WIND WRANGLER ENGINEERING SERVICES

FINAL DESIGN REPORT

Floating Offshore Wind Turbine Project

May 22, 2023

LETTER OF TRANSMITTAL

March 17, 2023

Dr. Robb Moss, PE
California Polytechnic State University
1 Grand Avenue
San Luis Obispo, CA 93405

Dear Dr. Moss,

Wind Wrangler Engineering Services is proud to present our 80% design submittal for the Floating Offshore Wind Farm Project that is to be situated 40 km NW off the coast of Morro Bay, CA. As per the Request for Design, this document contains our 80% design report, drawings, and applicable appendices.

The contents of the design report include our project understanding, scope of work, identified data and design constraints, and sustainability analysis. Additionally, we have included our design approach and recommendations with supporting work available in Appendices A-E. Included in these appendices are our structural and geotechnical calculations, design drawings, Class 2 Cost Estimate, and design schedule which is broken down into two schedules: permitting and construction.

Thank you for this opportunity to work alongside you to transform the Offshore Wind Farm Industry along the West Coast of the United States. If any further questions, comments, or concerns arise, please contact Cormack Williams via email at cwill124@calpoly.edu or via phone at (858) 602-2528.

Sincerely,

Cormack Williams

Cormack Williams
Project Manager, Geotechnical Specialist
Wind Wrangler Engineering Services

TABLE OF CONTENTS

PROJECT UNDERSTANDING

Overview

The emergence of new offshore wind energy projects developing for the Central Coast of California introduces the need for preliminary design from a Civil Engineering perspective of offshore floating wind turbines (FOWTs). The water off the Central Coast rapidly increases in depth, therefore, the proposed offshore windfarm contains floating turbines with a tethered mooring system anchored to the ocean floor subsurface. The wind farms will then connect to the power grid at the grid ties in Morro Bay using ocean bottom cabling. The proposed turbines will be of 14 MW nameplate capacity with up to 100 turbines located in the wind farm and interconnected via inter-array cable.

Site Location

The proposed wind farm location is 40 km offshore to the NW of Morro Bay near the NOAA buoy 46028, connecting to a power plant located in Morro Bay (Figure 1).

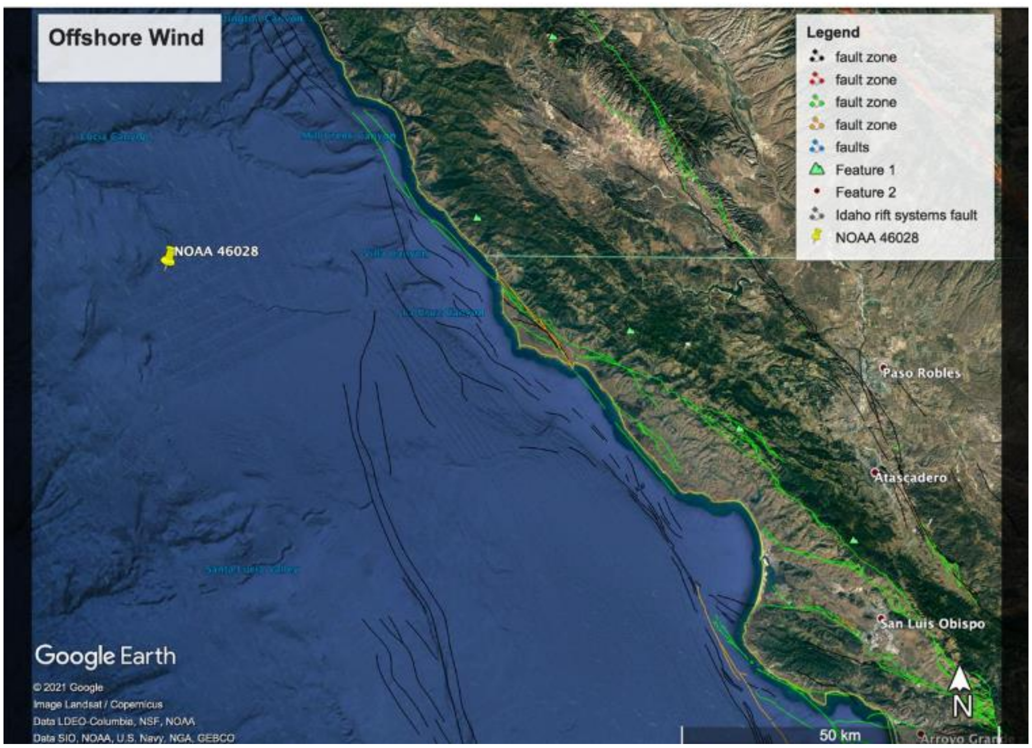


Figure 1. The current proposed wind farm location is about 40 km offshore to the NW of Morro Bay near NOAA buoy 46028 (Moss, R., 2022).

Project Objectives

The goal of this design project is to perform an 80% preliminary design of a single floating offshore wind platform for a 14 MW turbine. This preliminary design involves recommendations for structural design, geotechnical design, and construction planning. WWES is providing structural recommendations pertaining to the tower and floating platform, geotechnical recommendations for the mooring system consisting of the tether and anchor, and construction feasibility covering the budgeting, staging, construction, timeline, and delivery logistics from the Port of Hueneme.

Current Site Conditions

The current proposed wind farm location is roughly 40 km offshore to the NW of Morro Bay near NOAA buoy 46028 where consistent wind data has been recorded for over 27 years. The wind at this location has shown an average speed of 8.5 m/s from long term buoy data. The climatic mean and standard deviation plots for wind speed, significant wave height, and dominant wave period at buoy 46028 provided by the National Data Buoy Center (NDBC) and National Oceanic and Atmospheric Administration are displayed below as these site conditions are major influences in the FOWT design.

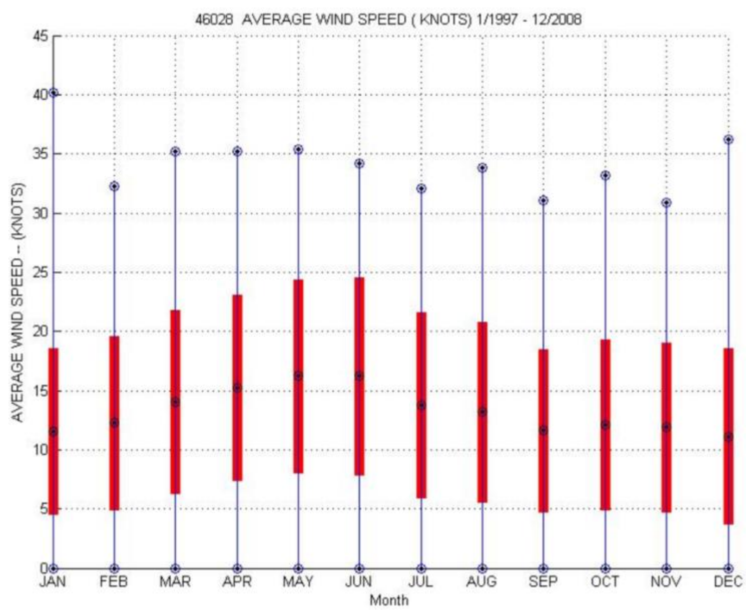


Figure 2. Station 46028 climatic mean and standard deviation plot for the average wind speed in knots from historical data from 1997-2008 provided by the NOAA (NDBC station page, 2023).

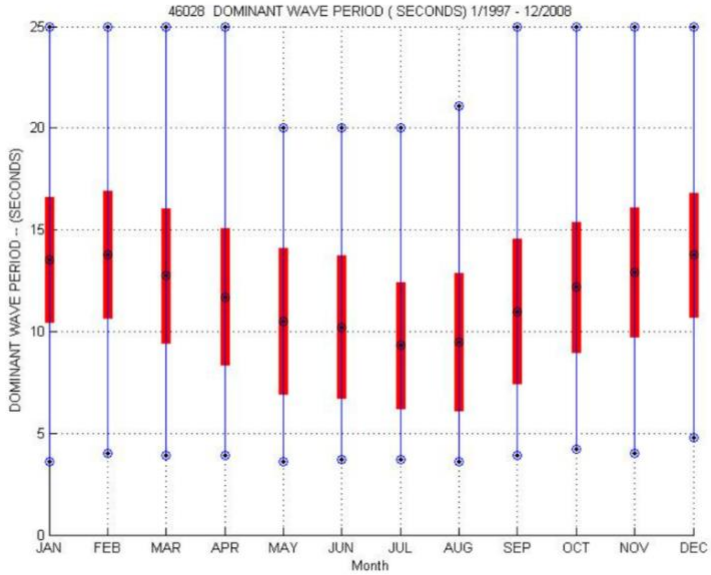


Figure 3. Station 46028 climatic mean and standard deviation plot for the significant wave height from historical data from 1997-2008 provided by the NOAA (NDBC station page, 2023).

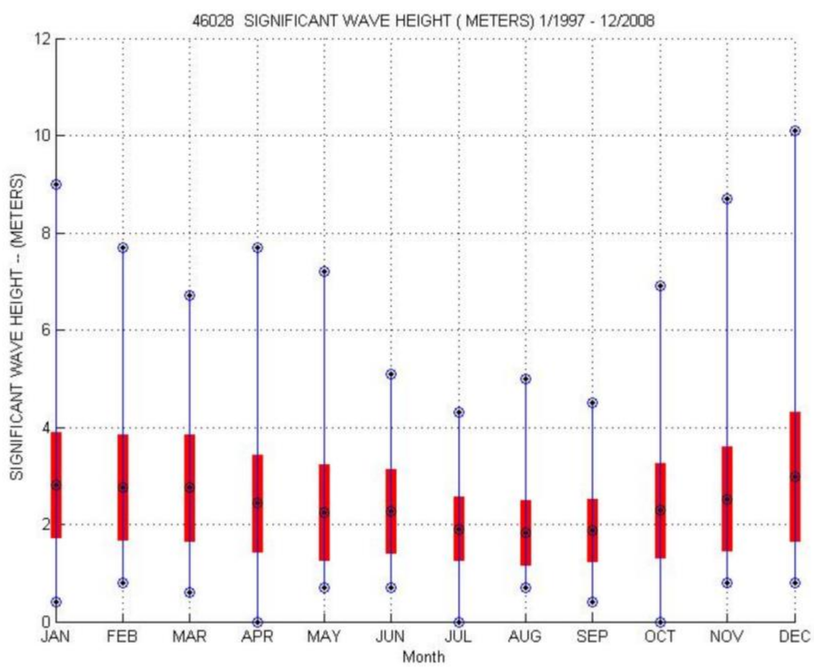


Figure 4. Station 46028 climatic mean and standard deviation plot for the dominant wave period from historical data from 1997-2008 provided by the NOAA (NDBC station page, 2023).

The depth of water to the continental shelf is roughly 800 to 1100 m with a slope of 1 km vertical to 10 km horizontal.

SCOPE OF WORK

Structural

Offshore structures are designed with respect to ultimate limit state (ULS) and fatigue limit state (FLS), meaning they must withstand extreme loads and are designed so that fatigue damage will occur only after a certain lifetime. The primary component of the structural work for the project is designing the floating platform and tower to withstand the wind, wave, and current environmental loading. The FOWT system consists of a mooring system, floating platform, tower, and a rotor-nacelle-assembly (RNA) which is a combination of the nacelle, gearbox, and rotor combining the hub and blades. Conceptual and preliminary stages of the FOWT design process were carried out. Buckling, yielding, and stability analyses were conducted on the tower and platform to ensure the structure was designed against the ULS. Fatigue assessment was carried out to analyze the FLS and ensure the structure will fulfill its intended design life of 20 years (DNV-OS-J103, 2013). Natural periods of the structure were compared to wave periods to avoid the negative effects of resonance.

Geotechnical

The geotechnical scope of work involves providing foundation recommendations for mooring the floating offshore wind turbine to the seafloor. The selected foundation type, suction caisson, is designed following Arany and Bhattacharya (2018) to mitigate uplift concerns due to environmental loading. A schedule of recommended caisson dimensions is provided as well as a figure showing caisson embedment depth versus capacity for a range of caisson diameters.

Construction

The construction scope of work includes a Class 2 Cost Estimate, Class 3 Design Schedule, and Project Execution Plan (PEP). The PEP contains an executive summary, execution phasing strategy, public outreach plan, construction safety plan, and quality control and assurance plans. Key construction considerations for this project includes establishing the project cost and schedule, mitigating unforeseen conditions, and ensuring public and construction on-site safety. To ensure these key considerations are properly addressed and construction operations run smoothly and efficiently, WWES will proactively coordinate with onsite and offsite agencies. WWES' proactive coordination also aids in ensuring and maintaining public and job site safety because it can anticipate potential hazards resulting from construction through properly managing concerns such as traffic control, danger zones, and waste areas.

Environmental Consideration

At WWES we aim to provide an environmentally sustainable design and construction plan. The development of floating offshore wind turbine farms has the potential to provide clean energy to millions of Americans and reduce greenhouse gas emission to prevent the impacts of climate change and contribute the Biden-Harris Administration commitment to deploying 30 gigawatts of offshore wind energy by 2030. However, floating offshore wind infrastructure presents risks to the environment off the coast of Morro Bay. Therefore, WWES strongly believes it is important to develop the proposed wind farm in a way that minimizes environmental impacts. To begin, one risk could be wildlife entanglement in the mooring system and power cables connected to the turbine. To combat this, WWES proposes a single tether system for each wind turbine, likely to pose a low risk because these tethers and cables are large and rigid (Kershaw, 2021). Additionally, the mooring line system may impact marine life at the surface of the ocean bottom because the tether and anchor may disrupt the movement of migratory fish. However, since the turbines will be placed 1 km apart, we believe that the tethers will be far enough from each other to not grossly obstruct marine life patterns.

There is also the potential of introducing non-native and invasive species to the wind turbine farm site because the turbines will be tugged from the Port of Hueneme to their final location off the coast of Morro Bay. However, since the Port of Hueneme recently received the Comprehensive Environmental Management Award, we believe that they have the proper invasive species mitigation measures to prevent these species from latching onto our turbines at port before they are towed to site. Furthermore, research conducted by the Bureau of Ocean Energy Management (BOEM) has shown that "offshore wind foundations may function like artificial reefs by creating new habitats which attracts marine organisms… and potentially increasing the biological diversity of the area" (Bureau of Ocean Energy Management, 2021). As such, the presence of our wind turbines may increase biological resources, if invasive species potential is properly mitigated.

DATA AND DESIGN CONSTRAINTS

Structural

Choosing a suitable FOWT is based on the design constraints of the construction site, installation site, and operating conditions. These involve water depth, environmental conditions, shore distance, and seabed properties. The FOWT is to be constructed in the Port of Hueneme and installed 40 km offshore to the NW of Morro Bay near the NOAA buoy 46028. The spar-type FOWT was chosen as it seemed to be the most suitable concept for the deep-water applications of this site. The lowered center of gravity suppresses pitch and roll motions and the ballast stabilization enables cost reduction by utilizing cheap materials. Furthermore, the spar allows a small waterplane area, reducing wave forces, and has a deep draft that reduces heave motions. Overall, the spar maintains a relatively simple and inexpensive platform geometry (Dinh et. al., 2013).

Environmental conditions were obtained from the National Data Buoy Center (NDBC) of the National Oceanic and Atmospheric Administration (NOAA) historical buoy data. Load combinations were calculated in accordance with DNVGL-ST-0437 (2016): *Loads and Site Conditions for Wind Turbines*. It was found that the combination of the maximum wind load due to extreme operating gust (EOG) at rated wind speed at the 1-year extreme wave height governed the environmental loading. This aligns with the findings of a study by de Souza et. al (2022) which states "load cases associated with the rated windspeed often govern the extreme loads" of larger FOWTs "unlike previous studies with 5 MW and 10 MW FWTs."

Geotechnical

Subsurface exploration is yet to be performed at the site beneath NOAA buoy 46028. However, we assume two general seafloor conditions for foundation design: sandy soil and clayey soil. For the sandy soil condition, we assume an effective friction angle of 26-32 degrees. For the clayey soil condition, we will utilize a boring log from a nearby deepwater site. This boring log shows very soft to soft olive gray clay to a depth of approximately 8.5 meters beneath the seafloor which gives way to firm to stiff olive gray clay until boring termination at a depth of approximately 61.8 meters. The surficial clay yielded a laboratory undrained shear strength of approximately 4.8 kPa, which increased approximately linearly by 1.8 kPa/m (Moss, 2022).

Construction

The construction of these 100 14 MW turbines offshore wind farm project has several constraints including the supply availability of turbine components for a 14 MW turbine, transportation process of turbine components to the onshore construction site and then to the offshore site, and the port size and bearing capacity. To account for the limited supply and manufacturing of 14 MW turbine components, we assumed a more conservative estimate for procurement time in the design schedule. Finding transportation and assembly equipment currently available with the capacity to handle the loads required by the turbine was also a challenge. As such, additional cranes, operating, and transportation equipment were assumed necessary and reflected by more conservative pricing in the cost estimate.

Lastly, port size and bearing capacity were limiting factors for the quantity of turbines that could be stored and assembled at a time. Due to the size constraints of the commercial side of Port Hueneme, WWES was only able to hold the assembly of one (1) turbine and storage of four (4) turbines at a time. Additionally, after consulting with a Port Hueneme Environmental Manager, this port, and all other ports in California, currently does not have the bearing capacity required to support wind turbine construction and will need additional foundation upgrades. According to the port's Environmental Manager, Port Hueneme currently has a bearing capacity of between 6-10 ksi and will likely need around 10 times this amount to support the wind turbine construction loads. However, financing for California port infrastructure upgrade projects is underway to support the US's renewable energy goals. So, by the time this project has passed the years long BOEM permitting approval process, Port Hueneme will likely have the foundation bearing capacity to support wind turbine construction.

DESIGN APPROACH AND RECOMMENDATIONS

Structural

Support Structure Design

WWES is proposing a deep draught spar-type offshore floating wind turbine. The proposed spar design consists of a 160 m long steel cylinder including 10 m of freeboard. The deep-water conditions off the coast of Morro Bay allow the spar's 150 m draft. For this preliminary 80%

design, the spar is modeled as an unstiffened cylinder, with a diameter of 25 m, and a constant thickness of 450 mm to sustain the buckling loads from the turbine tower and rotor-nacelle-assembly (RNA), while ensuring the floatability of the structure. See Appendix B.5 for calculations regarding buckling of the spar. The spar characteristic buckling stresses were calculated using Load and Resistance Factor Design (LRFD) methodology per DNVGL-RP-C202 (2019): *Buckling Strength of Shells.* The hydrostatic pressure causing circumferential stress governed the buckling stress. Although, this can be attributed to conservative assumptions made regarding the hydrostatic pressure demand. A model of the proposed FOWT is displayed below (Fig. 4),

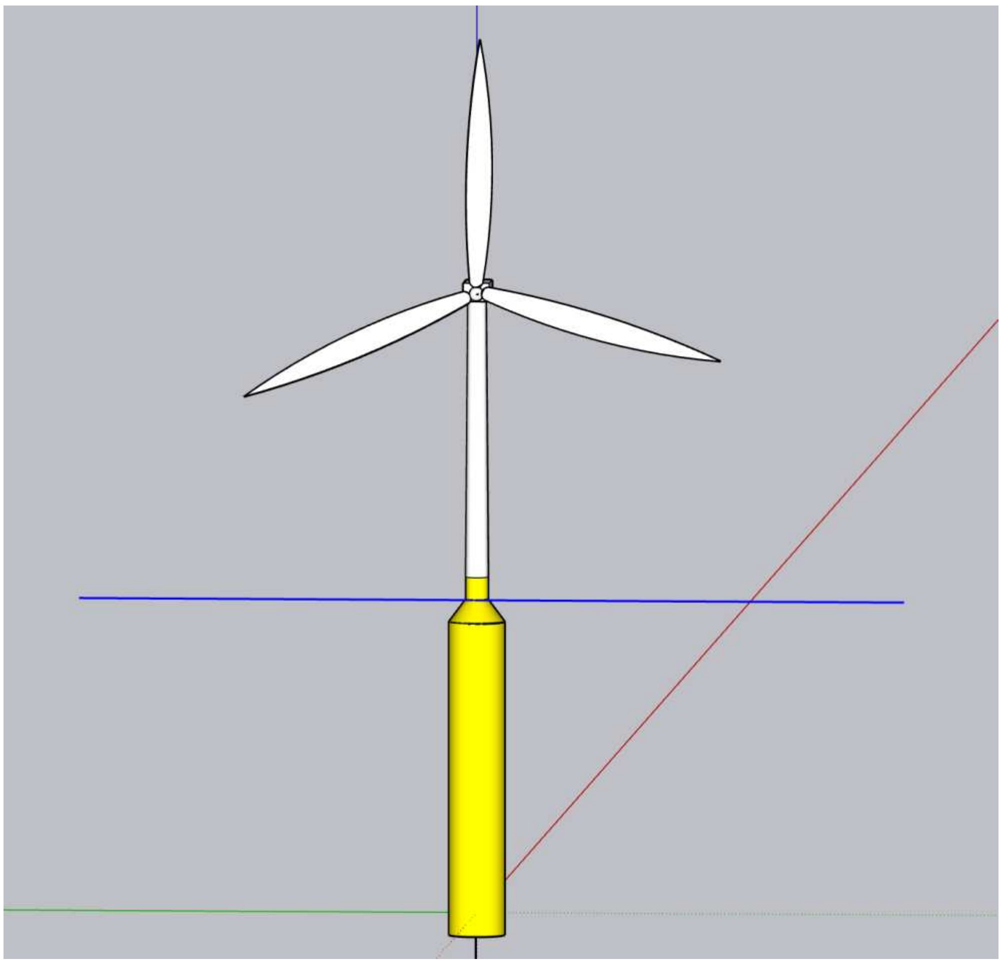


Figure 5. Model of proposed FOWT

The spar is ballasted with 22,808 tons of high-density concrete enhanced with magnetite, which is an iron ore that is a common ballast material for offshore applications because of its high density. The ballast volume was designed to provide sufficient stability to the FOWT and will be elaborated on. Above the permanent ballast is 4,155 tons of variable ballast made of seawater (open tank to the ocean). The level of the variable ballast is controlled by pumping compressed air to the top of the tank to achieve neutral buoyancy as the operating conditions of the turbine change. The spar linearly tapers off 10 m below the waterline in a conical transition to connect to the turbine tower and to lessen the wave effects near the waterline. Also, 10 m of freeboard is provided to prevent the turbine tower from being at sea level to protect from corrosion and to protect the maintenance deck from waves. Both the spar and tower are made of S420 steel, which is a common steel used for offshore applications (Igwemezie, 2019). A steel with high yield strength is chosen as the yield strength of hot-rolled steel decreases with the large wall thicknesses of the spar and tower. The main properties of the proposed floating platform are summarized in Table 1 below.

Table 1. Proposed spar floating platform properties

Spar Properties -S420		
Diameter	25	m
Thickness	450	mm
Total Length	160	m
Freeboard	10	m
Draft	150	m
Steel Mass	44497	tons
Permanent Ballast	22808	tons
Variable Ballast	4155	tons
Total Spar Mass	73862	tons

Tower Design

The SG 14-222 14 MW turbine produced by Siemens Gamesa Renewable Energy is used in the design of the proposed wind turbine. Technical specifications for the turbine are displayed below in Table 2 (de Vries, 2019).

Table 2. Technical specifications for the SG 14-222 (de Vries, 2019).

Siemens Gamesa 14 MW Turbine: SG 14-222DD		
Nominal power	14	MW
Blade length	107	m
Rotor diameter	222	m
Swept area	39000	m^2
Cut-in wind speed	3.5	m/s
Cut-out wind speed	28	m/s
Blade mass	55	tons
Nacelle height	10.4	m
Nacelle length	20.6	m
Nacelle width	11	m
Nacelle mass	600	tons

The turbine tower consists of a 125 m taper cylinder supporting the RNA with a nominal capacity of 14 MW. The cylindrical tower tapers from 10 m to 8 m with a constant thickness of 50 mm to support the buckling loads of the RNA. As a conservative measure, the self-weight of the tower was included in the point load for the tower buckling as well as contributions from the P-delta effect. See Appendix B.3 for tower buckling calculations. Tower yielding was analyzed using basic beam theory considering the thrust force acting on the rotor and the P-delta effect from the shift of the tower top under loading that gives rise to a moment arm for the RNA weight (Fredheim, 2022). See Appendix B.4 tower yielding calculations. Overall, the characteristic shell buckling of the tower governed over the column buckling of the tower and yielding of the tower. The main tower properties are displayed in Table 3 below.

Table 3. Proposed turbine tower properties

Tower Properties		
Bottom Diameter	10	m
Top Diameter	8	m
Thickness	50	mm
Tower Height	125	m
Hub Height	135	m
Mass	1494	tons

Stability Analysis

The intact stability of the structure is analyzed, however per DNV-OS-J103 (see page 81), for unmanned units, like wind turbines, damaged stability is not a requirement. The stability of the spar-type FOWT is provided by the magnetite enhanced concrete ballast. The stability of offshore structures is typically analyzed through its curve to static stability, which is a plot, shown below in Figure 6, of the righting arm of the FOWT vs the heeling angle caused by the environmental forces.

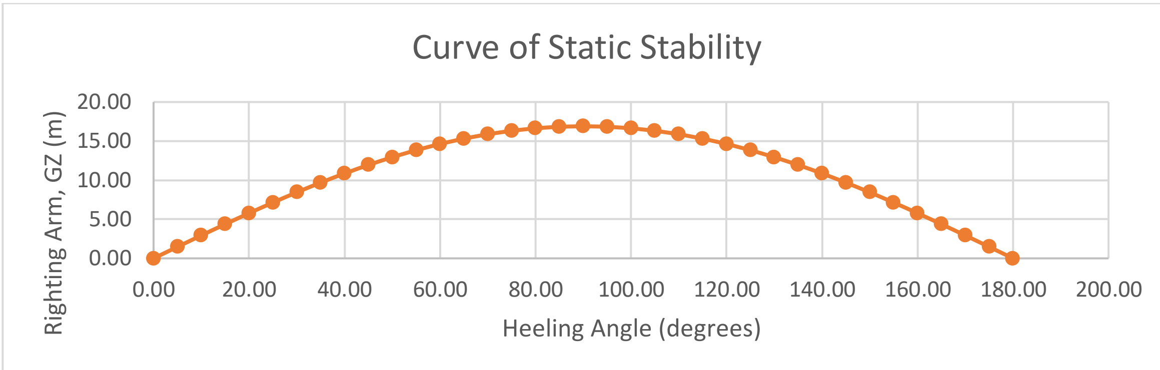


Figure 6. The Curve of Static Stability of the FOWT plots the righting arm of the structure vs the heeling angle due to environmental forces.

The spar can right itself irrespective of the angle of heel if the center of gravity is kept below the center of buoyancy by the ballast. Because of this attribute, it was determined in Figure 5 that the heeling angle at which a maximum righting arm of 16.89 m occurs is at 90 deg. This means that at this angle, the structure uses the most energy to put it back to its vertical position. However, the created curve of static stability seems to be inaccurate as it gives a very high maximum heeling angle (Bockute, 2019). To continue, offshore structures are also analyzed by their righting moment curves to ensure sufficient stability. The righting moment curve of the proposed FOWT is provided below Figure 7.

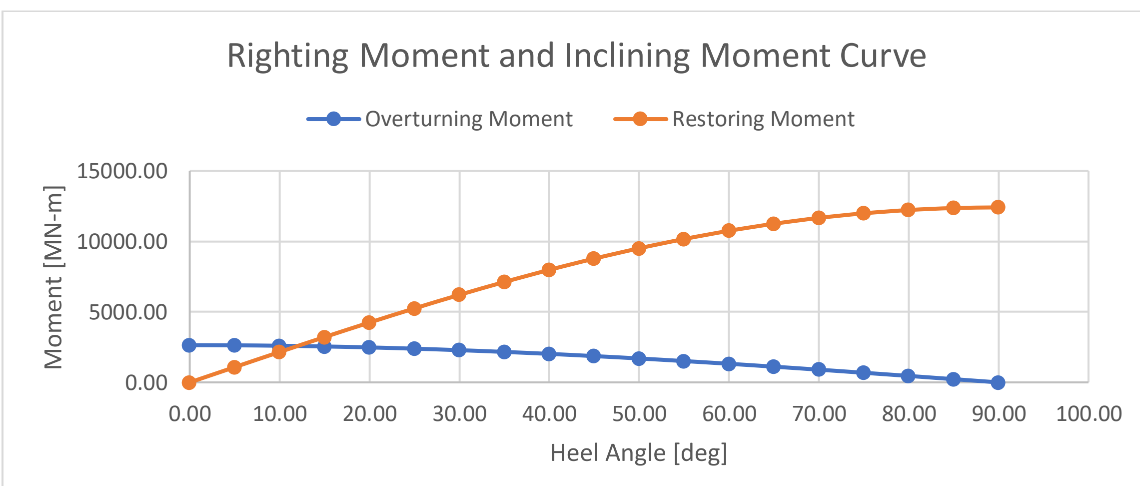


Figure 7. Plot of the righting moment and inclining moment vs the heeling angle due to environmental forces

Per DNV-OS-C301 (2001): *Stability and Watertight Integrity* (see page 14), the area under the righting moment curve to the second intercept or down flooding angle, whichever is less, shall not be less than 30% in excess of the area under the wind heeling moment curve to the same limiting angle. Because the spar-type floating platform is difficult to capsize, the graph of the righting and inclining moment does not have a second intercept to allow the stability to be analyzed per DNV code requirements. As shown in Figure 6, the largest restoring capacity is at 90 degrees. In absence of conforming design philosophy from DNV codes, the American Bureau of Shipping (ABS) codes were used to satisfy the stability of the FOWT. As such, *ABS: Guide for Building and Classing Floating Offshore Wind Turbines* (see page 134) states "for the spar-type floating substructure, the righting energy at the inclination angle of 30 degrees is to reach a value of not less than 30% in excess of the area under the overturning curve to the same limiting angle."

The overturning moment is conservatively determined by applying the wind, wave, and current loads as point loads on the structure to obtain the worst-case scenario. DNVGL-OS-C301 (2001) reports that the intact inclination angle is limited to 12 degrees for normal operating conditions as the power output of the structure will be seriously reduced for angles above this limit. Our proposed turbine has an inclination angle of 12 degrees which satisfies the provided recommendation. See Appendix B.6 for calculations regarding the stability of the FOWT. For the dimensions of the spar regarding draft and diameter, the stability of the structure governed the geometry of the spar through several iterations adjusting the geometry of the spar and amount of ballast to lower the center of gravity to ensure a sufficient restoring moment and reasonable heeling angle. Then, the hydrostatic pressure governed the wall thickness of the spar to prevent shell buckling.

Natural periods of the FOWT should fall outside of the "energy rich part of the wave spectra from 5-25 seconds" to avoid increased excitation due to resonance " (Johannessen, 2018). This matches the dominant period range of the installation location. The proposed FOWT satisfies this recommendation as it has a heave period of 25.628 s, a pitch period of 43.175 s, and a roll period of 43.175 s. The contribution of mooring lines was ignored for simplicity. See Appendix B.6 for calculations of the natural period.

Fatigue Analysis

FOWTs are highly dynamic due to the cyclic wind, wave, and current motion combined with the rotating turbine. The proposed FOWT is prone to fatigue due to this cycling, causing fatigue damage to be the usual design driving factor. Arany et. al. (2017) cites a study by Kucharczyk et al. (2012) where "it was identified that the fatigue endurance limit of the S355 steel is 260 MPa." According to Arany et. al. (2017) "fatigue endurance limit of the material means that under stress cycles with a magnitude lower than this value, the material can theoretically withstand any number of cycles." Arany et. al. (2017) cites this justification to assume the fatigue life of structural steel is sufficient. The same justification is used for the proposed FOWT as the maximum stress the tower base experiences is about 156.094 MPa, the maximum axial stress experienced in the spar is 13.183 MPa, and the grade of steel for the turbine tower is S420. See Appendix B.7 for fatigue related calculations. Therefore, in lieu of sophisticated simulation tools that are beyond the scope of this project to estimate the number of load cycles in the FOWT's design life, similar reasoning is used in the preliminary fatigue analysis of the tower. A more precise fatigue analysis will be carried out in the remaining 20% of the design.

Welded tubular joints are considered critical structural components of offshore platforms that function as weak spots for fatigue loading. Their fatigue performance is strongly influenced by the magnitude of the applied cyclic loading. However, fatigue analysis on welds is beyond the scope of 80% preliminary design and will be addressed per DNV-RP-C203 (2014): *Fatigue design of offshore steel structures* in the remaining 20% of the design.

Conclusions

Long term issues with fatigue and cracks propagating in welded structures are especially critical in the design life of large FOWT's. The large wall thickness of the steel shells in the design worsens this problem and there are challenges associated with welding such thick steel plates. Therefore, the utilization of stiffeners to enhance the design would allow thinner shells while maintaining sufficient buckling capacities. A tapered thickness along the spar and tower would aid this issue while a constant thickness was assumed for the purposes of the 80% preliminary design.

The mass of the turbine tower is on par with similar upscaled and existing large FOWTS. However, the proposed spar is significantly heavier than any similar conceptual design. This is likely due to conservative loading assumptions made and can be remedied with the aforementioned design improvements and more precise loading.

Geotechnical

Selection of Anchor Type

To anchor the floating wind turbine to the seafloor, WWES recommends implementation of a suction caisson foundation. Offshore structures utilize several different anchoring systems across a wide range of applications such as floating offshore oil and gas and floating semi-submersible structures. Available mooring systems for deepwater floating offshore structures include drilled shafts, driven piles, drag anchors, suction caissons, suction embedded plate anchors, and dynamically-penetrating or "torpedo" anchors (Randolph and Gourvenec, 2011). However, the suction caisson is quickly becoming the most widely used and studied anchoring system for floating offshore applications with several benefits including increased pullout resistance in both sand and clay relative to traditional piling and foundation techniques.

General Sizing and Installation

Suction caissons differ from traditional driven pile foundations both in their size and in method of installation. Suction caissons are large steel cylinders with one closed end and one open end, typically with an outside diameter ranging from 4 and 20 m. Diameters of traditional driven piles are usually no greater than 3 m. Suction caissons typically have a length-to-diameter ratio no greater than 5, whereas driven piles have a length-to-diameter ratio that can range between 30 and 60 (Iskander et al., 2011). Installation of suction caissons involves allowing the caisson to sink a short distance into the seafloor under its own self-weight, open-end first, creating a "seal" with soil plugging the inside of the caisson. This is followed by the application of suction as water is pumped out of the closed end of the caisson. This suction creates a pressure differential inside the caisson, pulling it down into the seafloor to full penetration depth without the use of a driving hammer (Iskander et al., 2011). The floating turbine is attached to the caisson via a tether connected to a padeye located on the outside of the caisson, placed at a depth such that soil resistance is mobilized through anchor horizontal translation instead of rotation. This depth is approximately two-thirds of the full caisson length in nearly all cases. (Arany and Bhattacharya, 2018; Randolph and Gourvenec, 2011).

Design Methodology

Arany and Bhattacharya (2018) provide methodology for suction caisson design in soft clay with undrained shear strength values increasing linearly from 15 kPa at a rate of 2 kPa/m and for medium sand with an effective friction angle of 30 degrees. These soil conditions are similar to those assumed to be present at and around NOAA buoy 46028, so we can apply the methods provided in Arany and Bhattacharya (2018) for suction caisson design. One major assumption of the design WWES provides is that the tether load at the mudline is equivalent to the tether load at the anchor. This is a conservative assumption, as the load at the anchor will be slightly less than the load at the mudline because the soil through which the tether travels between the seafloor and the padeye provides resistance to environmental loads. Koh et al. (2019) and Zhu et al. (2018) separately concluded that cyclic loading would have negligible effect on caisson ultimate capacity for moderate load inclination angles such as the one assumed by WWES.

Suction Caisson Recommendations

When designing suction caissons to moor the offshore wind turbine to the seabed, WWES assumes a homogeneous soil profile consisting of either clay or sand with index and strength characteristics as described above. Design drawing G-1 shows a schedule of recommendations for suction caisson dimensions for these two soil profiles. Appendix C contains a sample calculation for design dimensions in both soil types for a length-to-diameter ratio of 2 under the design environmental load of 18.106 MN. Appendix C also contains full tables of calculation parameters for whole length-to-diameter ratios from 2 to 5 under the design loading condition as well as extreme loads of 20, 22 and 24 MN. During installation, there exists the possibility that the caisson encounters an unknown stiff soil layer that is impossible to pass, either during the sinking-by-self-weight phase or the suction phase of installation. If this should occur before the caisson ultimate capacity surpasses the environmental loads, WWES recommends installation of a second caisson located far enough from the first to have negligible effect on its capacity. Figure 8 below shows caisson ultimate capacity versus depth achieved for whole-numbered caisson diameters from 4 to 8 meters.

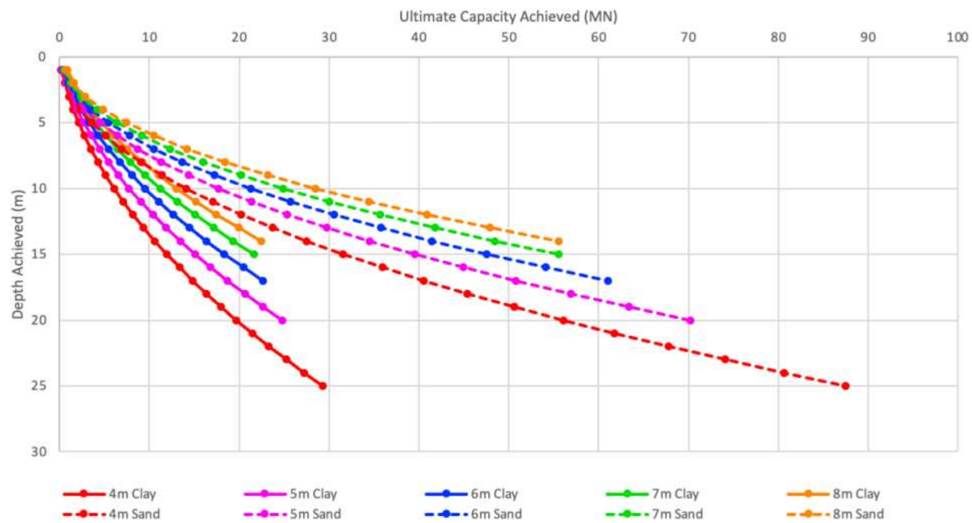


Figure 8. Ultimate Caisson Capacity versus Depth Achieved

Construction

Cost Estimate

Scope of Work:

The Scope of Work (SOW) of this project includes designing the specifications, construction staging, and installation of a 14 MW floating offshore wind turbine to be stationed as part of a 100-turbine farm 45 km NW off the coast of Morro Bay. This wind turbine is to be approximately 249 m above sea level at its highest point and have a single spar buoy, anchored by one embedded suction caisson. The water depth in this area is expected to be 800-1000 m deep with a subsurface profile of sandy and clayey soils. The scope of this Class 2 Cost Estimate accounts for the following construction and installation costs including, but not limited to, preconstruction port work, turbine component procurement, two (2) mobilizations, assembly, installation, and utility installation. Exclusions and assumptions can be found below. Additionally, the SOW has been organized within the Cost Estimate by project phase.

Cost Basis:

Most of our unit cost estimates were obtained from Catapult Offshore Renewable Energy's 2019 Wind Turbine Cost Estimates for farms in the United Kingdom. These line items costs were given in £/MW, so we converted to USD using the average 2019 GBP to USD conversion rates and then adjusted for inflation using Historical Consumer Indexes. Other unit costs, such as site assessment, were obtained from consultation with industry professionals and manufacturers, and adjusted for inflation accordingly.

Assumptions:

The Class 2 Cost Estimate values are based on current industry prices for a start date by the end of Quarter 2 of 2023, standard 40-hr daytime work weeks and a seven-month construction timeline for the assembly and installation offshore of a singular 14 MW wind turbine. Since the permitting process may take several years, the costs used may need to be adjusted again for inflation near the projects' projected start date. WWES also assumes that the Port of Hueneme construction areas have already been acquired or rented by the owner and that all labor is to be supplied locally. Additionally, we assume that no grading, earthwork, or resurfacing for road re-routes is required since the proposed construction areas are already level and drivable due to it being the largest commercial vehicular shipping port in California.

Exclusions

This Class 2 Cost Estimate excludes off-site hauling and disposal fees for demolition and construction waste, post-sunset commercial lighting, security systems, and construction equipment other than the large cranes included. Costs for overtime or schedule delays and night and weekend work are also excluded. Additionally, turbine demobilization, operations, and maintenance costs have been excluded. Furthermore, dampers for Vortex Induced Vibrations (VIV) have been excluded as this requirement may change as the last 20% of the design is refined. This estimate includes the construction costs for only one (1) turbine and excludes costs for the unassembled turbine components laid out on the project site plan; the purpose of those components is to depict proposed storage areas and turbine component quantities that could possibly be stored on site for future construction. Furthermore, safety and pollution mitigation measures beyond erosion control, including fall protection, scaffolding, and sandbags, are not included.

Contingencies

The Cost Estimate includes 20% and 40% contingencies within the soft costs category based on the risk analysis breakdown displayed below. Two contingency prices are offered to reflect the estimate for a typical Class 2 Cost Estimate but also to show a more conservative estimate value due to the possible risk associated with the fluctuating economic market, permitting timeline uncertainty, and changes in the offshore wind turbine component manufacturing industry. The overall risk analysis shown below accounts for financial, design, and technical risks arising from factors such as the economic market uncertainties, procurement and scheduling delays, and WWE's team expertise with the project's design elements.

Risk Analysis:

20% Contingency:

- 14% - Cost Risk: Estimate Based Off UK Pricing, Limited Availability of Equipment with Capacity for 14MW Turbines, Fluctuating Economy
- 3% - Design Risk: Conceptual Design Phase, Design Re-Working
- 3% - Technical Risk: Constructability and Stability Design

Total Risk: 20%

40% Contingency:

- 27% - Cost Risk: Estimate Based Off UK Pricing, Limited Availability of Equipment with Capacity for 14MW Turbines, Fluctuating Economy
- 5% - Design Risk: Conceptual Design Phase, Design Re-Working
- 8% - Technical Risk: Constructability and Stability Design

Total Risk: 40%

Project Execution Plan:

Executive Summary:

The Floating Offshore Wind Farm Project involves installing a farm of 100 14 MW wind turbines 40 km off the coast of Morro Bay, CA. The purpose of this wind farm is to harness wind energy as a renewable energy source to power and increase the capacity of the State of California's electrical grid. Using wind power as a renewable energy source will reduce the country's carbon footprint and reliance on unsustainable energy sources for electricity such as burning fossil fuels and natural gas. This Project Execution Plan assumes and only applies to the construction of one 14 MW turbine at a time.

Project Deliverables:

The construction portion of the Floating Offshore Wind Farm Project includes the assembly and installation of a singular 14MW offshore wind turbine. Turbine assembly will occur onshore at the Port of Hueneme in Los Angeles, CA and then transported to the offshore site off the coast of Morro Bay, CA. Temporary road-rerouting will also be required for port-side construction.

Outreach Plan:

WWES understands the impact this Floating Offshore Wind Turbine Project could have on the Port of Hueneme and its surrounding businesses, residents, visitors, especially due to construction noise levels and potential traffic congestion. To address the impact on the local community, WWES has compiled a public outreach plan with strategies for mitigating these inconveniences and improving overall safety.

1. *Public Meetings* – Hosting public meetings would provide local businesses, residents, and other impacted parties an opportunity to voice their opinions and concerns about the project, ask questions, and review project plans. Public meetings would also allow the project team to describe how the project will function, address any questions and concerns, and explain how they plan to disperse information and updates regarding safety and transportation to the community around the project site.

2. *Media* – Publicizing project information through different forms of media such as local and county-wide newspapers, conferences, social media, and television will help maximize audience reach. Using a widespread of media platforms will help the project team provide timely and consistent updates regarding community impact as the project progresses.

3. *Renewable Energy Education* – Offering renewable energy lectures and discussion dialogues to the community may also help with gaining public favor for the project in addition to educating people on why harnessing offshore wind energy is a great option

for powering our country from a sustainability standpoint. This educational offering could also inspire more sustainable habits and initiatives in the local community.

Execution Strategy – Rough Phasing:

Phase I – Permitting:

Phase I comprises of the permitting process, prior to construction. The permitting process may last up to a decade, as demonstrated in the Appendix E Permitting Schedule portion of the Design Schedule. The permitting time is dependent on how quickly the BOEM can review and approve of the various plans, site assessment surveys, and other documentation the project team must submit. This timeline may be reduced as offshore wind energy projects and technology become more common in the United States. Currently, there are four major stages to the BOEM project approval process:

Stage 1: NEPA Planning and Analysis (~ 2 years)
Stage 2: Lease Issuance (~1 year)
Stage 3: NEPA Approval of Site Assessment Plan (~2 years)
Stage 4: NEPA Approval of Construction & Operations Plan (~2 years)

Stage 1 consists of identifying port construction and offshore site areas and environmental reviews. Stage 2 involves the publishing of leasing notices, auctioning of leases, and lease issuance. Though project may have a site lease issued, this does not give them authority to begin construction. At the end of this permitting stage, they are only approved to begin site assessments. Stage 3 is the site assessment phase which involves devising a site assessment plan and characterization and conducting site surveys such as Resource and Metocean Assessments, Geological and Hydrological Surveys, and Subsurface Sampling. Once the site assessments in Stage 3 are approved, Stage 4 begins which is the Construction & Operations Plan approval process.

Phase II – Mobilization 1, Site Work, and Procurement at Port Site:

Once the Phase I Permitting Process is complete, Phase II begins which includes Mobilization I, Site Preparation, and Procurement at the port site, Port Hueneme.

Phase II begins with Mobilization I which involves installing traffic road barricades for impacted roads leading to the project site, new traffic redirection signage, temporary construction fencing and temporary sound barriers. Temporary facilities such as the job site trailer and restrooms will also be delivered and placed. A parking area for on-site workers will be established as well.

The Site Preparation aspect of Phase II consists of the demolition, traffic control and site work, and storage warehouse installation. Demolition includes demoing existing warehouse buildings and existing road pavement on the project site, as per the Demolition Plan. The site and traffic control work includes installing temporary road barriers for rerouting traffic around the site, filling in the areas where the warehouses were demoed with asphalt pavement, and installing more temporary traffic signage. Since the current purpose of the port is to store and ship vehicles, we assume that all existing open areas are acceptable for vehicular movement. So, new pavement will not be needed for the new roads created to reroute existing ones. Additionally, the prefabricated storage warehouse will be installed to complete site preparation.

The Procurement process includes procuring – ordering, manufacturing, and shipping - all onshore and offshore equipment, turbine components, and mooring and anchor system components. WWES assumed a timeline of one (1) year for this process to account for the turbine components being manufactured and shipped from Europe. The timeline may be reduced depending on the status of offshore wind turbine manufacturing technology advanced in both Europe and the United States..

Phase III – Assembly at Port Site:
Once Phase II is completed upon the successful delivery of the required procurement items, Phase III begins which is the turbine assembly. During this phase, the turbine's tower, blades, rotor, nacelle, foundation, and deflated spar buoy are assembled horizontally along the port using onshore cranes and a jackup vessel. Upon completion of this assembly, the turbine undergoes commissioning to ensure all components are without flaws and were assembled per manufacturer specifications.

Phase IV – Mobilization 2:
After the turbine assembly is completed at the port, Phase IV, Mobilization 2, begins. During this phase, trenching will be done for utility line placement and the suction caisson, assembled turbine, spar buoy ballast fill material, and offshore cranes are transported by vessel to the offshore site.

Phase V - Installation & Connections at Offshore Site:
Phase V begins once the components have arrived at the offshore site for the final turbine installation and utility connections. First, the suction caisson will be installed using a suction caisson-specific installation equipment. Then, the suction caisson will be tied to the mooring line. Next, the spar buoy will be filled with the ballast material to right the turbine from a horizontal to vertical position and the fully inflated turbine will be placed on the water above the suction caisson. The mooring line will then be connected to the spar buoy padeye. Simultaneously, the utility lines will be installed and buried from the onshore substation to the offshore turbine site and then connected to the wind turbine.

Phase VI – Commissioning, Demobilization, and Closeout:
After the turbine is installed and utilities connected, commissioning of the MEP and turbine work will occur. Once the commissioning processes are completed, demobilization of the

onshore port site begins. This involves removing the temporary facilities, fencing, road barriers, traffic signage, and equipment. During this phase, closeout documentation will also be collected for the final Turn Over Package (TOP) to be submitted to the project owners. Lastly, a Lessons Learned Session will be conducted among the project team and the project deemed complete.

Construction Safety Plan:

The construction industry has among the highest risk rates for worksite injuries and fatalities due to the potential site hazards that surround industry workers daily. As such, public and site-specific safety must be prioritized. The risk associated with these hazards can be alleviated through WWES and its contractors creating Site-Specific Safety Plans (SSSP) prior to stepping foot on site. The SSSP involves identifying site-specific hazards along with implementing safety measures for mitigating them.

All construction work performed on the project sites will be in accordance OSHA safety regulations in addition to complying with the following safety management program:

1. *General Safety Management Plan* – This will be a summary of the general methods all on-site personnel must implement and enforce to ensure safety on site. This plan includes general rules of conduct, required personal protection equipment (PPE), and an emergency action plan in the event of an accident. Failure to comply will result in disciplinary action.

2. *Subcontractor Supplies Site-Specific Safety Plan (SSSP)* – All subcontractors will be mandated to provide a Site-Specific Safety Plan for their respective trades prior to setting foot on site. These SSSP will then be reviewed by the General Contractor's Safety Lead for approval. Failure to provide this documentation in a timely manner may result in loss of job and back charges should it result in project delays.

3. *Chain of Command* – This will be a defined authority structure which allows for a clear understanding of roles, responsibilities, communication line, and hierarchical importance for notification in the event of an emergency or accident.

4. *Pre-Task Planning* – All subcontractors will be required to implement pre-task safety plans. These will require subcontractors to analyze their scope of work from a safety standpoint prior to performance and identify the work sequences, hazard trainings, controls, and emergency action plans required to protect all site personnel.

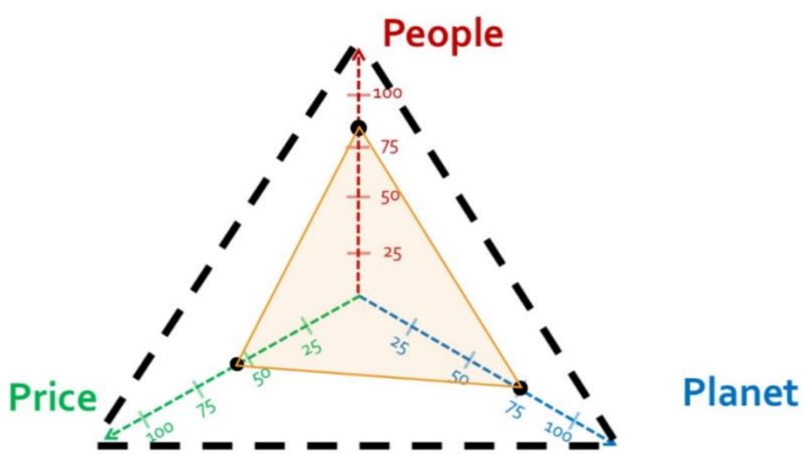
5. *Housekeeping* – All site personnel will practice good housekeeping to eliminate hazards such as trash, debris, and accident hazards. Trash and debris will be collected and placed in dumpsters at the end of each day. Objects will be removed from paths of

travel and objects that could result in tripping, impalement, or other hazards must be capped, flagged, and labeled accordingly.

6. _Accountability_ – All project personnel are responsible for providing and upkeeping a safe and health work environment. As such, the project will uphold a "see something say something" policy.

Quality Control and Quality Assurance:
All design work will be verified for compliance with the applicable structural and geotechnical codes for offshore wind turbine design prior to construction. All construction work will comply with OSHA, AASHTO, and BOEM requirements and be verified for adherence with the final construction drawings. Should substandard construction work or delivered equipment be identified, back orders will be issued at the subcontractor at fault's expense. Additionally, all subcontractors will be required to submit a Quality Management Plan which will be reviewed and approved by the General Contractor's Senior Project Manager. Furthermore, subcontractors must adhere to the inspection schedule per their contractual obligations to ensure quality control, quality assurance, and compliance with local, state, and federal ordinances. Finally, prior to project commissioning and closeout, all subcontractors must provide a completed and signed Quality Control Punch List to verify that their scope of work has been completed per contract and applicable code standards.

SUSTAINABILITY INDEX



People

Offshore wind is a rapidly growing industry on the central coast, creating new jobs. Our offshore wind turbines will benefit people because the renewable energy harnessed through them will reduce pollutants in our water sources and air supply and preserve our current fossil fuel supply. The rise in childhood and adult asthma cases has been linked to poor indoor air quality as a result from increased natural gas use in homes and off-gassing construction materials. Using renewable electricity energy from wind turbines can increase indoor air quality by eliminating the use of natural gas as an energy source in homes, therefore decreasing the risk of air quality related illnesses. In relation to public opinion, offshore wind farms that are constructed within view of the coast may be unpopular to residents because of aesthetics and property values. However, offshore farms still have less of a visual impact than onshore wind farms.

Planet

There are various environmental advantages attributed to the FOWT project. Offshore wind turbines provide a clean renewable source of energy that can provide power to the high energy demands of dense coastal communities while reducing CO_2 emissions (Hutchins, 2020). Offshore wind has the benefit of the presence of more frequent and stronger winds, yielding larger energy production as compared to onshore wind farms. Wind turbines also do not require fuel to operate and limiting the burning of fossil fuels will aid in slowing down climate change and protect more of the earth's natural resources and ecosystems from further harm. Additionally, while the effects of offshore wind turbines to marine and avian life are not fully understood and potentially harmful, the use of a floating turbine foundation as opposed to monopile, or jacket foundation is more environmentally friendly to subseafloor and seabed species. This is because the embedded suction caissons are relatively non-disruptive to the seafloor in terms of displacing subsurface organisms and sediment displacement during and after installation (BOEM, 2020). Furthermore, it is unlikely that the turbine and boats installing the turbines will introduce foreign invasive species to the offshore site due to its proximity to the Port of Hueneme.

Price

The proposed floating offshore wind turbine has a high upfront price tag due to its scale and magnitude. A FOWT requires large and complex infrastructure and therefore is more expensive and difficult to construct than onshore wind farms. In addition, the wind farm is difficult to access but needs more maintenance due to damaging winds and sea waves. However, the U.S. government has pledged federal aid to states in support of offshore farms to hit green energy goals in the future. In the long run, as the supply of fossil fuel resources is depleted and the demand for energy increases, the price of oil will increase. Wind, on the other hand, is a constant natural source of energy on earth, so the supply of wind energy will at a minimum stay the same and will increase as we become more adept at harnessing its energy to meet demand.

APPENDIX A:
DESIGN DRAWINGS

THE FLOATING OFFSHORE WIND TURBINE FARM PROJECT

PROJECT DESIGN AND CONSTRUCTION PLANS

SHEET INDEX

WIND WRANGLER ENGINEERING SERVICES TEAM

CORMACK WILLIAMS
CORMACK WILLIAMS – PROJECT MANAGER & GEOTECHNICAL SPECIALIST 05.22.2023

COURTNEY HUITT
COURTNEY HUITT – STRUCTURAL SPECIALIST 05.22.2023

AUDREY YU
AUDREY YU – CONSTRUCTION SPECIALIST 05.22.2023

FLOATING OFFSHORE WIND TURBINE FARM

WIND WRANGLER ENGINEERING SERVICES

SHEET NAME: COVER SHEET

SHEET NO: C-0

SCALE: NO SCALE

DATE: 05.22.2023

CREATED BY: AY

CHECKED BY: CH

GENERAL NOTES

1. ALL SITE WORK SHALL BE IN ACCORDANCE WITH THE CALIFORNIA CODE OF REGULATIONS, BOEM AND DET NORSKE VERITAS (DNV) DESIGN CODES.

2. ALL DRAWINGS SHALL BE USED IN CONCEPT WITH EACH OTHER IF THE CONTRACTOR DISCOVERS ANY DISCREPANCY BETWEEN THE DOCUMENTS, THE CONTRACTOR SHALL REQUEST IN WRITING A CLARIFICATION FROM THE ENGINEER. REFER TO THE ENGINEERING AND CONSTRUCTION DRAWINGS FOR PLACEMENT, ORIENTATION, AND COORDINATION OF WORK. INFORMATION SHOWN IN LARGER SCALE IS INTENDED TO SUPPLEMENT INFORMATION OF SMALLER, PRECEDING REFERENCE DRAWINGS. LARGER SCALE DRAWINGS TAKE PRECEDENCE OVER SMALLER SCALE DRAWINGS.

3. EXISTING WORK IS SHOWN FOR REFERENCE ONLY. THE OWNER AND/OR ENGINEER DO NOT GUARANTEE EXISTING CONDITIONS AS SHOWN ON THESE DOCUMENTS.

4. THE CONTRACTOR SHALL ASSUME SOLE AND COMPLETE RESPONSIBILITY FOR PROTECTION OF PUBLIC AND PRIVATE PROPERTY ADJACENT TO THE SITE AND HE SHALL, AT HIS EXPENSE, REPAIR OR REPLACE THE ORIGINAL CONDITION ALL EXISTING IMPROVEMENTS WITHIN OR ADJACENT TO THE JOB SITE WHICH ARE NOT DESIGNATED FOR REMOVAL AND WHICH ARE DAMAGED OR REMOVED AS A RESULT OF HIS OPERATIONS

5. THE CONTRACTOR SHALL MAINTAIN ALL EXISTING WORK AND SERVICES (MAIL, GARBAGE, UTILITIES, EMERGNECY, ETC. TO LANDOWNERS ADJACENT TO THE PROJECT ARE

6. THE CONTRACTOR IS RESPONSIBLE FOR THE PROTECTION OR PROPER RESETTING OF ALL EXISTING MONUMENTS AND OTHER SURVEY MARKERS. ANY SURVEY MONUMENTS DESTROYED BY THE CONTRACTOR SHALL BE REPLACED IN ACCORDANCE WITH THE STATE LAND SURVEYOR'S ACT AT THE CONTRACTOR'S EXPENSE.

7. THE CONTRACTOR SHALL COORDINATE CONSTRUCTION WITH THE APPROPRIATE UTILITY COMPANIES AND PRIVATE LANDOWNERS ADJACENT TO THE PROJECT SITE AREA.

8. THE CONTRACTOR SHALL EMPLOY ALL LABOR, EQUIPMENT, AND METHODS REQUIRED TO PREVENT THEIR OPERATIONS FROM PRODUCING DUST IN AMOUNTS DAMAGING PROPERTY, CULTIVATED VEGETATION, AND DOMESTIC ANIMALS OR CAUSING A NUISANCE TO PERSONS IN THE VICINITY OF THE JOB SITE. THE CONTRACTOR SHALL BE RESPONSIBLE FOR ANY DAMAGE CAUSED BY DUST RESULTING FROM HIS OPERATION. DUST ABATEMENT MUST COMPLY WITH CONSTRUCTION ACTIVITY MANAGEMENT PLAN.

9. THE CONTRACTOR(S) SHALL BE RESPONSIBLE FOR THEIR OWN CLEANUP AS WORK PROGRESSES.

INSURANCE AND SAFETY

1. NEITHER THE OWNER, NOR THE ENGINEER OF WORK WILL ENFORCE SAFETY MEASURES OR REGULATIONS AS THEY PERTAIN TO THE CONTRACTOR. THE CONTRACTOR SHALL DESIGN, CONSTRUCT, AND MAINTAIN ALL SAFETY DEVICES, INCLUDING TURBINE STORAGE AND TRANSPORT EQUIPMENT, AND SHALL BE SOLELY RESPONSIBLE FOR CONFORMING TO ALL LOCAL, STATE, AND FEDERAL SAFETY AND HEALTH STANDARDS, LAWS AND REGULATIONS.

2. ALL SITE PERSONNEL AND SITE ACTIVITIES SHALL COMPLY WITH OSHA REGULATIONS

CONSTRUCTION NOTES:

1. OWNER SHALL BE NOTIFIED AT LEAST 24 HOURS PRIOR TO STARTING CONSTRUCTION. ANY CONSTRUCTION DONE WITHOUT APPROVED PLANS OR PRIOR NOTIFICATION TO OWNER MAY BE REJECTED AND WILL BE AT THE CONTRACTOR'S RISK AND EXPENSE.

2. COMPACTION TESTS SHALL BE DONE ON SUBGRADE MATERIAL AND MATERIAL PLACED AS SPECIFIED. SAID TESTS SHALL BE COMPLETED BY A REPRESENTATIVE OF THE PORT OF HUENEME AND APPROVED BY THE SOILS ENGINEER PRIOR TO THE PLACEMENT OF THE NEXT MATERIAL.

3. OWNER MAY REQUEST REVISIONS IN THE PLANS TO SOLVE UNFORESEEN PROBLEMS THAT MAY ARISE IN THE FIELD. REVISIONS SHALL BE REVIEWED BY THE DESIGN ENGINEER AND THE OWNER PRIOR TO IMPLEMENTATION. THE INSPECTOR SHALL ALERT THE CONTRACTOR TO DEVIATIONS IN THE WORK FROM THE PLANS. THE CONTRACTOR SHALL REMEDY THE WORK TO COMPLY WITH THE PLANS TO THE SATISFACTION OF THE INSPECTOR.

4. THE CONSTRUCTION CONTRACTOR SHALL MAINTAIN A CURRENT, COMPLETE, AND ACCURATE RECORD OF ALL CHANGES WHICH DEVIATE FROM THE CONSTRUCTION AS PROPOSED IN THESE PLANS AND SPECIFICATIONS FOR THE PURPOSE OF PROVIDING THE ENGINEER WITH A BASIS FOR RECORD DRAWINGS. NO CHANGES SHALL BE MADE WITHOUT PRIOR APPROVAL OF THE SOILS ENGINEER, THE DESIGN ENGINEER, AND THE OWNER.

5. FIRE PROTECTION IS TO BE PROVIDED PRIOR TO CONSTRUCTION OF ANY BUILDINGS PER THE LATEST EDITION OF THE UNIFORM FIRE CODE WHICH REQUIRES THAT WATER MAINS AND HYDRANTS SHALL BE OPERABLE AND TESTED.A PORTION OR SECTION OF WATER LINES MAY BE PUT INTO OPERATION FOR FIRE PROTECTION.

6. RECORD DRAWINGS ARE TO BE PREPARED BY THE CONTRACTOR AFTER CONSTRUCTION IS COMPLETED. THE DESIGN ENGINEER SHALL BE PRESENT WHEN THE FINAL INSPECTION IS CONDUCTED.

7. CONTRACTOR SHALL RECYCLE MATERIALS AS FEASIBLE AND IN ACCORDANCE WITH THE CONSTRUCTION ACTIVITIES MANAGEMENT PLAN.

TRAFFIC NOTES:

1. NO SITE WORK SHALL BEGIN PRIOR TO THE INSTALLATION OF THE APPROPRIATE CONSTRUCTION SIGNAGE AND TRAFFIC CONTROL DEVICES.

2. ALL TRAFFIC CONTROL DEVICES SHALL CONFORM TO THE CURRENT EDITION OF THE CALIFORNIA MANUAL ON UNIFORM TRAFFIC CONTROL DEVICES.

3. AGGREGATE BASE:
   - 3.1. AGGREGATE BASE MATERIAL SHALL CONFORM TO THE APPLICABLE REQUIREMENTS OF SECTION 26 OF THE CALIFORNIA STATE STANDARD SPECIFICATIONS.
   - 3.2. AGGREGATE BASE AND SUBBASE MATERIAL SHALL BE COMPACTED TO A MINIMUM RELATIVE COMPACTION OF 95%. THE TOP 12 INCHES OF SUBGRADE BELOW AGGREGATE BASE GRADE SHALL BE COMPACTED TO A MINIMUM RELATIVE COMPACTION OF 95%.

4. ASPHALT:
   - 4.1. ASPHALT CONCRETE PACING SHALL CONFORM TO THE REQUIREMENTS FOR $\frac{3}{4}$ "TYPE B" ASPHALT CONCRETE AS SPECIFIED IN THE CURRENT EDITION OF THE STATE OF CALIFORNIA DEPARTMENT OF TRANSPORTATION STANDARD SPECIFICATIONS

STRUCTURAL NOTES:

1. THE CONTRACTOR SHALL VERIFY ALL SPECIFIED DIMENSIONS AND SPECIFIED ELEVATIONS PRIOR TO CONSTRUCTION AND ASSEMBLY. FIELD MEASUREMENTS AND SURVEYS MUST BE UTILIZED TO VERIFY SUCH DIMENSIONS.

2. ANY ALTERATIONS BETWEEN APPROVED PLAN SET SHALL BE VERIFIED BY THE ENGINEER.

ENVIRONMENTAL NOTES:

1. CONTRACTOR SHALL LIMIT DUST AND EXCESSIVE NOISE DURING CONSTRUCTION.

2. IN THE EVENT THE SOUND BARRIERS DO NOT PROVIDE SUFFICIENT NOISE PROTECTION FOR THE ADJACENT PROPERTIES, THE DESIGNATED SAFETY MANAGER MAY FORM A REVISED NOISE PROTECTION PLAN. PRIOR TO IMPLEMENTATION OF THE NEW PLAN, CONSULTATION WITH THE OWNER MUST OCCUR IF NEW PLAN EXCEEDS THE COST OF THE EXISTING CONTINGENCY BUDGET.

3. THE CONTRACTOR SHALL USE AN EROSION CONTROL PLAN DURING ALL PORT SITE CONSTRUCTION WORK.

4. IF ANY ARCHEOLOGICAL RESOURCES ARE DISCOVERED DURING CONSTRUCTION, ALL CONSTRUCTION ACTIVITIES MUST CEASE IMMEDIATELY, THE RESOURCES MUST BE DOCUMENTED, AND THE PROPER AUTHORITIES NOTIFIED. ALL CONSTRUCTION MAY RESUME AFTER THE RESOURCES EXHUMED AND THE PROPER AUTHORITIES HAVE SENT WRITTEN CONSENT THAT CONSTRUCTION MAY CONTINUE.

EMERGENCY ACCESS:

1. IN THE EVENT THAT PROJECT CONSTRUCTION CONTINUES DURING WET WINTER MONTHS, CONTRACTOR SHALL MAKE EVERY EFFORT TO MAINTAIN OR WINTERIZE THE ROADS FOR EMERGENCY VEHICLES.

2. IN THE EVENT OF A FIRE EMERGENCY ON SITE OR ON AN ADJACENT PROPERTY, HYDRANTS MUST REMAIN ACCESSIBLE AND A PORTION OR SECTION OF WATER LINES MAY BE PUT INTO OPERATION FOR FIRE PROTECTION.

FLOATING OFFSHORE WIND TURBINE FARM

WIND WRANGLER ENGINEERING SERVICES

SHEET NAME: GENERAL NOTES

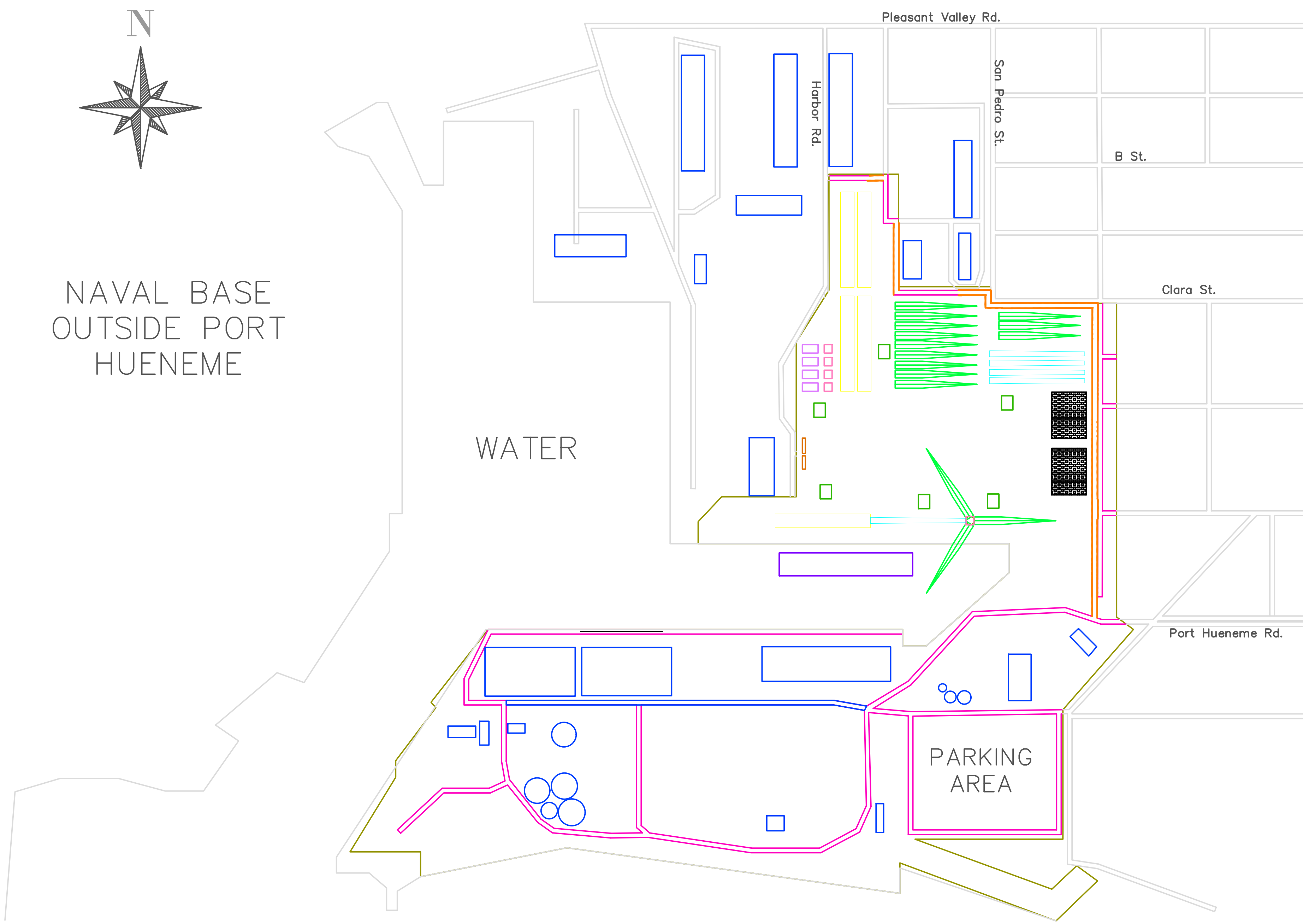
SHEET NO: C-1

SCALE: NO SCALE

DATE: 05.22.2023

CREATED BY: AY

CHECKED BY: CH



SITE PLAN: PORT HUENEME

SCALE: 1:7000

REGIONAL MAP

SCALE: NOT TO SCALE

LEGEND

- Port Hueneme Boundary
- Vicinity Area Roads
- Existing Roadway On Site
- Existing Buildings
- Turbine Blade
- Turbine Tower
- Turbine Hub
- Turbine Nacelle
- Highway Jersey Barrier
- Crawler Crane
- Jackup Vessel
- Temporary Warehouse
- Job Site Trailer & Restrooms

FLOATING OFFSHORE WIND TURBINE FARM

WIND WRANGLER ENGINEERING SERVICES

SHEET NAME: SITE PLAN – PORT

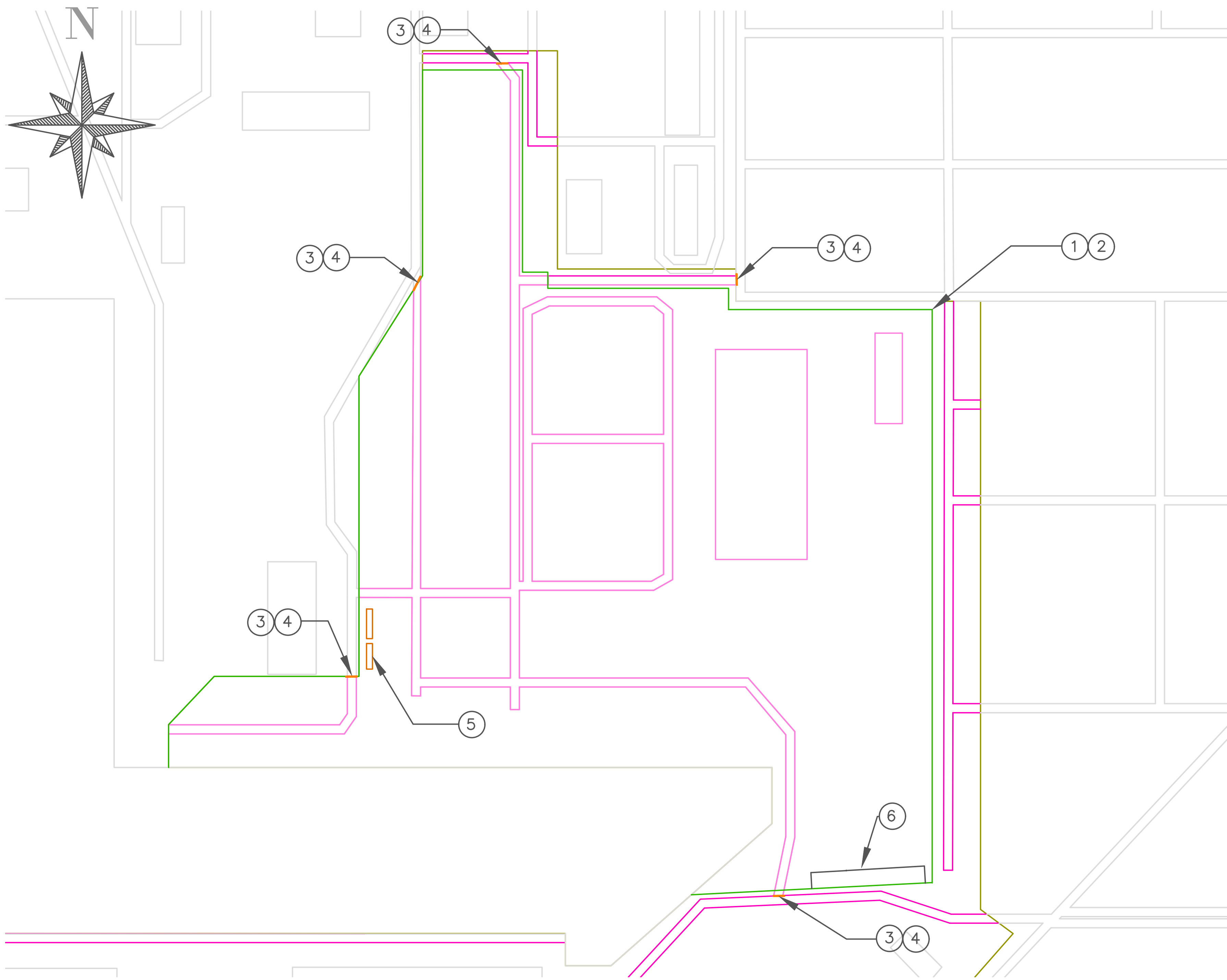
SHEET NO: C-2

SCALE: 1:7000

DATE: 05.22.2023

CREATED BY: AY

CHECKED BY: CH



PHASE 2: MOBILIZATION 1 PLAN – PORT

SCALE: 1:3500

LEGEND

- Port Hueneme Boundary
- Vicinity Area
- Existing Roads on Port
- Existing Site Features
- Highway Jersey Barrier
- Temporary Construction Fencing
- Job Site Trailer & Restrooms

GENERAL NOTES

1. Install temporary construction fencing.
2. Install temporary sound barriers along the construction fencing.
3. Install Highway Jersey barriers to block off roads from access to the site prior to road rerouting barriers are installed.
4. Install traffic control and road closure signage.
5. Install job site trailer and restrooms.
6. Construction fence throughway gate opening for deliveries, equipment, and people.

FLOATING OFFSHORE WIND TURBINE FARM

WIND WRANGLER ENGINEERING SERVICES

SHEET NAME:
PHASE 2: MOBILIZATION 1 PLAN – PORT

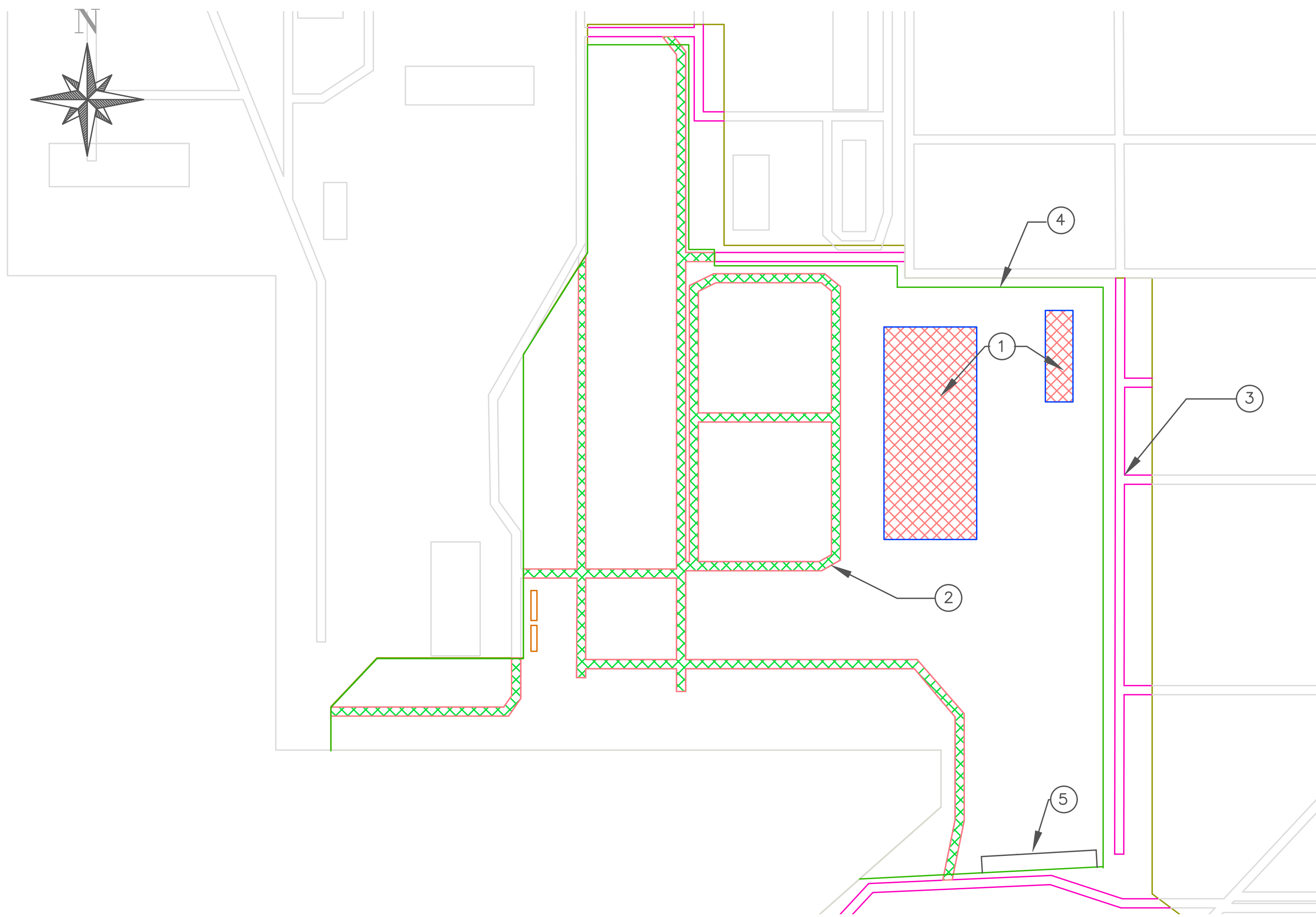
SHEET NO:
C-3

SCALE: 1:3500

DATE: 05.22.2023

CREATED BY: AY

CHECKED BY: CH



PHASE 2: DEMOLITION PLAN – PORT

SCALE: 1:3500

LEGEND

- Existing Road Demolition
- Existing Building Demolition
- Existing Roadway On Site
- Existing Buildings
- Port Hueneme Boundary
- Vicinity Area Roads

GENERAL NOTES

1. Existing building to be demolished.
2. Existing road to be demolished.
3. Existing port roads to remain
4. Construction fencing & sound proofing
5. Construction fence throughway gate opening for deliveries, equipment, and people.

FLOATING OFFSHORE WIND TURBINE FARM

WIND WRANGLER ENGINEERING SERVICES

SHEET NAME:
PHASE 2: DEMOLITION PLAN – PORT

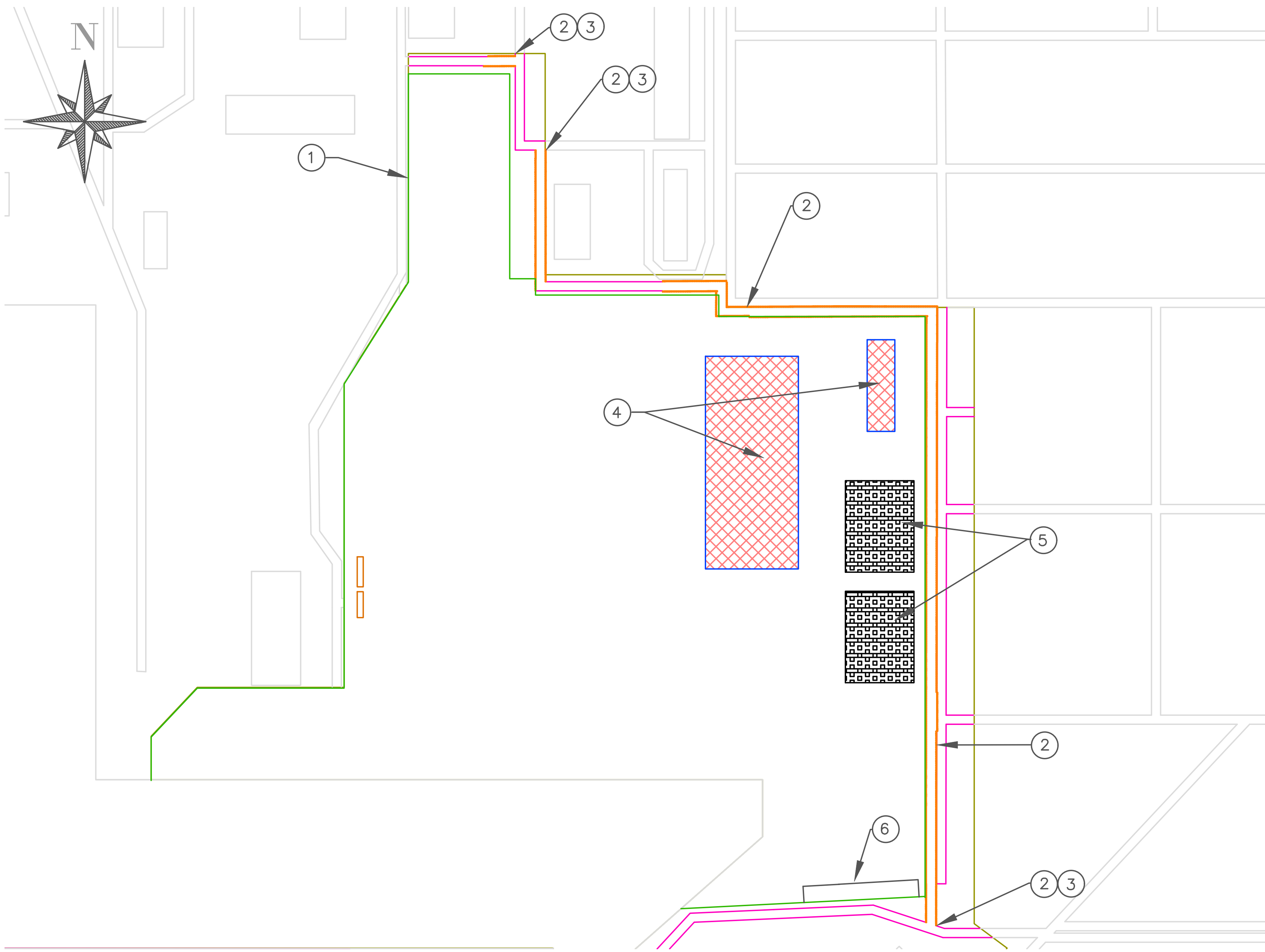
SHEET NO:
C-4

SCALE: 1:3500

DATE: 05.22.2023

CREATED BY: AY

CHECKED BY: CH



PHASE 2: SITE WORK PLAN – PORT

SCALE: 1:3500

LEGEND

- Port Hueneme Boundary
- Vicinity Area
- Existing Roads on Port
- Demolished Building Footprint
- Pavement Fill Area
- Temporary Warehouse
- Highway Jersey Barrier
- Temporary Construction Fencing
- Job Site Trailer & Restrooms

GENERAL NOTES

1. Construction fencing and sound proofing.
2. Install Highway Jersey barriers to reroute roads to be around the construction site.
3. Install traffic signage for rerouted roads.
4. Fill in building footprint area of demolished warehouses with asphalt pavement.
5. Install prefabricated temporary storage warehouses.
6. Construction fence throughway gate opening for deliveries, equipment, and people.

FLOATING OFFSHORE WIND TURBINE FARM

WIND WRANGLER ENGINEERING SERVICES

SHEET NAME:
PHASE 2:
SITE WORK PLAN – PORT

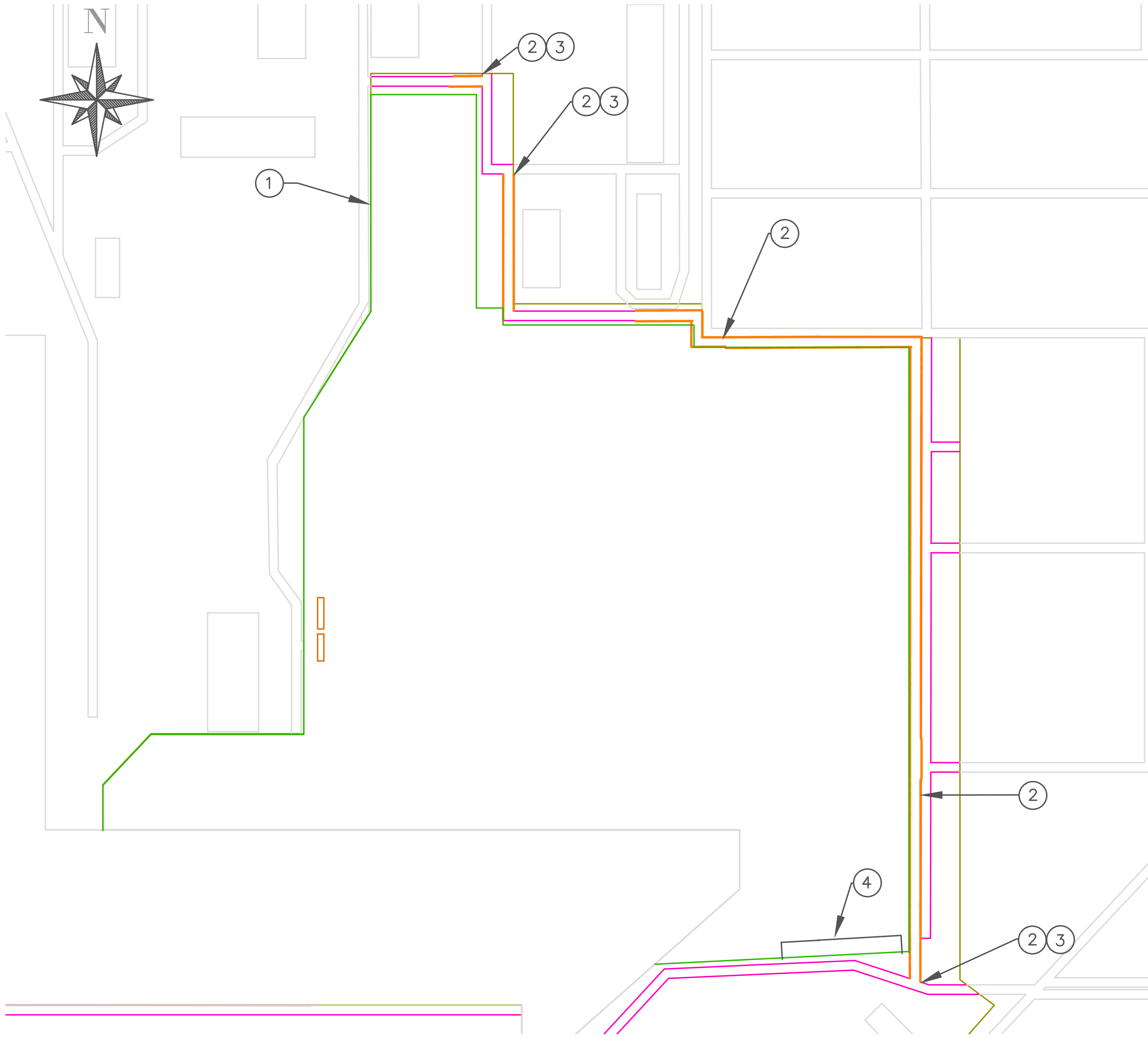
SHEET NO:
C-5

SCALE: 1:3500

DATE: 05.22.2023

CREATED BY: AY

CHECKED BY: CH



PHASE 2: TRAFFIC CONTROL PLAN – PORT

SCALE: 1:3500

LEGEND

- Port Hueneme Boundary
- Vicinity Area
- Existing Roads on Port
- Highway Jersey Barrier
- Temporary Construction Fencing
- Job Site Trailer & Restrooms

GENERAL NOTES

1. Construction fencing and sound proofing.
2. Install Highway Jersey barriers to reroute roads to be around the construction site.
3. Install traffic signage for rerouted roads.
4. Construction fence throughway gate opening for deliveries, equipment, and people.

FLOATING OFFSHORE WIND TURBINE FARM

WIND WRANGLER ENGINEERING SERVICES

SHEET NAME:
PHASE 2: TRAFFIC CONTROL PLAN –PORT

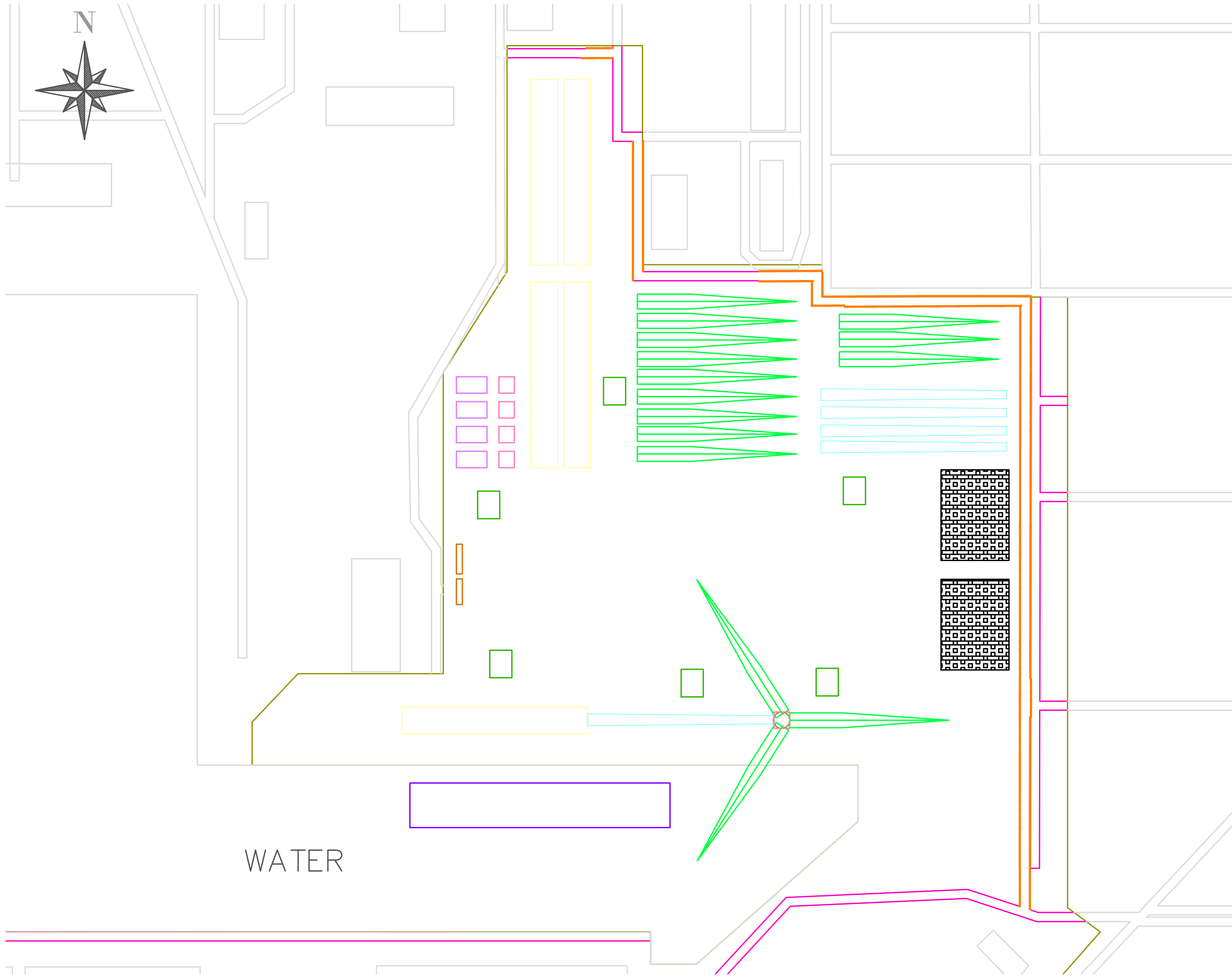
SHEET NO:
C-6

SCALE: 1:3500

DATE: 05.22.2023

CREATED BY: AY

CHECKED BY: CH



PHASE 3: ASSEMBLY AREA PLAN – PORT

SCALE: 1:3500

FLOATING OFFSHORE WIND TURBINE FARM

WIND WRANGLER ENGINEERING SERVICES

SHEET NAME: PHASE 3: ASSEMBLY AREA PLAN – PORT

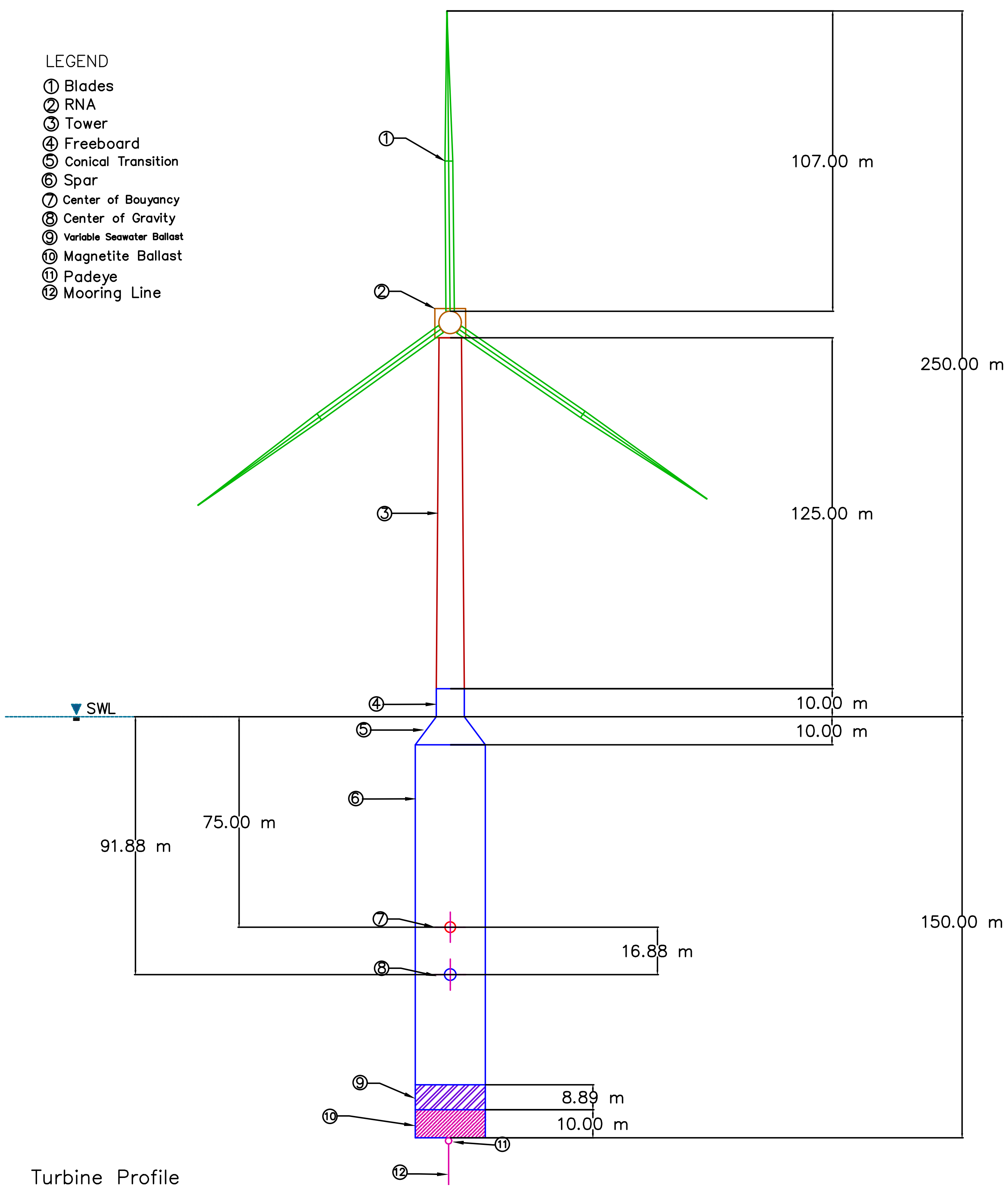
SHEET NO: C-7

SCALE: 1:3500

DATE: 05.22.2023

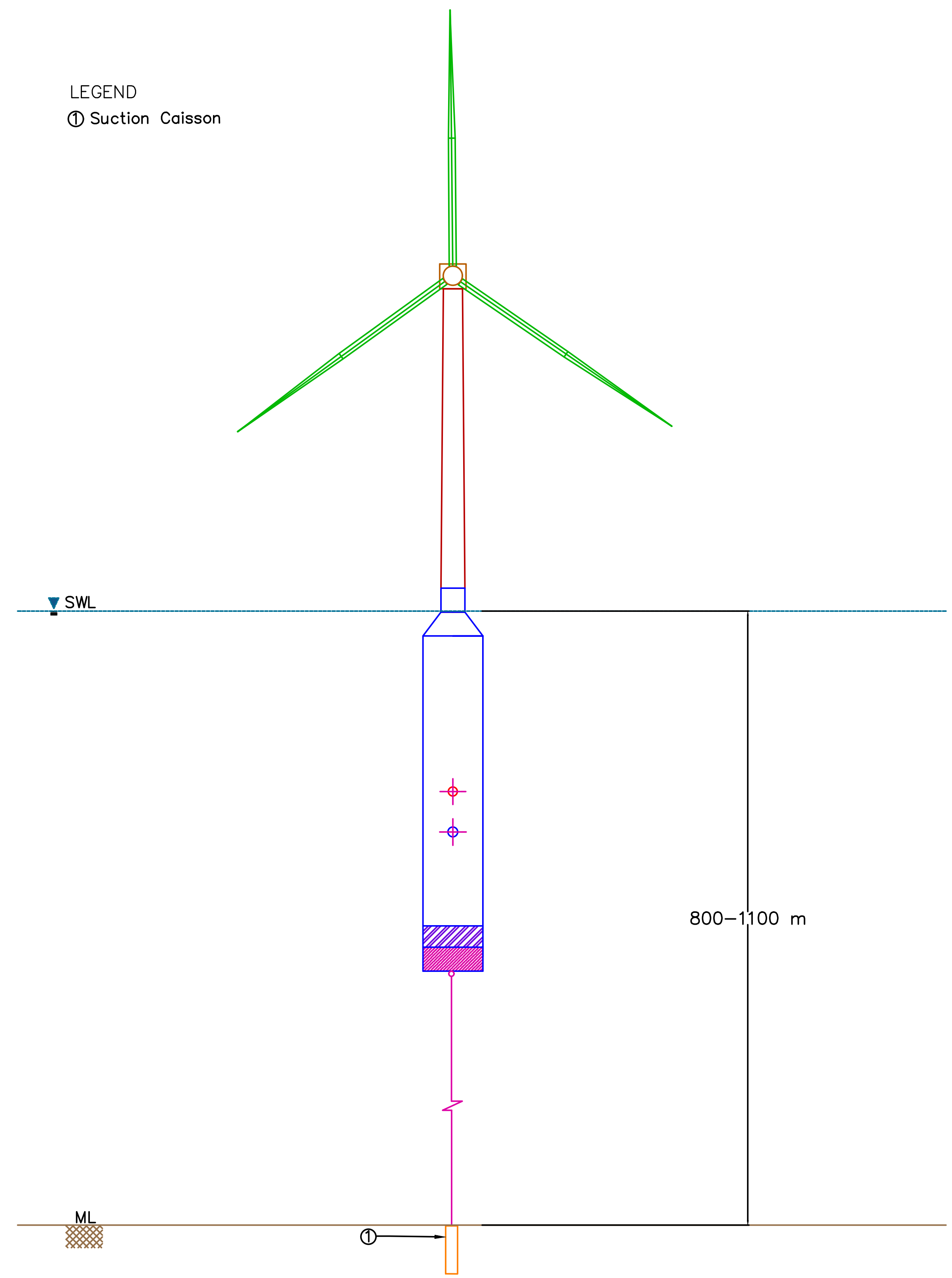
CREATED BY: AY

CHECKED BY: CH



Turbine Profile

Scale: 1:2000



Turbine with Suction Caisson Profile

Scale: 1:2500

FLOATING OFFSHORE WIND TURBINE FARM

WIND WRANGLER ENGINEERING SERVICES

SHEET NAME: STRUCTURAL PROFILES

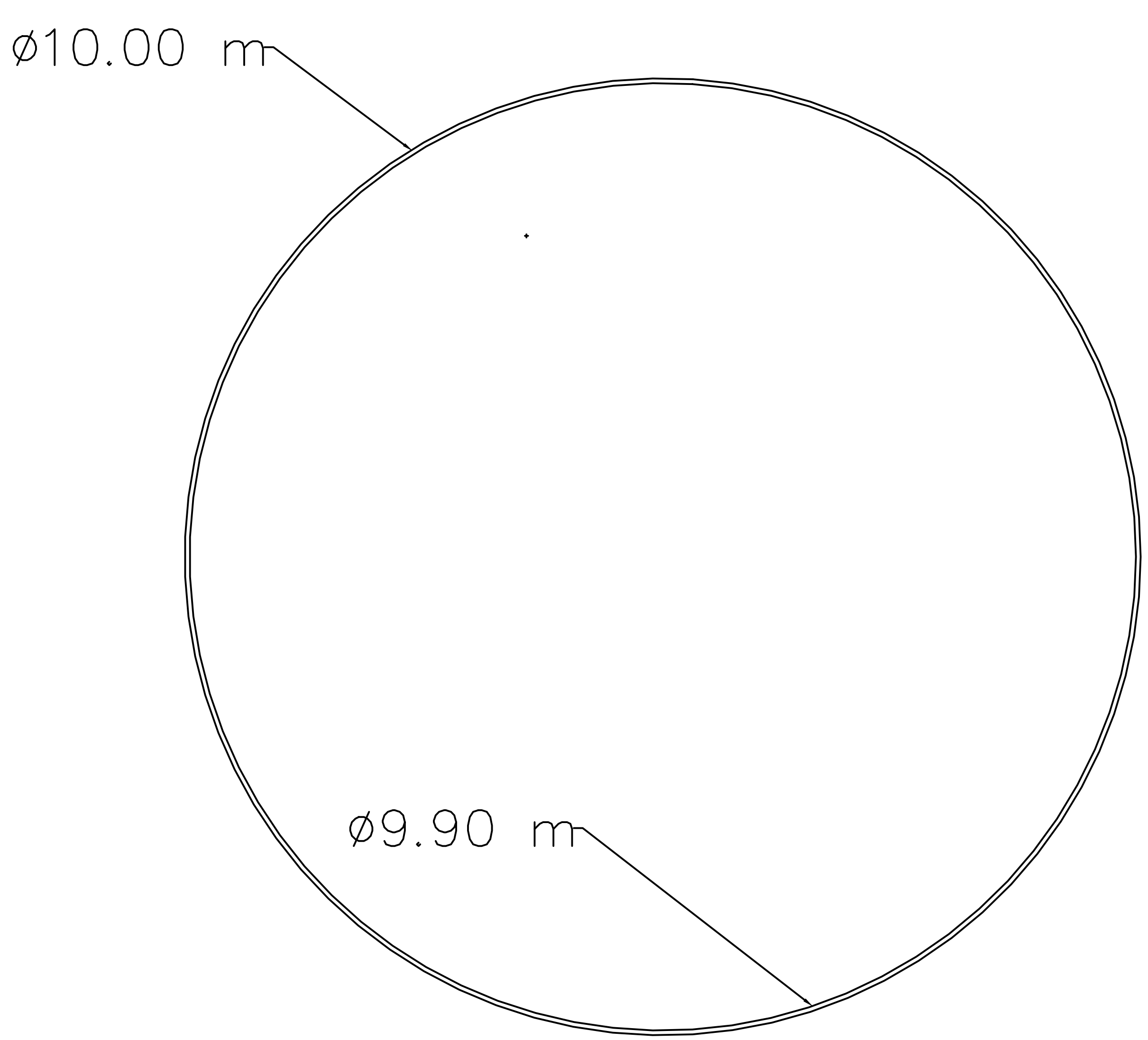
SHEET NO: S-1

SCALE: AS SHOWN

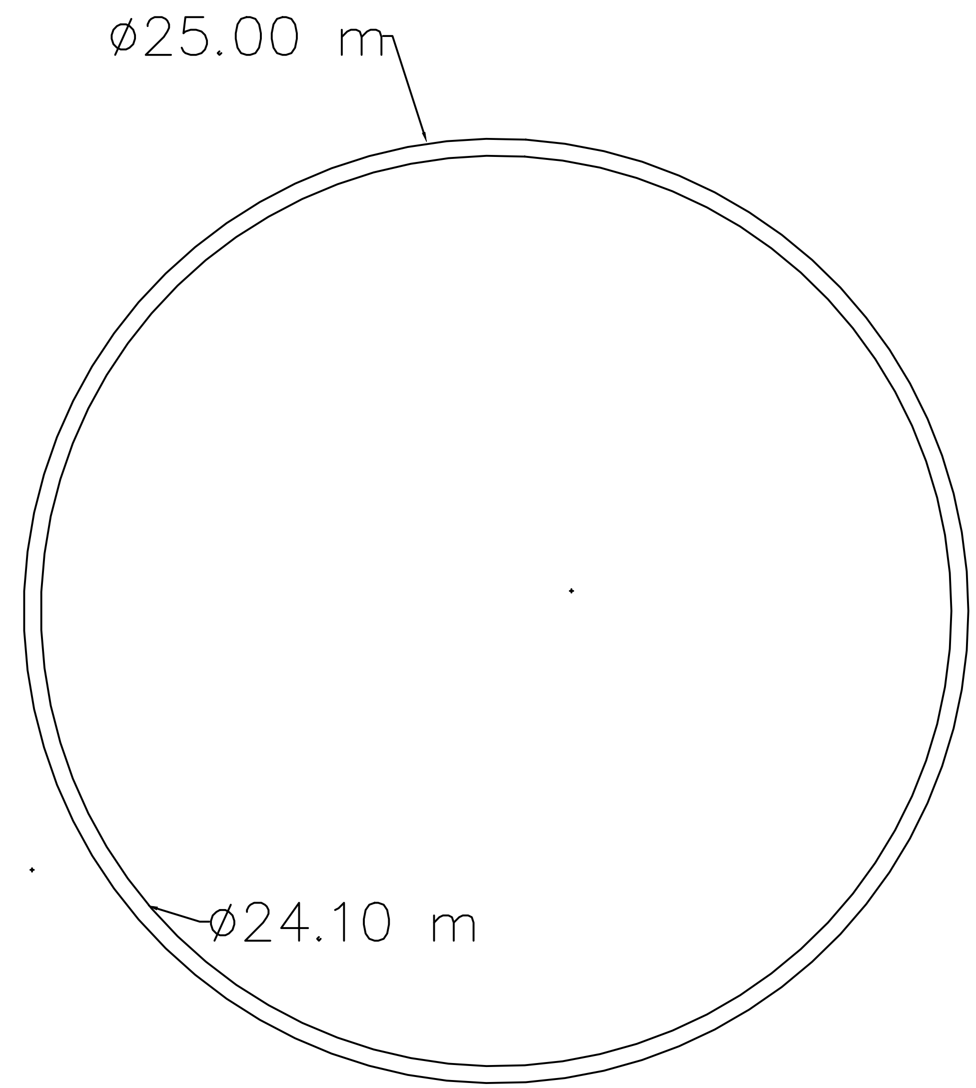
DATE: 05.22.2023

CREATED BY: CH

CHECKED BY: AY



3 Tower Section @ Widest Section
Scale: 1:250



4 Spar Section
Scale: 1:750

FLOATING OFFSHORE WIND TURBINE FARM

WIND WRANGLER ENGINEERING SERVICES

SHEET NAME:
STRUCTURAL SECTIONS

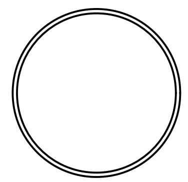
SHEET NO:
S-2

SCALE: AS SHOWN

DATE: 05.22.2023

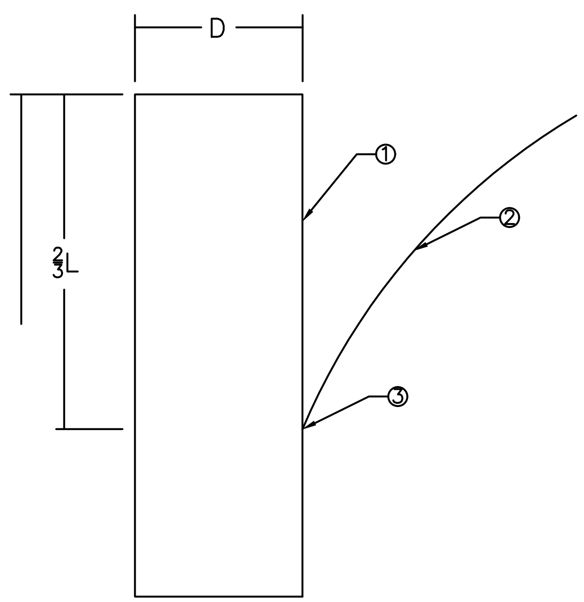
CREATED BY: CH

CHECKED BY: AY



Suction Caisson Plan

Scale: N/A



Suction Caisson Profile

Scale: N/A

Suction Caisson Design Recommendations					
Loading	L/D	Clay		Sand	
		Diameter (m)	Length (m)	Diameter (m)	Length (m)
18.106 MN (Design Load)	2	7.4	14.8	6.7	13.4
	3	5.9	17.7	5.6	16.8
	4	5.1	20.4	4.9	19.6
	5	4.5	22.5	4.5	22.5
20 MN (Extreme 1)	2	7.7	15.4	6.9	13.8
	3	6.1	18.3	5.8	17.4
	4	5.2	20.8	5.1	20.4
	5	4.7	23.5	4.6	23
22 MN (Extreme 2)	2	7.9	15.8	7.2	14.4
	3	6.3	18.9	5.9	17.7
	4	5.4	21.6	5.2	20.8
	5	4.8	24	4.8	24
24 MN (Extreme 3)	2	8.2	16.4	7.4	14.8
	3	6.5	19.5	6.1	18.3
	4	5.6	22.4	5.4	21.6
	5	5	25	4.9	24.5

Suction Caisson Dimension Schedule

Scale: N/A

LEGEND

L = length
D = outer diameter
① Suction Caisson
② Tether
③ Padeye

FLOATING OFFSHORE WIND TURBINE FARM

WIND WRANGLER ENGINEERING SERVICES

SHEET NAME: SUCTION CAISSON PLAN AND PROFILE VIEW

SHEET NO: G-1

SCALE: AS SHOWN

DATE: 05.22.2023

CREATED BY: CW

CHECKED BY: CH

APPENDIX B: STRUCTURAL

B.1:
ENVIRONMENTAL LOADS

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Note: All wind speed date from NOAA buoy 46028 historical data from NDBC station page

AVERAGE MONTHLY WIND SPEED (KNOTS)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	11.3	15.9	13.9	17.6	15.6	17.6	14.5					
1998								15.8	10.4	14.2	12.4	13.2
1999	11.4	12.1	14.6	15.8	19	16.5	13.4	15.1				
2000				15.7	17	11.3	16.9	14	11.5	11.9	13.1	9.1
2001	11.1	12.1	14.6	16.4	13.6	16.9	11.9	15.5	12	9.8	11.2	13.4
2002	13.2	9.7	11.8	12.7	17.1	19.6	12.3	11.8	11.9	9.9	9.3	10.8
2003	9	12.5	16.2	11.7	17.2	13.8	15.6	12.3	10.7	14.9	11	10.4
2004	12.6	12.2	13.9	13.1	16.3	17.3	11.4	12	13.9	12	11	9.8
2005	10.1	11.6	11.6	15.9	15.5	15.1	12.1	10.2	11.7	14	10.7	9.7
2006	11.9	11.1	11.1	11.6	16.3	15.4	13.3	11.2	10.6	9.1	14.7	10.9
2007	13.2	13.1	14.7	19.1	15.3	17.3	15.3	14.9	22.8			
2008			18.8	18	15.6	17.5	14.6	14.2	10.4	13.4	12.7	12.8

AVERAGE MONTHLY WIND SPEED (m/s)

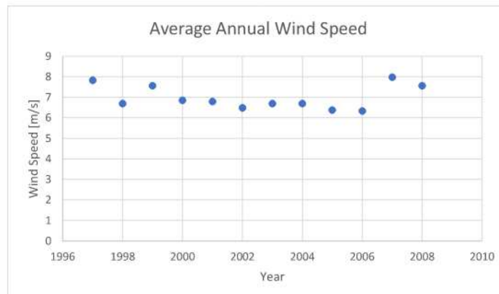
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	AVG
1997	5.812757202	8.179012346	7.150206	9.053498	8.024691	9.053498	7.458848						**7.81893**
1998								8.127572	5.349794	7.304527	6.378601	6.790123	**6.790123**
1999	5.864197531	6.224279835	7.510288	8.127572	9.773663	8.487654	6.893004	7.76749					**7.581019**
2000				8.076132	8.744856	5.812757	8.693416	7.201646	5.915638	6.121399	6.738683	4.68107	**6.887289**
2001	5.709876543	6.224279835	7.510288	8.436214	6.995885	8.693416	6.121399	7.973251	6.17284	5.041152	5.761317	6.893004	**6.79441**
2002	6.790123457	4.989711934	6.069959	6.532922	8.796296	10.0823	6.32716	6.069959	6.121399	5.092593	4.783951	5.555556	**6.434328**
2003	4.62962963	6.430041152	8.333333	6.018519	8.847737	7.098765	8.024691	6.32716	5.504115	7.664609	5.658436	5.349794	**6.657236**
2004	6.481481481	6.275720165	7.150206	6.738683	8.384774	8.899177	5.864198	6.17284	7.150206	6.17284	5.658436	5.041152	**6.665809**
2005	5.195473251	5.967078189	5.967078	8.179012	7.973251	7.76749	6.22428	5.246914	6.018519	7.201646	5.504115	4.989712	**6.352881**
2006	6.121399177	5.709876543	5.709877	5.967078	8.384774	7.921811	6.841564	5.761317	5.452675	4.68107	7.561728	5.606996	**6.310014**
2007	6.790123457	6.738683128	7.561728	9.825103	7.87037	8.899177	7.87037	7.664609	11.7284				**8.327618**
2008			9.670782	9.259259	8.024691	9.002058	7.510288	7.304527	5.349794	6.893004	6.532922	6.584362	**7.613169**
AVG	**5.932784636**	**6.304298125**	**7.263374**	**7.837636**	**8.347363**	**8.33801**	**7.075383**	**6.874299**	**6.476337**	**6.241427**	**6.064243**	**5.721308**	

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

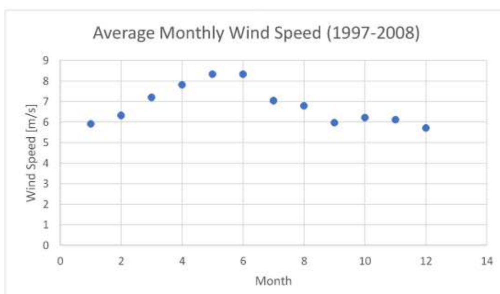
Average Annual Wind Speed

Year	Average Wind Speed [knot]	Average Wind Speed [m/s]
1997	15.2	7.818930041
1998	13	6.687242798
1999	14.7	7.561728395
2000	13.3	6.841563786
2001	13.2	6.790123457
2002	12.6	6.481481481
2003	13	6.687242798
2004	13	6.687242798
2005	12.4	6.378600823
2006	12.3	6.327160494
2007	15.5	7.973251029
2008	14.7	7.561728395



Monthly Average Wind Speed (1997-2998)

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind Speed [knot]	11.5	12.3	14	15.2	16.2	16.2	13.7	13.2	11.6	12.1	11.9	11.1
Wind Speed [m/s]	5.91563786	6.327160494	7.201646	7.81893	8.333333	8.333333	7.047325	6.790123	5.967078	6.22428	6.121399	5.709877



WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine	
Engineer: CH	Checked by: CW
Date: 5/22/2023	

Note: The weibull shape parameter is found using an online wind speed distribution tool

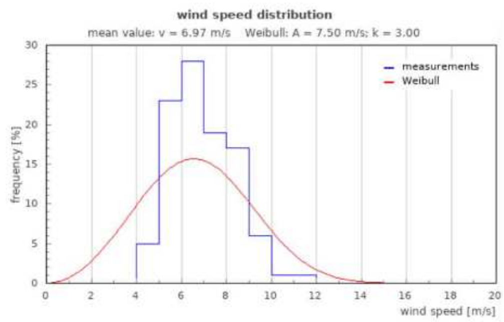
Bucket	Frequency	%
1	0	0%
2	0	0%
3	0	0%
4	0	0%
5	6	5%
6	28	23%
7	34	28%
8	23	19%
9	20	17%
10	7	6%
11	1	1%
12	1	1%
	0	
Total #	120	
Stdev	**1.371**	

Please enter the wind speed distribution into the table.

Class	Frequency in %
0 - 1 m/s	0.00
1 - 2 m/s	0.00
2 - 3 m/s	0.00
3 - 4 m/s	0.00
4 - 5 m/s	5.00
5 - 6 m/s	23.00
6 - 7 m/s	28.00
7 - 8 m/s	19.00
8 - 9 m/s	17.00
9 - 10 m/s	6.00
10 - 11 m/s	1.00
11 - 12 m/s	1.00
12 - 13 m/s	0.00
13 - 14 m/s	0.00
14 - 15 m/s	0.00
15 - 16 m/s	0.00
16 - 17 m/s	0.00
17 - 18 m/s	0.00
18 - 19 m/s	0.00
19 - 20 m/s	0.00
Sum	100.00

Refresh

Result



Source: https://wind-data.ch/tools/weibull.php?v0=0.00&v1=0&v2=0&v3=0&v4=5&v5=23&v6=28&v7=19&v8=17&v9=6&v10=1&v11=1&v12=0&v13=0&v14=0&v15=

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Environmental Load Calculations

$ton := 1000\ kg$

Turbine Parameters SG 14-222 DD		Refernece
Nominal Capacity	$14\ MW$	(Siemens Gamesa) SG 14-222 DD
Rotor Diameter	$D := 222\ m$	(Siemens Gamesa) SG 14-222 DD
Blade Length	$L_B := 107\ m$	(Siemens Gamesa) SG 14-222 DD
Rated Wind Speed	$U_R := 13\ \frac{m}{s}$	(Siemens Gamesa) SG 14-222 DD
Nacelle Mass:	$M_{nacelle} := 500000\ kg$	(Siemens Gamesa) SG 14-222DD
Blades Mass x3:	$M_{blades} := 165000\ kg$	(Siemens Gamesa) SG 14-222DD
Mass of RNA:	$M_{RNA} := M_{nacelle} + M_{blades}$	$M_{RNA} = 665000\ kg$
Mass of Tower	$m_t := 1493729\ kg$	(Preliminary Turbine Sizing Spreadsheet)
Tower Bottom Diameter	$D_b := 10\ m$	(Preliminary Turbine Sizing Spreadsheet)
Tower Top Diameter	$D_t := 8\ m$	(Preliminary Turbine Sizing Spreadsheet)
Hub Height Above Sea level	$z_{hub} := 135\ m$	(Preliminary Turbine Sizing Spreadsheet)
Hub Radius	$r_{hub} := 4\ m$	(Siemens Gamesa) SG 14-222 DD

Spar Parameters		
Lower Spar Diameter	$D_s := 25\ m$	(Preliminary Turbine Sizing Spreadsheet)
Coned Spar Diameter	$D_{s\_c} := 10\ m$	(Preliminary Turbine Sizing Spreadsheet)
Spar Draft	$B := 150\ m$	(Preliminary Turbine Sizing Spreadsheet)
Total Length	$L_T := 160\ m$	(Preliminary Turbine Sizing Spreadsheet)
Mass of the Ballast	$m_B := 2.28E+07\ kg$	(Preliminary Turbine Sizing Spreadsheet)
Mass of the Spar Buoy	$m_s := 4.45E+07\ kg$	(Preliminary Turbine Sizing Spreadsheet)

Center of Buoyancy below sea level	$z_B := 75$	(Preliminary Turbine Sizing Spreadsheet)
Volume of displacement	$V := 72060.28\ m^3$	(Preliminary Turbine Sizing Spreadsheet)

Wind Parameters

Weibull Distribution Shape Parameter	$\kappa := 3$	(Environmental Loading spreasheet) *note: site shows constant winds
Mean wind speed at the site	$\lambda := 8.5\ \frac{m}{s}$	(Project Background)
Wind Profile Exponent	$\gamma := \frac{1}{7}$	(typ value)
Surface Terrain	$z_0 := 0.0001$	DNV-RP-C205 (p. 16)- open sea with waves (most conservative case)
Turbulence scale parameter	$\Lambda_1 := 42\ m$	IEC 61400 (p. 25) where zhub>60m
Integral scale	$L_k := 8.1 \cdot \Lambda_1 = 340.2\ m$	IEC 61400 (p. 73) *note: most conservative scenerio used
Standard deviation	$\sigma_U := 1.371\ \frac{m}{s}$	(Environmental Loading spreasheet)
Turbulence Intensity	$I_{15} := \frac{\sigma_U}{\lambda} = 0.161$	DNV-RP-C205 (p. 14)
Density of Air	$\rho_a := 1.205\ \frac{kg}{m^3}$	DNV-RP-C205 (p. 123) @ 20 deg Celcius
Kinematic Viscosity of Air	$\nu_{air} := 1.50 \cdot 10^{-5}\ \frac{m^2}{s}$	DNV-RP-C205 (p. 123)@ 20 deg Celcius

Wave Parameters

Significant Wave Height	$H_{S50} := 10.1\ m$	(NOAA buoy data)
Peak Wave Period	$T_{S50} := 11.7\ s$	(NOAA buoy data) (4s-25s)
Density of Sea Water	$\rho_w := 1027.432\ \frac{kg}{m^3}$	@ 6.2 deg Celsius (Ibrahim, p. 6)
Water Depth	$S := 1100\ m$	(Project Background)
Kinematic Viscosity of Sea water	$\nu_{sea\_water} := 1.51 \cdot 10^{-6}\ \frac{m^2}{s}$	@ 6.2 deg Celsius (Ibrahim, p. 6)

Table F-1 Density and viscosity of fresh water, sea water and dry air

Temperature [°C]	Density, ρ, [kg/m³]			Kinematic viscosity, ν, [m²/s]		
	Fresh water	Sea water*	Dry air**	Fresh water	Sea water*	Dry air
0	999.8	1028.0	1.293	1.79×10^{-6}	1.83×10^{-6}	1.32×10^{-5}
5	1000.0	1027.6	1.270	1.52	1.56	1.36
10	999.7	1026.9	1.247	1.31	1.35	1.41
15	999.1	1025.9	1.226	1.14	1.19	1.45
20	998.2	1024.7	1.205	1.00	1.05	1.50
25	997.0	1023.2	1.184	0.89	0.94	1.55
30	995.6	1021.7	1.165	0.80	0.85	1.60

*) Salinity = 35 parts per thousand

**) The air density applies for a pressure of 1.013×10^5 Pa.

DNV-RP-C205 (see page 123)

Methodology

ULS load combinations defined in DNVGL-ST-0437

(E-1) the combination of the 50-year extreme wind speed (with the turbine shut down) and the maximum wave load due to the 50-year extreme wave height

(E-2) the combination of the maximum wind load due to Extreme Operating Gust (EOG) at rated wind speed and the 1-year extreme wave height

Wind Load on the Rotor (Thrust)

A simplified way to calculate the quasi-static approximation of the wind load is assuming that the wind speed is the sum of a mean wind speed component and a turbulent wind component. U=UR+uEOG

-The maximum wind load acts when the wind turbine is operating at the rated wind speed UR where the thrust curve reaches its maximum.

-(E-2) The maximum wind load is then given by the scenario when the wind turbine is operating at the rated wind speed and the 50-year extreme operating gust (EOG) when wind speed magnitude uEOG his the rotor.

Maximum wind load due to EOG at rated wind speed: $F_{u,EOG} = \frac{1}{2}\rho_a A_R C_T (U_R + u_{EOG})^2$

Rotor thrust according to DNV-OS-J103: $F_{thrust} = \frac{1}{2} \cdot \rho \cdot C_T \cdot A_{rotor} \cdot U_{10}^2$

50-year return period 10-min mean wind speed $U_{10\_50yr} := \lambda \cdot \left(-\ln\left(1 - 0.98^{\frac{1}{52596}}\right)\right)^{\frac{1}{\kappa}} = 20.856 \ \frac{m}{s}$

1-year return period 10-min mean wind speed $U_{10\_1yr} := 0.8 \cdot U_{10\_50yr} = 16.685 \ \frac{m}{s}$

50-year extreme operating gust speed at the rated wind speed

turbulence scale parameter $turb := \frac{L_k}{8.1} = 42 \ m$

characteristic standard deviation of wind speed $\sigma_{U\_c} := 0.11 \cdot U_{10\_1yr} = 1.835 \ \frac{m}{s}$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

$$u_{EOG} := min\left(1.35\ (U_{10\_1yr} - U_R),\ \frac{3.3 \cdot \sigma_{U\_c}}{1 + \frac{0.1 \cdot D}{turb}}\right) = 3.962\ \frac{m}{s}$$

Wind load due to the EOG at the rated wind speed- thrust force generated by wind perpendicular to the swept area of the blades

rotor swept area $A_R := \frac{D^2\ \pi}{4} = 38707.563\ m^2$

thrust coefficient $C_T := \frac{3.5\left(2\ U_R + 3.5\ \frac{m}{s}\right)}{{U_R}^2} \cdot \frac{m}{s} = 0.611$

$$F_{u\_EOG} := \frac{1}{2}\ \rho_a \cdot A_R \cdot C_T \cdot \left(U_R + u_{EOG}\right)^2 = 4.099\ MN \qquad \text{(E-2)}$$

-(E-1) During the 50-year extreme wind speed, the turbine is shut down. Therefore, the thrust load reduces to the wind drag force on the tower, blades and hub.

-If the wind speed is assumed to be constant with height (no wind shear) then the wind drag load in the 50-year extreme may be written as

Tower Drag

Wind drag load in 50-year extreme $F_{u,U50} = \frac{1}{2}\rho_a(3A_B C_{DB} + A_H C_{DH})U^2_{10,50yr} + F_{DT}(U_{10,50yr})$

Face area of a blade $A_B := L_B \cdot 5\ m = 535\ m^2$

Face area of the hub $A_H := \pi \cdot {r_{hub}}^2 = 50.265\ m^2$

Drag coefficient of the blade $C_{DB} := 0.45$

*note: maxiumum drag coefficent considered for airfoil type

Drag coefficient of the hub $C_{DH} := 1.16$

7. Rounded nose section	L/D	C_D
	0.5 1.0 2.0 4.0 6.0	1.16 0.90 0.70 0.68 0.64

DNV-RP-C205 Appendix E (see page 121)

Drag coefficient of tower circular cross section $C_{DT} := 0.5$ Assume long smooth circular cylinder
*note: conseravative value chosen

$$R_{e\_tow} := \frac{U_{10\_50yr} \cdot D_b}{\nu_{air}} = 1.39 \cdot 10^7$$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Drag force on tower $F_{DT} := \frac{1}{2} \cdot \rho_a \cdot C_{DT} \cdot U_{10\_50yr}{}^2 \cdot z_{hub} \cdot \frac{D_b + (2\ \gamma + 1) \cdot D_t}{(2\ \gamma + 1) \cdot (2\ \gamma + 2)} = 0.122\ MN$

Drag force on tower at rated wind speed $F_{DT\_UR} := \frac{1}{2} \cdot \rho_a \cdot C_{DT} \cdot U_R{}^2 \cdot z_{hub} \cdot \frac{D_b + (2\ \gamma + 1) \cdot D_t}{(2\ \gamma + 1) \cdot (2\ \gamma + 2)} = 0.047\ MN$

Wind load on the shut down structure in the 50-year extreme wind speed

$$F_{u\_U50} := \frac{1}{2} \cdot \rho_a \cdot (3 \cdot A_B \cdot C_{DB} + A_H \cdot C_{DH}) \cdot U_{10\_50yr}{}^2 + F_{DT} = 0.327\ MN \qquad \text{(E-1)}$$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Wave and current loads

Wave Loads

Diameter $D_D := D_b = 10\ m$ $D_I := D_b = 10\ m$

50-Year Extreme:

50-year significant wave period: $T_{S50} = 11.7\ s$

Number of waves in a 3-h sea state $N_{50} := \frac{10800\ s}{T_{S50}} = 923.077$

50-year extreme wave height: $H_{M50} := H_{S50} \cdot \sqrt{\frac{1}{2} \ln\left(N_{50}\right)} = 18.661\ m$

Linear (Airy) wave theory is chosen as this floating tubrine will be installed in deep water where the linear approximation is more appropriate.

The drag load in highest when the surace elevation is maximal, the inerta load is highest when the surface elevation is zero. Therefore, the maximum drag load and interia load occur at different time instants, although calcualting the maxima seperatley and them summing them to obstain the total wave force is a conservative approach.

Surface elevation: $\eta_D := \frac{H_{M50}}{2} = 9.331\ m$ $\eta_I := 0\ m$

Wave length: $\lambda_{wave} := \frac{g \cdot T_{S50}^{\ 2}}{2\ \pi} = 213.655\ m$

Wave number: $k := \frac{2\ \pi}{\lambda_{wave}} = 0.029\ \frac{1}{m}$

Water depth: $S = 1100\ m$

Use Morision's equation for wave load calculation

$$F = \underbrace{\rho C_m V \dot{u}}_{F_I} + \underbrace{\frac{1}{2} \rho C_d A u |u|}_{F_D},$$

(the sum of drag and interia force of the wave)

The maximum of the drag load for the 50-year extreme wave height

Drag coefficent on the spar: $C_{D\_spar} := 1$ *note: conservative value was chosen

$v_{wave} := \lambda_{wave} \cdot \frac{1}{T_{S50}} = 18.261\ \frac{m}{s}$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

$$R_{e\_spar} := \frac{v_{wave} \cdot D_D}{\nu_{sea\_water}} = 1.209 \cdot 10^8$$

$$P_D := \frac{1}{8\,k} \cdot \left(e^{2k \cdot \left(S + \frac{H_{M50}}{2}\right)} - e^{-2k \cdot \left(S + \frac{H_{M50}}{2}\right)} - e^{2k \cdot (S-B)} + e^{-2k \cdot (S-B)} \right) + \frac{H_{M50}}{4} + \frac{B}{2} = 921881750851580000000000000\ m$$

$$F_{D\_max\_50yr} := \frac{1}{2} \cdot \rho_w \cdot D_D \cdot C_{D\_spar} \cdot \frac{\pi^2\ H_{M50}{}^2}{T_{S50}{}^2\ (\sinh(k \cdot S))^2} \cdot P_D = 3.796\ MN$$

The maximum of the 50-year intertia load

Added mass coefficient: Per DNV-RP-C205 (see page 58), the added mass coefficient for a surface piercing vertical cylinder for long periods is given by

$$C_A := 1$$

Inertia coefficient: $C_m := 1 + C_A = 2$ DNV-RP-C205 (pg. 52)

$$A_p := \frac{D_I{}^2 \cdot \pi}{4} = 78.54\ m^2$$

$$P_I := \frac{\sinh(k \cdot S) - \sinh(k \cdot (S-B))}{k} = 1880022375802090\ m$$

$$F_{I\_max\_50yr} := 2\ \pi^2 \cdot C_m \cdot \rho_w \cdot A_p \cdot \frac{H_{M50}}{T_{S50}{}^2\ \sinh(k \cdot S)}\ P_I = 14.588\ MN$$

50-year extreme wave load: $F_{w\_50yr} := F_{I\_max\_50yr}$ $F_{w\_50yr} = 14.588\ MN$ (E-1)

1-Year Extreme

1-year significant wave height $H_{S1} := 0.8 \cdot H_{S50}$

1-year significant wave period $T_{S1} := 11.1 \cdot \sqrt{\frac{H_{S1}}{g}} = 10.076\ s$

Number of waves in a 3-h sea state $N_1 := \frac{10800\ s}{T_{S1}} = 1071.903$

1-year extreme wave height $H_{M1} := H_{S1} \cdot \sqrt{\frac{1}{2} \ln(N_1)} = 15.092\ m$

Surface elevation: $\eta_D := \frac{H_{M1}}{2} = 7.546\ m$ $\eta_I := 0\ m$

Wave length: $\lambda_{wave} := \frac{g \cdot T_{S1}{}^2}{2\ \pi} = 158.445\ m$

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Wave number: $k := \dfrac{2\,\pi}{\lambda_{wave}} = 0.04\,\dfrac{1}{m}$

Water depth: $S = 1100\ m$

Use Morision's equation for wave load calculation

$$F = \underbrace{\rho\, C_m\, V\, \dot{u}}_{F_I} + \underbrace{\frac{1}{2}\,\rho\, C_d\, A\, u\, |u|}_{F_D},$$

(the sum of drag and interia force of the wave)

The maximum of the drag load for the 50-year extreme wave height

Drag coefficent on the spar: $C_{D\_spar} := 1$

$$v_{wave} := \lambda_{wave} \cdot \frac{1}{T_{S1}} = 15.726\ \frac{m}{s}$$

$$R_{e\_spar} := \frac{v_{wave} \cdot D_D}{\nu_{sea\_water}} = 1.041 \cdot 10^{8}$$

$$P_D := \frac{1}{8\,k} \cdot \left(e^{2k \cdot \left(S + \frac{H_{M1}}{2}\right)} - e^{-2k \cdot \left(S + \frac{H_{M1}}{2}\right)} - e^{2k \cdot (S - B)} + e^{-2k \cdot (S - B)}\right) + \frac{H_{M1}}{4} + \frac{B}{2} = 443803336804740000000000000000000000000\ m$$

$$F_D := \frac{1}{2} \cdot \rho_w \cdot D_D \cdot C_{D\_spar} \cdot \frac{\pi^2\ H_{M1}{}^2}{T_{S1}{}^2\ (\sinh(k \cdot S))^2} \cdot P_D = 2.609\ MN$$

The maximum of the 1-year intertia load

Added mass coefficient: Per DNV-RP-C205 (see page 58), the added mass coefficient for a surface piercing vertical cylinder for long periods is given by

$C_A := 1$

Inertia coefficient: $C_m := 1 + C_A = 2$ DNV-RP-C205 (pg. 52)

$$A_p := \frac{D_I{}^2 \cdot \pi}{4} = 78.54\ m^2$$

$$P_I := \frac{\sinh(k \cdot S) - \sinh(k \cdot (S - B))}{k} = 110629173121586000000\ m$$

$$F_{I\_max\_50} := 2\,\pi^2 \cdot C_m \cdot \rho_w \cdot A_p \cdot \frac{H_{M1}}{T_{S1}{}^2\ \sinh(k \cdot S)}\ P_I = 11.911\ MN$$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Total wave load: $F_{w\_1yr} := F_{I\_max\_50}$ $F_{w\_1yr} = 11.911\ MN$ (E-2)

Current Load Calculation:

Diameter of spar: $D_p := D_s = 25\ m$

Constant velocity profile: $v_c := 0.05 \cdot U_{10\_50yr} = 1.043\ \frac{m}{s}$ (conservative estimate)

Drag coefficient of spar: $C_{DP} := 1$

$$R_{e\_spar} := \frac{v_c \cdot D_s}{\nu_{sea\_water}} = 1.727 \cdot 10^7$$

Current Load: $F_C := \frac{1}{2} \cdot \rho_w \cdot D_p \cdot C_{DP} \cdot {v_c}^2 \cdot B = 2.095\ MN$

Total Loads:

(E-1) $F_{E\_1} := F_{u\_U50} + F_{w\_50yr} + F_C = 17.01\ MN$

Wind: $F_{u\_U50} = 0.327\ MN$
Wave: $F_{w\_50yr} = 14.588\ MN$
Current: $F_C = 2.095\ MN$

(E-2) $F_{E\_2} := F_{u\_EOG} + F_{w\_1yr} + F_C = 18.106\ MN$ **GOVERNS**

Wind: $F_{u\_EOG} = 4.099\ MN$
Wave: $F_{w\_1yr} = 11.911\ MN$
Current: $F_C = 2.095\ MN$

B.2:
HULL SIZE AND STABILITY

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Spar Hull	S420	
D_o	25	m
R_o	12.5	m
t	0.45	m
D_i	24.1	m
R_i	12.05	m
Area	34.71	m^2
Total Length	160	m
Draft	150	m
Main Spar Volume	4858.94	m^3
Displacement	68722.34	m^3
Conical Transition length	10	m
Conical Transition t	0.45	m
Top D_o	10	m
Top D_i	9.1	m
Top R_o	5	m
Top R_i	4.55	m
Conical Transition vol	241.04	m^3
Displacement	2552.54	m^3
Freeboard	10	m
Freeboard volume	135.01	m^3
Displacement	785.40	m^3
Total Spar Volume	5234.99	m^3
Total Spar Mass	44497439.81	kg
Displacement	72060.28	m^3
Buoyancy Force	7.39E+07	kg
CoB	**-75**	**m**

Fixed Ballast		
Magnetite height	10	m
r_i	12.05	m
Mass	22808355.36	kg
CoG	-145	m
Volume	4561.7	m^3

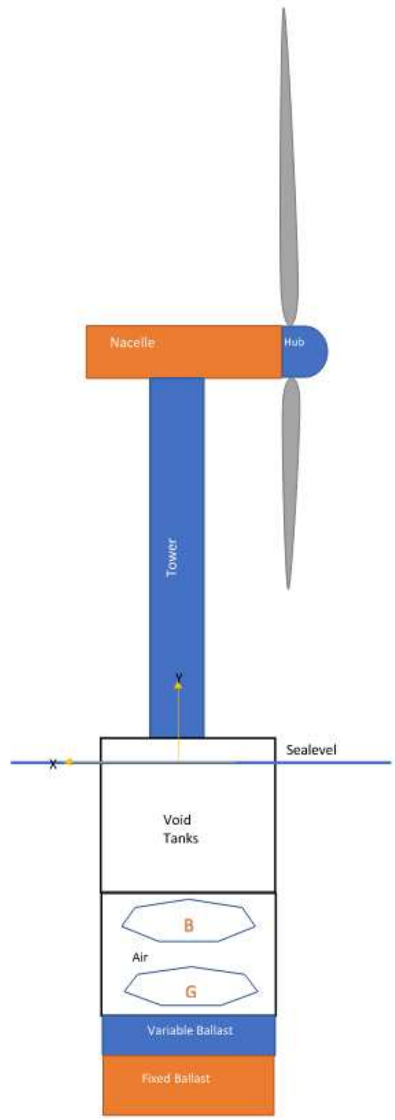
*note: height of ballast chosen through iterative process to ensure sufficent restoring moment

Variable Ballast		
Seawater Height	8.89	m
r_i	12.05	
Mass	4154764.227	kg
CoG	-135.5570794	m
Volume	4053.43	m^3

*note: length of variable ballast iterated to achieve neutral buoancy

Spar Hull Mass		
Mass	44497439.81	kg
CoG	-70	m
Mass Spar + Ballast	67305795	kg

Wind Turbine- 14 MW		
Rotor and Nacelle	SG 14-222DD	
Hub Height	135	m
Nacelle Mass	600000	kg
Blades Mass x3	165000	kg
RNA Mass	765000	kg
CoG	135	m
Nacelle Width	11	m
Nacelle Height	10.4	m
Nacelle Length	20.6	m
Hub Radius	4	m



Tower	S420	
Bottom D_o	10	m
Top d_o	8	m
Bottom R_o	5	m
Top r_o	4	m
Bottom R_i	4.95	m
Top r_i	3.95	m
Tower Height	125	m
Tower Thickness	0.05	m
Volume	175.73	m^3
Tower Mass	1493729	kg
CoG Tower	72.5	m

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Properties

Seawater Density	1025	kg/m^3
Magnetite Density	5000	kg/m^3
Steel density	8500	kg/m^3 (Escalera Mendoza et al., 2022, p. 5)

Mass Summary

Part	Mass, kg		CoG, m	Restoring Moment, kg-m	
Hull	4.45E+07		-70	-3.11E+09	
Variable Ballast	4.15E+06		-135.6	-5.63E+08	
Fixed Ballast	2.28E+07		-145	-3.31E+09	
RNA	7.65E+05		135	1.03E+08	
Tower	1.49E+06		72.5	1.08E+08	
Mooring	1.43E+05				
Total	7.39E+07			-6.77E+09	
Total Weight	**7.39E+07**	**kg**		**7.25E+02**	**MN**
Structure Weight	**7.37E+07**	**kg**		**7.23E+02**	**MN**
	Global COG		**-91.88**	**m**	

Structure w/o ballast	**4.68E+07**	**kg**	**4.68E+04**	**tons**

Balance of Mass

Displacement Weight	7.39E+07	kg
Total Weight	7.39E+07	kg
Net	0.00E+00	kg

Stability of Hull

CoG	-91.88	m
CoB	-75	m
BG	**16.88**	**m**

Mooring

Weight	150	kg/m
		assumption based on similar FOWTs

B.3:
TOWER BUCKLING

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Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Buckling Strength of Tower -ULS
-These calculations follow LRFD to analyze the ULS of the turbine tower

Load and Resistance Factor Design (LRFD): Per DNVGL-OS-C101 (see page 11), load and resistance factor design (LRFD) is a method for design where uncertainties in loads (demand) are represented with a load factor and uncertainties in resistance (capacity) are represented with a with a material.

Ultimate Limit States (ULS): Failure or collapse of all or part of structure due to loss of structural stiffness or exceedance of load-carrying capacity. Overturning, capsizing, yielding, and buckling are typical examples of ULS (DNV-OS-J103, 16). ULS corresponds to the ultimate resistance for carrying loads.

Assumptions:
-Tower platform assumed rigid and tower fixed at base and free at top (Fredheim, 2022)
-Tower made of S420 steel, which is common for offshore applications (Igwemezie, 2019, p.9)

S420 Steel		References
Yield Strength	$f_y := 390\ MPa$	(EN 10025-4, p. 20) *note: yield strength lowered as a function of thickness
Poisson's Ratio	$\nu := 0.3$	(EN 10025-4, p. 20)
Young's Modulus:	$E := 210\ GPa$	(EN 10025-4, p. 20)
Density:	$\rho_s := 8500\ \frac{kg}{m^3}$	(Escalera Mendoza et al., 2022, p. 5)

*note: higher density assumed to account for the mass for secondary structures such as bolts and flanges

Tower Parameters

Thickness:	$t := 50\ mm$	(Tower Buckling Strength Calcs)
Bottom Outer Diameter:	$d_{o\_2} := 10\ m$	(Tower Buckling Strength Calcs)
Top Outer Diameter:	$d_{o\_1} := 8\ m$	(Tower Buckling Strength Calcs)
Length:	$l := 125\ m$	(Tower Buckling Strength Calcs)
Hub Radius:	$r_{hub} := 4\ m$	(Siemens Gamesa) SG 14-222DD
Nacelle Mass:	$M_{nacelle} := 500000\ kg$	(Siemens Gamesa) SG 14-222DD
Blades Mass x3:	$M_{blades} := 165000\ kg$	(Siemens Gamesa) SG 14-222DD
Mass of RNA:	$M_{RNA} := M_{nacelle} + M_{blades}$	$M_{RNA} = 665000\ kg$
Top Inner Diameter:	$d_{i\_1} := d_{o\_1} - 2 \cdot t$	$d_{i\_1} = 7.9\ m$
Bottom Inner Diameter:	$d_{i\_2} := d_{o\_2} - 2\ t$	$d_{i\_2} = 9.9\ m$
Top Outer Radius:	$r_{o\_1} := \frac{d_{o\_1}}{2}$	$r_{o\_1} = 4\ m$
Bottom Outer Radius:	$r_{o\_2} := \frac{d_{o\_2}}{2}$	$r_{o\_2} = 5\ m$

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Since the tower is tapered, the elastic buckling strength of a conical shell may be taken equal to the elastic buckling resistance of an equivalent unstiffened cylindrical shell defined by the nominal thickness and (DNVGL-RP-C202, p. 37):

Angle: $\alpha := \operatorname{atan}\left(\frac{\frac{d_{o\_2} - d_{o\_1}}{2}}{l}\right)$ $\alpha = 0.458\ deg$

Equivalent outer radius of conical shell: $r_{o\_e} := \frac{r_{o\_1} + r_{o\_2}}{2 \cdot \cos(\alpha)}$ $r_{o\_e} = 4.5\ m$

Equivalent length of conical shell: $l_e := \frac{l}{\cos(\alpha)}$ $l_e = 125.004\ m$

Equivalent inner radius of conical shell: $r_{i\_e} := r_{o\_e} - t$ $r_{i\_e} = 4.45\ m$

Area: $A := \pi \cdot r_{o\_e}^{2} - \pi \cdot r_{i\_e}^{2}$ $A = 1.406\ m^2$

Buckling Resistance of Cylindrical Shells (DNV-RP-C202, pg. 18)
These stability requirement calculations check the stability for shells subjected to axial compression from the RNA and bending from the rotor thrust. Shear is neglected as it is not expected to govern the tower design.

1) Global Buckling- analyzed using Euler Buckling and does not involve the deformation of the cross section and can be analyzed using method of beams (Fredheim, 2022)

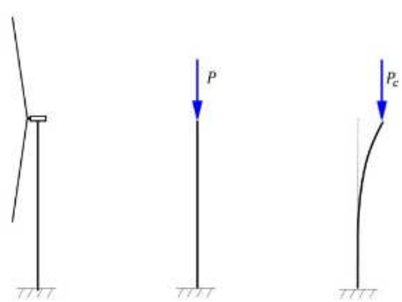

Figure 4.11: Buckling of built-in column.

(Fredheim, 2022)

The tower is consdiered a beam with a point load equal to the weight of the RNA. As a conservative measure, the total weight of the tower is included in the point load (Fredheim, 2022, p. 86).

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Capacity

Critical buckling load: $P_c = (\frac{\pi}{l_e})^2 EI_z$

Moment of Inertia: $I := \frac{\pi}{4}\left(r_{o\_e}{}^4 - r_{i\_e}{}^4\right)$ $I = 14.078\ m^4$

Radius of gyration: $r := \sqrt{\frac{I}{A}}$ $r = 3.164\ m$

For boundary condtions, the tower is assumed fixed at the base and free at the tower top.

Effective length factor: $k_e := 2$ Tower analyzed as canteliver (fixed at the base)

Critical buckling stress: $\sigma_{cr} := \frac{\pi^2 \cdot E}{\left(\frac{k_e \cdot l}{r}\right)^2}$ $\sigma_{cr} = 332.075\ MPa$

Yield Stress: $f_y = 390\ MPa$ > $\sigma_{cr} = 332.075\ MPa$ **OK**

Critical Buckling Load: $P_{cr\_1} := \left(\frac{\pi}{k_e \cdot l}\right)^2 \cdot E \cdot I$ $P_{cr\_1} = 466.867\ MN$

The critical stress cannot be larger than the yielding stress of the material. Therefore, if $\sigma_{cr} >$ fy, the critical buckling load will be calculated as follows:

Critical Buckling Load: $P_{cr\_2} := f_y \cdot A = 548.304\ MN$ $P_{cr\_2} = 548.304\ MN$

According to DNVGL-OS-C101 (see page 20), the resistance factor (ϕ) relates to the material factor (γ_M) and is applied to determine the design resistance (Rd) as follows:

The material factor (γ_M) is determined following DNVGL-OS-C101 (see page 48).

3.1.3 If DNVGL-RP-C202 is applied, the material factor for shells shall be in accordance with Table 2.

Table 2 Material factors γ_M for buckling

Type of structure	$\lambda \le 0.5$	$0.5 < \lambda < 1.0$	$\lambda \ge 1.0$
Shells of single curvature (cylindrical shells, conical shells, rings and/or stiffeners)	1.15	0.85 + 0.60 λ	1.45
Note that the slenderness is based on the buckling mode under consideration. λ = reduced slenderness parameter $= \sqrt{\frac{f_y}{f_E}}$ f_y = specified minimum yield stress f_E = elastic buckling stress for the buckling mode under consideration.			

Reduced Slenderness Parameter: $\lambda := \sqrt{\frac{f_y}{558.22\ MPa}}$ $\lambda = 0.836$

Because $0.5 < \lambda = 0.836 < 1.0$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Therefore,

Material Factor: $\gamma_M := 0.85 + 0.6 \cdot \lambda$ $\gamma_M = 1.352$

Resistance Factor: $\phi := \frac{1}{\gamma_M}$ $\phi = 0.74$

Design Global Buckling Resistance $R_d := \phi \cdot P_{cr\_1}$ $R_d = 345.441\ MN$

Demand:

Mass of RNA: $M_{RNA} = 665000\ kg$ (Siemens Gamesa) SG 14 222DD

Self weight of tower: $M_{tow} := \rho_s \cdot A \cdot l$ $M_{tow} = 1493777.198\ kg$

*As a conservative measure the total weight of the tower is included in the point load

Characteristic Load: $F_k := M_{RNA} \cdot g + M_{tow} \cdot g$ $F_k = 21.17\ MN$

Per DNVGL-OS-C101 for permanent loads, the load factor is as follows (see page 21). However, according to DNV-OS-J101 (see page 70), for global buckling, the material factor γ_M shall be 1.2 as a minimum. Therefore, load combination (a) is used.

Load Factor: $\gamma_{f\_G\_a} := 1.3$

Table 2 Load factors γ_f for ULS

Combination of design loads	Load categories			
	G	Q	E	D
a)	1.3	1.3	0.7	1.0
b)	1.0	1.0	1.3	1.0

Load categories are:
G = permanent load
Q = variable functional load
E = environmental load
D = deformation load
For description of load categories see Sec.2.

Ultimate Limit State (ULS) $F_d := \gamma_{f\_G\_a} \cdot F_k$ $F_d = 27.521\ MN$

$F_d = 27.521\ MN$ << $R_d = 345.441\ MN$ **OK**

2) Characteristic Buckling

According to DNV-OS-J101 (see page 69), buckling analysis shall be based on the characteristic buckling resistance for the most unfavorable buckling mode. Buckling stability of shell structures may be checked according to DNV-RP-C202.

Per DNVGL-RP-C202 (see page 18), the stability reiquirement for shells subjected to one or more of the following components:
-axial compression or tension
-bending
-cirumferential compression or tension
-torsion
-shear
is given by:

$$\sigma_{j,Sd} \le f_{ksd}$$

where σ_{j_Sd} = design equivalent von Mises' stress
fksd = the deisgn shell buckling strength

Design equivalent von Mises' stress:

$$\sigma_{j,Sd} = \sqrt{(\sigma_{a,Sd} + \sigma_{m,Sd})^2 - (\sigma_{a,Sd} + \sigma_{m,Sd})\sigma_{h,Sd} + {\sigma_{h,Sd}}^2 + 3{\tau_{Sd}}^2}$$

$\sigma_{a,Sd}$ = design axial stress in the shell due to axial forces (tension positive), see equation (2.2.2)
$\sigma_{m,Sd}$ = design bending stress in the shell due to global bending moment (tension positive), see equation (2.2.3)

Design shell buckling strength:

$$f_{ksd} = \frac{f_{ks}}{\gamma_M}$$

where fks = the characteristic buckling strength
γ_M = the material factor

$$\gamma_M = 1.15 \quad for\ \bar{\lambda}_s < 0.5$$
$$\gamma_M = 0.85 + 0.60\bar{\lambda}_s \quad for\ 0.5 \le \bar{\lambda}_s \le 1.0$$
$$\gamma_M = 1.45 \quad for\ \bar{\lambda}_s > 1.0$$

Characteristic buckling strength:

$$f_{ks} = \frac{f_y}{\sqrt{1 + \bar{\lambda}_s^4}}$$

Reduced shell slenderness:

$$\bar{\lambda}_s^2 = \frac{f_y}{\sigma_{j,Sd}}\left[\frac{\sigma_{a0,Sd}}{f_{Ea}} + \frac{\sigma_{m0,Sd}}{f_{Em}} + \frac{\sigma_{h0,Sd}}{f_{Eh}} + \frac{\tau_{Sd}}{f_{E\tau}}\right]$$

f_{Ea} = elastic buckling strength for axial force
f_{Em} = elastic buckling strength for bending moment

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Calculate design stresses

-Design axial stress:

Per DNVGL-RP-C202 (see page 13), the design axial stress for a cylindrical shell due to axial forces without longitudinal stiffeners is (tension positive):

$$\sigma_{a,Sd} = \frac{N_{Sd}}{2\pi r t}$$

Design axial force: $N_{Sd} := -F_k$ $N_{Sd} = -21.17\ MN$

Design axial stress: $\sigma_{a\_Sd} := \frac{N_{Sd}}{2 \cdot \pi \cdot r_{o\_e} \cdot t}$ $\sigma_{a\_Sd} = -14.974\ MPa$

Per DNVGL-OS-C101 (see page 21), two combination of design loads (a & b) must be considered in both operating and temporary conditions

Load factors for ULS: According to DNV-OS-J101 (see page 102), the point load from RNA and tower self weight is a permanent load (G)

a) $\gamma_{f\_G\_a} = 1.3$

b) $\gamma_{f\_G\_b} := 1.0$

Design axial stresses:

a) $\sigma_{a\_Sd\_a} := \gamma_{f\_G\_a} \cdot \sigma_{a\_Sd}$ $\sigma_{a\_Sd\_a} = -19.467\ MPa$

b) $\sigma_{a\_Sd\_b} := \gamma_{f\_G\_b} \cdot \sigma_{a\_Sd}$ $\sigma_{a\_Sd\_b} = -14.974\ MPa$

-Design bending stress:

Per DNVGL-RP-C202 (see page 13), the design bending stress for a cylindrical shell without longitudinal stiffeners is (tension positive):

$$\sigma_{m,Sd} = \frac{M_{1,Sd}}{\pi r^2 t}\sin\theta - \frac{M_{2,Sd}}{\pi r^2 t}\cos\theta$$

Bending moment from wind force: $F_{env} := 4.10\ MN$ (Environmental Load Calcs)

$M_{env} := F_{env} \cdot (l + r_{hub})$ $M_{env} = 528.9\ m \cdot MN$

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

The shift of the tower top under loading gives rise to a moment arm for the RNA weight. The tower will experience a horizontal displacement of the tower top when exposed to a thrust force. This is known as the P-delta effect (Fredheim, 2022, 44).

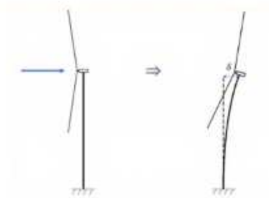

Figure 4.13: Illustration of a bottom-fixed wind turbine tower bending.

(Fredheim, 2022)

Tower top displacement: $\delta := \dfrac{M_{RNA} \cdot g \cdot l^3}{3 \cdot E \cdot I}$ $\delta = 1.436\ m$

Bending moment from P-delta: $M_{P\_delta} := M_{RNA} \cdot g \cdot \delta$ $M_{P\_delta} = 9.365\ m \cdot MN$

Total Moment: $M := M_{env} + M_{P\_delta}$ $M = 538.265\ m \cdot MN$

Design bending stress: $\sigma_{m\_Sd} := -\dfrac{M}{\pi \cdot {r_{o\_e}}^2 \cdot t}$ $\sigma_{m\_Sd} = -169.209\ MPa$

Load factors for ULS: Wind loads are environmental loads (E)

a) $\gamma_{f\_E\_a} := 0.7$

b) $\gamma_{f\_E\_b} := 1.3$

Design bending stresses:

a) $\sigma_{m\_Sd\_a} := \gamma_{f\_E\_a} \cdot \sigma_{m\_Sd}$ $\sigma_{m\_Sd\_a} = -118.446\ MPa$

b) $\sigma_{m\_Sd\_b} := \gamma_{f\_E\_b} \cdot \sigma_{m\_Sd}$ $\sigma_{m\_Sd\_b} = -219.972\ MPa$

<u>Calculate elastic buckling strengths:</u>

-<u>Elastic buckling strength for axial force:</u>

From DNVGL-RP-C202 (see page 21) the axial elastic buckling strength of unstiffened circular cylinder shell is given by equation 3.4.1:

$$f_E = C\frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{l}\right)^2$$

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine	
Engineer: CH	Checked by: CW
Date: 5/22/2023	

$\rho_a := 0.5 \cdot \left(1 + \frac{r_{o\_e}}{150\ t}\right)^{-0.5} = 0.395$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Curvature Parameter: $Z_{l\_a} := \frac{l^2}{r_{o\_e} \cdot t} \cdot \sqrt{1-\nu^2}$ $\quad Z_{l\_a} = 66243.658$

$\xi_a := 0.702\ Z_{l\_a}$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Reduced Buckling Coefficient: $C_a := \psi_a \cdot \sqrt{1 + \left(\frac{\rho_a \cdot \xi_a}{\psi_a}\right)^2}$ $\quad C_a = 18381.833$

Shell Buckling Strength: $f_{Ea} := C_a \cdot \frac{\pi^2\ E}{12 \cdot (1-\nu^2)} \left(\frac{t}{l}\right)^2$ $\quad f_{Ea} = 558.22\ MPa$

-Elastic buckling strength for bending moment:

From DNVGL-RP-C202 (see page 21) the bending elastic buckling strength of unstiffened circular cylinder shell is given by equation 3.4.1:

$$f_E = C \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{t}{l}\right)^2$$

where l the distance between ring frames. However, since the shell is unstiffened, l is the length of the entire tower.

$\psi_m := 1$

$\rho_m := 0.5 \cdot \left(1 + \frac{r_{o\_e}}{300\ t}\right)^{-0.5} = 0.439$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Curvature Parameter: $Z_{l\_m} := \frac{l^2}{r_{o\_e} \cdot t} \cdot \sqrt{1-\nu^2}$ $\quad Z_{l\_m} = 66243.658$

$\xi_m := 0.702\ Z_{l\_m}$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Reduced Buckling Coefficient: $C_m := \psi_m \cdot \sqrt{1 + \left(\frac{\rho_m \cdot \xi_m}{\psi_m}\right)^2}$ $\quad C_m = 20392.86$

Shell Buckling Strength: $f_{Em} := C_m \cdot \frac{\pi^2\ E}{12 \cdot (1-\nu^2)} \left(\frac{t}{l}\right)^2$ $\quad f_{Em} = 619.291\ MPa$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Calculate characteristic buckling strength of cylindrical shells

According to DNVGL-RP-C202 (see page 19):

$$\sigma_{a0,Sd} = \begin{cases} 0 & if\ \sigma_{a,Sd} \geq 0 \\ -\sigma_{a,Sd} & if\ \sigma_{a,Sd} < 0 \end{cases}$$

$$\sigma_{m0,Sd} = \begin{cases} 0 & if\ \sigma_{m,Sd} \geq 0 \\ -\sigma_{m,Sd} & if\ \sigma_{m,Sd} < 0 \end{cases}$$

$\sigma_{a\_Sd\_a} = -19.467\ MPa$ < 0 therefore $\sigma_{a0\_Sd\_a} := -\sigma_{a\_Sd\_a}$ $\sigma_{a0\_Sd\_a} = 19.467\ MPa$

$\sigma_{a\_Sd\_b} = -14.974\ MPa$ < 0 therefore $\sigma_{a0\_Sd\_b} := -\sigma_{a\_Sd\_b}$ $\sigma_{a0\_Sd\_b} = 14.974\ MPa$

$\sigma_{m\_Sd\_a} = -118.446\ MPa$ < 0 therefore $\sigma_{m0\_Sd\_a} := -\sigma_{m\_Sd\_a}$ $\sigma_{m0\_Sd\_a} = 118.446\ MPa$

$\sigma_{m\_Sd\_b} = -219.972\ MPa$ < 0 therefore $\sigma_{m0\_Sd\_b} := -\sigma_{m\_Sd\_b}$ $\sigma_{m0\_Sd\_b} = 219.972\ MPa$

Design equivalent von Mises' stress:

a) $\sigma_{j\_Sd\_a} := \sqrt{(\sigma_{a\_Sd\_a} + \sigma_{m\_Sd\_a})^2}$ $\sigma_{j\_Sd\_a} = 137.913\ MPa$

b) $\sigma_{j\_Sd\_b} := \sqrt{(\sigma_{a\_Sd\_b} + \sigma_{m\_Sd\_b})^2}$ $\sigma_{j\_Sd\_b} = 234.946\ MPa$

Reduced shell slenderness:

a) $\lambda_{s\_bar\_a}2 := \frac{f_y}{\sigma_{j\_Sd\_a}} \cdot \left(\frac{\sigma_{a0\_Sd\_a}}{f_{Ea}} + \frac{\sigma_{m0\_Sd\_a}}{f_{Em}} \right)$ $\lambda_{s\_bar\_a}2 = 0.639$

b) $\lambda_{s\_bar\_b}2 := \frac{f_y}{\sigma_{j\_Sd\_b}} \cdot \left(\frac{\sigma_{a0\_Sd\_b}}{f_{Ea}} + \frac{\sigma_{m0\_Sd\_b}}{f_{Em}} \right)$ $\lambda_{s\_bar\_b}2 = 0.634$

Characteristic buckling strength:

a) $f_{ks\_a} := \frac{f_y}{\sqrt{1 + \lambda_{s\_bar\_a}2^2}}$ $f_{ks\_a} = 328.564\ MPa$

b) $f_{ks\_b} := \frac{f_y}{\sqrt{1 + \lambda_{s\_bar\_b}2^2}}$ $f_{ks\_b} = 329.359\ MPa$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

$$\gamma_M = 1.15 \quad for\ \overline{\lambda_s} < 0.5$$
$$\gamma_M = 0.85 + 0.60\overline{\lambda}_s \quad for\ 0.5 \le \overline{\lambda_s} \le 1.0$$
$$\gamma_M = 1.45 \quad for\ \overline{\lambda_s} > 1.0$$

Material factor:

a) $\lambda_{s\_bar\_a} := \sqrt{\lambda_{s\_bar\_a}2} = 0.8$ therefore $\gamma_{M\_a} := 0.85 + 0.6 \cdot \lambda_{s\_bar\_a} = 1.33$

b) $\lambda_{s\_bar\_b} := \sqrt{\lambda_{s\_bar\_b}2} = 0.796$ therefore $\gamma_{M\_b} := 0.85 + 0.6 \cdot \lambda_{s\_bar\_b} = 1.328$

Design shell buckling strength:

a) $f_{ksd\_a} := \dfrac{f_{ks\_a}}{\gamma_{M\_a}}$ $\quad f_{ksd\_a} = 247.077\ MPa$

a) $f_{ksd\_b} := \dfrac{f_{ks\_b}}{\gamma_{M\_b}}$ $\quad f_{ksd\_b} = 248.049\ MPa$

Stability requirement:

a) $\sigma_{j\_Sd\_a} = 137.913\ MPa$ < $f_{ksd\_a} = 247.077\ MPa$ **OK**

b) $\sigma_{j\_Sd\_b} = 234.946\ MPa$ < $f_{ksd\_b} = 248.049\ MPa$ **OK**

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Project: Floating Offshore Wind Turbine	
Engineer: CH	Checked by: CW
Date: 5/22/2023	

3) Column Buckling - involving axial and bending stress per DNV codes

According to DNVGL-RP-C202 (see page 30), column buckling strength should be assessed if

radius of gyration of cylinder section: $i := \sqrt{\frac{I}{A}}$ $\quad i = 3.164\ m$

$\left(\frac{k_e \cdot l}{i}\right)^2 = 6241.406 \quad > \quad 2.5 \cdot \frac{E}{f_y} = 1346.154$

Therefore, column buckling strength should be assesed.

Euler buckling strength: $f_E := \frac{\pi^2 \cdot E \cdot I}{(k_e \cdot l)^2 \cdot A}$ $\quad f_E = 332.075\ MPa$

Reduced characteristic buckling strength factors: $a := 1 + \frac{f_y^{\,2}}{f_{Ea}^{\,2}}$ $\quad a = 1.488$

$b := 0$

$c := -f_y^{\,2} \cdot \frac{1}{MPa^2}$ $\quad c = -152100$

Reduced characteristic buckling strength: $f_{ak} := \frac{b + \sqrt{b^2 - 4 \cdot a \cdot c}}{2 \cdot a} \cdot MPa$ $\quad f_{ak} = 319.703\ MPa$

Design local buckling strength: $f_{akd} := \frac{f_{ak}}{\gamma_{M\_a}}$ $\quad f_{akd} = 240.414\ MPa$

Reduces column slenderness: $\lambda_{bar} := \sqrt{\frac{f_{ak}}{f_E}}$ $\quad \lambda_{bar} = 0.981$

Per DNVGL-RP-C202 (see page 31), the characteristic buckling strength, fkc, for column buckling may be defined as:

$$f_{kc} = \left[1.0 - 0.28\bar{\lambda}^2\right] f_{ak} \qquad for\ \bar{\lambda} \le 1.34$$

$$f_{kc} = \frac{0.9}{\bar{\lambda}^2} f_{ak} \qquad for\ \bar{\lambda} > 1.34$$

$\lambda_{bar} = 0.981 \quad < \quad 1.34$

Therefore, the characteristic column buckling strength of the tower is calculated as follows:

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ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Characteristic buckling strength: $f_{kc} := \left(1.0 - 0.28\ \lambda_{bar}^{2}\right) \cdot f_{ak}$ $f_{kc} = 233.521\ MPa$

According to DNV-OS-J101 (see page 70), for global buckling, the material factor shall be 1.2 as a minimum. Therefore, load combination (a) is used.

Design column buckling strength: $f_{kcd} := \frac{f_{kc}}{\gamma_{M\_a}}$ $f_{kcd} = 175.606\ MPa$

Per DNVGL-RP-C202 (see page 31), the stability requirement for shell-column subjected to axial compression and bending compression is given by:

$$\frac{\sigma_{a0\_Sd\_a}}{f_{kcd}} + \frac{1}{f_{akd}} \cdot \left(\left(\frac{\sigma_{m\_Sd\_a}}{1 - \frac{\sigma_{a0\_Sd\_a}}{f_E}}\right)^{2}\right)^{0.5} = 0.634 \quad < \quad 1.0 \quad \textbf{OK}$$

Conclusion: Characteristic shell buckling of the tower governed over the column buckling of the tower.

B.4:
TOWER YIELDING

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Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Tower Yielding Check-ULS

-These calculations follow LRFD to analyze the ULS of the tower

S420 Steel — **References**

Yield Strength	$f_y := 390\ MPa$	(EN 10025-4, p. 20) *note: yield strength lowered as a function of thickness
Poisson's Ratio	$\nu := 0.3$	(EN 10025-4, p. 20)
Young's Modulus:	$E := 210\ GPa$	(EN 10025-4, p. 20)
Density:	$\rho_s := 8500\ \frac{kg}{m^3}$	(Escalera Mendoza et al., 2022, p. 5)

*note: higher density assumed to account for the mass for secondary structures such as bolts and flanges

Tower Parameters

Thickness:	$t := 50\ mm$	(Tower Buckling Strength Calcs)
Bottom Outer Diameter:	$d_{o\_2} := 10\ m$	(Tower Buckling Strength Calcs)
Top Outer Diameter:	$d_{o\_1} := 8\ m$	(Tower Buckling Strength Calcs)
Length:	$l := 125\ m$	(Tower Buckling Strength Calcs)
Hub Radius:	$r_{hub} := 4\ m$	(Siemens Gamesa) SG 14-222DD
Nacelle Mass:	$M_{nacelle} := 500000\ kg$	(Siemens Gamesa) SG 14-222DD
Blades Mass x3:	$M_{blades} := 165000\ kg$	(Siemens Gamesa) SG 14-222DD
Mass of RNA:	$M_{RNA} := M_{nacelle} + M_{blades}$	$M_{RNA} = \left(6.65 \cdot 10^5\right)\ kg$
Top Inner Diameter:	$d_{i\_1} := d_{o\_1} - 2 \cdot t$	$d_{i\_1} = 7.9\ m$
Bottom Inner Diameter:	$d_{i\_2} := d_{o\_2} - 2\ t$	$d_{i\_2} = 9.9\ m$
Top Outer Radius:	$r_{o\_1} := \frac{d_{o\_1}}{2}$	$r_{o\_1} = 4\ m$
Bottom Outer Radius:	$r_{o\_2} := \frac{d_{o\_2}}{2}$	$r_{o\_2} = 5\ m$
Top Inner Radius:	$r_{i\_1} := \frac{d_{i\_1}}{2}$	$r_{i\_1} = 3.95\ m$
Bottom Outer Radius:	$r_{i\_2} := \frac{d_{i\_2}}{2}$	$r_{i\_2} = 4.95\ m$
Area:	$A := \pi \cdot r_{o\_1}^2 - \pi \cdot r_{i\_1}^2$	$A = 1.249\ m^2$
Moment of Inertia:	$I := \frac{\pi}{4}\left(r_{o\_1}^4 - r_{i\_1}^4\right)$	$I = 9.866\ m^4$
Section Modulus:	$S := \frac{\pi \cdot \left(r_{o\_1}^4 - r_{i\_1}^4\right)}{4 \cdot r_{o\_1}}$	$S = 2.467\ m^3$

Environmental Loads

Thrust Force:	$T := 4.10\ MN$	(Environmental Load Calcs)

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Load Factor: $\gamma_F := 1.3$ (DNVGL-OS-C101, p. 21)

In operational conditions, the tower will be exposed to a bending moment due to the thrust force acting at the tower top. There will also be bending moments from the wind acting on the tower. The moment at the tower base is caluclated from moment equilibrium. If considering a scenerio of only thrust force, then the moment at tower base is given by force times moment arm (Fredheim, 2022, 43).

Moment at tower base: $M := \gamma_F \cdot T \cdot l$ $M = 666.25\ m \cdot MN$

Bending stress at tower base: $\sigma_{thrust} := \dfrac{M}{S}$ $\sigma_{thrust} = 270.115\ MPa$

The shift of the tower top under loading gives rise to a moment arm for the RNA weight. The tower will experience a horizontal displacement of the tower top when exposed to a thrust force. This is known as the P-delta effect (Fredheim, 2022, 44).

Figure 4.13: Illustration of a bottom-fixed wind turbine tower bending.

Tower top displacement: $\delta := \dfrac{M_{RNA} \cdot g \cdot l^3}{3 \cdot E \cdot I}$ $\delta = 2.049\ m$

Bending moment from P-delta: $M_{P\_delta} := M_{RNA} \cdot g \cdot \delta$ $M_{P\_delta} = 13.364\ m \cdot MN$

Bending stress due to P-delta: $\sigma_{P\_delta} := \dfrac{M_{P\_delta}}{S}$ $\sigma_{P\_delta} = 5.418\ MPa$

Total bending stress: $\sigma_b := \sigma_{thrust} + \sigma_{P\_delta}$ $\sigma_b = 275.533\ MPa$

For the structure to be safe from failure, the bending stress is required to be lower than the yield stress divided by the material factor (Fredheim, 2022, 44).

According to DNV-OS-C101 (see page 13), the material factor, γ_M, for ULS yield check should be 1.15 for steel.

Material factor: $\gamma_M := 1.15$

$\sigma_b = 275.533\ MPa$ < $\dfrac{f_y}{\gamma_M} = 339.13\ MPa$ **OK**

B.5:
SPAR BUCKLING

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Date: 5/22/2023

Spar Buckling Strength-ULS

-These calculations follow LRFD to analyze the ULS of the spar hull

Load and Resistance Factor Design (LRFD): Per DNVGL-OS-C101 (see page 11), load and resistance factor design (LRFD) is a method for design where uncertainties in loads (demand) are represented with a load factor and uncertainties in resistance (capacity) are represented with a with a material factor.

Ultimate Limit States (ULS): Failure or collapse of all or part of structure due to loss of structural stiffness or exceedance of load-carrying capacity. Overturning, capsizing, yielding, and buckling are typical examples of ULS (DNV-OS-J103, 16). ULS corresponds to the ultimate resistance for carrying loads.

Spar made of S420 steel, which is common for offshore applications (Igwemezie, 2019, p.9)

S420 Steel		References
Yield Strength	$f_y := 380\ MPa$	(EN 10025-4, p. 20) *note: yield strength lowered as a function of thickness
Poisson's Ratio	$\nu := 0.3$	(EN 10025-4, p. 20)
Young's Modulus:	$E := 210\ GPa$	(EN 10025-4, p. 20)
Density:	$\rho_s := 8500\ \frac{kg}{m^3}$	(Escalera Mendoza et al., 2022, p. 5)

*note: higher density assumed to account for the mass for secondary structures such as bolts and flanges

Spar Parameters

Thickness:	$t := 450\ mm$	
Outer Diameter:	$d_o := 25\ m$	(Preliminary Turbine Sizing Spreadsheet)
Total Length:	$L_T := 160\ m$	(Preliminary Turbine Sizing Spreadsheet)
Freeboard:	$L_F := 10\ m$	(Preliminary Turbine Sizing Spreadsheet)
Variable Ballast Depth:	$L_{vb} := 8.89\ m$	(Preliminary Turbine Sizing Spreadsheet)
Inner Diameter:	$d_i := d_o - 2 \cdot t$	$d_i = 24.1\ m$
Outer Radius:	$r_o := \frac{d_o}{2}$	$r_o = 12.5\ m$
Inner Radius:	$r_i := \frac{d_i}{2}$	$r_i = 12.05\ m$
Area:	$A_s := \pi \cdot r_o^2 - \pi \cdot r_i^2$	$A_s = 34.707\ m^2$
Draft Length:	$L_d := L_T - L_F$	$L_d = 150\ m$
Spar Length:	$L_s := 140\ m$	

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Volume: $V_s := A_s \cdot L_s$ $V_s = 4858.944\ m^3$

Self Weight of Spar: $M_{spar} := V_s \cdot \rho_s$ $M_{spar} = 41301026.36\ kg$

Freeboard Parameters

Outer diameter: $d_{f\_o} := 10\ m$

Thickness: $t_f := 450\ mm$

Freeboard height: $L_F := 10\ m$

Inner diameter: $d_{f\_i} := d_{f\_o} - 2 \cdot t_f$ $d_{f\_i} = 9.1\ m$

Outer radius: $r_{f\_o} := \frac{d_{f\_o}}{2}$ $r_{f\_o} = 5\ m$

Inner radius: $r_{f\_i} := \frac{d_{f\_i}}{2}$ $r_{f\_i} = 4.55\ m$

Area: $A_F := \frac{\pi}{4} \cdot (d_{f\_o})^2 - \frac{\pi}{4} \cdot (d_{f\_i})^2$ $A_F = 13.501\ m^2$

Volume: $V_F := A_F \cdot L_F$ $V_F = 135.01\ m^3$

Mass: $M_F := V_F \cdot \rho_s$ $M_F = 1147584.526\ kg$

Conical Transition Parameters

Outer top diameter: $d_{c\_o\_1} := 10\ m$

Outer bottom diameter: $d_{c\_o\_2} := 25\ m$

Thickness: $t_c := 450\ mm$

Height: $h_c := 10\ m$

Inner top diameter: $d_{c\_i\_1} := d_{c\_o\_1} - 2 \cdot t_c$ $d_{c\_i\_1} = 9.1\ m$

Inner bottom diameter: $d_{c\_i\_2} := d_{c\_o\_2} - 2 \cdot t_c$ $d_{c\_i\_2} = 24.1\ m$

Outer top radius: $r_{c\_o\_1} := \frac{d_{c\_o\_1}}{2}$ $r_{c\_o\_1} = 5\ m$

Inner top radius: $r_{c\_i\_1} := \frac{d_{c\_i\_1}}{2}$ $r_{c\_i\_1} = 4.55\ m$

Outer bottom radius: $r_{c\_o\_2} := \frac{d_{c\_o\_2}}{2}$ $r_{c\_o\_2} = 12.5\ m$

Inner bottom radius: $r_{c\_i\_2} := \frac{d_{c\_i\_2}}{2}$ $r_{c\_i\_2} = 12.05\ m$

Area cone top: $A_{c\_1} := \frac{\pi}{4} \cdot (d_{c\_o\_1})^2 - \frac{\pi}{4} \cdot (d_{c\_i\_1})^2$ $A_{c\_1} = 13.501\ m^2$

Volume of cone: $V_c := \left(\frac{1}{3} \cdot \pi \cdot h_c\right) \left(\left(r_{c\_o\_1}{}^2 + r_{c\_o\_2}{}^2 + r_{c\_o\_1} \cdot r_{c\_o\_2}\right) - \left(r_{c\_i\_1}{}^2 + r_{c\_i\_2}{}^2 + r_{c\_i\_1} \cdot r_{c\_i\_2}\right)\right)$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

$V_c = 241.039\ m^3$

Mass of cone: $M_c := V_c \cdot \rho_s$ $M_c = 2048828.919\ kg$

Total Spar Volume: $V_{S\_total} := V_s + V_F + V_c$ $V_{S\_total} = 5234.993\ m^3$

Total Spar Mass: $M_{S\_total} := M_{spar} + M_F + M_c$ $M_{S\_total} = 44497439.806\ kg$

<u>Tower Parameters</u>

Nacelle Mass: $M_{nacelle} := 500000\ kg$ (Siemens Gamesa) SG 14-222DD
Blades Mass x3: $M_{blades} := 165000\ kg$ (Siemens Gamesa) SG 14-222DD
Mass of RNA: $M_{RNA} := M_{nacelle} + M_{blades}$ $M_{RNA} = 665000\ kg$
Mass of Tower: $M_{tow} := 1493729\ kg$ (Preliminary Turbine Sizing Spreadsheet)

Thickness: $t_{tow} := 50\ mm$ (Tower Buckling Strength Calcs)
Bottom Outer Diameter: $d_{t\_o\_2} := 10\ m$ (Tower Buckling Strength Calcs)
Top Outer Diameter: $d_{t\_o\_1} := 8\ m$ (Tower Buckling Strength Calcs)

Hub Radius: $r_{hub} := 4\ m$ (Siemens Gamesa) SG 14-222 DD

Length: $L_T := 125\ m$ (Tower Buckling Strength calcs)

Top Inner Diameter: $d_{t\_i\_1} := d_{t\_o\_1} - 2 \cdot t_{tow}$ $d_{t\_i\_1} = 7.9\ m$
Bottom Inner Diameter: $d_{t\_i\_2} := d_{t\_o\_2} - 2\ t_{tow}$ $d_{t\_i\_2} = 9.9\ m$

Top Outer Radius: $r_{t\_o\_1} := \frac{d_{t\_o\_1}}{2}$ $r_{t\_o\_1} = 4\ m$

Bottom Outer Radius: $r_{t\_o\_2} := \frac{d_{t\_o\_2}}{2}$ $r_{t\_o\_2} = 5\ m$

Top Inner Radius: $r_{t\_i\_1} := \frac{d_{t\_i\_1}}{2}$ $r_{t\_i\_1} = 3.95\ m$

Bottom Outer Radius: $r_{t\_i\_2} := \frac{d_{t\_i\_2}}{2}$ $r_{t\_i\_2} = 4.95\ m$

Moment of Inertia: $I_{tow} := \frac{\pi}{4} \left({r_{t\_o\_1}}^4 - {r_{t\_i\_1}}^4 \right)$ $I_{tow} = 9.866\ m^4$

Section Modulus: $S_{tow} := \frac{\pi \cdot \left({r_{t\_o\_1}}^4 - {r_{t\_i\_1}}^4 \right)}{4 \cdot r_{t\_o\_1}}$ $S_{tow} = 2.467\ m^3$

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Buckling Resistance of Cylindrical Shells (DNV-RP-C202, 18)
These stability requirement calculations check the stability for shells subjected to axial compression from the tower and circumferential compression due to the deep sea water.

1) Characteristic Buckling

According to DNV-OS-J101 (see page 69), buckling analysis shall be based on the characteristic buckling resistance for the most unfavorable buckling mode. Buckling stability of shell structures may be checked according to DNV-RP-C202.

Per DNVGL-RP-C202 (see page 18), the stability reiquirement for shells is subjected to the following components:
-axial compression or tension
-cirumferential compression or tension
is given by:

$$\sigma_{j,Sd} \le f_{ksd}$$

where σ_{j_Sd} = design equivalent von Mises' stress
fksd = the deisgn shell buckling strength

Design equivalent von Mises' stress:

$$\sigma_{j,Sd} = \sqrt{(\sigma_{a,Sd}+\sigma_{m,Sd})^2 - (\sigma_{a,Sd}+\sigma_{m,Sd})\sigma_{h,Sd} + \sigma_{h,Sd}^{\ 2} + 3\tau_{Sd}^{\ 2}}$$

$\sigma_{a,Sd}$ = design axial stress in the shell due to axial forces (tension positive), see equation (2.2.2)
$\sigma_{m,Sd}$ = design bending stress in the shell due to global bending moment (tension positive), see equation (2.2.3)
$\sigma_{h,Sd}$ = design circumferential stress in the shell due to external pressure (tension positive), see equation (2.2.8), (2.2.9), or (2.2.14)

Design shell buckling strength:

$$f_{ksd} = \frac{f_{ks}}{\gamma_M}$$

where fks = the characteristic buckling strength
γ_M = the material factor

$$\gamma_M = 1.15 \quad for\ \bar{\lambda}_s < 0.5$$
$$\gamma_M = 0.85 + 0.60\bar{\lambda}_s \quad for\ 0.5 \le \bar{\lambda}_s \le 1.0$$
$$\gamma_M = 1.45 \quad for\ \bar{\lambda}_s > 1.0$$

Characteristic buckling strength:

$$f_{ks} = \frac{f_y}{\sqrt{1+\bar{\lambda}_s^4}}$$

Reduced shell slenderness:

$$\bar{\lambda}_s^2 = \frac{f_y}{\sigma_{j,Sd}}\left[\frac{\sigma_{a0,Sd}}{f_{Ea}} + \frac{\sigma_{m0,Sd}}{f_{Em}} + \frac{\sigma_{h0,Sd}}{f_{Eh}} + \frac{\tau_{Sd}}{f_{E\tau}}\right]$$

f_{Ea} = elastic buckling strength for axial force

f_{Em} = elastic buckling strength for bending moment

f_{Eh} = elastic buckling strength for hydrostatic pressure, lateral pressure and circumferential compression

Calculate design stresses

-Design axial stress:

Per DNVGL-RP-C202 (see page 13), the design axial stress for a cylindrical shell due to axial forces without longitudinal stiffeners is (tension positive):

$$\sigma_{a,Sd} = \frac{N_{Sd}}{2\pi r t}$$

Design axial force: $N_{Sd} := -(M_{RNA} + M_{S\_total} + M_{tow})\ g$ $\quad N_{Sd} = -457.541\ MN$

*As a conservative measure the total weight of the spar is included in the point load

Design axial stress: $\sigma_{a\_Sd} := \dfrac{N_{Sd}}{2 \cdot \pi \cdot r_o \cdot t}$ $\quad \sigma_{a\_Sd} = -12.946\ MPa$

Per DNVGL-OS-C101 (see page 21), two combination of design loads (a & b) must be considered in both operating and temporary conditions

Load factors for ULS: According to DNV-OS-J101 (see page 102), the point load from RNA and tower self weight is a permanent load (G)

a) $\gamma_{f\_G\_a} := 1.3$

b) $\gamma_{f\_G\_b} := 1.0$

Design axial stresses:

a) $\sigma_{a\_Sd\_a} := \gamma_{f\_G\_a} \cdot \sigma_{a\_Sd}$ $\quad \sigma_{a\_Sd\_a} = -16.829\ MPa$

b) $\sigma_{a\_Sd\_b} := \gamma_{f\_G\_b} \cdot \sigma_{a\_Sd}$ $\quad \sigma_{a\_Sd\_b} = -12.946\ MPa$

-Design circumferential stress:

Per DNV-OS-J103 (see page 58), in case solid ballast is used, the beneficial effect of horizontal pressure set up by the solid ballast and counteracting external pressure shall normally not be accounted for in the buckling checks for vertical shell elements. However, the beneficial effect of horizontal pressure from ballast water can always be considered in these checks.

Per DNVGL-RP-C202 (see page 14), for an unstiffened cylinder the circumferential membrane stress may be taken as (tension is positive):

$$\sigma_{h,Sd} = \frac{p_{Sd} r}{t}$$

Seawater Density: $\rho := 1025\ \dfrac{kg}{m^3}$

Depth of variable ballast: $L_{vb} = 8.89\ m$

The value for the hydrostatic pressure on the bottom of the spar used as a conservative assumption

Hydrostatic pressure from ocean: $P_{ocean} := -\rho \cdot g \cdot L_s$ $P_{ocean} = -1.407\ MPa$

Hydrostatic pressure from variable ballast: $P_{vb} := \rho \cdot g \cdot L_{vb}$ $P_{vb} = 0.089\ MPa$

Overall hydrostatic pressure: $p_{Sd} := P_{ocean} + P_{vb}$ $p_{Sd} = -1.318\ MPa$

Design circumferential stress: $\sigma_{h\_Sd} := \frac{p_{Sd} \cdot r_o}{t}$ $\sigma_{h\_Sd} = -36.608\ MPa$

Load factors for ULS: According to DNVGL-OS-C101 (see page 21), the load factors for when permanent loads, like hydrostatic pressure, are well defined are as follows:

a) $\gamma_{f\_G\_a} := 1.2$

b) $\gamma_{f\_G\_b} = 1$

Design circumferential stresses:

a) $\sigma_{h\_Sd\_a} := \gamma_{f\_G\_a} \cdot \sigma_{h\_Sd}$ $\sigma_{h\_Sd\_a} = -43.93\ MPa$

b) $\sigma_{h\_Sd\_b} := \gamma_{f\_G\_b} \cdot \sigma_{h\_Sd}$ $\sigma_{h\_Sd\_b} = -36.608\ MPa$

Calculate elastic buckling strengths:

-Elastic buckling strength for axial force:

From DNVGL-RP-C202 (see page 21) the axial elastic buckling strength of unstiffened circular cylinder shell is given by equation 3.4.1:

$$f_E = C\frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{l}\right)^2$$

where l the distance between ring frames. However, since the shell is unstiffened, l is the length of the entire spar draft.

$\psi_a := 1$

$\rho_a := 0.5 \cdot \left(1 + \frac{r_o}{150\ t}\right)^{-0.5} = 0.459$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Curvature Parameter: $Z_{l\_a} := \frac{L_d^{\,2}}{r_o \cdot t} \cdot \sqrt{1-\nu^2}$ $Z_{l\_a} = 3815.757$

$\xi_a := 0.702\ Z_{l\_a}$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Reduced Buckling Coefficient: $C_a := \psi_a \cdot \sqrt{1+\left(\frac{\rho_a \cdot \xi_a}{\psi_a}\right)^2}$ $C_a = 1230.254$

Shell Buckling Strength: $f_{Ea} := C_a \cdot \frac{\pi^2 \; E}{12 \cdot (1-\nu^2)} \left(\frac{t}{L_d}\right)^2$ $f_{Ea} = 2101.521 \; MPa$

-Elastic buckling strength for lateral/hydrostatic pressure

According to DNVGL-RP-C202 (see page 21), for hydrostatic pressure if

$\frac{L_s}{r_o} = 11.2$ > $2.25 \cdot \sqrt{\frac{r_o}{t}} = 11.859$ **NO**

then the elastic buckling strength may be calculated as:

Elastic Buckling Strength: $f_{Eh\_1} := 0.25 \cdot E \cdot \left(\frac{t}{r_o}\right)^2$ $f_{Eh\_1} = 68.04 \; MPa$

According to DNVGL-RP-C202 (see page 21), for hydrostatic pressure if

$\frac{L_s}{r_o} = 11.2$ < $2.25 \cdot \sqrt{\frac{r_o}{t}} = 11.859$ **OK**

then the elastic buckling strength may be calculated as:

From DNVGL-RP-C202 (see page 21) the axial elastic buckling strength of unstiffened circular cylinder shell is given by equation 3.4.1:

$$f_E = C\frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{l}\right)^2$$

where l the distance between ring frames. However, since the shell is unstiffened, l is the length of the entire spar draft.

$\psi_h := 2$

$\rho_h := 0.6$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 22)

Curvature Parameter: $Z_l := \frac{L_s^2}{r_o \cdot t} \cdot \sqrt{1-\nu^2}$ $Z_l = 3323.948$

$\xi_h := 1.04 \cdot \sqrt{Z_l}$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Reduced Buckling Coefficient: $C_h := \psi_h \cdot \sqrt{1+\left(\frac{\rho_h \cdot \xi_h}{\psi_h}\right)^2}$ $C_h = 36.031$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Shell Buckling Strength: $f_{Eh\_2} := C_h \cdot \frac{\pi^2 E}{12 \cdot (1-\nu^2)} \left(\frac{t}{L_s}\right)^2$ $f_{Eh\_2} = 70.656\ MPa$

Calculate characteristic buckling strength of cylindrical shells

According to DNVGL-RP-C202 (see page 19):

$$\sigma_{a0,Sd} = \begin{cases} 0 & if\ \sigma_{a,Sd} \geq 0 \\ -\sigma_{a,Sd} & if\ \sigma_{a,Sd} < 0 \end{cases}$$

$$\sigma_{m0,Sd} = \begin{cases} 0 & if\ \sigma_{m,Sd} \geq 0 \\ -\sigma_{m,Sd} & if\ \sigma_{m,Sd} < 0 \end{cases}$$

$$\sigma_{h0,Sd} = \begin{cases} 0 & if\ \sigma_{h,Sd} \geq 0, \text{ internal net pressure} \\ -\sigma_{h,Sd} & if\ \sigma_{h,Sd} < 0, \text{ external net pressure} \end{cases}$$

$\sigma_{a\_Sd\_a} = -16.829\ MPa$ < 0 therefore $\sigma_{a0\_Sd\_a} := -\sigma_{a\_Sd\_a}$ $\sigma_{a0\_Sd\_a} = 16.829\ MPa$

$\sigma_{a\_Sd\_b} = -12.946\ MPa$ < 0 therefore $\sigma_{a0\_Sd\_b} := -\sigma_{a\_Sd\_b}$ $\sigma_{a0\_Sd\_b} = 12.946\ MPa$

$\sigma_{h\_Sd\_a} = -43.93\ MPa$ < 0 therefore $\sigma_{h0\_Sd\_a} := -\sigma_{h\_Sd\_a}$ $\sigma_{h0\_Sd\_a} = 43.93\ MPa$

$\sigma_{h\_Sd\_b} = -36.608\ MPa$ < 0 therefore $\sigma_{h0\_Sd\_b} := -\sigma_{h\_Sd\_b}$ $\sigma_{h0\_Sd\_b} = 36.608\ MPa$

Design equivalent von Mises' stress:

a) $\sigma_{j\_Sd\_a} := \sqrt{(\sigma_{a\_Sd\_a})^2 - (\sigma_{a\_Sd\_a}) \cdot \sigma_{h\_Sd\_a} + \sigma_{h\_Sd\_a}{}^2}$ $\sigma_{j\_Sd\_a} = 38.389\ MPa$

b) $\sigma_{j\_Sd\_b} := \sqrt{(\sigma_{a\_Sd\_b})^2 - (\sigma_{a\_Sd\_b}) \cdot \sigma_{h\_Sd\_b} + \sigma_{h\_Sd\_b}{}^2}$ $\sigma_{j\_Sd\_b} = 32.153\ MPa$

Reduced shell slenderness:

a) $\lambda_{s\_bar\_a}2 := \frac{f_y}{\sigma_{j\_Sd\_a}} \cdot \left(\frac{\sigma_{a0\_Sd\_a}}{f_{Ea}} + \frac{\sigma_{h0\_Sd\_a}}{f_{Eh\_2}}\right)$ $\lambda_{s\_bar\_a}2 = 6.234$

b) $\lambda_{s\_bar\_b}2 := \frac{f_y}{\sigma_{j\_Sd\_b}} \cdot \left(\frac{\sigma_{a0\_Sd\_b}}{f_{Ea}} + \frac{\sigma_{h0\_Sd\_b}}{f_{Eh\_2}}\right)$ $\lambda_{s\_bar\_b}2 = 6.196$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Characteristic buckling strength:

a) $f_{ks\_a} := \dfrac{f_y}{\sqrt{1+\lambda_{s\_bar\_a}2^2}}$ $f_{ks\_a} = 60.19\ MPa$

b) $f_{ks\_b} := \dfrac{f_y}{\sqrt{1+\lambda_{s\_bar\_b}2^2}}$ $f_{ks\_b} = 60.545\ MPa$

$$\gamma_M = 1.15 \qquad for\ \overline{\lambda_s} < 0.5$$
$$\gamma_M = 0.85 + 0.60\overline{\lambda}_s \qquad for\ 0.5 \le \overline{\lambda_s} \le 1.0$$
$$\gamma_M = 1.45 \qquad for\ \overline{\lambda_s} > 1.0$$

Material factor:

a) $\lambda_{s\_bar\_a} := \sqrt{\lambda_{s\_bar\_a}2} = 2.497$ therefore $\gamma_{M\_a} := 1.45$

b) $\lambda_{s\_bar\_b} := \sqrt{\lambda_{s\_bar\_b}2} = 2.489$ therefore $\gamma_{M\_b} := 1.45$

Design shell buckling strength:

a) $f_{ksd\_a} := \dfrac{f_{ks\_a}}{\gamma_{M\_a}}$ $f_{ksd\_a} = 41.51\ MPa$

a) $f_{ksd\_b} := \dfrac{f_{ks\_b}}{\gamma_{M\_b}}$ $f_{ksd\_b} = 41.755\ MPa$

Stability requirement:

a) $\sigma_{j\_Sd\_a} = 38.389\ MPa$ < $f_{ksd\_a} = 41.51\ MPa$ OK

b) $\sigma_{j\_Sd\_b} = 32.153\ MPa$ < $f_{ksd\_b} = 41.755\ MPa$ OK

Conclusion: Lateral/hydrostatic pressure causing the circumferential/hoop stress governs. Although, this can be attributed to conservative assumptions made regarding the hydrostatic pressure demand.

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

2) Conical Transition (from spar to tower)

S420 Steel

Yield Strength $f_y := 360\ MPa$ (EN 10025-4, p. 20)
*note: yield strength lowered as a function of thickness

Parameters

Outer top diameter: $d_{c\_o\_1} := 10\ m$

Outer bottom diameter: $d_{c\_o\_2} := 25\ m$

Thickness: $t_c := 450\ mm$

Height: $h_c := 10\ m$

Inner top diameter: $d_{c\_i\_1} := d_{c\_o\_1} - 2 \cdot t_c$ $d_{c\_i\_1} = 9.1\ m$

Inner bottom diameter: $d_{c\_i\_2} := d_{c\_o\_2} - 2 \cdot t_c$ $d_{c\_i\_2} = 24.1\ m$

Outer top radius: $r_{c\_o\_1} := \frac{d_{c\_o\_1}}{2}$ $r_{c\_o\_1} = 5\ m$

Inner top radius: $r_{c\_i\_1} := \frac{d_{c\_i\_1}}{2}$ $r_{c\_i\_1} = 4.55\ m$

Outer bottom radius: $r_{c\_o\_2} := \frac{d_{c\_o\_2}}{2}$ $r_{c\_o\_2} = 12.5\ m$

Inner bottom radius: $r_{c\_i\_2} := \frac{d_{c\_i\_2}}{2}$ $r_{c\_i\_2} = 12.05\ m$

Area cone top: $A_{c\_1} := \frac{\pi}{4} \cdot (d_{c\_o\_1})^2 - \frac{\pi}{4} \cdot (d_{c\_i\_1})^2$ $A_{c\_1} = 13.501\ m^2$

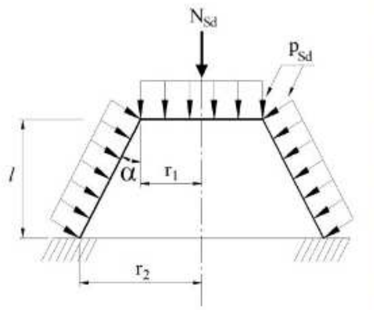
Volume of cone: $V_c := \left(\frac{1}{3} \cdot \pi \cdot h_c\right) \left(\left(r_{c\_o\_1}^{\ 2} + r_{c\_o\_2}^{\ 2} + r_{c\_o\_1} \cdot r_{c\_o\_2}\right) - \left(r_{c\_i\_1}^{\ 2} + r_{c\_i\_2}^{\ 2} + r_{c\_i\_1} \cdot r_{c\_i\_2}\right)\right)$

$V_c = 241.039\ m^3$

Mass of cone: $M_c := V_c \cdot \rho_s$ $M_c = 2048828.919\ kg$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023



(DNVGL-RP-C202, pg 37)

The elastic buckling strength of a conical shell may be taken equal to the elastic buckling resistance of an equivalent unstiffened cylindrical shell defined by the nominal thickness and:

Angle: $\alpha := \operatorname{atan}\left(\dfrac{\dfrac{d_{c\_o\_2} - d_{c\_o\_1}}{2}}{h_c}\right)$ $\alpha = 36.87\ deg$

Equivalent radius of conical shell: $r_e := \dfrac{r_{c\_o\_1} + r_{c\_o\_2}}{2 \cdot \cos(\alpha)}$ $r_e = 10.938\ m$

Equivalent length of conical shell: $l_e := \dfrac{h_c}{\cos(\alpha)}$ $l_e = 12.5\ m$

Per DNVGL-RP-C202 (see page 39), The characteristic buckling strength of a conical shell may be determined according to the procedure given for unstiffened cylindrical shells

Calculate design stresses:

-Design axial stress:

Per DNVGL-RP-C202 (see page 13), the design axial stress for a cylindrical shell due to axial forces without longitudinal stiffeners is (tension positive):

$$\sigma_{a,Sd} = \frac{N_{Sd}}{2\pi r t}$$

Design axial force: $N_{Sd\_c} := -\left(M_{RNA} + M_c + M_{tow}\right) g$ $N_{Sd\_c} = -41.262\ MN$

*As a conservative measure the total weight of the spar is included in the point load

Design axial stress: $\sigma_{a\_Sd\_c} := \dfrac{N_{Sd\_c}}{2 \cdot \pi \cdot r_e \cdot t_c}$ $\sigma_{a\_Sd\_c} = -1.334\ MPa$

Per DNVGL-OS-C101 (see page 21), two combination of design loads (a & b) must be considered in both operating and temporary conditions

Load factors for ULS: According to DNV-OS-J101 (see page 102), the point load from RNA and tower self weight is a permanent load (G)

a) $\gamma_{f\_G\_a} := 1.3$

b) $\gamma_{f\_G\_b} := 1.0$

Design axial stresses: a) $\sigma_{a\_Sd\_a} := \gamma_{f\_G\_a} \cdot \sigma_{a\_Sd\_c}$ $\sigma_{a\_Sd\_a} = -1.735\ MPa$

b) $\sigma_{a\_Sd\_b} := \gamma_{f\_G\_b} \cdot \sigma_{a\_Sd\_c}$ $\sigma_{a\_Sd\_b} = -1.334\ MPa$

-Design circumferential stress:

Per DNVGL-RP-C202 (see page 14), for an unstiffened cylinder the circumferential membrane stress may be taken as (tension is positive):

$$\sigma_{h,Sd} = \frac{p_{Sd} r}{t}$$

Seawater Density: $\rho := 1025\ \frac{kg}{m^3}$

Depth of cone: $h_c = 10\ m$

The value for the hydrostatic pressure on the bottom of the cone used as a conservative assumption

Hydrostatic pressure from ocean: $p_{Sd\_c} := -\rho \cdot g \cdot h_c$ $p_{Sd\_c} = -0.101\ MPa$

Design circumferential stress: $\sigma_{h\_Sd} := \frac{p_{Sd\_c} \cdot r_e}{t_c}$ $\sigma_{h\_Sd} = -2.443\ MPa$

Load factors for ULS: According to DNVGL-OS-C101 (see page 21), the load factors for when permanent loads, like hydrostatic pressure, are well defined are as follows:

a) $\gamma_{f\_G\_a} := 1.2$

b) $\gamma_{f\_G\_b} = 1$

Design circumferential stresses: a) $\sigma_{h\_Sd\_a} := \gamma_{f\_G\_a} \cdot \sigma_{h\_Sd}$ $\sigma_{h\_Sd\_a} = -2.932\ MPa$

b) $\sigma_{h\_Sd\_b} := \gamma_{f\_G\_b} \cdot \sigma_{h\_Sd}$ $\sigma_{h\_Sd\_b} = -2.443\ MPa$

Calculate elastic buckling strengths:

-Elastic buckling strength for axial force:

From DNVGL-RP-C202 (see page 21) the axial elastic buckling strength of unstiffened circular cylinder shell is given by equation 3.4.1:

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

$$f_E = C\frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{l}\right)^2$$

where l the distance between ring frames. However, since the shell is unstiffened, l is the length of the entire spar draft.

$\psi_a := 1$

$\rho_a := 0.5 \cdot \left(1 + \frac{r_e}{150\ t_c}\right)^{-0.5} = 0.464$ Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Curvature Parameter: $Z_{l\_a} := \frac{h_c^{\ 2}}{r_e \cdot t_c} \cdot \sqrt{1-\nu^2}$ $Z_{l\_a} = 19.382$

$\xi_a := 0.702\ Z_{l\_a}$ Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Reduced Buckling Coefficient: $C_a := \psi_a \cdot \sqrt{1 + \left(\frac{\rho_a \cdot \xi_a}{\psi_a}\right)^2}$ $C_a = 6.39$

Shell Buckling Strength: $f_{Ea} := C_a \cdot \frac{\pi^2\ E}{12 \cdot (1-\nu^2)} \left(\frac{t_c}{h_c}\right)^2$ $f_{Ea} = 2455.804\ MPa$

-Elastic buckling strength for lateral/hydrostatic pressure

According to DNVGL-RP-C202 (see page 21), for hydrostatic pressure if

$\frac{l_e}{r_e} = 1.143$ > $2.25 \cdot \sqrt{\frac{r_e}{t_c}} = 11.093$ **NO**

then the elastic buckling strength may be calculated as:

Elastic Buckling Strength: $f_{Eh\_1} := 0.25 \cdot E \cdot \left(\frac{t_c}{r_e}\right)^2$ $f_{Eh\_1} = 88.869\ MPa$

According to DNVGL-RP-C202 (see page 21), for hydrostatic pressure if

$\frac{l_e}{r_e} = 1.143$ < $2.25 \cdot \sqrt{\frac{r_e}{t_c}} = 11.093$ **OK**

then the elastic buckling strength may be calculated as:

From DNVGL-RP-C202 (see page 21) the axial elastic buckling strength of unstiffened circular cylinder shell is given by equation 3.4.1:

$$f_E = C\frac{\pi^2 E}{12\left(1-\nu^2\right)}\left(\frac{t}{l}\right)^2$$

where l the distance between ring frames. However, since the shell is unstiffened, l is the length of the entire spar draft.

$\psi_h := 2$

$\rho_h := 0.6$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 22)

Curvature Parameter: $Z_l := \frac{h_c^2}{r_e \cdot t_c} \cdot \sqrt{1-\nu^2}$ $Z_l = 19.382$

$\xi_h := 1.04 \cdot \sqrt{Z_l}$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Reduced Buckling Coefficient: $C_h := \psi_h \cdot \sqrt{1+\left(\frac{\rho_h \cdot \xi_h}{\psi_h}\right)^2}$ $C_h = 3.398$

Shell Buckling Strength: $f_{Eh\_2} := C_h \cdot \frac{\pi^2 \ E}{12 \cdot \left(1-\nu^2\right)} \left(\frac{t_c}{h_c}\right)^2$ $f_{Eh\_2} = 1306.024 \ MPa$

Calculate characteristic buckling strength of cylindrical shells

According to DNVGL-RP-C202 (see page 19):

$\sigma_{a\_Sd\_a} = -1.735 \ MPa$	< 0	therefore	$\sigma_{a0\_Sd\_a} := -\sigma_{a\_Sd\_a}$	$\sigma_{a0\_Sd\_a} = 1.735 \ MPa$
$\sigma_{a\_Sd\_b} = -1.334 \ MPa$	< 0	therefore	$\sigma_{a0\_Sd\_b} := -\sigma_{a\_Sd\_b}$	$\sigma_{a0\_Sd\_b} = 1.334 \ MPa$
$\sigma_{h\_Sd\_a} = -2.932 \ MPa$	< 0	therefore	$\sigma_{h0\_Sd\_a} := -\sigma_{h\_Sd\_a}$	$\sigma_{h0\_Sd\_a} = 2.932 \ MPa$
$\sigma_{h\_Sd\_b} = -2.443 \ MPa$	< 0	therefore	$\sigma_{h0\_Sd\_b} := -\sigma_{h\_Sd\_b}$	$\sigma_{h0\_Sd\_b} = 2.443 \ MPa$

Design equivalent von Mises' stress:

a) $\sigma_{j\_Sd\_a} := \sqrt{\left(\sigma_{a\_Sd\_a}\right)^2 - \left(\sigma_{a\_Sd\_a}\right) \cdot \sigma_{h\_Sd\_a} + \sigma_{h\_Sd\_a}{}^2}$ $\sigma_{j\_Sd\_a} = 2.553 \ MPa$

b) $\sigma_{j\_Sd\_b} := \sqrt{\left(\sigma_{a\_Sd\_b}\right)^2 - \left(\sigma_{a\_Sd\_b}\right) \cdot \sigma_{h\_Sd\_b} + \sigma_{h\_Sd\_b}{}^2}$ $\sigma_{j\_Sd\_b} = 2.119 \ MPa$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Reduced shell slenderness:

a) $\lambda_{s\_bar\_a}2 := \frac{f_y}{\sigma_{j\_Sd\_a}} \cdot \left(\frac{\sigma_{a0\_Sd\_a}}{f_{Ea}} + \frac{\sigma_{h0\_Sd\_a}}{f_{Eh\_2}} \right)$ $\lambda_{s\_bar\_a}2 = 0.416$

b) $\lambda_{s\_bar\_b}2 := \frac{f_y}{\sigma_{j\_Sd\_b}} \cdot \left(\frac{\sigma_{a0\_Sd\_b}}{f_{Ea}} + \frac{\sigma_{h0\_Sd\_b}}{f_{Eh\_2}} \right)$ $\lambda_{s\_bar\_b}2 = 0.41$

Characteristic buckling strength:

a) $f_{ks\_a} := \frac{f_y}{\sqrt{1 + \lambda_{s\_bar\_a}2^2}}$ $f_{ks\_a} = 332.373\ MPa$

b) $f_{ks\_b} := \frac{f_y}{\sqrt{1 + \lambda_{s\_bar\_b}2^2}}$ $f_{ks\_b} = 333.073\ MPa$

$\gamma_M = 1.15 \quad for\ \overline{\lambda}_s < 0.5$
$\gamma_M = 0.85 + 0.60\overline{\lambda}_s \quad for\ 0.5 \le \overline{\lambda}_s \le 1.0$
$\gamma_M = 1.45 \quad for\ \overline{\lambda}_s > 1.0$

Material factor:

a) $\lambda_{s\_bar\_a} := \sqrt{\lambda_{s\_bar\_a}2} = 0.645$ therefore $\gamma_{M\_a} := 0.85 + 0.60 \cdot \lambda_{s\_bar\_a}$ $\gamma_{M\_a} = 1.237$

b) $\lambda_{s\_bar\_b} := \sqrt{\lambda_{s\_bar\_b}2} = 0.64$ therefore $\gamma_{M\_b} := 0.85 + 0.60 \cdot \lambda_{s\_bar\_b}$ $\gamma_{M\_b} = 1.234$

Design shell buckling strength:

a) $f_{ksd\_a} := \frac{f_{ks\_a}}{\gamma_{M\_a}}$ $f_{ksd\_a} = 268.684\ MPa$

a) $f_{ksd\_b} := \frac{f_{ks\_b}}{\gamma_{M\_b}}$ $f_{ksd\_b} = 269.857\ MPa$

Stability requirement:

a) $\sigma_{j\_Sd\_a} = 2.553\ MPa$ < $f_{ksd\_a} = 268.684\ MPa$ OK

b) $\sigma_{j\_Sd\_b} = 2.119\ MPa$ < $f_{ksd\_b} = 269.857\ MPa$ OK

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

3) Freeboard

S420 Steel

Yield Strength $f_y := 360\ MPa$ (EN 10025-4, p. 20)
*note: yield strength lowered as a function of thickness

Parameters

Outer diameter: $d_{f\_o} := 10\ m$

Thickness: $t_f := 450\ mm$

Freeboard height: $L_F := 10\ m$

Inner diameter: $d_{f\_i} := d_{f\_o} - 2 \cdot t_f$ $d_{f\_i} = 9.1\ m$

Outer radius: $r_{f\_o} := \frac{d_{f\_o}}{2}$ $r_{f\_o} = 5\ m$

Inner radius: $r_{f\_i} := \frac{d_{f\_i}}{2}$ $r_{f\_i} = 4.55\ m$

Area: $A_F := \frac{\pi}{4} \cdot (d_{f\_o})^2 - \frac{\pi}{4} \cdot (d_{f\_i})^2$ $A_F = 13.501\ m^2$

Volume: $V_F := A_F \cdot L_F$ $V_F = 135.01\ m^3$

Mass: $M_F := V_F \cdot \rho_s$ $M_c = 2048828.919\ kg$

Calculate design stresses:

-Design axial stress:

Per DNVGL-RP-C202 (see page 13), the design axial stress for a cylindrical shell due to axial forces without longitudinal stiffeners is (tension positive):

$$\sigma_{a,Sd} = \frac{N_{Sd}}{2\pi r t}$$

Design axial force: $N_{Sd\_c} := -(M_{RNA} + M_F + M_{tow})\ g$ $N_{Sd\_c} = -32.424\ MN$

*As a conservative measure the total weight of the freeboard is included in the point load

Design axial stress: $\sigma_{a\_Sd\_c} := \frac{N_{Sd\_c}}{2 \cdot \pi \cdot r_{f\_o} \cdot t_f}$ $\sigma_{a\_Sd} = -12.946\ MPa$

Per DNVGL-OS-C101 (see page 21), two combination of design loads (a & b) must be considered in both operating and temporary conditions

Load factors for ULS: According to DNV-OS-J101 (see page 102), the point load from RNA and tower self weight is a permanent load (G)

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

a) $\gamma_{f\_G\_a} := 1.3$

b) $\gamma_{f\_G\_b} := 1.0$

Design axial stresses: a) $\sigma_{a\_Sd\_a} := \gamma_{f\_G\_a} \cdot \sigma_{a\_Sd\_c}$ $\sigma_{a\_Sd\_a} = -2.982\ MPa$

b) $\sigma_{a\_Sd\_b} := \gamma_{f\_G\_b} \cdot \sigma_{a\_Sd\_c}$ $\sigma_{a\_Sd\_b} = -2.294\ MPa$

-Design bending stress:

Per DNVGL-RP-C202 (see page 13), the design bending stress for a cylindrical shell without longitudinal stiffeners is (tension positive):

$$\sigma_{m,Sd} = \frac{M_{1,Sd}}{\pi r^2 t}\sin\theta - \frac{M_{2,Sd}}{\pi r^2 t}\cos\theta$$

Bending moment environmental forces:

$F_{wind} := 4.10\ MN$ (Environmental Load Calcs)

$F_{wave} := 11.917\ MN$ (Environmental Load Calcs)

$F_{env} := F_{wind} + F_{wave} = 16.017\ MN$

$M_{env} := F_{env} \cdot (L_T + r_{hub} + L_F)$ $M_{env} = 2226.363\ m \cdot MN$

The shift of the tower top under loading gives rise to a moment arm for the RNA weight. The tower will experience a horizontal displacement of the tower top when exposed to a thrust force. This is known as the P-delta effect (Fredheim, 2022, 44).

Figure 4.13: Illustration of a bottom-fixed wind turbine tower bending.

(Fredheim, 2022)

Tower top displacement: $\delta := \frac{M_{RNA} \cdot g \cdot L_T^3}{3 \cdot E \cdot I_{tow}}$ $\delta = 2.049\ m$

Bending moment from P-delta: $M_{P\_delta} := M_{RNA} \cdot g \cdot \delta$ $M_{P\_delta} = 13.364\ m \cdot MN$

Total Moment: $M := M_{env} + M_{P\_delta}$ $M = 2239.727\ m \cdot MN$

Design bending stress: $\sigma_{m\_Sd} := -\frac{M}{\pi \cdot r_{f\_o}^2 \cdot t_f}$ $\sigma_{m\_Sd} = -63.371\ MPa$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Load factors for ULS: Wind and wave loads are environmental loads (E)

a) $\gamma_{f\_E\_a} := 0.7$

b) $\gamma_{f\_E\_b} := 1.3$

Design bending stresses:

a) $\sigma_{m\_Sd\_a} := \gamma_{f\_E\_a} \cdot \sigma_{m\_Sd}$ $\quad \sigma_{m\_Sd\_a} = -44.36\ MPa$

b) $\sigma_{m\_Sd\_b} := \gamma_{f\_E\_b} \cdot \sigma_{m\_Sd}$ $\quad \sigma_{m\_Sd\_b} = -82.383\ MPa$

Calculate elastic buckling strengths:

-Elastic buckling strength for axial force:

From DNVGL-RP-C202 (see page 21) the axial elastic buckling strength of unstiffened circular cylinder shell is given by equation 3.4.1:

$$f_E = C\frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{l}\right)^2$$

where l the distance between ring frames. However, since the shell is unstiffened, l is the length of the entire spar draft.

$\psi_a := 1$

$$\rho_a := 0.5 \cdot \left(1 + \frac{r_{f\_o}}{150\ t_f}\right)^{-0.5} = 0.482$$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Curvature Parameter: $Z_{l\_a} := \frac{{L_F}^2}{r_{f\_o} \cdot t_f} \cdot \sqrt{1-\nu^2}$ $\quad Z_{l\_a} = 42.397$

$\xi_a := 0.702\ Z_{l\_a}$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Reduced Buckling Coefficient: $C_a := \psi_a \cdot \sqrt{1 + \left(\frac{\rho_a \cdot \xi_a}{\psi_a}\right)^2}$ $\quad C_a = 14.394$

Shell Buckling Strength: $f_{Ea} := C_a \cdot \frac{\pi^2\ E}{12 \cdot (1-\nu^2)} \left(\frac{t_f}{L_F}\right)^2$ $\quad f_{Ea} = 5532.23\ MPa$

-Elastic buckling strength for bending moment:

From DNVGL-RP-C202 (see page 21) the bending elastic buckling strength of unstiffened circular cylinder shell is given by equation 3.4.1:

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

$$f_E = C\frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{l}\right)^2$$

where l the distance between ring frames. However, since the shell is unstiffened, l is the length of the entire tower.

$\psi_m := 1$

$\rho_m := 0.5 \cdot \left(1 + \frac{r_{f\_o}}{300\ t_f}\right)^{-0.5} = 0.491$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Curvature Parameter: $Z_{l\_m} := \frac{L_F^2}{r_{f\_o} \cdot t_f} \cdot \sqrt{1-\nu^2}$ $Z_{l\_m} = 42.397$

$\xi_m := 0.702\ Z_{l\_m}$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells (see page 21)

Reduced Buckling Coefficient: $C_m := \psi_m \cdot \sqrt{1 + \left(\frac{\rho_m \cdot \xi_m}{\psi_m}\right)^2}$ $C_m = 14.647$

Shell Buckling Strength: $f_{Em} := C_m \cdot \frac{\pi^2\ E}{12 \cdot (1-\nu^2)} \left(\frac{t_f}{L_F}\right)^2$ $f_{Em} = 5629.685\ MPa$

<u>Calculate characteristic buckling strength of cylindrical shells</u>

According to DNVGL-RP-C202 (see page 19):

$\sigma_{a\_Sd\_a} = -2.982\ MPa$ < 0 therefore $\sigma_{a0\_Sd\_a} := -\sigma_{a\_Sd\_a}$ $\sigma_{a0\_Sd\_a} = 2.982\ MPa$

$\sigma_{a\_Sd\_b} = -2.294\ MPa$ < 0 therefore $\sigma_{a0\_Sd\_b} := -\sigma_{a\_Sd\_b}$ $\sigma_{a0\_Sd\_b} = 2.294\ MPa$

$\sigma_{m\_Sd\_a} = -44.36\ MPa$ < 0 therefore $\sigma_{m0\_Sd\_a} := -\sigma_{m\_Sd\_a}$ $\sigma_{m0\_Sd\_a} = 44.36\ MPa$

$\sigma_{m\_Sd\_b} = -82.383\ MPa$ < 0 therefore $\sigma_{m0\_Sd\_b} := -\sigma_{m\_Sd\_b}$ $\sigma_{m0\_Sd\_b} = 82.383\ MPa$

Design equivalent von Mises' stress:

a) $\sigma_{j\_Sd\_a} := \sqrt{(\sigma_{a\_Sd\_a} + \sigma_{m\_Sd\_a})^2}$ $\sigma_{j\_Sd\_a} = 47.341\ MPa$

b) $\sigma_{j\_Sd\_b} := \sqrt{(\sigma_{a\_Sd\_b} + \sigma_{m\_Sd\_b})^2}$ $\sigma_{j\_Sd\_b} = 84.676\ MPa$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Reduced shell slenderness:

a) $\lambda_{s\_bar\_a}2 := \frac{f_y}{\sigma_{j\_Sd\_a}} \cdot \left(\frac{\sigma_{a0\_Sd\_a}}{f_{Ea}} + \frac{\sigma_{m0\_Sd\_a}}{f_{Em}}\right)$ $\lambda_{s\_bar\_a}2 = 0.064$

b) $\lambda_{s\_bar\_b}2 := \frac{f_y}{\sigma_{j\_Sd\_b}} \cdot \left(\frac{\sigma_{a0\_Sd\_b}}{f_{Ea}} + \frac{\sigma_{m0\_Sd\_b}}{f_{Em}}\right)$ $\lambda_{s\_bar\_b}2 = 0.064$

Characteristic buckling strength:

a) $f_{ks\_a} := \frac{f_y}{\sqrt{1 + \lambda_{s\_bar\_a}2^2}}$ $f_{ks\_a} = 359.265\ MPa$

b) $f_{ks\_b} := \frac{f_y}{\sqrt{1 + \lambda_{s\_bar\_b}2^2}}$ $f_{ks\_b} = 359.265\ MPa$

$\gamma_M = 1.15 \quad for\ \overline{\lambda}_s < 0.5$

$\gamma_M = 0.85 + 0.60\overline{\lambda}_s \quad for\ 0.5 \le \overline{\lambda}_s \le 1.0$

$\gamma_M = 1.45 \quad for\ \overline{\lambda}_s > 1.0$

Material factor:

a) $\lambda_{s\_bar\_a} := \sqrt{\lambda_{s\_bar\_a}2} = 0.253$ therefore $\gamma_{M\_a} := 1.15$

b) $\lambda_{s\_bar\_b} := \sqrt{\lambda_{s\_bar\_b}2} = 0.253$ therefore $\gamma_{M\_b} := 1.15$

Design shell buckling strength:

a) $f_{ksd\_a} := \frac{f_{ks\_a}}{\gamma_{M\_a}}$ $f_{ksd\_a} = 312.404\ MPa$

a) $f_{ksd\_b} := \frac{f_{ks\_b}}{\gamma_{M\_b}}$ $f_{ksd\_b} = 312.405\ MPa$

Stability requirement:

a) $\sigma_{j\_Sd\_a} = 47.341\ MPa$ < $f_{ksd\_a} = 312.404\ MPa$ **OK**

b) $\sigma_{j\_Sd\_b} = 84.676\ MPa$ < $f_{ksd\_b} = 312.405\ MPa$ **OK**

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

4) Ballast

Ballast Material Parameters

Magnetite density: $\rho_{mag} := 5000 \frac{kg}{m^3}$

Depth of ballast: $d_{ballast} := 10\ m$

S420 yield stress: $f_y = 360\ MPa$

Magnetite stess: $\sigma_{mag} := \rho_{mag} \cdot d_{ballast} \cdot g = 0.49\ MPa$

$f_y = 360\ MPa$ >> $\sigma_{mag} = 0.49\ MPa$ **OK**

B.6:
STABILITY

WIND WRANGLER ENGINEERING SERVICES

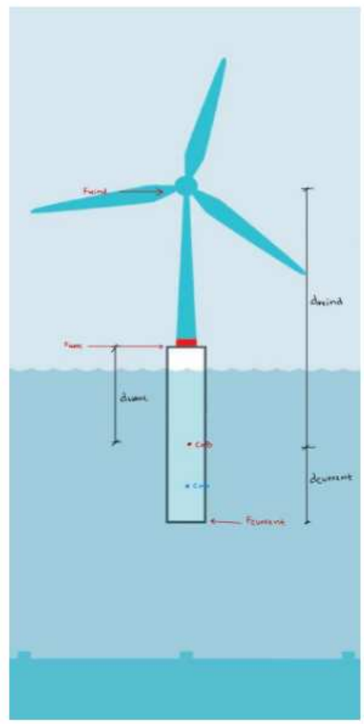
Project: Floating Offshore Wind Turbine	
Engineer: CH	Checked by: CW
Date: 5/22/2023	

	Environmental load factor		1.30 (DNVGL-OS-C101, pg. 21)
Environmental Loads			**Factored Loads**
Wind Load	F_{wind}	4.10 MN	5.33 MN
Wave Load	F_{wave}	11.91 MN	15.48 MN
Current Load	$F_{current}$	2.10 MN	2.72 MN
Significant Wave Height	H_s	10.10 m	NOAA buoy data

Environmental Forces Parameters		
Wind Moment Arm	d_{wind}	210.00 m
Current Moment Arm	$d_{current}$	75.00 m
Wave moment Arm	d_{wave}	85.10 m

*note: turbine assumed to rotate about CoB (Johannessen, 2018, p. 55)

Vertical Coordinates		
Mooring Line Action Coord	z_{MLA}	0.00 m
Environmental Force Coord	z_{env}	289.00 m
Center of Buoyancy Coord	z_{CB}	75.00 m
Center of Gravity Coord	z_{CG}	58.12 m



Structure Parameters		
Mass of Spar	m_{spar}	67305795.17 kg
Weight of Spar	W_{spar}	660.27 MN
Moment of Waterplane Area	I_w	490.87 m^4
Buoyancy Force	F_B	73861788.53 kg
		724.58 MN
Total Weight of Turbine	W_T	723.19 MN
Volume of Displaced Water	V_S	72060.28 m^3
Mass of Mooring	m_{moor}	142500.00 kg
Weight of Mooring	W_m	1.40 MN

Restoring Moment Parameters		
	BG	16.88 m
Metacentric Radius	BM	0.01 m
Metacentric Height	GM	16.89 m
	KG	58.12 m
	KM	75.01 m

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

$KN = KM \sin\theta$

Restoring Moment: $M_R = (F_B * z_{CB} - W_{spar} * z_{CG}) \sin\theta + KM \sin\theta * W_m$

M [MN-m]	Θ [deg]	M [MN-m]	KN [m]	M_{moor} [MN-m]	M_R [MN-m]
12315.58	0.00	0.00	0.00	0.00	0.00
12315.58	5.00	1073.37	6.54	9.14	1082.51
12315.58	10.00	2138.58	13.02	18.21	2156.79
12315.58	15.00	3187.51	19.41	27.14	3214.64
12315.58	20.00	4212.18	25.65	35.86	4248.04
12315.58	25.00	5204.79	31.70	44.31	5249.10
12315.58	30.00	6157.79	37.50	52.43	6210.22
12315.58	35.00	7063.92	43.02	60.14	7124.07
12315.58	40.00	7916.30	48.21	67.40	7983.70
12315.58	45.00	8708.43	53.04	74.14	8782.57
12315.58	50.00	9434.28	57.46	80.32	9514.60
12315.58	55.00	10088.33	61.44	85.89	10174.22
12315.58	60.00	10665.60	64.96	90.81	10756.41
12315.58	65.00	11161.70	67.98	95.03	11256.73
12315.58	70.00	11572.86	70.48	98.53	11671.39
12315.58	75.00	11895.93	72.45	101.28	11997.22
12315.58	80.00	12128.48	73.87	103.26	12231.74
12315.58	85.00	12268.71	74.72	104.45	12373.17
12315.58	90.00	12315.58	75.01	104.85	12420.43

Inclining Moment: $M_I = (F_{wind} * d_{wind} + F_{wave} * d_{wave} + F_{current} * d_{current}) \cos\Theta$

M [MN-m]	Θ [deg]	M_I [MN-m]
2641.00	0.00	2641.00
2641.00	5.00	2630.95
2641.00	10.00	2600.88
2641.00	15.00	2551.01
2641.00	20.00	2481.73
2641.00	25.00	2393.56
2641.00	30.00	2287.18
2641.00	35.00	2163.38
2641.00	40.00	2023.13
2641.00	45.00	1867.47
2641.00	50.00	1697.60
2641.00	55.00	1514.82
2641.00	60.00	1320.50
2641.00	65.00	1116.14
2641.00	70.00	903.28
2641.00	75.00	683.54
2641.00	80.00	458.61
2641.00	85.00	230.18
2641.00	90.00	0.00

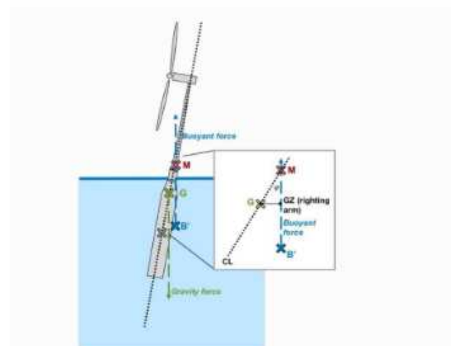
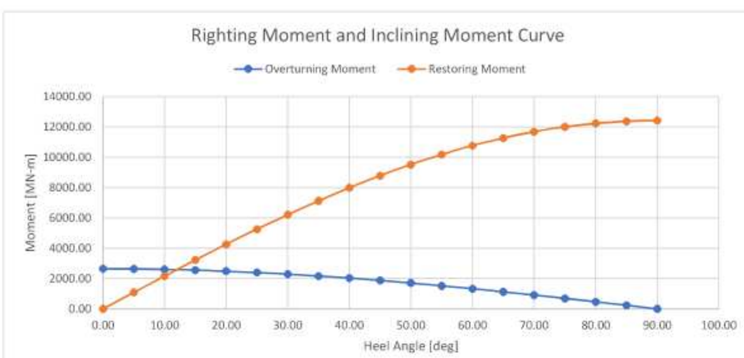


Fig. 38 Static stability of floating offshore wind turbine in pitched position.



Θ_e [deg]	M_I [MN-m]	M_R [MN-m]	Net
12.00	2583.25	2583.25	0.00

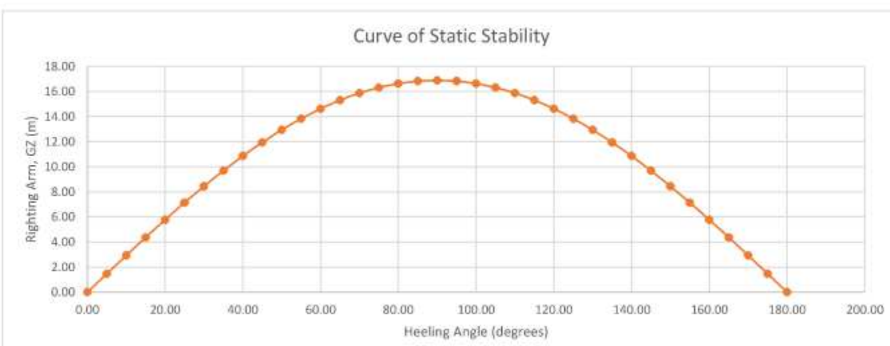
1.3 x Heeling Energy to restore 30 deg	93142.59	
Restoring Energy to restore 30 deg	93153.23	OK

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Static Stability Curve: GZ= KN - KG * sinΘ

GZ [m]	Θ [deg]	KN [m]	GZ [m]
0.00	0.00	0.00	0.00
1.47	5.00	6.54	1.47
2.93	10.00	13.02	2.93
4.37	15.00	19.41	4.37
5.78	20.00	25.65	5.78
7.14	25.00	31.70	7.14
8.45	30.00	37.50	8.45
9.69	35.00	43.02	9.69
10.86	40.00	48.21	10.86
11.94	45.00	53.04	11.94
12.94	50.00	57.46	12.94
13.84	55.00	61.44	13.84
14.63	60.00	64.96	14.63
15.31	65.00	67.98	15.31
15.87	70.00	70.48	15.87
16.32	75.00	72.45	16.32
16.63	80.00	73.87	16.63
16.83	85.00	74.72	16.83
16.89	90.00	75.01	16.89
16.83	95.00	74.72	16.83
16.63	100.00	73.87	16.63
16.32	105.00	72.45	16.32
15.87	110.00	70.48	15.87
15.31	115.00	67.98	15.31
14.63	120.00	64.96	14.63
13.84	125.00	61.44	13.84
12.94	130.00	57.46	12.94
11.94	135.00	53.04	11.94
10.86	140.00	48.21	10.86
9.69	145.00	43.02	9.69
8.45	150.00	37.50	8.45
7.14	155.00	31.70	7.14
5.78	160.00	25.65	5.78
4.37	165.00	19.41	4.37
2.93	170.00	13.02	2.93
1.47	175.00	6.54	1.47
0.00	180.00	0.00	0.00



From this graph, it can be seen that the heeling angle at which a maximum righting arm happens is 90 deg. This means that the strucutre at this angle uses the most energy to put it back to its initial position. The value of the maxiumum righting arm appears to be 16.89 m. The created curve of static stability seems to we wrong as it gives a very high maxiumum heeling angle (Bockute, 2019, 33).

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine	
Engineer: CH	Checked by: CW
Date: 5/22/2023	

Intact Stability of Structure -ULS

These calculations go along with the Stability spreadsheet to provide more information on analysis methodologies.
These calculations ensure the intact stability of the structure. Per DNV-OS-J103 (see page 81), for unmanned units, like a wind turbine, damaged stability is not a requirement.

S420 Steel		References
Yield Strength	$f_y := 360\ MPa$	(EN 10025-4, p. 20)
Poisson's Ratio	$\nu := 0.3$	(EN 10025-4, p. 20)
Young's Modulus:	$E := 210\ GPa$	(EN 10025-4, p. 20)
Density:	$\rho_s := 8500\ \frac{kg}{m^3}$	(Escalera Mendoza et al., 2022, p. 5)

*note: higher density assumed to account for the mass for secondary structures such as bolts and flanges

Tower Parameters

Base Diameter:	$d_{b\_tow} := 10\ m$	(Tower Buckling Strength Calcs)
Thickness:	$t_{tow} := 50\ mm$	(Tower Buckling Strength Calcs)
Top Diameter:	$d_{t\_tow} := 8\ m$	(Tower Buckling Strength Calcs)
Length:	$L_{tow} := 125\ m$	(Tower Buckling Strength Calcs)
Hub Radius:	$r_{hub} := 4\ m$	(Siemens Gamesa) SG 14-222 DD
Hub Height:	$z_{hub} := 135\ m$	(Tower Buckling Strength Calcs)
Outer Diameter:	$d_{o\_tow} := d_{b\_tow}$	$d_{o\_tow} = 10\ m$
Inner Diameter:	$d_{i\_tow} := d_{o\_tow} - 2\ t_{tow}$	$d_{i\_tow} = 9.9\ m$
Inner Radius:	$r_{o\_tow} := \frac{d_{o\_tow}}{2}$	$r_{o\_tow} = 5\ m$
Outer Radius:	$r_{i\_tow} := \frac{d_{i\_tow}}{2}$	$r_{i\_tow} = 4.95\ m$
Area:	$A_{tow} := \pi \cdot r_{o\_tow}^2 - \pi \cdot r_{i\_tow}^2$	$A_{tow} = 1.563\ m^2$

Spar Parameters

Thickness:	$t_{spar} := 450\ mm$	(Spar Buckling Strength Calcs)
Outer Diameter:	$d_{o\_spar} := 25\ m$	(Spar Buckling Strength Calcs)
Total Length:	$L_{T\_spar} := 160\ m$	(Preliminary Turbine Sizing Spreadsheet)
Freeboard:	$L_F := 10\ m$	(Preliminary Turbine Sizing Spreadsheet)
Variable Ballast Depth:	$L_{vb} := 8.89\ m$	(Preliminary Turbine Sizing Spreadsheet)
Displaced Volume:	$V := 72060.28\ m^3$	(Preliminary Turbine Sizing Spreadsheet)

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Inner Diameter: $d_{i\_spar} := d_{o\_spar} - 2 \cdot t_{spar}$ $d_{i\_spar} = 24.1\ m$

Outer Radius: $r_{o\_spar} := \frac{d_{o\_spar}}{2}$ $r_{o\_spar} = 12.5\ m$

Inner Radius: $r_{i\_spar} := \frac{d_{i\_spar}}{2}$ $r_{i\_spar} = 12.05\ m$

Area: $A_{spar} := \frac{\pi}{4} \cdot d_{o\_spar}^{2} - \frac{\pi}{4} \cdot d_{i\_spar}^{2}$ $A_{spar} = 34.707\ m^2$

Draft Length: $L_d := L_{T\_spar} - L_F$ $L_d = 150\ m$

Self Weight of Spar: $M_{spar} := A_{spar} \cdot L_{T\_spar} \cdot \rho_s$ $M_{spar} = 47201172.983\ kg$

Moment of Inertia: $I_{spar} := \frac{\pi}{4}\left(r_{o\_spar}^{4} - r_{i\_spar}^{4}\right)$ $I_{spar} = 2615.609\ m^4$

Waterplane moment of inertia: $I_w := \frac{\pi}{64} \cdot d_{b\_tow}^{4}$ $I_w = 490.874\ m^4$

Total mass of structure: $M_T := 7.37E+07\ kg$ (Preliminary Turbine Sizing Spreadsheet)

Ballast Parameters: (magentite)

Magentite Density: $\rho_{mag} := 5000\ \frac{kg}{m^3}$

Inner area: $A_{inner} := \pi\ \left(r_{i\_spar}\right)^2 = 456.167\ m^2$

Depth of ballast: $L_{ballast} := 10\ m$

Mass of ballast: $M_{ballast} := A_{inner} \cdot L_{ballast} \cdot \rho_{mag} = 22808355.364\ kg$

(Preliminary Turbine Sizing Spreadsheet)
*note: length of ballast chosen through iterative process to ensure sufficent restoring moment

Seawater Parameters:

Seawater density: $\rho_w := 1025\ \frac{kg}{m^3}$

Water depth: $d_w := 1100\ m$

Waterline area: $A_{wl} := \pi \cdot \left(r_{o\_spar}\right)^2 = 490.874\ m^2$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Environmental Forces:

The angle of heel that the buoy may be assumed to result from wind, wave, and current loads. The worst case is usually assumed when the moments produced by the wave, current, and wind forces are all trying to heel the buoy in the same direction.

Wave force: $F_{wave} := 11.91\ MN$ (Environmental load calcs)
Thrust force: $F_{thrust} := 4.10\ MN$ (Environmental load calcs)
Current force: $F_{current} := 2.10\ MN$ (Environmental load calcs)

Significant wave height: $H_{wave} := 10.1\ m$ (NOAA historical buoy data)

Stated in DNV-OS-J103 (see page 81), for deep draught floaters such as spars, the metacentric height GM shall be equal to or greater than 1.0 m.
The metacentric height GM is defined as the difference between the vertical level of the metacentre and the vertical level of the centre of gravity and shall be calculated on the basis of the maximum vertical centre of gravity VCG

Inclining Moment
-moment caused by environmental forces and moment arms to create a heel of the structure

Assumptions
-the force from the drag on the turbine tower is small compared to the thrust force on the rotor and can therefore be neglected
-rotation of the structure is about the center of buoyancy (CoB) (Johannessen, 2018, p. 55)
-thrust force applied at the center of the hub (zhub) as a point load conservatively
-wave force applied at significant wave height as a point load conservatively
-current load applied as a point load at the bottom of the hull conservatively

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

FBD

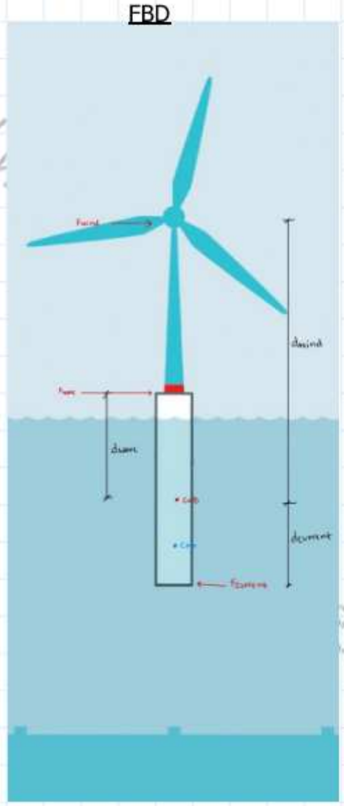


Fig. 38 Static stability of floating offshore wind turbine in pitched position.

(Geometry-WISDEM 2.0 documentation)

Per DNV-OS-C106 (see page 13), the load factors for ultimate limit state area as follows:

Table A1 Load factors – ULS			
Combination of design loads	*Load categories*		
	Permanent and variable functional loads, $\gamma_{f,G,Q}$	*Environmental loads, $\gamma_{f,F}$*	*Deformation loads, $\gamma_{f,D}$*
a)	1.2 [1)]	0.7	1.0
b)	1.0	1.3	1.0
1) If the load is not well defined e.g. masses or functional loads with great uncertainty, possible overfilling of tanks etc. the coefficient should be increased to 1.3.			

Environmental load factor: $\gamma_{f\_E} := 1.3$ (Conservatively use **ULS-b**)

Factored thrust load: $F_t := \gamma_{f\_E} \cdot F_{thrust}$ $F_t = 5.33\ MN$

Factored current load: $F_c := \gamma_{f\_E} \cdot F_{current}$ $F_c = 2.73\ MN$

Factored wave load: $F_w := \gamma_{f\_E} \cdot F_{wave}$ $F_w = 15.483\ MN$

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Project: Floating Offshore Wind Turbine	
Engineer: CH	Checked by: CW
Date: 5/22/2023	

Location of center of buoyancy: $d_{CB} := 75\ m$ (Preliminary Turbine Sizing Spreadsheet) *note: measured from waterline

$z_{CB} := L_d - d_{CB}$ $z_{CB} = 75\ m$ *note: measured from keel

Location of center of gravity: $d_{CG} := 91.88\ m$ (Preliminary Turbine Sizing Spreadsheet) *note: measured from waterline

$z_{CG} := L_d - d_{CG}$ $z_{CG} = 58.12\ m$ *note: measured from keel

Buoyancy force: $F_B := 7.39E{+}07\ kg \cdot g$ (Preliminary Turbine Sizing Spreadsheet)

$F_B = 724.711\ MN$

Total mass of support structure: $m_{spar} := M_{spar} + M_{ballast}$ $m_{spar} = 70009528.347\ kg$

Total mass of structure: $M_T = 73700000\ kg$ (Preliminary Turbine Sizing Spreadsheet)

The inclining moment is calculated by (Johannessen, 2018, p. 55):

Inclining Moment: $M_I := F_t \cdot (z_{hub} + d_{CB}) + F_w \cdot (H_{wave} + d_{CB}) + F_c \cdot (L_d - d_{CB})$ $M_I = 2641.653\ m \cdot MN$

Volume of fluid displaced: $V = 72060.28\ m^3$ (Preliminary Turbine Sizing Spreadsheet)

Distance between center of gravity and center of buoyancy: $BG := 16.88\ m$ (Preliminary Turbine Sizing Spreadsheet)

Metacentric radius: $BM := \frac{I_w}{V}$ $BM = 0.007\ m$

Metacentric height: $GM := BM + BG$ $GM = 16.887\ m$

The DNV-OS-J103 gives the intact stability requirements for Deep Draught Floaters (Spar), which are: "For deep draught floaters such as spars, the metacentric height GM shall be equal to or greater than 1.0 m. The GM is defined as the difference between the vertical level of the metacenter and the vertical level of the center of gravity and shall be calculated on the basis of the maximum vertical center of gravity VCG."

$GM = 16.887\ m$ > 1.0 m **OK**

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Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

The equation used to calculate the restoring moment includes the contribition of the ballast and the mooring forces (Ng et. al., 2020, p. 360)

$$M_{\mathrm{R,roll}} = \left(\underbrace{\rho g I_{xx}}_{\alpha} + \underbrace{F_{\mathrm{B}} \cdot z_{\mathrm{CB}} - mg \cdot z_{\mathrm{CG}}}_{\beta} + \underbrace{C_{44,\mathrm{moor}}}_{\gamma} \right) \sin(\phi)$$

$$M_{\mathrm{R,pitch}} = \left(\overbrace{\rho g I_{yy}}^{\alpha} + \overbrace{F_{\mathrm{B}} \cdot z_{\mathrm{CB}} - mg \cdot z_{\mathrm{CG}}}^{\beta} + \overbrace{C_{55,\mathrm{moor}}}^{\gamma} \right) \sin(\theta)$$

The standard DNVGL-OS-C301 reports that intact inclination angle is limited to 6° and 12° for normal operating conditions and survival conditions or output of the structure will be seriously reduced for angles above this limit
.

$\theta_e := 12\ deg$ = 12 deg **OK**
(Preliminary Turbine Sizing Spreadsheet)

Conclusions: For the dimensions of the spar regarding length and diameter, the stability of the structure governed the geometry of the spar through several iterations adjusting the geometry of the spar and amount of ballast to lower the center of gravity to ensure a sufficent restoring moment and reasonable heeling angle. Then the lateral/hydrostatic pressure governed the thickness of the spar to prevent shell buckling.

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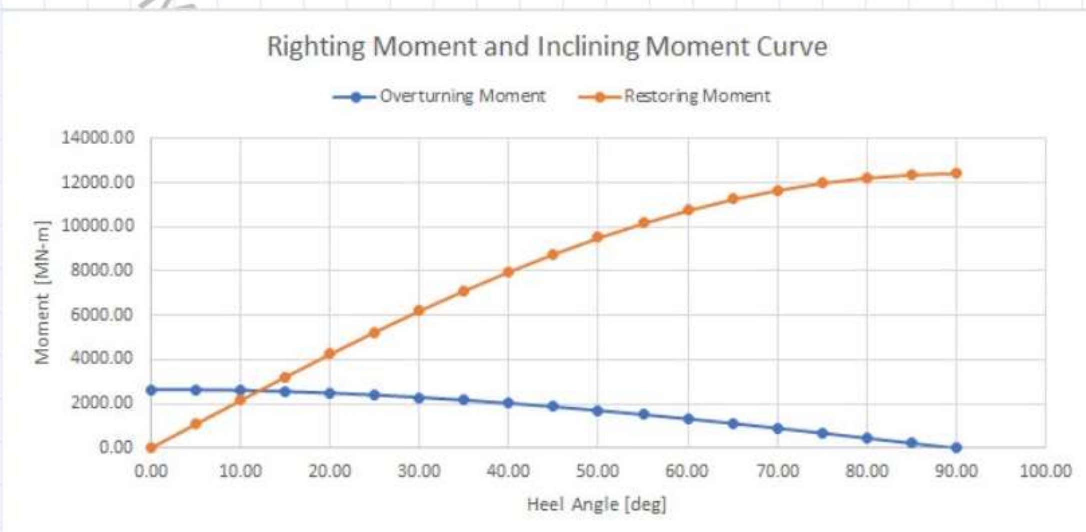
Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Per DNV-OS-C301 (see page 14), The area under the righting moment curve to the second intercept or downflooding angle, whichever is less, shall be not less than 30% in excess of the area under the wind heeling moment curve to the same limiting angle. The righting moment curve shall be positive over the entire range of angles from upright to the second intercept.

Per ABS (see page 134), for the Spar-type floating substructure, the righting energy (area under the righting moment curve) at the inclination angle of 30 degrees is to reach a value of not less than 30% in excess of the area under the overturning moment curve to the same limiting angle (safety factor 1.3). In all cases, the righting moment curve is to be positive over the entire range of angles from upright and all downflooding angles are to be greater than 30 degrees.



(Preliminary Turbine Sizing Spreadsheet)

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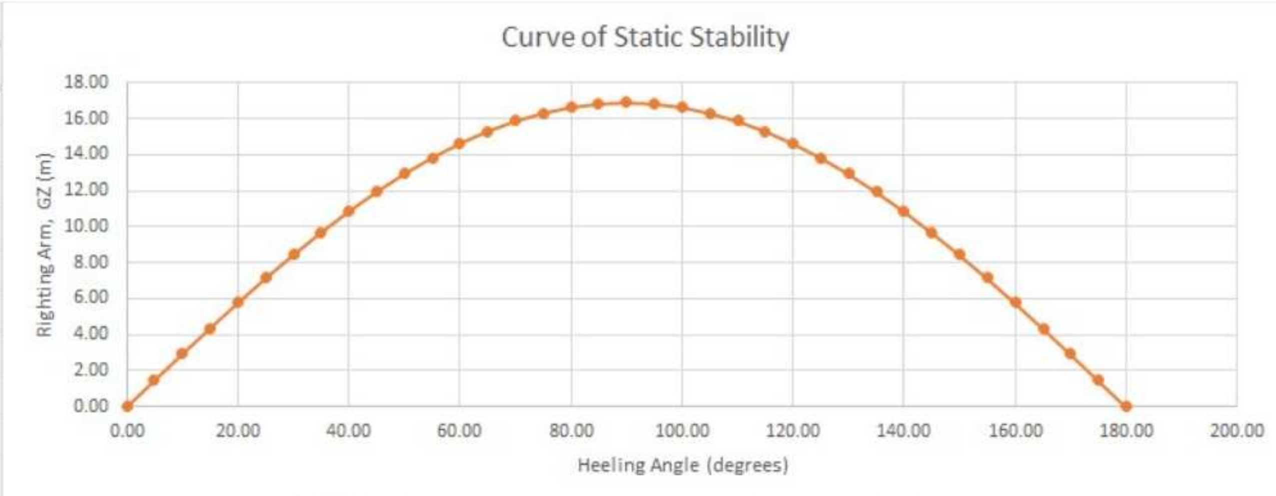
Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023



(Preliminary Turbine Sizing Spreadsheet)

Righting Arm: GZ = KN - KG*sin θ (Bockute, 2019, p. 26)

From this graph, it can be seen that the heeling angle at which a maximum righting arm happens is 90 deg. This means that the structure at this angle uses the most energy to put it back to its initial position. The value of the maxiumum righting arm appears to be 16.89 m. The created curve of static stability seems to we wrong as it gives a very high maxiumum heeling angle (Bockute, 2019, p. 33).

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Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Dynamic Analysis:

Hydrostatic Stiffness

Heave stiffness (Z): $C_{33} := \rho_w \cdot g \cdot A_{wl}$ $C_{33} = 4.934 \frac{MN}{m}$

"Spar platforms have xz and yz symmetry and their restoring capabilities are equal in both roll and pitch (C44 = C55), as well as drag in surge and sway. Pitch stability is mainly achieved by the position of the COG, which intentionally is placed as far down in the structure as possible. This is the reason why spar platforms have so deep draught" (Johannessen, 2018, 14).

Roll stiffness (X): $C_{44} := \rho_w \cdot g \cdot V \cdot GM$ $C_{44} = 12231.738\ MN \cdot \frac{m}{rad}$

Pitch stiffness (Y): $C_{55} := C_{44}$ $C_{55} = 12231.738\ MN \cdot \frac{m}{rad}$

Hydrostatic stiffness matrix: $H := \begin{bmatrix} C_{33} & 0 & 0 \\ 0 & C_{44} & 0 \\ 0 & 0 & C_{55} \end{bmatrix} = \begin{bmatrix} 4.934 & 0 & 0 \\ 0 & 12231.738\ m^2 & 0 \\ 0 & 0 & 12231.738\ m^2 \end{bmatrix} \frac{MN}{m}$

Added Mass

For heave, the added mass is assumed as half of the dispalced mass of the volume of a sphere with the same raduis as the bottom (de Souza, 2022, p. 4) (wisdem).

Heave: $A_{33} := \left(\frac{8}{6} \cdot \pi \cdot r_{o\_spar}{}^3\right) \cdot \rho_w$ $A_{33} = 8385761.64\ kg$

Surge: $A_{11} := \rho_w \cdot \pi \cdot V$ $A_{11} = 232043647.42\ kg$

Pitch: $A_{55} := \rho_w \cdot \pi \cdot r_{o\_spar}{}^2 \cdot \frac{L_d{}^3}{3}$ $A_{55} = 566038910729.802\ kg \cdot m^2$

Roll: $A_{44} := A_{55}$ $A_{44} = 566038910729.802\ kg \cdot m^2$

Mass moment of inertia $I_{xx} := M_T \cdot r_{o\_spar}{}^2$ $I_{xx} = 11515625000\ kg \cdot m^2$

Mass Matrix:

Heave: $M_{33} := M_T$ $M_{33} = 73700000\ kg$

Surge: $M_{11} := M_T$ $M_{11} = 73700000\ kg$

Pitch: $M_{55} := I_{xx}$ $M_{55} = 11515625000\ kg \cdot m^2$

Roll: $M_{44} := I_{xx}$ $M_{55} = 11515625000\ kg \cdot m^2$

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Natural Period:

"Natural periods of the structure should be outside of the energy rich part of the wave spectra from 5-25 seconds" (Johannessen, 2018, 15). This matches the period range for the proposed location from the NOAA buoy data.

The heave natural period must be longer than 25 s. The pitch natural period must be always 5.0 s longer than the heave natural period to avoid coupling effects (de Souza, 2022, 3)

For simplification, the restoring force of the mooring lines in heave motion is ignored (Attwood et al., 2013, 36)

Heave:

$$T_{n33} := 2\ \pi \sqrt{\frac{M_{33}+A_{33}}{C_{33}}} \qquad T_{n33} = 25.628\ s$$

The contribution of mooring lines was ignored for pitch (Attwood et al. 1013, 36)

Pitch:

$$T_{55} := 2\ \pi \sqrt{\frac{M_{55}+A_{55}}{C_{55}}} \qquad T_{55} = 43.175\ s$$

Roll:

$$T_{44} := 2\ \pi \sqrt{\frac{M_{55}+A_{44}}{C_{44}}} \qquad T_{44} = 43.175\ s$$

The design is maintains the heave, pitch, and roll periods outside of the wave period spectrum (5-25s)

B.7:
FATIGUE

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Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Fatigue Analysis

These calculations include the assessment of the fatigue of the tower material and spar material. Fatigue analysis of welded joints are not included as they are beyond the scope of the project.

S420 Steel		References
Yield Strength	$f_y := 390\ MPa$	(EN 10025-4, p. 20) *note: yield strength lowered as a function of thickness
Poisson's Ratio	$\nu := 0.3$	(EN 10025-4, p. 20)
Young's Modulus:	$E := 210\ GPa$	(EN 10025-4, p. 20)
Density:	$\rho_s := 8500\ \frac{kg}{m^3}$	(Escalera Mendoza et al., 2022, p. 5)

*note: higher density assumed to account for the mass for secondary structures such as bolts and flanges

Tower Parameters

Thickness:	$t_t := 50\ mm$	(Tower Buckling Strength Calcs)
Bottom Outer Diameter:	$d_{t\_o\_2} := 10\ m$	(Tower Buckling Strength Calcs)
Top Outer Diameter:	$d_{t\_o\_1} := 8\ m$	(Tower Buckling Strength Calcs)
Length:	$l_t := 125\ m$	(Tower Buckling Strength Calcs)
Hub Radius:	$r_{hub} := 4\ m$	(Siemens Gamesa) SG 14-222DD
Nacelle Mass:	$M_{nacelle} := 500000\ kg$	(Siemens Gamesa) SG 14-222DD
Blades Mass x3:	$M_{blades} := 165000\ kg$	(Siemens Gamesa) SG 14-222DD
Mass of RNA:	$M_{RNA} := M_{nacelle} + M_{blades}$	$M_{RNA} = (6.65 \cdot 10^5)\ kg$
Freeboard:	$L_F := 10\ m$	(Hull Size and Stability Spreadsheet)
Top Inner Diameter:	$d_{t\_i\_1} := d_{t\_o\_1} - 2 \cdot t_t$	$d_{t\_i\_1} = 7.9\ m$
Bottom Inner Diameter:	$d_{t\_i\_2} := d_{t\_o\_2} - 2\ t_t$	$d_{t\_i\_2} = 9.9\ m$
Top Outer Radius:	$r_{t\_o\_1} := \frac{d_{t\_o\_1}}{2}$	$r_{t\_o\_1} = 4\ m$
Bottom Outer Radius:	$r_{t\_o\_2} := \frac{d_{t\_o\_2}}{2}$	$r_{t\_o\_2} = 5\ m$
Top Inner Radius:	$r_{t\_i\_1} := \frac{d_{t\_i\_1}}{2}$	$r_{t\_i\_1} = 3.95\ m$
Bottom Inner Radius:	$r_{t\_i\_2} := \frac{d_{t\_i\_2}}{2}$	$r_{t\_i\_2} = 4.95\ m$
Area:	$A_t := \pi \cdot r_{t\_o\_2}^2 - \pi \cdot r_{t\_i\_2}^2$	$A_t = 1.563\ m^2$
Tower Mass:	$M_{tow} := 1493729\ kg$	(Hull Size and Stability Spreadsheet)

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine	
Engineer: CH	Checked by: CW
Date: 5/22/2023	

Spar Parameters

Thickness:	$t := 450\ mm$	
Outer Diameter:	$d_o := 25\ m$	(Preliminary Turbine Sizing Spreadsheet)
Total Length:	$L_T := 160\ m$	(Preliminary Turbine Sizing Spreadsheet)
Freeboard:	$L_F := 10\ m$	(Preliminary Turbine Sizing Spreadsheet)
Variable Ballast Depth:	$L_{vb} := 8.89\ m$	(Preliminary Turbine Sizing Spreadsheet)
Inner Diameter:	$d_i := d_o - 2 \cdot t$	$d_i = 24.1\ m$
Outer Radius:	$r_o := \frac{d_o}{2}$	$r_o = 12.5\ m$
Inner Radius:	$r_i := \frac{d_i}{2}$	$r_i = 12.05\ m$
Area:	$A_s := \pi \cdot r_o^2 - \pi \cdot r_i^2$	$A_s = 34.707\ m^2$
Draft Length:	$L_d := L_T - L_F$	$L_d = 150\ m$
Spar Length:	$L_s := 140\ m$	
Volume:	$V_s := A_s \cdot L_s$	$V_s = \left(4.859 \cdot 10^3\right)\ m^3$
Self Weight of Spar:	$M_{spar} := V_s \cdot \rho_s$	$M_{spar} = \left(4.13 \cdot 10^7\right)\ kg$

Freeboard Parameters

Outer diameter:	$d_{f\_o} := 10\ m$	
Thickness:	$t_f := 450\ mm$	
Freeboard height:	$L_F := 10\ m$	
Inner diameter:	$d_{f\_i} := d_{f\_o} - 2 \cdot t_f$	$d_{f\_i} = 9.1\ m$
Outer radius:	$r_{f\_o} := \frac{d_{f\_o}}{2}$	$r_{f\_o} = 5\ m$
Inner radius:	$r_{f\_i} := \frac{d_{f\_i}}{2}$	$r_{f\_i} = 4.55\ m$
Area:	$A_F := \frac{\pi}{4} \cdot \left(d_{f\_o}\right)^2 - \frac{\pi}{4} \cdot \left(d_{f\_i}\right)^2$	$A_F = 13.501\ m^2$
Volume:	$V_F := A_F \cdot L_F$	$V_F = 135.01\ m^3$
Mass:	$M_F := V_F \cdot \rho_s$	$M_F = \left(1.148 \cdot 10^6\right)\ kg$

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ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Conical Transition Parameters

Outer top diameter: $d_{c\_o\_1} := 10\ m$

Outer bottom diameter: $d_{c\_o\_2} := 25\ m$

Thickness: $t_c := 450\ mm$

Height: $h_c := 10\ m$

Inner top diameter: $d_{c\_i\_1} := d_{c\_o\_1} - 2 \cdot t_c$ $\quad d_{c\_i\_1} = 9.1\ m$

Inner bottom diameter: $d_{c\_i\_2} := d_{c\_o\_2} - 2 \cdot t_c$ $\quad d_{c\_i\_2} = 24.1\ m$

Outer top radius: $r_{c\_o\_1} := \frac{d_{c\_o\_1}}{2}$ $\quad r_{c\_o\_1} = 5\ m$

Inner top radius: $r_{c\_i\_1} := \frac{d_{c\_i\_1}}{2}$ $\quad r_{c\_i\_1} = 4.55\ m$

Outer bottom radius: $r_{c\_o\_2} := \frac{d_{c\_o\_2}}{2}$ $\quad r_{c\_o\_2} = 12.5\ m$

Inner bottom radius: $r_{c\_i\_2} := \frac{d_{c\_i\_2}}{2}$ $\quad r_{c\_i\_2} = 12.05\ m$

Area cone top: $A_{c\_1} := \frac{\pi}{4} \cdot (d_{c\_o\_1})^2 - \frac{\pi}{4} \cdot (d_{c\_i\_1})^2$ $\quad A_{c\_1} = 13.501\ m^2$

Volume of cone: $V_c := \left(\frac{1}{3} \cdot \pi \cdot h_c\right) \left(\left(r_{c\_o\_1}^2 + r_{c\_o\_2}^2 + r_{c\_o\_1} \cdot r_{c\_o\_2}\right) - \left(r_{c\_i\_1}^2 + r_{c\_i\_2}^2 + r_{c\_i\_1} \cdot r_{c\_i\_2}\right)\right)$

$V_c = 241.039\ m^3$

Mass of cone: $M_c := V_c \cdot \rho_s$ $\quad M_c = \left(2.049 \cdot 10^6\right)\ kg$

Total Spar Volume: $V_{S\_total} := V_s + V_F + V_c$ $\quad V_{S\_total} = \left(5.235 \cdot 10^3\right)\ m^3$

Total Spar Mass: $M_{S\_total} := M_{spar} + M_F + M_c$ $\quad M_{S\_total} = \left(4.45 \cdot 10^7\right)\ kg$

Environmental Parameters

Wind: $F_{wind} := 4.099\ MN$ (Environmental Load Calcs)

Wave: $F_{wave} := 11.911\ MN$ (Environmental Load Calcs)

Current: $F_{current} := 2.095\ MN$ (Environmental Load Calcs)

Significant Wave Height: $H_s := 10.1\ m$ (NOAA Buoy Data)

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine	
Engineer: CH	Checked by: CW
Date: 5/22/2023	

A wind turbine under the cylic loadings from wind and wave is expected to operate for a design life of 20 years. During the design period, fatigue damage is known to be a critical problem. The key component is the connection detail of the wind turbine dower to the floating platform (Li et. al., 2018, p.10).

"Fatigue analysis based on DNV-RP-C203, which reccomends bi-linear S-N curves for offshore structures subjected to wind and wave loads. The accumulated damange is calculated at different sections of the platform and tower. All conditions are analyzed assume aligned wind and wave loads. The 1-hour fatigue damage accumulation on D1h is estimated from the average axial stress time-series of the 4 realizations, which are obtained from each section's axial force Nx and fore-aft bending moment M": (de Souza et. al., 2022, p. 10)

$$\sigma_x = \frac{N_x}{A} + \frac{Mr}{I_y},$$

where A is the annular section area, r is the section radius, and Iy is the section modulus around the bending axis

Tower

Stress in Tower			Reference
Load factor:	$\gamma_F := 1.0$		DNV-OS-J101 p. 62
Material factor:	$\gamma_M := 1.1$		DNV-OS-J101 p. 62
Axial Load	$N_x := \gamma_F \cdot (M_{RNA} + M_{tow}) \cdot g$	$N_x = 21.17\ MN$	

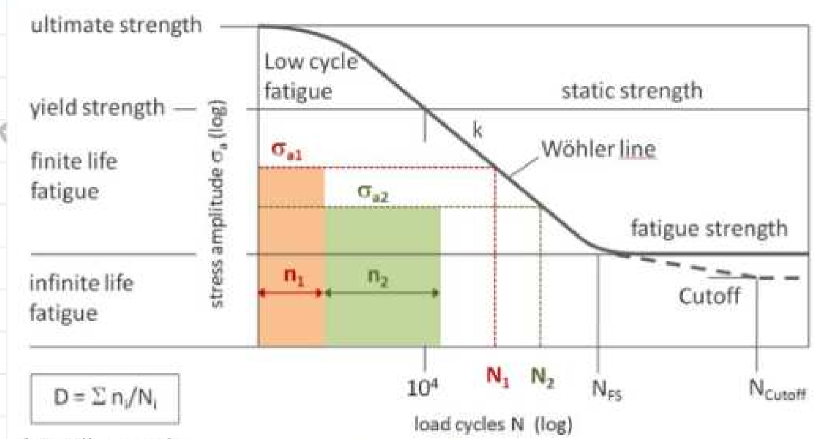
Self weight of tower included as a conservative measure to estimate maximum stress

Area:	$A_t := \pi \cdot r_{t\_o\_1}^2 - \pi \cdot r_{t\_i\_1}^2$	$A_t = 1.249\ m^2$	
Section radius:		$r_{t\_o\_2} = 5\ m$	
Moment:	$M := 538.265\ (m \cdot MN)$		(Tower Buckling Strength Calcs)
Moment of inertia:	$I_y := \frac{\pi}{4} \cdot r_{t\_o\_2}^4 - \frac{\pi}{4} \cdot r_{t\_i\_2}^4$	$I_y = 19.342\ m^4$	
Stress in Tower:	$\sigma_x := \frac{N_x}{A_t} + \frac{M \cdot r_{t\_o\_2}}{I_y}$	$\sigma_x = 156.094\ MPa$	

WIND WRANGLER
ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

In a study by Kucharczyk et al. (2012) it was identified that the fatigue endurance limit of the S355 steel is 260 MPa. Fatigue endurance limit of the material means that under stress cycles with a magnitude lower than this value, the material can theoretically withstand any number of cycles. A graphic of this concept is shown below. In Arany et. al. (2017) this justification is cited to assume that the fatigue life of the structural steel is sufficient.



(Friedl, 2019)

The fatigue life of the tower structural steel is thus considered sufficient because:

$\sigma_x = 156.094\ MPa$ < 260 MPa

S420 has a higher yield strength than S355

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Project: Floating Offshore Wind Turbine
Engineer: CH Checked by: CW
Date: 5/22/2023

Spar

<u>Stress in Spar</u> <u>Reference</u>

Load factor: $\gamma_F := 1.0$ DNV-OS-J101 p. 62

Axial Load $N_x := \gamma_F \cdot (M_{RNA} + M_{tow} + M_{S\_total}) \cdot g$ $N_x = 457.541\ MN$

Self weight of spar included as a conservative measure to estimate maximum stress

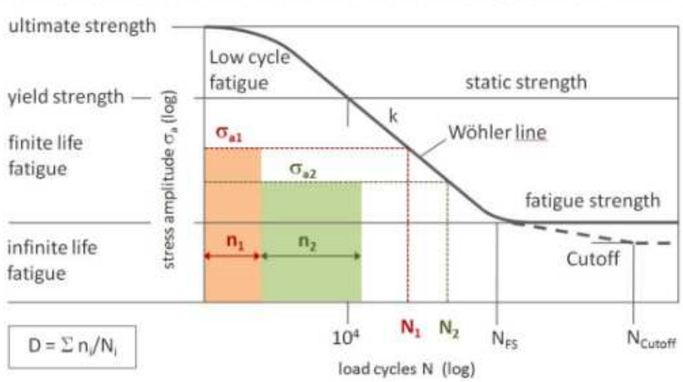
Area: $A_s := \pi \cdot r_o^2 - \pi \cdot r_i^2$ $A_t = 1.249\ m^2$

Section radius: $r_o = 12.5\ m$

Moment: The spar is assumed to experience no bending moment to to its free end as an idealized simplification

Stress in Spar: $\sigma_x := \frac{N_x}{A_s}$ $\sigma_x = 13.183\ MPa$

In a study by Kucharczyk et al. (2012) it was identified that the fatigue endurance limit of the S355 steel is 260 MPa. Fatigue endurance limit of the material means that under stress cycles with a magnitude lower than this value, the material can theoretically withstand any number of cycles. A graphic of this concept is shown below. In Arany et. al. (2017) this justification is cited to assume that the fatigue life of the structural steel is sufficient.



(Friedl, 2019)

The fatigue life of the spar material is thus considered sufficient because:
$\sigma_x = 13.183\ MPa$ << 260 MPa
S420 has a higher yield strength than S355

APPENDIX C: GEOTECHNICAL

SOIL DESIGN PARAMETERS			
Sand		Clay	
ϕ' (degrees)	26	s_u at toe (kPa)	4.8 + 1.8*L
γ' (kN/m^3)	9.43	γ' (kN/m^3)	5.5
K	0.5616	$s_{u,avg}$ (kPa)	(9.6 + 1.8*L)/2

ENVIRONMENTAL LOADS	
Load Case	Load (MN)
Design (per Structural)	18.106
Extreme 1	20
Extreme 2	22
Extreme 3	24

CAISSON DESIGN PARAMETERS	
γ_{steel} (kN/m^3)	78.5
interface friction angle (degrees)	17
interface friction coefficient	0.36
N_c (reverse end bearing factor)	9
tether angle at anchor (degrees)	20

Environmental Loads per Structural:

(E-1) $F_{E-1} = 17.01$ MN

(E-2) $F_{E-2} = 18.106$ MN ← controls

Failure Plane of caisson following Randolph and Gourvenec (2011) and Supachawarote et al. (2004):

$$FP = \left(\frac{H_u}{H_m}\right)^a + \left(\frac{V_u}{V_m}\right)^b < 1$$

where

H_u and V_u = horizontal and vertical components of the applied tether load at padeye

H_m and V_m = horizontal and vertical anchor capacities

$$a = \frac{L}{D} + 0.5$$

$$b = \frac{L}{3D} + 4.5$$

L = caisson penetration depth

D = caisson diameter

Caisson Parameters for L/D = 2:

$D_{clay} = 7.4$ m

$L_{clay} = 14.8$ m

$D_{sand} = 6.7$ m

$L_{sand} = 13.4$ m

Wall thickness (t) is calculated with a diameter - wall ratio of 70 (Arany and Bhattacharya 2018):

$$t_{clay} = \frac{7.4\,m}{70} = 0.106\ m$$

$$t_{sand} = \frac{6.7\,m}{70} = 0.096\ m$$

Calculation of horizontal capacity

- in clay following Randolph and Gourvenec (2011)

$$H_m = L\, D\, N_p\, \overline{S_u}$$

where

L = penetration depth = 14.8 m

D = caisson diameter = 7.4 m

N_p = lateral bearing capacity factor = 10.5 per Table 2, Arany and Bhattacharya (2018)

$\overline{S_u}$ = average undrained shear strength over embedded length of caisson = 17.94 kPa per boring log

$$H_m = (14.8\text{ m})(7.4\text{ m})(10.5)(17.94\text{ kPa})$$

$$H_{m_{clay}} = 20.84\text{ MN}$$

- in sand

$$H_m = LQ_{av}$$

where $LQ_{av} = \frac{1}{2} D\, N_q\, \gamma' L^2$

and $N_q = e^{\pi \tan\phi} \tan\left(45° + \frac{\phi}{2}\right)$ per DNV (1992)

where $\phi = 26°$

$$\rightarrow N_q = e^{\pi \tan 26°} \tan\left(45° + \frac{26°}{2}\right)$$

$$N_q = 7.41$$

$$\rightarrow LQ_{av} = \frac{1}{2}(6.7\text{m})(7.41)(9.43\text{ kN/m}^3)(13.4\text{ m})^2$$

$$LQ_{av} = 42.02\text{ MN}$$

$$H_{m_{sand}} = 42.02\text{ MN}$$

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine	
Engineer: CW	Checked by: CH
Date: 5/22/2023	

Calculation of vertical capacity in sand following Houlsby et al. (2005a) and Houlsby et al. (2005b):

$$V_{m_{sand}} = W + \gamma' Z_e^2 \, y\left(\frac{L}{Z_e}\right)(K \tan\delta)_e \, \pi D + \gamma' Z_i^2 \, y\left(\frac{L}{Z_i}\right)(K \tan\delta)_i \, \pi (D - 2(.107))$$

where

W = caisson weight = 2338.93 kN

γ' = submerged sand unit weight = 9.43 kN/m³ (assumed)

δ = interface friction angle, assumed to be 17°

K = lateral earth pressure coefficient = $1 - \sin\phi = 1 - \sin 26° = .562$

$Z = D/(4K\tan\delta)$

$$y\left(\frac{L}{Z}\right) = e^{-(L/Z)} - 1 + \frac{L}{Z}$$

e/i = external or internal portion of caisson

$$Z_e = \frac{D_e}{4K\tan\delta} = \frac{6.7\,m}{4(.562)\tan 17°} = 9.75\,m$$

$$Z_i = \frac{D - 2t}{4K\tan\delta} = \frac{6.7 - 2(.096)}{4(.562)\tan 17°} = 9.62\,m$$

$$V_{m_{sand}} = 2338.93\,kN + 9.43\,kN/m^3 (9.75\,m)^2 \left(e^{-\frac{13.4\,m}{9.75\,m}} - 1 + \frac{13.4\,m}{9.75\,m}\right)(.562 \tan 17°)(\pi)(6.7\,m)$$
$$+ (9.43\,kN/m^3)(9.62\,m)^2 \left(e^{-\frac{13.4\,m}{9.62\,m}} - 1 + \frac{13.4\,m}{9.62\,m}\right)(.562 \tan 17)(\pi)(6.7\,m - 2(.096))$$

$$V_{m_{sand}} = 6423.52\,kN = 6.423\,MN$$

Wind Wrangler ES | | Geotechnical

Calculation of vertical capacity in clay (Randolph and Gourvenec 2011):

$$V_{m_1} = W + A_{se}\alpha_e \bar{s_u} + N_c s_u A_e$$
$$V_{m_2} = W + A_{se}\alpha_e \bar{s_u} + A_{si}\alpha_i \bar{s_u}$$
$$V_{m_3} = W + A_{se}\alpha_e \bar{s_u} + W_{plug}$$
} smallest controls

where W = caisson weight

A_{se} = external shaft surface area

A_{si} = internal shaft surface area

α_e = external interface friction coefficient

α_i = internal interface friction coefficient

(same = 0.36)

$N_c = 9$ = reverse end bearing factor

$s_u = 31.08$ kPa = undrained shear strength at caisson toe

$\bar{s_u} = 17.94$ kPa = average s_u across embedment depth of caisson

W_{plug} = effective soil plug weight

A_e = external cross-sectional area $= \frac{\pi D^2}{4}$

$\gamma'_{clay} = 5.5$ kN/m³

$\gamma_{steel} = 78.5$ kN/m³

$$W = (\gamma_{steel})\left(\frac{\pi D^2}{4}L - \frac{\pi(D-2t)^2}{4}(L-t)\right)$$
$$W = (78.5\ kN/m^3)\left(\frac{\pi(7.4)^2}{4}(14.8) - \frac{\pi(7.4-2(.106))^2}{4}(14.8-.106)\right)$$
$$W = 3151.28\ kN$$
$$A_{se}\alpha_e\bar{s_u} = (\pi DL)(.36)(17.94\ kPa)$$
$$A_{se}\alpha_e\bar{s_u} = \pi(7.4\ m)(14.8\ m)(.36)(17.94\ kPa)$$
$$A_{se}\alpha_e\bar{s_u} = 2244.42\ kN$$
$$N_c s_u A_e = (9)(31.08\ kPa)\frac{\pi(7.4\ m)^2}{4}$$
$$N_c s_u A_e = 12030.31\ kN$$
$$A_{si}\alpha_i\bar{s_u} = \pi(D-2t)(L)(.36)(17.94\ kPa)$$
$$A_{si}\alpha_i\bar{s_u} = \pi(7.4(2(.106))(14.8)(.36)(17.94\ kPa)$$
$$A_{si}\alpha_i\bar{s_u} = 2212.36\ kN$$
$$W_{plug} = \gamma'_{clay}\left(\frac{\pi(D-2t)^2}{4}\right)(L-t)$$
$$W_{plug} = 5.5\ kN/m^3\left(\frac{\pi(7.4-.106)^2}{4}\right)(14.8-.106)$$
$$W_{plug} = 3280.09\ kN$$

$$V_{m_1} = 3151.28 + 2244.42 + 12030.31$$
$$V_{m_1} = 17565.36\ kN = 17.565\ MN$$
$$V_{m_2} = 3151.28 + 2244.42 + 2212.36$$
$$V_{m_2} = 7608.06\ kN = 7.608\ MN$$
$$V_{m_3} = 3151.28 + 2244.42 + 3280.09$$
$$V_{m_3} = 8675.79\ kN = 8.676\ MN$$

$V_{m_2} = 7.608\ MN$ controls

Wind Wrangler ES		Geotechnical

Assuming tether load at anchor is equal to tether load at mudline and tether angle at anchor $\theta_A = 20°$

$H_u = F_{E-2} \cos\theta_A$ and $V_u = F_{E-2} \sin\theta_A$

$H_u = (18.106\ MN)\cos 20°$ $V_u = (18.106\ MN)\sin 20°$

$H_u = 17.014\ MN$ $V_u = 6.193\ MN$

FP check in clay:

$$\left(\frac{H_u}{H_{m_{clay}}}\right)^{\frac{L}{D}+0.5} + \left(\frac{V_u}{V_{m_{clay}}}\right)^{\frac{L}{3D}+4.5} < 1$$

$$\left(\frac{17.014\ MN}{20.84\ MN}\right)^{2+0.5} + \left(\frac{6.193\ MN}{7.608\ MN}\right)^{\frac{2}{3}+4.5} = 0.948 < 1$$

A caisson with D = 7.4 m and L = 14.8 m is STABLE in clay under the design load of 18.106 MN.

FP check in sand:

$$\left(\frac{H_u}{H_{m\,sand}}\right)^{\frac{L}{D}+0.5} + \left(\frac{V_u}{V_{m\,sand}}\right)^{\frac{L}{3D}+4.5} < 1$$

$$\left(\frac{17.014\ MN}{42.02\ MN}\right)^{2.5} + \left(\frac{6.193\ MN}{6.423\ MN}\right)^{\frac{2}{3}+4.5} = 0.932 < 1$$

A caisson with D = 6.7 m and L = 13.7 m is STABLE in sand under the design load of 18.106 MN

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CW Checked by: CH
Date: 5/22/2023

Caisson Dimensions and Calculations for Environmental Loading Case: Design Load (18.106 MN)

$F_{E\text{-}2}$ (MN)	18.106	MN
Hu	17.014	MN
Vu	6.193	MN

Caisson Design for L/D = 2				Caisson Design for L/D = 3			
CLAY		SAND		CLAY		SAND	
L/D	2	L/D	2	L/D	3	L/D	3
D	7.4	D	6.7	D	5.9	D	5.6
L	14.8	L	13.4	L	17.7	L	16.8
t_{wall}	0.1057143	t_{wall}	0.09571429	t_{wall}	0.08428571	t_{wall}	0.08
a	2.5	a	2.5	a	3.5	a	3.5
b	5.167	b	5.167	b	5.500	b	5.500
Np	10.5	Nq	7.407	Np	10.5	Nq	7.407
$H_{m,clay}$ (MN)	**20.84**	**$H_{m,sand}$ (MN)**	**42.02**	**$H_{m,clay}$ (MN)**	**22.73**	**$H_{m,sand}$ (MN)**	**55.20**
$W_{caisson}$	3151.28	$W_{caisson}$	2338.93	$W_{caisson}$	2310.39	$W_{caisson}$	1975.57
A_{se}	2244.42	Z_e	9.75	A_{se}	2448.37	Z_e	8.15
A_{si}	2212.36	Z_i	9.62	A_{si}	2413.39	Z_i	8.04
W_{plug}	3280.09	γ_e (L/Z)	0.63	W_{plug}	2499.65	γ_e (L/Z)	1.19
V_{m1}	17565.36	yi (L/Z)	0.64	V_{m1}	13779.22	yi (L/Z)	1.21
V_{m2}	7608.06	**$V_{m,sand}$ (MN)**	**6.42**	V_{m2}	7172.15	**$V_{m,sand}$ (MN)**	**6.49**
V_{m3}	8675.79			V_{m3}	7258.40		
$V_{m,clay}$ (MN)	**7.61**			**$V_{m,clay}$ (MN)**	**7.17**		
FP_{clay}	**0.9476715**	**FP_{sand}**	**0.93200561**	**FP_{clay}**	**0.80871042**	**FP_{sand}**	**0.78807432**
Stable?	**YES**	Stable?	**YES**		**YES**		**YES**

Caisson Design for L/D = 4				Caisson Design for L/D = 5			
CLAY		SAND		CLAY		SAND	
L/D	4	L/D	4	L/D	5	L/D	5
D	5.1	D	4.9	D	4.5	D	4.5
L	20.4	L	19.6	L	22.5	L	22.5
t_{wall}	0.0728571	t_{wall}	0.07	t_{wall}	0.06428571	t_{wall}	0.06428571
a	4.5	a	4.5	a	5.5	a	5.5
b	5.833	b	5.833	b	6.167	b	6.167
Np	10.5	Nq	7.407	Np	10.5	Nq	7.407
$H_{m,clay}$ (MN)	**25.30**	**$H_{m,sand}$ (MN)**	**65.74**	**$H_{m,clay}$ (MN)**	**26.63**	**$H_{m,sand}$ (MN)**	**79.56**
$W_{caisson}$	1952.90	$W_{caisson}$	1732.04	$W_{caisson}$	1658.01	$W_{caisson}$	1658.01
A_{se}	2725.16	Z_e	7.13	A_{se}	2868.50	Z_e	6.55
A_{si}	2686.22	Z_i	7.03	A_{si}	2827.52	Z_i	6.46
W_{plug}	2155.22	γ_e (L/Z)	1.81	W_{plug}	1851.99	γ_e (L/Z)	2.47
V_{m1}	12311.67	yi (L/Z)	1.85	V_{m1}	11010.70	yi (L/Z)	2.51
V_{m2}	7364.28	**$V_{m,sand}$ (MN)**	**6.34**	V_{m2}	7354.03	**$V_{m,sand}$ (MN)**	**6.52**
V_{m3}	6833.28			V_{m3}	6378.50		
$V_{m,clay}$ (MN)	**6.83**			**$V_{m,clay}$ (MN)**	**6.38**		
FP_{clay}	**0.7308252**	**FP_{sand}**	**0.87249101**	**FP_{clay}**	**0.91835525**	**FP_{sand}**	**0.72997321**
Stable?	**YES**		**YES**	Stable?	**YES**		**YES**

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine	
Engineer: CW	Checked by: CH
Date: 5/22/2023	

Caisson Dimensions and Calculations for Environmental Loading Case: Extreme 1 (20 MN)

F_{E-2} (MN)	**20**	**MN**					
Hu	**18.794**	**MN**					
Vu	**6.840**	**MN**					
	Caisson Design for L/D = 2				**Caisson Design for L/D = 3**		
CLAY		**SAND**		**CLAY**		**SAND**	
L/D	**2**	**L/D**	**2**	**L/D**	**3**	**L/D**	**3**
D	7.7	D	6.9	D	6.1	D	5.8
L	15.4	L	13.8	L	18.3	L	17.4
t_{wall}	0.11	t_{wall}	0.09857143	t_{wall}	0.08714286	t_{wall}	0.08285714
a	2.5	a	2.5	a	3.5	a	3.5
b	5.167	b	5.167	b	5.500	b	5.500
Np	10.5	Nq	7.407	Np	10.5	Nq	7.407
$H_{m,clay}$ (MN)	**23.23**	**$H_{m,sand}$ (MN)**	**45.89**	**$H_{m,clay}$ (MN)**	**24.93**	**$H_{m,sand}$ (MN)**	**61.33**
$W_{caisson}$	3550.29	$W_{caisson}$	2554.70	$W_{caisson}$	2553.40	$W_{caisson}$	2194.89
A_{se}	2502.51	Z_e	10.05	A_{se}	2685.35	Z_e	8.44
A_{si}	2466.76	Z_i	9.90	A_{si}	2646.99	Z_i	8.32
W_{plug}	3695.42	y_e (L/Z)	0.63	W_{plug}	2762.56	y_e (L/Z)	1.19
V_{m1}	19681.81	yi (L/Z)	0.64	V_{m1}	15165.20	yi (L/Z)	1.21
V_{m2}	8519.56	**$V_{m,sand}$ (MN)**	**7.02**	V_{m2}	7885.73	**$V_{m,sand}$ (MN)**	**7.21**
V_{m3}	9748.22			V_{m3}	8001.31		
$V_{m,clay}$ (MN)	**8.52**			**$V_{m,clay}$ (MN)**	**7.89**		
FP_{clay}	**0.91020341**	**FP_{sand}**	**0.98450228**	**FP_{clay}**	**0.82936329**	**FP_{sand}**	**0.76357747**
Stable?	**YES**	Stable?	**YES**		**YES**		**YES**
	Caisson Design for L/D = 4				**Caisson Design for L/D = 5**		
CLAY		**SAND**		**CLAY**		**SAND**	
L/D	**4**	**L/D**	**4**	**L/D**	**5**	**L/D**	**5**
D	5.2	D	5.1	D	4.7	D	4.6
L	20.8	L	20.4	L	23.5	L	23
t_{wall}	0.07428571	t_{wall}	0.07285714	t_{wall}	0.06714286	t_{wall}	0.06571429
a	4.5	a	4.5	a	5.5	a	5.5
b	5.833	b	5.833	b	6.167	b	6.167
Np	10.5	Nq	7.407	Np	10.5	Nq	7.407
$H_{m,clay}$ (MN)	**26.71**	**$H_{m,sand}$ (MN)**	**74.13**	**$H_{m,clay}$ (MN)**	**30.09**	**$H_{m,sand}$ (MN)**	**84.99**
$W_{caisson}$	2070.05	$W_{caisson}$	1952.90	$W_{caisson}$	1889.05	$W_{caisson}$	1771.02
A_{se}	2877.11	Z_e	7.43	A_{se}	3241.57	Z_e	6.70
A_{si}	2836.01	Z_i	7.32	A_{si}	3195.26	Z_i	6.60
W_{plug}	2284.50	y_e (L/Z)	1.81	W_{plug}	2110.06	y_e (L/Z)	2.47
V_{m1}	13020.68	yi (L/Z)	1.85	V_{m1}	12485.05	yi (L/Z)	2.51
V_{m2}	7783.17	**$V_{m,sand}$ (MN)**	**7.15**	V_{m2}	8325.88	**$V_{m,sand}$ (MN)**	**6.96**
V_{m3}	7231.65			V_{m3}	7240.68		
$V_{m,clay}$ (MN)	**7.23**			**$V_{m,clay}$ (MN)**	**7.24**		
FP_{clay}	**0.92848566**	**FP_{sand}**	**0.77408638**	**FP_{clay}**	**0.77925847**	**FP_{sand}**	**0.8977635**
Stable?	**YES**	Stable?	**YES**	Stable?	**YES**	Stable?	**YES**

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CW Checked by: CH
Date: 5/22/2023

Caisson Dimensions and Calculations for Environmental Loading Case: Extreme 2 (22 MN)

F_{E-2} (MN)	**22**	**MN**					
Hu	**20.673**	**MN**					
Vu	**7.524**	**MN**					
Caisson Design for L/D = 2				**Caisson Design for L/D = 3**			
CLAY		**SAND**		**CLAY**		**SAND**	
L/D	**2**	**L/D**	**2**	**L/D**	**3**	**L/D**	**3**
D	7.9	D	7.2	D	6.3	D	5.9
L	15.8	L	14.4	L	18.9	L	17.7
t_{wall}	0.11285714	t_{wall}	0.10285714	t_{wall}	0.09	t_{wall}	0.08428571
a	2.5	a	2.5	a	3.5	a	3.5
b	5.167	b	5.167	b	5.500	b	5.500
Np	10.5	Nq	7.407	Np	10.5	Nq	7.407
$H_{m,clay}$ (MN)	**24.93**	**$H_{m,sand}$ (MN)**	**52.14**	**$H_{m,clay}$ (MN)**	**27.27**	**$H_{m,sand}$ (MN)**	**64.56**
$W_{caisson}$	3834.19	$W_{caisson}$	2902.62	$W_{caisson}$	2812.87	$W_{caisson}$	2310.39
A_{se}	2685.02	Z_e	10.48	A_{se}	2937.04	Z_e	8.59
A_{si}	2646.66	Z_i	10.33	A_{si}	2895.09	Z_i	8.47
W_{plug}	3990.91	y_e (L/Z)	0.63	W_{plug}	3043.30	y_e (L/Z)	1.19
V_{m1}	21183.04	yi (L/Z)	0.64	V_{m1}	16640.95	yi (L/Z)	1.21
V_{m2}	9165.86	**$V_{m,sand}$ (MN)**	**7.97**	V_{m2}	8645.00	**$V_{m,sand}$ (MN)**	**7.59**
V_{m3}	10510.12			V_{m3}	8793.21		
$V_{m,clay}$ (MN)	**9.17**			**$V_{m,clay}$ (MN)**	**8.65**		
FP_{clay}	**0.98710419**	**FP_{sand}**	**0.84107185**	**FP_{clay}**	**0.84547389**	**FP_{sand}**	**0.97107377**
Stable?	**YES**	Stable?	**YES**		**YES**		**YES**
Caisson Design for L/D = 4				**Caisson Design for L/D = 5**			
CLAY		**SAND**		**CLAY**		**SAND**	
L/D	**4**	**L/D**	**4**	**L/D**	**5**	**L/D**	**5**
D	5.4	D	5.2	D	4.8	D	4.8
L	21.6	L	20.8	L	24	L	24
t_{wall}	0.07714286	t_{wall}	0.07428571	t_{wall}	0.06857143	t_{wall}	0.06857143
a	4.5	a	4.5	a	5.5	a	5.5
b	5.833	b	5.833	b	6.167	b	6.167
Np	10.5	Nq	7.407	Np	10.5	Nq	7.407
$H_{m,clay}$ (MN)	**29.69**	**$H_{m,sand}$ (MN)**	**78.57**	**$H_{m,clay}$ (MN)**	**31.93**	**$H_{m,sand}$ (MN)**	**96.56**
$W_{caisson}$	2318.20	$W_{caisson}$	2070.05	$W_{caisson}$	2012.21	$W_{caisson}$	2012.21
A_{se}	3197.66	Z_e	7.57	A_{se}	3439.61	Z_e	6.99
A_{si}	3151.98	Z_i	7.46	A_{si}	3390.47	Z_i	6.89
W_{plug}	2558.36	y_e (L/Z)	1.81	W_{plug}	2247.63	y_e (L/Z)	2.47
V_{m1}	14519.18	yi (L/Z)	1.85	V_{m1}	13269.10	yi (L/Z)	2.51
V_{m2}	8667.85	**$V_{m,sand}$ (MN)**	**7.58**	V_{m2}	8842.28	**$V_{m,sand}$ (MN)**	**7.91**
V_{m3}	8074.23			V_{m3}	7699.45		
$V_{m,clay}$ (MN)	**8.07**			**$V_{m,clay}$ (MN)**	**7.70**		
FP_{clay}	**0.8589773**	**FP_{sand}**	**0.96074924**	**FP_{clay}**	**0.95930516**	**FP_{sand}**	**0.73532013**
Stable?	**YES**	Stable?	**YES**	Stable?	**YES**	Stable?	**YES**

WIND WRANGLER ENGINEERING SERVICES

Project: Floating Offshore Wind Turbine
Engineer: CW Checked by: CH
Date: 5/22/2023

Caisson Dimensions and Calculations for Environmental Loading Case: Extreme 2 (24 MN)

F_{E-2} (MN)	24	MN
Hu	22.553	MN
Vu	8.208	MN

Caisson Design for L/D = 2			
CLAY		SAND	
L/D	2	L/D	2
D	8.2	D	7.4
L	16.4	L	14.8
t_{wall}	0.11714286	t_{wall}	0.10571429
a	2.5	a	2.5
b	5.167	b	5.167
Np	10.5	Nq	7.407
$H_{m,clay}$ (MN)	**27.62**	**$H_{m,sand}$ (MN)**	**56.61**
$W_{caisson}$	4287.79	$W_{caisson}$	3151.28
A_{se}	2974.94	Z_e	10.77
A_{si}	2932.45	Z_i	10.62
W_{plug}	4463.06	y_e (L/Z)	0.63
V_{m1}	23574.74	yi (L/Z)	0.64
V_{m2}	10195.18	**$V_{m,sand}$ (MN)**	**8.65**
V_{m3}	11725.80		
$V_{m,clay}$ (MN)	**10.20**		
FP_{clay}	0.92881994	FP_{sand}	0.86096126
Stable?	YES	Stable?	YES

Caisson Design for L/D = 3			
CLAY		SAND	
L/D	3.0	L/D	3
D	6.5	D	6.1
L	19.5	L	18.3
t_{wall}	0.09285714	t_{wall}	0.08714286
a	3.5	a	3.5
b	5.500	b	5.500
Np	10.5	Nq	7.407
$H_{m,clay}$ (MN)	**29.39**	**$H_{m,sand}$ (MN)**	**71.35**
$W_{caisson}$	3089.36	$W_{caisson}$	2553.40
A_{se}	3165.19	Z_e	8.88
A_{si}	3119.97	Z_i	8.75
W_{plug}	3342.43	y_e (L/Z)	1.19
V_{m1}	18009.32	yi (L/Z)	1.21
V_{m2}	9374.52	**$V_{m,sand}$ (MN)**	**8.39**
V_{m3}	9596.98		
$V_{m,clay}$ (MN)	**9.37**		
FP_{clay}	0.87766017	FP_{sand}	0.90453226
	YES		YES

Caisson Design for L/D = 4			
CLAY		SAND	
L/D	4	L/D	4
D	5.6	D	5.4
L	22.4	L	21.6
t_{wall}	0.08	t_{wall}	0.07714286
a	4.5	a	4.5
b	5.833	b	5.833
Np	10.5	Nq	7.407
$H_{m,clay}$ (MN)	**32.88**	**$H_{m,sand}$ (MN)**	**87.99**
$W_{caisson}$	2585.44	$W_{caisson}$	2318.20
A_{se}	3541.06	Z_e	7.86
A_{si}	3490.47	Z_i	7.75
W_{plug}	2853.28	y_e (L/Z)	1.81
V_{m1}	16128.28	yi (L/Z)	1.85
V_{m2}	9616.97	**$V_{m,sand}$ (MN)**	**8.49**
V_{m3}	8979.78		
$V_{m,clay}$ (MN)	**8.98**		
FP_{clay}	0.77565191	FP_{sand}	0.82461372
Stable?	YES	Stable?	YES

Caisson Design for L/D = 5			
CLAY		SAND	
L/D	5	L/D	5
D	5	D	4.9
L	25	L	24.5
t_{wall}	0.07142857	t_{wall}	0.07
a	5.5	a	5.5
b	6.167	b	6.167
Np	10.5	Nq	7.407
$H_{m,clay}$ (MN)	**35.83**	**$H_{m,sand}$ (MN)**	**102.72**
$W_{caisson}$	2274.36	$W_{caisson}$	2140.61
A_{se}	3859.45	Z_e	7.13
A_{si}	3804.31	Z_i	7.03
W_{plug}	2540.46	y_e (L/Z)	2.47
V_{m1}	14934.19	yi (L/Z)	2.51
V_{m2}	9938.12	**$V_{m,sand}$ (MN)**	**8.41**
V_{m3}	8674.26		
$V_{m,clay}$ (MN)	**8.67**		
FP_{clay}	0.7898896	FP_{sand}	0.85869568
Stable?	YES	Stable?	YES

Ultimate Capacity vs. Achieved Embedment Depth for Diameters of 4m, 5m, 6m, 7m, and 8m

Capacity vs. Depth for 4 m Diameter		
	Clay	Sand
Depth (m)	Capacity (MN)	Capacity (MN)
1	0.29	0.19
2	0.63	0.61
3	1.05	1.31
4	1.55	2.30
5	2.13	3.57
6	2.78	5.11
7	3.49	6.94
8	4.28	9.04
9	5.15	11.43
10	6.09	14.09
11	7.11	17.03
12	8.20	20.26
13	9.37	23.76
14	10.62	27.53
15	11.94	31.59
16	13.34	35.93
17	14.81	40.55
18	16.36	45.44
19	17.98	50.61
20	19.68	56.07
21	21.46	61.80
22	23.31	67.81
23	25.24	74.10
24	27.24	80.67
25	29.32	87.52

Capacity vs. Depth for 5 m Diameter		
	Clay	Sand
Depth	Capacity (MN)	Capacity (MN)
1	0.40	0.28
2	0.82	0.79
3	1.35	1.67
4	1.98	2.90
5	2.71	4.49
6	3.54	6.43
7	4.47	8.71
8	5.48	11.35
9	6.57	14.33
10	7.75	17.67
11	9.03	21.35
12	10.41	25.38
13	11.87	29.76
14	13.44	34.49
15	15.09	39.59
16	16.84	44.99
17	18.69	50.76
18	20.63	56.88
19	22.66	63.36
20	24.79	70.18

Capacity vs. Depth for 6 m Diameter		
	Clay	Sand
Depth	Capacity (MN)	Capacity (MN)
1	0.53	0.39
2	1.04	1.00
3	1.69	2.05
4	2.45	3.53
5	3.33	5.43
6	4.33	7.76
7	5.45	10.51
8	6.69	13.67
9	8.05	17.26
10	9.50	21.26
11	11.04	25.68
12	12.70	30.53
13	14.46	35.79
14	16.35	41.46
15	18.34	47.56
16	20.45	54.08
17	22.67	61.01

Capacity vs. Depth for 7 m Diameter		
	Clay	Sand
Depth	Capacity (MN)	Capacity (MN)
1	0.69	0.55
2	1.30	1.24
3	2.05	2.45
4	2.95	4.18
5	3.98	6.40
6	5.16	9.12
7	6.47	12.32
8	7.92	16.02
9	9.52	20.21
10	11.25	24.88
11	13.12	30.05
12	15.09	35.70
13	17.16	41.84
14	19.36	48.47
15	21.70	55.59

Capacity vs. Depth for 8 m Diameter		
	Clay	Sand
Depth	Capacity (MN)	Capacity (MN)
1	0.90	0.74
2	1.59	1.52
3	2.46	2.89
4	3.49	4.86
5	4.68	7.40
6	6.03	10.50
7	7.54	14.17
8	9.21	18.39
9	11.03	23.18
10	13.02	28.53
11	15.17	34.44
12	17.47	40.91
13	19.93	47.93
14	22.50	55.52

APPENDIX D:
COST ESTIMATE

CLASS 2 COST ESTIMATE

PROJECT: FLOATING OFFSHORE WIND TURBINE

DATE: 05.22.2023

HARD COSTS							
SCOPE	**DESCRIPTION**	**QTY**	**UNIT**	**UNIT COST**	**TOTAL**	**INFLATION ADJUSTMENT**	**SOURCE**
PRECONSTRUCTION							
SITE ASSESSMENT					**SECTION SUBTOTAL**	**$772,079.07**	
Environmental Impact Assessments Surveys	Impact assessments, benthic fish and shellfish, ornithological, marine mamammal, etc, per 14	1.00	EA	$204,520.68	$204,520.68	$252,859.00	Catapult*
Resource and Metocean Assessment	Structure, sensors, maintenance, per 14 MW Turbine	1.00	EA	$12,173.56	$12,173.56	$15,050.77	Catapult*
Geological and Hydrological Surveys	Geophysical, geotechnical, hydrographic surveys, per 14 MW Turbine	1.00	EA	$204,520.68	$204,520.68	$252,859.00	Catapult*
Site Survey (Port)	Topographical, conventional, avg	42.39	Acre	$1,637.09	$69,400.08	$92,373.01	02 21 13.09
Boundary Survey Markers (Port)	Lot Location and lines, avg	42.39	Acre	$1,095.49	$46,440.39	$61,813.16	02 21 13.13**
Subsurface Drilling & Sampling	Borings, drawings, report & recommendations, mobilization & demobilization	32.00	EA	$2,280.30	$72,969.60	$97,124.11	02 32 13**
DEMOLITION					**SECTION SUBTOTAL**	**$155,142.88**	
Building Demolition	Single-story buildings, no salvage included, wood	349,604.31	CF	$0.26	$90,897.12	$120,986.03	02 41 16**
Pavement Removal	Pavement Removal, bituminous roads, 3" thick	1,200.57	SY	$4.04	$4,850.32	$6,455.88	02 41 13.17**
Curb Removal	curbs, concrete, plain	5,862.48	LF	$3.55	$20,811.81	$27,700.97	02 41 13.16**
ROAD RE-ROUTING					**SECTION SUBTOTAL**	**$1,892,593.56**	
Striping	Acrylic waterborne, white or yellow, 4" wide	2,931.24	LF	$0.32	$938.00	$1,159.69	32 17 23.13**
Asphalt Pavement Fill	Asphalt pavement, 3"	349,604.31	SF	$5.00	$1,748,021.55	$1,890,060.14	HomeServe************
Traffic Directional Signage	24"x24" stock signs, reflectorized, steel post 10'	8.00	EA	$138.89	$1,111.12	$1,373.73	10 14 53.20**
					PHASE SUBTOTAL	$2,819,815.51	
PORT SITE CONSTRUCTION							
TEMPORARY CONSTRUCTION					**SECTION SUBTOTAL**	**$54,834,199.07**	
Port Marshaling	Port Marshaling, 18-24 months construction	1.00	EA	$50,000,000.00	$50,000,000.00	$54,062,838.57	Energy Policy***********
Temporary Sound Barriers	Noise Barrier, 50' high	276,208.80	SF	$34.00	$187,821.98	$249,995.12	U.S. DOT***
Temporary Construction Fencing	Chain link, 6' high, 11 ga.	5,524.18	LF	$7.13	$39,387.37	$52,425.45	01 56 26**
Temporary Road Barriers	Highway Jersey Barrier, Portable, 60"x21"	1,172.50	EA	$399.95	$468,939.93	$468,939.93	Seton****
PREFABRICATED BUILDINGS					**SECTION SUBTOTAL**	**$3,305,453.12**	
Storage Warehouse	Modular warehouse	59,997.98	SF	$55.00	$3,299,888.82	$3,299,888.82	Green Building Elements*****
Jobsite Trailer	Trailer, furnished, 32'x8', buy	1.00	EA	$1,025.00	$1,025.00	$1,364.30	01 52 13**
Restrooms	Standard Porta-Potty, buy	6.00	EA	$700.00	$4,200.00	$4,200.00	FusionSite******
TURBINE COMPONENTS PROCUREMENT					**SECTION SUBTOTAL**	**$23,172,226.45**	
Nacelle					**PART SUBTOTAL**	**$6,976,439.13**	
Bedplate	Bedplate, per 14 MW Turbine	1.00	EA	$336,882.00	$336,882.00	$416,503.83	Catapult*
Main bearing	Main bearing, per 14 MW Turbine	1.00	EA	$336,882.00	$336,882.00	$416,503.83	Catapult*
Main shaft	Main shaft, per 14 MW Turbine	1.00	EA	$336,882.00	$336,882.00	$416,503.83	Catapult*
Gearbox	Gearboxm per 14 MW Turbine	1.00	EA	$1,179,087.00	$1,179,087.00	$1,457,763.40	Catapult*
Generator	Generator, per 14 MW Turbine	1.00	EA	$1,684,410.00	$1,684,410.00	$2,082,519.14	Catapult*
Power take-off	Power take-off, per 14 MW Turbine	1.00	EA	$117,908.70	$117,908.70	$145,776.34	Catapult*
Control System	Control Systemm, per 14 MW Turbine	1.00	EA	$421,102.50	$421,102.50	$520,629.79	Catapult*
Yaw system	Yaw system, per 14 MW Turbine	1.00	EA	$286,349.70	$286,349.70	$354,028.25	Catapult*
Yaw bearing	Yaw bearing, per 14 MW Turbine	1.00	EA	$117,908.70	$117,908.70	$145,776.34	Catapult*
Nacelle auxiliary systems	Nacelle auxiliary systems, per 14 MW Turbine	1.00	EA	$117,908.70	$117,908.70	$145,776.34	Catapult*
Nacelle cover	Nacelle cover, per 14 MW Turbine	1.00	EA	$168,441.00	$168,441.00	$208,251.91	Catapult*
Small engineering componenets	Small engineering componenets, per 14 MW Turbine	1.00	EA	$421,102.50	$421,102.50	$520,629.79	Catapult*
Structural fasteners	Structural fasteners, per 14 MW Turbine	1.00	EA	$117,908.70	$117,908.70	$145,776.34	Catapult*
Rotor					**PART SUBTOTAL**	**$4,081,737.52**	
Blades	Blades, per 14 MW Turbine	1.00	EA	$2,189,733.00	$2,189,733.00	$2,707,274.89	Catapult*
Hub casting	Hub casting, per 14 MW Turbine	1.00	EA	$252,661.50	$252,661.50	$312,377.87	Catapult*
Blade bearings	Blade bearings, per 14 MW Turbine	1.00	EA	$336,882.00	$336,882.00	$416,503.83	Catapult*
Pitch system	Pitch system, per 14 MW Turbine	1.00	EA	$168,441.00	$168,441.00	$208,251.91	Catapult*
Spinner	Spinner, per 14 MW Turbine	1.00	EA	$33,688.20	$33,688.20	$41,650.38	Catapult*
Rotor auxiliary systems	Rotor auxiliary systems, per 14 MW Turbine	1.00	EA	$67,376.40	$67,376.40	$83,300.77	Catapult*
Fabricated steel components	Fabricated steel components, per 14 MW Turbine	1.00	EA	$134,752.80	$134,752.80	$166,601.53	Catapult*
Structural Fasteners	Structural Fasteners, per 14 MW Turbine	1.00	EA	$117,908.70	$117,908.70	$145,776.34	Catapult*
Tower					**PART SUBTOTAL**	**$2,195,025.32**	
Steel	Steel - S355, 2550 tons/turbine	1.00	EA	$1,657,500.00	$1,657,500.00	$2,049,248.98	Catapult*
Tower internals	Tower internals, per 14 MW Turbine	1.00	EA	$117,908.70	$117,908.70	$145,776.34	Catapult*
Spar Buoy					**PART SUBTOTAL**	**$4,823,369.57**	
Steel	Steel - S355, 2900 tons/turbine	1.00	EA	$1,885,000.00	$1,885,000.00	$2,330,518.45	Catapult*
Magnetite Ballast	Magnetite Ballast, 12220 tons/turbine	1.00	EA	$2,016,300.00	$2,016,300.00	$2,492,851.12	Catapult*
Turbine Foundation					**PART SUBTOTAL**	**$4,625,974.90**	
Transition Piece	Transition Piece, per 14 MW Turbine	1.00	EA	$1,704,339.00	$1,704,339.00	$2,107,158.35	Catapult*
Corrosion Protection	Corrosion Protection, per 14 MW Turbine	1.00	EA	$340,867.80	$340,867.80	$421,431.67	Catapult*
Scour Protection	Scour Protection, per 14 MW Turbine	1.00	EA	$1,696,433.90	$1,696,433.90	$2,097,384.88	Catapult*
Embedded Suction Caisson					**PART SUBTOTAL**	**$469,680.00**	
Suction Caisson	(1) 6mx15m suction caisson, per 14 MW Turbine	1.00	EA	$469,680.00	$469,680.00	$469,680.00	Deep Foundations Conference*******
TURBINE COMPONENT SHIPMENT TO PORT SITE					**SECTION SUBTOTAL**	**$15,420,000.00**	
Blade Transport	Blade transport from Europe to Port Site, incl. racks	3.00	EA	$870,000.00	$2,610,000.00	$2,610,000.00	NREL************
Nacelle Transport	Nacelle transport from Europe to Port Site, incl. transport frames	1.00	EA	$5,350,000.00	$5,350,000.00	$5,350,000.00	NREL************
Tower Transport	Tower transport from Europe to Port Site, incl. cradles	1.00	EA	$3,150,000.00	$3,150,000.00	$3,150,000.00	NREL************
Spar Buoy Transport	Spar Buoy transport from Europe to Port Site, incl. transport frames	1.00	EA	$2,870,000.00	$2,870,000.00	$2,870,000.00	NREL************
Transition Piece Transport	Transition piece transport from Europe to Port Site, incl. transport frames	1.00	EA	$1,440,000.00	$1,440,000.00	$1,440,000.00	NREL************
ASSEMBLY & EQUIPMENT					**SECTION SUBTOTAL**	**$50,546,312.39**	
On-Shore Cranes	Liebherr LR 11350	4.00	EA	$10,830,540.00	$43,322,160.00	$43,322,160.00	Lectura Specs********
Boom Lift	Snorkel 2100SJ	6.00	MONTH	$9,969.00	$59,814.00	$59,814.00	Fork Lift America*********
Assembly	Assembly labor, wind turbine supplier aspects of installation, commissioning, per 14 MW Turb	1.00	EA	$5,794,752.60	$5,794,752.60	$7,164,338.39	Catapult*
					PHASE SUBTOTAL	$147,278,191.03	

Wind Wrangler Engineering Services

OFF-SHORE SITE CONSTRUCTION							
TRANSPORT					**SECTION SUBTOTAL**	**$3,859,925.93**	
Offshore Heavy Lift Crane	Svanen Heavy Lift Vessel, >100m water depth, 8700 ton capacity, 5 days	1.00	EA	$3,111,680.00	$3,111,680.00	$3,802,925.93	DECOMTOOLS**********
Tug boats	Pull capacity: 60 tons	3.00	Day	$19,000.00	$57,000.00	$57,000.00	Deep Foundations Conference*******
INSTALLATION					**SECTION SUBTOTAL**	**$3,188,457.52**	
Turbine Installation	Turbine Installation at Off-Shore Wind Farm Location, per 14 MW Turbine	1.00	EA	$852,169.50	$852,169.50	$1,053,579.17	Catapult*
Foundation Installation	Foundation Installation at Off-Shore Wind Farm Location, per 14 MW Turbine	1.00	EA	$1,704,339.00	$1,704,339.00	$2,107,158.35	Catapult*
Embedded Suction Caisson Install	Medium AHV (150 ton pulling capacity), 1.26 days for install per turbine	1.00	EA	$27,720.00	$27,720.00	$27,720.00	Deep Foundations Conference*******
					PHASE SUBTOTAL	**$7,048,383.46**	
UTILITIES							
CABLES					**SECTION SUBTOTAL**	**$3,518,954.36**	
Utility Cables	Export cable, array cable, cable protection, per 14 MW Turbine	1.00	EA	$2,846,246.06	$2,846,246.06	$3,518,954.36	Catapult*
SUBSTATIONS					**SECTION SUBTOTAL**	**$4,593,605.03**	
Offshore Substation	Installation, electrical System, facilities, structure, per 14 MW Turbine	1.00	EA	$2,726,942.26	$2,726,942.26	$3,371,453.19	Catapult*
Onshore Substation	Construction, buildings, access and security, electrical equipment and systems, per 14 MW Tur	1.00	EA	$937,386.52	$937,386.52	$1,158,937.18	Catapult*
Operations Base	Operations, per 14 MW Turbine	1.00	EA	$51,130.10	$51,130.10	$63,214.66	Catapult*
INSTALLATION					**SECTION SUBTOTAL**	**$4,585,326.19**	
Utility trenching	Offshore cable burial, per 14 MW Turbine	1.00	EA	$340,867.80	$340,867.80	$421,431.67	Catapult*
Onshore Cable Installation	Onshore export cable installation, per 14 MW Turbine	1.00	EA	$85,216.88	$85,216.88	$105,357.83	Catapult*
Offshore Cable Installation	Offshore cable pull-in, electrical testing and termination, cable-laying vessel, survey works, rou	1.00	EA	$3,282,678.00	$3,282,678.00	$4,058,536.69	Catapult*
					PHASE SUBTOTAL	**$12,697,885.57**	
					HARD COSTS SUBTOTAL	**$169,844,275.57**	

SOFT COSTS (20% Contingency)		
LINE ITEM	**PERCENTAGE**	**TOTAL**
GC Overhead	12.00%	$20,381,313.07
GC Profit	3.00%	$5,095,328.27
Regulatory Fees & Permits	8.00%	$13,587,542.05
Bonds & Insurance	1.50%	$2,547,664.13
Taxes	8.00%	$13,587,542.05
Contingency	20.00%	$33,968,855.11
	SOFT COSTS SUBTOTAL	**$89,168,244.67**
	TOTAL PROJECT COST	**$259,012,520.24**

SOFT COSTS (40% Contingency)		
LINE ITEM	**PERCENTAGE**	**TOTAL**
GC Overhead	12.00%	$20,381,313.07
GC Profit	3.00%	$5,095,328.27
Regulatory Fees & Permits	8.00%	$13,587,542.05
Bonds & Insurance	1.50%	$2,547,664.13
Taxes	8.00%	$13,587,542.05
Contingency	40.00%	$67,937,710.23
	SOFT COSTS SUBTOTAL	**$123,137,099.79**
	TOTAL PROJECT COST	**$292,981,375.35**

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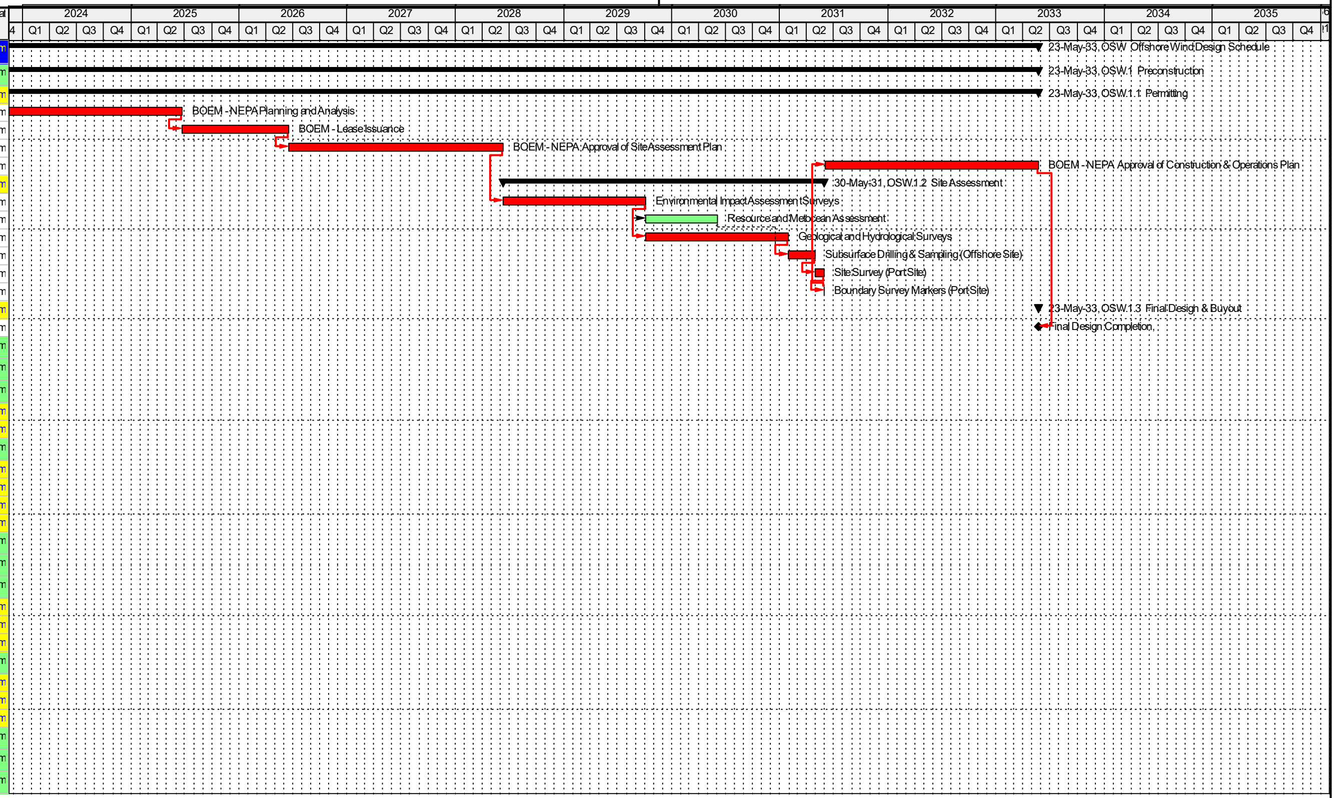
APPENDIX E:
DESIGN SCHEDULES

Offshore Wind Design Schedule | Permitting Schedule | May 22, 2023

Activity ID	Activity Name	Original Duration	Start	Finish	Total Float
OSW	Offshore Wind Design Schedule	120m 0.20w	03-Jul-23	23-May-33	0m
OSW.1	Preconstruction	120m 0.20w	03-Jul-23	23-May-33	0m
OSW.1.1	Permitting	120m 0.20w	03-Jul-23	23-May-33	0m
PER1000	BOEM - NEPA Planning and Analysis	24m	03-Jul-23	23-Jun-25	0m
PER1010	BOEM - Lease Issuance	12m	24-Jun-25	18-Jun-26	0m
PER1020	BOEM - NEPA Approval of Site Assessment Plan	24m	19-Jun-26	09-Jun-28	0m
PER1030	BOEM - NEPA Approval of Construction & Operations Plan	24m	02-Jun-31	23-May-33	0m
OSW.1.2	Site Assessment	36m 0.20w	12-Jun-28	30-May-31	0m
SA1000	Environmental Impact Assessmen tSurveys	16m	12-Jun-28	04-Oct-29	0m
SA1010	Resource and Metocean Assessment	8m	05-Oct-29	03-Jun-30	8m
SA1020	Geological and Hydrological Surveys	16m	05-Oct-29	29-Jan-31	0m
SA1030	Subsurface Drilling & Sampling (Offshore Site)	3m	30-Jan-31	30-Apr-31	0m
SA1040	Site Survey (Port Site)	1m	30-Apr-31	29-May-31	0m
SA1050	Boundary Survey Markers (Port Site)	0m 0.20w	30-May-31	30-May-31	0m
OSW.1.3	Final Design & Buyout	0m	23-May-33	23-May-33	0m
FD1000	Final Design Completion	0m		23-May-33	0m
OSW.2	Mobilization 1 - Port Site	0m			0m
OSW.3	Demolition - Port Site	0m			0m
OSW.4	Site Work - Port Site	0m			0m
OSW.4.1	Traffic Control	0m			0m
OSW.4.2	Prefabricated Buildings	0m			0m
OSW.5	Procurement	0m			0m
OSW.5.1	Onshore Equipment	0m			0m
OSW.5.2	Turbine Components	0m			0m
OSW.5.3	Anchor Components	0m			0m
OSW.5.4	Offshore Equipment	0m			0m
OSW.6	Assembly	0m			0m
OSW.12	Mobilization 2 - Offshore Site	0m			0m
OSW.7	Installation	0m			0m
OSW.7.1	Utility Lines Installation	0m			0m
OSW.7.2	Anchor Installation	0m			0m
OSW.7.3	Turbine Installation	0m			0m
OSW.8	Utility Connections	0m			0m
OSW.8.1	Mechanical Equipment	0m			0m
OSW.8.2	Electrical Utilities	0m			0m
OSW.8.3	Power Utilities	0m			0m
OSW.9	Commissioning	0m			0m
OSW.10	Demobilization	0m			0m
OSW.11	Closeout	0m			0m

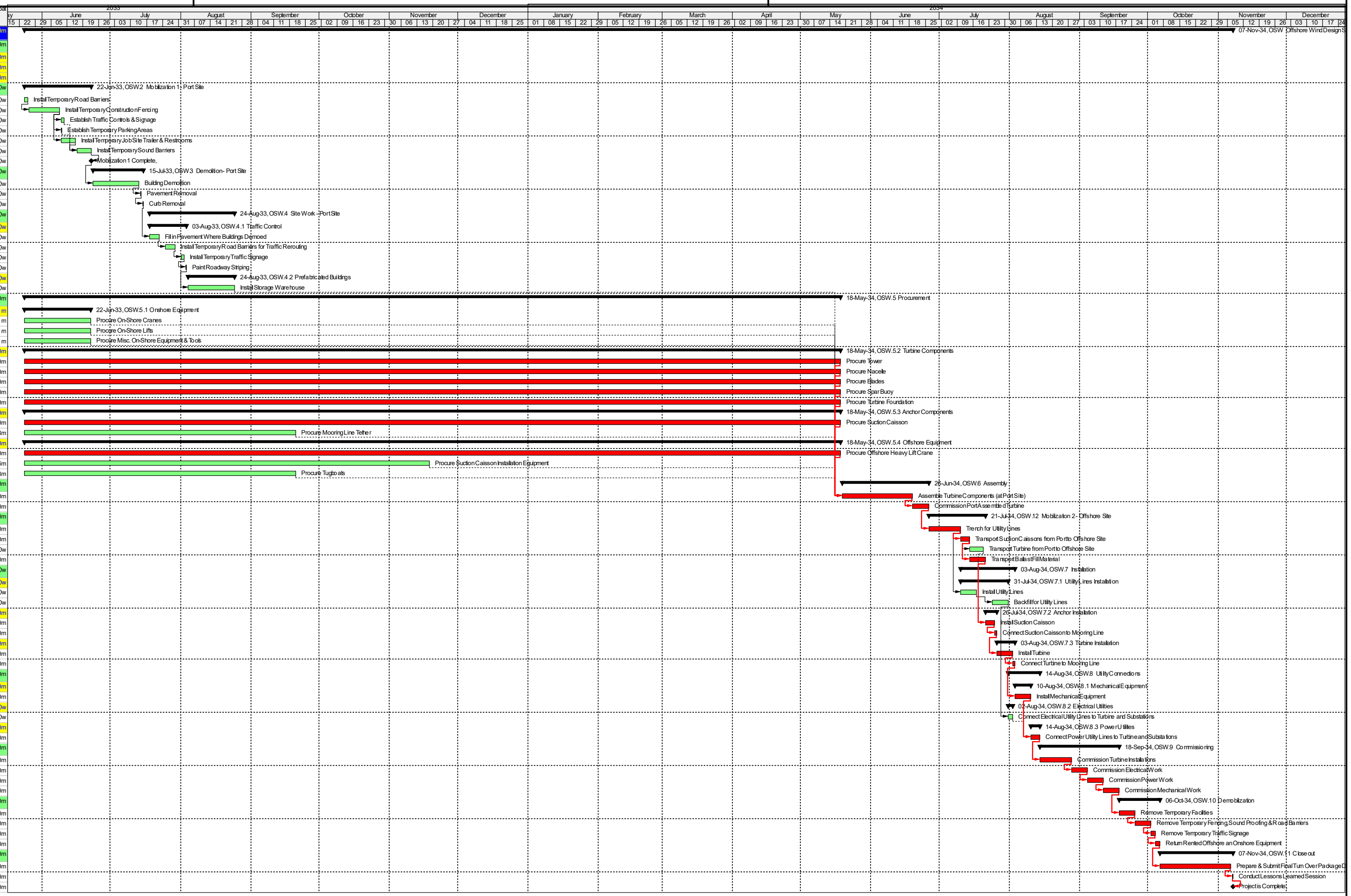


Actual Level of Effort | Remaining Work
Actual Work | Critical Remaining ...

Wind Wrangler Engineering Services

Offshore Wind Design Schedule | Construction Schedule | May 22, 2023

Activity ID	Activity Name	Original Duration	Start	Finish	Total Float
OSW	**Offshore Wind Design Schedule**	17m3.10w	24-May-33	07-Nov-34	0m
OSW.1	**Preconstruction**	0m			0m
OSW.1.1	**Permitting**	0m			0m
OSW.1.2	**Site Assessment**	0m			0m
OSW.1.3	**Final Design & Buyout**	0m			0m
OSW.2	**Mobilization 1 - Port Site**	1m0.10w	24-May-33	22-Jun-33	8m3.80w
MO1000	Install Temporary Road Barriers	0m0.40w	24-May-33	25-May-33	8m3.80w
MO1010	Install Temporary Constrution Fencing	0m2.00w	26-May-33	08-Jun-33	8m3.80w
MO1020	Establish Traffic Controls & Signage	0m0.40w	09-Jun-33	10-Jun-33	9m0.10w
MO1030	Establish Temporary Parking Areas	0m0.20w	09-Jun-33	09-Jun-33	9m0.30w
MO1040	Install Temporary Job Site Trailer & Restrooms	0m1.00w	09-Jun-33	15-Jun-33	8m3.80w
MO1050	Install Temporary Sound Barriers	0m1.00w	16-Jun-33	22-Jun-33	8m3.80w
MO1060	Mobilization 1 Complete	0m		22-Jun-33	8m3.80w
OSW.3	**Demolition - Port Site**	0m3.40w	23-Jun-33	15-Jul-33	8m3.80w
DE1000	Building Demolition	0m3.00w	23-Jun-33	13-Jul-33	8m3.80w
DE1010	Pavement Removal	0m0.20w	14-Jul-33	14-Jul-33	8m3.80w
DE1020	Curb Removal	0m0.20w	15-Jul-33	15-Jul-33	8m3.80w
OSW.4	**Site Work - Port Site**	1m1.30w	18-Jul-33	24-Aug-33	8m3.80w
OSW.4.1	**Traffic Control**	0m2.60w	18-Jul-33	03-Aug-33	8m3.80w
SW1000	Fill in Pavement Where Buildings Demoed	0m1.00w	18-Jul-33	22-Jul-33	8m3.80w
SW1010	Install Temporary Road Barriers for Traffic Rerouting	0m1.00w	25-Jul-33	29-Jul-33	8m3.80w
SW1020	Install Temporary Traffic Signage	0m0.40w	01-Aug-33	02-Aug-33	8m3.80w
SW1030	Paint Roadway Striping	0m0.20w	03-Aug-33	03-Aug-33	8m3.80w
OSW.4.2	**Prefabricated Buildings**	0m3.00w	04-Aug-33	24-Aug-33	8m3.80w
PB2000	Install Storage Warehouse	0m3.00w	04-Aug-33	24-Aug-33	8m3.80w
OSW.5	**Procurement**	12m	24-May-33	18-May-34	0m
OSW.5.1	**Onshore Equipment**	1m	24-May-33	22-Jun-33	11m
EQ1000	Procure On-Shore Cranes	1m	24-May-33	22-Jun-33	11m
EQ1010	Procure On-Shore Lifts	1m	24-May-33	22-Jun-33	11m
EQ1020	Procure Misc. On-Shore Equipment & Tools	1m	24-May-33	22-Jun-33	11m
OSW.5.2	**Turbine Components**	12m	24-May-33	18-May-34	0m
TC1000	Procure Tower	12m	24-May-33	18-May-34	0m
TC1010	Procure Nacelle	12m	24-May-33	18-May-34	0m
TC1020	Procure Blades	12m	24-May-33	18-May-34	0m
TC1030	Procure Spar Buoy	12m	24-May-33	18-May-34	0m
TC1040	Procure Turbine Foundation	12m	24-May-33	18-May-34	0m
OSW.5.3	**Anchor Components**	12m	24-May-33	18-May-34	0m
AC1000	Procure Suction Caisson	12m	24-May-33	18-May-34	0m
AC1010	Procure Mooring Line Tether	4m	24-May-33	20-Sep-33	8m
OSW.5.4	**Offshore Equipment**	12m	24-May-33	18-May-34	0m
EQ2000	Procure Offshore Heavy Lift Crane	12m	24-May-33	18-May-34	0m
EQ2010	Procure Suction Caisson Installation Equipment	6m	24-May-33	18-Nov-33	6m
EQ2020	Procure Tugboats	4m	24-May-33	20-Sep-33	8m
OSW.6	**Assembly**	1m1.00w	19-May-34	26-Jun-34	0m
A1000	Assemble Turbine Components (at Port Site)	1m	19-May-34	19-Jun-34	0m
A1010	Commission Port Assembled Turbine	0m1.00w	19-Jun-34	26-Jun-34	0m
OSW.12	**Mobilization 2 - Offshore Site**	0m3.80w	26-Jun-34	21-Jul-34	0m
MO2000	Trench for Utility Lines	0m2.00w	26-Jun-34	10-Jul-34	0m
MO2010	Transport Suction Caissons from Port to Offshore Site	0m0.80w	10-Jul-34	14-Jul-34	0m
MO2020	Transport Turbine from Port to Offshore Site	0m0.80w	14-Jul-34	20-Jul-34	0m0.20w
MO2030	Transport Ballast Fill Material	0m1.00w	14-Jul-34	21-Jul-34	0m
OSW.7	**Installation**	0m3.60w	10-Jul-34	03-Aug-34	0m0.60w
OSW.7.1	**Utility Lines Installation**	0m3.00w	10-Jul-34	31-Jul-34	0m1.20w
IN1000	Install Utility Lines	0m1.00w	10-Jul-34	17-Jul-34	0m1.20w
IN1010	Backfill for Utility Lines	0m1.00w	24-Jul-34	31-Jul-34	0m1.20w
OSW.7.2	**Anchor Installation**	0m0.60w	21-Jul-34	26-Jul-34	0m
IN1020	Install Suction Caisson	0m0.40w	21-Jul-34	25-Jul-34	0m
IN1050	Connect Suction Caisson to Mooring Line	0m0.20w	25-Jul-34	26-Jul-34	0m
OSW.7.3	**Turbine Installation**	0m1.20w	26-Jul-34	03-Aug-34	0m
IN1030	Install Turbine	0m1.00w	26-Jul-34	02-Aug-34	0m
IN1040	Connect Turbine to Mooring Line	0m0.20w	02-Aug-34	03-Aug-34	0m
OSW.8	**Utility Connections**	0m2.00w	31-Jul-34	14-Aug-34	0m
OSW.8.1	**Mechanical Equipment**	0m1.00w	03-Aug-34	10-Aug-34	0m
ME1000	Install Mechanical Equipment	0m1.00w	03-Aug-34	10-Aug-34	0m
OSW.8.2	**Electrical Utilities**	0m0.40w	31-Jul-34	02-Aug-34	0m1.20w
E1000	Connect Electrical Utility Lines to Turbine and Substations	0m0.40w	31-Jul-34	02-Aug-34	0m1.20w
OSW.8.3	**Power Utilities**	0m0.40w	10-Aug-34	14-Aug-34	0m
P1000	Connect Power Utility Lines to Turbine and Substations	0m0.40w	10-Aug-34	14-Aug-34	0m
OSW.9	**Commissioning**	1m0.70w	14-Aug-34	18-Sep-34	0m
COM1000	Commission Turbine Installations	0m2.00w	14-Aug-34	28-Aug-34	0m
COM1010	Commission Electrical Work	0m1.00w	28-Aug-34	04-Sep-34	0m
COM1020	Commission Power Work	0m1.00w	04-Sep-34	11-Sep-34	0m
COM1030	Commission Mechanical Work	0m1.00w	11-Sep-34	18-Sep-34	0m
OSW.10	**Demobilization**	0m2.80w	18-Sep-34	06-Oct-34	0m
DMO1000	Remove Temporary Facilities	0m1.00w	18-Sep-34	25-Sep-34	0m
DMO1010	Remove Temporary Fencing, Sound Proofing & Road Barriers	0m1.00w	25-Sep-34	02-Oct-34	0m
DMO1020	Remove Temporary Traffic Signage	0m0.40w	02-Oct-34	04-Oct-34	0m
DMO1030	Return Rented Offshore an Onshore Equipment	0m0.40w	04-Oct-34	06-Oct-34	0m
OSW.11	**Closeout**	1m0.20w	06-Oct-34	07-Nov-34	0m
CL1000	Prepare & Submit Final Turn Over Package Documentation	1m	06-Oct-34	06-Nov-34	0m
CL1010	Conduct Lessons Learned Session	0m0.20w	07-Nov-34	07-Nov-34	0m
CL1020	Project is Complete	0m		07-Nov-34	0m



Actual Level of Effort | Remaining Work
Actual Work | Critical Remaining ...

Wind Wrangler Engineering Services

APPENDIX F: REFERENCES

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