# Performance Modeling of a Variable-Geometry Oscillating Surge Wave Energy Converter on a Raised Foundation

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# PERFORMANCE MODELING OF A VARIABLE-GEOMETRY OSCILLATING SURGE WAVE ENERGY CONVERTER ON A RAISED FOUNDATION

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## ABSTRACT

*This paper analyzes the power capture potential, structural loadings, and costs associated with an oscillating surge wave energy converter (OSWEC) operating on a raised foundation. The raised OSWEC offers opportunities for reduced installation costs, improved energy production, and greater flexibility of deployment when compared with fixed-bottom models. In this investigation, we simulated several different foundation geometries using WEC-Sim to estimate power capture and structural loads. In an effort to maximize power capture, several cases in which flat plates of varying size were attached to the top of the foundation, under and parallel with the OSWEC, were also simulated. These plates were found to enhance power capture by preventing the wave-induced pressure from passing underneath the OSWEC, diverting this pressure toward the OSWEC instead. The OSWEC was simulated in the six Wave Energy Prize sea states, which were chosen as a representative sample of U.S. deployment sites. A first-order estimate of structural costs was calculated using the Wave Energy Prize ACE metric, with the foundation comprised predominantly of steel-reinforced concrete and the OSWEC comprised of A36 steel. Influence of foundation geometry on power capture, structural loadings, and ACE are topics of particular interest. This work has been inspired by advances in large-scale additive manufacturing techniques that have the potential to dramatically reduce the cost of subsea foundations. These advancements may enable cost-effective WEC systems to be deployed on raised foundations.*

## INTRODUCTION

While the wave energy field has been the subject of simulation, scale model testing, and precommercial project testing for some time now, it remains one of the youngest and a promising field in modern renewable energy technology. The global wave energy resource is estimated to be around 30,660 TWh/yr [1], making it a vast energy resource that remains largely untapped. Many methods have been tested in the hopes of generating utility-scale energy from ocean waves, but most wave energy converters (WECs) have proven largely ineffective at the task, given their high cost of energy. This work attempts to reduce the cost of energy for an oscillating surge wave energy converter (OSWEC) by placing the device on a raised foundation.

This study is a continuation of the research performed by the National Renewable Energy Laboratory (NREL) on OSWECs with variable geometry [2]. These variable-geometry OSWECS have rotating flaps on the face of the OSWEC that can be opened and closed to tune the hydrodynamics of the device depending on the current sea state. This hydrodynamic tuning maximizes power capture in a wider range of sea states than for fixed geometry models. Additionally, opening flaps allows for load shedding in extreme sea states, reducing structural costs and increasing the lifespan of mechanical components because of reduced fatigue damage. Other notable OSWECs include Aquamarine's Oyster [3], AW Energy's WaveRoller [4], Resolute Marine En-

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ergy's surge WEC [5], and Langlee's OSWEC [6]. This work is also supporting a U.S. Department of Energy Technology Commercialization Fund award provided to NREL and the University of Massachusetts Amherst to pursue a model-scale experimental wave tank test of the system proposed in this work [7]. The analysis presented in this paper will be used to guide the model design and identify the most promising system design features to investigate in the future.

Placing an OSWEC on a raised foundation enables deployment in water depths greater than those possible for bottom-fixed models. Wave pressure decreases exponentially with depth, so bottom-fixed models must either increase structural costs to reach the water surface, or allow a significant amount of wave energy to pass overhead. Moving the OSWEC to deeper water provides many potential benefits; among them are reduced issues regarding sediment transport and environmental impacts nearshore [8], easier and cheaper deployment and installation as work boats will not have to risk grounding in shallow water, and improved wave energy resource in deeper water [1]. Advances in offshore wind turbine foundations may be useful in wave energy applications, and recent advances in large-scale additive manufacturing techniques [9] have the potential to substantially reduce the cost of subsea foundations. Furthermore, it may be possible to design the foundation geometry to improve power capture by focusing the incident wave pressure.

This paper investigates the effect of altering foundation geometry near the WEC in an effort to cost-effectively improve power capture. By placing large plates underneath and parallel with the OSWEC, wave-induced pressure may be pushed up onto the device, rather than passing underneath. The increased power capture may be sufficient to offset increased structural costs caused by increased wave-induced loads on the foundation. This paper begins with a model description, which outlines the tools used and why they were chosen. A section on performance metrics follows, which discusses how the results were interpreted and compared. The results section describes how performance and the performance-to-cost ratio is affected by foundation geometry. A first-order stuctural analysis of the foundation is also presented. The conclusions section summarizes the findings of the study, and lists areas for future investigation.

## MODEL DESCRIPTION

### Device Geometry

The wave energy converter in this project can be simplified by modeling it as a flat plate, hinged at its base, and rotating in the pitch angular direction, as shown in Figure 1. In order to prevent the plate from making contact with the foundation while rotating, the bottom face has been rounded. Dimensions for the plate are shown in Figure 2. The structural mass density, $\rho_m$, is defined as half of the fluid density, $\rho_w$, and the structural mass is assumed to be evenly distributed. The pitch moment of inertia, $I_{55}$, was obtained from SolidWorks [10] CAD models.

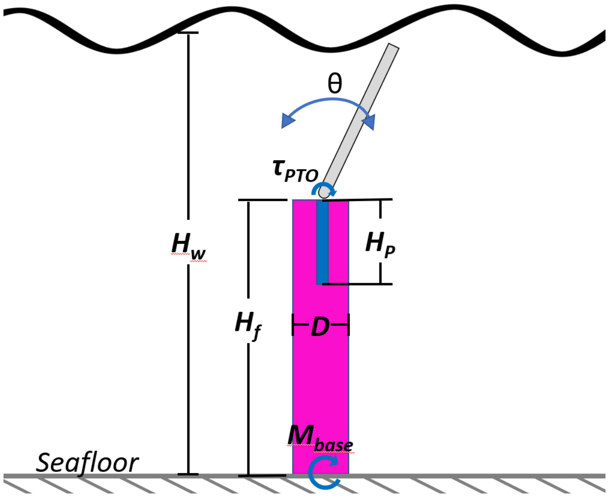

**FIGURE 1**. THE ORIENTATION OF THE OSWEC. THE OSWEC IS DEPICTED IN LIGHT GREY, THE FOUNDATION IN MAGENTA, AND THE "PRESSURE PLATES" IN BLUE. FOR THIS STUDY, $H_W = 35$ METERS AND $H_F = 25$ METERS.

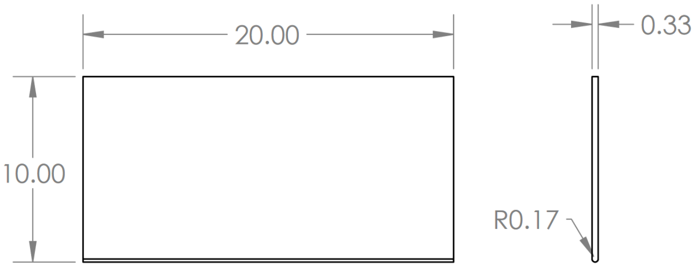

**FIGURE 2**. DIMENSIONS OF THE OSWEC IN METERS.

Monopile geometries were selected to represent the foundations used to raise the OSWEC off the seabed. Dimensions and properties for the monopile foundations were inspired by those used in offshore wind turbine applications [11]. These monopiles are hollow cylinders made of either reinforced concrete or steel. Wall thickness for concrete monopiles is 10 cm, and wall thickness for steel monopiles is calculated using the following equation:

$$t = 0.635 + \frac{D}{100}[cm] \tag{1}$$

where $t$ is the wall thickness in cm, and $D$ is the outer diameter of the foundation, in cm [12]. The monopile foundation diameters of 2, 3, 4, 5, 6, and 8 m were analyzed in a water depth of 35 m. A36 steel and high-strength reinforced concrete were chosen as foundation materials, with their structural properties obtained from MatWeb [13].

In an effort to push wave-induced pressure onto the OSWEC, several foundation designs were simulated in which "pressure plates" were attached to the top of the foundation, underneath and parallel with the OSWEC. These plates run the entire width of the OSWEC with submergence depths ($H_P$) of 1, 3, 5, 10, and 25 m below the OSWEC. For simplicity, the pressure plates are assumed to be 0.33 m thick, sharing this dimension with the OSWEC. They are assumed to be constructed of the same material used to construct the foundation. Figure 3 provides an example SolidWorks CAD rendering of the OSWEC, monopile foundation, and pressure plates.

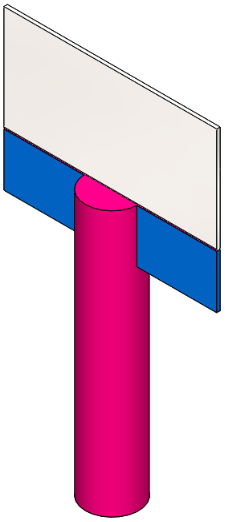

**FIGURE 3**. THE OSWEC (LIGHT GREY) SITTING ON A MONOPILE FOUNDATION (MAGENTA) WITH PRESSURE PLATES ATTACHED (BLUE).

### Hydrodynamic Modeling and Simulation

The OSWEC and all foundations were built in SolidWorks, providing the mass, volume, mass moments of inertia, and centroidal moments of inertia. These 3-dimensional models were then meshed in Rhinoceros [14], a separate modeling software, for use in a hydrodynamic modeling tool. In order to gain insight into how the foundation geometry affects the OSWEC hydrodynamics, three-dimensional hydrodynamic modeling was completed for all foundations and pressure plate sizes and linear hydrodynamic coefficients were obtained from WAMIT version 7.3 at a frequency step of size 0.02 rad/s for wave frequencies between 0 and 10 rad/s, as well as at infinite frequency [15].

Each system configuration was simulated using WEC-Sim [16], an open-source tool developed by NREL and Sandia National Laboratories. Using hydrodynamic coefficients obtained from WAMIT, WEC-Sim is able to simulate the response of a variety of wave energy converters in various sea states. WEC-Sim was used to measure the OSWEC power production, power-take-off torque, and foundation forces.

For this study, the six sea states described by the Wave Energy Prize [17] were chosen as a representative sample of wave conditions in the United States. Each of the six sea states are represented by a Bretschneider spectrum characterized by a significant wave height, peak wave period, power flux, and wave heading, as shown in Table 1. The Wave Energy Prize documentation also includes scaling factors for each sea state, which provides an encounter probability of each sea state at several locations in U.S. waters.

**TABLE 1**. WAVE ENERGY PRIZE SEA STATES SIGNIFICANT WAVE HEIGHT, $H_S$, PEAK PERIOD, $T_P$, WAVE POWER FLUX, $C_P$, AND HEADING.

| Sea State | $H_S$ [m] | $T_P$ [s] | $C_P$ [kW/m] | Heading [deg] |
|---|---|---|---|---|
| 1 | 2.34 | 7.31 | 16.7 | 10 |
| 2 | 2.64 | 9.86 | 29.0 | 0 |
| 3 | 5.36 | 11.52 | 141.1 | -70 |
| 4 | 2.05 | 12.71 | 23.1 | -10 |
| 5 | 5.84 | 15.23 | 233.5 | 0 |
| 6 | 3.25 | 16.50 | 79.8 | 0 |

### Structural Analysis

A first-order structural analysis was performed to provide insight into suitable monopile diameters and materials. While smaller foundations may be desirable for their lower construction cost, all foundations must be able to sustain loading without yielding. Using bending moment data, collected at the bottom of the foundation in WEC-Sim, the following equation was used to calculate maximum stress in the structural material:

$$\sigma = -\frac{M_{base} * y}{I_c} \tag{2}$$

where $\sigma$ is the stress in the material, $M_{base}$ is the bending moment at the base of the foundation, $y$ is the distance from the centroid to the point where stress is being calculated, and $I_c$ is the centroidal moment of inertia of the foundation cross section. $M_{base}$

was obtained by recording the 98th percentile moment value at the fixed constraint on the foundation at the seafloor for each WEC-Sim run for a given configuration. The maximum recorded value was then used as $M_{base}$ for that configuration. The centroid represents the point about which the area of a shape is evenly distributed [18]. In the case of the annular monopile foundation cross sections, the centroid is always the point about which the inner and outer diameters are concentric. Maximum compressive stress occurs at the rear of the base of the foundation, opposite the wave-facing side, as shown in Figure 4. Maximum compressive stress is considered, as the yield stress for A36 steel is lower in compression than it is in tension, and concrete is assumed to be reinforced well enough that it will not fail in tension. Compressive yield strengths for A36 steel and concrete are provided in Table 2. In this report, a safety factor of 1.75 is considered and is calculated using the following equation:

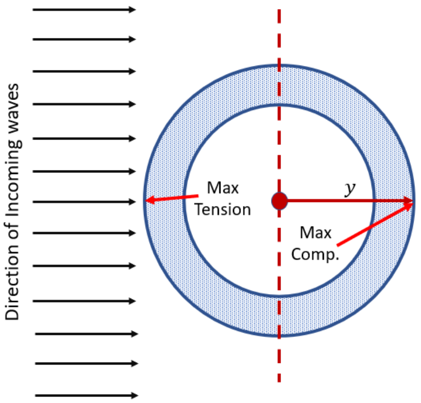

**FIGURE 4**. SIMPLIFIED VIEW OF A CROSS SECTION OF THE MONOPILE FOUNDATION, TAKEN AT ITS BASE.

$$SF = \frac{\sigma}{\sigma_{yield}} \tag{3}$$

where $SF$ is the safety factor, $\sigma$ is the calculated stress in the material, and $\sigma_{yield}$ is the appropriate yield stress of the material (tensile or compressive).

Note that this analysis assumes that the bending moment at the base of the foundation provided by WEC-Sim is a sufficient summation of the loads on the foundation. Additionally, no fatigue analysis is performed, which may be necessary given the cyclic loads experienced by undersea foundations. As a result, safety factors presented here may be higher than they would be in practice.

## PERFORMANCE METRICS

Device performance was quantified using the Average Climate Capture Width per Characteristic Capital Expenditure (ACE) metric used for the Wave Energy Prize [19]. Average climate capture width (ACCW) is equal to the power captured by the WEC divided by the incident wave energy flux per meter crest width, as in the equations below:

$$ACCW_j = \frac{\sum_{i=1}^{n} \Xi_{ij} \langle AP(i) \rangle}{\langle C_P(j) \rangle} \tag{4}$$

$$\overline{ACCW} = \sum_{j=1}^{7} \frac{ACCW_j}{7} \tag{5}$$

where $ACCW_j$ is the average climate capture width at site $j$, $n$ is the number of sea states, $\Xi_{ij}$ is the scaling factor for sea state $i$ at each location $j$, $\langle AP(i) \rangle$ is the average mechanical power absorbed by the WEC for each sea state, $i$, and $\langle C_P(j) \rangle$ is the incident average annual wave energy flux for site $j$.

Characteristic capital expenditure (CCE) is an estimate of the material cost of a WEC based on the mass of the load-bearing structure. The Wave Energy Prize provides low, medium, and high manufactured material costs (MMC) for six different materials. This study uses the medium MMC with the MMC and density values for steel and reinfored concrete provided in Table 2. CCE is defined by the following equation:

$$CCE = \sum_{k=1}^{N} m_k \cdot MMC_k \tag{6}$$

where $k$ is the material index, $N$ denotes the number of key structural materials, $m_k$ is the total mass of material $k$, and $MMC_k$ is the manufactured material cost per unit mass of material $k$. Mass information from SolidWorks was used as input to calculate CCE.

**TABLE 2**. MANUFACTURED MATERIAL COSTS FOR CONCRETE AND STEEL.

| Material | Density $[\frac{kg}{m^3}]$ | $\sigma_{yield}(comp.)[MPa]$ | MMC $[\frac{\$}{kg}]$ |
|---|---|---|---|
| A36 Steel | 7850 | 152 | 3 |
| Concrete | 2300 | 70 | 0.51 |

ACE can then be obtained by dividing $\overline{ACCW}$ by CCE:

$$ACE = \frac{\overline{ACCW}}{CCE} \tag{7}$$

This metric provides an initial estimate of the device performance relative to the cost of construction of the load-bearing structure. The higher the ACE, the more cost-effective the WEC is likely to be.

## RESULTS AND DISCUSSION

The results of this study are presented to illustrate 1) the effect of varying pressure plate size and 2) the effect of varying foundation diameter on power capture and structural requirements of the foundation. For clarity and brevity, while discussing varying plate size, a constant foundation diameter of 5 m is assumed, unless otherwise specified. Likewise, while discussing varying foundation diameter, we assumed that no pressure plates are present.

### ACCW and ACE

ACCW values depend only on foundation and OSWEC geometry, as no cost analysis is performed when calculating ACCW. Therefore, these values are presented first to demonstrate how the OSWEC's performance changes as a result of foundation geometry. As shown in Figure 5, for a foundation diameter of 5 m, ACCW increases steadily as pressure plates stretch deeper into the water column. This is believed to be caused by an increase in the amount of wave-induced pressure that is pushed up onto the WEC, rather than passing underneath. This theory is supported by Figure 6, which shows that ACCW increases as foundation diameter increases. The larger frontal surface area from increasing diameter monopile foundations may mimic the effect of adding pressure plates.

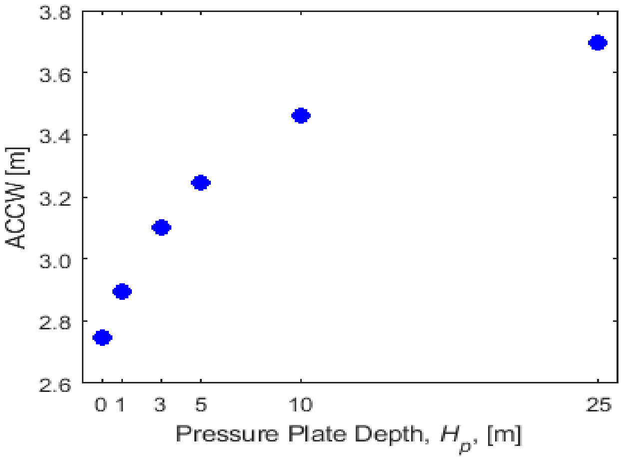

**FIGURE 5**. AVERAGE CLIMATE CAPTURE WIDTH (ACCW) VALUES WITH A FOUNDATION DIAMETER OF 5 METERS.

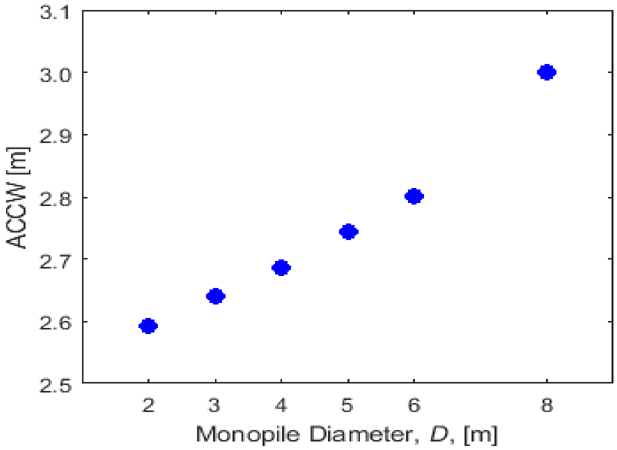

**FIGURE 6**. AVERAGE CLIMATE CAPTURE WIDTH (ACCW) VALUES WITH NO PRESSURE PLATES ATTACHED.

Though ACCW increases with pressure plate size, adding pressure plates may not always be advisable, given the added material cost associated with their installation. Given that there are no industry standards for installing these plates, some assumptions are made about their construction. Though the plates are modeled as having a thickness of 33 cm, they are assumed to be 3 cm thick for mass calculations. Assuming that the plates are thinner than they are modeled to be takes into account the fact that these plates will likely not need to be solid. For example, steel plates could be constructed by bolting pieces of sheet metal together, which would drastically reduce the amount of material used.

ACE values for steel foundations, shown in Figures 7 and 8, will be discussed first. Given steel's high manufactured material cost, adding extra steel to a structure has the potential to greatly reduce ACE. This is shown most profoundly in Figure 8, where ACE falls steadily as foundation diameter grows. Though ACCW rises with foundation diameter, the cost of the added steel is enough to significantly reduce ACE. Note that these results do not take structural requirements into account. For example, while the 2-m-diameter and 3-m-diameter foundations have a high ACE, foundations of this size would not have survived the wave conditions that were simulated.

Figure 7 shows that adding steel can be beneficial in certain cases. For a foundation diameter of 5 m, ACE rises to a peak with pressure plate size before falling. When 10-m pressure plates are attached, ACE is improved by 35% over the case with no plates. ACE only falls again when 25-m plates are attached, because of the significant extra mass of steel offsetting any performance gains. Figure 9 shows the relative contributions of the OSWEC, pressure plates, and foundation to overall CCE. The combined CCE of the OSWEC and pressure plates is small compared to the CCE of the foundation.

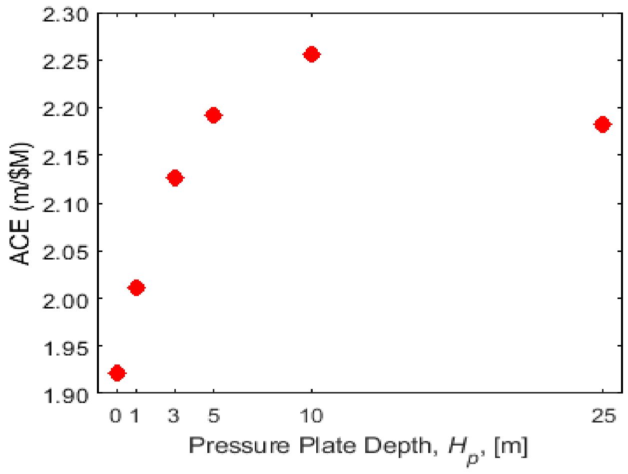

**FIGURE 7**. ACE VALUES WITH A STEEL FOUNDATION DIAMETER OF 5 M AND A PLATE THICKNESS OF 3 CM.

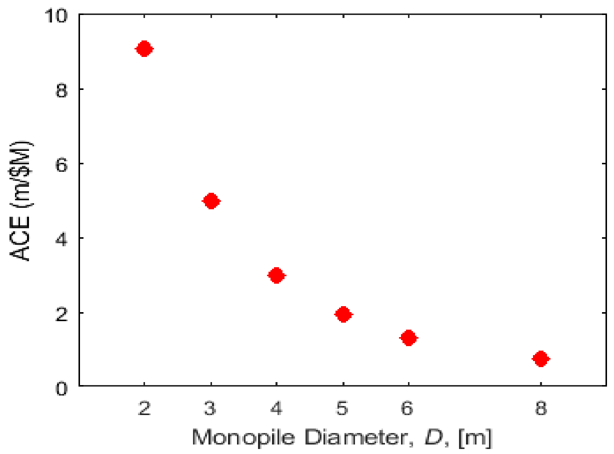

**FIGURE 8**. ACE VALUES FOR STEEL FOUNDATIONS WITH NO PRESSURE PLATES ATTACHED.

ACE values for concrete foundations are presented in Figures 10 and 11. These ACE values are larger than their counterparts for steel foundations, but they follow the same trends. Concrete pressure plates are assumed to be 10 cm thick, which is the same as the walls of the monopile foundation, to account for differing construction methods as it is likely that more concrete than steel would need to be used. Plate thickness is an important metric that will need to be refined through further testing and analysis. With no pressure plates attached, ACE falls as foundation diameter grows. When plate size is varied, ACE peaks at the 10-m plate size, and drops again for the 25-m plate size. Note that ACE values are significantly higher for concrete foundations than they are for steel foundations. Though this gap will shrink when safety factors are discussed, concrete foundations generally performed better than steel foundations in this study.

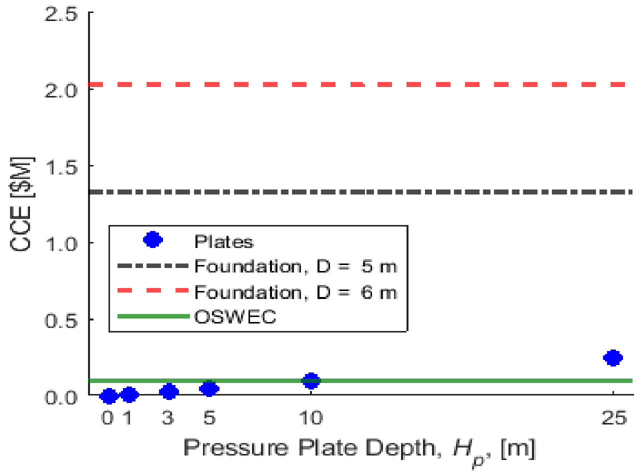

**FIGURE 9**. COMPARING CONTRIBUTIONS TO CCE FOR STEEL FOUNDATIONS AND PLATES WITH A PLATE THICKNESS OF 3 CM.

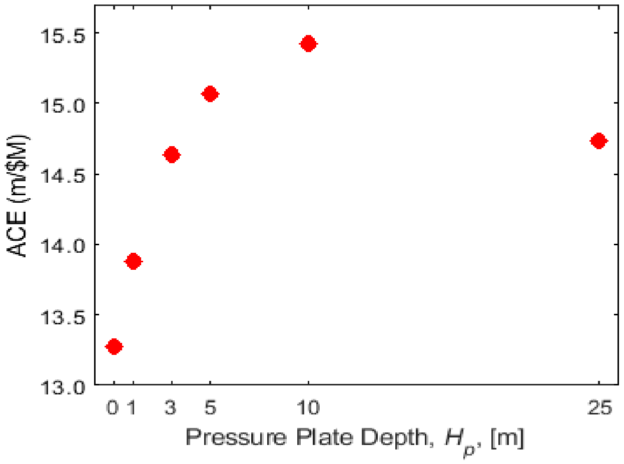

**FIGURE 10**. ACE VALUES WITH A CONCRETE FOUNDATION DIAMETER OF 5 M AND A PLATE THICKNESS OF 10 CM.

Figure 12 shows the relative contributions to CCE by the

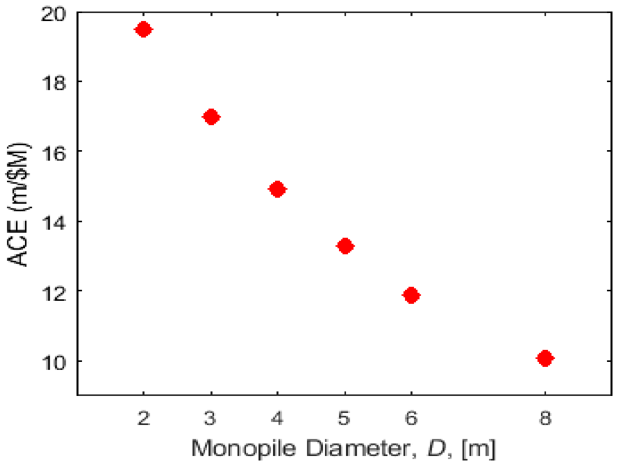

**FIGURE 11**. ACE VALUES FOR CONCRETE FOUNDATIONS WITH NO PRESSURE PLATES ATTACHED.

OSWEC, pressure plates, and foundation. The concrete foundation accounts for the majority of the total CCE. The steel OSWEC comes next, contributing half as much to CCE as the foundation. Up to the plate sizes that produce the maximum ACE values, the added CCE from the 10-cm-thick pressure plates is smaller than the added CCE from the foundation and OSWEC. For the largest plate size, added CCE from the plates is approximately half of the CCE from the OSWEC.

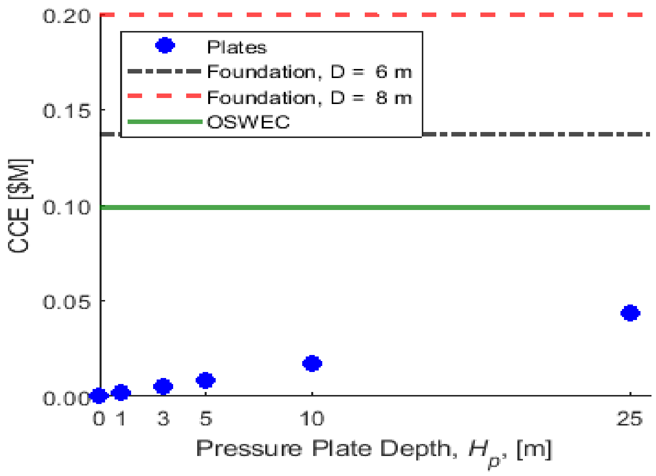

**FIGURE 12**. COMPARING CONTRIBUTIONS TO CCE FOR CONCRETE FOUNDATIONS AND PLATES WITH A PLATE THICKNESS OF 10 CM.

### Safety Factor

The monopile foundation structural safety factor shrinks as pressure plate size increases, and grows as foundation diameter increases, as shown in Figures 13 and 14. Attaching pressure plates may cause a "parachute effect," as the plates provide more surface area for wave-induced pressure to induce a bending moment in the foundation. Safety factors are generally higher for steel foundations, given steel's higher compressive yield strength.

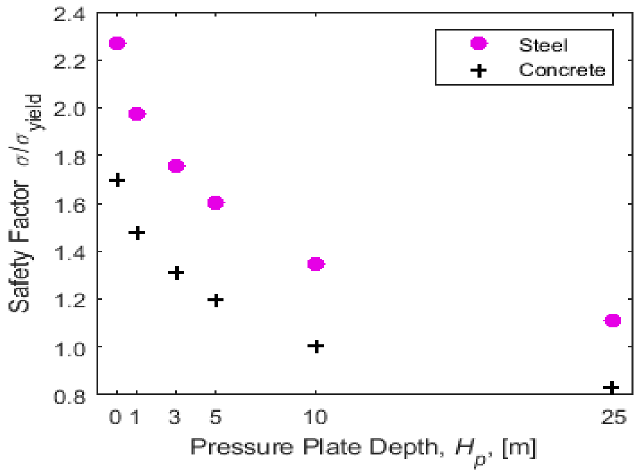

**FIGURE 13**. SAFETY FACTORS FOR VARIOUS PRESSURE PLATE SIZES ON A 5-M-DIAMETER FOUNDATION.

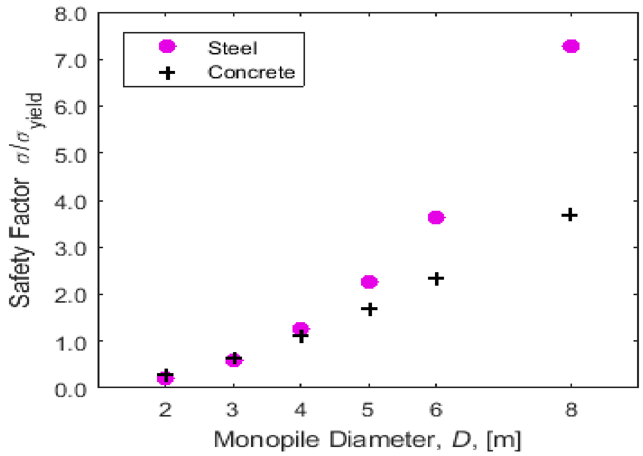

**FIGURE 14**. SAFETY FACTORS FOR VARIOUS FOUNDATION DIAMETERS WITH NO PRESSURE PLATES ATTACHED.

Tables 3 and 4 show the maximum ACE value achieved by the various pressure plate sizes for which the safety factor is greater than 1.75. In other words, these are the configurations that performed the best while still meeting structural requirements. A safety factor of 1.75 meets the medium safety factor described by the Wave Energy Prize [17]. It should be noted that increasing pressure plate size sometimes requires moving to a larger foundation diameter, resulting in a decreased ACE. Because of this, improving ACCW does not always improve ACE when structural requirements are considered.

**TABLE 3**. MAX STEEL ACE WITH $SF > 1.75$ FOR ALL PLATE SIZES

| $H_P$ [m] | $D$ [m] | $SF$ | $ACCW$ [m] | $ACE$ [m/\$M] |
|---|---|---|---|---|
| No Plates | 5 | 2.27 | 2.75 | 1.92 |
| 1 | 5 | 1.97 | 2.89 | 2.01 |
| 3 | 5 | 1.76 | 3.10 | 2.13 |
| 5 | 6 | 2.76 | 3.30 | 1.51 |
| 10 | 6 | 2.23 | 3.49 | 1.57 |
| 25 | 6 | 1.87 | 3.70 | 1.56 |

**TABLE 4**. MAX CONCRETE ACE WITH $SF > 1.75$ FOR ALL PLATE SIZES (10 CM THICK)

| $H_P$ [m] | $D$ [m] | $SF$ | $ACCW$ [m] | $ACE$ [m/\$M] |
|---|---|---|---|---|
| No plates | 6 | 2.35 | 2.80 | 11.9 |
| 1 | 6 | 2.06 | 2.96 | 12.5 |
| 3 | 6 | 1.84 | 3.16 | 13.2 |
| 5 | 6 | 1.79 | 3.30 | 13.5 |
| 10 | 8 | 2.51 | 3.57 | 11.4 |
| 25 | 8 | 2.17 | 3.73 | 11.2 |

Figures 9 and 12 show that increasing foundation diameter can dramatically increase CCE. For this reason, it is desirable to reduce loading of the foundation such that the smallest possible foundation diameter may be used. Based on previous research into variable-geometry OSWECs [2], it is reasonable to assume that variable-geometry components may be implemented for this purpose. To approximate the effect of a variable-geometry OSWEC with a load-shedding geometry, a modified OSWEC was modeled with a hole in the middle to relieve some amount of the wave-induced pressure, as shown in Figure 15.

Figure 16 shows how the surge wave-exciting force on the foundation changes when the modified OSWEC is used in place of the standard OSWEC. The surge wave-exciting force on the foundation is lower at all frequencies when the modified OSWEC is used, with a reduction of 8% at the peak. This demonstrates that a variable-geometry OSWEC with open geometry may result in lower forces on the foundation. The phase of the surge wave-exciting force begins to deviate around 0.6 rad/s with the peak surge wave-excitation force for the standard OSWEC occurring later during the wave cycle compared to the modified OSWEC. The influence of the OSWEC on the foundation can be thought of as a horizontal point force at the hinge connection. This horizontal force has a component from the surge-wave excitation force as well as reaction forces because of the OSWEC motion. As discussed in [2] the phase difference between the OSWEC motion and the surge wave-excitation force can result in a near zero horizontal force drastically reducing the moment at the base of the foundation. Although this interaction is not fully explored in this work, this will be important to consider in later design studies.

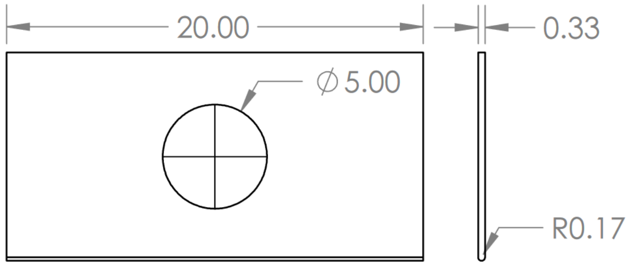

**FIGURE 15**. DIMENSIONS OF THE MODIFIED OSWEC IN METERS.

Tables 3 and 4 describe necessary foundation diameters for an OSWEC without variable geometry. To determine whether a variable-geometry OSWEC may reduce cost, the modified OSWEC was simulated on the next foundation size down. This will provide insight into whether a variable-geometry OSWEC can improve survivabilty in extreme sea states, thus reducing structural requirements for the foundation and ultimately boosting ACE.

Figure 17 shows how safety factor improved when the modified OSWEC was used in place of the standard OSWEC on steel foundations. For the case with no plates and plate sizes of 1 m and 3 m, the foundation diameter is 4 m. For plate sizes of 5 m, 10 m, and 25 m, the foundation diameter is 5 m. For all sizes of pressure plates, safety factor improved by roughly 30% when the modified OSWEC was used. For pressure plate sizes of 5 m and

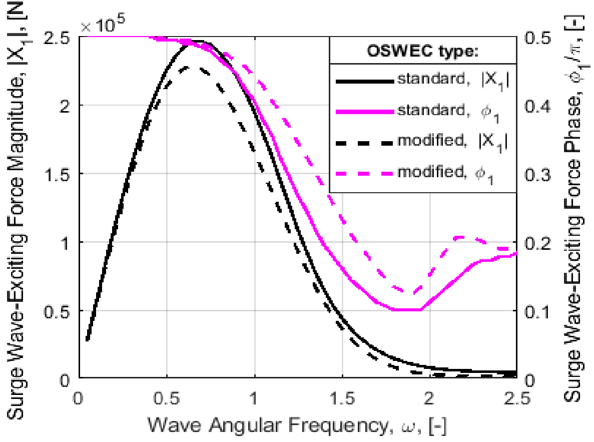

**FIGURE 16**. SURGE WAVE-EXCITING FORCE ON THE FOUNDATION WITH A STANDARD AND MODIFIED OSWEC.

10 m, the safety factor improved enough to clear the threshold value of 1.75.

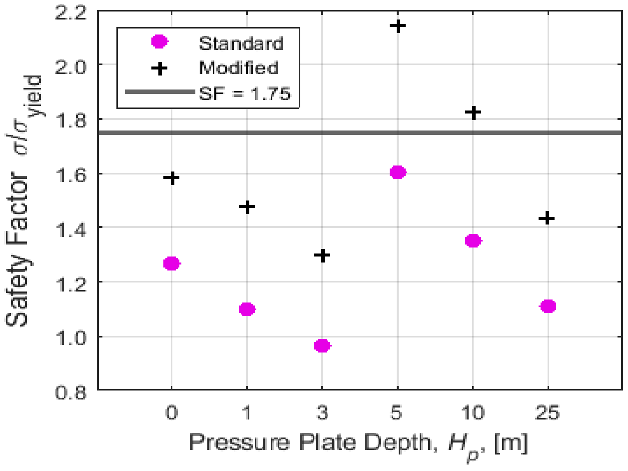

**FIGURE 17**. COMPARISON OF SAFETY FACTORS FOR STEEL FOUNDATIONS WHEN STANDARD AND MODIFIED OSWECS ARE USED.

Figure 18 shows how safety factor changed when the modified OSWEC was substituted for the standard OSWEC on concrete foundations. For the case with no plates and plate sizes of 1 m, 3 m, and 5 m, the foundation diameter is 5 m. For plate sizes of 10 m and 25 m, the foundation diameter is 6 m. Again, safety factor improved by around 30% when the modified OSWEC was used. For four out of six of the pressure plate sizes, the safety factor was bumped above the threshold value of 1.75.

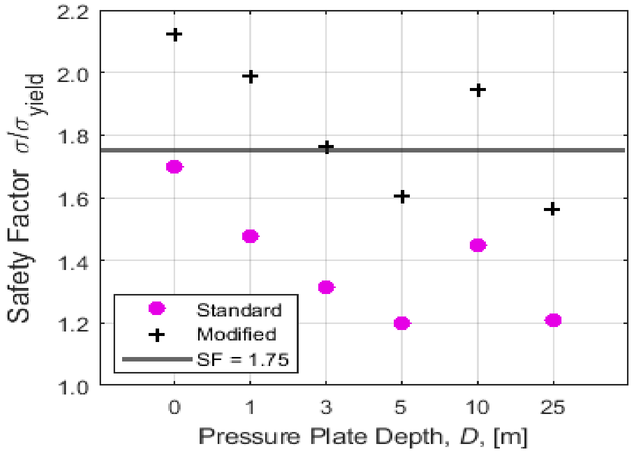

**FIGURE 18**. COMPARISON OF SAFETY FACTORS FOR CONCRETE FOUNDATIONS WHEN STANDARD AND MODIFIED OSWECS ARE USED.

## CONCLUSIONS

Results of this study show that a foundation-mounted OSWEC may be a cost-effective method for generating energy from ocean waves. The Wave Energy Prize documentation lists an ACE threshold of 3.0 m/$M as a “necessary requirement to win the prize” [17]. ACE values for concrete foundations in this study peaked in the low teens, a promising preliminary estimate. Even if characteristic capital expenditure increased as a result of more rigorous structural analysis, it is likely that an OSWEC on a raised foundation would still surpass the Wave Energy Prize’s ACE threshold. Steel foundations provided *ACE* values around 2, significantly lower than those for concrete foundations. Even so, steel foundations should continue to be investigated, especially if these devices are to be placed in shallower depths of water. Given steel’s high manufactured material cost, reducing foundation size could be critical to increasing *ACE* for OSWECs mounted on steel foundations. Variable-geometry OSWECs that can shed loads in extreme sea states may reduce CCE by reducing the necessary foundation diameter.

Foundation geometry should be considered when designing an OSWEC on a raised foundation. This study found that the addition of pressure plates significantly increased *ACE* in some cases, without necessitating a significantly more costly foundation. Optimizing foundation geometry for OSWEC power capture may be an inexpensive and easy pathway to increase *ACE*.

Monopile foundations such as those used for offshore wind turbines appear to be good candidates to support OSWECs. Even with the relatively deep 35-m water depth, at least one of the tested foundation diameters was sufficient to maintain a safety factor of 1.75 or above in all cases. While moving to deeper water may test the limits of these foundations [11], moving to shallower water would likely suit them well.

## FUTURE WORKS

As mentioned earlier, these devices may be very well suited to water depths shallower than the ones listed here. Moving to shallower water may provide many benefits, including smaller foundation forces, greater proportion of depth reached by pressure plates, and reduced length of foundations. All of these benefits may work to reduce the characteristic capital expenditure associated with a raised OSWEC. While the power flux of ocean waves does decrease as water depth decreases, the reduced *CCE* may greatly offset any decrease in performance.

While various sizes of pressure plates were examined in this study, the rectangular shape always remained the same. Tweaking the geometry of these plates may be a cheap way to increase ACE. For example, angling the plates toward the OSWEC may assist in pushing wave-induced pressure onto the device. Or, tapering the plate depth as it reaches the outer edges of the OSWEC may reduce CCE without significantly impacting ACCW.

Finally, the size of the OSWEC itself may be tuned to maximize ACE. In general, larger OSWECs capture more energy from waves at the cost of added material. A larger or smaller OSWEC may be better suited to this application than the size tested here.

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