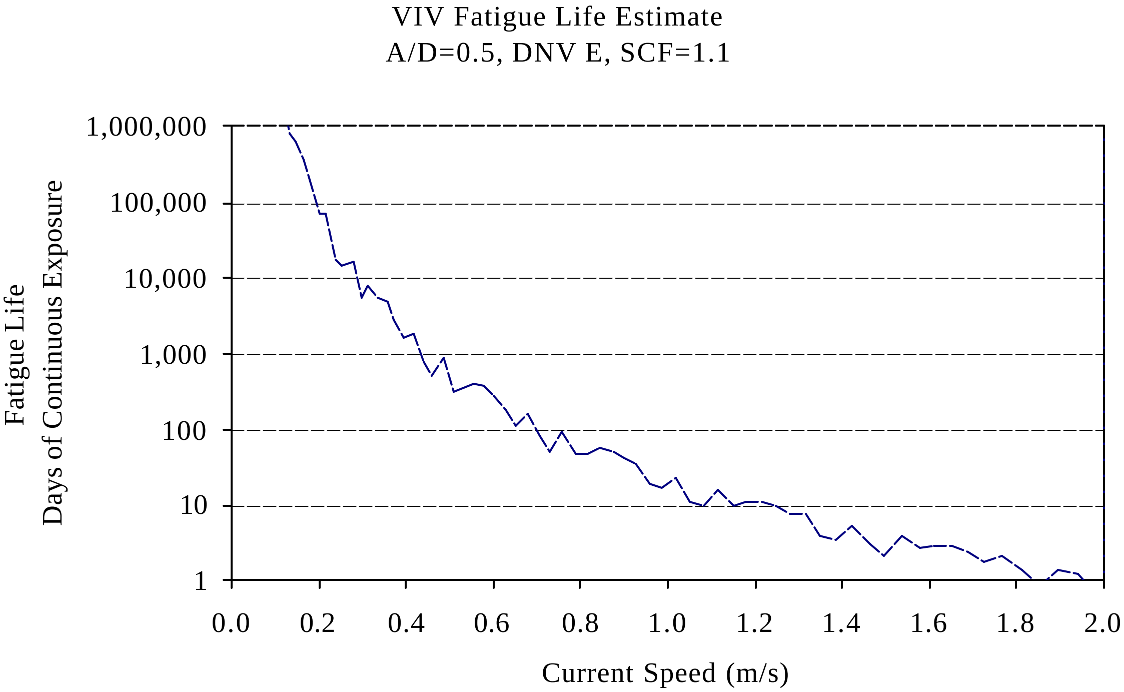

Figure 7. VIV Fatigue Life Under Continuous Exposure