CalWave
Power Technologies

CWPT Open Water Demonstration
DE-EE0008097.0000
Budget Period 1

Mooring Design and Analysis Report

May 29, 2019

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VARIABLES & DEFINITION

VARIABLES AND CONSTANTS

Table 1 Variables & Definitions

VARIABLE	DESCRIPTION	UNIT
W	Width	m
L	Length	m
T	Thickness	m
V	Displaced Water Volume by Absorber	m^3
hOp	Operating depth; Vertical distance between mean water line and top of absorber body	m
Alpha	Mooring angle between mooring line/PTO tether and horizontal tank floor	Deg
C	Target PTO Damping Coefficient	Ns/m
K	Target Spring Coefficient	N/m
H	Tank water depth	m
Hs	Significant Wave Height	m
Tp	Dominant Wave Period	s
Te	Energy Period	S
omega	Wave Direction measured in a positive rotation coordinates defined in this document	Deg

FURTHER CONVENTIONS

CalWave is using the following convention for the positioning and orientation of the global coordinate system. This convention is equal to the most common convention used in Naval Architecture and specifically in wave energy conversion related research & development:

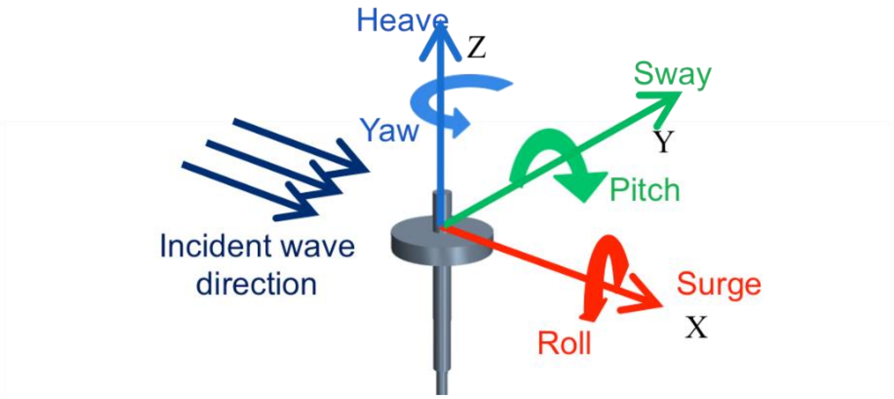

Figure 1: Global Coordinate System Position and Orientation used throughout this report. Picture / Scheme by WECSim - Theory section (https://wec-sim.github.io/WEC-Sim/theory.html)

INTRODUCTION

The objective of the project is to advance the Technology Readiness Level (TRL) of the Wave Energy Converter (WEC) developed by CalWave Wave Power Technologies Inc (CalWave) through advanced numerical simulations, dynamic hardware tests, and ultimately a scaled open water demonstration deployment while continuing to exceed DOE's target ACE threshold of 3m/M$. The outcomes of Budget Period 1 will be a detailed design of the scaled demonstration unit and bench testing of the critical hardware components. In Budget Period 2, the key outcomes will be deployment and operation of the demonstration unit at an open water site which replicates full scale ocean conditions, and performance and load measurements will be used to validate the high techno-economic performance (ACE) of the device full scale device, as measured by the "Average Climate Capture Width per Characteristic Capital Cost" (ACE) metric defined for the Wave Energy Prize.

This report focuses on the Mooring and Anchoring aspects of the CalWave demonstration project and contains documentation and analysis of the following components:

1. *Derivation and justification of the design mooring pattern*
2. *Derivation of the design mooring line length*
3. *Anchor and supplementary component design*
4. *Taut mooring line from Anchor to PTO belt connection*
5. *Connection points (anchor to mooring line & mooring line to PTO belt)*

In the following sections each component design in presented, along with considerations and alternative design options that were determined to be less suitable for this deployment. Finally, the report concludes with lessons learned and suggestions for further evaluation in moving to larger scale deployments.

Note on units:

Metric units have been maintained as standard for design purposes. However, many suppliers that were collaborated with in the process of the development of the anchoring and mooring system work primarily in imperial units and therefore both sets of units appear throughout this document, largely depending on which suppliers were prominently involved in supporting the design evolution of various components. The term 'ton' in this document refers exclusively to U.S. tons.

1. GENERAL MOORING DESIGN AND PATTERN

1.1 OPERATING CONDITIONS

CalWave's WEC is a taut moored device. Additionally, variables, angles, and conventions are shown in the schematic for further use in this document. Note, that these figures represent a schematic view of the setup. Actual lengths, distances, and angles might differ from the schematic drawing. All of the relevant mooring variables such as mooring angle alpha with the vertical, mooring line length LM and others change as a function of the water depth h as well as the submergence depth of the device, here hOp.

The mooring pattern, which cannot be changed after installation and deployment of the device, is derived from the operating point of the device during the main design operating case. The design operating point of the device is derived from realistic Joint Probability Distribution Diagrams for relevant deployment sites of a full-scaled device.

The most beneficial submergence depth h_{Op} is derived from the design wave state (H_s,T_p) and thus leads to the mooring setup that dictates the anchor locations M_i for the deployment. However, this is again a function of the water depth at the deployment locations.

From the schematics in **Error! Reference source not found.** and **Error! Reference source not found.** it ca n be seen that:

$$b\_Op(i) = h(i) - Design\_hOp - PTO.z;$$

$$a\_Op(i) = b\_Op(i)/tand(alpha);$$

$$c\_Op(i) = sqrt(a\_Op(i)^\wedge 2 + b\_Op(i)^\wedge 2);$$

and

$$M.R(i) = a\_Op(i) + sqrt(PTO.y^\wedge 2 + PTO.x^\wedge 2);$$

$$M.X(i) = cosd(gamma)*M.R(i);$$

$$M.Y(i) = sind(gamma)*M.R(i);$$

$$M.Z(i) = h(i).$$

Thus, for different water depths h, the following anchor locations and spreads are derived from this operating case:

Table 2: Anchor position / measures for a range of water depths. The relevant water depths are highlighted in blue color.

h	M.R	M.x	M.y	h	M.R	M.x	M.y
15	12.79	9.04	9.04	**28**	25.79	18.24	18.24
15.5	13.29	9.40	9.40	**28.5**	26.29	18.59	18.59
16	13.79	9.75	9.75	**29**	26.79	18.94	18.94
16.5	14.29	10.10	10.10	**29.5**	27.29	19.30	19.30
17	14.79	10.46	10.46	**30**	27.79	19.65	19.65
17.5	15.29	10.81	10.81	**30.5**	28.29	20.00	20.00
18	15.79	11.17	11.17	**31**	28.79	20.36	20.36
18.5	16.29	11.52	11.52	**31.5**	29.29	20.71	20.71
19	16.79	11.87	11.87	**32**	29.79	21.06	21.06
19.5	17.29	12.23	12.23	**32.5**	30.29	21.42	21.42
20	17.79	12.58	12.58	**33**	30.79	21.77	21.77
20.5	18.29	12.93	12.93	**33.5**	31.29	22.13	22.13
21	18.79	13.29	13.29	**34**	31.79	22.48	22.48
21.5	19.29	13.64	13.64	**34.5**	32.29	22.83	22.83
22	19.79	13.99	13.99	**35**	32.79	23.19	23.19
22.5	20.29	14.35	14.35	**35.5**	33.29	23.54	23.54
23	20.79	14.70	14.70	**36**	33.79	23.89	23.89
23.5	21.29	15.05	15.05	**36.5**	34.29	24.25	24.25
24	21.79	15.41	15.41	**37**	34.79	24.60	24.60

In combinations with the site characterization, the above table leads to the target anchor locations. Note, that for each anchor point M_i the table can lead to slightly different mooring locations due to the difference in anchor depths / sea floor depth.

A sensitivity analysis has been conducted on the accuracy of the anchor locations. More specifically, it is of interest to assess how deviation from the ideal mooring positions (due to practical installation considerations) leads to deviations in the device characteristic oscillations or performance. As Figure 2 exemplary shows, for a water depth of h = 21.5 m a deviation from an accurate anchor position along the diagonal/radius of the mooring watch circle only leads to a single digit angle deviation in the mooring. Mooring angle deviations of that scale can fully be compensated by the absorber body controller without significant effect on the device performance.

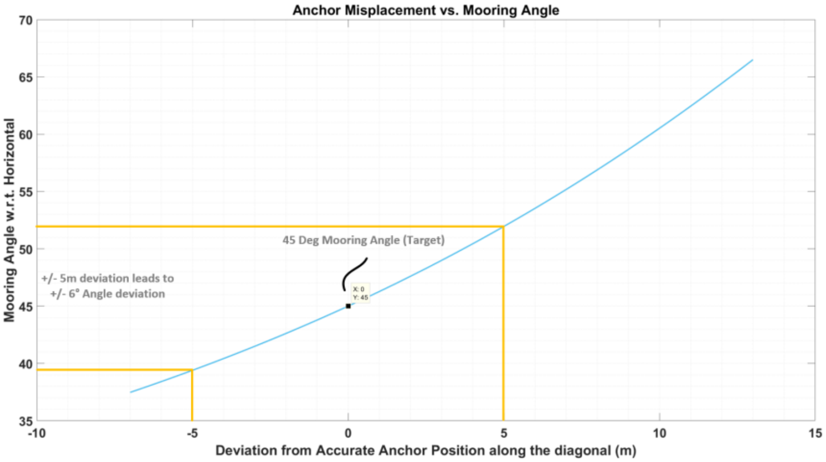

Figure 2: Deviation from an accurate anchor position and effect on mooring angle alpha with respect to the horizontal/sea floor.

2. ANCHOR COMPONENTS & DESIGN

Based on the general device design, targeted deployment site characteristics, accompanying mooring layout and load calculations and simulations, as well as lessons learned, and data collected from multiple scaled tank tests, the following anchor requirements and specifications have been determined:

2.1 SUMMARY OF ANCHOR REQUIREMENTS AND SPECIFICATIONS:

1) **Maximum Line Tension:**
Maximum line tension is based on the maximum torque the PTO can exert onto the mooring tether. If this tension is reached the reactive parts of the PTO will trade force against increased velocity (e.g. motor slips; for more information, see the *PTO bench test report*). Thus, this PTO related maximum force value sets the limit on the maximum design line tension.

2) **Line Angle (with respect to the horizonal/sea floor):**
The angle measured between the mooring line and the sea floor is dependent on the variable submergence depth of the absorber which, again, is based on the wave environment. Based on a probability approach, the most energy contributing case leads to the target design mooring angle alpha of 45 Degrees. This value is achieved with the proposed mooring pattern and a submergence depth h_{Op} of the absorber body of $h_{Op} = 0.75$m measured between the SWL and the top of the absorber body (see **Error! Reference source not found.**). For the deployment location the exact submergence depth of the anchors (deviation of +/- 1m in depth/z position) leads to slight deviations in the mooring angle for each of the anchors. This is taken into consideration for the device modeling and the absorber body controls are capable of compensating for these deviations.

3) **Vertical Component of Tension:**
Based on the target design mooring angle with the seafloor as well as the maximum allowed mooring force the vertical mooring force component can be derived.

4) **Horizontal Component of Tension:**

Based on the target design mooring angle with the seafloor as well as the maximum allowed mooring force the horizontal mooring force component can be derived.

5) **Anticipated Load Cycles:**
Based on the deployment site characteristics as well as the device sizing, the oscillating characteristics and the target deployment time of 6-8 month the anticipated load cycles for the mooring were derived.

6) **Minimum Safety Factor:**
Partial safety factor method in IEC 62600-103 EDI & DNVGL-OS-E301. However, a 20% increase in safety factor has been identified as possible risk mitigation strategy due to novelty of mooring configuration (see Risk Management Reporting).

7) **Desired Safety Factor:**
See point 6.

8) **Anchor Depth:**
For the targeted deployment location, the average water depth for the mooring anchors were derived from *gis* data of the sea floor.

9) **Deployment Location Seafloor:**

2.2 ANCHOR DESIGN FRAMEWORK

During the design of the anchor options, next to feasibility and sufficiency in holding capacity, the following input/topics were included in the analysis:

- **Friction Coefficient**[1]

Rough concrete on coralline sand:	0.66
Smooth concrete on coralline sand:	0.63
Rough steel on coralline sand:	0.63
Smooth steel on coralline sand:	0.2

For ease of calculations, a consistent friction coefficient of 0.63 is used. However, it is understood that this is a more conservative estimate for concrete than for steel; and that in both cases care needs to be taken to ensure surfaces are sufficiently rough to achieve desired friction levels. This is particularly important in the case of steel anchors.

- **Economy vs. novelty of design**

- **Deployment logistics:**

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[1] Thompson, D; Beasley, D (2012) "Handbook for Marine Geotechnical Engineering", SP-2209-OCN, Naval Facilities Engineering Service Center, Port Hueneume, CA February 2012

Most specifically crane and vessel capacity and transportation costs. Optimum pier for deployment is limited to a 3-ton crane and optimum deployment vessel is limited to 2-ton A-frame capacity. Cost of dive operations at depths below 50' (15 m).

- **Permitting considerations:**
  Helical sand screws deemed infeasible due complications with iterative permitting required to obtain sand layer samples prior to detailed design

- **Archimedes' Principle (difference between 'wet weight' and 'dry weight'):**
  Apparent mass when submerged = Mass – (density of water*volume of displaced water by the anchor)

  This becomes a more significant consideration for concrete which is less dense than steel and therefore requires a larger volume for the same weight.

  - Density of concrete: 2240 kg/m^3 (140 lb/ft^3)
  - Density of steel: 7850 kg/m^3 (490 lb/ft^3)
  - Density of sea water: 1025 kg/m^3 (64 lb/ft^3)

2.3 DESIGN OPTIONS

Based on the target design requirements and specifications as well as the additional mooring design inputs the following anchor options were derived:

2.3.1 Concrete Block(s) as Deadweight Anchors

Concrete block used as deadweight anchors are a common approach with existing designs being found in all types of marine and offshore applications. Nevertheless, as a type of deadweight anchor with a medium density material, concrete block anchors require large lift capacities for deployment and transportation logistics. These costs need to be taken into account for the anchor design.

- Pro: Existing design that is commonly used for anchoring
- Con: Requirement of large lift capacity for deployment and transportation logistics; cost

Figure 3: Example of the specific concrete block anchors considered for deployment. Note, that this picture includes a block of similar but not exact required size (picture provided by Truston Technologies, Inc.).

A concrete block anchor would consist of a pre-existing design from a known anchoring system supplier (Truston Technologies, Inc.). The design includes a steel rebar reinforced inner cage with embedded steel chain exposed on three sides for transportation and mooring line connection. The above Figure 3 is a representative example of a similar concrete block anchor of a similar (not exact) size of the demonstration scale anchors.

Assuming a conservative friction coefficient of 0.63 (concrete on sand) and a safety factor of 2; the minimum wet weight (apparent weight when submerged) of a concrete block anchor is:

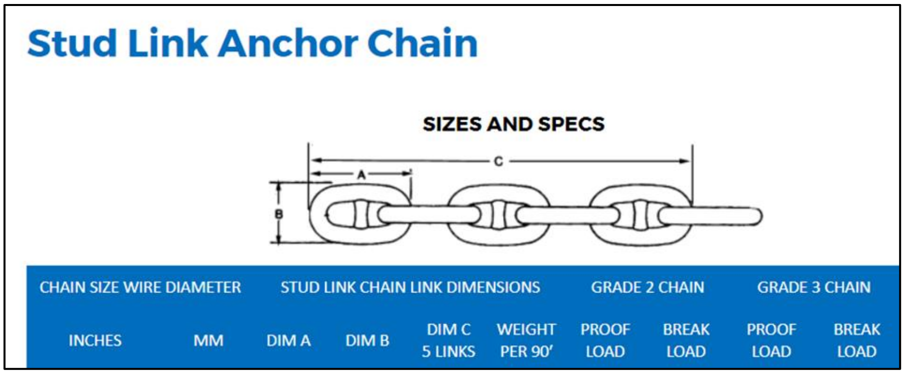
- Safety factor *(vertical component of force + (horizontal component of force/friction coefficient))

To obtain the dry weight and volume of the concrete block, this force is offset by the density of seawater:

- wet weight / (density of concrete - density of seawater) = dry weight
- dry weight/2240kg/m^3 = volume

As it can be seen, single block anchors of this size pose a significant challenge in economic transportation and deployment, which is a leading cause of investigating lower cost alternatives.

Also, to be considered is the required chain dimensions for the connection to the synthetic mooring line (see 3. Mooring Line Components & Design). As the chain is required to be specified for lifting the weight of the concrete block, which is nearly twice the weight in air as it is submerged, the chain will inherently be sufficiently strong for the derived tether loads during the deployment. Additionally, the anchor is sized to prevent the horizontal component of force from overcoming the static friction between the block and the seafloor as well as the drag across the seafloor, which again is significantly oversized compared to the force acting on the chain itself.



Stud Link Anchor Chain

SIZES AND SPECS

CHAIN SIZE WIRE DIAMETER		STUD LINK CHAIN LINK DIMENSIONS				GRADE 2 CHAIN		GRADE 3 CHAIN	
INCHES	MM	DIM A	DIM B	DIM C 5 LINKS	WEIGHT PER 90'	PROOF LOAD	BREAK LOAD	PROOF LOAD	BREAK LOAD

Figure 4: Chain strength chart (Waterman Supply Catalog; http://watermansupply.com/wp-content/uploads/2017/08/Stud-Link-Catalog.pdf)

2.3.2 Fabricated Steel Frame with Concrete Block(s)

- Pro: Built of individual components less than 2.75 ton, allowing for assembly using more economical vessels and local pier infrastructure; potentially reducing cost.
- Con: Increased novelty/risk compared to an existing anchor design; cost of dive operations for assembly.

In this alternative, gravity-based anchor option, a steel frame or sled would be fabricated enabling concrete blocks to be placed such that a relatively large anchor can be built in-situ with smaller components. This option introduces the need for potentially more complex dive operations in exchange for reducing the need for large vessels and cranes required for a single block large anchor. The design being developed for this anchoring option includes either a cruciform frame or flat steel plate. From a design perspective, the primary concerns for the steel structure are bending moment due to horizontal force and center deflection due to uplift force.

A simple flat steel plate with an additional connecting center pipe is the simplest structure and likely the most cost effective. A first principle CAD model and FEA result is shown in Figure 5.

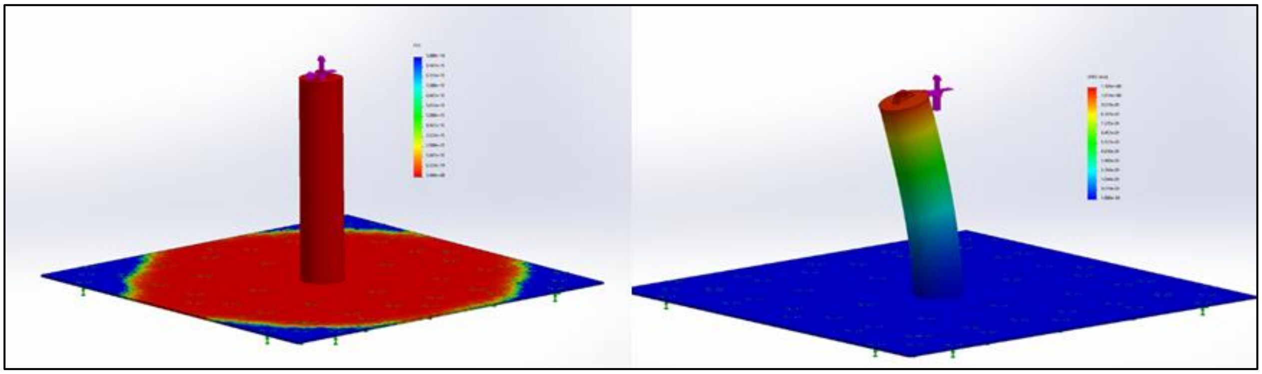


Figure 5: Steel Sled with Flat Plate in Deflection (left) and Bending Moment (right)

Further analysis on the flat plate design remains; specifically related to:

- Bending moment and deflection
- If/any additional stiffeners are required for further structural integrity

- Weld fatigue
- Padeye connection
- Ensuring rough steel on bottom surface (low friction coefficient of smooth steel on sand)
- Surface area available for anodes or other corrosion protection

To help alleviate the potentially lower steel on sand friction coefficient, the steel plate could be fabricated such that the concrete blocks overhang the plate and are in contact with the seafloor around the outer edges.

The below calculations are used to determine the size of the center pipe required to maintain below a maximum bending stress of 150 MPa with a load safety factor of 2. Note that these firsthand calculations are based on a bending pipe with the load applied to the center of the pipe though providing a sufficient estimate.

Table 3 Steel Frame Center Pipe Dimensions

Steel Pipe specifications				
outside diameter		in		m
thickness		in		m
inside diameter		in		m
x-section area		in^2		m^2
length of pipe		in		m
Moment of inertia		in^4		m^4
Normal stress		**psi**		**MPa**
Bending moment		ft-lb		kNm
Bending stress		**psi**		**MPa**

Assumptions:

- Material: A36 (<8” thick)
- Youngs Modulus (M_y): 200 GPa
- Yield Strength: 250 MPa
- Max Bending Stress: 150 MPa (60% of Yield Strength)
- Y-Component Load $(force_y)$:
- Safety Factor: 2.0

Calculations:

- Cross-Section $(force_y)$: $\pi * \left(\frac{OD-ID}{2}\right)^2$
- Moment of Inertia (MI): $\left(\frac{\pi}{64}\right) * (OD-ID)^4$
- Bending Moment (BM): $(force_y) * length\ of\ pipe$
- Bending Stress (BS): $\frac{BM*\frac{OD}{2}}{MI}$

The other primary concern is deflection of the flat plate, the subject of the below hand calculations;

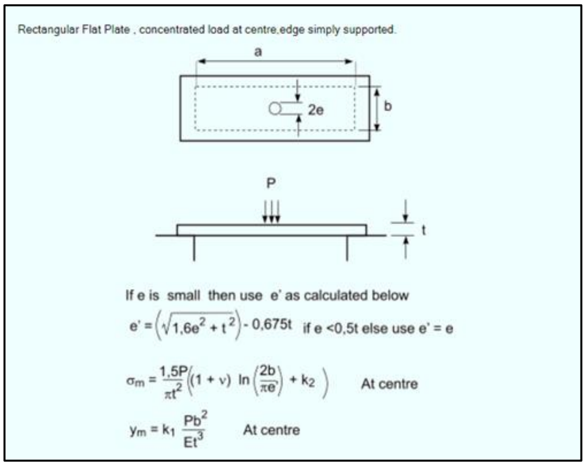
Table 4 Steel Plate Dimensions

Steel Plate Deflection				
Material	**A36**			
Plate length		in		mm
Plate width		in		mm
Area		ft^2		m^2
Plate thickness		in		mm
Load – normal (incl. SF)		lbs		kN
Load – axial (incl. SF)		lbs		kN
Load application radius (ro)		in		mm
Load over small concentric circle		psi		N/mm
Youngs modulus		psi		GPa
Poissons ratio				
Stress at center				MPa
Deflection				mm

Assumptions:

- Material:	A36 (<8” thick)
- Youngs Modulus (M_y):	200 GPa
- Yield Strength:	250 MPa
- Max Bending Stress:	150 MPa (60% of Yield Strength)
- X-Component Load $(force_x)$:	
- Safety Factor:	2.0

Calculation:



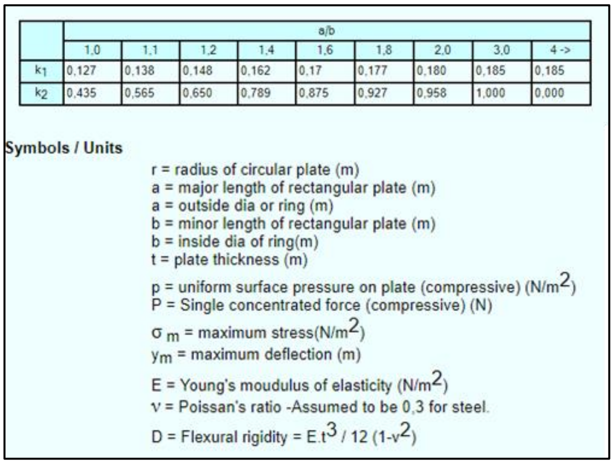
Rectangular Flat Plate , concentrated load at centre,edge simply supported.

If e is small then use e' as calculated below

$$e' = \left(\sqrt{1{,}6e^2 + t^2}\right) - 0{,}675t \quad \text{if } e < 0{,}5t \text{ else use } e' = e$$

$$\sigma_m = \frac{1{,}5P}{\pi t^2}\left((1+\nu)\ \ln\left(\frac{2b}{\pi e'}\right) + k_2\right) \quad \text{At centre}$$

$$y_m = k_1 \frac{Pb^2}{Et^3} \quad \text{At centre}$$



	a/b								
	1,0	1,1	1,2	1,4	1,6	1,8	2,0	3,0	4 ->
k_1	0,127	0,138	0,148	0,162	0,17	0,177	0,180	0,185	0,185
k_2	0,435	0,565	0,650	0,789	0,875	0,927	0,958	1,000	0,000

Symbols / Units

r = radius of circular plate (m)
a = major length of rectangular plate (m)
a = outside dia or ring (m)
b = minor length of rectangular plate (m)
b = inside dia of ring(m)
t = plate thickness (m)

p = uniform surface pressure on plate (compressive) (N/m^2)
P = Single concentrated force (compressive) (N)

σ_m = maximum stress(N/m^2)
y_m = maximum deflection (m)

E = Young's moudulus of elasticity (N/m^2)
ν = Poissan's ratio -Assumed to be 0,3 for steel.

D = Flexural rigidity = E.t^3 / 12 (1-v^2)

Figure 6: Flat Plate Stress & Deflection Calculations
(http://www.roymech.co.uk/Useful_Tables/Mechanics/Plates.html)

The primary weight of the anchor would be in the form of concrete blocks. It was initially considered to design reinforced concrete blocks specific to this application but determined to be infeasible due to design costs and comparison with more cost-effective existing bulk manufactured designed, such as the 2-ton concrete blocks commonly used for retaining walls (pictured below).

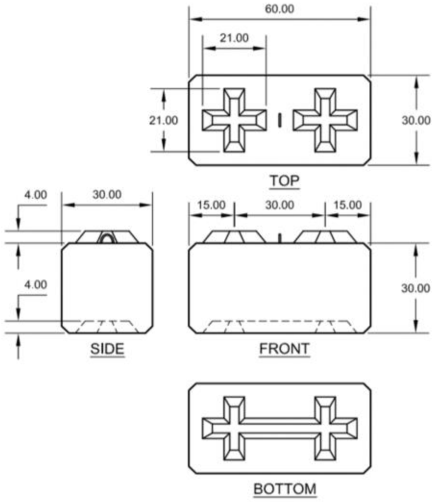


Figure 7: Retaining Wall Concrete Blocks (dimensions in inches)

As these blocks are designed for use as self-locking stacked retaining walls (without the need for grout) it is anticipated that they would sufficiently support their own weight and remain in place on the seafloor. However, it would be possible to tension the blocks onto the steel frame with the use of a top plate and spacer bolts.

These blocks would be stacked on either the steel flat plate or a steel cruciform, as shown in Figure 8.

Figure 8: Concrete Blocks on Steel Plate (left) and Cruciform (right)

In this configuration, several concrete blocks would be required to provide enough weight with sufficient safety factor. The retaining wall blocks are 31.25 ft^3 each and weight 4000 lb, giving them a density of 128 lb/ft^3 (somewhat less dense than what is assumed for the reinforced single solid block concrete option, due to less reinforcing internal steel rebar).

3. MOORING LINE COMPONENTS & DESIGN

3.1 SUMMARY OF MOORING LINE REQUIREMENTS/SPECIFICATIONS

1) **Mooring Line Length:**
   The mooring line length reaching from the anchor connection to the PTO belt connection shackle is derived from the survival case and thus, the maximum target submergence depth of the device (see **Error! Reference source not found.**).

2) **Max Line Load/Tension:**
   Maximum line tension is based on the maximum torque the PTO can exert onto the mooring tether. If this tension is reached the reactive parts of the PTO will trade force against increased velocity (e.g. motor slips; for more information, see the *PTO bench test report*). Thus, this PTO related maximum force value sets the limit on the maximum design line tension.

3) **Anticipated Load Cycles:**
   Based on the deployment site characteristics as well as the device sizing, the oscillating characteristics and the target deployment time of 6-8 month the anticipated load cycles for the mooring were derived.

4) **Max Elongation:**
   The maximum allowed elongation of the mooring line length was iteratively derived for different mooring line diameters, respectively minimum breaking forces and thus stiffnesses. The 30 mm was ultimately set as a maximum allowed elongation target to stay an order of magnitude below the stiffness of the combined PTO system. Thus, the elongation of the mooring line for operating cases does not significantly affect the performance of the device.

3.2 MOORING LINE DESIGN CONSIDERATIONS

Mooring line has been determined to be of stiff Dyneema or similar High Modulus Polyethene (HMPE) due to its high strength and stiffness properties, as well as its resistance to fatigue. The length of the mooring line required is determined based on the considerations discussed in chapter **Error! Reference source not found.**. Because of the significant oversizing of the mooring line in order to maintain operational stiffness, the anticipated load cycles will operate at less than 5% of the max loading of the mooring line. Therefore, fatigue of the mooring line was not considered as a primary design consideration.

The mooring line will be spliced on both ends, with load applied to set the splice prior to commencing normal operation. However, it may not be possible to apply enough load to fully set the splices, therefore some minor loss of power production efficiency may be noticed in the first few cycles of operation until the splices are fully set.

3.3 STIFFNESS/ELONGATION

Due to the effect that elongation in the mooring line during operations has a dampening effect on the WEC power stroke and thus a negative correlation with power production efficiency, by far the most restrictive design requirement on the mooring line is the stiffness. In order to achieve this maximum elongation during operation requirement, the mooring line is greatly oversized for ultimate strength.

The rope manufacturers have relatively little test data for elongation at this point in the load cycle; however, suppliers have indicated that an extrapolation using the second order polynomial of the trendline from existing data will give a roughly accurate understanding of elongation at lower loading profiles. In the chart below, the blue line indicates actual data points from supplier load testing and the orange line is the extrapolated results. Test data has been reviewed from three different manufacturers with similar results.

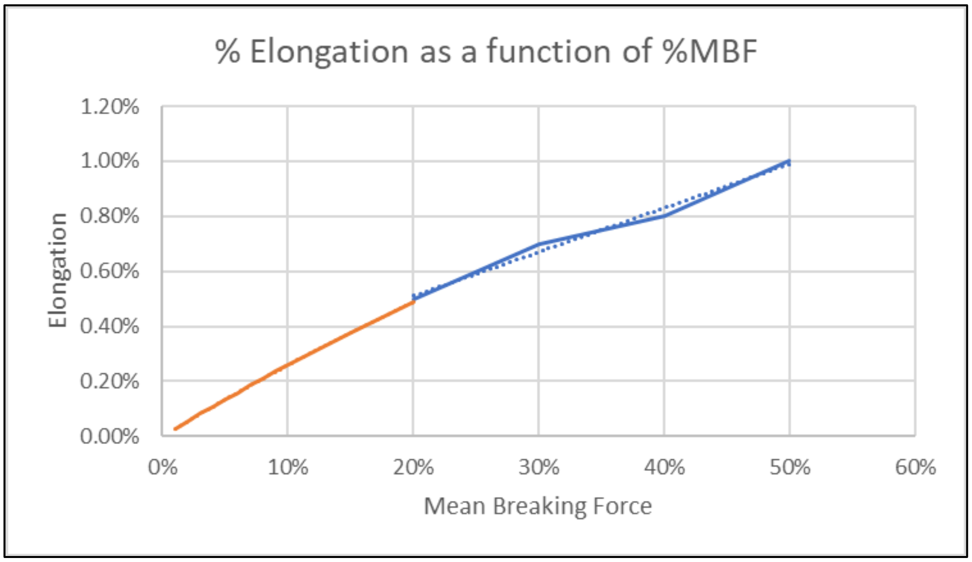


Figure 9: Mooring Line Elongation vs. % Mean Breaking Force. The blue line indicates actual data points from supplier load testing and the orange line are extrapolated results based on a second order polynomial.

At 4% of Mean Breaking Force (MBF) it is expected the mooring line will have 0.11% elongation.

3.4 CHAFE PROTECTION

For best protection against fatigue loading, a circular thimble has been chosen at both connection points instead of the more common teardrop style chafe gear. As these are not common stock items, they will need to be procured as fabricated items. In order to avoid corrosion, they are specified as 316 stainless steel, or composite. An example of a similar sized composite thimble is shown below;

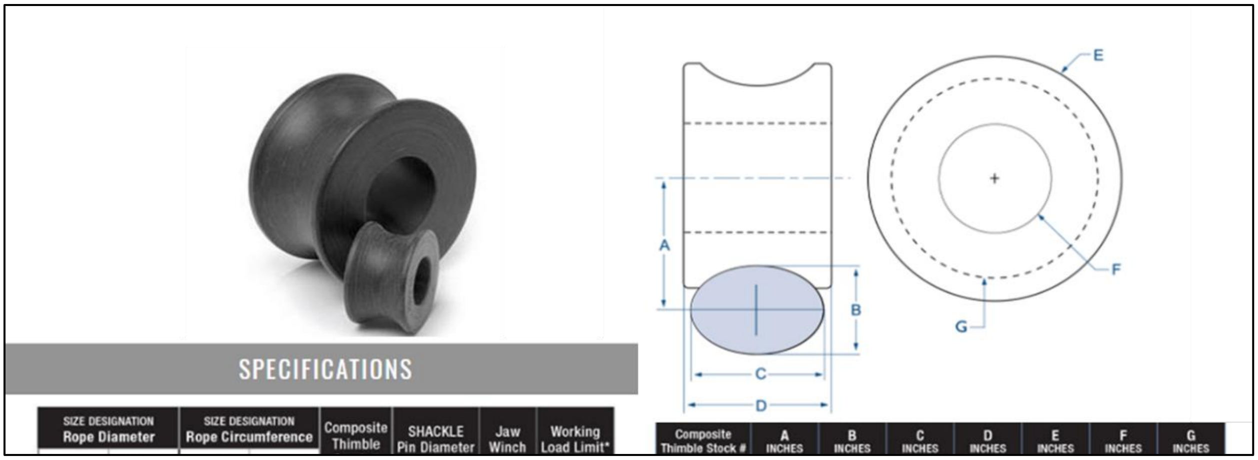


Figure 10: Example of Circular Thimble w/Dimensions

4. CONNECTION HARDWARE

4.1 SUMMARY OF CONNECTION HARDWARE REQUIREMENTS/SPECIFICATIONS

1) **Max Line Load:**
Maximum line tension is based on the maximum torque the PTO can exert onto the mooring tether. If this tension is reached the reactive parts of the PTO will trade force against increased velocity (e.g. motor slips; for more information, see the *PTO bench test report*). Thus, this PTO related maximum force value sets the limit on the maximum design line tension.

2) **Load Angle:**
The angle measured between the mooring line and the sea floor is dependent on the variable submergence depth of the absorber which, again, is based on the wave environment. Based on a probability approach the most energy contributing case leads to the target design mooring angle alpha of 45 Degree.

Note, that the load angle during dynamic oscillation of the device changes depending on the position of the absorber body. However, the dynamic change in the mooring/load angle is in the range of +/- 3 Degree.

3) **Anticipated Load Cycles:**
Based on the deployment site characteristics as well as the device sizing, the oscillating characteristics and the target deployment time of 6-8 month the anticipated load cycles for the mooring were derived.

4) **Width of PTO/Connecting Belt:**
Belt width is determined by the PTO design (See PTO test report).

5) **Width of Anchor Connection:**

The primary design considerations for the connection hardware are to consider the dimensions of the components being connected (anchor padeye or chain and WEC PTO belt), corrosion resistance, fatigue and any possibility for chafing or pinch points.

4.2 ANCHOR TO MOORING LINE CONNECTION

This connection is dependent on the final selection of the anchor and detailed design of connecting chain or padeye. The width of this connection is more aligned with standard products than the PTO connection point and therefore suitable for a standard marine shackle.

Similar to the embedded chain in the concrete block anchor, the bow style shackle would be oversized to accommodate wear. The rounded, or bow, side of the shackle connects to the anchor chain and the flat, pin, side of the shackle attaches to the mooring thimble. Spacers will be used as necessary to ensure a tight fit on both sides of the connection.

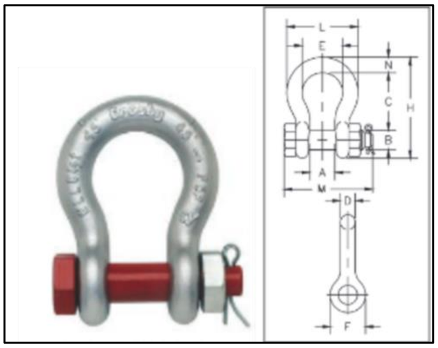
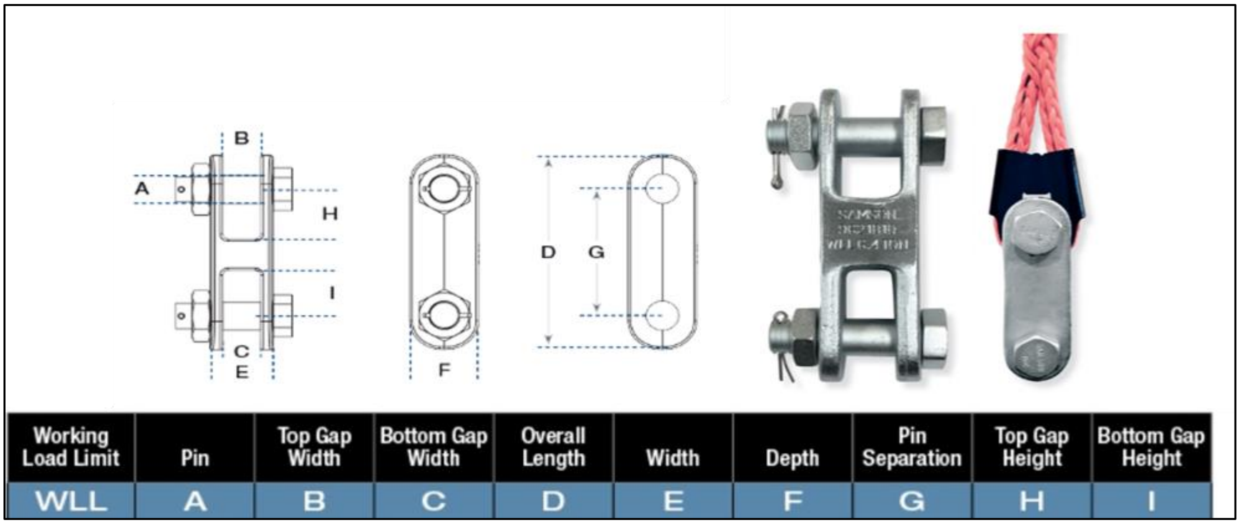


Figure 11: Anchor Shackle Dimensions considered for connecting the anchor to the mooring line.

4.3 MOORING LINE TO PTO BELT CONNECTION

Due to the width of the PTO Belt, it is required to design and fabricate a H-link for this connection. This will allow better resistance from fatigue and reduce risk of belt edges rubbing on connection hardware. Figure 12 shows a representative example of a similarly sized product.



Working Load Limit	Pin	Top Gap Width	Bottom Gap Width	Overall Length	Width	Depth	Pin Separation	Top Gap Height	Bottom Gap Height
WLL	A	B	C	D	E	F	G	H	I

Figure 12: Standard H-link Adaptor

This product basic design concept will be maintained and modified to allow for the difference between the width of the flat belt and mooring line. The below **Error! Reference source not found.** illustrates dimensions and concept modifications for the required fabricated design. The pin for the mooring line side of the H-link adapter can be a standard marine 1" shackle bolt, with nut and cotter pin for added security. During deployment it will be noted not to tack weld the nut in place, which is often a tempting method of ensuring against inadvertent loosening but has negative effects on load characteristics particularly in terms of fatigue loading. For the belt side H-link adapter pin the non-standard length will require a special order.

5. BILL OF MATERIALS

Table 5 shows a list of components required for the anchoring and mooring system. This list is not inclusive of additional required lifting and rigging equipment, which will be further developed in collaboration with the various manufacturers and included in the IO&M Plan.

Table 5: Bill of Materials

Category	Item	Quantity	Lead Time
Anchor	Anchor	4	12 – 20 weeks[1]
Mooring	HMPE mooing line	4	6 weeks[2]
Mooring	Thimble	4	4-6 weeks[1]
Connection	Upper H-link adaptor	4	6-8 weeks[1]
Connection	H-link adaptor bolt w/nut and cotter pin	4	3-5 weeks[1]
Connection	H-link adaptor pin w/nut and cotter pin	4	2-3 weeks[1]
Connection	Lower Shackle w/pins	4	2-3 weeks[1]

[1] estimate

[2] supplier quotes

6. ADDITIONAL INFORMATION

6.1 DEPLOYMENT CONSIDERATION

Not included in this report is a comprehensive list of rigging, lifting, and marine operations associated equipment for use in the deployment and recovery of the anchoring and mooring system. This detail is provided in the IO&M Plan. However, it is important to note that deployment and recovery feasibility was a dominant consideration in anchor design selection. This was largely related to limited economical options for vessels with crane capacities greater than 5 tons and limited crane capacity at the Scripps Institute of Oceanography pier.

For the single solid block anchor, the primary concern for deployment (aside from vessel and transportation costs) involves the ability to lower the anchor in a controlled manner and guarantee a landing location on the seafloor that aligns with the mooring grid geometry requirements. In large part, the complication of landing the anchor is alleviated with the use of the modular anchor design that can be lowered in parts; however, this introduces its own complications and potentially significant dive operations costs.

In budget period 2, once the vessel operators and dive services contractors are on contract and their time can be paid for more detailed operations reviews, the full deployment methodology for both options will be considered and a decision made in collaboration with the individuals who will be directly involved in the deployment and recovery operations.

6.2 SENSORS AND MONITORING

There are no directly connected sensors in the mooring and anchoring system for the scaled WEC deployment. Mooring line tension and angle are desired parameters for monitoring. Options were investigated for direct measurement of these parameters, including both acoustic load cells and directly wiring a load cell communication cable from the mooring line back to the WEC. However, it was determined that due to the PTO action causing the mooring belt to dynamically change length and orientation, the complexity and risk of routing a load cell cable from the mooring line to the WEC was infeasible for this deployment.

Additionally, after investigating options for wireless acoustic load cells, it was not felt that there was enough confidence in economically incorporating at this scale. Instead mooring line tension is derived from PTO parameters (shaft torque, motor current) and the accuracy of this derivation verified on the PTO test bench. This verification occurs by including a load cell on the test bench actuator to directly measure mooring loads and compare with the derived parameters. Mooring line angle is derived from the WEC inertial measurement units (IMUs).

In future larger scale deployments, it will again be investigated if direct measurement of these parameters is feasible.

6.3 COMMENTS FOR SCALABILITY

Many challenges encountered during the anchoring and mooring design process were specific to the scale of the deployment and will should not be as challenging at larger scale; while some logistical challenges will be of greater complexity at larger scale.

Challenges unique to smaller scale:

1. Accessing the interior of the WEC at sea was determined to be infeasible at the targeted scale. This was decided based on the small freeboard when floating and the minimal amount of space inside the WEC. As the WEC grows in scale the PTO components are not anticipated to increase in size in the same proportion as the WEC internal volume, thereby allowing for more room for access.

Challenges to anticipate at larger scale:

1. Costs of anchoring and mooring solutions and complexity of anchor deployments should be expected to increase significantly with scale. Mooring loads increase to the power of 3 (Froude scaling) if the climate scales relative, too. Point gravity-based options are likely to become infeasible in large- or full-scale deployments.

2. Permitting is a significant challenge at any scale; but being considered a temporary research focused deployment is fundamentally different than permitting for a long-term commercial deployment. Pre-permitted sites such as PMEC will be instrumental in pre-commercial deployments, while also understanding the significant resources that will be involved in commercial permitting in the future.

APPENDIX A – LESSONS LEARNED & FUTURE CONSIDERATIONS

Summary of Lessons Learned

1) **Deployment methodology and vessel availability is a dominant consideration in anchor selection**
2) **Anchor types requiring seafloor samples which adds complexity to permitting process**
3) **Difficult to include direct mooring line tension measurement**
4) **Remote mooring line connection/disconnection desired at larger scale**
5) **Gravity anchors well suited for smaller scale, but may be cost prohibitive at full-scale**
6) **Providing safe access to transfer personnel to the WEC at sea will require significant considerations at larger scale (not practical at 1:5 scale)**

During the course of the anchoring and mooring system design development several alternative anchor designs and auxiliary equipment options were considered and ultimatly decided to either not be economically or otherwise feasable, or constitute additional risk that was determined to not be validated within the boundries of the scaled device deployment. In some cases this was due to budgetary or schedule considerations, and in some cases this was due to the specifics of the required permitting process. A few of these considerations are discussed below for completeness and to capture the information for consideration in future deployments.

A.1 HELICAL SAND SCREWS

The sandy seafloor present near the deployment site in San Diego initially led to helical sand screws as a likely anchor solution. However, several complications with this concept led to it being abandoned during the permitting process. The permitting process itself was the defining element in no longer pursuing sand screws in that a separate permit would have been needed to first take vibracore samples of the seafloor to verify the sand layer depth and sand consistency at increasing depths in the sand layer. Once a sample had been obtained, the calculations to support detailed design of the sand screw anchor and installation process could have been determined and a new permit applied for to allow the sand screw installation. This was needed because the clay content in the sand below the seafloor has significant impact on the required dimensions of the sand screw anchors and the deployment torque and depth. It is also important to verify the sand layer depth to prevent contact with the bedrock below the sand layer during deployment.

As CalWave progresses to larger scale deployments, requiring increasing anchor load capacity, sand screws and rock bolt anchors will likely become more economical than gravity -ased anchors.

The below helical sand screw concept design is based on documentation of sand layer samples previously taken near the test site.

Helical sand screws are commonly used on sandy seafloors with benthic properties similar to those found at the demonstration test site. Advantages of using sand screws is the ability to ensure an accurate placement and reduced vessel capacity requirements compared to gravity anchor options. However, the disadvantage is the costs associated with dive pre-surveys including environmental considerations with vibracore samples and operational practicalities of installation at the proposed depth and torque requirements.

The sand screws may be installed with a single long screw at each anchor point.This depth and holding capacity per sand screw can potentially be reduced by installing multiple sand screws and connecting in a chain bridle, or similar.

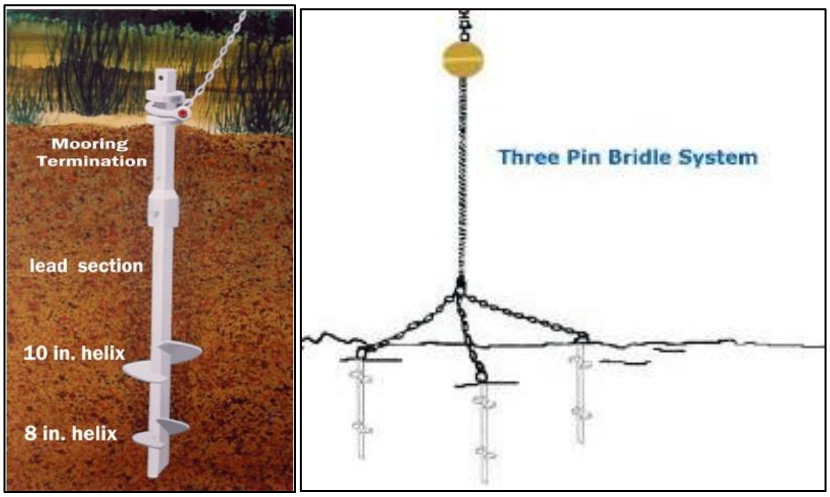


Figure 13 Helical Sand Screw (left – single, right – three pin bridle)

The installation would be performed using a torque motor powered from a hydraulic power unit (HPU). In the case of multiple, smaller, sand screws a diver operated submersible torque motor can be used, with an appropriately sized torque arm reacting against the seafloor. In the case of a single, larger, sand screw the required installation torque is likely too large for safe use with a torque arm and a frame would be manufactured to react against the seafloor at multiple points.

A picture and specifications are provided below for an example torque motor sufficiently sized for installing large capacity sand screws.

Figure 14: Torque Motor

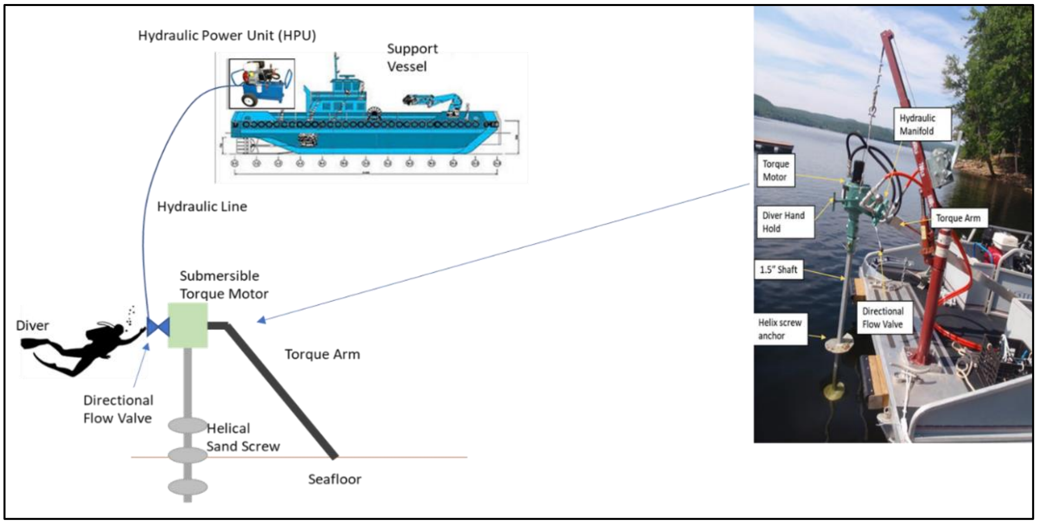


Figure 15: Sand Screw Installation

A.2 EMBEDMENT ANCHORS

Similar to the helical sand screw option, embedment anchors were initially considered, and likely will be more economically feasible options than gravity-based anchor for larger scale deployments. However, also similar to the helical sand screw option, the need for vibracore samples and associated permits to complete an informed detailed analysis and design of this solution made this an infeasible option for the current 1:5 scale WEC deployment. An example of two embedment anchors is provided below. This figure and the following figure related to deployment methodology are taken from a document prepared for Oregon Wave Energy Trust; *Embedment Anchors for Reduced Scope Mooring Test and Validation Plan* (contract #: OWET/BSCE#1, document #: 1303-10-101).

Figure 16: Embedment Anchors

Embedment anchors use the weight of the sand layer on the seafloor to minimize the required anchor mass. This is accomplished by embedding the anchor at a specified depth within the sand layer, as pictured below;

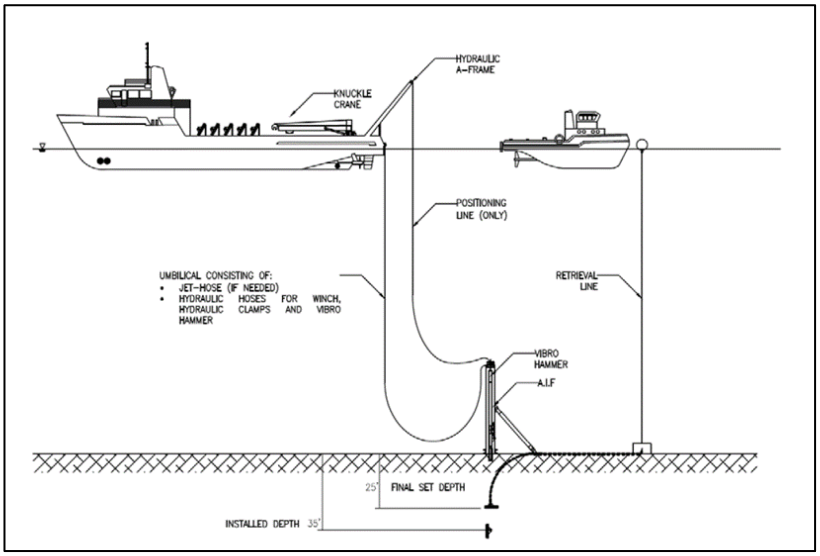


Figure 17: Embedment Anchor Installation

Initial rough calculations for a simple style embedment anchor are approximately one-third the mass needed for a gravity style anchor. However, the calculations are highly dependent on the angle of internal friction, which is very dependent on sand layer composition.

Table 6: Embedment Anchor Initial Calculations

Embedment Anchor Calculations		
Plate thickness		in
Non-embedded surface dimensions		ft^2
length		in
width		in
Plate dimensions		ft^2
length		in
width		in
Anchor weight		lbs
Projected plate area (Ah)		ft^2
Plate depth		ft
Unit weight of soil		lbs/ft^3
Angle of internal friction		
Nq (from table)		
Plate effective unit weight		lb/ft^2
Plate effective weight		lb

Qu		kN

A.3 BAG ANCHORS

Use of anchor bags aggregated into a net and connected to a mooring line was considered as option for gravity-based anchoring. Tension Technologies International (TTI) has performed testing and validation for design and deployment of such a solution for renewable energy projects (additional documentation available). In multiple discussions with TTI it was agreed that the existing nets and all test data could be supplied to CalWave free of charge in exchange for an engineering support contract to facilitate any design modifications and CalWave agreeing to provide TTI with test data to support further development of the anchor bag solution for renewable energy.

This solution had initial promise and solutions were discussed with dive services contractors about using a suction pump to fill the bags in-situ with seafloor sand and thus avoid costs related to transportation. Quotes were obtained for the bags which proved to be economically reasonable. However, the existing nets available had been designed for a 56 ton anchor and thus modification of the anchor size would require additional modelling to determine dynamic response of the net.

It was then discussed with permitting agencies and the deployment site owner and found that disrupting the required seafloor sand would cause unacceptable threat to sea life habituating in the sand layer and an alternative for aggregate used to fill the bags was required. Next ¾" crushed rock was considered but disregarded due to the possibility of the rock puncturing the polypropylene bags.

This solution was not considered for further investigation due in part to the above reasons, but also in large part because it was determined to be difficult to impossible to quantitatively validate the risk of geometric compliance of the net leading to an uncertain or inconsistent location of the anchor to mooring line connection as well as a dampening effect on power production (similar to mooring line elongation considerations). However, this could be an economical option for future deployments where schedule and budget is allocated for dynamic modelling of the solution.

Figure 18: Anchor Bag Testing

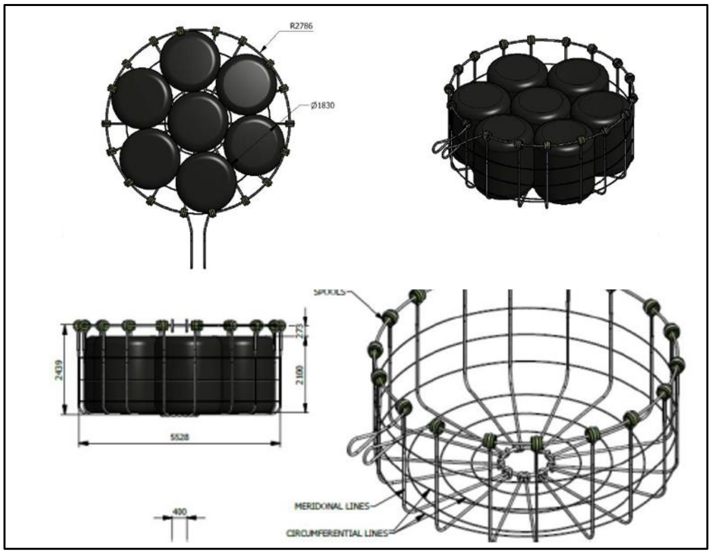


Figure 19: Anchor Bag Dimensions

A.4 REMOTE DISCONNECTION OPTION

An option for enabling remote connection and disconnection between the mooring line and mooring belt was considered. The primary driver for this consideration was that the requirement for the WEC to further submerge during storm events resulted in the belt needing to be long enough that the belt to mooring line interface could not reasonably occur at the surface. This is largely an artifact of the relatively shallow deployment depth at the test site and the scaling of extreme sea states.

Therefore, the remote connection option had significant potential advantages by removing the need for divers to make this connection. However, it was decided that the additional risk and complexity of introducing new equipment into this deployment was not sufficiently justified by a cost comparison of the remote connector versus cost of shallow water diving for manual connection.

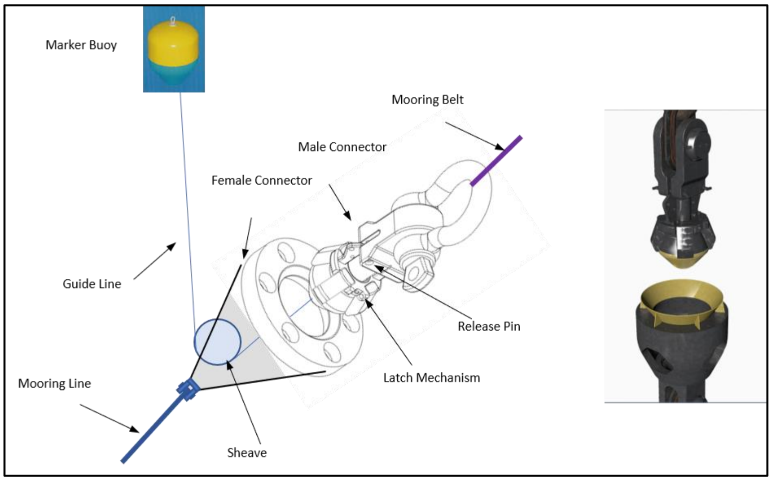
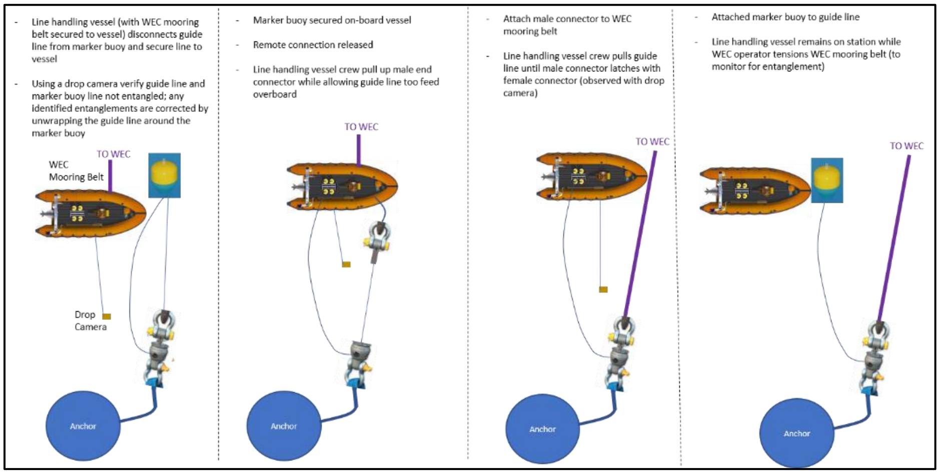


Figure 20: Remote Mid-Line Disconnection

During initial anchor installation, remote connector female end would be attached to anchor mooring line, and mated male end attached to the corresponding marker buoy. The guide line would also be connected to the same marker buoy, with additional length of guide line stoppered off to allow for recovery and deployment operations.

A provisional connection sequence is illustrated below. Should this become the prevailing connection option, the methodology and sequence will be updated in further detail.



- Line handling vessel (with WEC mooring belt secured to vessel) disconnects guide line from marker buoy and secure line to vessel
- Using a drop camera verify guide line and marker buoy line not entangled; any identified entanglements are corrected by unwrapping the guide line around the marker buoy

- Marker buoy secured on-board vessel
- Remote connection released
- Line handling vessel crew pull up male end connector while allowing guide line too feed overboard

- Attach male connector to WEC mooring belt
- Line handling vessel crew pulls guide line until male connector latches with female connector (observed with drop camera)

- Attached marker buoy to guide line
- Line handling vessel remains on station while WEC operator tensions WEC mooring belt (to monitor for entanglement)

Figure 21: Remote Mid-Line Connection Sequence