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Coupling Soil-Foundation Models to MHK Device Dynamic Models to Tighten the Design Envelope

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1 Summary

The purpose of this Seedling project is to couple a marine renewable energy (MRE) dynamics simulation software with the soil-foundation models in the OC6 Phase II project [Bergua et al., 2021] and evaluate the software's performance. This is a first step to accurately evaluating soil-foundation impacts on other types of MRE, like wave or current energy converters (WECs, CECs). OC6 Phase II compares offshore wind turbine (OWT) simulations using several different soil-foundation models to identify and fill key gaps in soil-foundation analyses. WEC-Sim was chosen to model the OC6 Phase II offshore wind turbine and various load cases because of its adaptability, accuracy of hydrodynamic loads, and ability to apply an arbitrary wind loading. Of the four methods used in OC6, the apparent fixity soil-foundation method was coupled with WEC-Sim. Technical challenges with flexible hydrodynamic bodies, added mass and external function libraries inhibited the ability to compare the WEC-Sim results to other OC6 participants. These challenges required that the WEC-Sim model of the OC6 OWT use a combination of rigid and flexible bodies to ensure a numerically stable solution. The rigid monopile creates a more stiff system and causes smaller amplitude motion under hydrodynamic loading and higher dominant frequency of motion under wind loading. These discrepancies are expected based on the increased stiffness of the WEC-Sim case.

The impact of soil-foundation dynamics on wave energy converter performance is still an open question. Future work should continue to use WEC-Sim to analyze these impacts due to its adaptability and accuracy. However future work should refocus on rigid WEC archetypes, many of which have been modeled and validated with WEC-Sim. Coupling these preexisting WEC models with appropriate soil-foundation methods will expedite the ability to accurately assess this important impact while avoiding the technical challenges of structurally flexible bodies.

2 Methodology

This section summarizes the proposed tasks and describes the processes used to accomplish each task. The project lead was Adam Keester who took over for Kelley Ruehl, and managed all budgeting, project administration and technical work. Kelley initiated the original proposal idea and served as advisor to Adam throughout the project.

2.1 Proposed Objective and Tasks

2.1.1 Objective

This Seedling Proposal aims to develop and release an open-source code that couples an MRE device dynamic model with a foundation and soil model (REDWIN). The coupled model can be internally compared to the results of OC6 Phase II. The coupled code will especially be compared to Load Cases 4.X and 5.X which focus on accurate soil-foundation coupling under hydrodynamic loads and hydrodynamic plus aerodynamic loads respectively. Note that this timeline does not allow for formal submission to OC6 Phase II, but an internal comparison to the results will be completed regardless. A successful coupled model will predict foundation movement within 10% of other REDWIN-coupled models and capture all peak excitation frequencies. OC6 Phase II contains numerous submissions (high and low fidelity and experimental data) that can be compared. The coupled MRE-REDWIN code will be released to the MRE community to improve dynamic simulations and better account for the soil-foundation interactions. Once released, the project's usage can be tracked with Google Analytics or other open-source platform statistics on number and location of users, downloads, site visits, and code improvements (e.g. pull requests).

2.1.2 Proposed $50,000 Plan

This project will encompass several major tasks that can each benefit the MRE community (Table 1). As a whole, the tasks serve to properly identify the best pathway to address the soil-foundation problem, directly simulate the effects, compare the influence on MRE to the impacts on offshore wind turbines, and evaluate the need for further research in this area.

With the lower funding level, this work will focus on coupling WEC-Sim or CACTUS and REDWIN for comparison to the OC6 Phase II work. The OC6 comparison consists of both verification and validation of the model.

Table 1: Proposed tasks under the $50,000 plan.

Task	Description
1	Evaluate the MRE code (WEC-Sim, CACTUS, etc) most appropriate for soil-foundation analysis of the OC6 Phase II device.
2	Develop a dynamic model of the OC6 Phase II device in the code chosen in (1)
3	Couple the device dynamic model (2) with the REDWIN soil-foundation model
4	Verify and validate the results of the coupled model (3) with results from OC6 Phase II
5	Publish report with findings from (4) numerical model coupling
6	Release coupled numerical model as an open-source code

2.2 MRE Code Evaluation

Task 1 of this project was to evaluate the MRE software most appropriate for analysis of the OC6 device (Table 1 OC6 Phase II analyzes an OWT with several different soil-foundation models (hereafter Phase II of OC6 is implied, unless specified otherwise). The OWT model consists of three bodies, shown in Figure 1: a flexible monopile (seabed to above still water line), a flexible tower (monopile to the rotor) and a rigid rotor-nacelle-assembly (RNA). Blade dynamics are not simulated, instead they are simplified to a 6DOF force time series applied on the rigid RNA. The load cases require the ability to model flexible beams, an arbitrary force time series, and soil-foundation effects. OC6 compares four standard soil-foundation methods, the most advanced of which is the Norwegian Geotechnical Institute's (NGI) new macro-element model, REDWIN [Skau et al., 2018].

This choice of software was primarily limited to WEC-Sim and CACTUS because they are both used to simulate MRE dynamics and performance, and were both developed at Sandia where expertise on their use is most easily accessible. The abilities of each software to model the OC6 Phase II OWT is described below.

CACTUS's primary use is for hydrokinetic turbine design and analysis [Murray and Barone, 2011]. It calculates the loads, performance and dynamics of submerged turbine blades. Empirical relations are available for tower drag and for induced turbine velocities due to other blunt bodies (tower, shroud, etc). Turbine tower dynamics and flexibility are not modeled. Some bottom-fixed hydrokinetic turbine studies use monopiles, jackets or gravity foundations that REDWIN is intended to model [Chatzigiannakou, 2019, Thake, 2005], making a resultant CACTUS-REDWIN coupling pertinent. However CACTUS does not contain the ability to model hydrodynamic loading, a key portion of the advanced OC6 Phase II load cases.

WEC-SIM's primary use is for wave energy converter design and analysis [Ruehl et al., 2021, Ogden et al., 2021]. It calculates the wave-induced hydrodynamic loads on submerged bodies, rigid body dynamics, and power performance of wave energy converters. General non-hydrodynamic bodies are readily available to represent the tower and RNA.

Currently WEC-Sim can model the hydrodynamics of flexible modes through its generalized body mode capability [van Rij et al., 2017b]. This feature considers the wave excitation, radiation damping, added mass and hydrodynamic coupling in a flexible degree of freedom. The generalized body mode

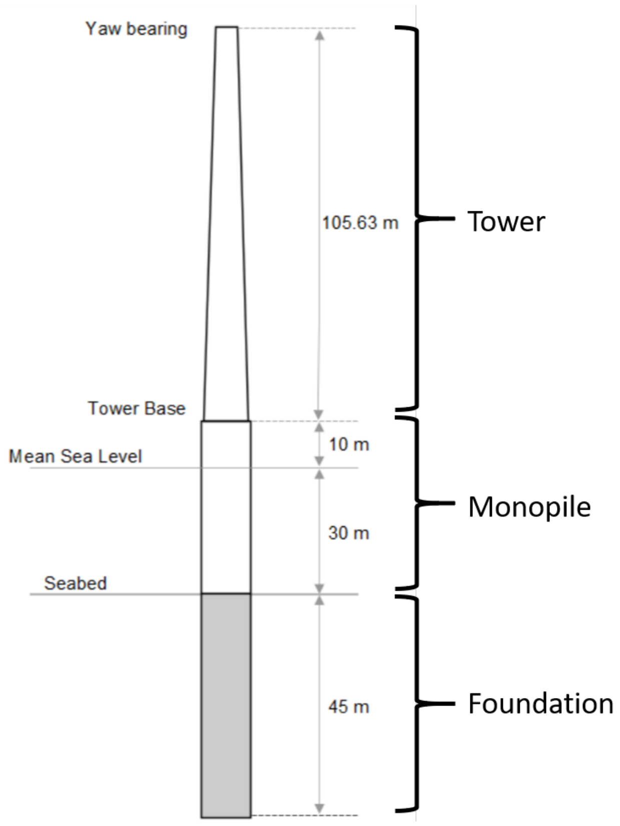

Figure 1: Schematic of the OWT showing the monopile and tower. The RNA (not shown) is fixed at the tower top. Illustration from [Bergua et al., 2021], Figure 6.

feature does not consider structural dynamics of flexible beams as required in the OC6 case. The structural effects in the OC6 case dominate the dynamics, whereas WEC-Sim's generalized body mode feature is intended to model cases where hydrodynamic effects drive the motion of bodies. Typically the structural dynamics of a flexible beam would be modeled using Timoshenko or Euler-Bernoulli beam theory [Bergua et al., 2021].

WEC-Sim can model an arbitrary force time series, arbitrary foundation constraints and links easily with custom force-response interactions (like the soil-foundation models). Some WEC studies contain foundations appropriate for analysis with REDWIN [Wilson et al., 2016, Burge et al., 021, Chatzigiannakou, 2019, van Rij et al., 2017a, Li et al., 2011, Cossu et al., 2018, Tom et al., 2016] or look at combined WEC-offshore wind systems [Ren et al., 2018, Gkaraklova et al., 2021, O'Kelly-Lynch et al., 2020 Clark, 2020, O'Sullivan, 2014, Aubault et al., 2011, Peiffer and Roddier, 2012], which make a coupled WEC-Sim-REDWIN application relevant to the industry.

Ultimately, WEC-Sim is chosen for this analysis due to its adaptability, ability to accurately model hydrodynamic loads, and the ability to easily create arbitrary external loads and new modules with Simscape Multibody as required by the OC6 Phase II scenario.

2.3 Model Development

The OC6 Phase II model was created in MATLAB, Simulink and Simscape Multibody using WEC-Sim. The Mathworks signal processing toolbox is also used for certain frequency-domain post-processing analyses, though this is not required to run the model. Wind loading time series data and model parameters are available from the OC6 Phase II project. The REDWIN function library is available from NGI through the OC6 project.

The WEC-Sim library and Simulink interface make it straightforward to create and set-up the bodies and forcings. To create a structurally flexible body in WEC-Sim the forcing in each body remains the same, but the rigid structure itself is replaced with a Simscape Flexible Cylinder (Figure 2). The hydrodynamic forces are applied at the body's center of gravity following WEC-Sim standards.

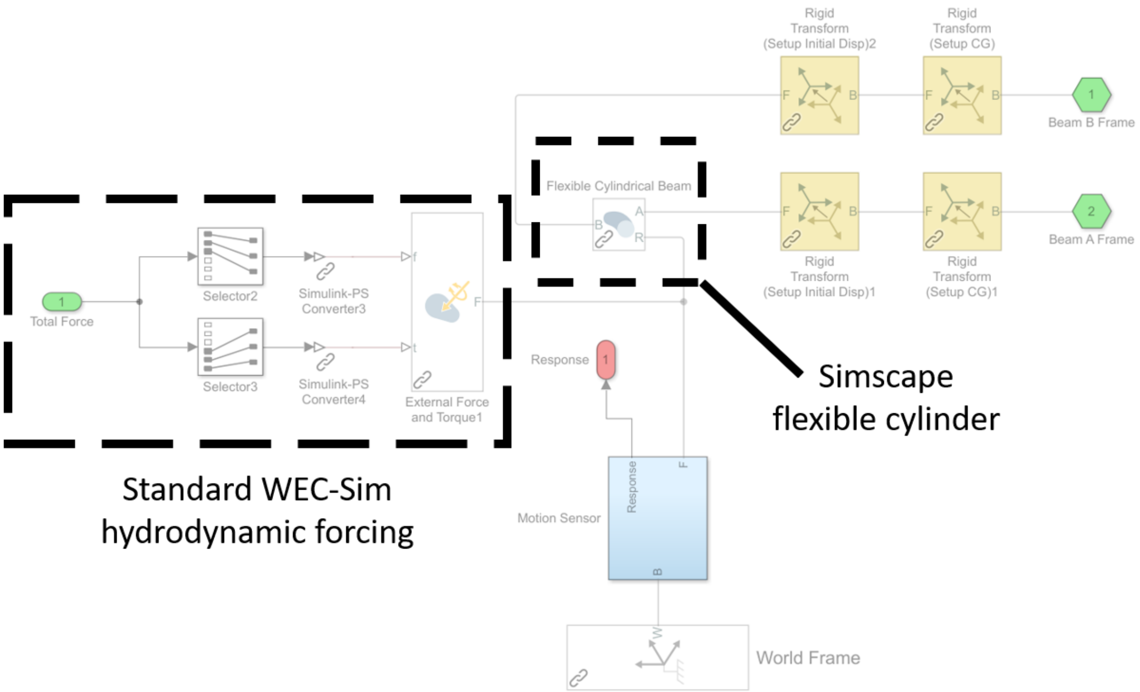

Figure 2: Flexible body block in WEC-Sim showing the standard WEC-Sim hydrodynamic forcing and the flexible cylinder that replaces rigid bodies.

WEC-Sim's preexisting fixed constraints connect all bodies together. Two of the four OC6 soil-foundation methods were tested: the apparent fixity (AF) method and the REDWIN macro-element model (RW).

The AF method is a low fidelity, linear soil-foundation method in the OWT industry. It represents the motion at the soil-foundation interface using a flexible substructure. This substructure is a flexible, non-hydrodynamic beam cantilevered at some depth beneath the seabed (Figure 3). The structural properties of the foundation beam are prescribed such that the monopile motion at the seabed is identical to the real embedded pile. In this way the monopile response "appears as if fixed" at some depth below the seabed. Only linear structural stiffness is considered in this approach. No additional damping is included.

The RW model is a "macro-element model" that simplifies the soil-foundation dynamics into a single 6DOF force [Skau et al., 2018]. It accurately represents the soil-foundation hysteresis using nonlinear stiffness and damping. There is no additional substructure to model, but it requires integrating NGI's dynamic link library (DLL) into WEC-Sim. This was done by leveraging WEC-Sim's MoorDyn block as an example that can be modified to run the REDWIN DLL. A free constraint connects the monopile to the seabed. The REDWIN model then supplies the calculated macro-element forces at the seabed given some motion (Figure 4).

This project utilized WEC-Sim's drag body Morison Element formulation to account for hydrodynamic forcing. WEC-Sim post-processing scripts were created to save and compare relevant data to OC6 results.

The Seedling timeline did not allow for formal submission to OC6 Phase II, so comparison was conducted internally. These results may be published at a later date after formal release of OC6 Phase II results.

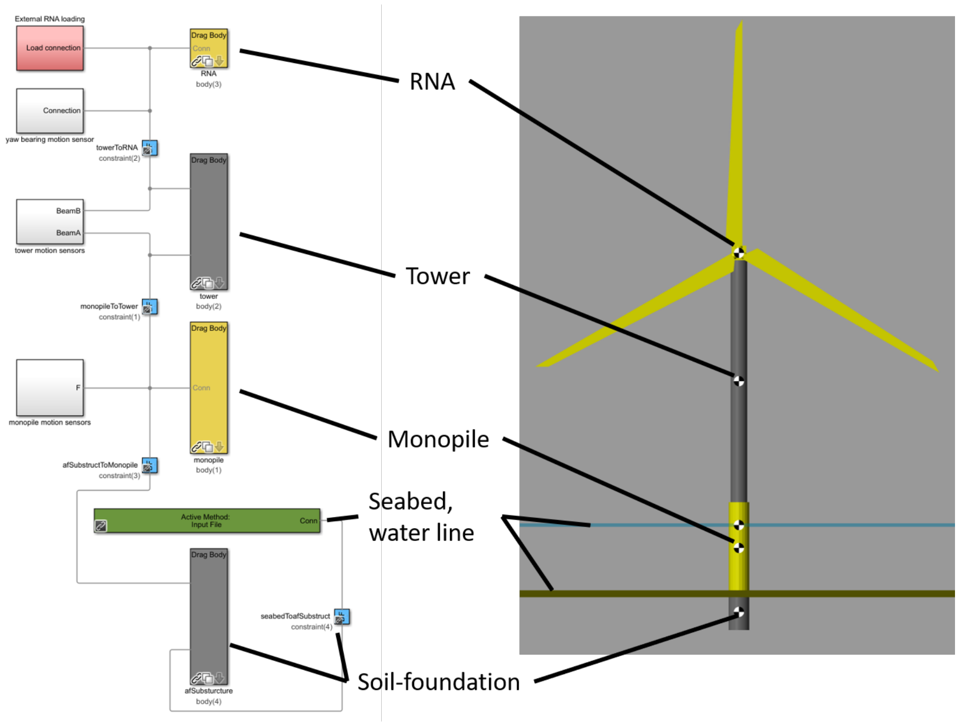

Figure 3: OWT with AF soil-foundation model, visualization (left) and block diagram (right). Yellow, rigid bodies (RNA, monopile); gray, flexible bodies (tower, foundation); blue, fixed constraints; red, external wind load; white, motion sensors.

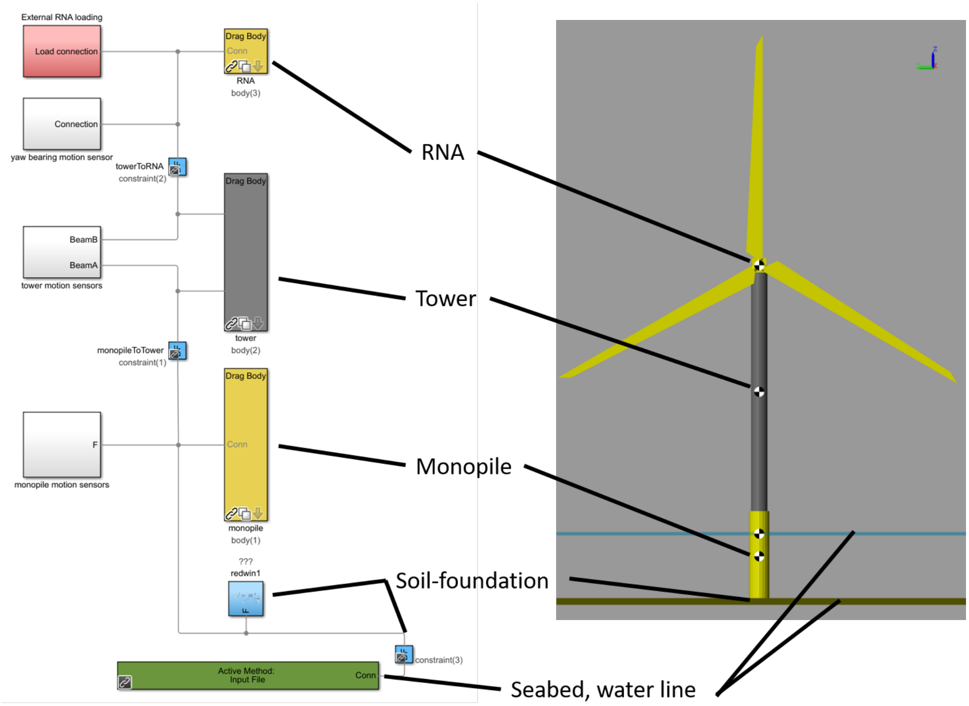

Figure 4: OWT with RW soil-foundation model, visualization (left) and block diagram (right). Yellow, rigid bodies (RNA, monopile); gray, flexible bodies (tower); blue, constraints; red, external wind load; white, motion sensors.

3 Challenges Encountered

The challenges encountered in this seedling were predominantly technical in nature. Engineering challenges limited the success of modeling the OC6 Phase II OWT with WEC-Sim and Simscape Multibody. Challenges discussed here will include the numerically stiff flexible beam problem, added mass and Simscape Multibody limitations.

3.1 Flexible Beam

The foremost engineering challenge was integrating a flexible body into WEC-Sim. WEC-Sim is largely a rigid body simulation tool and it applies a single 6DOF force on each body's center of gravity. This is critical because the distribution of hydrodynamic forces on a body are not accounted for. The summation of hydrodynamic forces on a rigid body can be transformed and applied most anywhere without changing the robustness of the simulation. However, when the total hydrodynamic force along a 30m monopile is summed and applied at a single point on a flexible body, WEC-Sim has very poor numerical stability. This single concentrated force causes the flexible beam to bend unphysically at the point of application.

Additionally, WEC-Sim typically handles numerically non-stiff problems which are easier to solve. Flexible beam simulations are very stiff numerical problems and are difficult to solve. MATLAB contains several stiff differential equation solvers for this purpose, but they are computationally expensive and creating robust solutions is difficult [Mathworks, 2021]. Even when testing short simulations the high numerical stiffness causes long run times and decreases the amount of work that could be completed on a short-term project.

3.2 Added Mass

Added mass is especially difficult to handle with flexible beams. Added mass is a special multi-directional fluid dynamic phenomenon that most physics software cannot account for well. It is an inertial force that depends on a body's acceleration. Numerical solvers are trying to predict the acceleration at a future time-step, so the added mass force becomes inaccurate and unstable without special treatment.

Simscape Multibody flexible beams are not compatible with WEC-Sim's current added mass formulation. In every attempted simulation, flexible bodies became unstable due to the added mass force and the simulation crashed. The added mass force could be neglected if the Keulegan-Carpenter number is very large and added mass is insignificant. However, in this OC6 model the Keulegan-Carpenter number (Eq 1) is in an intermediate range (on the order of 0.1-1) and added mass cannot be neglected. This issue occurs with both WEC-Sim's hydrodynamic and Morison Element forces.

$$K_c = \frac{velocity * time}{length} \tag{1}$$

3.3 Attempted Solutions

Many attempted workarounds for the numerical stability problem were tested (Table 2). The only working solutions involve removing the added mass force altogether and using a hybrid rigid-flexible simulation. Based on the Keulegan-Carpenter number of this scenario, the added mass force is dominant and removing it entirely would be inaccurate. The most accurate, stable workaround is to model the monopile as a rigid body. The tower and AF foundation are flexible because they are above the water line and below the seabed respectively and do not contain hydrodynamic forcing. However this set-up is difficult to verify against the OC6 results because the bodies are represented differently. This comparison is discussed further in Section 4, Key Findings.

Table 2: Attempted solutions for the numerical stability challenge (non-exhaustive).

Solution description	Outcome
Apply standard hydrodynamic and/or Morison element forces on a flexible beam	Crash
Calculate strip-theory Morison element forces	Crash
Include viscous drag, linear damping, structural damping	Crash
Apply hydrodynamic and Morison element forces without added mass	Success
Use various numerical solvers and time steps	Crash
Apply a long ramp time to slowly increase the added mass force	Crash
Apply the hydrodynamic and/or Morison element forces at the beam end	Crash
Delay the start time of the added mass force to allow for initial transients to decay	Crash
Treat the monopile as a rigid body but the tower and foundation as flexible	Success
Filter high frequency noise from the wind forcing	Crash
Distribute the hydrodynamic or Morison element forces along the monopile	Crash

The REDWIN soil-foundation model caused additional challenges. The supplied DLL does not return error codes so debugging is very difficult. During all attempted simulations, even with the hybrid rigid-flexible set-up described above, the REDWIN library crashes without providing information. This problem can likely be resolved by further discussion with NREL (OC6 leads) or NGI (REDWIN developers) but there was not sufficient time to use this model on top of the other technical difficulties.

OC6 does compare two other soil-foundation models to the apparent fixity and REDWIN solutions. OWT analyses also utilize the coupled springs (CS) and distributed springs (DS) methods. Coupled springs give similar results to the AF method so it is not used here [Bergua et al., 2021]. The DS method is the current standard for OWT analysis and in this case uses 61 nonlinear springs distributed across the foundation. WEC-Sim requires that each of these springs be represented in both the coded input file and the block diagram, making it very time consuming to implement. This could be streamlined in the future by creating a custom block that will automatically add and remove springs based on the number input, reducing manual intervention by a user. For these reasons and the technical difficulties with the RW library, only the AF soil-foundation model is tested here.

4 Key Findings

At the time of this report OC6 Phase II has concluded, but publications containing the official results have not been released. This section will show results similar to those tentatively used in that upcoming OC6 paper so that comparisons can be drawn. The official results from OC6 Phase II can be referenced against this work when published.

Table 3 compares the WEC-Sim model (hybrid rigid-flexible bodies and the apparent fixity soil-foundation) with the approximate results of other OC6 participants in several key parameters. The tower top x displacement at equilibrium is larger than the other participants by 46%. Likewise the 1st and 2nd bending mode frequencies are 10% and 34% larger than the other participants respectively. These discrepancies are likely due to the required modeling differences. A rigid monopile can be viewed as an infinitely stiff version of the real flexible monopile. An increase in stiffness increases the natural frequency of a system, which is what the WEC-Sim results below show in comparison to the other OC6 participants.

Figures 5 and 6 show the power spectral density (PSD) of the x acceleration at the yaw bearing and the fore aft bending moment at the seabed for Load Case 3.1 (light wind loading only). The first peak frequency of the yaw bearing x acceleration clearly appears at 0.26 Hz and reaches a similar magnitude as the OC6 participants (around 10^1). The second peak frequency is much larger than the OC6 participants at approximately 1.6 Hz, consistent with the increase described in Table 3. The fore-aft bending moment at the seabed shows similar results with accurate magnitudes at peak

Table 3: Comparison of the OC6 soil-foundation models with the WEC-Sim AF model. Percent error is relative to the OC6 AF method.

Load case	Parameter	AF/CS	DS	RW	WEC-Sim (% error)
1.2	Tower top x displacement [m]	0.225	0.2375	0.2375	0.32904 (46%)
2.3	1st Fore-aft bending mode frequency [Hz]	0.25	0.24	0.245	0.2746 (10%)
2.3	2nd Fore-aft bending mode frequency [Hz]	1.2	1.12	1.17	1.602 (34%)

frequencies ($10^{17}, 10^{15}$ respectively), while the 2nd peak frequency is much larger than the other OC6 participants.

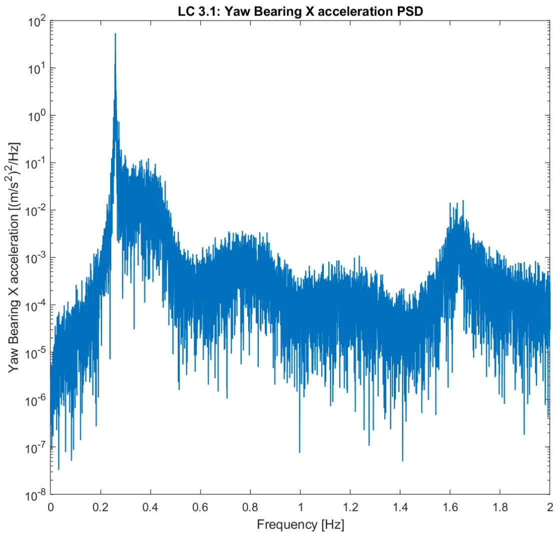

Figure 5: Load case 3.1 yaw bearing x acceleration PSD.

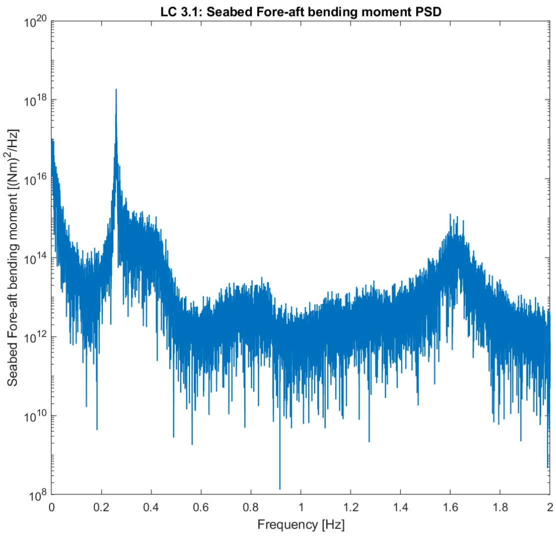

Figure 6: Load case 3.1 seabed fore-aft bending moment PSD.

Load Case 4.2 analyzes the OWT in irregular wave conditions and without wind loading. The yaw bearing x acceleration has the same dominant frequency as other participants, but a much lower magnitude (Figure 7). This is due to this case only containing hydrodynamic loading. The hydrodynamic loading is only applied to the rigid monopile. This rigidity causes smaller amplitude motion than with flexible body, which results in less motion at the yaw bearing. This effect is not seen in Load Case 3.1 because the wind loading at the tower top is dominant and can still bend the flexible tower in the WEC-Sim case. Similar results are seen in Figure 8.

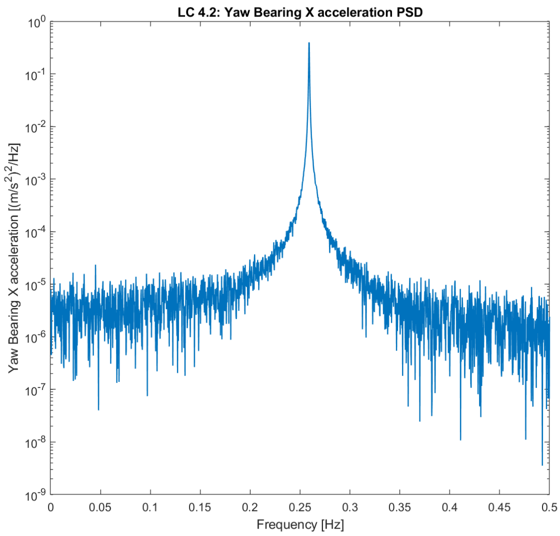

Figure 7: Load case 4.2 yaw bearing x acceleration PSD.

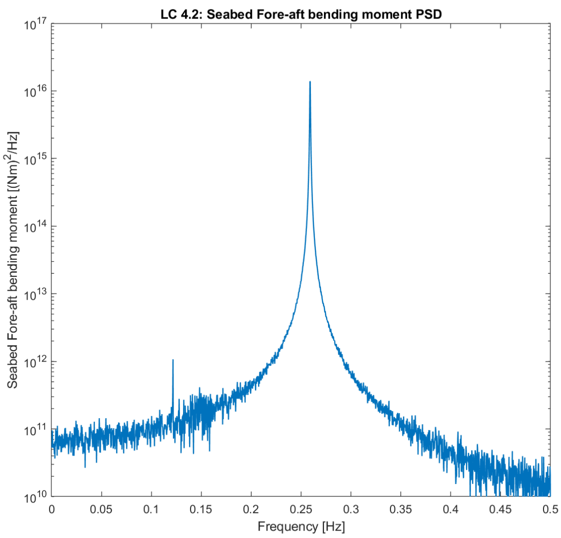

Figure 8: Load case 4.2 seabed fore-aft bending moment PSD.

Load Case 5.1 contains an irregular wave loading and a light wind loading at the RNA. Figures 9, 10 again show the frequency distribution of the yaw bearing x-acceleration and the seabed fore-aft bending moment. Results are similar to Load Case 3.1. The first peak frequency is accurate while the second is much larger than other OC6 participants. PSD magnitudes and shapes are similar to the OC6 results aside from the position of the 2nd peak frequency.

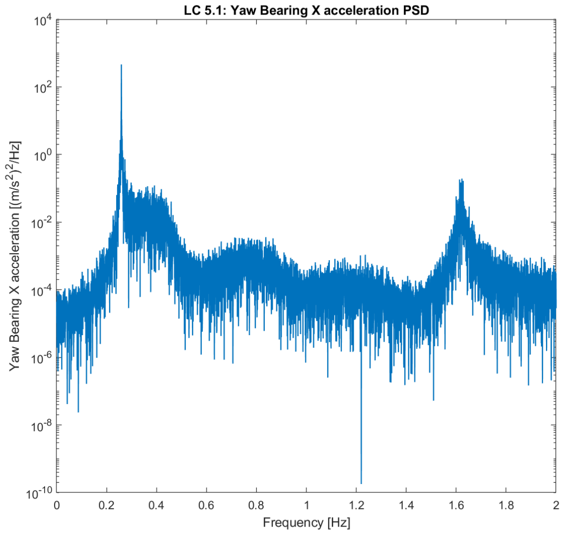

Figure 9: Load case 5.1 yaw bearing x acceleration PSD.

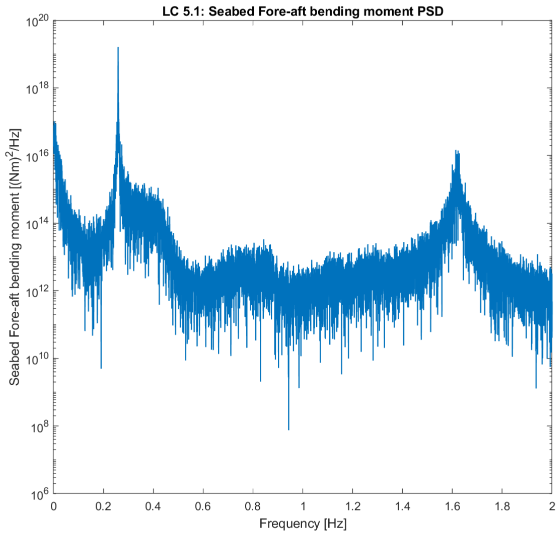

Figure 10: Load case 5.1 seabed fore-aft bending moment PSD.

In summary, the hybrid rigid-flexible bodies in WEC-Sim with the apparent fixity soil-foundation model are generally comparable to the OC6 results with a few key discrepancies. Especially the 2nd peak frequency of motion is much larger than the OC6 participants (1.6 Hz vs 1.2 Hz) and the magnitudes of motion is lower in the cases with only hydrodynamic loading. These are primarily attributed to the WEC-Sim case using a rigid monopile, instead of a flexible one. If a numerically stable, flexible hydrodynamic monopile can be used in future work, it is expected that WEC-Sim results will converge to those of the other OC6 participants.

5 Final Product

The hybrid rigid-flexible OC6 case will be hosted as a private repository on the WEC-Sim GitHub organization at the conclusion of this work. If and when the cases are numerically and stable, this work can be made public. The project will be made available upon request to researchers who wish to use the work or investigate challenges further.

Some WEC-Sim modules were created for the AF and RW soil-foundation models including flexible non-hydrodynamic bodies and a REDWIN soil-foundation block. These cases are not numerically robust, so it is recommended they are not merged with the WEC-Sim source code. A special copy of the source code with these additions will be added to the example case. The scripts to automate the input set-up and post-processing for each OC6 load case will also be included with the model. Users who want to investigate this case with the REDWIN model can contact the OC6 Phase II organizers or NGI to obtain the relevant library.

6 Lessons Learned

This Seedling research was limited by technical challenges. The primary difficulty was implementing hydrodynamic flexible bodies into WEC-Sim, a software developed for rigid body dynamics. The added mass formulation with a flexible body was especially problematic. The inability to create a numerically stable, flexible hydrodynamic body limited how these results could be compared to the other OC6 Phase II participants. However those discrepancies noted in Section 4 are reasonable given the modeling differences. Other difficulties included using an externally-developed DLL which required more user support than time allowed. If it becomes possible to implement a more robust flexible beam in WEC-Sim and Simscape Multibody, this research can be quickly restarted and compared to OC6 Phase II again.

6.1 Future work

OC6 Phase II was originally proposed to identify gaps in OWT soil-foundation methods and compare industry standards to a new macro-element model [Bergua et al., 2021, Skau et al., 2018]. The original Seedling proposal included a Phase II path where the REDWIN model could be applied to various wave or current energy converters that use appropriate monopile or jacket structures. Since the comparison to OC6 was limited, the original Phase II path is not viable. However, the importance of soil-foundation models for wave energy converters is still an open question. Future work should pursue this question more directly. Instead of continuing to model an OWT with WEC-Sim and then transitioning to analyzing WEC technology, future studies should bypass the flexible OWT challenges and directly study soil-foundation models for WECs. WEC-Sim is proven to accurately model a wide range of rigid WECs [Ruehl et al., 2021], so these geometries can be coupled with appropriate soil-foundation models. This path addresses the outstanding question of soil-foundation methods for wave energy converters, while avoiding the technical challenges encountered in this work.

7 Acknowledgements

Members of the WEC-Sim development team, especially Kelley Ruehl, Nathan Tom, and Yi-Hsiang Yu, were very helpful and provided insight during the various technical challenges of this work. Kelley also initiated the original proposal idea and provided guidance on budgeting and project management. The assistance of these staff members is greatly appreciated.

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