California North Coast Offshore Wind Studies

Anchoring Technology Risk Assessment

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Schatz Energy Research Center
Humboldt State University
Arcata, CA 95521 | (707) 826-4345

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MOTT MACDONALD

Anchoring Technology Risk Assessment

North Coast Offshore Wind

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Prepared by:	Aaron Porter, PE	**Date:**	9-14-2020
Approved by:	Shane Phillips, PE	**Checked by:**	Abby Mitchell, PE

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1 Introduction

Mott MacDonald prepared this memorandum for Schatz Energy Research Center (SERC) at Humboldt State University and the California Governor's Office of Planning and Research to assess risks of anchoring technology supporting the buildout of floating offshore wind (floating OSW) farms off the North Coast of California (North Coast). This memorandum is part of the North Coast Offshore Wind Study led by SERC, which assesses the potential for OSW wind energy generation along the North Coast.

As floating offshore wind is developed offshore of the North Coast of California, potential anchor[1] types need to be assessed at the potential installation locations. To date, no known assessment of anchor type to support floating OSW has been conducted for the region offshore of the North Coast of California. A pre-feasibility level desktop assessment was conducted to assess potential floating offshore wind anchor options and risks relative site conditions within the Humboldt Call Area and the Notional Cape Mendocino Area, shown in. The intent of this memorandum was to provide an initial assessment of concept-level risks of different anchor types for these areas, and to help guide further studies.

To date, pilot scale floating offshore wind projects utilized oil and gas industry anchor technologies, but the coupled behavior of floating wind turbines, and the large volume of units means that alternative solutions may be required (James et al., 2018). Innovation is likely to occur with regards to anchors, and moorings for floating wind[2]. Anchoring and mooring technology and techniques are likely to change by the time of deployment (assumed to be 4+ years), as well as the level of detail of site conditions. Therefore, this assessment has been kept as high-level as possible while providing assessment of existing technologies based on site conditions.

This memorandum contains a basis of analysis (assumptions, anchor type categories assessed, etc.), a summary of site conditions, an assessment of anchor types relative to potential mooring strategies, an assessment of anchor types relative to site conditions, and a summary of risks for the region relative to hazards and constraints. This memorandum is not intended to provide recommendations for the type of anchors to be utilized at site, and cost considerations have not been included at this time.

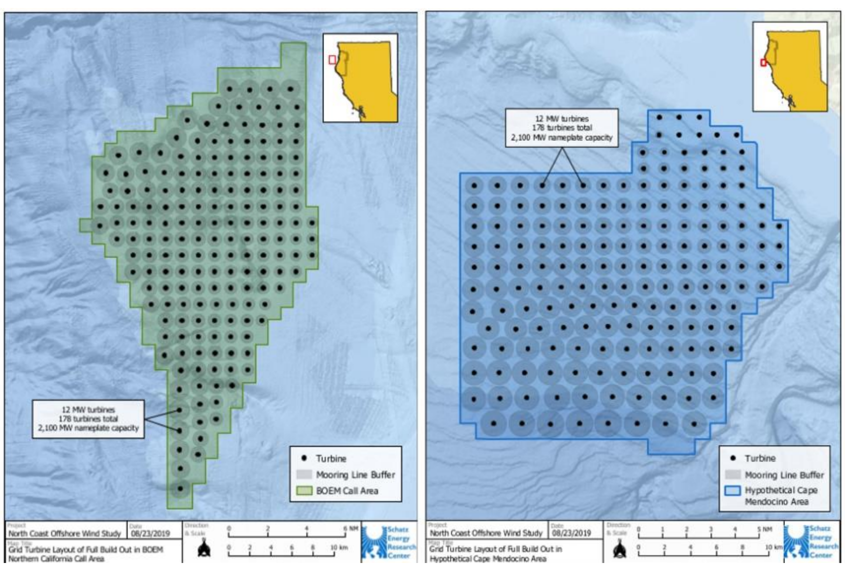

Figure 1 Study Areas – BOEM call area (left) and Notional Cape Mendocino Area (right). Potential mooring line buffer area shown at 1x depth (Source: SERC).

[1] Anchors can be defined as the systems that transfer loads between the mooring lines or tendons of the station keeping system (e.g., floating wind substructures) and the seabed soils (DNVGL-ST-0119).

[2] A good summary of likely innovation needs for floating wind mooring and anchoring is located within Carbon Trust (2019).

2 Basis of Analysis

The following background information and criteria provided a framework for the assessment.

2.1 Anchoring Background

Anchoring and mooring of an offshore wind farm can consist of 20-50% of installation costs, depending on project specific conditions and needs (Golightly, 2017)[3], and therefore the type of anchor selected is a highly engineered element of the design. This memorandum does not provide a detailed assessment of appropriate anchoring technologies for the area. A summary of some of the key considerations for anchor selection on a project-by-project basis for design is listed below:

- Mooring
  - Mooring Loads (including type of structure and metocean conditions)
  - Load direction(s)
  - Mooring line scope
  - Precision of positioning
  - Devices - Single vs multi-device
- Seabed Conditions
  - Soil conditions (type, thickness, and heterogeneity)
  - Water depth
  - Seabed slope
  - Hazards (seismic, other)
- Installation and Maintenance
  - Installation Cost and Efficiency
  - Potential loss of embedment - Creep effects, fatigue
  - Retrieval requirements

There are many types of specific anchor types that are developed for different purposes, and the anchor is designed in tandem with the mooring system. In general, drag and deadweight anchors are widely used in the deep ocean, however, they do not perform well on steep seafloors (NAVFAC, 2012). Pile and direct embedment anchors are typically used where less expensive types of shallow anchors (e.g., drag) cannot mobilize sufficient resistance (NAVFAC, 2012). This assessment has parameterized the anchor types into four categories for clarity, as shown below, with additional details (advantages/disadvantages) in the appendix.

- Drag Embedded Plates
  - Drag embedment anchor (DEA)
  - Vertically loaded anchors (VLA)
  - Direct Embedment Plate Anchors
- Pile driven
  - Dynamic (or torpedo)
  - Suction embedded

[3] May only be applicable to certain types of anchors which may or may not be appropriate for the study areas.

- Piles and Caissons
  - Driven/drilled pile anchor
  - Suction caissons
  - Dynamic
- Gravity-Base Anchors (e.g., deadweight)

There are limited examples of installed floating offshore wind devices, and therefore anchoring strategy. Principle Power has utilized drag anchors for semi-submersible floating OSW installations in Portugal. Equinor has utilized caisson/pile anchors for spar floating OSW installations in Norway and Scotland. Both of these projects were installed in much shallower water than the areas studied off the North Coast of California.

2.2 Study Criteria

- Purpose:
  - Provide an initial assessment of concept-level risks of different anchor types on the North Coast.
- Level of assessment:
  - Intended to be conceptual in nature. Work was conducted at a pre-feasibility level.
  - Installation vessels were not assessed and would be need to analyzed in more detail.
- Assumptions and Exclusions
  - Assessment of mooring line type, design, and configuration was not part of this assessment.
  - This work was not intended to be comprehensive. Material within this document should not be used for project planning or commercial purposes. It is intended only to provide an initial conceptual assessment of different anchor type risks for conditions found in the study area, and to document potential risks.
  - Anchor technology for large-scale commercial floating offshore wind is currently in an early stage, with developments on-going. This memorandum was not intended to assess newly developed anchors which may be better suited for the area, but instead to help document potential risks.
  - This assessment was not intended to select, prescribe, or develop new types of anchors which should be utilized in these areas
  - Cost evaluation was not within the scope of this assessment, but will affect the selection of anchor type by developers. Supply and installation cost will vary by anchor type, and the costs at the time of deployment may be different than present costs as new technology and installation efficiencies are developed.
  - Anchor loads not assessed relative to device and mooring line types, or available substrate.
  - Any differentiation between floating wind units and floating substations not assessed.
- Methods:
  - The assessment was conducted based on a desktop literature review and site condition application assessment. No engineering calculations, modeling, or design was conducted.
  - Literature review included guidance documents, standards, and scientific papers. The following documents were reviewed and incorporated as part of development of this memorandum.
    - American Bureau of Shipping (2013) – Offshore Anchor Data for Preliminary Design of Anchors of Floating Offshore Wind Turbines (Kim, 2013)
    - American Bureau of Shipping (2014) – Guideline for Building and Classing Floating Offshore Wind Turbine Installations (American Bureau of Shipping, 2014)
    - Carbon Trust (2018) – Floating Wind Joint Industry Project (James et al., 2018)

- DNVGL-ST-0119 (2018) – Floating Wind Turbine Structures (DNV GL, 2018)
- United States Naval Facilities Engineering Command - SP-2209OCN Handbook for Marine Geotechnical Engineering Data (NAVFAC, 2012)

– Data: All site condition data was either provided by HSU, or is publicly available (e.g., Marine Cadastre).

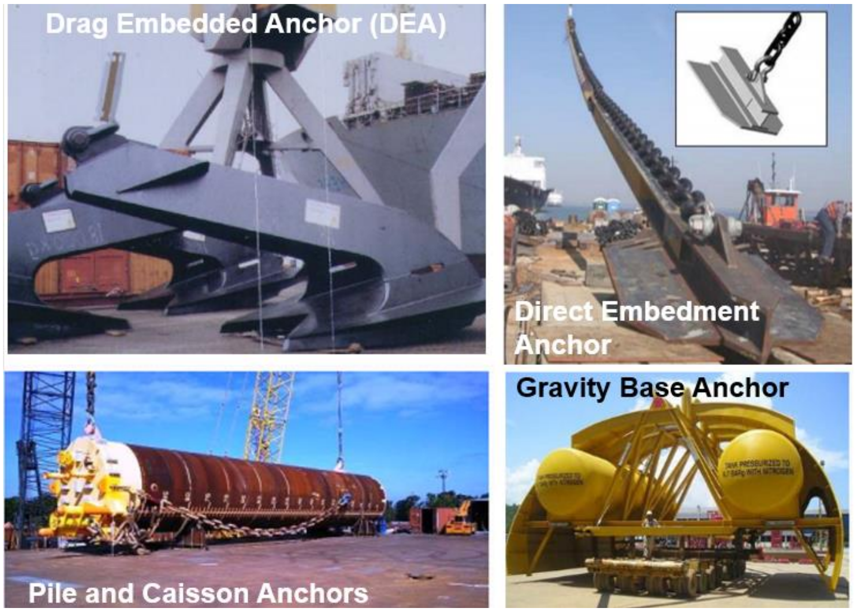

Figure 2. Assessed Anchor Categories

3 Existing Conditions

Existing conditions were compiled to develop the hazards and constraints which may affect concept level anchoring assessment. Information was collected from the public domain, and hazard information was also provided by Humboldt State University (HSU). The potential hazards and constraints are listed in Table 1 and Table 2. Seabed slope, substrate, and gas hydrates were mapped (Figure 3, Figure 4 and Figure 5) to provide a guide to the potential locations of these constraints and hazards. Assessment of the hazards and constraints relative to anchor type are addressed in Sections 4 and 5.

Table 1. Potential Site Constraints

Element	Conditions	Sources
Water Depth -	Humboldt Call Area: 1,640-3,610 feet Notional Cape Mendocino Area 328-3,610 feet	NOAA Northern CA DEM and NOAA Central California DEM
Seabed grades and slopes (Figure 3)	Seabed slope typically less than 10 degrees Portions of study area greater than 10 degrees, more so in the BOEM call area.	NOAA Northern CA DEM and NOAA Central California DEM
Substrate (Figure 4)	Conditions appear mostly homogeneous, with dominant substrate of soft mud[4]. Bands of rock are apparent within the Humboldt Call area. The shallow portion of the Notional Cape Mendocino Area contains sand Thickness of the substrate layers was not documented and therefore may vary across the sites.	Substrate conditions in the study areas were provided by HSU (2019). The data set was compiled for BOEM by Oregon State University (2014) and depicts seafloor substrate types as interpreted from a multitude of seafloor mapping surveys, including multibeam sonar, sidescan sonar, sediment grab samples, cores samples, seismic reflection profiles, and still or video image.[5]

Table 2. Potential Site Hazards

Element	Conditions	Sources
Seismic	• One of the most active seismic areas in North America. • Surface fault rupture and deformation • Seismic shaking could result in large accelerations and durations	HSU, 2019
Submarine Landslides and Turbidites	• Flows may be more likely in the mapped mud wasting zones, or mud canyon categories. • Turbidities could be trigged by seismic activity.	HSU, 2019
Gas Hydrates (Figure 5)	• Gas hydrates may exist in portions of the Humboldt Call Area as shown in Figure 6 from two different data collection methods (l). • Exact extent of gas hydrates is not known. • Depth of the gas hydrates is not known	Provided by HSU, source: Yun et. al, 1999

[4] The terms mud canyon wall, floor, ridge, are understood to indicate the physical location, and not necessarily a change in substrate type. The term “mud” used to classify unconsolidated surface sediments with 90% of material < 0.0625mm in diameter (silts and clays), and remainder of material < 2mm in diameter.

[5] Exact conditions may differ from what is depicted in **Figure 4**.

[6] Maps provided by HSU. Notional Cape Mendocino Area not assessed.

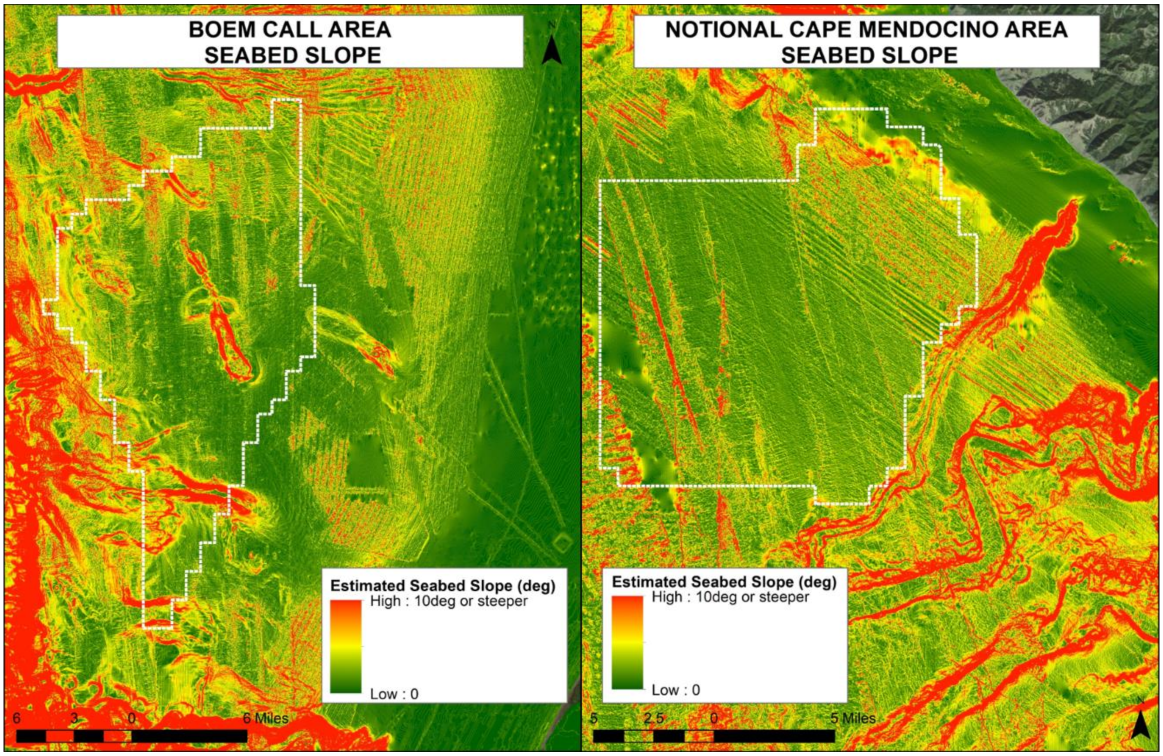

Figure 3. Seabed Slope in Study Areas (BOEM Call Area - left, and Cape Mendocino - right)

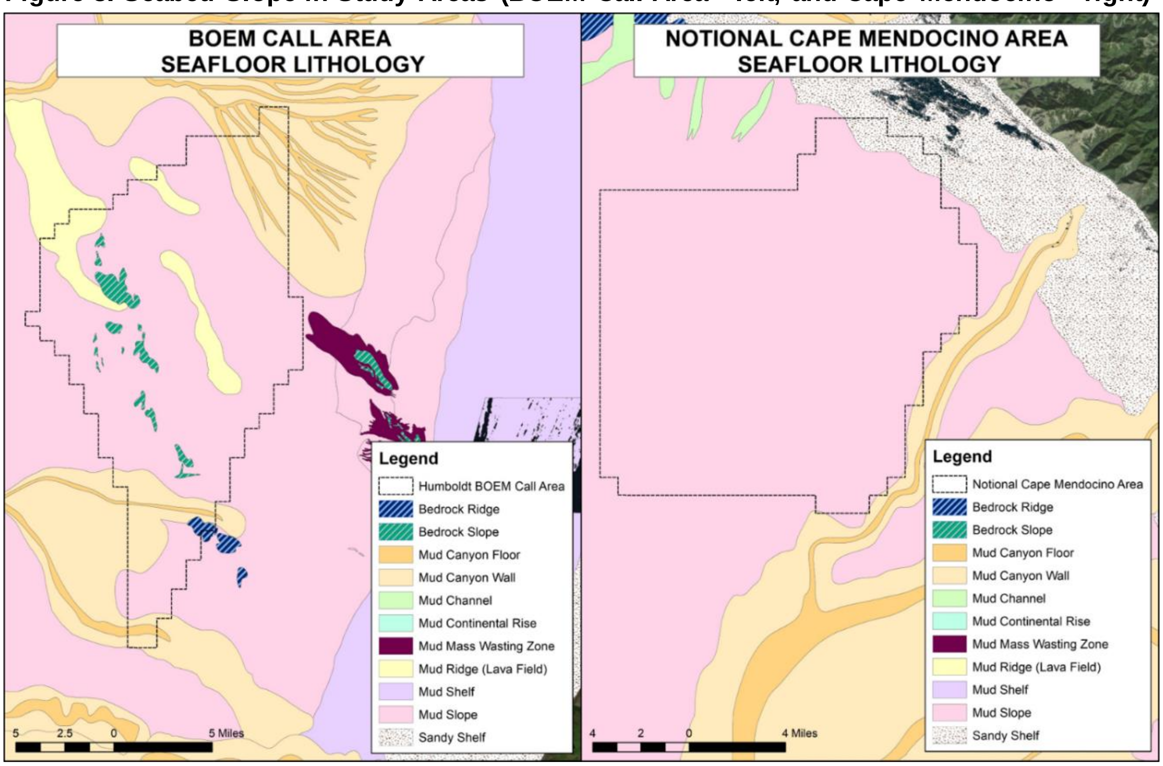

Figure 4. Mapped Substrate within Study Areas

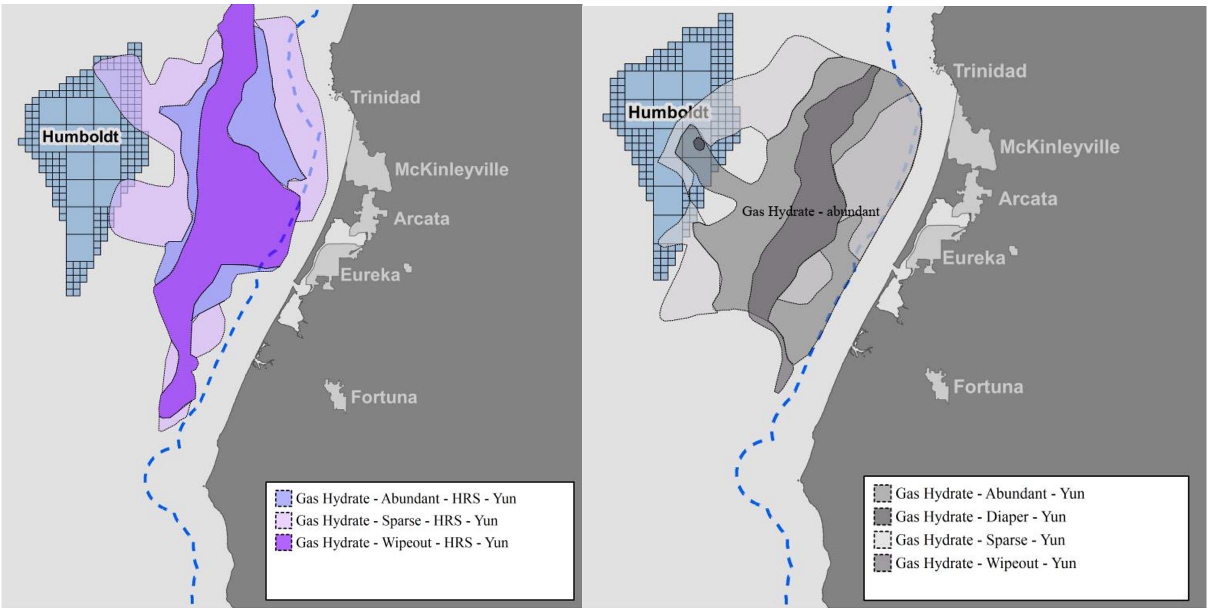

Figure 5. Mapped Gas Hydrate Areas (Provided by HSU, source: Yun et. al, 1999) based on different geophysical sensing tools/technologies (high frequency seismic – left panel, and low frequency multichannel seismic reflection (right panel)

4 Anchoring Assessment - Mooring Strategy

Though specific offshore wind substructures may have specialized mooring systems, the type of mooring system has been parameterized into either catenary, or taut, for this assessment. The type of mooring line used will be engineered, and may vary from device to device, and by project size. The mooring line type influences the anchor type selected. A summary of typically suitability is located in Table 3.

Ideally the number of anchors for a floating windfarm will be minimized to reduce total at-sea time for installation and investigations, and therefore cost. The industry may be moving towards potentially using a single anchor for multiple lines – or attaching mooring lines from multiple devices to a single large anchor. If a multi-line anchor system is used the anchor needs to have multi-directional load carrying capacity. Risks for a multiline anchor system include introducing a system of interconnection throughout the floating OSW mooring network, and potentially causing a failure within network as loads shift in response to a single failure. The designer is to determine the worst scenario by analyzing several cases of broken line, including lead line broken and adjacent line broken cases (American Bureau of Shipping, 2014).

<u>Assessment</u>: **Pile/Caisson type is likely more favorable if multi-line anchors are selected. If retrieval is required, drag or certain types of pile/caisson anchors are more favorable.**

Table 3. Mooring Considerations for Anchor Types

Anchor Category Type	Mooring Line (typical)	Single vs Multiline	Retrieval
Drag embedded Plates	Catenary	Challenging for multiline. Load ring can be used, great caution should be used.	Typically, retrievable.
Direct embedded Plate Anchor	Catenary, taut	Directional preference, not typically suitable (load ring can be used, but with great caution. DNVGL-ST-0119 assumes not suitable.	Not typically retrievable.
Piles and Caissons	Catenary, taut	Suitability for multiline still unknown, but can accommodate a range of load angles.	Suction is typically retrievable, driven is not.
Gravity Anchor	Catenary	Challenges for multiline. Load ring can be used, great caution should be used.	Not typically retrievable.

5 Anchoring Assessment - Constraints and Hazards

Assessments have been conducted to document the constraints and hazards relative to potential anchor types within the areas of study. Conditions within the project area were assessed relative to characteristics of the four main anchor types. Specific manufacturers may have, or will have by the time of deployment, developed technology to mitigate the constraints and hazards noted within this document.

5.1 Substrate

A summary of the assessment of substrate relative to anchor types is provided in Table 4.

Assessment: Certain types of drag embedded, direct embedded, and pile/caisson anchors would likely be favorable based on cross-reference of site conditions and typical anchor technology preferences, depending on depth of substrate. If substrate thickness above bedrock is not sufficient for these anchor types alternative anchoring technologies/techniques may be required.

Table 4. Seabed Sediment Type Assessment

Anchor Category Type	Substrate Types	Sediment Layer thickness
Drag Embedded Plates	Vertically loaded anchors good in soft material, which is found within study area. Drag anchors generally good for sands and stiff clays, and may not be favorable.	Sediment layer 3-5 times fluke length typically required.
Direct Embedded Plate Anchor	Suited for soft clay, stiff clay, sand, stratified profiles. Likely favorable.	Thick layer required. Heterogeneous/ Homogeneous layer preference depends on type.
Piles and Caissons	Suited for soft clay, stiff clay, sand, stratified profiles. Likely favorable. Some types prefer homogeneous soil layers.	Thick layer required – Likely 15 meters or greater.
Gravity Anchor	Generally good for sands and stiff clays, but is likely favorable for rocky/thin areas.	Can be installed on thin substrate layers.

5.2 Water Depth and Seabed Slope

A summary of the assessment of anchor types relative to the water depth and seabed slope is provided in Table 5.

Assessment: Based on historical trends, and depending on technology development, direct embedment or pile/caisson anchors may be favorable for some areas of the study areas due to depth. For most of the study areas slope may not be a constraint, but steep slopes within the Call Area may affect choice of anchor to provide flexibility in installation location, depending on scale of production.

Table 5. Anchor Types Relative to Water Depth and Seabed Slopes in Study Area

Anchor Category Type	Installation in Deep (1,600ft.) Water (Oil & Gas Sector)7	Slope less than 10 degrees	Slope more than 10 degrees
Drag Embedded Plates	A few examples	Good	May not perform well
Direct Embedded Plate Anchor	One example	Good	Good
Piles and Caissons	Many examples	Good	Good
Gravity Anchor	A few examples	Good	May not perform well

5.3 Hazards

A summary of the hazard and subsequent risks are provided in Table 6.

Assessment: Hazards in the area which affect anchoring include seismic shaking, submarine landslides and turbidites, and gas hydrates. The three hazards initially identified need to be incorporated into any anchoring design, and may affect placement of anchors, but are not likely to preclude anchoring. At this level of analysis, the hazards have not been assessed relative to the specific anchor types.

Table 6. Anchor Hazard Summary

Potential Hazard	Assessment - Risk to Anchor System
Seismic - Surface Fault Rupture, Deformation, and Shaking.	Seismic is a risk but likely not a showstopper (James et al., 2018). Motion effects need to be incorporated into analysis and design for all anchor types. Displacement of anchors due to liquefaction more of a risk in taut mooring lines (Esfeh & Kaynia, 2019).
Submarine Landslides and Turbidites	Could result in displacement of anchoring system. Risk areas should be assessed for all anchor types. Turbidites could be trigged by seismic activity. All areas noted to be outside mapped mud mass wasting zones (submarine landslides), but more analysis likely needed.
Gas Hydrates	Anchor installation could result in destabilization of subsurface sediment. More detailed investigation needed for all anchor types. Gas Hydrates may require localized removal prior to anchor installation depending on depth of anchor and depth of the hydrates.

[7] Liu et al., 2018.

[8] Sea-bottom deposits formed by massive undersea slope failures (per USGS).

6 Summary

A pre-feasibility level desktop assessment was conducted to assess potential floating offshore wind anchor options and risks relative site conditions within the Humboldt Call Area and the Notional Cape Mendocino Area. A summary of findings is provided below:

- Anchor Types
  - Drag anchors may not be favorable based on available site substrate information (soft mud).
  - Different anchor types may be needed within the call area due to topography and different soil types (e.g., bedrock vs mud), and may affect serialization of the anchor types for projects in this area.
  - Pockets of hard substrate exist in the Humboldt Call area. In areas where soft material is either a thin layer or not present, gravity type anchors or piles may be more likely – and multi-line anchors may not be favored in these areas.
  - Single-line anchors do not appear to be restricted relative to different anchor types for most of the study areas. Drag embedded, direct embedded, pile, and gravity anchors all appear to not be precluded due to site conditions, though each have their own costs, and risks and benefits.
  - If multiline anchors are to be used some type of pile anchor types may be more likely. Though soft substrate appears to be in most of the study areas, the thickness/stratification of substrate is not known.
- Constraints and Hazards
  - Site hazards are unlikely to preclude anchorage in the area, but the location, frequency, and severity of the hazards need to be considered in design of the anchors and mooring system redundancy.
  - At the water depths found in the project area piles and caisson type anchors have historically been more commonly used.
- Next Steps
  - Marine geotechnical investigation consisting of boring or coring to determine sediment profile and properties within anchoring area will be needed to finalize anchoring selection.
  - Optimization of the anchor type should be conducted with input from the geotechnical data collection campaign, mooring analysis, performance analysis, cost sensitivity analysis, and other
- A summary of risks relative to the assessment constraints and hazards for the study areas is provided in Table 7.

Table 7. Anchoring Risks within Study Area

Constraint/Hazard	Risk Assessment
Mooring Line Type	Mooring line type (e.g., catenary, taught) will greatly affect anchor type selected.
Multi-Line Anchoring	If selected, may limit anchor type, but could result in fewer total anchors. Optimization of the anchor type should be conducted with input from the geotechnical data collection campaign, mooring analysis, performance analysis, and cost sensitivity analysis.
Anchor Retrieval	Depending on anchor type, retrieval may not be feasible.
Water Depth	Water depth may limit the selection of anchor type.
Seabed grades and slopes	Areas of steep slopes may limit the selection of anchor type in localized areas.
Substrate	Soft material and bands of bedrock may limit some anchor type options. Thickness of material will affect anchor selection and design. Geotechnical investigation consisting of boring or coring to determine sediment profile and properties within anchoring area will be needed to finalize anchoring selection.
Seismic - Fault Rupture Deformation/ Shaking.	Seismic is a risk but likely not a showstopper (James et al., 2018). Motion effects need to be incorporated into analysis and design for all anchor types. Displacement of anchors could occur.
Submarine Landslides and Turbidites	Displacement of anchors could occur. Subsequent mapping may result in anchor planform optimization.
Gas Hydrates	Anchor installation could result in destabilization of subsurface sediment. Based on subsequent mapping, anchor planform design may be optimized.

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Appendix

Anchoring Technology: Additional Details

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Appendix: Anchoring Technology

Additional Details

Parameterized Anchor Types

1. Gravity-base anchor (deadweight)
2. Piles and Caissons

- Driven/drilled pile anchor
- Suction caissons

3. Direct embedment plate anchors

- Pile driven
- Dynamic
- Suction embedded - SEPLA

4. Drag Embedded Plates

- Drag embedment anchor (DEA)
- Vertically loaded anchors (VLA)

Performance of Foundation and Anchor Types as Function of Seafloor and Loading Conditions

NAVFAC (2012)

Table 1.3-5. Performance of Foundation and Anchor Types as a Function of Seafloor and Loading Conditions

Item	Performance[a] for Following Types:			
	Deadweight	*Pile*	*Direct Embedment*	*Drag*
Seafloor Material Type				
Soft clay, mud	++	+	++	++
Soft clay layer (0-20 ft thick), over hard layer	++	++	o	+
Stiff clay	++	++	++	++
Sand	++	++	++	++
Hard glacial till	++	++	++	+
Boulders	++	o	o	o
Soft rock or coral	++	++	++	o
Hard, monolithic rock	++	+	+	o
Seafloor Topography				
Moderate slopes, <10 deg	++	++	++	++
Steep slopes, >10 deg	o	++	++	o
Loading Direction				
Downward load component (foundations)	++	++	o	o
Omni-directional (not down)	++	++	++	o
Uni-directional (not-down)	++	++	++	++
Large uplift component	++	++	++	o
Lateral Load Range				
To 100,000 lb	++	+	++	++
100,000 to 1,000,000 lb	+	++	+	++
Over 1,000,000 lb	o	++	o	o

[a] ++ = functions well
\+ = normally is not the preferred choice
o = does not function well

Advantages and Disadvantages – Deadweight

Anchor Type	Advantages	Disadvantages
Gravity	• No setting required • Reliable on thin sediment layer • Simple design	• Lateral load resistance is low. • Lateral load resistance decreases with seafloor slope • Usually non-retrievable

Advantages and Disadvantages – Piles and Caissons

Anchor Type	Advantages	Disadvantages
Driven/drilled Piles	• Resists uplift and lateral forces, any load angle • Wide range of types and sizes available • No setting required • No risk of anchor dragging • Precise positioning	• Generally an expensive option, more expensive in deeper water • Low efficiency • Requires more extensive knowledge of soil conditions than other options • Non-yielding anchor type • Non-retrievable
Suction Caissons	• No setting required • No risk of anchor dragging • Retrievable anchor • Can work at any load angle • Precise positioning • Simple installation	• Requires thick layer of soil before rock • May require homogeneous soil • Partially capacity loss under sustained loads • Low efficiency • Can require large installation vessels
Dynamically installed piles	• Can work at many load angles	• Some uncertainty in positioning • Suitability for multi-line is uncertain

Advantages and Disadvantages – Direct Embedded

Anchor Type	Advantages	Disadvantages
Suction Embedded Plate Anchor (SEPLA)	• Precise positioning • Intermediate installation cost	• May be limited to soft clay only • Brittle failure at high load angles
Driven Plate Anchors	• Precise positioning • Good in heterogeneous clays	• Installation can be costly • Brittle failure at high load angles
Dynamically Embedded Plate Anchors	• Lower cost option	• Newer anchor type • Brittle failure at high load angles • May be limited to soft clays • Moderate uncertainty in position

Advantages and Disadvantages – Drag Embedded

Anchor Type	Advantages	Disadvantages
Drag embedded anchor (DEA)	• Broad experience of use • Wide range of types and sizes available • Inexpensive installation	• Low resistance to uplift loads • Requires long line scope • Requires setting distance • Loading usually limited to one direction • Not good in soft clays • Moderate uncertainty in positioning
Vertically loaded anchors	• Good in soft clay • Inexpensive installation	• Requires homogeneous soil • High uncertainty in positioning • Not good at high load angles