D3.2 MOORING SYSTEM DESIGN TECHNICAL REPORT

ADVANCED TIDGEN® POWER SYSTEM
US DEPARTMENT OF ENERGY AWARD: DE-EE0007820

D-TD20-10130

Revision 1 – January 30, 2018

Ocean Renewable Power Company, LLC
254 Commercial St., Ste. 119B
Portland, ME 04101
Phone (207) 772-7707
www.orpc.co

Revision History

Revision	Rev. Date	Description	Originator	Approver
1	1/30/2018	Initial Release	N. Hayes	C. Marnagh

Purpose

This document is deliverable D3.2, Mooring System Design Analysis, which fulfills milestone 3.1 for the project:

Award No.:	DE-EE0007820, effective 11/1/2016
Project Title:	Advanced TidGen® Power System
Prime Recipient:	ORPC Maine
Principal Investigator:	Jarlath McEntee, P.E.

The document provides the technical design of the mooring system along with supporting analysis and FMEA.

Mooring Design

The analytical design of the Advanced TidGen® mooring system was performed primarily by Maine Marine Composites (MMC). A report on their work is provided in Appendix A. ORPC provided MMC with a series of the most critical load cases based on a preliminary loads analysis and field experience during the OcGen® deployment. Environmental conditions, DNVGL load factors and device physical properties were also provided by ORPC to MMC for analysis. In select cases where ORPC was unable to provide information MMC utilized their experience and relevant DNVGL standards for information.

Throughout the design process, ORPC duplicated the analyses performed by MMC to build expertise and confidence in the analysis of moorings in-house. ORPC analysis proved to be capable and verified well with MMC's analysis.

ORPC Design Additions

The analysis provided by MMC raised two design cases to be further developed. The first is the case of snap loads on the turbines in the instance where a bridle or primary line fails. The second case is of line clashing between primary and redundant mooring lines. The redundant lines are there in case of a primary failure and prevent the device from being removed from the anchors and causing further damage to the device or private property.

Snap Load Mitigation

The current design handles snap loads by oversizing the mooring lines, in this case 2-3/4" stud link chain, to handle the peak load. This leads to heavier than necessary mooring lines, which increases on-shore handling costs and device buoyancy requirements. A second option that is being pursued is mooring line suppressors. Using a combination of steel and molded plastic springs, a suppressor can be manufactured to handle the snap load. One such company, TFI Marine, provided initial analysis indicating a 3-meter spring can reduce the shock load by more than 70%. By distributing the load over a longer time frame the load is reduced, see Figure 1. The mooring line suppressor has an added benefit of reducing fatigue loads from the turbine rotation being transmitted to the mooring lines.

Figure 1 Mooring line suppressor comparison for snap loads

Line Clashing

As shown in section 4.4.3 in Appendix A, the redundant lines may clash with the primary lines during operation causing increased wear rates and increasing the likelihood of failure of either the redundant or primary line. MMC offered two solutions to mitigate the risk. ORPC's preferred solution is to use rigid spreader bars to keep the lines a fixed distance apart. Spreading the lines further apart may prevent clashing but would not prevent touchdown of the redundant line on the anchor. The leading cause of mooring line corrosion and abrasion is touch down on the anchor or seafloor, rigid spreader bars would prevent that from occurring. The rigid spreader also provides a means to secure the power and data cable along the mooring lines without interfering with mooring line operation.

Failure Mode Effects Analysis

The design FMEA can be found in Appendix B.

Appendix A

PROJECT TITLE: *TidGen Mooring Design*	
Client/Client Ref: Ocean Renewable Power Company	Document Title: TidGen Final Design Review: Mooring Analysis
Project No:	Project Document No: ORPCTidGen_MMC_Mooring_Analysis

Rev.	Effective Date	Description	Made by	Checked by	Approved by
0	12/15/2017	SUBMITTED FOR REVIEW	MM/RHA		

NOTES:

Contents

1 Executive Summary

Maine Marine Composites (MMC) has developed a simulation model to design a mooring system for Ocean Renewable Power Company's (ORPC's) TidGen tidal energy converter. This document describes the simulation model, results, and the status of the current mooring system design.

A preliminary anchor design is also proposed by MMC. The anchor is primarily a concrete gravity anchor. Structural steel is embedded inside the concrete to provide strength for the chain connection points. Steel L Channels also protrude underneath the concrete to act as a skirt to provide additional resistance

1.1 Remaining Tasks

- Final sizing of mooring lines and shackles, based on final design loads. Account for design loads from final TidGen design.
- Sizing of anchor steel structure. A preliminary anchor design has been proposed, but additional analysis will be required to determine the size of the steel components.
  - Complete detailed design (parts list, assembly, etc.)
  - Material selection for underwater deployment and corrosion resistance
- Modify design to avoid line clashing
- Examine potential for Vortex Induced Vibration (VIV)
- Cost analysis of various methods for mitigating transient shocks during line failure

2 Overview

2.1 Objective

The objective of this work is to develop a mooring system for Ocean Renewable Power Company's (ORPC's) TidGen system, in accordance with Det Norske Veritas (DNV) guidelines and operating standards.

The primary standards consulted were DNV OS-E301: *Position Mooring*, and DNV OS-E302: *Offshore Mooring Chain*.

2.2 Analysis Plan

DNV OS-E301 identifies three limit states:

- Ultimate Limit State (ULS)
- Accidental Limit State (ALS)
- Fatigue Limit State (FLS)

An OrcaFlex simulation model of the TidGen and mooring system was developed to simulate conditions corresponding to each limit state. Through simulation, a mooring line was designed that could withstand the loads from each limit state. In both the ALS and the ULS, a safety factor of 1.4175 was used, as specified by ORPC.

3 Simulation Model Specifications

The software program OrcaFlex by Orcina (see Appendix for details) was used to simulate the mooring loads of the TidGen under various design conditions. The dimensions of the mooring lines in the model are shown in Figure 2.

The mooring dimensions depend on the deployment site, but the general arrangement is the same. Four bridle lines connect the TidGen to a spreader structure. The spreader is fastened to the anchor with two primary mooring lines and four redundant lines. The redundant lines are not intended to be highly loaded during normal operation, but ensure that the system remains on station in the event that one of the primary lines fails.

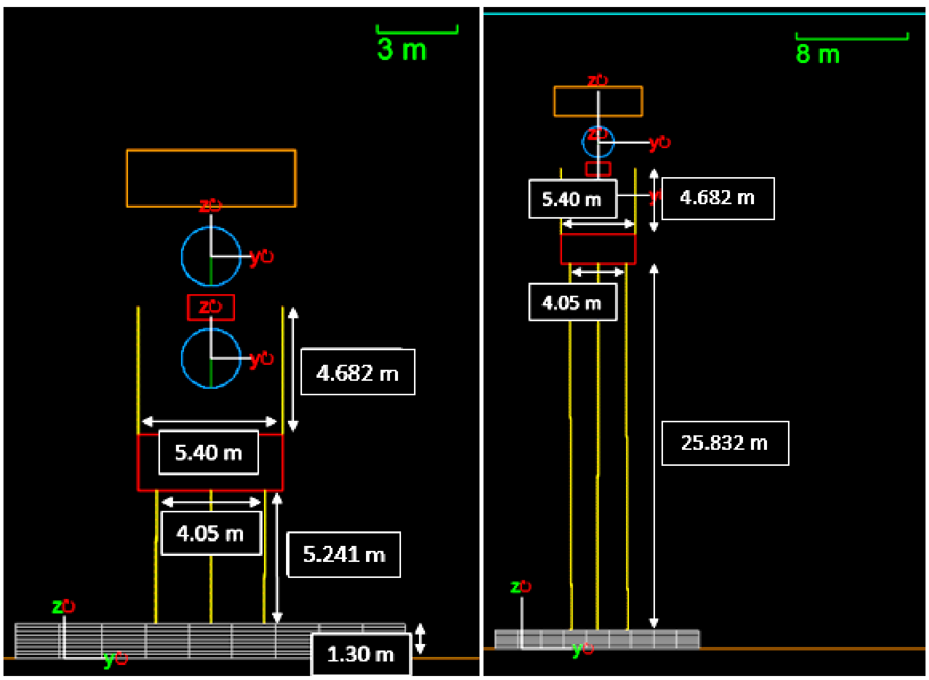


Figure 2: Layout of mooring lines and TidGen in OrcaFlex simulation model. Lines are shown in yellow. TGU is shown in blue, Upper Nacelle is shown in red.

3.1 Deployment Sites

Two deployment sites were analyzed in the OrcaFlex simulation:

- Cobscook
- Western Passage

Environmental conditions at each site are listed in Table 1.

Table 1: Environmental conditions at Cobscook and Western Passage deployment sites

	Cobscook	Western Passage
Waves	(none)	(none)
Current Velocity @ Surface	2.25 m/s	3.50 m/s
Current Velocity @ Seabed	0.00 m/s	0.00 m/s
Current Exponent	7	7
Current Direction	Perpendicular to Cross-Flow Turbine Axle	Perpendicular to Cross-Flow Turbine Axle
Water Depth	25.0 m	45.5 m

3.2 Turbine Structure

The mass, volume, and drag of the various structural elements of the TidGen were provided by ORPC. Hydrodynamic added mass coefficients were estimated from the literature (DNV-RP-C205).

Table 2: Mass and inertia properties of TidGen structure in OrcaFlex simulation

	TGU and Center Nacelle	Upper Nacelle[1]	Anchor
Mass (te)	140	0	270
Volume (m^3)	57.7	91.0	
Ixx ($te.m^2$)	1060	0	
Iyy ($te.m^2$)	16.8E3	0	
Izz ($te.m^2$)	16.2E3	0	
TCG (m)	0.00	+/- 7.27	
VCG (m)	1.66	4.82	

[1] Two Upper Nacelles are specified

Table 3: Hydrodynamic coefficients of structural members in OrcaFlex simulation

	TGU and Center Nacelle	Upper Nacelle[1]	Anchor
Long. Drag Coef.	1.2	0.45	1.2
Vert. Drag Coef.	1.2	0.45	N/A
Long. Drag Area	31.6	23.1	11.2
Vert. Drag Area	46.0	81.0	0
Long. Added Mass Coef.	1	1	N/A
Vert. Added Mass Coef.	1	1	N/A
Long. Hydro. Mass	23.3	31.2	N/A
Vert. Hydro. Mass	49.1	383.4	N/A
Seabed Friction Coef.	N/A	N/A	0.6
Seabed Drag Area	N/A	N/A	85.5

[1] Two Upper Nacelles are Specified

3.3 TGU

The drag due to the TGU is the most significant contributor to lateral load on the mooring lines. The lift and drag coefficients on the TGU were provided by ORPC and are shown in Figure 3. These coefficients were not varied with Reynolds Number.

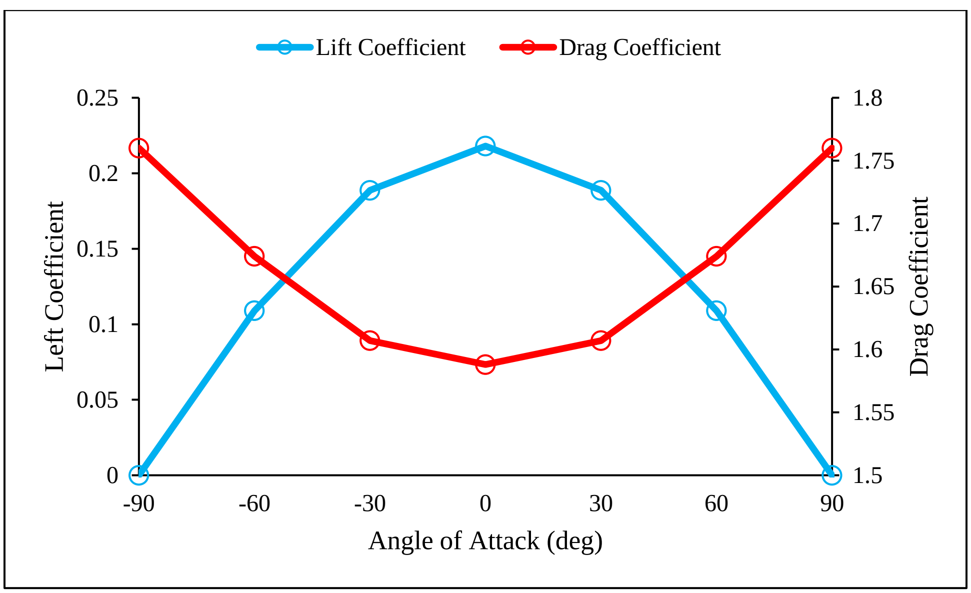


Figure 3: Lift and drag coefficients of TGU blades

Eight TGU elements are specified. Each TGU element has a span of 6.25 meters and a chord length of 2.2 meters. Outermost TGU elements are centered +/- 10.78 meters horizontally from the center. Inner TGU elements are centered +/- 3.78 meters from the center. Vertical locations of the TGU elements are +/- 1.9 meters.

3.4 Mooring

The material and dimensions of each mooring and bridle line is specified in Table 4. A 2.75” stud anchor chain is required to survive the transient loads on the bridle and redundant mooring lines in the event of a line failure.

Table 4: Length and material of mooring lines in OrcaFlex simulation

	Site	Length (m)	Material
Port Line	Cobscook	5.241	2.75” Stud Chain
Port Fore Redundant Line	Cobscook	5.776	2.75” Stud Chain
Port Aft Redundant Line	Cobscook	5.776	2.75” Stud Chain
Starboard Line	Cobscook	5.241	2.75” Stud Chain
Stbd. Fore Redundant Line	Cobscook	5.776	2.75” Stud Chain
Stbd. Aft Redundant Line	Cobscook	5.776	2.75” Stud Chain
Port Line	Western Passage	25.832	2.75” Stud Chain
Port Fore Redundant Line	Western Passage	26.391	2.75” Stud Chain
Port Aft Redundant Line	Western Passage	26.391	2.75” Stud Chain
Starboard Line	Western Passage	25.832	2.75” Stud Chain
Stbd. Fore Redundant Line	Western Passage	26.391	2.75” Stud Chain
Stbd. Aft Redundant Line	Western Passage	26.391	2.75” Stud Chain
Port Fore Bridle	All	4.682	2.75” Stud Chain
Port Aft Bridle	All	4.682	2.75” Stud Chain
Starboard Fore Bridle	All	4.682	2.75” Stud Chain
Starboard Aft Bridle	All	4.682	2.75” Stud Chain

The axial elasticity of the chain is dependent upon the particular manufacturer. DNV recommends a minimum axial stiffness of $k = 5.6 \times 10^{10} \frac{N}{m^2}$ for stud chain. OrcaFlex recommends a value of $k = 6.40 \times 10^{10} \frac{N}{m^2}$ for 2.75” chain. This later value was used in the simulations, being the more conservative of the two values.

Typical rules of thumb for chain material properties are presented below. These values come from three sources: DNV (DNV OS-E301), Orcina (OrcaFlex User Manual), and Anchor Marine Houston (http://www.anchormarinehouston.com/) – one of several potential distributors identified.

- *Axial stiffness*
  - Source: DNV
    - Stud chain $k = 5.6 \times 10^{10} \frac{N}{m^2}$
    - Studless chain $k = (5.40 - 0.0040\ d) \times 10^{10} \frac{N}{m^2}$ (Grade R3; d in mm)
  - Source: Orcina
    - Stud chain $k = 6.40 \times 10^{10} \frac{N}{m^2}$
    - Studless chain $k = 5.44 \times 10^{10} \frac{N}{m^2}$
- *Unit Mass*
  - Source: Anchor Marine Houston
    - Stud chain $m = 0.0219 \times d^2 \frac{kg}{m}$ (d in mm)
    - Studless chain $m = 0.0202 \times d^2 \frac{kg}{m}$ (d in mm)
  - Source: Orcina
    - Stud chain $m = 0.0219 \times d^2 \frac{kg}{m}$ (d in mm)
    - Studless chain $m = 0.0199 \times d^2 \frac{kg}{m}$ (d in mm)
- *Unit Volume*
  - Source: Anchor Marine Houston
    - Stud chain $\forall = 1.095/10^5\ d^2 \frac{m^3}{m}$ (d in mm)
    - Studless chain $\forall = 1.05/10^5\ d^2 \frac{m^3}{m}$ (d in mm)

4 Simulation States

4.1 Ultimate Limit State

Table 5: Summary of simulation conditions

Location		*Western Passage*	*Cobscook*
Braked Turbines		*None*	*None*
Braked CD	-	0.100	0.100
Braked CL	-	0.000	0.000
Freewheel Turbines		*All*	*All*
Freewheel CD	-	1.760	1.760
Freewheel CL	-	0.218	0.218
U	m/s	3.50	2.25
Depth Exponent	-	7	7

Table 6: Results of OrcaFlex simulations

Location		Western Passage	Cobscook
Static Mooring Load	**kN**	877	586
Transient Mooring Load	**kN**	1957	2286
Net Buoyancy	**kN**	510	510
Mooring Angle	**deg**	51.1	27.7
Set Down	**m**	11.1	1.1
Pitch Angle	**deg**	20.9	9.1

Table 7: Mooring design load and required anchor size

	Location	Western Passage	Cobscook
Safety Factor	-	1.4175	1.4175
Friction Coefficient	-	0.6	0.6
Concrete Density in Water	te/m^3	1.275	1.275
Anchor Vertical Design Load	kN	781	735
Anchor Lateral Design Load	kN	2393	1378
Anchor Volume	m^3	191.3	110.2
Mooring Design Load	kN	2774	3240

4.2 Accidental Limit State

The ALS is intended to ensure that the mooring system is strong enough to withstand failure of a single mooring line. According to the simulation model, the largest loads from the ALS are transient loads in the seconds immediately following a line failure. Four conditions were simulated to determine the transient mooring line loads during various failure events. The following conditions were simulated:

1. Failure of single primary mooring line
2. Failure of single fore bridle line
3. Failure of single aft bridle line
4. Failure of TGU brake (simulated by changing the drag coefficient of the TGU from brake to freewheel condition within one revolution)

The maximum loaded line and corresponding safety factors are shown in Table 8. The time history of the most severe case is shown in Figure 4.

Table 8: Maximum tension during ALS simulations

Condition	Site	Highest Loaded Line	Maximum Tension kN	Safety Factor -
Port Primary Line Failure	Cobscook	Port Fore Redundant Line	1419	2.59
	Western Passage	Port Fore Redundant Line	1812	2.03
Port Fore Bridle Failure	Cobscook	Port Aft Bridle	2023	1.82
	Western Passage	Port Aft Bridle	1311	2.80

Port Aft Bridle Failure	Cobscook	Port Fore Bridle	2286	1.61
	Western Passage	Port Fore Bridle	1957	1.88
Brake Failure	Cobscook	Port & Stbd. Primary Line	598.7	6.14
	Western Passage	Port & Stbd. Primary Line	845.8	4.34

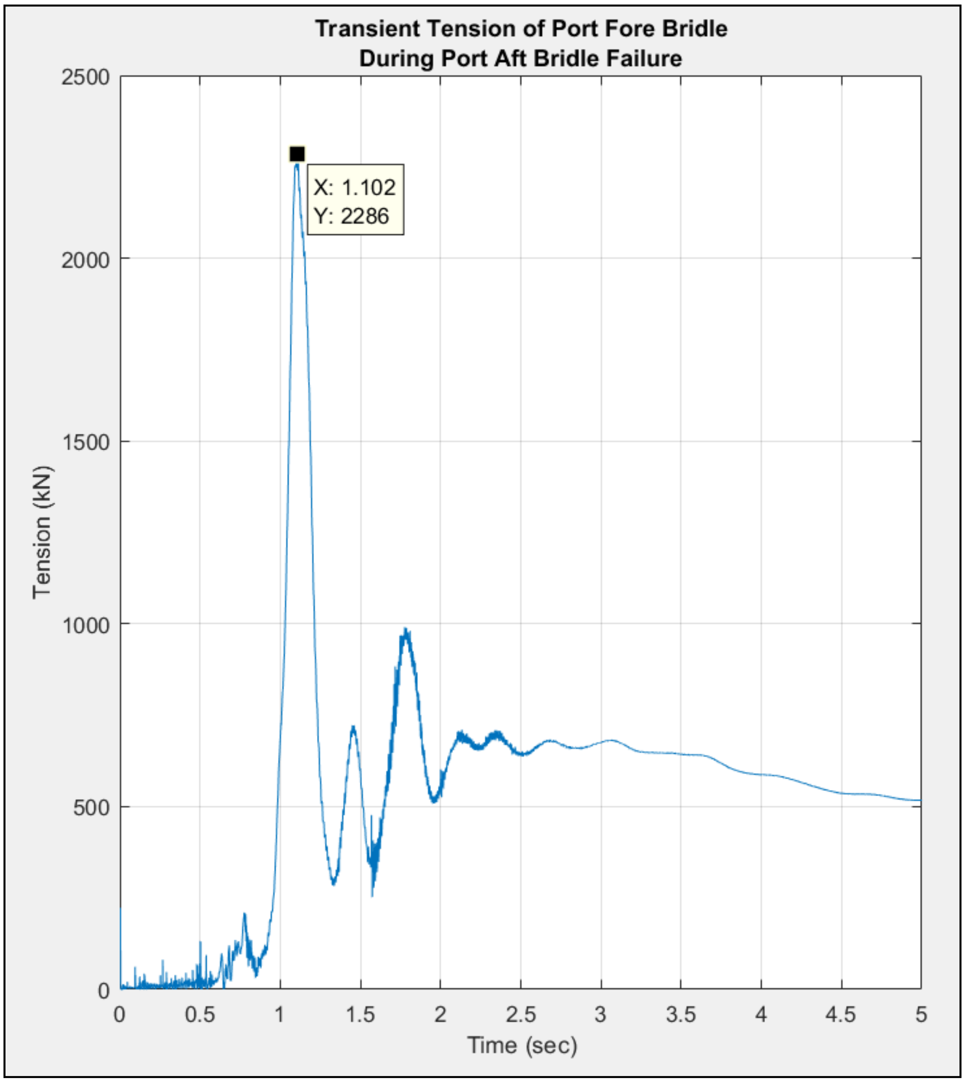


Figure 4: Simulation time history of fore bridle during aft bridle failure

4.3 Fatigue Limit State

Annual fatigue damage for both the Western Passage and Cobscook deployment sites was computed. Damage was calculated using S-N fatigue analysis. The S-N curve parameters are given in Figure 5. Damage was computed by simulating the operation of the TidGen over a tide cycle (scaled from the synthesized tide cycle used in development of the OcGen), shown in Figure 6 and Figure 7. The turbine was assumed to be rotating at 1 Hz during the entire simulation. Vortex Induced Vibration (VIV) was not included in the simulation.

F 200 Fatigue properties

201 The following equation can be used for the component capacity against tension fatigue:

$$n_c(s) = a_D s^{-m}$$

This equation can be linearised by taking logarithms to give:

$$\log(n_c(s)) = \log(a_D) - m \cdot \log(s)$$

$n_c(s)$ = the number of stress ranges (number of cycles)
s = the stress range (double amplitude) in MPa
a_D = the intercept parameter of the S-N curve
m = the slope of the S-N curve

The parameters a_D and m are given in Table F1 and the S-N curves are shown in Fig.6.

Table F1 S-N Fatigue Curve Parameters

	a_D	m
Stud chain	$1.2 \cdot 10^{11}$	3.0
Studless chain (open link)	$6.0 \cdot 10^{10}$	3.0
Stranded rope	$3.4 \cdot 10^{14}$	4.0
Spiral rope	$1.7 \cdot 10^{17}$	4.8

Figure 5: Fatigue S-N curve parameters (source: DNV OS-E301)

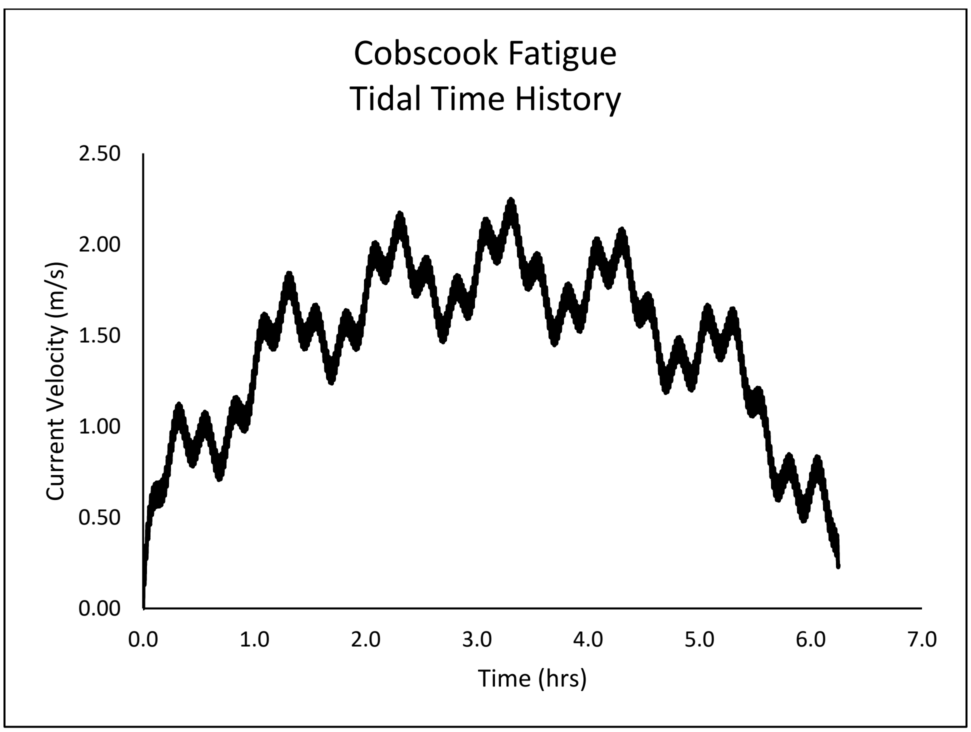


Figure 6: Simulated current velocity of a half tide cycle, Cobscook deployment site.

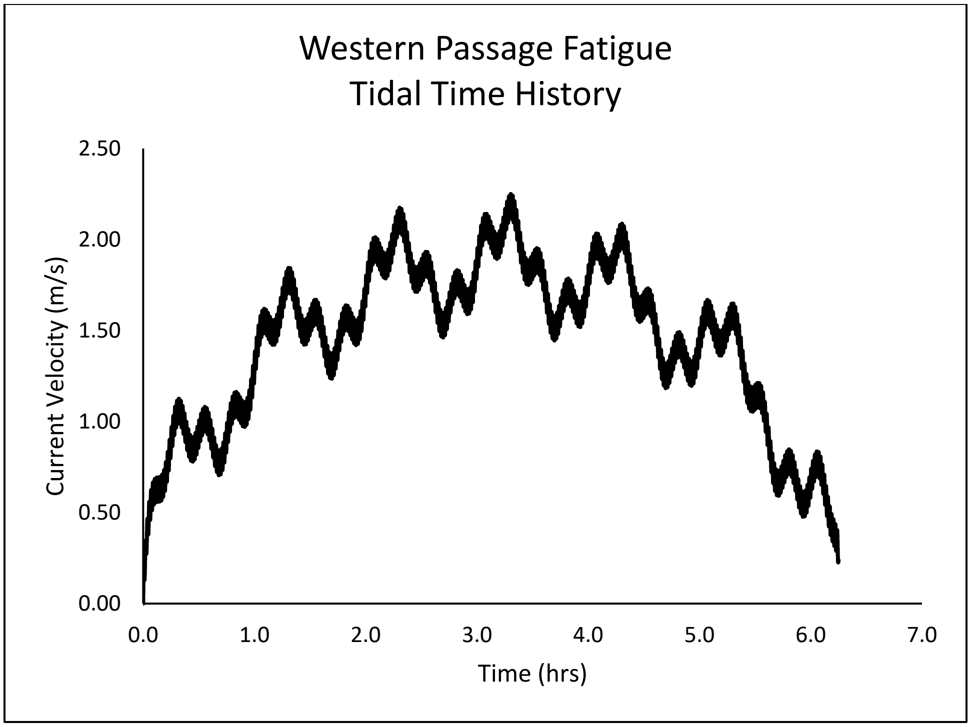


Figure 7: Simulated current velocity of a half tide cycle, Western Passage deployment site.

Table 9: Fatigue lifetime and annual damage results

	Western Passage		Cobscook	
	Lifetime (years)	Annual Damage	Lifetime (years)	Annual Damage
Primary Mooring Line	43	2.306e-2	120	8.308e-3
Redundant Line	28,773	3.476e-5	254,851,221	3.924e-9
Bridle Line	219	4.569e-3	1,122	8.914e-4

4.4 Other Considerations

4.4.1 Vortex Induced Vibration

It is recommended that testing be undertaken in the next budget period to ascertain the likelihood and magnitude of VIV.

4.4.2 Corrosion Allowance

DNV OS-E301 recommends the chain diameter be increased by 0.3 mm/year of service life to offset material degradation from corrosion.

4.4.3 Line Collision

The potential for line collision exists between the redundant and primary mooring lines in the Western Passage deployment site (see Figure 8). This is owing to the fact that the redundant lines are intended to be slack during normal operation. Several options could be employed to prevent collisions from occurring, including:

- Adding a rigid spreader bar, connected from each redundant line to the primary line, to ensure that there is always space between the lines
- Increasing the separation distance between the anchor connection points of the redundant lines and the primary line

Additionally, when the redundant lines are slack there is potential for the bottom of the line to sit on top of the anchor during the largest set-down of the TGU.

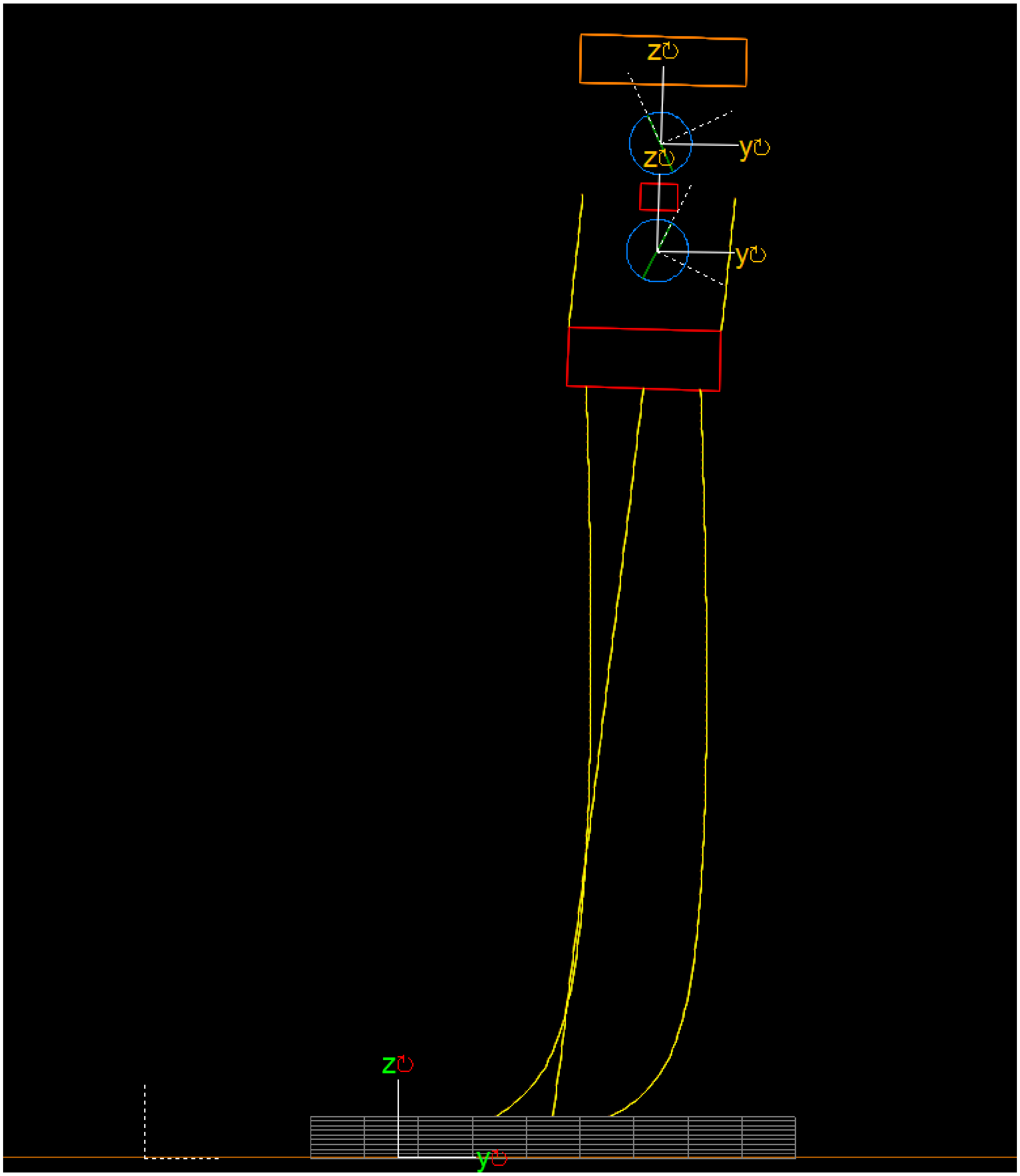


Figure 8: Screenshot of line clashing observed in Western Passage simulations

5 Gravity Anchor

5.1 Anchor Design Considerations

The goals of a gravity anchor are to:

- Provide a fixed reference location on the seafloor that not move during any foreseeable loading conditions
- Resist a prescribed set of vertical and horizontal load conditions

- Have a long operating lifetime, resist corrosion and abrasion
- Cost as little as possible to manufacture
- Cost as little as possible to deploy and retrieve

Common materials in gravity anchors are concrete and steel reinforcements. Concrete is relatively inexpensive material that easily can be molded into a desired shape. Embedding steel reinforcements in concrete protects the steel from corrosion. On the other hand, concrete has a density of about 2,400 kg/m^3 and water has a density of 1,000 kg/m^3, so the submerged weight of concrete is 1,400 kg/m^3. Steel has a density of 7,700 kg/m^3 so its submerged weight is 6,700 kg/m^3, about 4.8 times higher than concrete. Thus, an anchor that includes a significant percentage of steel will be much more compact than one constructed entirely of concrete.

MMC has developed a preliminary design for a gravity anchor for this application.

Anchor weight:	2,417 kN
Dimensions:	17,178 mm Length x 7,500 mm Width x 1,500 mm Height
Concrete density in water:	1.275 te/m^3
TGU uplift force:	510 kN

The anchor is a block with vertical sides so that it will not embed below the seafloor in such a way as to prevent the removal of the anchor. The anchor-barge attachment points are arbitrarily located 1 meter from either end of the anchor. A sketch of the anchor is in Figure 9.

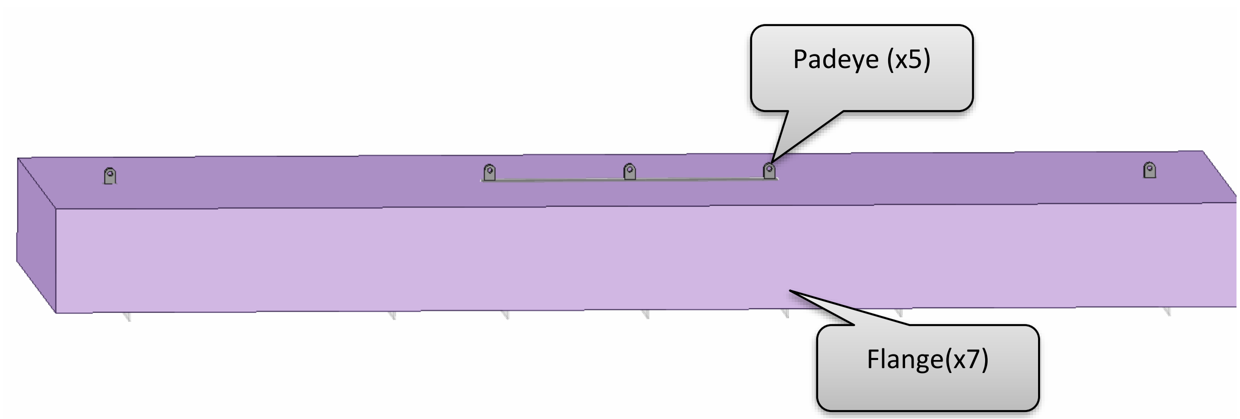


Figure 9. Steel Reinforced Concrete gravity anchor

The gravity anchor consists of a steel plate buried at the bottom of a concrete block. Steel structure carries the load up through the concrete to padeyes exposed above the block. Figure 10 shows the steel bottom plate and the structure.

Exposed small steel flanges underneath the plate will grip any small rock outcroppings or embed in sand or mud. If a rock juts above the seafloor so that there is a concentrated load at a point on one of the flanges, the flange should crush slightly and the anchor will distribute the load more evenly. The flanges extend close to the edges of the block so that there is a path for water to be drawn under the block during retrieval. This will help to break the anchor free without creating a temporary vacuum underneath it.

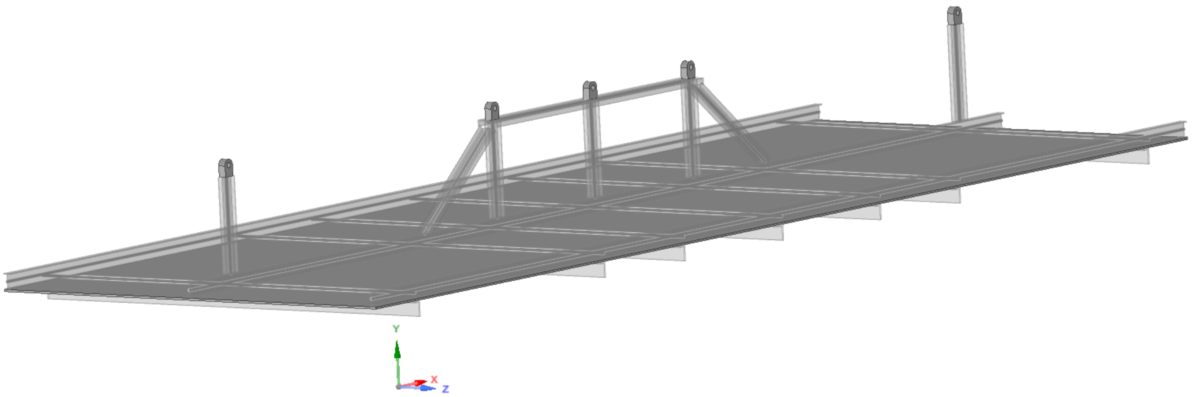


Figure 10. Steel plate, frame and padeyes embedded in concrete gravity anchor

Figure 11 shows the skeleton of the proposed structure without the bottom plate. The structure is composed of stock I-Beams and flanges.

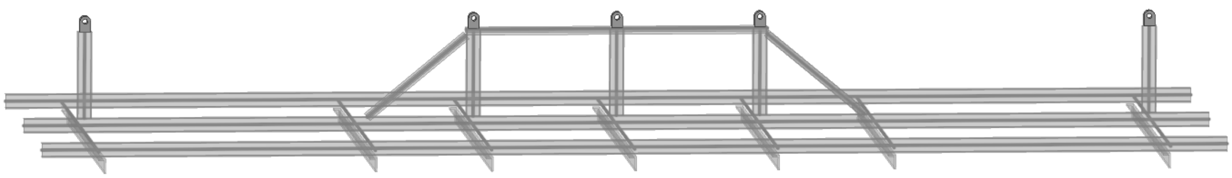
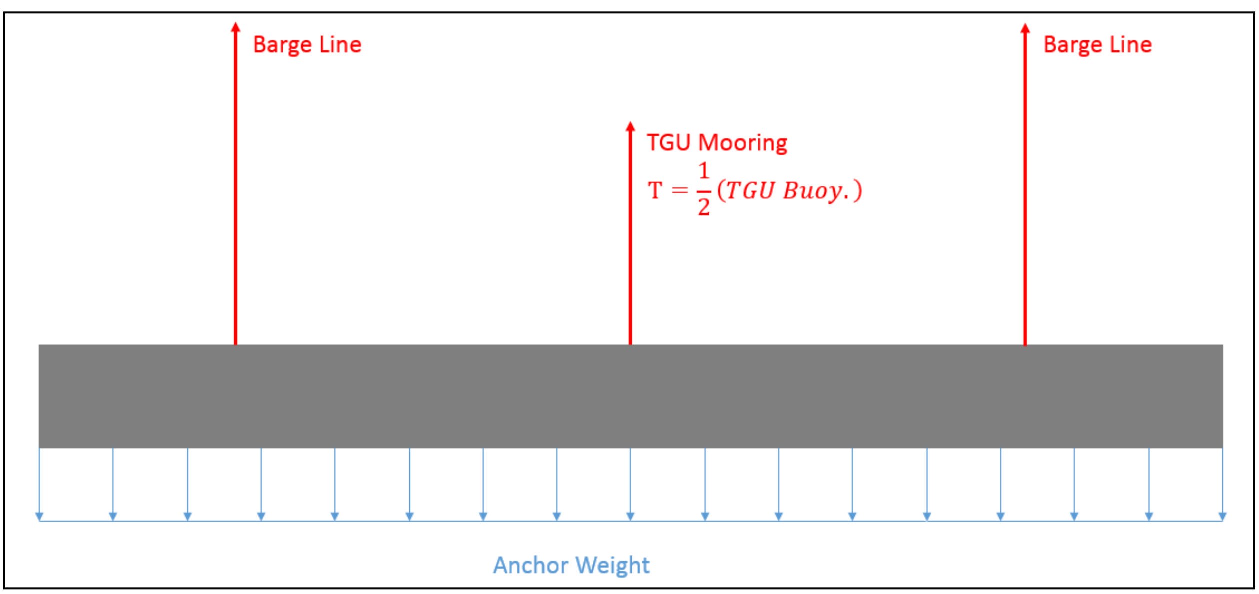


Figure 11. Steel frame and padeyes without bottom plate

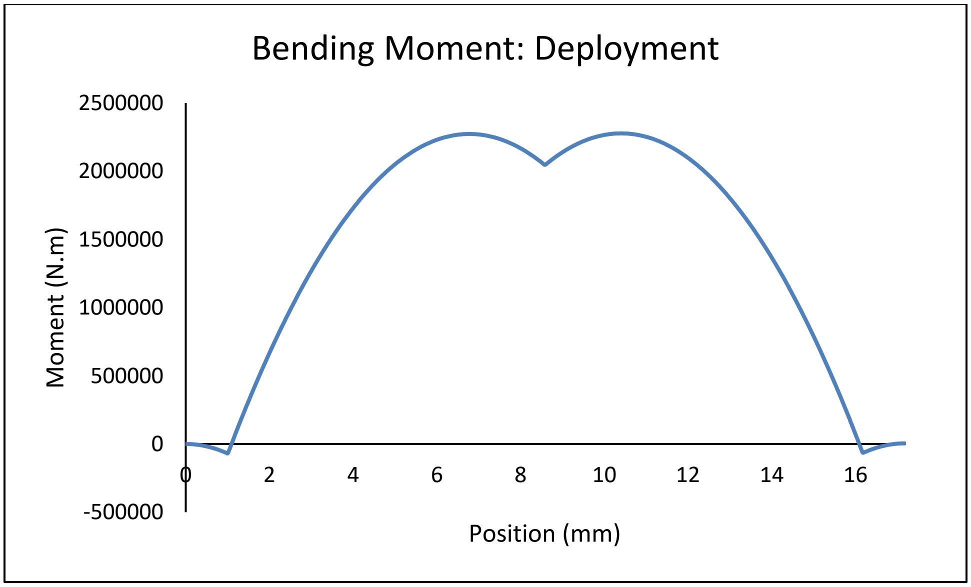
5.2 Anchor Bending Stress

5.2.1 Condition 1: Deployment (Western Passage Deployment Site)

Objective: first analysis of bending stress during deployment. The anchor is suspended from two lines attached to the deployment barge. A third line connects the anchor to the TGU. The weight of the anchor is uniformly distributed.



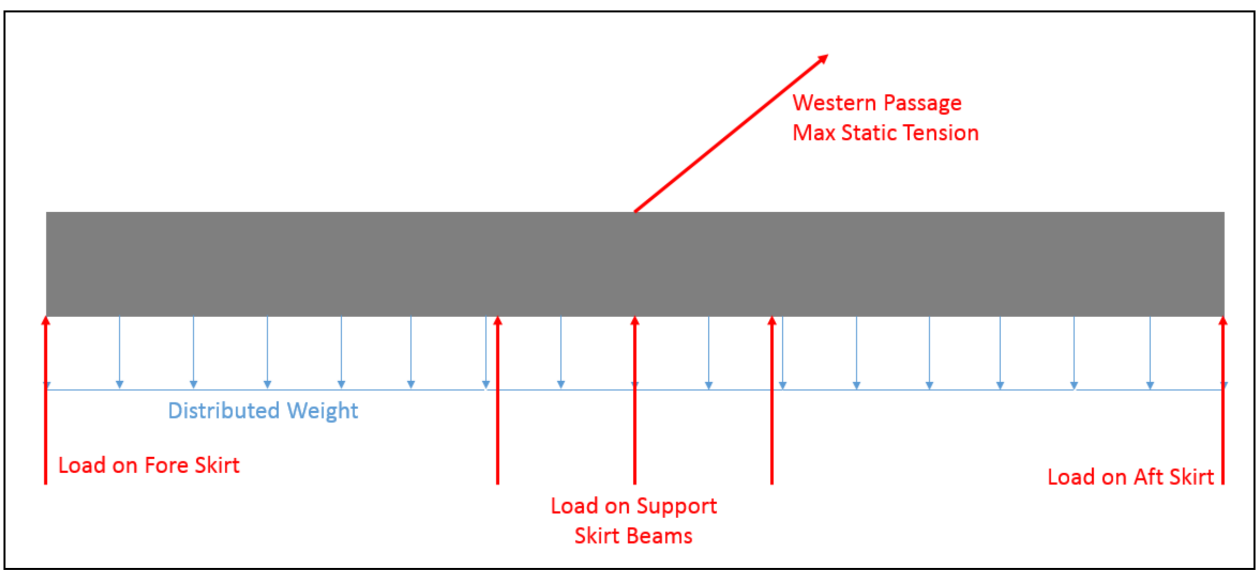
The bending moment diagram is as follows.

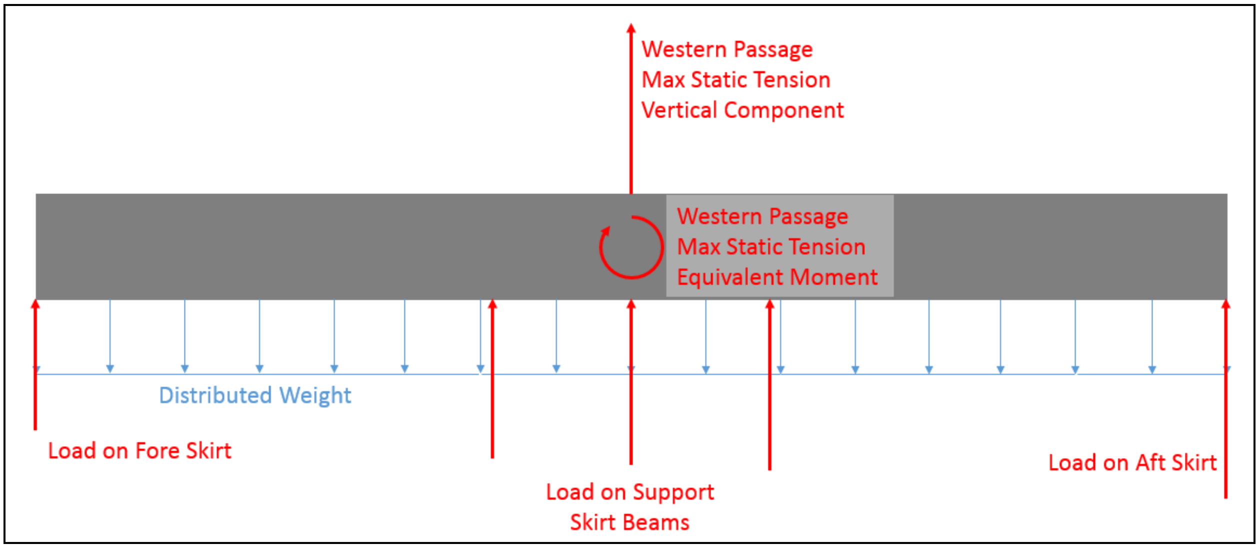


The maximum bending moment is 2,277 kN*m. Using simple bending moment-stress relationships $\left(\sigma = -\frac{My}{I}\right)$, the maximum stresses in the concrete are $8.45 \times 10^5\ Pa$ in tension and $-8.33 \times 10^5\ Pa$ in compression. Assuming a representative Ultimate Strength of $5.00 \times 10^6\ Pa$ in tension and $4.10 \times 10^7\ Pa$ in compression, the stresses are well below the Ultimate Strength of the concrete.

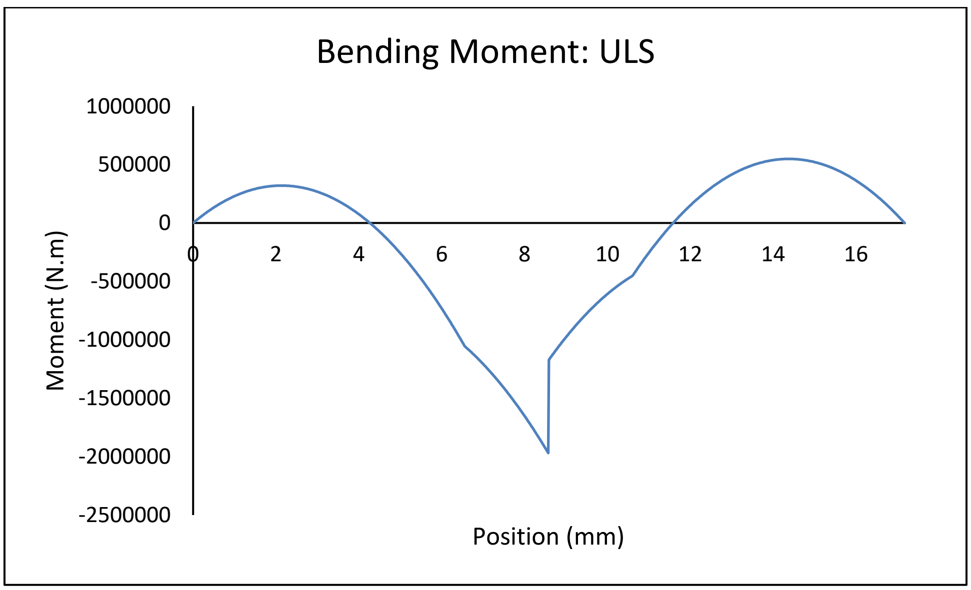
5.2.2 Condition 2: Ultimate Operational Limit State (Western Passage Deployment Site)

Objective: first analysis of bending stress of the anchor during maximum operating (static) load. The load on the anchor from the TGU is the maximum operational (ULS) load and is applied along the primary mooring line at the centroid of the top of the anchor.





The weight of the anchor is uniformly distributed. The reaction load on the seafloor is applied at five points: at either end of the anchor, and at the location of each of the three mooring connection points. This is derived from the assumption that flanges will be located at each of these locations that will form the skirt of the anchor and will be the primary contact points with the seabed. The magnitude of each reaction point is solved for such that the net force and moment are zero. The bending moment diagram is as shown.



Again using simple stress-strain relationships and bending moment equations, the maximum stresses on the concrete are found to be $6.89 \times 10^5\ Pa$ in tension and $-4.01 \times 10^5\ Pa$ in compression.

APPENDIX 1.CAPABILITIES OF ORCAFLEX

OrcaFlex is a time-domain multibody hydrodynamics simulator developed by Orcina, Ltd., optimized for simulation of floating bodies connected by solid structures and lines. Mooring lines are modeled using finite element techniques. The OrcaFlex model includes axial and radial stiffness, added mass and damping, seafloor friction and other physical effects. OrcaFlex is an accurate and efficient simulator for complex systems including free floating and fixed structures, submerged structures and interconnection lines.

OrcaFlex includes a graphical user interfaces and a dialog-box-based interface to specify mechanical properties. OrcaFlex includes powerful post-process capabilities including spectral analyses, static and animated displays, and charts of all important system values and derived values.

Although OrcaFlex does not include a potential flow module to calculate added mass and damping for floating objects, it has the ability to import hydrodynamic databases generated by ANSYS Aqwa. The user has the choice of using potential flow models for floating objects, or to use hydrostatic models augmented by Morison drag coefficients.

OrcaFlex is ideally suited for analyzing dynamic offshore applications. The software models the dynamic behavior of mooring lines, ropes, chains, umbilicals, and pipes using a one-dimensional finite element scheme. Each line is segmented into a series of nodes connected by massless segments, shown in Figure 12. The segments contain axial, bending, and (optionally) torsional stiffness and damping, as shown in Figure 13. Nodes contain mass and buoyancy information.

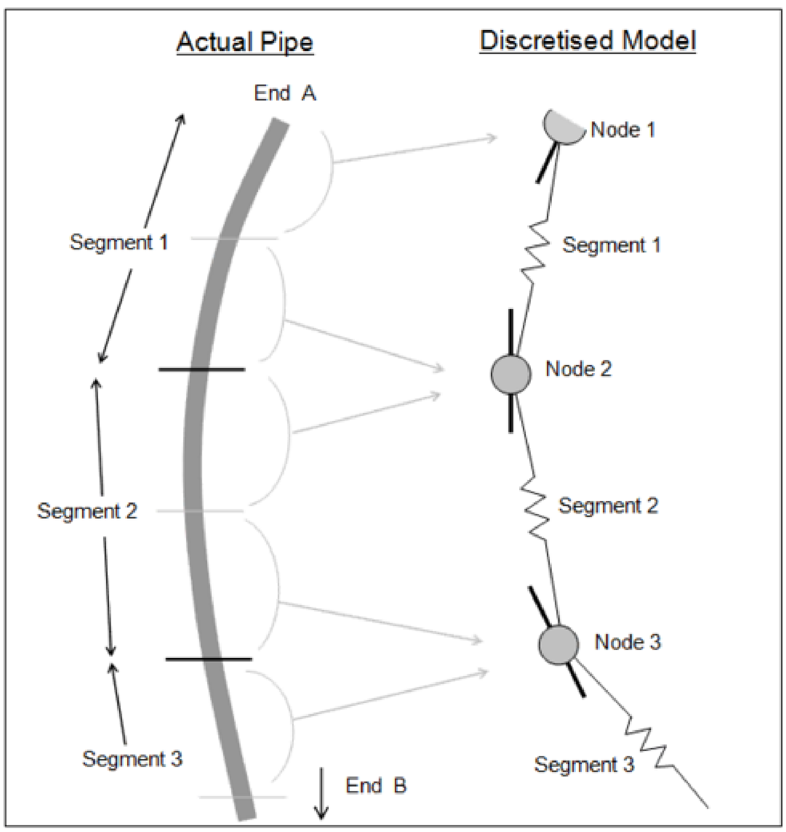


Figure 12: Typical segmentation of mooring line. Source: OrcaFlex User Manual, https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/.

Calculation of dynamic line behavior is done in five stages:

1. Calculation of tension forces from axial stiffness and damping contributions.
2. Calculation of bending moments at each node.
3. Calculation of shear forces at each node.
4. Calculation of torsional moments at each node.
5. Application of mass, drag, added mass, buoyancy, and wave effects (modeled using Morison's Equation), and calculation of total load at each node.

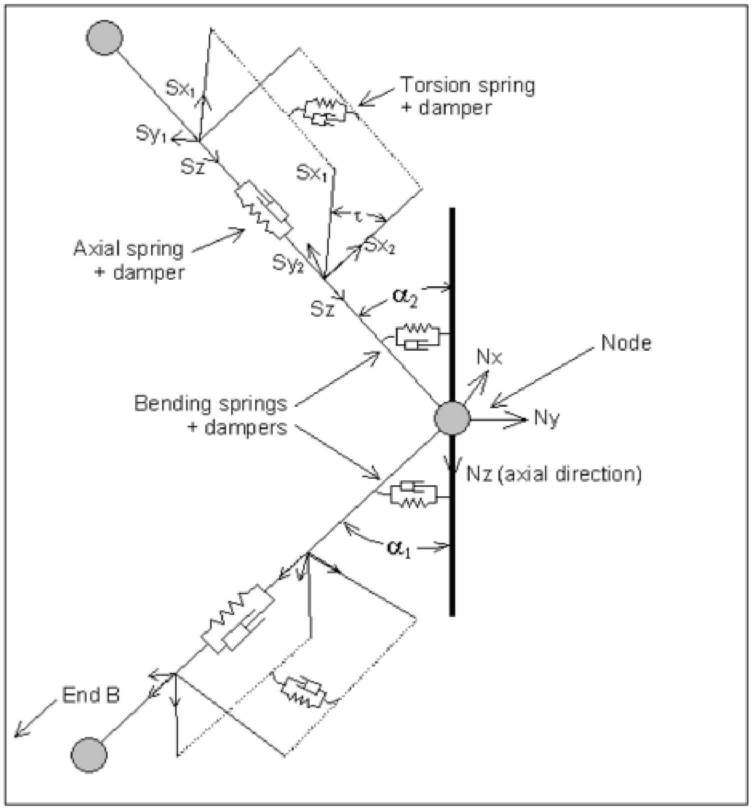


Figure 13: Representation of segment spring and damping components. Source: OrcaFlex User Manual, https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/.

Vessel and buoy wave loading and motion may be calculated in two ways. A simplified approach is to use Morison's Equation, which assumes that the loading on the body depends on an added mass coefficient and a drag coefficient. A Morison's Equation based approach for calculating wave loading is well documented in the literature.

A complex approach involves computation of radiation and diffraction loads using Potential Flow Theory. Such computation is done externally and is input into OrcaFlex in the form of a hydrodynamic database containing information on added mass, radiation damping, and Froude-Krylov and diffraction loads or linear Response Amplitude Operators (RAOs).

Similarly, wave drift and sum frequency loads are calculated externally but may be applied to the motion of a vessel inside OrcaFlex. Motion is calculated through the convolution integral of an impulse response function.

Appendix B

Project: TidGen® 2.0 Commercial Design

System: TidGen® 2.0

Components and functions

ID	Component	Function	Tech. Class	Failure mode	Failure mechanism or cause	Detection	Consequence	Current Controls	Risk Ranking			Comments	Recommended Actions
									Cons.	Prob.	Risk		
P-TD20-10096	Anchors	Provide holding power for device	2										
				Anchor holding failure	Poor estimate of surface friction leads to sliding	Possible abnormal loads or pitching	Device moves out of flow, off a cliff, damages P&D cable	Follow DNV Guidelines for surface friction in our environment	4	2	Med		Subsystem testing in western passage
				Anchor holding failure	Estimate of turbine drag low, anchor size consequently too small	Possible abnormal loads or pitching	Device moves out of flow, off a cliff, damages P&D cable		4	2	Med		Subsystem testing of turbines for loads analysis
A-TD20-10094	Mooring Lines	Provide tensioned connection between anchors and rigid bridle	1										
				Primary Line Failure	Excessive Corrosion	Abnormal line tension after line failure	Redundant lines take up load, Device has slightly out of normal orientation	Chain is increased in size for corrosion allowance	2	1	Low		
				Primary Line Failure	Shackle Abrasion	Abnormal line tension after line failure	Redundant lines take up load, Device has slightly out of normal orientation	Chain and shackles provied additional degres of freedom for rotation	2	1	Low		
A-TD20-10093				Redundant Line Failure	Chain Abrasion	Regular inspection	Reserve capacity is halved.	None	2	4	Med		Secure redundant line with spacer to primary line, add abrasion coating/cover to lower end of redundant chain
P-TD20-10092	Rigid Bridle	Spread the connection between mooring lines and device	2										
A-TD20-10093	Bridle connection lines	Provide a tensioned connection between the rigid bridle and the	1										
				Bridle Line Failure	Excessive Corrosion	Abnormal line tension after line failure, abonormal TGU orientation	TGU is not operateable, possible P&D loss	Chain is oversized for corrosion allowance, consequence for handling snap loads	3	1	Low		
				Bridle Line Failure	Shackle abrasion	Abnormal line tension after line failure, abonormal TGU orientation	TGU is not operateable, possible P&D loss	Chain and shackles provied additional degres of freedom for rotation	3	1	Low		
				Bridle Line Failure	Shock load from primary line failure	Abnormal line tension after line failure, abonormal TGU orientation	TGU is not operateable, possible P&D loss	Chain oversized to handle snap load	3	1	Low		Investigate mooring line suprresors to mitigate snap load