OCS Study
BOEM 2017-049

Geophysical and Geotechnical Investigation Methodology Assessment for Siting Renewable Energy Facilities on the Atlantic OCS

US Department of the Interior
Bureau of Ocean Energy Management
Office of Renewable Energy Programs

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US Department of the Interior
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DISCLAIMER

Study concept, oversight, and funding were provided by the US Department of the Interior, Bureau of Ocean Energy Management (BOEM), Environmental Studies Program, Washington, DC, under Contract Number M15PX00051. This report has been technically reviewed by BOEM, and it has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the US Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

REPORT AVAILABILITY

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FUGRO MARINE GEOSERVICES, INC.

EXECUTIVE SUMMARY

Study Title:

Geophysical and Geotechnical Investigation Methodology Assessment for Siting Renewable Energy Facilities on the Atlantic OCS

INTRODUCTION

BOEM is responsible for managing energy and mineral resources on the Outer Continental Shelf (OCS). This includes ensuring that future renewable energy facilities located within the Atlantic Outer Continental Shelf (OCS) are properly studied using appropriate geophysical and geotechnical equipment and employing a series of standardized methodologies. Offshore renewable energy includes, but is not limited to, wind, wave, ocean current, solar, and hydrogen production energy.

The Atlantic OCS is considered by BOEM to be a "Frontier Region" where little information exists about the geologic conditions and how those conditions may impact development of offshore wind farms. In contrast, regions such as the Gulf of Mexico, Baltic and North Seas have significantly more information and experience regarding geologic conditions and how those conditions may affect construction and performance of oil and gas structures and offshore wind structures. Although experience in planning, designing, constructing, and operating marine structures in those regions provide valuable knowledge that can be transferred to the Atlantic OCS wind industry, the combination of water depths, geologic conditions, and wind farm developments will present a unique combination of variables for the nascent US Atlantic wind industry.

The purpose of this study is to investigate and assess the various methodologies and equipment choices for providing site investigations that identify shallow hazards, geologic hazards, biological conditions, geotechnical properties, and archaeological resources in accordance with 30 CFR 585.626 and 585.627. The information presented in this study is based on decades of experience accumulated by the oil and gas industry offshore, about a decade of experience accumulated by the offshore wind industry in Europe, and the understanding of the geology within the Atlantic OCS. Hence, the information developed during this study should prove to be a valuable resource for future US offshore wind development projects especially within the Atlantic OCS.

We note that geophysical and geotechnical equipment and investigation techniques are continually evolving in response to industry needs. In the offshore wind industry evolution is driven in a large part based on a desire to reduce construction and operational costs, developing larger wind turbines, developing wind farms in frontier regions, and knowledge gained from construction and operation of existing wind farms. Site investigation methods for seismic reflection surveying, seismic data processing, and measuring dynamic soil properties are among the most rapidly evolving areas for the industry. Therefore, we believe that this study represents a snap shot in time of a changing industry.

We thank the staff at the BOEM for their support in preparing this study. We also thank Dr. Melissa Landon and Dr. Mark Legg for their contributions to this study.

OVERVIEW OF THE STUDY

This report is divided into six volumes that address various aspects of the scope of this study. Volume content is organized as follows:

- Volume 1 – Wind Farm Facilities, Geologic and Bathymetric Conditions, and Site Investigation Approaches: Introduces the typical components of offshore wind farms, provides a concise introduction about geologic characteristics within the Atlantic OCS, introduces the various offshore foundation types and systems for offshore wind turbines, lists the main factors that control the selection of a specific foundation system, and provides examples of alternative plans that can be adopted to conduct geophysical and geotechnical site investigations.

- Volume 2 – Geophysical Surveys Benefits and Risks: Analyzes the benefits and risks associated with the different techniques adopted during geophysical surveys and the viability of using the different techniques within the Atlantic OCS.

- Volume 3 – Geotechnical Investigation Benefits and Risks: Analyzes the benefits and risks associated with the different in-situ tests adopted during geotechnical investigations and the viability of using the different techniques within the Atlantic OCS. It introduces the different laboratory tests and the design parameters that can be measured using each of them. It also presents additional details about choosing the number and type of in-situ and laboratory tests for each foundation type.

- Volume 4 – Best Practice Recommendations for Geophysical Surveys: Presents best practice recommendations for survey techniques and equipment for geophysical surveys.

- Volume 5 – Best Practice Recommendations for Geotechnical Investigations: Presents best practice recommendations for geotechnical site investigation techniques and equipment for these investigations.

- Volume 6 – Geophysical and Geotechnical Guidebook: A guidebook for equipment selection and utilization dependent on the site conditions and structures anticipated for future offshore renewable projects within the Atlantic OCS.

FUGRO MARINE GEOSERVICES, INC.

VOLUME 1

WIND FARM FACILITIES, GEOLOGIC AND BATHYMETRIC CONDITIONS, AND SITE INVESTIGATION APPROACHES

Study Title:

Geophysical and Geotechnical Investigation Methodology Assessment for Siting Renewable Energy Facilities on the Atlantic OCS

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1.1 INTRODUCTION

The Bureau of Ocean Energy Management (BOEM) is responsible for managing energy and mineral resources on the Outer Continental Shelf (OCS). This includes administering leases and providing regulatory oversight for future renewable energy facilities located within the Atlantic OCS. Lessees are required to conduct geophysical and geotechnical surveys that employ a series of standardized methodologies. Offshore renewable energy includes, but is not limited to, wind, wave, ocean current, solar, and hydrogen production energy.

The Atlantic OCS is considered by BOEM to be a “Frontier Region” where little information exists about the geologic conditions and how those conditions may impact development of offshore wind farms. In contrast, regions such as the Gulf of Mexico, Baltic and North Seas have significantly more information and experience regarding geologic conditions and how those conditions may affect construction and performance of oil and gas structures and offshore wind structures. Although experience in planning, designing, constructing, and operating marine structures in those regions provide valuable knowledge that can be transferred to the Atlantic OCS wind industry, the combination of water depths, geologic conditions, and wind farm developments present a unique combination of conditions for the nascent US Atlantic wind industry.

The purpose of this study is to investigate and assess the various methodologies and equipment choices for providing site investigations that identify shallow hazards, geologic hazards, biological conditions, geotechnical properties, and archaeological resources in accordance with 30 CFR 585.626 and 585.627. The information presented in this study is based on decades of experience accumulated by the oil and gas industry offshore, about a decade of experience accumulated by the offshore wind industry in Europe, and the understanding of the geology within the Atlantic OCS. Hence, the information developed during this study should prove to be a valuable resource for future US offshore wind development projects especially within the Atlantic OCS.

The analysis and design of windfarm foundation systems tends to benefit from the decades of experience accumulated by the oil and gas industry offshore. However, it still imposes new challenges that need to be thoroughly considered when compared to the marine oil and gas structures. The major differences between offshore wind turbines and oil and gas platforms are detailed in Houlsby et al. (2005), Schneider et al. (2010), Schneider and Senders (2010), and Landon Maynard and Schneider (2010). The salient differences can be summarized as follows:

- **Consequence of Failure.** Failure of offshore wind turbines is not generally associated with human fatalities, which is frequently the case for oil and gas platforms. On the other hand, interruption or reduction of electric power grids can have major socioeconomic consequences, especially, as different communities rely more on offshore wind energy. These socioeconomic consequences should be carefully evaluated while selecting the design criteria for offshore wind turbines.
- **Tolerance.** The tolerances used in the design of offshore wind turbines are generally stricter than the ones used to design the oil and gas platforms. This is attributed to the fact that even minor variances have a significant impact on foundation/top structure performance.

- **Natural Frequency.** To avoid resonance (see glossary at the end of this report), oil and gas platforms are designed such that their natural frequency differs from the frequency of environmental loading (e.g. storms). In the case of offshore wind turbines, the motion of the rotor and blades applies dynamic loading within two distinct frequency windows. The frequency of the environmental loads falls in a third window. In order to avoid resonance, the natural frequency of the wind turbine system should reside outside the three aforementioned frequency windows. Hence, it is more critical to accurately predict the natural frequency of the wind turbine system compared to oil and gas platforms. Bhattacharya et al. (2012) lists the first natural frequency of few wind turbine systems in operation.
- **Fatigue.** The design of oil and gas platforms is generally controlled by storm loading that applies relatively large amplitudes over a limited number of cycles. On the other hand, wind turbine design is governed by small amplitude cyclic loading with number of cycles reaching into the billions within the lifetime of the structure. Hence, it is exceedingly important to investigate the long-term behavior of the system under cyclic loading (fatigue) as it is more important than its ultimate capacity (Houlsby et al., 2005).
- **Loads.** In the case of offshore wind turbines, the vertical and lateral loads are in most cases considerably smaller than the loads applied to oil and gas platforms. On the other hand, the lateral loads can be considerably higher compared to the vertical loads (about 60% of the vertical loads) in the case of offshore wind turbines (Houlsby et al. 2005). Hence, the lateral and rotational stiffness of the foundation system controls the design of the foundation of wind turbines (Rahim and Stevens, 2013).
- **Site Investigation and Characterization.** Oil and gas platforms are generally widely spaced and have a limited footprint. Hence, site investigation and characterization for such projects is generally focused on a limited area. On the other hand, commercial wind farms comprise a large number of turbines spread over a relatively large area. Therefore, it is likely that several geologic conditions and features within a single wind farm (e.g. sand waves or paleo-channels) will be encountered. Therefore, both site investigation and site characterization play a major role in a successful design of a wind farm. Unless required by a certifying body (e.g. ABS, DNV or Lloyd's Register) or regulatory agency, it will almost always be more cost-effective to perform geotechnical investigations at a limited number of locations and conduct a detailed / broad-based geophysical investigation to tie the exploration together. In this case, the integration of geophysical and geotechnical information becomes an integral component to defensible wind farm design. While the cost of an offshore geotechnical investigation is generally a small fraction in the overall cost of an oil and gas platform, it represents a significantly higher percentage for the overall cost of the foundation system of a wind turbine (Landon Maynard and Schneider 2010). Hence, it is critical to optimize the offshore site characterization program from a cost perspective.

Several regulating and certifying agencies (e.g. DNV) recommend design guidance/analyses that are required to be performed to ensure that the performance of the wind turbine is acceptable throughout its lifespan. Almost all of the requirements related to the different types of foundations are based on a rigorous and comprehensive understanding of the characteristics of the marine sediments and the environmental loadings. Most of this information is collected through wide-ranging laboratory testing protocols in addition to offshore geophysical investigations and in-situ geotechnical testing. Rahim and Stevens (2013) provide a complete list of requirements that need to be considered while designing wind turbine foundation systems. They also provide a full suite of geotechnical design parameters that need to be measured to properly design the foundation systems.

Owing to the major aforementioned differences between offshore wind turbines and oil and gas platforms, guidance and recommendations applicable to the analysis and design of offshore wind turbine foundation systems were essential. This document combines the experience accumulated over the years by the oil and gas industry and the experience accumulated by the wind industry in Europe to prepare guidance and recommendations relevant to offshore wind farms. The intent of this section is to provide an overview of the different foundation systems used for offshore wind turbines and the viability of using these systems. This section also presents an introduction to various vessels that can be used for offshore investigations. In addition, it introduces various in-situ and laboratory testing regimes that are routinely conducted in offshore applications. General guidelines about planning a successful site investigation campaign along with designing an optimized laboratory testing program are provided as well. It is important to note that every project is unique in nature. Hence, a qualified marine geotechnical engineer should evaluate the viability of these guidelines given the site and project-specific circumstances.

Several agencies have prepared various documents that provide detailed guidelines and recommendations regarding the site investigations (geophysical and geotechnical), analysis, design and installation of the various foundation systems. The scope of this document is to provide the reader with more generic guidelines that can greatly assist in preparing site investigations and laboratory testing programs. For further details, the reader is referenced to the guidelines provided by the following agencies (referenced in the upcoming volumes as applicable). It is important to note that this is not intended to be a comprehensive list of all available guidelines / agencies:

- Det Norske Veritas (DNV; e.g., DNVGL-ST-0126)
- American Petroleum Institute (API; e.g., API RP 2GEO)
- American Bureau of Shipping (ABS; e.g., ABS, 2014a and ABS, 2014b)
- Norwegian petroleum industry (NORSOK Standards; e.g., NORSOK G-001)
- International Organization of Standardization (ISO; e.g., ISO-19902)
- Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585 by BOEM
- Geotechnical & Geophysical Investigations for Offshore and Nearshore Developments by the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE)
- Guidance Notes for the Planning and Execution of Geophysical and Geotechnical Ground Investigations for Offshore Renewable Energy Developments by the Society for Underwater technology (SUT).

It is important to note that whenever possible, the references cited within the various volumes of this document were directly investigating /addressing offshore wind farms. In some cases, documents prepared for the oil and gas industry are also cited wherever applicable. The literature in the broad topic addressed by this document is immense. Hence, the cited references are not, and cannot be, comprehensive.

1.2 OVERVIEW OF THE STUDY

This report is divided into six volumes that address various aspects of the scope of this study. Volume content is organized as follows:

- Volume 1 (current volume): Introduces the typical components of offshore wind farms, provides a concise introduction about geologic characteristics within the Atlantic OCS, introduces the various offshore foundation types and systems for offshore wind turbines, lists the main factors that control the selection of a specific foundation system, and provides examples of alternative plans that can be adopted to conduct geophysical and geotechnical site investigations.

- Volume 2: Analyzes the benefits and risks associated with the different techniques adopted during geophysical surveys and the viability of using the different techniques within the Atlantic OCS.

- Volume 3: Analyzes the benefits and risks associated with the different in-situ tests adopted during geotechnical investigations and the viability of using the different techniques within the Atlantic OCS. It introduces the different laboratory tests and the design parameters that can be measured using each of them. It also presents additional details about choosing the number and type of in-situ and laboratory tests for each foundation type.

- Volume 4: Presents best practice recommendations for survey techniques and equipment for geophysical surveys.

- Volume 5: Presents best practice recommendations for geotechnical site investigation techniques and equipment for these investigations.

- Volume 6: A guidebook for equipment selection and utilization dependent on the site conditions and structures anticipated for future offshore renewable projects within the Atlantic OCS.

1.3 COMPONENTS OF OFFSHORE WIND FARMS

A typical offshore wind farm consists of multiple wind turbines to generate electricity and an electric service platform (ESP) to collect the generated electricity through inter-array cables. The electricity is then transferred onshore through an export cable to enter the power grid.

1.3.1 Offshore Wind Turbine Structure

A typical offshore wind turbine structure consists of five main components: 1) foundation, 2) support structure, 3) tower, 4) nacelle, and 5) rotor blades. Table 1.1 lists the definitions of these individual components. Foundation types used offshore include piles, suction caissons, gravity-based foundations, and anchors. Foundation systems (alternatively called support structures or sub-structures) can have variable structural configurations including mono configuration (monopiles and mono-suction caissons), gravity-based foundations, space frame foundations (jackets, tripods, and tri-piles) and floating structures.

Table 1.1. Typical components of offshore wind turbine structures

Component	Definition
Foundation	Component(s) that is in direct contact with the marine sediments (e.g., piles, suction caissons, and anchors).
Support Structure	Transitional component that connects the foundation to the tower (e.g., jackets, mooring lines, and semi-submersibles)
Tower	Structural element that connects the support structure to the nacelle
Nacelle*	Supports the rotor and converts the rotational energy into electrical energy
Rotor*	Extracts the kinetic energy of wind and converts it to rotational energy

*Definitions based on: "A Guide to an Offshore Wind Farm," published on behalf of the Crown Estate

1.3.2 Electrical Service Platforms (ESPs) & Inter-Array Export Cables

An electrical service platform (ESP) is typically constructed either in the center of the wind farm or on the periphery, to collect electricity from the wind turbines. ESPs are usually larger and heavier than wind turbines and are most often founded on jacket structures with multiple cylindrical, open-ended pipe piles as anchoring points. The main dynamic loads applied to these platforms result from storms and wave action. Hence, its design criteria are typically similar to oil and gas platforms as opposed to offshore wind turbines. Other design considerations that must be addressed include the connection between the submarine cable and the topsides.

Power generated by individual turbines must be sent to a central repository / ESP conveyed by a series of buried, intra-field interconnected electrical cables. The electricity is then transferred onshore via an export cable that connects the ESP to an existing power grid. Depending on the number of turbines and aerial extent of the windfarm, the development may consist of tens of miles to hundreds of miles of trenched, covered or seabed-level electrical cables. It is important to note that seabed conditions will control the routing of such cables, and so by extension, a thorough understanding of the shallow surface conditions across the site is paramount. Considerations such as the design of J-Tubes (hang-off electrical conduits; See the glossary at the end of this volume) and scour protection around the touch-down point, where the cable enters the seabed, all have to be addressed. Understanding the frictional characteristics of the cable armor-to-soil interface may control or inhibit certain cable routes or configurations. The selection of electrical cable construction and material choice (armor) will also play a role since cable types have real-world route length limits. In addition, their submerged weight / unit length will govern hypothetical embedment depths as well as impact installation frictional resistance from the seabed. Nearshore geotechnical borings may also be required if the cable is to connect to the land via conduits installed by horizontal directional drilling (HDD) methods. Potential cable damage hazards include: 1) seabed variations/mobility leading to exposure and suspensions, 2) seismic activity, 3) iceberg scour, 4) submarine landslides, 5) dredging hazard, 6) fishing/trawling, 7) anchor hazard and 8) dropped objects/construction. Fishing and anchors, by far, make up approximately 50% of all impacts to submarine cable systems.

Inter-array cables connect each turbine to the electrical service platform (ESP), while the export cable is typically the main cable that connects the whole wind farm, through the ESP, to an onshore grid. Conducting a cable burial risk assessment is an integral part of the design of an offshore wind farm. An essential step in this risk assessment study is to conduct a detailed site characterization by integrating geotechnical and geophysical data collected along the different cable routes (especially the export cable).

1.4 ATLANTIC OUTER CONTINENTAL SHELF

The Atlantic OCS is considered to be a “Frontier Region” where little information exists about the geologic conditions and how those conditions may impact development of offshore wind farms. In contrast, regions such as the Gulf of Mexico and North Sea have significantly more information and experience regarding geologic conditions and how those conditions may affect construction and performance of oil and gas structures and O&G/offshore wind structures, respectively.

The continental shelf is a broad region that ranges from about 50 to 250 kilometers (km) wide, slopes gently toward the shelf break, and is demarcated by the 200-meter water depth contour at the shelf break. Water depths within about 100 km of the mainland are typically less than 60 meters (Figures 1.1 through 1.3). Water depths from the state/federal boundary (3-nautical mile limit) to 100 km offshore in the Northern Atlantic are predominantly 30 to 60 meters but are shallower in the Mid-Atlantic and Southern Atlantic where they are about 15 to 50 meters.

The northern and mid-Atlantic continental shelf formed predominantly as a result of the upbuilding and outbuilding related to cyclical rise and fall of sea levels since the Cretaceous time (Moore and Curray, 1963; Garrison, 1970; and Uchupi, 1970). The wedge of sedimentary Cretaceous to Quaternary aged units thicken to the south and southeast in the northern Atlantic and to the east in the Mid-Atlantic. In addition to the upbuilding and outbuilding processes that built the northern and mid-Atlantic shelf, the southern Atlantic shelf construction is partially attributed to carbonate accretion and reef build-up (Uchupi, 1970). Triassic, Jurassic, and Paleozoic basement rocks lie approximately 1 to 3 km below the seafloor of the continental shelf (Uchupi, 1970).

Geologic processes that occurred during the Quaternary are responsible for creating geologic conditions that will have some of the most significant effects in design and construction of future wind farm foundations and cables. During the Quaternary, at least three major glacial events occurred and the southern limit of the last glacial advance is approximately along Long Island, Martha’s Vineyard, and Nantucket Island (Figure 1.4). Depositional and erosional processes occurring during glacial and inter-glacial periods have created a complex array of geomorphic elements and shallow stratigraphy on the continental shelf.

During glacial periods, major river systems crossed the continental shelf and connected to the sea via the canyons on the shelf break (Figure 1.4). As the sea level rose during the interglacial period, the shoreline transgressed across the shelf and a fluvial, lagoonal, estuarine, and barrier system deposits sediments on the erosional surface. Those “transgressive deposits” infilled low areas (e.g. former drainages) and are commonly comprised of clay, silt, and sand. Barrier and nearshore deposits were left in place and comprise many of the ridges seen on the continental shelf today. Also, shoal retreat massifs, associated with inlets near rivers tracked the retreat of rivers and left thick sandy deposits in place on the shelf (Swift, 1970). After submergence of the shelf, the depositional environment transitioned to a marine environment. The thickness of the marine deposits varies as a function of sediment supply and in some areas the marine deposits mask underlying paleolandforms. Large paleolandforms (e.g. shelf valleys) can still be observed on the shelf today.

Quaternary aged deposits cover most of the continental shelf. Thickness of the Quaternary deposits ranges from a few to about 40 meters. The thickest sections of Quaternary sediments are generally associated with paleodrainage infills, shoal retreat massifs, or glacial outwash deposits. In some areas such as the New York Bight, offshore New Jersey, and Onslow Bay south of Lookout Point (Figure 1.4), pre-Quaternary units may be exposed at the seafloor or shallowly buried. Geologic units that directly underlie Quaternary deposits are primarily sedimentary units of Pliocene, Miocene, or Cretaceous in age. Little is known about the geotechnical properties of the Pre-Quaternary units beneath the OCS.

Today, oceanic conditions continue to modify the seafloor. Rates and magnitude of seafloor topography changes are related to water depth, bottom currents, and seafloor substrate. The Atlantic OCS is considered to be a storm dominated environment. Although waves and currents can generate bottom currents, storm events, including tropical storms and nor'easters are inferred to be the dominate sediment transport mechanism on the Atlantic OCS (Swift et al., 1981).

Geologically, the Atlantic OCS can be separated into three zones. The North Atlantic zone includes the New England region where geologic conditions were strongly influenced by glacial processes (Figure 1.4). The Mid-Atlantic zone is non-glacial and north carbonaceous region of the South Atlantic zone. The following section describes general conditions of each zone.

1.4.1 Northern Atlantic OCS: Glacial and Proglacial Sites

The Northern Atlantic region is an area where the shallow geologic conditions are largely influenced by past glacial processes. Late Wisconsin and Illinoisan glaciers are interpreted to have extended south to Long Island, Martha's Vineyard, and Nantucket Islands (refer to Figure 1.4). Glacial and proglacial geology are predominant in the Northern Atlantic OCS Wind Energy Areas. Glacial deposits generally consist of till, eskers, kames, and moraines. Glacial till is typically comprised of a silt and clay matrix with variable amounts of sand, gravel, and cobbles in a poorly stratified composition. Glaciers have overridden the till deposits which result in overconsolidated deposits. Moraine deposits are left in place at the margins of the ice sheets as the glaciers melted and retreated. Moraine deposits are comprised of sand, gravel, cobbles, and boulders. High-resolution bathymetric surveys have revealed boulders on the moraines that are commonly 1 to 6 meters in diameter and some have been observed up to 15 meters in diameter. Moraines have prominent seafloor expressions in bathymetric data. Kames and eskers were deposited by streams that flowed beneath or within glaciers and are typically comprised of sand and gravel that form long sinuous ridges.

The area beyond the margin or in front of the ice sheet is referred to as the proglacial area. Glacial outwash and glacio-lacustrine deposits are the predominant deposits in that environment. Glacial outwash deposits formed as meltwater flowed in fluvial systems across the gently sloping plain. The fluvial systems were often comprised of braided river systems that deposited thick sections of sandy deposits. Glacio-lacustrine sediments were deposited in impounded proglacial lakes. Proglacial lakes typically formed by meltwater trapped in a depression caused by isostatic depression of the ice sheet or an area dammed by a moraine or detached ice block in front of the ice sheet. Sediments deposited in the proglacial lakes are referred to as glacio-lacustrine deposits and are typically comprised of alternating thin (varved) layers of silt and clay or fine sand and silt/clay. Deltas and fan deposits comprised of sand can be present where streams entered the proglacial lake.

Transgressive deposits typically overlie the glacial deposits and are thickest where they infill former topographic lows (e.g. paleo-drainages such as the Block Island canyon). Transgressive deposits are typically comprised of fine-grained, sandy, or interbedded deposits. Marine deposits generally comprise the surficial deposits and are sandy in shallow water regions and fine-grained in deeper water areas (e.g. Block Island and Rhode Island Sounds, the “mud patch” region south of Martha’s Vineyard Island). In areas where the marine and transgressive deposits are thin, glacial deposits may be exposed on the seafloor. Winnowing of finer grained marine deposits may also expose glacial cobbles/boulders on the seafloor.

Pre-Quaternary units are typically Pliocene to Cretaceous in age. Pliocene units are considered to be non-indurated. Cretaceous units have not been drilled, tested, and logged extensively offshore so little geotechnical information is available for them. Cretaceous units are inferred to outcrop at the seafloor in portions of the New York Bight, they are also inferred to directly underlie the Quaternary deposits in some areas, and they may be present elsewhere within the depth interval for piled foundations. Where Cretaceous units have been drilled and sampled offshore, their materials have been described as partially cemented or having indurated layers.

The Northern Atlantic is geologically complex and material types could exhibit a high degree of variability both laterally and horizontally. Variability of material type and properties is anticipated be greater than areas to the south.

1.4.2 Mid-Atlantic OCS: Non-Glacial in Origin

The Mid-Atlantic zone extends from the glacial limit and outwash plains in the Northern Atlantic to approximately Cape Lookout of North Carolina. Seafloor morphology in this region is characterized as ridge and swale topography. The ridges are comprised of sand and have a northeastern trending crestline, are typically 2 to 4 meters high (trough-to-crest), a few hundred meters wide at their base, and may extend 3 to 6 km long. The largest ridges exhibit trough-to-crest heights of up to 10 meters. The ridges represent shoreface deposits abandoned in place as the shoreline transgressed across the shelf. Modern oceanographic processes continue to modify the ridges.

Holocene marine deposits comprise most of the seafloor. The marine deposits are primarily sandy materials and may be fine-grained clay or silt in swales. Where the marine deposits are absent, older Pleistocene deposits may be present. Pleistocene gravels have been mapped in some swales and also a fairly extensive area offshore Central New Jersey. The gravel deposits offshore New Jersey are likely an offshore extension of the Bradenton formation which is mined onshore for its aggregates. Elsewhere, dredging offshore Virginia has also encountered Pleistocene gravel and cobble deposits.

Underlying the Holocene marine deposits and ridges generally lie the transgressive deposits. Transgressive deposits were deposited as the fluvial-estuarine-barrier system migrating across the shelf during the Holocene sea-level rise. Transgressive deposits infilled low areas (e.g. former drainages) and are commonly comprised of clay, silt, and sand. They are thickest where they infill large paleo-channel systems from former drainages (e.g. Hudson, Delaware, Susquehanna, James, and Roanoke Rivers). Channel infills in large paleo-drainages may be 30 to 40 meters thick.

Pleistocene deposits underlie the transgressive deposits except in localized areas where the Pleistocene deposits may be exposed on the seafloor (as previously described). Pleistocene deposits were placed during glacial and inter-glacial cycles and the deposits from older cycles may be present in whole, part, or may be absent due to erosion. Correlating Pleistocene units over large spatial areas is often challenging due to the heterogeneity of the deposits and former erosional processes. Pleistocene deposits are commonly comprised of sand with varying amounts of fine-grained deposits, gravel, or fine-grained units.

Pre-Quaternary deposits that directly underlie the Quaternary unit are interpreted to be primarily Pliocene age marine deposits. Pliocene-aged units in central and northern New Jersey may be shallowly buried beneath the seafloor, but are typically deeper elsewhere in the Mid-Atlantic. Piled foundations may also encounter Miocene age units in the Mid-Atlantic.

1.4.3 Southern Atlantic OCS: Non-Glacial in Origin and Carbonates

The Southern Atlantic OCS has similarities to the Mid-Atlantic in terms of Quaternary geologic processes and units. The seafloor exhibits ridge-and-swale topography and buried drainages are present beneath the marine deposits. Transgressive deposits underlie the marine deposits. Pleistocene deposits are predominantly sandy with varying amount of fine-grained sediments and gravel.

However, the Southern Atlantic represents a transitional area where carbonates begin to be common within shelf strata. Although the shelf located west of Blake Plateau was constructed by upbuilding of the shelf and outbuilding of the slope, the Blake Plateau and Escarpment were built by carbonate accretion or reef platform (Uchupi, 1970; Figure 1.4). Pre-Quaternary units may include marl and limestone. Pliocene age deposits have a higher carbonate content than their counterparts in the Mid-Atlantic and some are considered to be marls. Tertiary units outcrop south of Lookout Point in Onslow Bay where Quaternary deposits are thin to absent due to low sediment supply (Mixon and Pilkey, 1976; Figure 1.4). In Onslow Bay, Mixon and Pilkey (1976) indicate that the Tertiary units exposed at the seafloor may be lithified. Elsewhere along the nearshore region South Carolina and Georgia, weakly cemented Pre-Quaternary units are limestone have been encountered by shallow borings (USACE, 2007; USACE, 2014). Mixon and Pilkey (1976) also interpret some Pleistocene materials to have been deposited in a shallow sea environment and are weakly cemented. Tangible information about the presence of carbonates in the Southern Atlantic OCS is very limited and largely restricted to nearshore data. Although the existing information suggests that the wind planning areas are not located on carbonate platforms like the Florida and Bahama platforms, the information does indicate there is a potential for carbonaceous materials to be present that are weakly cemented.

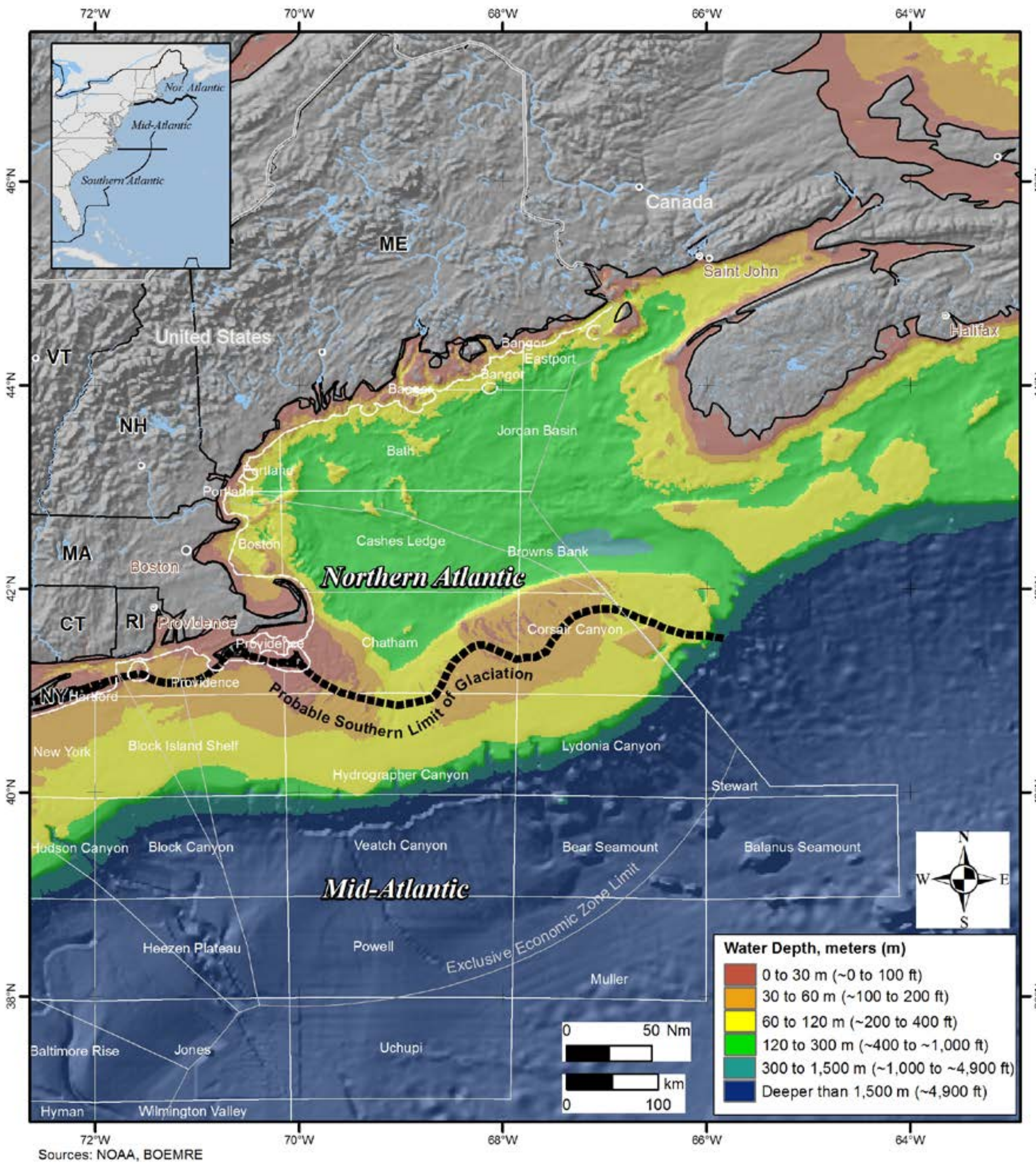

Figure 1.1. Water depths within the Northern Atlantic OCS

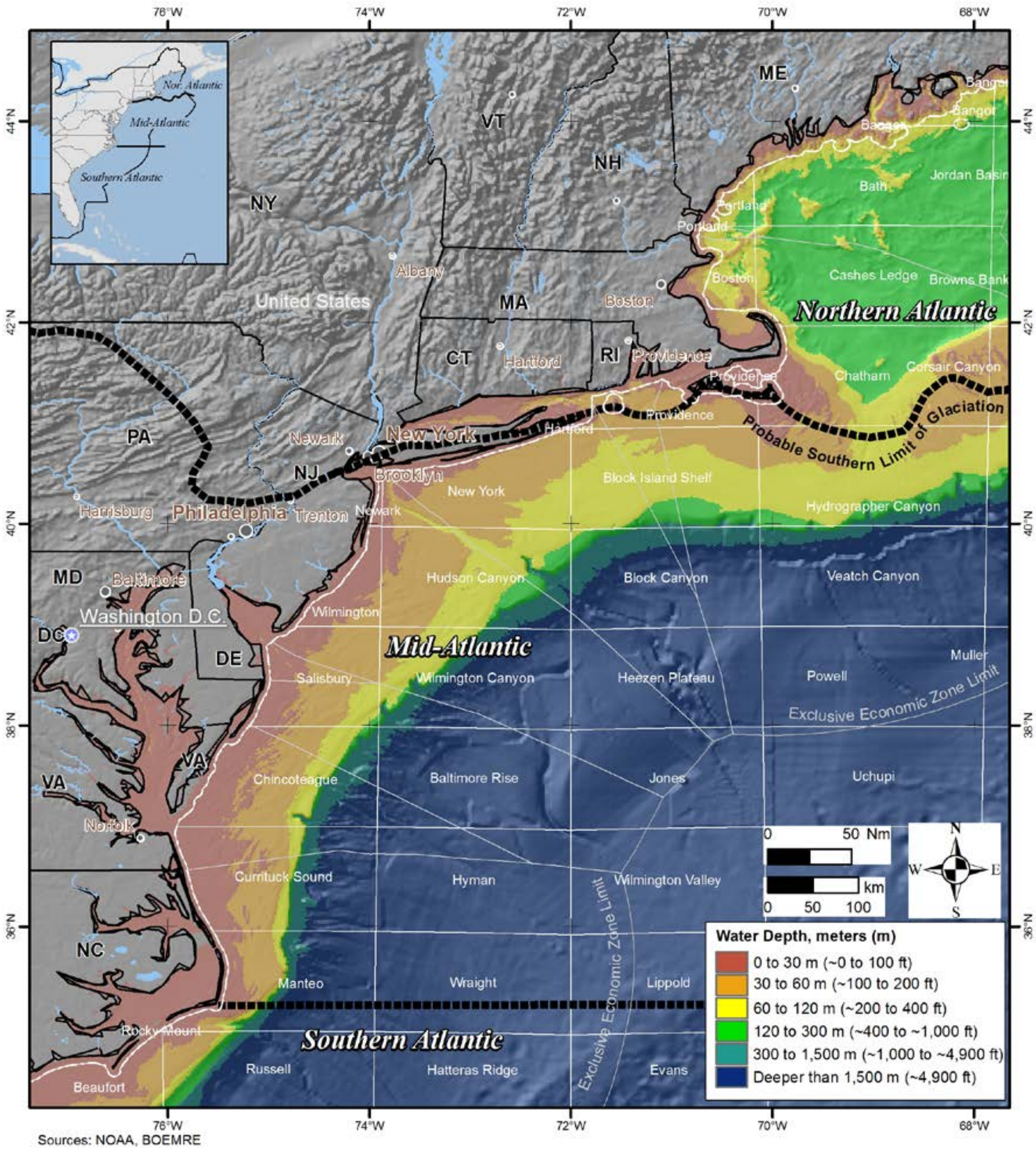

Figure 1.2. Water depths within the Mid-Atlantic OCS

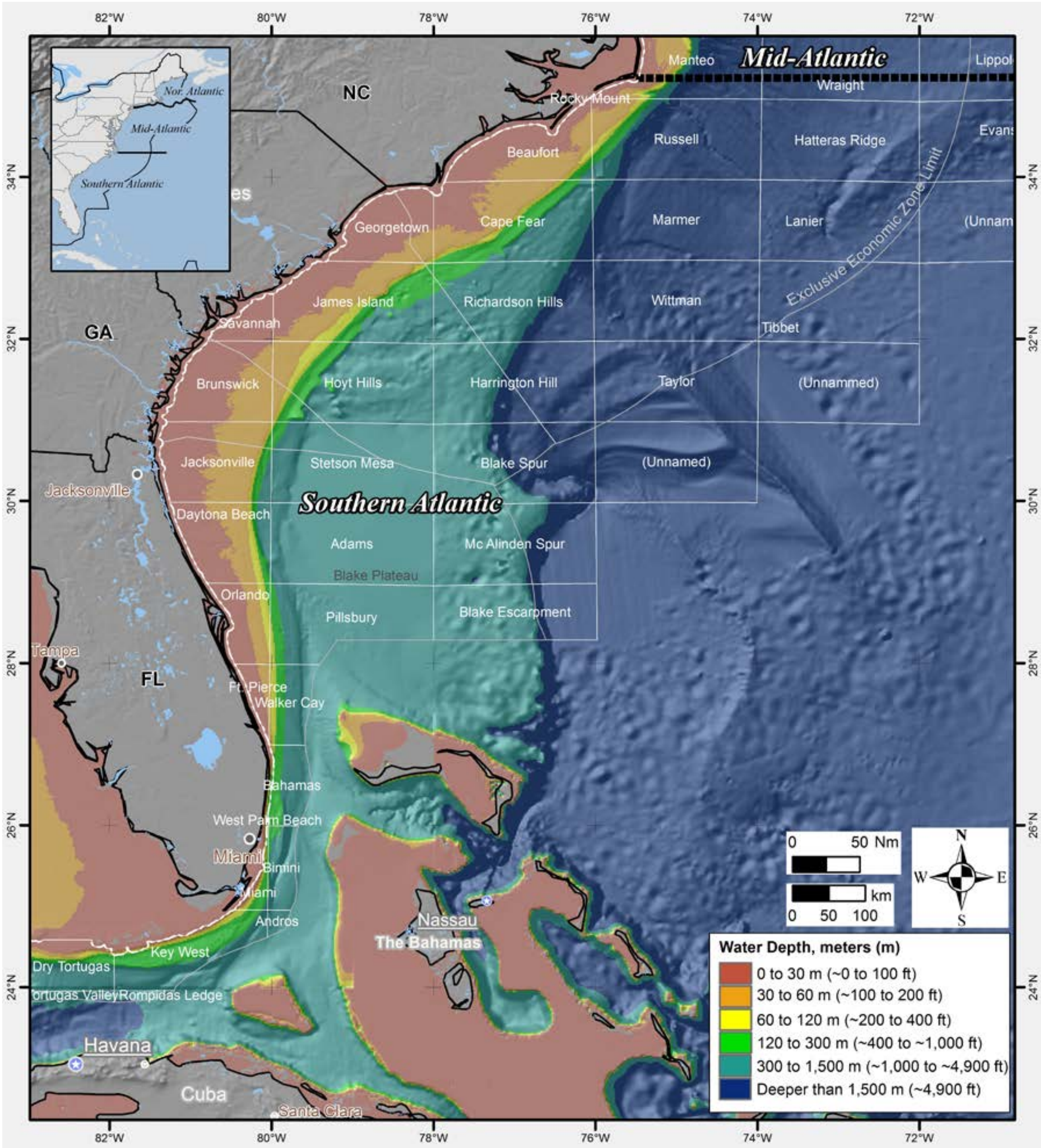

Figure 1.3. Water depths within the Southern Atlantic OCS

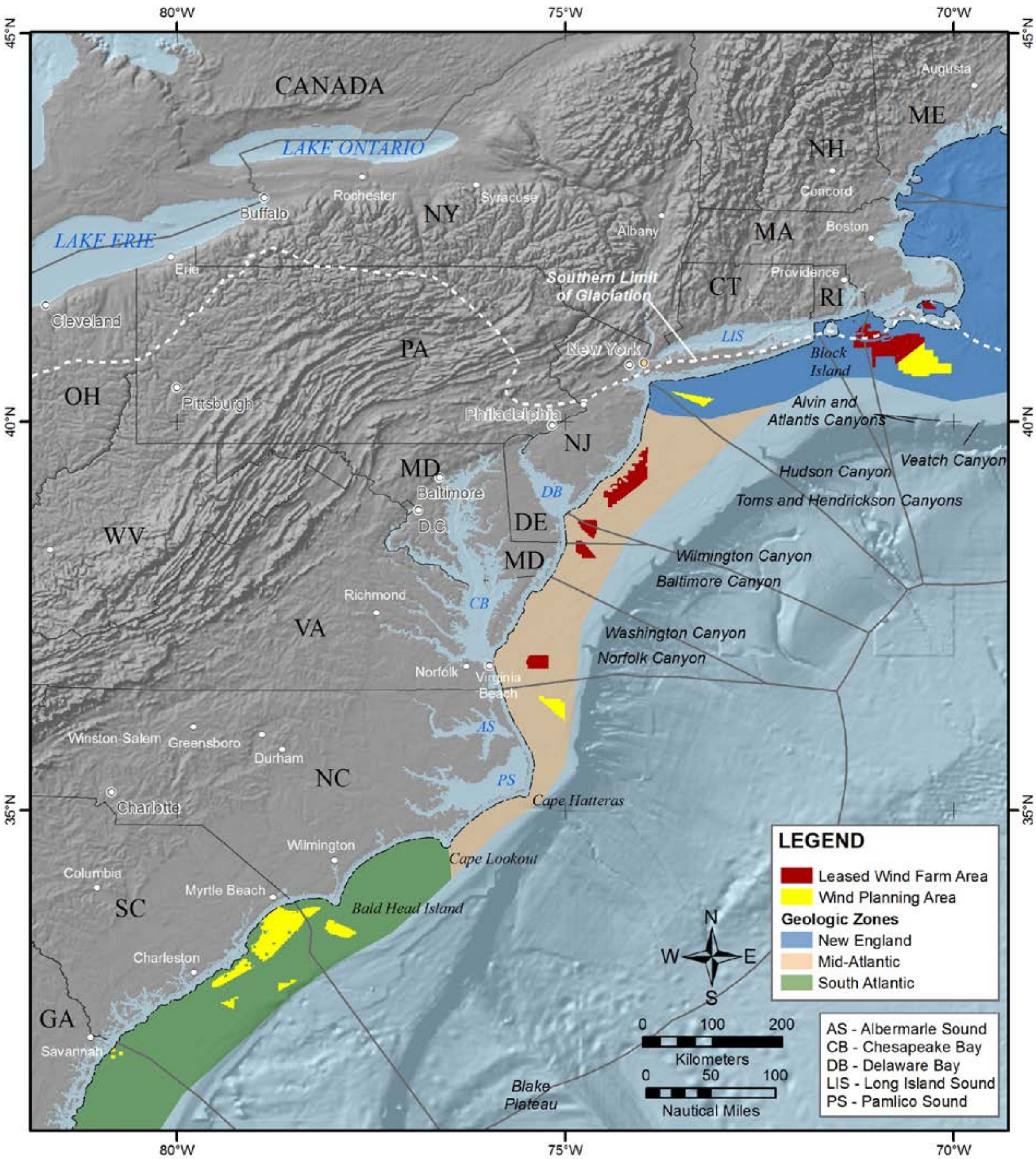

Figure 1.4. Regional geologic zonation

1.5 FOUNDATION SYSTEMS

The US wind farm market is in its infancy when compared to the European wind industry. In fact, there are no existing, fully operational wind turbines, installed within the Atlantic Outer Continental Shelf as of the end of 2015. As a result, guidance with respect to suitable foundation types for the Atlantic OCS can only be made as analogs from systems currently installed in Europe and other parts of the world. As of the end of 2012, 74% of offshore wind turbines in Europe were founded on monopiles, 16% were founded on gravity-based foundations, 5% on jackets, 3% on tri-piles, and 2% on tripods (EWEA, 2013). By 2020, it is projected that the monopole share will drop to about 50-60%, the concrete gravity-based will drop to about 5%, and the jackets/tripods will increase to approximately 35-40% (Kaiser and Snyder, 2012).

This section presents an overview the different types of foundations and the structural configuration of support structures suitable for offshore wind farms. It also explains the basis on which the different foundation systems are generally selected. The conditions that favor each foundation system and its range of applicability are addressed in Section 2.4.

1.5.1 Offshore Foundation Types

1.5.1.1 Piles

Piles are widely used for offshore applications, especially if the surficial marine sediments are considerably loose, weak, or the foundations are required to resist fairly large lateral/tensile loads. They are deployed in several configurations of the support structure such as monopiles, jackets, tripods, tri-piles, and anchors for floating turbines. The versatility of piles, along with the considerable amount of experience accumulated over the years makes them the most widely used foundation type for offshore applications.

Typical analyses conducted as part of the design of a driven pile includes axial pile capacity, lateral pile capacity (deflection-controlled), drivability analysis (and developing soil resistance to driving curves), developing lateral and axial load transfer curves (p-y, t-z, and Q-z curves), investigating the effect of cyclic loading and group effect on the axial and lateral behavior, investigating the pile displacement under service loads (using p-y, t-z, and Q-z curves), and investigating the pile behavior under fatigue loads (use the predicted range of soil stiffness under fatigue loading in that analysis). Several of the aforementioned analyses are conducted using empirical, semi-empirical, or simplified analytical methods. Numerical modeling is becoming exceedingly popular, especially in analyzing complex configurations and/or complex ground conditions. For example, the combined effects of vertical and lateral loads on pile response can be checked using numerical modeling (Rahim and Stevens, 2013). It is important to note that no matter which design approach is adopted, a marine geotechnical investigation (including in-situ and laboratory testing programs) is essential for a successful design. Geotechnical properties of the foundations soils can be approximated by way of various methods, however, local data extracted from the seabed using advanced in-situ testing is the standard approach. Pile design can essentially be broken down into three discernable stages:

Stage 1 – Installation. Monitoring of piles as they are driven in the field is essential to ensure that the design capacity is achieved and the structural integrity of the piles was not compromised during the driving process. Interruptions in the driving plan allow for pore water dissipation from soil surrounding the piles (known as soil setup). Under some conditions, setup might lead to a substantial increase in the number of blow counts required to resume driving. In some extreme cases, setup might result in premature pile refusal. Hence, it is important to plan for unscheduled interruptions in the driving activities (e.g. break down of hammers, major storms that shut down field operations). This is especially important if the site conditions favor fast setup. For example, cylindrical piles in certain clay profiles can gain 30-40% in the pile side friction over the first few days after driving. Moreover, depending on the length of the piles, on site welding might be necessary to achieve the design capacity. This represents additional challenge to the installation operations.

Due to the noise associated with pile driving, a marine mammal observer is typically on board to stop the driving operations if marine mammals are in the vicinity of the job site. Another important aspect of driving piles is how to support them while being driven. This is especially critical when piles are driven in deeper water. Sometimes a device called a fast-frame may be required to clamp the pipe at seabed level while it is being driven. This devise usually consists of a square, skirted steel footing with a clamshell clamping devise atop the base plate. Additional calculation checks may be required to ensure overturning stability is assessed since the pile will stick up from the seabed. Hence, it is essential to plan for the construction stage from the early phases of the project to ensure the availability of the suitable resources on the construction site.

Stage 2 – Operating. The vertical capacity and load-deflection behavior of offshore driven piles can be investigated using a wide variety of analyses with various levels of sophistication. The type of analysis selected depends on many factors including the nature of wind turbine loads and ground conditions, among many other factors. Pile capacity invariably gets stronger over time especially when clay soils are encountered. However, piles installed in predominantly sand profiles may experience a reduction in vertical and lateral resistance; this can be attributed to localized scour effects, grain crushing and dilatency effects.

Stage 3 – Removal. Several decommissioning options are available for the foundations of offshore structures. These options include leave-in-place, partial removal, or complete removal. The decommissioning option is chosen based on economic and environmental factors, among others. It is important to note that BOEM requires piles to be removed to depth of 15 feet below mudline. The preferential decommissioning option should be considered during the design and installation stages of the foundation system. It is imperative that the degree of soil setup be closely studied since the load required to extract the pile at the end of life could be significant. Sometimes, vibratory devices can be used, in addition to surface crane lift, to coax the pile out of the seabed. If piles are to be left in place, usually they are cut flush with the seafloor. Scour studies then become an important consideration since the pile head may slowly become exposed thereby constituting a possible navigational hazard or impediment to fishing activities.

Applicability of Piles. Piles are suitable for a wide variety of soil conditions. Sites characterized by the presence of shallow bedrock, boulders, cobble, and coarse gravel are the exception since the pile is more susceptible to damage and permanent deformations if driven in these materials. Hence, some parts of the Northern Atlantic OCS will be problematic for pile installations. The information collected during geophysical and geotechnical explorations will help the designer in assessing the viability of using driven piles. Moreover, care should be taken while designing driven piles in calcareous materials because the cementation of this material is typically lost during the driving stage. This results in considerably low skin friction values. While a lot of experience has been accumulated over the past few decades when it comes to designing driven piles in calcareous sediments, much of this experience was accumulated from sites in Australia. Moreover, individual experience and site-specific experience still play a major role in the design of piles in calcareous soil conditions. Calcareous sediments, of some degree, are likely to be encountered in the southern Atlantic OCS region.

1.5.1.2 Suction Caissons

Similar to piles, suction caissons are versatile foundations that can be adopted in several structural configurations including mono-suction caissons and fixed jackets. Hence, they are applicable to a wide variety of water depths depending on the configuration of the foundation system (Table 1.2). While piles are generally driven in place using a hammer, suction caissons are installed in place using suction pressure, as the name implies. The design of suction caissons spans three different stages that need to be addressed.

Stage 1 – Installation. Suction caissons are generally transported or barged to the planned position offshore then allowed to penetrate the surficial marine sediments under their own weight. The suction caissons are controlled-lowered during this self-penetration phase (Figure 1.5). Afterwards, subsea pumps on remotely operated vehicles (ROV) pump water from inside the caisson, which applies a negative pressure (suction) on the top plate of the caisson. Once the suction overcomes the skin friction along the walls of the caisson, it starts to penetrate until the top plate is approximately at mudline. Usually, a suction caisson is left in place with up to 1 m (3 feet) of stick-up (See the glossary at the end of this report), but this depends on the location of the sacrificial anodes that are used to mitigate caisson corrosion. The typical range in applied pressures to install (or remove) the caisson are on the order of 400-800 kPa (60-120 psi). Since the installation does not require repetitive impacts from hammers, as seen with standard piles, suction piles do not suffer from fatigue accumulation.

The maximum allowable suction during the installation process must be carefully estimated. If the applied suction exceeds certain limits, the soil inside the caisson can heave considerably into the void, and/or suffer remolding and a reduction in shear strength or relative density. It can also lead to the formation of piping channels around the caisson walls, which prevents the suction pressure from being maintained. This may prevent further penetration of the caisson during installation. Installation issues to consider are: 1) final angle of suction caisson tilt, 2) final orientation / azimuth of the pad eye of the suction caisson (only relevant when caisson is used as an anchor), 3) caisson underdrive and overdrive (most suction caissons cannot be overdriven owing to the structural top plate, but underdrive may result in inadequate capacity or large overturning moments) and 4) premature refusal. Several methods have been suggested and validated to predict the pressure required to achieve full penetration of the suction caisson. These methods are either based on finite element modeling (e.g. Erbrich and Tjelta 1999) or classical approaches that adopt simplifying assumptions (e.g. Houlsby and Byrne 2005a and 2005b). A CPT-based methodology is described by Houlsby et al. (2005).

During the installation stage, it is more conservative to use upper bound soil shear strength parameters with an appropriate soil sensitivity (lower bound sensitivity) to determine the remolded strength of the soil during installation. It is also important to note that the controlling soil remolding mechanisms for suction caisson self-weight penetration versus pump-assisted suction penetration are very different. Therefore, the degree of post-installation soil setup may vary considerably over the installed length in the self-weight embedment depth zone versus the suction-installed embedment depth zone.

Other considerations regarding the installation of suction caissons center around the final depth, attitude and orientation of the installed pile. For example, suction caissons can only tolerate around 5° of tilt and -2-ft of underdrive. Unexpected variations in soil strength or fabrication tolerances in steel stiffeners can also lead to unacceptable pile twist during installation. Up to 10° of twist has been observed in the oil and gas industry; this issue may have implications for foundation to tower fit-up.

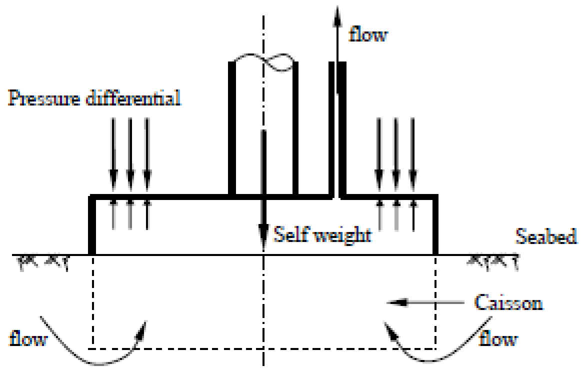

Figure 1.5. Installation schematic of suction caissons
Schematic diagram of the installation of suction caissons by pumping water out to create differential pressure that pushes the caisson in position (Source: Nguyen-Sy, 2005)

Stage 2 – Operating. As an integral part of the foundation design, the suction caisson is analyzed and treated as a skirted gravity-based foundation. This includes static and dynamic analysis to investigate the stability and performance of the foundation throughout the lifetime of the wind turbine.

The capacity of suction caissons can be checked using limit equilibrium analyses, bearing capacity equations, or numerical modeling. More recently, numerical modeling is being used more often. It is generally required to account for effect of cyclic degradation on the capacity of suction caissons. Cyclic degradation of the different soil strata is generally obtained by conducting laboratory tests on good quality samples collected from the seafloor or soil reconstituted as best possible to the in situ condition. It is important to choose the stresses applied in the laboratory to mimic the projected in-situ conditions. To this end, the capacity under cyclic loading can be estimated in two rounds. Typical soil parameters (obtained from the literature [e.g., Andersen 2004] or prior experience in similar soil conditions) are used in the first round to define the potential failure plane and estimate the average and cyclic shear stresses applied on the different soil elements. These realistic stresses are then used in the laboratory to measure the cyclic soil parameters. In the second round, soil parameters measured from laboratory tests in conjunction with applied loads are then used to predict the behavior of the suction caisson.

One other very important item to ensure that the long term suction pile bearing capacity is maintained surrounds the sealing of the butterfly values at the top of the caisson. Usually, suction caissons have two of these valves positioned side-by-side and co-located in the center of the steel top plate. These valves are wound to the closed position via hydro-mechanical actuators torqued by the ROV arms. Historical evidence has shown that sometimes these valves leak over time; this leakage can result in a reduction of the mobilized end bearing and transference of applied load to side friction. Periodic monitor of pile performance is crucial to ensure unexpected pile behavior is inhibited. Emergency covers can also be applied during installation if one or both of these valves cannot completely close.

Stage 3 – Removal. At the end of the lifetime of the foundation, the installation process can be reversed by pumping water inside the caisson to remove it. This process is relatively simple which makes suction caissons an appealing alternative to other foundation types that are more difficult to remove during decommissioning. However, if thixotropic setup (e.g. strengthening of formerly sheared soil at the soil-caisson interfaces) has not been accurately defined, then additional lift force from a surface crane may be required during the suction caisson removal if higher hydraulic pressures cannot be used effectively. If too much pressure is applied, one may run the risk of destroying the soil plug located on the underside of the top plate, resulting in complete loss of pumping force. The size of the pump (and ROV carrying it) should be selected such that its capacity is in line with the design embedment and extraction pressures. Careful consideration to both, required and allowable pressure, is paramount. Industry experience indicates that the majority of soil conditions encountered on many oil and gas suction pile projects run very close to the average of the lower and upper soil strength bounds. However, only the upper bound soil profile should be used in conjunction with the lower bound soil sensitivity when determining the required and allowable extraction pressures. This ensures inherent calculation conservatism.

Applicability of Suction Caissons. Table 1.2 summarizes the applicability of installing/using suction caissons in different types of marine sediments. Suction caissons can be installed in both clay and sand layers. Clay layers are generally assumed to be loaded under undrained conditions (see Duncan and Wright, 2005). Sand layers can be either partially drained or fully drained (see Duncan and Wright, 2005 for these definitions) depending on the loading rate, the permeability of the sand, and the size of the caisson (Houlsby et al. 2005). The drainage condition of the soil deposits dictates the relevant strength parameters (e.g. undrained shear strength or effective friction angle) and subsequently the type of laboratory tests to be assigned (e.g. drained or undrained tests). Potential installation problems can arise while installing suction caissons in stiff clays if the water depth is limited because the net suction that can be achieved in shallow water is much smaller than deep water installation scenarios (Houlsby et al. 2005). Understanding the strength of the soil to up to 1.5 x pile outside diameter (minimum) below the design pile tip elevation is very important since underlying stiffer soil layers can hinder caisson installation based on proximity pressure effects. Even the presence of thin sand layers can inhibit suction installation; therefore, the accurate discretization of even subtle material types can control the installation.

Additional Notes. Caissons create a hard point discontinuity on the seafloor that affects fluid and sediment motion. As such, scour can have a major impact on suction caissons performance because of the decrease in effective length and therefore, capacity. Scour problems are particularly relevant for suction caissons installed in sandy materials in relatively shallow waters (Houlsby et al. 2005) or potentially in high current environments for a number of soil types. Hence, it is important to predict, and account for the effect of scour, or design appropriate scour protection systems.

Table 1.2. The applicability of suction caissons embedded within various materials

Soil	Applicability (based on Houlsby and Byrne 2005a)
Sand, clay, and sand over clay	Probably suitable.
Clay over sand	Possibly problematic, even if previous installations in such conditions were possible. The encountered sand may have permeability characteristics which can result in loss of suction when the tip of the caisson reaches the sand.
Interbedded materials	Should be suitable, but no recorded cases in this type of materials.
Stiff clay	Problematic, especially if fissured (See the glossary at the end of this report).
Coarse materials	Deposits with a considerable amount of gravel are likely to be problematic. Some glacial tills are likely be problematic as well.
Silt	Should be suitable, but no methods had been developed specifically for partially drained conditions that may develop.

1.5.1.3 Gravity-Based Foundations

Gravity-based foundations rely on dead weight to withstand lateral loads and overturning moments applied to the wind turbine system. Gravity foundations are normally concrete and, in some cases, constructed with a concrete or steel skirt around the edge that penetrates into the soil to enhance lateral and overturning stability. Skirts can increase axial and lateral capacities by adding skin friction and lateral earth pressure along the skirt walls. Internal skirts can be used in large diameter foundations (*4C offshore* website). Settlement, horizontal displacement, and rotation become particularly important for gravity-based foundations owing to the considerable weight of this type of foundation system combined with its relatively shallow depth (Rahim and Stevens 2013). Gravity-based foundations usually require a relatively flat mudline and associated scour protection. Any major heterogeneity in the soil deposit below gravity-based foundations can result in differential settlements which could lead to unacceptable rotation of the tower of the wind turbine.

Applicability of Gravity-Based Foundations. It is not viable for sites with weak (soft or loose) soil layers near surface. It is also unsuitable in sites characterized with major heterogeneities near surface due to the sensitivity of this foundation system to differential settlement. Moreover, the footprint of this foundation system is typically large which might have environmental implications.

1.5.1.4 Anchors

Permanent anchors are used to keep buoyant structures (e.g. floating wind turbines) in place. Hence, they are mostly used in deeper water applications (greater than 60 meters / 200 ft). There is a variety of anchor types and sizes available, which can be classified as either surface gravity anchors (box anchors / grillage and berm anchors) or embedded anchors (piles / suction caissons / drag embedment anchors / SEPLA / dynamically penetrating anchors, see the glossary at the end of this report). Randolph and Gourvenec (2011) describe each one of these anchors, introduce its design principle, and list projects where they were adopted in practice for offshore oil and gas related projects.

Applicability of Anchors. The applicability of anchors used for floating wind turbines depend on the type of the adopted anchor. Drag embedment anchors and dynamically penetrating anchors share the disadvantage of not knowing the final position and embedment depth of the anchor. This might lead to uncertainties in the capacity of the anchors especially for heterogeneous sites. The favorable and unfavorable conditions for using piles, suction caissons and gravity-based foundations as anchors are similar to the conditions described in the previous sections. The water depths in which anchors are favorable is deeper than the water depth suitable for other foundation systems such as GBS or jacket foudnations.

1.5.2 Foundation Systems (Support Structures or Sub-Structures)

1.5.2.1 Mono Configuration

Monopiles are the most commonly used foundation system for offshore wind turbines in shallow to medium water depths (typically less than 30 m / 100 ft). It is worth mentioning that some monopiles were recently driven in 40 m water depth. Monopiles can reach considerably large diameters up to 7.0 m (23 ft) and have typical length to diameter ratios of 2 to 6 (Figure 1.6).

1.5.2.2 Gravity-Based Foundations

Up to 2012, 16% of offshore wind turbines were founded on concrete gravity-based foundations (Figure 1.7). This has provided the engineering community with a fair amount of experience in the design and construction of this foundation system. Typically, they are filled with gravel and stone to increase stability. This foundation system is generally adopted in shallow to medium water depths (generally less than 30 m / 100 ft).

1.5.2.3 Jackets

This foundation system is applicable for sites with water depth ranging from 30 to 60 meters (100 to 200 ft; Musial et al., 2006), but it has been used in shallower waters (e.g., Tamra offshore wind farm, water depth = 4 - 9 m / 13 - 30 ft [*4C Offshore* website]) and is planned to be used in deeper water as well (*4C Offshore* website). Several configurations and installation procedures of fixed jackets have been developed over the years (e.g., Figure 1.8). It is the most widely used system among the three space frame foundation systems (i.e., jackets, tripods, and tri-piles). Part of the popularity of this foundation system is the considerable experience accumulated by the oil and gas industry related to its application. Moreover, the wave and current loads applied on this foundation system are relatively small because they consist of interconnected braces with limited cross-sectional area when compared to the overall stiffness of the system (*4C offshore* website). Jackets can be founded either on piles or suction caissons.

1.5.2.4 Tripods

Tripods are considered a light weight version of the full steel jacket type foundation system (*4C offshore* website). It can be founded on driven piles or suction caissons. This foundation system is applicable in water depths up to 35 m (115 ft; Figure 1.9).

1.5.2.5 Tri-Piles

Tri-piles are considered a rigid frame that consists of cylindrical tubes that connects the wind turbine to three driven piles (Figure 1.10).

1.5.2.6 Foundations for Floating Structures

Several substructure systems can be used for floating wind turbines including tension leg platform (TLP), SPAR, and low roll floater (See the glossary at the end of this report and Figure 1.11). These are generally applicable for relatively deep waters (deeper than 60 m / 200 ft). The different anchors mentioned in the previous section can be used to anchor and maintain the position of floating wind turbines. The reader is referred to Butterfield et al. (2005) and Robertson and Jonkman (2011) for additional information about the loads applied to and the challenges related to floating offshore wind turbines.

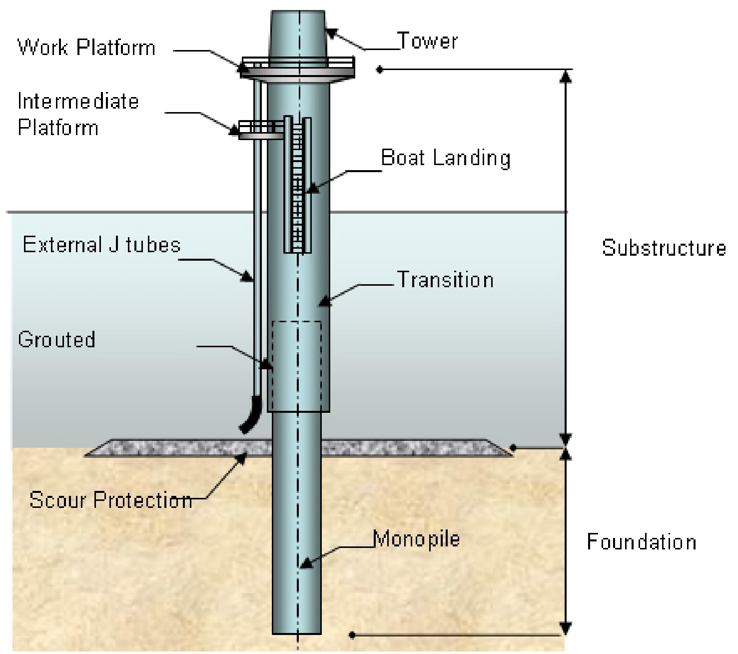

Figure 1.6. Schematic diagram of a monopile foundation system
(Source: Mott MacDonald: "Offshore Wind – IEEE Boston PES", 11/16/2010) – Pending approval from BOEM and Mott MacDonald

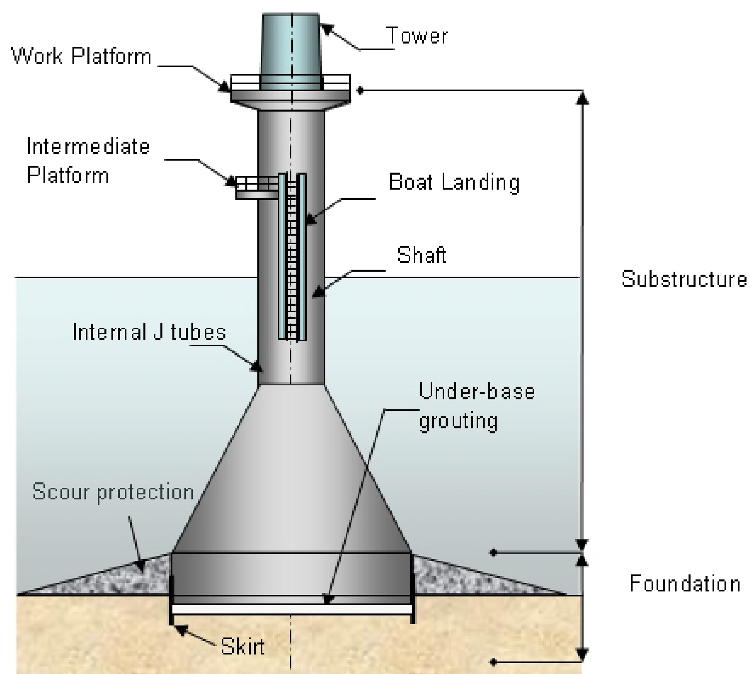

Figure 1.7. Schematic diagram of a gravity-based foundation system
(Source: Mott MacDonald: "Offshore Wind – IEEE Boston PES", 11/16/2010)

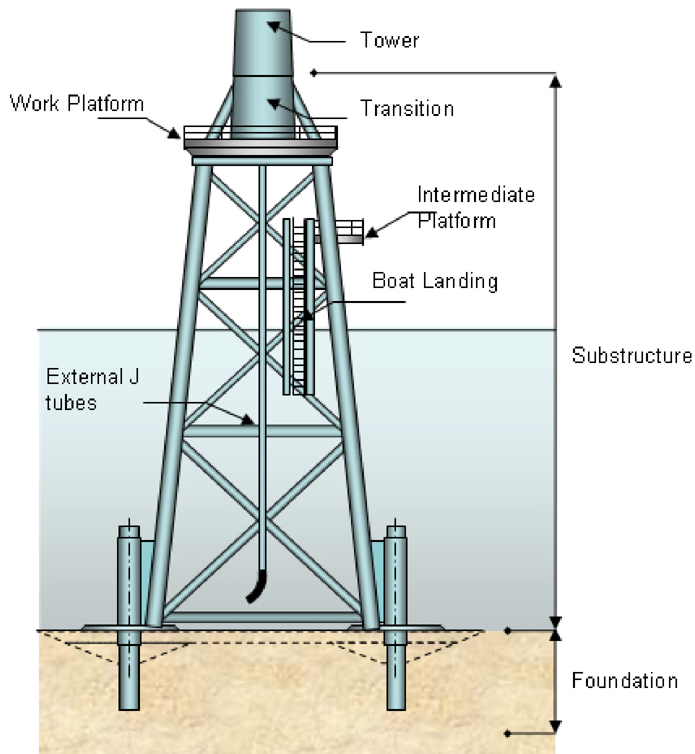

Figure 1.8. Schematic diagram of a jacket foundation system
(Source: Mott MacDonald: "Offshore Wind – IEEE Boston PES", 11/16/2010)

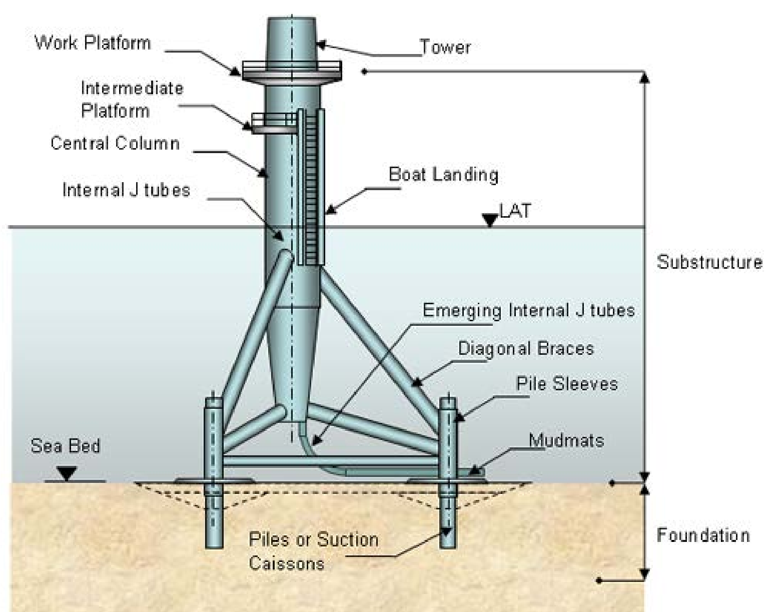

Figure 1.9. Schematic diagram of a tripod foundation system
(Source: Mott MacDonald: "Offshore Wind – IEEE Boston PES", 11/16/2010)

Figure 1.10. Tri-pile foundation used in BARD Offshore 1 wind farm
(Source: *4C Offshore* website – through BARD Offshore 1 website)

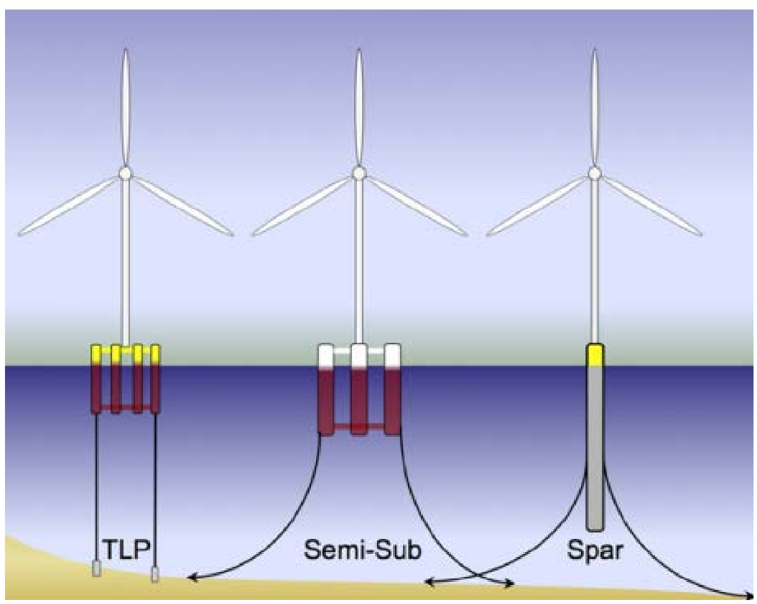

Figure 1.11. Schematic diagram of different floating wind turbines
(Source: Modified from http://www.principlepowerinc.com/)

1.6 SELECTION OF THE FOUNDATION SYSTEM

As presented in Table 1.3 (mostly based on the *4C offshore* and *LORC* websites), a wide variety of foundation / substructure systems have already been implemented or are being tested for different wind farms around the world. In the United States, several wind farm projects are at various stages ranging from planning through to early construction. For example,

- Block Island Wind Farm: Located 4.5 km (2.8 miles) offshore Rhode Island, consisting of five wind turbines. This represents the first offshore wind farm constructed in North America. Water depths range from 23 and 28 m (75 and 92 ft). The foundation system consists of jackets founded on four piles each. The diameter of each pile is 1.8 m (6 ft).
- VOWTAP (Virginia Offshore Wind Technology Advancement Project): Initial design was completed for this project and then went through two rounds of procurement for construction. Construction contract was not awarded and project has been put on hold. Twisted jackets are planned to be used for these demonstration wind turbines. The project is located 43 km (26.7 Miles) offshore Virginia. The water depth ranges between 20 and 26 m (66 and 85 ft). The twisted jacket will be founded on a central caisson (diameter = 2.75 m / 9 ft) and three piles (diameter =1.5 m / 5 ft).
- WindFloat Pacific: This project planned to include a total of five semi-submersible floating foundations located about 24 km (15 miles) offshore Oregon. Project has been put on hold.
- Icebreaker or LEEDCo (Lake Erie Energy Development Corporation): A total of 6 3-MW offshore wind turbines are planned to be constructed in Lake Erie about 13-16 km (8-10 miles) offshore. The project is currently planning to use mono-suction caissons.
- Fishermen's Atlantic City Windfarm Phase I: Located approximately 5 km (3 Miles) offshore New Jersey. It consists of six 4-MW wind turbines founded on twisted jackets. Water depth ranges between 8 and 12 m (26 - 39 ft).
- New England Aqua Ventus I project: University of Maine deployed and tested a one eighth (1/8) scale floating wind turbine about 3.5 km (2 miles) offshore Maine (DeepCwater project). They used suction caissons as anchors for this demonstration wind turbine. The New England Aqua Ventus I project is a demonstration project proposed to build two 6-MW wind turbines founded on semi-submersible platforms.

Table 1.4 lists the advantages and disadvantages of the various foundation / substructure systems. The selection of the suitable foundation system is not a simple process, since it depends on many factors, which include: geotechnical, geological and geophysical site conditions, water depth, environmental loads, size of the wind turbines, overall costs, and environmental regulations. Junginger et al. (2004) reported that the foundation cost represented 15-25% of the total cost of offshore wind farms in Europe (5 - 10% for onshore wind farms). Rahim and Stevens (2013) reported that the cost of the wind turbine foundation could be up to 45% of the total cost. Hence, the selection of the optimum foundation system and properly designing it without unnecessary conservatism is particularly important for offshore wind farms. This section presents the major factors used to select a suitable foundation system for offshore wind turbines.

Table 1.3. Examples of various foundation systems and associated wind farm

Foundation System	Wind Farm	Location	Notes
Monopiles	Horns Rev 1	17.9 km (11 miles) off the west coast of Denmark in the North Sea	-Pile diameter = 4 m (13 ft) -Pile embedment = 25 m (82 ft) -Water Depth = 6 - 14 m (20 - 46 ft)
Mono-suction caisson	Frederikshavn Offshore Wind Farm	3.2 km (2 miles) off the northern coast of Denmark in the Kattegat Sea	-One turbine founded on mono-suction caisson as part of a research and development project -Caisson diameter = 12 m (40 ft) -Caisson embedment = 6 m (20 ft) -Water depth = 4 m (13 ft)
Gravity-based	Nysted	10.8 km (6.7 Miles) offshore Denmark in the Baltic Sea	-Consisted of a prefabricated concrete caisson ballasted and positioned on the seabed[1] -Top diameter = 11 m (36 ft) -The foundation sunk 0.3-9.5 m (1 – 31 ft) into seabed -Water Depth = 6 - 10 m (20 – 33 ft)
Tripods	Alpha Ventus	56 km (35 Miles) offshore Germany in the North Sea	-Six turbines were founded on tripods and six on jackets in that wind farm. -Tripod’s pile embedment = 25-45 m (82 - 148 ft) -Water Depth = 28 - 30 m (92 – 98 ft)
Jacket foundation with piles	Alpha Ventus	56 km (35 Miles) offshore Germany in the North Sea	-Pile embedment = 40 m (131 ft) -Water Depth = 28 - 30 m (92 – 98 ft)
Jacket foundation with suction caisson	Borkum Riffgrund 1 offshore wind farm	54 km (34 miles) offshore Germany in the North Sea	-Only one turbine is founded on suction caisson jacket -Water depth = 23 - 29 m (75 - 95 ft)
Tri-piles	BARD offshore I	100km (62 miles) offshore Germany in the North Sea	-Pile diameter = 3.4 m (11 ft) -Water depth = 40 m (130 ft)
Floating spar buoy with drag embedment anchors	Hywind (one full-scale turbine, demo project)	10 km (6 miles) offshore Norway in the North Sea	-Spar floater with three mooring lines -Water depth = 200 m (656 ft)

[1]AARSLEFF Website
[2]Sif Group Website

Table 1.4. Advantages and disadvantages of different foundation systems

Foundation System	Advantages	Disadvantages
Piles (mono-configuration, space frame, or anchor)	-Have been used for decades (since 1940s). Hence, ample experience had been accumulated over the years by designers and contractors -Simple to manufacture and install -Minimal seabed preparation -Less susceptible to seabed mobility and scour effects due to its relatively deep penetration. It is still important to account for the projected scour depth (i.e., increase the penetration depth) during the design phase -Can be accurately installed at predetermined coordinates	-Not suitable for deep soft soil deposits -Can have environmental implications due to the noise and vibrations generated during the pile driving installation process -Weather sensitive, time consuming installation -Fatigue (see the glossary at the end of this report) affects the pile and the surrounding soil during installation -Difficult to remove during decommissioning
Suction caissons (mono-configuration, space frame, or anchor)	-Installation in very deep water using pumps is invariably cheaper with less technical challenges than driven piles (Randolph and Gourvenec 2011) -Decommissioning cost is much lower when compared to piles once the life-time of the foundation system is over. It can usually be removed by pumping water inside the caisson to extract it from the seabed -Reduced noise and vibrations are not associated with its installation process; hence, it is preferred over piles from an environmental perspective -Can be accurately installed at preset coordinates which gives them advantage over other types of anchors (Houlsby and Byrne 2005a)	-Susceptible to scour especially in shallow water if surficial sediments are granular (may require scour protection measures) -Most suitable for homogeneous soils -Require ROV for installation (the adoption of ROV-supplied or surface vessel-supplied air will depend on water depth and mobilized equipment) -Highly sensitive to ensure verticality during installation procedures
Gravity-based	-Transfer loads extremely well -Simple installation -Ballast (e.g., heavy stones and sand) is sometimes used to achieve the required weight -Reduced noise and vibrations are not associated with its installation process; hence, it is preferred over piles from an environmental perspective	-Large footprint at seafloor. -Large settlements especially with soft soil deposits -More prominent effect of scour on stability (if surficial sediments are coarse grained) -Not suitable when surficial layers are weak

Foundation System	Advantages	Disadvantages
		-Heavy weight -More suitable for homogeneous soils with a flat bathymetry
Space frames (Jackets / Tripods / Tri-piles)	-Have been used for decades (since 1940s). Hence, ample experience had been accumulated over the years by designers and contractors -Simple to manufacture and install -Minimal seabed preparation -Less susceptible to seabed mobility and scour effects due to its relatively deep penetration. It is still important to account for the projected scour depth (i.e. increase the penetration depth) during the design phase -Can be accurately installed at predetermined coordinates	-Most of the disadvantages applicable to piles or suction caissons are applicable for space frames as well
Drag embedment anchors	-Available in many types and sizes which result in a wide variety of holding capacity -As new anchors are developed, its holding capacity increases with respect to the weight of the anchor -Do not usually require sophisticated geotechnical data because they can be field proof-tested. This can result in a less expensive geotechnical investigation -Short installation time -Excellent ultimate holding capacity in both sands and clays (UHC) to weight ratios -Economical -Retrievable and reusable -Variable anchor types and tonnages prove useful in world-wide soil conditions -Initiation drag point can be adjusted when seabed real-estate is at a premium	-Layered stratigraphy may inhibit anchor embedment depth. Some anchors may skip along the interface without embedding if clay over sand profiles are encountered -Prediction of anchor performance/behavior rely on difficult to predict embedment trajectory during installation -Variable anchor performance under cyclic loading scenarios -Some require ROV support; tugs or installation vessels with high bollard pull ratings (> 150 Te) are most often required -Proof load test and keying (orientation) required and limited by pulling capacity of installation vessels -Soil information required over a wider area but this depends on the drag required for embedment depth -Difficult to predict final anchor depth and inclination -May only be suitable for

Foundation System	Advantages	Disadvantages
		weak/weathered rock Rock UHC relies entirely on the anchoring load application point at the tip of the anchor
Dynamically penetrating anchors	-Fast deployment -High holding capacity -Economical -Effective in soft clays	-Difficult to predict final anchor depth, inclination and holding capacity -Limited design and verification experience since it is mostly proprietary technology mainly used in Brazil (Randolph and Gourvenec, 2011) -Response under dynamic load not well understood -Not suitable for layered and granular soils

1.6.1 Factor 1 – Geotechnical / Geological Site Conditions

Geotechnical and geological site conditions, as well as regional and site-specific geohazards play a major role in selecting a suitable foundation system. Hence, before a final foundation system is selected, it is important to conduct: 1) desktop studies to evaluate the geotechnical and geological site conditions as well as potential geohazards and constraints based on previous studies and 2) conduct geophysical and geotechnical investigations.

Geotechnical and Geological Site Conditions. There are many examples where the site-specific conditions play a role in favoring a specific foundation system over another. For example, piles are preferable in relatively loose or weak marine sediments (e.g. Sothern Atlantic OCS). Gravity-based foundations are preferable in dense sediments or highly over consolidated sediments (e.g. North Sea or Grand Banks). Skirted gravity-based foundations can be an acceptable option in weak sediments depending on the applied loads. Gravity-based and suction caissons can be problematic in areas characterized with highly variable bathymetry or areas with major spatial variability in the strength of the shallow marine sediments (e.g. paleo-channels). While it is not the objective of this report to provide an exhaustive list of examples where specific foundation systems are preferred or discouraged, Table 1.5 provides an extended list of such conditions.

Geohazards and Constraints. Keer and Cardinell (1981) differentiated between geohazards and constraints as follows: 1) Geohazards have a relatively high risk since their potential for damage cannot be completely eliminated (e.g., slope stability) and 2) constrains have a lower risk level since their effect can be reduced or eliminated using an engineered solution (e.g., shallow gas). A team composed of geotechnical engineers, geologists and geophysicists typically work on identifying geohazards and constraints on regional and site-specific scales (Kvalstad, 2007). This is typically followed by risk assessment that is used to provide engineered solutions and/or management plans to mitigate the different geohazards and constraints. If a risk is still credible even in the presence of mitigation measures, then it cannot be removed from the risk matrix. Typical natural offshore geohazards and constraints include:

- **Sand Wave Fields**. Sand waves or seabed dunes form on the seafloor. They can be on the order of feet or hundreds of feet in aerial extent and several tens of feet in height. These bed-forms can be mobile and migrate across the seafloor during the life of marine structures and pile up or erode depending on the nature of the ambient current conditions. The morphology of the bedform can often be correlated with the energy of the ambient fluid environment. The presence of large scale bedforms in any prospective windfarm development area may be indicative of a high level of scour potential.

- **Bottom Currents and Scour.** Bottom currents can impart lateral and torsional loads to foundations; this effect is exacerbated when suspended sediment exists within the water column. Scour is more prominent in granular soils but worldwide evidence has shown that certain cohesive materials are also susceptible to this phenomenon. Scour can be broken down into two categories 1) global scour and 2) local scour. Global scour is the removal of a very large portion of the seabed (usually be regional hydraulic processes) whereas local scour is normally caused by the mere presence of some structure placed on, or embedding within, the seabed. Geometrical considerations, along with soil type, control the nature and extent of local scour. Scour is initiated when a soil particle begins to lift. This point of initiation occurs when the applied seabed stress, from passing fluid flow, exceeds the critical shear stress or inter-particle force keeping the soil particle bound to the seabed. These currents can erode or scour the material adjacent to, or beneath, the foundation. Suspended sediments can be abrasive in nature and when combined with high current velocities can wear away at foundation components. Typical geophysical surveys can delineate bed-forms that are at risk of active / passive seabed mobility.

- **Slope Instability.** A failure scenario where marine slopes undergo unacceptable movements. This geohazard is typically relevant to regions with one or more of the following characteristics (not a comprehensive list): 1) relatively large bathymetric gradients, 2) weak marine sediments, 3) relatively strong currents and waves, 4) nearby seismic activity, and 5) presence of shallow gas pockets. Slope instability can have major implications on various foundation systems including: a reduction of its vertical and/or lateral capacities as well as triggering additional movement of the foundations that can result in unacceptable operating conditions for the offshore wind turbines. Many slope instabilities had been reported along the Atlantic OCS over the years (e.g. Figure 5.10 in Hance and Wright, 2003). The majority of these are coincidental with the outer sloping edges / canyons of the Atlantic OCS.

- **Filled Channels**. Channel deposits are ordinarily infilled with less competent material. A typical sequence may consist of a fining upward sequence including clay atop silts, underlain by sands atop gravels. If foundations are founded within this sequence, unmitigated settlements may occur or more adversely, differential settlement may govern the foundation performance.

- **Complex Seabed Morphology.** Seabed morphology in shallow waters of the Atlantic OCS may reveal more complex structure when compared to deep-water morphology. This is premised on the elevated energy regimes that become more prevalent when water depth decreases. The effects of wind, waves and current are exacerbated in shallow waters. The net effect, especially in granular materials, is to have mobile bedforms that envelope, in some cases, the entire seabed. The proximity of the wind farm to continental outfalls (rivers, streams etc.) has an effect on these bedforms since the material may be derived from estuarine sources. Proximal and distal sedimentary facies, which are characterized by grain size/shape, specific gravity and mineralogy play a role in the determination of morphology continuity.

- **Shallow Gas.** Gas trapped in shallow sediments can be derived from biogenic activities or seeping upwards from a deeper gas reservoir source. If abundant, gas can initiate a blowout while drilling or driving piles through the gas charged sediments. Sediments with shallow gas tend to absorb P-wave energy because they are generally characterized by low compression. This can result in acoustic blanking in the seismic profiles (Kvalstad, 2007) which can assist in locating areas with shallow gas. Gas charged sediments can also enhance the signal strength of a horizon due to an increase in the relative difference in density / porosity.
- **Liquefaction.** A phenomenon in which the strength and stiffness of a soil is reduced by shaking induced by seismic activity or other rapid loading regime. Liquefaction occurs in relatively loose, coarse grained, saturated soils, that is, soils in which the space between individual particles is completely filled with water. Under rapid loading conditions, relatively loose sand particles tend to compress under undrained conditions. This results in an increase in pore water pressure that precipitates a major reduction in the shear strength of the soil. Liquefaction can lead to both vertical and horizontal displacement of a structure especially if the seabed is sloped.
- **Ice Gouging / Scour.** Seabed gouging by ice is a phenomenon where floating ice features (typically icebergs and sea ice ridges) drift into shallower areas where their keel comes into contact with the seabed. Maps showing iceberg pathways for eastern Canada show flow vectors predominantly in a NE-SW trend indicating potential movement along the US eastern seaboard. As they keep drifting, the keel imparts bulldozer forces into the seabed and creates furrows most often referred to as scours or gouges. Gouge widths can be on the order of 1000-ft whereas gouge length can be more than a mile. Typical depths are in the 0.5 to 3.0-ft range. Anything deeper than 6-ft most probably was caused by some form of extreme event. However, the high arctic in Canada has seen a few on the order of 30-NM in length and as deep as 25-ft. Upon contact with the seabed, a pressure ridge will develop and a certain influence zone below the seabed will be affected by the passing ice keel. Most infrastructure, such as pipelines and cables should be buried (at a minimum) well below the anticipated depth of the ice keel. Multibeam surveys can be used to delineate the presence and lateral extent of ice scours. Trend analysis can be undertaken; the results of which can be considered in the placement of foundations and electrical cables.
- **Seismicity.** The effects of seismic activity can be far reaching. Foundations can experience partial to full loss of bearing or sliding support, unmitigated differential movements or post-earthquake reduction in soil strength. Additionally, structural members may undergo repetitive loading which in turn can weaken structural connections, to the detriment of the foundation. Seismic loads can shake the structure

in two directions in the horizontal plane and in the vertical plane (up or down), simultaneously. Also, inertial loads from displaced water need to be accounted for in the foundation design. Seismic foundation design must also address the amount of damage that any particular foundation can sustain and still be operational.

Table 1.5. A list of geotechnical/geological site conditions for foundation type selection

Foundation Type	Favorable Conditions	Unfavorable Conditions
Piles*	-Can be installed in a wide range of soil conditions including weak to stiff fine grained sediments and loose to dense coarse grained materials -Uniformity in underlying strata	-Presence of boulders, cobbles, and coarse gravel -Calcareous soils: They exhibit variable strength characteristics under static and cyclic loads; they also can have high initial strength but low residual strength. They are often characterized by brittle sand grains bound by weak to strong cementation. This result in loss of bearing capacity due to the installation process and only partial increase of soil strength after installation. -Soils susceptible to the formation of pile down-drag conditions (See the glossary at the end of this report).
Suction caissons**	-Check Table 1.2 for details	-Check Table 1.2 for details
Gravity-based***	-Rock outcrops, highly OC clay, or dense sand -Flat, featureless seabed	-Highly variable near surface geology (e.g. paleo-channels) -Highly variable bathymetry -Weak near surface marine sediments -Nearby ports with shallow bathymetric soundings
Drag embedment anchors	-Installation in hard clays and sands result in higher holding capacity than soft clays -Homogeneous soil profiles -Shallow to deep water depths	-Interlayered soils of varying competencies -Rock and very hard near surface conditions -Variable seabed slopes over short distances…this can affect the drag portion of the installation since it is hard to maintain the fluke/shank reference angle

* Most of the conditions listed for piles are also applicable to the dynamically penetrating anchors
** Most of the conditions listed for suction caissons are also applicable to the suction embedded plate anchors (SEPLA)
***Most of the conditions listed for gravity-based foundations are also applicable to box anchors and grillage and berm anchors

1.6.2 Factor 2 – Water Depth

Water depth is one of the most important factors used to select a suitable foundation system. As water depth increases, the current, wave and wind loads typically increase; but this is not always the case. Moreover, the height of the foundation system increases to maintain the wind tower and turbine above water surface. Hence, water depth variation can change the size and nature of the stresses applied to the foundation system. Based on performance and cost, each foundation system is usually most suited for a specific range of water depths which can vary based on many geologic and environmental factors. Table 1.6 lists the typical water depth ranges where each foundation system is deemed viable. The listed foundation systems can be adapted, outside these depth ranges, if the project-specific circumstances dictate. The presence of reefs may act as an impediment to a viable foundation design.

Table 1.6. Water depth ranges where the foundation systems are generally feasible

Foundation System	Water Depth	Notes
Mono configuration (piles or caissons)	Up to 30 m (100 ft)*	-This category is for structures affixed directly to the seabed (i.e. not floating) -Suction caissons are feasible up to 40 m according to Ibsen et al. (2005)
Gravity-based	Up to 30 m (100 ft)*	-Some developers report the possibility of installing their gravity-based systems in waters up to 60 m (200 ft) deep (e.g. Gravitas Gravity Base).
Jackets	30 – 60 m (100 -200 ft)*	-Can be tripod or quadripod -Jacket can be founded on piles or suction caissons -pile depths can range from 20 to 50 m (66 to 164 ft)
Tripods	Up to 35 m (115 ft)**	-Can be founded on piles or suction caissons
Floating structures (anchors)	Deeper than 60 m (200 ft)*	-Some systems are reported to be cost effective starting from 35 m (115 ft) -The system can be anchored using piles or suction caissons as well as other anchor types

*Source: Musial et al. (2006)
**Source: E.ON Offshore Wind Energy Factbook (2012)

1.6.3 Factor 3 – Environmental Loads

Environmental loads (i.e. wind, current, wave, and ice; Figure 1.12) depend on the location of the project and water depth, among other factors. The environmental loads should be considered while choosing the foundation system. For example, if the foundation system is subjected to relatively high tensile, overturning moments, and/or lateral loads, gravity-based foundations are likely to be considered unsuitable. Table 1.7 presents some of the favorable and unfavorable conditions created on the structure from environmental loading for the different foundation types.

Table 1.7. A list of environmental loading conditions that influence foundation type choice

Foundation Type	Favorable Conditions	Unfavorable Conditions
Piles*	-Relatively high lateral, vertical and/or tensile loads	-Design shape can exacerbate scour potential by creating eddy currents around the pile base
Suction caissons**	-Effective for axial (downward and upward) loads	-Strong currents that increase the scour susceptibility -Locations where dense sands may be encountered -High lateral or eccentric loads
Gravity-based***	-Large vertical loads -High impact loads -Less susceptible to dynamic loading conditions	-Strong currents that increase the scour susceptibility -Seafloor sediments susceptible to local scour. Scour protection systems can be applied in this case
Drag embedment anchors	-High initiation or embedment loads	-Cyclic loading

* Most of the conditions listed for piles are also applicable to the dynamically penetrating anchors
** Most of the conditions listed for suction caissons are also applicable to the suction embedded plate anchors (SEPLA)
***Most of the conditions listed for gravity-based foundations are also applicable to box anchors and grillage and berm anchors used for floating systems

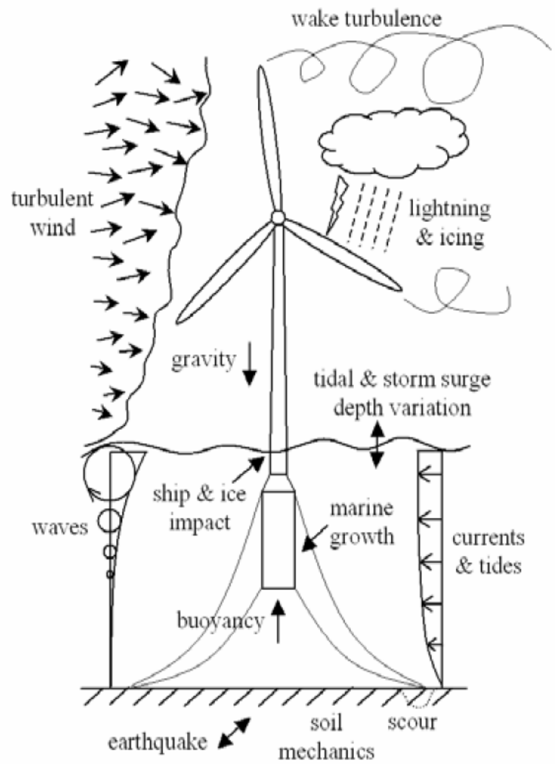

Figure 1.12. Sources of loading on offshore wind turbines
(Source: Butterfield et al., 2005)

1.6.4 Factor 4 – Size and Type of the Wind Turbines

As the size of the wind turbine increases (e.g., megawatt capacity, blade length, height above sea-level), the loads on the foundation system increase, which will affect the selected foundation system. Also, as the size and type of the wind turbine changes, its frequency of vibration will differ. Hence, various foundation systems and/or layouts may be required to ensure that the wind turbine system does not resonate and remains in operational compliance during extreme loading as well as operating conditions.

1.6.5 Factor 5 – Manufacturing, Installation and Maintenance Costs

Depending on the location of the project, the cost associated with manufacturing, installation, and maintenance of the foundation system can vary considerably. Hence, a developer should consider the overall initial and lifecycle (including removal, if required) costs associated with each foundation system when selecting the preferred option to move forward with. A single foundation solution is in most cases better, from a cost perspective, than various foundation designs. Nevertheless, some site-specific conditions might dictate using multiple foundation systems in different parts of the wind farm acreage. For example, a combination of monopiles and jackets were used in the EnBW Baltic 2 wind farm, offshore Germany, due to the large variability in water depths within the site. Monopiles were used up to a water depth up to about 35 m (115 ft) and jackets were used in deeper waters (*4C Offshore* website).

1.6.6 Factor 6 – Environmental Regulations

Environmental regulations can influence the choice of the foundation system. For example: piles could be discouraged if the noise and vibrations associated with the pile driving installation process are deemed unacceptable (e.g. negatively impact marine mammals); or gravity-based foundations could be discouraged if the foundation footprints are so large that they negatively impact marine life habitats. Gravity-based foundations could be discouraged if the negative environmental impact is considered too high to warrant any one particular foundation type.

1.7 PLANNING FOR A SUCCESSFUL SITE INVESTIGATION CAMPAIGN

There are many advantages and disadvantages surrounding the individual components to a successful site investigation program. There are various legitimate reasons to employ integrated geophysical and geotechnical investigation approaches. The most important reason is the obvious advantage of using results from the geophysical data to plan/advantageously place geotechnical explorations in optimal locations to characterize the variable conditions within the project area. This advantage might not be possible if geophysical and geotechnical campaigns are conducted in parallel, unless enough resources from the geophysical and geotechnical sides are deployed so that the geophysical data is processed and interpreted in near real time and the geotechnical team works constantly on updating the geotechnical plan to accommodate the information provided from the geophysical part. This option is rarely feasible depending on the available resources, experience of the project team, and complexity of site conditions. On the other hand, conducting both investigations in sequence will result in much larger time windows to plan and design the geotechnical investigation. If the favorable weather window for offshore investigations is narrower than the investigation window, the investigations should be split between two years/seasons or multiple vessels need to be deployed simultaneously. Operating multiple vessels in the same site impose additional risks that should be assessed carefully by an experienced professional. It is important to note that preparing a site investigation campaign can be a challenging process because it encompasses many of variables that need to be accounted for during the planning stage and updated, whenever necessary, while conducting the field work. Since each project is unique, the optimum investigation plan will be unique for each project.

This section introduces three different site investigation approaches that could be adopted for offshore wind farms. The benefits and risks associated with each plan will be discussed in this section. However, other Volumes in this study will reference these three approaches and provide additional discussion where appropriate. The provided plans are not and cannot be comprehensive. The benefits and risks of these plans, as well as other plans, should be carefully evaluated in light of project-specific information by a geotechnical engineer and a geoscientist with extensive experience in the offshore industry. Hence, the guidelines presented in this document are presented for guidance purposes only and are not intended to replace the professional experience.

1.7.1 Single Investigation / Survey

In this scenario, the plan is prepared such that the geophysical and geotechnical investigations are conducted in a single season/year. Depending on the favorable weather window for offshore investigations, the complexity of subsurface conditions, and the size of the wind farm, multiple vessels might be needed to execute the investigation plan. It is standard practice to allow one to two months between the geophysical survey and the geotechnical investigation program to allow sufficient time for processing geophysical data collected and obtain clearance from archeological experts to conduct geotechnical (intrusive) investigations. Hence, it is highly unlikely that the geophysical and geotechnical investigations will be undertaken in the same season.

Advantages. Conducting a single survey has the following advantages: 1) geotechnical and geophysical investigations can be completed in one season (or two subsequent seasons) which would help expedite the overall wind farm development process; and 2) the geophysical surveys will provide the geotechnical team with much detail across the whole project area. This allows for a more-informed decision making process throughout the campaign.

Disadvantages. 1) If the full lease area will not be fully developed during a single go-around, then some areas may be unnecessarily surveyed; 2) it may be necessary to utilize multiple vessels to complete the investigations in one summer season (or two subsequent summers). Managing multiple vessels, working simultaneously, in the same area includes logistical challenges that can negatively affect the entire campaign if not managed properly by an experienced professional, 3) it would require a significant capex to complete, and 4) since all data is collected in a single phase, it limits the possibility of applying changes to the planned geotechnical site investigation (type, number and locations of in-situ tests and sampling protocols) and / or considering different foundation systems as more information is available to the geotechnical team.

1.7.2 Phased Approach

Conducting site investigations using a phased approach allows for some flexibility in how and when the wind farm is developed. Hence, it has many advantages when compared with the single phase approach. The main advantages are as follows:

- Distribute capex costs over more than one year. This is especially beneficial if the developer plans to develop the lease area in separate geographic phases.
- Use the survey information to provide input into how they develop a lease area. Higher risk areas and lower cost areas may be identified and incorporated into the phased development plans to mitigate risk and reduce construction and O&M costs.
- Begin gathering site information in parallel to other initial planning stages which allows the geotechnical and geophysical teams to update the exploration protocols in the light of information collected in preliminary phases.
- In the case of geophysical surveys, BOEM has provided line spacing requirements for high resolution geophysical surveys that support site characterization studies and line spacing for marine archaeologic resource assessment surveys. Line spacing (30-meter primary by 500-meter tie lines) is significantly tighter for marine archaeology surveys than for high resolution geophysical surveys (HRG; 150-meter

primary line by 500-meter tie lines). If a phased approach is adopted, developers will not be required to conduct a survey for the full commercial lease area during one survey that meets BOEM's HRG and marine archaeology survey requirements. Instead, geophysical surveys can be conducted along a coarse grid in the first year. Once a certain area is selected for constructing the wind farm, more detailed geophysical surveys that meet BOEM's requirements can then be conducted within the area selected for development rather than the whole lease area.

In this section we present two phased investigation approaches. Both assume a timeline of two years for the geophysical and geotechnical investigations.

- **Phased Approach (Scenario A).** In this approach, Season 1 geophysical surveys are conducted along an equally-spaced grid based on a 150-meter line spacing multiplier, such as 900 meter by 900 meter. 150 meters is equal to the minimum line spacing requirement for HRG surveys and is a multiplier of the 30-meter line spacing requirement for marine archeology surveys. The equally spaced lines would provide some flexibility to the Developer for layout out their turbine locations. During Season 2, the design level survey that would meet COP requirements would be completed.

In Scenario A, the number of geotechnical explorations (borehole and/or CPT) conducted in the first year equals about 10-15% of the number of planned wind turbines. The locations of these explorations should be selected based on the collected geophysical data. If the water depth varies considerably within the lease area, it is good practice to conduct the different exploration points in different water depths. In sites that are found to be homogeneous, the site is divided into regions with equal area in a manner to have one field exploration in each of these regions. These geotechnical explorations are typically extended two to four times the foundation diameter below the foundation design tip elevation. In this scenario, the retrieved samples are used to conduct classification tests, shear strength tests, and few cyclic/dynamic tests. The objective of applying this scenario is to collect enough data in the first year to conduct preliminary analyses of the foundation system(s). These preliminary analyses are then used to refine the explorations and laboratory tests conducted in the second campaign to optimize the design of the foundation system(s).

- **Phased Approach (Scenario B).** The amount of information collected in the first year in this scenario is considerably less than the information collected as part of Scenario A presented above. A regional geophysical survey is conducted during the first year as part of this scenario. Different line spacing for primary and tie lines (e.g. 1.5 km by 3 km) that work on a 150 meter and 30-meter multiplier would be adopted. During the second year of the survey, the remaining lines required to complete the design and satisfy COP requirements would be completed. The number of geotechnical explorations (borehole and/or CPT) conducted in the first year equals about 4-6% of the number of planned wind turbines. The locations of these explorations should be selected based on the collected geophysical data. In this case, the retrieved samples are used to conduct classification tests and some strength tests. In this scenario, the cyclic tests are conducted on samples collected as part of the second campaign. Hence, the preliminary analyses of the foundation systems are less detailed compared to scenario A presented above.

- **Scenario A versus Scenario B.** 1) Scenario A allows for more flexibility of placing turbines on line intersections in the future if the wind turbine array orientation is not known at the time compared to Scenario B; 2) Scenario A provides a more complete picture of site conditions during the first year of investigation; 3) the availability of test results from cyclic laboratory tests in the first campaign of Scenario A allows for a detailed preliminary design of the foundation system. This allows the project team to optimize the foundation design using the data collected during the second year's campaign; and 4) on the other hand; Scenario A requires more line kilometers of geophysical data to be collected and more expensive laboratory tests during the first year.

1.7.3 Typical Duration of Offshore Site Investigation Program

Many parameters play a role in determining the duration of an offshore site investigation program. These parameters include size of the wind farm; number, depth and type of investigations; weather conditions; vessel type; among many other parameters. Hence, several assumptions should be considered while reporting typical duration times.

In providing typical duration times for geophysical and geotechnical investigations in this report we assume a typical offshore wind farm that includes one hundred (100) 6-MW turbines founded on monopiles. We also assume typical ranges for standby weather time and production rates. It is important to note that the weather standby and production rates can vary considerably between different projects. Hence, the information provided in this section is for illustration purposes only and should not be assumed to be suitable for budgetary planning and scheduling of future developments.

It may take one vessel on the order of 300 to 400 days (inclusive of 30% weather standby) to complete the geophysical survey at the most restrictive line spacing (marine archaeology survey) with 24-hour operations. The phased approaches will significantly reduce the number of survey days in Season 1. Season 2 survey days would likely be reduced from those shown in Table 1.8, since sections of the lease area would likely not be surveyed because the developer decided not to build it an area out or would defer to a future phase of development. Table 1.8 presents a summary of how survey work could be distributed using the different approaches.

Table 1.8. Geophysical Investigation

Operation Type	Duration of Site Investigation (days)				
	Single Phase	2-Phased (Scenario A)		2-Phased (Scenario B)	
		Season 1	Season 2	Season 1	Season 2
24-Hour Day Operations	300 to 400	25 to 35	275 to 370	10 to 20	290 to 380

Table 1.9 presents typical durations for geotechnical investigations for the hypothetical offshore wind farm described above. It is clear from the table that the vessel type can have a strong impact on the duration. Hence, the duration of the program is an additional factor to account for while selecting the vessel type beside the cost and availability of the vessels. It is

also important to note that the duration window can vary considerably depending on the project-specific characteristics (e.g. foundation system and weather conditions). Hence, these characteristics should be carefully evaluated to decide during the planning stage whether more than one vessel is necessary.

Table 1.9. Geotechnical Investigation

Vessel Type	Duration of Site Investigation (days) - Assuming One Vessel				
	Single Phase	2-Phased (Scenario A)		2-Phased (Scenario B)	
		Season 1	Season 2	Season 1	Season 2
DP	120-235	20-35	105-210	10-20	115-225
Jack-up	225-350	30-50	200-310	15-20	215-345
Anchored	135-255	20-40	120-225	10-20	130-245

1.8 GLOSSARY

down-drag: Down-drag is a condition that occurs in piles founded in soft compressible soils. In some cases, the settlement of the soft soil is more than the downward movement of the pile along a certain length of the pile. The force applied by the soil along this portion of the pile is downward. This increase the loads on the piles and more importantly results in a considerable increase in settlement that can impact the pile integrity, if not correctly accounted for.

drag embedment anchors: Drag embedment anchors are employed in the same manner that anchors from surface vessels are. They generally weigh a few tons up to tens of tons and have a variety of configurations with various dimensions and fluke/shank angles selected for their specific embedment characteristics. They are installed by dragging across the seabed until they embed into the seafloor.

dynamically penetrating anchors: These anchors are dropped to the seafloor and utilize their mass and kinetic energy to penetrate the seabed; they rely on side friction and reverse end bearing for resistance.

fatigue: Pile fatigue usually occurs after multiple cycles of loading and can affect the strength of the steel, thereby reducing its lifespan.

Soil fatigue can be described as a reduction in soil strength over repeated cycles that occur relatively slowly. However, high frequency cycles with high loads can actually increase the soil strength but generally only temporarily.

fissured: Fissured clay is usually firm to stiff but as the name implies contains cracks which can result in differential, or reduced, strength.

J-Tubes (hang-off electrical conduits): Rigid, cylindrical tubes that protect the electrical cables where they leave the turbine foundation and connect to the seafloor.

resonance: Resonance is the tendency of a mechanical system to respond at greater amplitude when the frequency of its oscillations matches the system's natural frequency of vibration (its resonance frequency or resonant frequency) than it does at other frequencies. This can lead to fatigue and subsequent failure, over time.

SEPLA: Suction embedded plate anchor. A suction pile is used to drive the plate anchor to a pre-defined penetration depth after which the pile is extracted and the anchor proof-loaded.

SPAR:	Type of floating platform typically used in very deep water. It consists of a single cylinder that supports the wind turbine and is permanently anchored to the seabed via a three or four, anchor spread.
stick-up:	Stick-up of a suction caisson is defined as the portion of the caisson that remains above the seabed after final embedment is achieved.
tension leg platform (TLP):	Tension legged platform. A series of vertical cables or tendons are affixed to the seabed via piles loaded in the vertical tension.

1.9 REFERENCES

4C Offshore Website: http://www.4coffshore.com/.

AARSLEFF Website: http://www.aarsleff.com/referencer/ref/Nysted%20Offshore%20Wind%20Farm.

American Bureau of Shipping (2014a). “Bottom-Founded Offshore Wind Turbine Installations,” Published January 2013, Updated July 2014.

American Bureau of Shipping (2014b). “Floating Offshore Wind Turbine Installations,” Published January 2013, Updated July 2014.

American Petroleum Institute (2011). “Geotechnical and Foundation Design Considerations, ANSI/API,” Recommended Practice 2GEO, First Edition, April 2011, API, Washington, D.C.

Andersen, K.H. (2004). “Cyclic Clay Data for Foundation Design of Structures Subjected to Wave Loading,” Cyclic Behavior of Soils and Liquefaction Phenomena, Triantafyllidis, T (Ed.), London, UK: Taylor & Francis Group.

Bhattacharya, S., Cox, J.A., Lombardi, D., and Muir Wood, D. (2012). “Dynamics of Offshore Wind Turbines Supported on Two Foundations,” Proceedings of the Institution of Civil Engineers Geotechnical Engineering 166 April 2013 Issue GE2 Pages 159–169 http://dx.doi.org/10.1680/geng.11.00015 Paper 1100015.

Butterfield, S., Musial, W., Jonkman, J., Sclavounos, P. (2005). “Engineering Challenges for Floating Offshore Wind Turbines,” Copenhagen Offshore Wind Conference, Copenhagen, Denmark October 26–28, 2005.

Det Norske Veritas (2016). “DNVGL-ST-0126 – Support Structures for Wind Turbines,” dated 2016-04-01.

Duncan, J.M., and Wright, S.G. (2005). “Soil Strength and Slope Stability,” John Wiley & Sons.

E.ON. (2012). “E.ON Offshore Wind Energy Factbook,” E.ON Climate & Renewables – September 2012.

Erbrich, C.T. and Tjelta T.I. (1999). “Installation of bucket foundations and suction caissons in sand: geotechnical performance,” Offshore Technology Conference, Houston, TX, 1999, Paper OTC 10990.

EWEA (2013). “The European Offshore Wind Industry – Key Trends and Statistics 2012,” A report by the European Wind Energy Association, dated January 2013.

Garrison, L.E. (1970) “Development of Continental Shelf South of New England,” The American Association of Petroleum Geologists Bulletin, Vol. 54, No. 1, pp. 109-124.

Hance, J.J., and Wright, S.G. (2003). “Submarine Slope Stability,” Project Report Prepared for the Minerals Management Service Under the MMS/OTRC Cooperative Research Agreement - Task Order 18217 - MMS Project 421.

Houlsby, G. T., Ibsen, L.B., and Byrne, B.W. (2005). “Suction Caissons for Wind Turbines,” Frontiers in Offshore Geotechnics: ISFOG 2005 – Gourvenec & Cassidy (eds), Taylor & Francis Group, London, ISBN 0 415 39063 X.

Houlsby, G. T. and Byrne, B. W. (2005a) “Design Procedures for Installation of Suction Caissons in Clay and Other Materials”, Proc. ICE, Geotechnical Eng., Vol. 158 No. GE2, pp 75–82.

Houlsby, G. T. and Byrne, B. W. (2005b) “Design Procedures for Installation of Suction Caissons in Sand”, Proceedings ICE, Geotechnical Eng., Vol. 158 No. GE3, pp 135–144.

Ibsen, L.B., Liingaard, M., and, Nielsen, S.A. (2005). “Bucket Foundation, a status,” Proc. Copenhagen Offshore Wind Conference, Copenhagen, Denmark.

ISO-19902. “Petroleum and Natural Gas Industries – Fixed Offshore Structures”.

Junginger, M., Faaij, A., and Turkenburg, W.C. (2004). "Cost Reduction Prospects for the Offshore Wind Farms," Wind Engineering, 28:1, 97–118.

Kaiser, M.J., and Snyder, B.F. (2012). “Chapter 2: Offshore Wind Energy System Components,” Offshore Wind Energy Cost Modeling, Installation and Decommissioning, Green Energy and Technology, Springer-Verlag London.

Keer, F.R., and Cardinell, A.P. (1981). “Potential Geologic Hazards and Constraints for Blocks in Proposed Mid-Atlantic OCS Oil and Gas Lease Sale 59,” United States Department of the Interior, Geological Survey, Open-File Report 81-725.

Kvalstad, T.J. (2007). “What is the Current “Best Practice” in Offshore Geohazard Investigations? – A State-of-the-Art Review,” Proceedings of the 2007 Offshore Technology Conference, Houston, TX.

Landon Maynard, M. and Schneider, J. (2010). “Geotechnics for developing offshore renewable energy infrastructure industries in the US,” 2nd Int. Symp. on Frontiers in Offshore Geotechnics (ISFOG), University of Western Australia, Perth, Western Australia, 8-10 November.

LORC Website: http://www.lorc.dk/.

Moore, D.G. and Curray, J.R. (1963). “Sedimentary framework of the continental terrace off Norfolk, Virginia and Newport, Rhode Island,” American Assocation of Petroleum Geologists Bulletin, Vol. 47, No. 12, pp. 2051-2054.

Musial, W., Butterfield, S., and Ram, B. (2006). “Energy from Offshore Wind,” Proceedings of the 2006 Offshore Technology Conference, Houston, TX.

Nguyen-Sy, L. (2005). “The Theoretical Modelling of Circular Shallow Foundation for Offshore Wind Turbines,” Doctoral Dissertation, The University of Oxford, Oxford, England

NORSOK G-001. “Marine Soil Investigations,” Standards Norway.

Rahim, A., and Stevens, R.F. (2013). “Design Procedures for Marine Renewable Energy Foundations,” Proceedings of the 1st Marine Energy Technology Symposium, METS13, April 10-11, Washington, D.C.

Randolph, M., and Gourvenec, S. (2011). “Offshore Geotechnical Engineering,” Spon Press, 520 pages.

Robertson, A.N., and Jonkman, J.M. (2011). “Loads Analysis of Several Offshore Floating Wind Turbine Concepts,” International Society of Offshore and Polar Engineers 2011 Conference, Maui, Hawaii, June 19-24, 2011.

Schneider, J.A., Landon Maynard, M., Senders, M. (2010). “Geotechnical Engineering for Offshore Wind Turbine Foundations,” Sea Technology, 51(9), 29-33.

Schneider, J.A., and Senders, M. (2010). “Foundation Design: A Comparison of Oil and Gas Platforms with Offshore Wind Turbines,” Marine Technology Society Journal, 44: pp 32-51.

Sif Group Website: http://sif-group.com/en/references/wind-references.

Swift, D.J., Duane, D.B., and Field, M.E. (1981), "Evolution of a classic sand ridge field: Maryland sector, North American inner shelf," *Sedimentology*, vol.28, p. 461-482.

The Crown Estate. “A guide to an Offshore Wind Farm,” Published on behalf of The Crown Estate: http://www.thecrownestate.co.uk/media/5408/ei-a-guide-to-an-offshore-wind-farm.pdf.

Uchupi, E. (1970). “Atlantic Continental Shelf and Slope of the United States - Shallow Structure,” USGS Professional Paper 529-I.

United States Army Corps of Engineers (USACE) (2014). “Charleston Harbor Post-45 Deepening Feasibility Study, Appendix B Geotechnical Report.” Report issued May 11, 2015 by USACE Charleston District, South Carolina.

United States Army Corps of Engineers (USACE) (2007). “Supplemental Studies to Determine Potential Ground-water Impacts to the Upper Floridan Aquifer, Savannah Harbor Expansion Project.” Final Report issued June 2007 by USACE Savannah District, Georgia.

VOLUME 2

GEOPHYSICAL SURVEYS BENEFITS AND RISKS

Study Title:

Geophysical and Geotechnical Investigation Methodology Assessment for Siting Renewable Energy Facilities on the Atlantic OCS

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2.1 GEOPHYSICAL DATA TYPES

2.1.1 General Overview

Geophysical surveys are required as part of the Site Assessment Plan (SAP), Construction Operations Plan (COP), and General Activities Plan (GAP) in accordance with Title 30 of the Code of Federal Regulations Part 585 (CFR 585). Data collected during the surveys are also used to support the NEPA analysis. The site characterization surveys are used to support the preparation of the Facility Design Report and Fabrication and Installation Report which are reviewed and certified by a Verification Agent (CVA). Survey methodology and application of the geophysical data used to support the facility design and installation reports will be qualified by the CVA using relevant guidance and standards.

Geophysical surveying supports three general types of studies in the offshore wind development process: engineering, environmental, and marine archaeological. This study focuses on high-resolution geophysical (HRG) surveys that are used to support engineering studies. However, this report also describes where engineering geophysical data may be multi-purposeful and can be used to support environmental and/or archaeological studies.

Objectives of geophysical surveys in support of engineering studies include characterization of site conditions and geologic constraints, and evaluating potential geohazards. Site conditions characterized through geophysical surveys typically include water depth, seafloor morphology, seafloor sediments, and subsurface geology. Examples of shallow geohazards evaluated using geophysical data include sediment transport, boulders, shallowly buried paleochannels infilled with soft sediments, slope instability, faulting, and gas seep/shallow gas.

Geophysical surveys for engineering studies are used to perform seafloor mapping and sub-seafloor investigation. A variety of remote sensing techniques can be utilized to provide comprehensive characterization of the site conditions. Equipment type and survey design should be selected to the suit the site conditions and project needs (e.g. anticipated foundation embedment depth).

Environmental or biological surveys investigate for the presence of live bottoms, hard bottoms, topographic features of interest, and surveys of other marine resources such as fish populations, marine mammals, sea turtles and sea birds.

Archaeological resource assessment surveys also implement geophysical survey technology to investigate for the potential historic and prehistoric archaeological resource, as required by the National Historic Preservation Act (NHPA) of 1966.

Some useful guidance documents for marine surveying include:

- Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585, BOEM, July 2015
- Guidelines for Providing Archaeological and Historic Property Information, Pursuant to 30 CFR Part 585, BOEM, July 2015

- Guidelines for Submission of Spatial Data for Atlantic Offshore Renewable Energy Development Site Characterization Surveys, BOEM, February 2013
- IHO Standards for Hydrographic Surveys, Special Publication No. 44, International Hydrographic Organization, 2008
- Hydrographic Surveying Engineering Manual EM10-2-1003, United States Army Corps of Engineers
- Marine Geophysics Data Acquisition, Processing, and Interpretation Guidance Notes, English Heritage, 2013
- Geotechnical & Geophysical Investigations for Offshore and Nearshore Developments, International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), September 2005
- Guidance Notes for the Planning and Execution of Geophysical and Geotechnical Ground Investigations for Offshore Renewable Energy Developments, Society for Underwater Technology, May 2014.
- Recommended Practice DNV-RP-J301, Subsea Power Cables in Shallow Water Renewable Energy Application, DNV, 2014
- Standard for Geotechnical Site and Route Surveys, Minimum Requirements for the Foundation of Offshore Wind Turbines, BSH, 2003
- International Cable Protection Committee (ICPC) Recommendations 1 through 14
- Assessment and Management of Unexploded Ordnance (UXO) Risk in the Marine Environment, CIRIA, 2015

2.1.2 Seafloor Mapping

Seafloor mapping is typically conducted by performing bathymetric, side scan sonar, seismic and magnetometer surveys. Those types of surveys are used to measure the water depth, investigate seafloor conditions, and locate potential objects (e.g. shipwreck) on the seafloor. Seafloor mapping data can be collected to provide “full data coverage” (e.g. side scan sonar and swath bathymetry) of the wind farm area or the data can be collected along discrete survey lines (e.g. magnetometer data).

Although line spacing requirements are provided in BOEM’s G&G and Archaeological Survey Guidance documents (BOEM 2015a and 2015b, respectively), in shallow water areas, it may be necessary to survey at closer line spacing to attain full coverage for swath bathymetry and/or side scan sonar surveys.

Since bathymetry surveys have a smaller swath footprint than side scan sonar surveys, bathymetry surveys usually require the closest line spacing. Common approaches in shallow waters for attaining full coverage employ either closer line spacing and collect with all systems or will go back and run bathymetric infill lines to infill where there are data gaps. Bathymetric line spacing requirements can be determined by conducting a performance test to determine the swath width that will meet the data accuracy and precision requirements provided in the G&G Guidance document (BOEM, 2015). The G&G Guidance document recommends that data should be consistent with the International Hydrographic Organization (IHO) Special Order survey standards from 0 to 40-meter water depths and with 1a survey standards beyond 40-meter water depth (IHO Standards for Hydrographic Surveys, 2008).

2.1.3 Bathymetry

Bathymetry data are collected to measure the water depth and used to develop highly informative seafloor elevation models. Accurate water depths are important for the design of wind turbines and are used to help determine various design parameters (e.g. superstructure height, landing ladder, etc.) and loading conditions. Seafloor elevation models are used to evaluate seafloor morphology (e.g. presence of sand waves), seabed conditions, anthropogenic hazards, and geohazards.

Using swath bathymetry to obtain full bathymetric data coverage is encouraged in the G&G Guidance document and is considered to be the state of the practice in European offshore wind farms and internationally in large marine infrastructure projects. Swath bathymetry can be collected using either a multibeam echosounder or an interferometric system. Figure 2.1 presents a comparison of data collected by the two systems. BOEM recommends that bathymetric surveys meet IHO Special Order requirements for water depths up to 40 meters and Order 1a requirements for water deeper than 40 meters (IHO, 2008). BOEM also recommends the use of system that can produce gridded data with resolution of at least 0.5 meter in water depths shallower than 50 meters and 1 meter or better than 2 percent of water depth resolution in water depths beyond 50 meters. Table 2.1 summarizes the horizontal and vertical accuracy requirements for bathymetric surveys.

Table 2.1. Calculated Bathymetry Survey Standards at Varying Water Depths Typical of the Atlantic OCS*

Water Depth (m)	IHO Order	Maximum Allowable THU[1] (m) 95% Confidence level	Maximum Allowable TVU[2] (±m) 95% Confidence level	Minimum Required Feature Detection (m)[3]	Gridded Data Resolution (m)
Less than 6	Special Order	2.00	0.25 (approximately)	1.0	0.5
10	Special Order	2.00	0.26	1.0	0.5
15	Special Order	2.00	0.27	1.0	0.5
20	Special Order	2.00	0.29	1.0	0.5
25	Special Order	2.00	0.31	1.0	0.5
30	Special Order	2.00	0.34	1.0	0.5
35	Special Order	2.00	0.36	1.0	0.5
40	Special Order	2.00	0.39	1.0	0.5

Water Depth (m)	IHO Order	Maximum Allowable THU[1] (m) 95% Confidence level	Maximum Allowable TVU[2] (±m) 95% Confidence level	Minimum Required Feature Detection (m)[3]	Gridded Data Resolution (m)
45	Order 1A	7.25	0.77	4.5	0.5
50	Order 1A	7.50	0.82	5.0	1.0
55	Order 1A	7.75	0.87	5.5	1.1
60	Order 1A	8.00	0.93	6.0	1.2
65	Order 1A	8.25	0.98	6.5	1.3
70	Order 1A	8.50	1.04	7.0	1.4
75	Order 1A	8.75	1.10	7.5	1.5
80	Order 1A	9.00	1.15	8.0	1.6
85	Order 1A	9.25	1.21	8.5	1.7
90	Order 1A	9.50	1.27	9.0	1.8
95	Order 1A	9.75	1.33	9.5	1.9
100	Order 1A	10.00	1.39	10.0	2.0

*Calculations based on recommendations of BOEM (2015a) with reference to IHO (2008) standards.

[1]**Total Horizontal Uncertainty**: The contributions of both the systematic and random components of uncertainty affecting the positioning of a sounding or feature. Assuming a normal distribution of error about the true value for this 2-D quantity, a 95% confidence level is defined as 2.45 x standard deviation. For IHO Special Order specifications, the THU is 2 meters and for IHO Order 1a, the THU is equal to 5 meters +5% of the depth.

[2]**Total Vertical Uncertainty**: The contributions of both the systematic and random components of uncertainty of the reduced depths (the observed depths after corrections related to the survey, post processing and adjustment to a vertical datum). Assuming a normal distribution of error about the true value for this 1-D quantity, a 95% confidence level is defined as 1.96 x standard deviation. Since there are both constant and depth dependent uncertainties that affect the uncertainty of depth, the maximum allowable TVU is calculated using two parameters (a and b) along with the water depth (d). The parameter "a" represents the constant uncertainty and the coefficient "b" is the uncertainty which varies with depth. TVU for a specific depth is equal to $\pm\sqrt{(a^2+(b \cdot d))}$. For IHO Special Order specifications, the TVU is calculated using a = 0.25 meters and b = 0.0075 and for IHO Order 1a, the TVU is calculated using a = 0.5 meters and b = 0.013.

[3]**Feature detection:** For IHO Special Order specifications, the required feature detection is 1 meter and refers to a cubic feature that has equal sides. For IHO Order 1a, beyond a depth of 40 meters, the feature detection requirement (in meter cubes) is equal to a value of 10% of the depth.

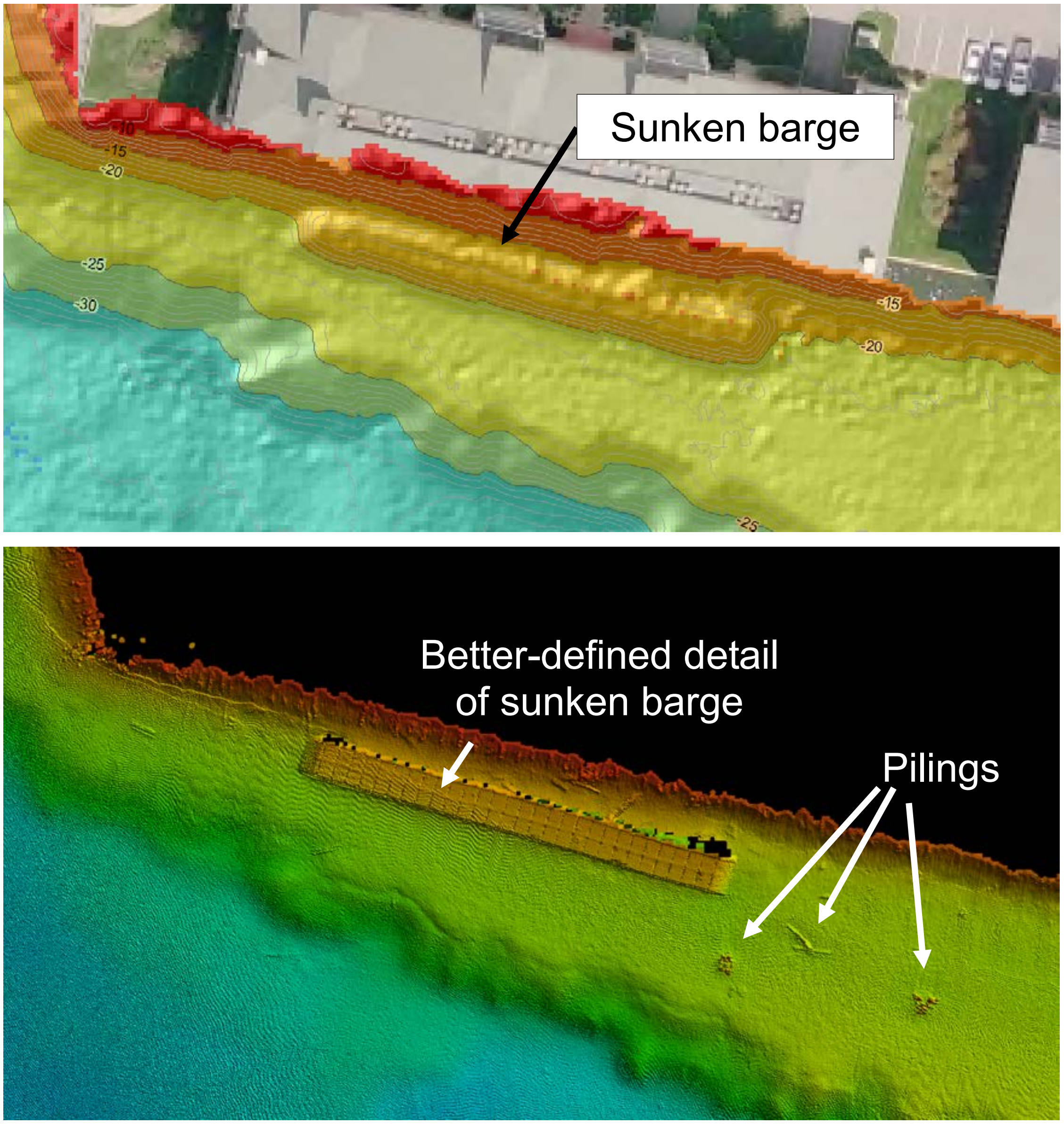

Figure 2.1. Comparison of bathymetric data density

Upper image was collected using an interferometric system and the lower image was collected using a beam-forming system. Note the improved detail of the sunken barge and pilings in the lower image that has a higher data density than the upper image. Water depth where barge is located is approximately 6m and then deepens to approximately 10m in the lower portion of the images (Source: Mitchell and Smith, 2014).

Beam-forming systems (multibeam) generally provide high accuracy but limited resolution across a narrow angle limited swath. Interferometric systems provide high resolution across a wide swath but with limited accuracy and poor performance at nadir. Newer interferometric systems however have addressed some of these issues, especially multipath and nadir performance issues.

Multibeam echosounders use a beam-forming technique to ensonify the seafloor. The recorded travel time for the beams are converted to distance or water depth. The resolution of a multibeam system largely depends on the number of beams used, beam separation angle, frequency of acoustic energy, and update rates. Multibeam systems also provide co-registered bathymetry and backscatter intensity measurements that can be used to simulate side scan sonar. Swath widths can be approximately 3 to 5 times the water depth and meet IHO Special Order requirements.

Interferometric systems were developed for use in collecting swath bathymetry in shallow water environments. Interferometric systems use phase differencing between arrival times at a receiver array to calculate the beam's direction and depth. Interferometric systems also provide co-registered side scan sonar imagery with bathymetry as opposed to the backscatter available with multibeam systems and higher resolution sonar imagery is achievable using longer transducer arrays. Swath widths can be approximately 6 to 12 times the water depth and meet IHO Special Order requirements.

Single beam echosounders collect a water depth measurement directly beneath the sensor. This technology was developed in the 1940's and used as the primary means of hydrographic surveying until the multibeam technology was developed in the early 1990's. Although water depth measurements are considered to be accurate, data density and the ability to define seafloor elevation variability across tracklines is related to the survey line spacing. Irregular seafloor areas and important features such as sand waves or boulders are difficult to interpret and characterize with single beam echosounders.

Table 2.2 summarizes the advantages and disadvantages of the various systems as applied to different water depths.

Table 2.2. Bathymetric Survey Systems

<table>
<tr><th>Foundation Type</th><th>Monopile
Water Depth Range ≤30m</th><th>Jacket/Tripod/Suction Caisson
Water Depth Range = 30 to 60m</th><th>Floating Turbine
Water Depth Range ≥60m</th></tr>
<tr><td rowspan="2">Multibeam</td><td colspan="3">Advantages:
*Accurate water depth and detailed seafloor bathymetry
*Backscatter intensity can be acquired with same MBES to provide additional bottom type information</td></tr>
<tr><td>Disadvantages:
*May require survey infill lines where water depth is very shallow</td><td>Disadvantages:
*May require dual head sensor if detailed information needed of seafloor (e.g. evaluate presence of boulders)</td><td>Disadvantages:
*May require dual head sensor if detailed information needed of seafloor (e.g. evaluate presence of boulders)</td></tr>
<tr><td>Interferometric</td><td>Advantages:
*Can be used in very shallow water where full coverage swath bathymetry is not efficient
*Typically used in <20m water depth
*Can be used to create side scan-like image of seafloor
Disadvantages:
*Does not provide detailed information about seafloor conditions
*Data gap in between vessel tracklines</td><td>Limitation
*Lower data density than MBES system
*Typically used in <20m water depth</td><td>Limitation
*Exceeds typical water depth</td></tr>
<tr><td rowspan="2">Single Beam</td><td>Advantages:
*Can be used in very shallow water (<5m) where full coverage swath bathymetry is not efficient
*Lower cost to acquire and process than swath bathymetry</td><td>Advantages:
*Lower cost to acquire and process than swath bathymetry</td><td>Advantages:
* Dual frequency SBES can be used to define seafloor if very soft materials are present (e.g. definition of nepheloid layer)
*Lower cost to acquire and process than swath bathymetry</td></tr>
<tr><td colspan="3">Disadvantages:
*Does not provide detailed information about seafloor conditions
*Data gap in between vessel tracklines</td></tr>
</table>

2.1.3.1 Multi-Purpose Potential for Bathymetry Data

High resolution bathymetric data provide valuable information that can be used to evaluate seafloor conditions and morphology, geohazards, and anthropogenic hazards. Detailed elevation models can be used to map sand waves, irregular seafloor areas, hard bottoms, rock out crops, boulders, and gas escape features. These models can also be used to identify anthropogenic hazards or shipwrecks exposed at the seafloor. Seafloor penetrating survey systems such as seismic reflection or magnetometers are required to investigate for shipwrecks, hazards or features buried below the seafloor.

2.1.3.2 Biological Surveys

Backscatter (BS), or reflected energy from seabed mapping systems, can be used to ascertain the spatial distribution of seafloor sediments, define benthic communities, assist with archeological studies and map shipwrecks or other cultural features (Lurton et al., 2015). Many research institutions, throughout the industry, have assimilated their findings and developed guidelines and recommendations surrounding backscatter measurements acquired by seafloor mapping systems (GEOHAB, 2015). Institutions such as UNB in Canada and UNH in the USA, are leaders in this endeavor. Sixty-five to eighty percent of backscatter applications consist of marine habitat mapping and seafloor sediment type assessment. Each of which can be beneficial to site characterizations undertaken within the Atlantic OCS. However, the processing of backscatter, in a reliable and repeatable manner, is one of the most arduous tasks in marine survey data processing for a number of reasons.

Unlike the well-established standards (e.g., IHO Standards) used in the collection of bathymetric data, the propagation of uncertainty in backscatter data is not as well understood nor is it as well documented. As with most geophysical techniques, measurement errors result from the acquisition parameters used and the type of equipment utilized. Certain vessels are built to acquire geophysical data with high precision and accuracy with a well-calibrated navigation system. Often vessels of opportunity are used in the acquisition of backscatter data whereby backscatter equipment is attached (e.g., pole-mounted) to a ship with unknown positioning accuracy. Positioning methods, the assortment of acquisition systems and the variable methods of data processing all propagate errors in the resulting backscatter imagery which make it very difficult to test data repeatability.

Backscatter is primarily acquired through multibeam echo sounding (MBES) data acquisition; BS can also be obtained from side scan sonar (SSS) surveys but for the sake of sticking with industry approach methods, it is not the center of this report. As the name implies, backscatter is the rebounding of energy signals resulting from an incoming acoustic wave. In general, two levels of information can be obtained and include 1) water depth / bathymetry and 2) acoustic reflectivity. Intrinsically, a hard material will transmit higher intensity echoes as compared with a softer seafloor material. Additionally, a rough surface scatters more acoustic energy than a smooth seafloor surface. It is this latter phenomenon of reflectivity which can be used to infer bottom type from acoustic data acquired during site characterization surveys.

MBES-derived backscatter imagery cannot replace the SSS system in the identification of geologic and archaeologic features given the higher resolution of SSS. The superiority of backscatter images produced with a multibeam echosounder comes from the improvement of data repeatability and superb positioning which makes it preferable for certain studies, such as benthic habitat characterization. Additionally, MBES backscatter data can assist improving the positioning accuracy of data acquired with a SSS.

Considering that MBES utilizes an array of transducers that ensonify the seafloor with incoming acoustic energy, there is an angular dependence on backscatter strength that effects the distribution of energy (Lurton et al., 2015). The interface roughness will directly impact the ratio of backscatter intensity to incident angle. Highest quality BS is obtained between 15 to 60 degrees of incident angle. As such, it is important to understand that survey line spacing may need to be adjusted to accommodate the required overlap of outer beams.

Fluid sediments (e.g. soft clays or plastic silts with high water contents) will show higher BS intensity at low incident angles followed by a constant BS intensity over a wide range in incident angle. However, rock or coarse sediments (which usually have a roughened surface) can be characterized by almost constant BS intensity over a wide range of incident angles with a slightly higher initial peak intensity at very low incident angles.

Much in the same way as a geophysical seismic surveys can define structure and stratigraphy based on acoustic impedance contrasts, acoustic facies (i.e. the spatial distribution of seafloor patches with similar acoustic responses) can be delineated using backscatter. However, it is important to note that these facies can only be quantified in terms of their relative, not absolute, energy response. For example, sediment class is one of the ways in which backscatter can be used to infer the distribution of benthic habitats or substrate characterizations. Typical processing shows that mean backscatter intensity can be correlated with increasing grain size and surface roughness but the relative differences may be subtle, or large, at any one particular site.

Typical acoustic categories, indicative of various seabed materials, can range from -5 dB to -25 dB for sandy gravels to gravel, -10 dB to -30 dB for coarse to medium sand and from -17 dB to -40 dB for fine sand (Lucieer et al., 2015).

Automated classification of the backscatter data requires clean data devoid of artifacts. One of the most common artifacts that challenge automated classification systems is the nadir. Interferometric systems are known to have nadir artifacts that are problematic when attempting to use automated classification methods.

Backscatter software is not new to the field of geophysics. In fact, four of the main software packages for BS assessment include 1) QPS Fledermaus, 2) CARIS, 3) ESRI-ARC GIS and 4) QPS Geocoder. Each of which allows the user to apply backscatter corrections and produce mosaics that illustrate the distribution of BS intensity across the site. This information can be superimposed upon MBES data for integrated interpretation purposes. What is not readily discernable are the coding routines used within each program in which the backscatter intensity is automatically correlated with seabed grain size and/or surface roughness.

One of the more robust seafloor classification procedures stems from Questor Tangent's QTC Multiview System in which zones of MBES data are clustered for subsequent classification using a proprietary expert system. Over 130 parameters can be extracted from MBES data but most reside within a bathymetry, backscatter mosaic and/or angular dependence category. However, the final classification model requires ground-truthing with sediment samples in order to calibrate the model. Sediment samples should be acquired within the various BS intensity categories as determined from the software output. Moreover, there are many other programs in existence that claim to offer reliable seabed classification. It is very important to note and understand that the onus and responsibility would lie with the developer and / or the geological consultant to define what routine / program is most appropriate for the site.

As indicated, BS is just one tool in an arsenal of available geophysical interpretation techniques that can aid in the spatial distribution of benthic habitat, seafloor material type and other physical parameters such as roughness and or density. They can be used to complement investigations within the Atlantic OCS but should be used only while exercising a high degree of engineering judgment in how the results affect the overall site investigation.

2.1.3.3 Marine Archaeology Surveys

Data from interferometric systems can also be used to create acoustic images of the seafloor that are similar to side scan sonar images. Recent studies have investigated the capabilities of interferometric systems for identification of archaeological resources and object detection (e.g. Bright et al., 2013; Gostnell, 2004; and Gostnell at al., 2006). Results from those studies indicate that interferometric systems have attractive attributes including:

- Ability to collect wide swaths of data that meet or exceed side scan sonar ranges for object detection in shallow water,
- Provide more accurate georeferenced data than towed sonars, and
- Are able to detect small objects (as small as 0.5 to 1 meter) in shallow water (<15 meters).

During 2013, BOEM conducted field testing that compared side scan sonar to an interferometric system for detecting objects in support of marine archaeological investigations. The study reported that the interferometric system was capable of resolving cultural materials in the water depth ranges tested (18 to 40 meters) at the line spacing intervals tested (75 to 100 meters). Based on those results, BOEM deemed the interferometric system used in the study to be adequate for conducting surveys for identification under Section 106 of the NHPA within the water depth and line spacing that were tested (Bright et al., 2013). The study also indicated that future testing would need to be conducted to verify interferometric system capabilities in deeper water (e.g. up to 200 meters) and for wider swath widths.

2.1.3.4 Other Important Considerations for Bathymetry Data

Successfully collecting useful and accurate bathymetry data also relies on other aspects including (but not limited to):

- Recording accurate positioning,
- Correcting vessel and sensor movement,
- Sound velocity information, and

- Vertical datum adjustments.

Modern offshore survey positioning requires the use of the Global Navigation Satellite System (GNSS). Currently only the United States NAVSTAR Global Positioning System (GPS) and the Russian GLONASS are global operational GNSSs. Requirements for survey-grade GNSS receivers are that they record the full-wavelength carrier phase and signal strength of the L1 and L2 frequencies and they track at least eight satellites simultaneously on parallel channels. These dual-frequency receivers limit the effects of ionospheric delay and, increase the reliability of processed results over longer baselines while providing an expanded satellite constellation providing robust geometry.

The speed of sound data determined via the application of water column casts, are critical for accurately computing water depths and are to be measured either directly, using a direct measurement sound velocity sensor or indirectly calculated from conductivity, temperature and pressure measurements. Speed of sound profile measurement are required to correct the multibeam data for the sound speed propagation and ray path variability through the water column that provides a vertical and across-track correction.

Speed of sound profiles are to be measured at a sufficient frequency to ensure that the horizontal and depth accuracies for IHO Special Order or Order 1A survey standards are met. A continuous profiling system is required and the speed of sound profiles are measured at the maximum rate possible while the instrument is being lowered and raised.

Additionally, the surface sound velocity is continuously measured and applied in real time to the multibeam system. This is accomplished by installing a direct read sound velocimeter co-located with the multibeam echosounder head. Speed of sound measurements at the water's surface are applied to the data recording software in real time.

Continuous monitoring of the multibeam data and observable water conditions are required to determine if a change in the sound velocity has occurred necessitating additional sound velocity profile measurements. Data monitoring consists of watching for refraction (ray-bending) effects in the data. These will include mismatch in the overlap of survey lines and a trend towards a curvature of the data from the outer beams.

Observable water conditions consist of effects that give an indication of a change in the sound velocity profile. These include, but are not limited to, an observation of: a change in measured surface sound speed, an inflow of fresh water, or a sediment plume, wind/wave action causing surface mixing, significant rainfall, traversing of currents, surface water temperature change, etc. Any such indications shall result in a new sound velocity profile measurement to be required.

Sound velocity casts are either made be manually deploying a probe or using a moving profiler. In order to perform manual casts, the vessel will need to stop and this may not be possible if the vessel is towing other sensors in the water. Moving sound velocity profilers offer more flexibility and by performing casts without stopping the vessel this also has the advantage of being able to take more casts during a survey period improving the overall accuracy of the bathymetric data. Areas where mixing between fresh and salt water occurs (e.g. inner continental shelf near the mouth of the Hudson River) are complex and may require frequent monitoring of sound velocity changes. Typical data artifacts resulting from inaccurate sound velocity information include “herringbone” or “smiles” in the bathymetric data or apparent vertical steps between adjacent swaths.

Bathymetry data in the shallower water expected for offshore wind farm projects should be adjusted (reduced) to an agreed upon common “local” or “project” vertical datum to correct for water level at the time of the survey. Doing this ensures that the bathymetric data being collected can be compared to other surveys and will be used by project engineers during the design phase. These vertical adjustments are made by applying corrections to the acquired data reducing all bathymetric data to the common datum.

The preferred and most accurate method to determine the adjustment values is by using GNSS (satellite) data. In areas with low tidal variations or in deeper water using tidal measurements may be acceptable. The preference should always be to use GNSS methods as using tidal corrections must be carefully planned to avoid tidal busts in data. Tide gauges along the shoreline should be carefully vetted for suitability in use of tidal corrections.

Distance between survey area and tide gauge should be considered and location of the tide gauge. Tide gauges located inside protected harbors, near island areas, or near at the mouth of a major bay (e.g. Chesapeake, Delaware, etc.) may not accurately depict tidal conditions at an offshore survey area. It may be necessary to deploy a bottom mounted pressure gauge in the survey area or use tidal modeling to support tidal corrections.

2.1.4 Side Scan Sonar

Side scan sonar data are collected to create an acoustic picture of the seafloor by measuring the amplitude of the backscattered return signals. The collected data are rendered in a way that provides a photo-like image of the seafloor. Dark and light colors in the imagery represent areas of varying acoustic reflectivity and absorption. In general, harder bottoms (gravel and sand) will have higher reflectivity than softer bottoms (silt and clay). The angle of the seafloor can also influence the amplitude of the reflectivity. Areas with a seafloor slope (e.g. sand wave flank) that provide an angle closer to a normal angle of incidence (90 degrees) will reflect more sonar energy than a flatter seafloor that results in a more oblique angle to incoming sonar energy.

Features with positive or negative relief can be observed in sonar data. Features that rise above the seafloor will generate a shadow in the data. Using the length of the shadow and distance relationship between the sonar, seafloor, and target, the object’s approximate height above seafloor can be estimated. Side scan sonar data are used to locate anthropogenic hazards (e.g. shipwrecks, pipelines, UXO’s, etc.) and potential geohazards (e.g. boulders, sand waves, pock marks, etc.).

Side scan sonar data are also used to interpret seafloor conditions (e.g. sediment type, boulder zones, rock outcrops, hard bottom areas, etc.). Care should be taken in creating a mosaic with adequate contrast that allows interpreters to discern bottom conditions. For example, reflectivity contrast should adequate for discerning predominantly fine from medium grained sand. Grab samples should be collected to provide ground truthing and aid in interpreting seafloor sediment type and features. Grab sample locations should be selected based on review of the side scan sonar data and locations should be selected in order to ground truth characteristic reflectivity areas. A rule of thumb would be at least one grab sample every 3 to 4 square kilometers. Side scan sonar data can also be used to select bottom photograph or video locations to help characterize bottom conditions.

When surveying, the side scan towfish altitude should be based on water depth, range of the instrument, line spacing, and ability to provide adequate data overlap. When towing a sonar, there will be some uncertainty in the true position of the fish. As water depth increases, and more cable out is required to tow the fish closer to the seabed, this uncertainty in the position of the fish increases. Therefore, mitigation of positional inaccuracy is accomplished by using an ultra-short base-line (USBL) system in deeper water surveys.

A USBL system consists of a hydrophone that transmits and receives a signal from a beacon mounted on the towed system. By observing the time delay of the signal and observations of the speed of sound in water together with the phase angle of the returning signal, a range and bearing to the beacon is calculated and positioned. For optimum performance the system must be appropriately installed, calibrated and operated and may deliver relative accuracies of better than 0.5 percent slant range between the hydrophone and beacon. It is recommended that contractors adhere to the relevant guidelines described in IMCA document S 017 (2011) - Guidance on vessel USBL systems for use in off shore survey and positioning operations.

2.1.4.1 Multi-Purpose Potential for Side Scan Sonar Data

Side scan sonar data area commonly used to interpret bottom conditions in support of engineering studies. However, they can also be used to support marine archaeological assessments and biological surveys. Side scan sonar data are one of the primary sources of data used to interpret a shipwreck and to identify objects that might be related to past human inhabitants. Side scan sonar data are also used in biological surveys to interpret live bottom, hard bottom, or areas of environmental interest.

During operation of the wind farm facility, side scan sonar data can also be used to monitor conditions along the cable route and check for exposed cables, assess condition of scour protection for turbines or cables, assess conditions at the base of turbines, or monitor bottom benthic habitat response after a wind farm has been constructed.

2.1.5 Magnetometer

BOEM (2015a and 2015b) indicates that for HRG surveys in water depths of 100 meters or less, a magnetometer should be deployed to detect ferrous objects or other magnetically susceptible materials, composed of iron, iron alloys such as steel, cobalt and/or nickel. Well in advance of mobilization, a Desktop Study (DTS) should be carried out to ascertain the location and spatial distribution (if broken and scattered) of known ferromagnetic objects (e.g., ship wrecks) on or near the seabed and the likelihood of encountering magnetic anomalies attributed to poorly documented or unknown sources encountered during surveying operations.

2.1.5.1 Background Information

The Earth's magnetic field varies both spatially and temporally owing to a number of interacting phenomena acting upon the magnetic field. The Earth itself is sometimes described as a magnet and this property has allowed navigators for centuries to determine how to move from one point to the next through the use of a magnetic compass. The north arrow on the compass points to the magnetic north pole which wanders in a somewhat circular pattern around the geographic pole over time. These slow changes are known as secular variations and are used in paleomagnetism studies to understand, among other phenomena, the movement of the tectonic plates over Geologic time. Secular variation is believed to result from the convection of charged particles in the Earth's outer, fluid core. The total magnetic intensity measured in the field is largely controlled by the influence of the field produced within the Earth's core. Within the areas designated as Wind Energy Areas (WEAs) along the Atlantic OCS, the total magnetic field ranges from approximately 47,500 nT in the Georgia WEA OCS blocks to 52,000 nT in the Massachusetts WEA. Based on the US/UK World Magnetic Model, Epoch 2015.0 (www.ngdc.noaa.gov/geomag/WMM/data/WMM2015), the annual change in the total magnetic field varies between -100 nT near the Massachusetts WEA to approximately -115 nT near the Georgia WEA OCS blocks.

Other known variations in the Earth's magnetic field result from external forces such as diurnal variations that form as a result from the flow of charged particles from the ionosphere towards the magnetic poles associated with the tidal forces of the Sun and the Moon. Diurnal variations pose the largest problem when trying to interpret (or grid) data in the same general vicinity but collected at different times. The collection of cross lines (or tie-lines) may help eliminate the influence the effects of diurnal variation, but to do this the magnetometer(s) of the survey need to positioned at the same altitude as the original (or primary) line.

Magnetic storms, produced from charged solar particles interacting with the ionosphere also contribute to large, but relatively brief variations in the Earth's magnetic field. The somewhat chaotic nature of the influence of these magnetic storms makes it near impossible to remove their influence during a typical magnetic survey unless base stations or gradiometers are employed, especially during very powerful magnetic storms, known as coronal mass ejections (CMEs). Carrier et al. (2015) caution that many magnetic variations produced by geomagnetic storms could be misinterpreted as archaeological sites if not properly resolved.

Magnetic surveys (both airborne and marine) have been undertaken by geoscientists for decades to understand anomalous features associated with variation in the ferromagnetic properties of the sediment and rock located in the Earth's crust. Variations in the magnetic field originating from secular variations, magnetic storms and diurnal variations must be removed in order to observe magnetic anomalies associated with the material making up the Earth's crust. Large magnetic anomalies, stretching over several kilometers of the Earth have helped define basin architecture, plate boundaries and the composition of basement material. Smaller wavelength anomalies related to geologic phenomena have been used by geologists to define economic ore bodies, understand the structural fabric of geologic bodies and map underlying geologic formations. Most natural sedimentary rocks are inherently non-magnetic. Only mineralization or man-made features would result in an increase in magnetic intensity above ambient.

2.1.5.2 Uses of a Magnetometer Survey for Offshore Renewable Development

Designing a magnetometer survey to aid in the development of offshore renewable energy is generally concerned only with small-wavelength magnetic anomalies largely resulting from past human activities. Like geologic studies of the magnetic field, diurnal, secular and magnetic storm effects need to be removed in addition to the influence of ferromagnetic minerals found in the Earth's crust. The magnetic anomalies of concern for this report are associated with human activities and fall into two main categories: 1) obstacles or hazards that need to be avoided or removed prior to construction or 2) culturally significant archaeological artifacts that need to be documented, researched and avoided or possibly excavated during offshore wind energy development.

Some examples of anthropogenic magnetic anomalies that would be defined as construction obstacles or hazards include Munitions of Explosive Concern (MEC), also known as Unexploded Ordnance / UXO, active or abandoned submarine cables/pipelines and abandoned debris from marine vessels (e.g. detached anchors, pieces of broken metal wear, fishing equipment). On the Atlantic OCS, the presence of submarine pipelines and cables would likely be documented and are therefore expected to be encountered during surveying. While the risk of encountering UXO's would be highest near dumping grounds or in areas with a history of military exercises (e.g., near firing ranges) the chance encounter of MECs in non-designated military activity areas is also a possibility. For example, MECs can be encountered away from designated areas if the MEC was moved from the original dumping site due to vigorous current action or if the MEC was originally dumped at an undocumented site. MECs entrained in fishing gear can be moved great distances from the original site; therefore, it is important to note that they can be encountered unexpectedly as well. Vessel debris, on the other hand, would likely be found unexpectedly and could require intervention during offshore activities.

Vessel debris along with more intact shipwrecks are perhaps the most likely archaeological artifacts that will be uncovered through the use of magnetometers on the Atlantic OCS. Unfortunately, magnetometers cannot distinguish the origin or age of various small duration magnetic anomalies located at, or just below, the seafloor. This is why BOEM (2015a and 2015b) recommend collecting side scan sonar imagery and bathymetric data in tandem with a magnetic survey, in the hopes that some portion of the anomaly will be visible on the seafloor to allow for proper identification. BOEM's (2015a and 2015b) guidelines explicitly state that possible correlation of magnetometer anomalies with side scan sonar targets should be determined and if feasible, the likely origin of these seafloor anomalies researched.

2.1.5.3 Survey Parameters

The main field parameters that must be determined before carrying out a magnetometer survey are 1) the type of magnetometer utilized, 2) the number and geometry (i.e., linear arrays, horizontal and or vertical gradiometers), 3) the spacing between adjacent magnetometer tracklines, and 4) the maximum altitude of the sensor. The magnetic field can be measured as a vector or as a total magnetic field. The three main types of magnetometers used in surveying are the fluxgate magnetometer, the proton-precession magnetometer and the optically pumped magnetometer. All of these magnetometers have their own advantages and disadvantages which will be discussed in detail in the "Guidebook for Widely Available Equipment" presented in the 6th volume of this report.

2.1.5.4 Diurnal Storms, Base Stations and Gradiometers

The use of nearby base stations located on land or anchored to the seafloor can be used to monitor temporal variations in the geomagnetic field caused by the flow of charged particles within the ionosphere (diurnal variations and variations caused by magnetic storms). These base stations need to have precise timing, be synchronized with the field instrument and positioned away from objects made of ferrous and/or high electrically conductive materials. The ambient magnetic field is measured periodically (up to 1 measurement per second) at these base stations.

When two or more magnetometers are used in conjunction, the longitudinal, horizontal and/or vertical magnetic gradient can be calculated. Unlike single sensor magnetometers, gradiometers do not require the use of base stations. Gradiometers are typically used for UXO detection and archaeological studies where the Analytic Signal is produced by measuring the change (derivative) in the magnetic field in the x, y and z position. Zero gradients denote the contact between magnetic and nonmagnetic bodies.

In Europe, UXO surveys are typically acquired and processed by one company and delivered for further analysis to a second team comprised of UXO experts (often former military experts), who then deliver the final UXO analysis to the client (be that a wind energy developer, a dredging company or a utility company). Prior to data acquisition, the client provides the acquisition company with specific guidelines to assure that the magnetometer survey is completed with optimal coverage in order to eliminate the potential for encountering unexploded ordnance during subsequent operations. It is the client who defines the maximum allowable sensor altitude and line spacing, often under the guidance of a UXO expert. Data collected outside of the client's specification are later reshot by the acquisition company to meet the client's specifications with infilled lines. If specific identified magnetic targets require further investigation, an ROV can be deployed to investigate the object or area of interest in order to mitigate potential risks. However, for detection via ROV cameras, the UXO must have a surface expression to be detected and not buried beneath the seafloor. If shallow burial is suspected, more invasive techniques may be required to excavate the potential UXO with the utmost caution.

2.1.5.5 Pre-Survey Tests

Prior to conducting a UXO magnetometer survey, the acquisition company will run a test somewhat equivalent to a bathymetric patch test (known as an acceptance or verification test) where an object of known weight and dimension is lowered to the seafloor and survey lines running in four distinct directions (e.g., north-south, east-west, south-north and west-east) will pass over the object. This acceptance test is used to verify positioning, repeatability (similar size and shape of the object) and determine the influence of background noise on the detectability of the anomaly. In some cases, the result of the acceptance test has been used to setup the survey's specifications, such as line spacing, altitude limits and anomaly detection cutoff.

The ability to detect a ferromagnetic object on or beneath the seafloor, given a specific magnetometer type, is largely a function of the dimensions and weight of the magnetically susceptible object, the distance between the sensor and the object (which can be optimized by positioning the magnetometer as close to the seafloor as possible), the object's orientation in relation to the sensor's orientation, the presence of background noise and the spacing between adjacent survey tracklines. BOEM (2015a and 2015b) require continuous monitoring of the position and altitude of the magnetometer. Echosounders or altimeters are generally recommended (or optional) for marine magnetometers and provide a way of measuring the distance between the seafloor and the flying height of the magnetometer (called layback calculation using an equation for the catenary). The horizontal distance can be manually calculated using the fish depth and cable length but for very high precision positioning, underwater acoustic positioning systems may be required, especially in areas with strong currents. Presently, BOEM requires that magnetometer sensor be towed no more than 6 meters above the seafloor to ensure that large magnetically susceptible objects are resolved. This is called drape-flying.

2.1.5.6 Survey Planning

In BOEM's Guidelines for Geological, Geotechnical and Archaeological Surveys (BOEM, 2015a; BOEM, 2015b), three distinct line spacing requirements are defined by the objective of the individual survey. For project siting surveys, line spacing for hazard assessment should have primary lines running 150 meters or less and tie lines positioned at most, 500 meters apart. For surveying along a transmission route, line spacing should run along the centerline with parallel lines located every 150 meters on either side of the centerline route optimally covering the entire region affected by installation activities. At least three equidistant tie-lines should be positioned along the survey corridor at most 500 meters apart from one another. The line spacing for both the project siting and transmission route survey are similar in separation distance and vary mainly by the orientation of the lines. The 150 m by 500 m line spacing for these two survey categories will likely be sufficient to identify any pipeline or cable crossings and very large ferromagnetic objects that could be detrimental to construction. Archaeological surveys require tighter line spacing, with primarily lines spaced no more than 30 meters apart and perpendicular tie-lines spaced 150 meter apart. In the case on UXO surveys in the areas of prior military conflict, line spacing is typically 4 meters or less.

The specification of line spacing (and altimeter specifications) should be determined by the size of the object of interest because the intensity of the magnetic field caused by a ferromagnetic material decreases with the cube of the distance to the object. Hall (1966) published an equation relating change in magnetic field intensity (ΔM, in nT) to the shape ($\frac{A}{B}$, the length-to-width ratio), weight (W, in tons) and distance (D, in meters) from the sensor to target, expressed as:

$$\Delta \mathrm{M} = 10^4 \frac{A}{B} \frac{W}{D^3}$$

If the smallest discernable change in the magnetic field that can be reliably detected is ΔM = 5 nT, then the distance between the sensor and the magnetic object can be determined from Hall's (1966) equation as:

$$D = \sqrt[3]{\frac{10^4 \frac{A}{B} W}{5}}$$

For an object lying directly under a magnetometer at a distance of 6 m, it would be possible to resolve a 100 kg anchor if the length-to-width ratio is approximately 1 (Plets et al., 2013). If line spacing is 30 meters and the altitude is 6 meters, a feature midway between the two tracklines would be over 16 m from the nearest sensor and with a length-to-width ratio is approximately 1, the ferromagnetic object would need to weigh close to 2,000 kg. A common way to determine the weight or type of object knowing the anomaly's magnetic intensity and distance from the object is through the use of a nomogram (Figure 2.2; Breiner, 1999). Table 2.3 lists some commonly encountered UXO objects and their total field amplitude (peak-to-peak).

Table 2.3. Common UXO and Total Field Amplitude (Peak-to-Peak) measured at a given sensor distance above the object

Altitude (meters)	105 mm shell	155 mm shell	100 lb bomb	250 lb bomb	500 lb bomb	Mk.IV Ground Mine
2	11nT	41nT	75nT	160nT	300nT	1350nT
3	3nT	12nT	23nT	49nT	91nT	485nT
4	<2nT	5nT	10nT	21nT	40nT	223nT
5	<1nT	2.5nT	5nT	10.5nT	20nT	120nT
6	<0.5nT	<2nT	3nT	6nT	12nT	70nT
8	<<0.5nT	<<1nT	1nT	2.5nT	5nT	30nT
10	<0.1nT	<0.5nT	0.5nT	1nT	2.5nT	10nT

(green)	Detectable against background noise
(yellow)	Marginal detectability against background noise
(red)	Not detectable against background noise

A magnetometer's ability to detect an anomaly is generally related to the distance between the magnetometer and the object, the mass of iron in the object, and the shape of the object. Therefore, it is desirable to tow the magnetometer as close to the seabed as safely possible. Care should be taken when towing the magnetometer across sand ridges, that are common in the Mid-Atlantic region, while maintaining a minimum altitude and avoiding running the sensor into the seabed. The sand ridges can be 3 to 10 meters tall and a few hundred meters wide.

2.1.5.7 Data Processing

After collecting magnetometer data, the raw data (consisting of the raw magnetic field measurement, the altimeter of the sensor, the date and time of the data collection, the positioning of the sensor, the line name or number, and in some instances a signal-to-noise qualifier) is processed to produce a gridded representation of the total magnetic field and/or the total analytic field. Prior to gridding the data, layback must be added to the navigation and navigation spikes and other navigation errors must be corrected. This process often involves smoothing and despiking the navigation data. Next, the altimeter data is despiked and then the raw magnetometer data is analyzed. Where clear spikes or errors in magnetic readings are seen, the data is removed or smoothed over if the number of data points are minimal.

For single sensor magnetometers, the main correction comes from removing the diurnal change during the survey period which typically is removed by subtracting a best-fit line from each surveyed line to produce a residual containing both anomalies from geologic features and near-seafloor magnetic objects. Without an array of magnetometers or gradiometers, the removal of the influence of geologic bodies is problematic because a small (or large and distal) magnetic object may give a similar anomaly to a geologic body. Therefore, geologic phenomena are not removed from single sensor, largely spaced magnetometer surveys and anomalies (or targets) are picked manually looking at each line individually. The total field is gridded and the targets are displayed on this grid after correlating with side scan or bathymetric targets.

For arrays of magnetometers or gradiometers, the analytic signal is produced by calculating the change in the magnetic field intensity between several magnetometers. The resulting analytic signal is gridded after removing (filtering) low amplitude, larger wavelength anomalies believed to attributed to geologic bodies, thus leaving only high amplitude, short duration anomalies that likely correspond to anthropogenic magnetic objects. The creation of the analytic signal creates a grid with only positive values and an anomaly that appears as a dipole in the total field is represented as a peak, so that the maximum value of the anomaly should be positioned on top of the object creating the anomaly.

If using a phased approach in geophysical surveying, the collection of magnetometer data poses a problem with integration that will be a function of the sensor used, the sensor's position relative to the magnetic object, the altitude of the sensor and the correction for secular and diurnal variations between the two surveys. If the same magnetometer is used between two distinct surveys collected over (or infilling) a prior survey, the data could be merged and regridded through the use of crosslines to correct for diurnal and secular effects in order to best fit the newly acquired data with the older dataset. If the altitude or orientation of the sensor varies considerably between the two surveys, the combining of the two datasets to create a single grid will likely be problematic.

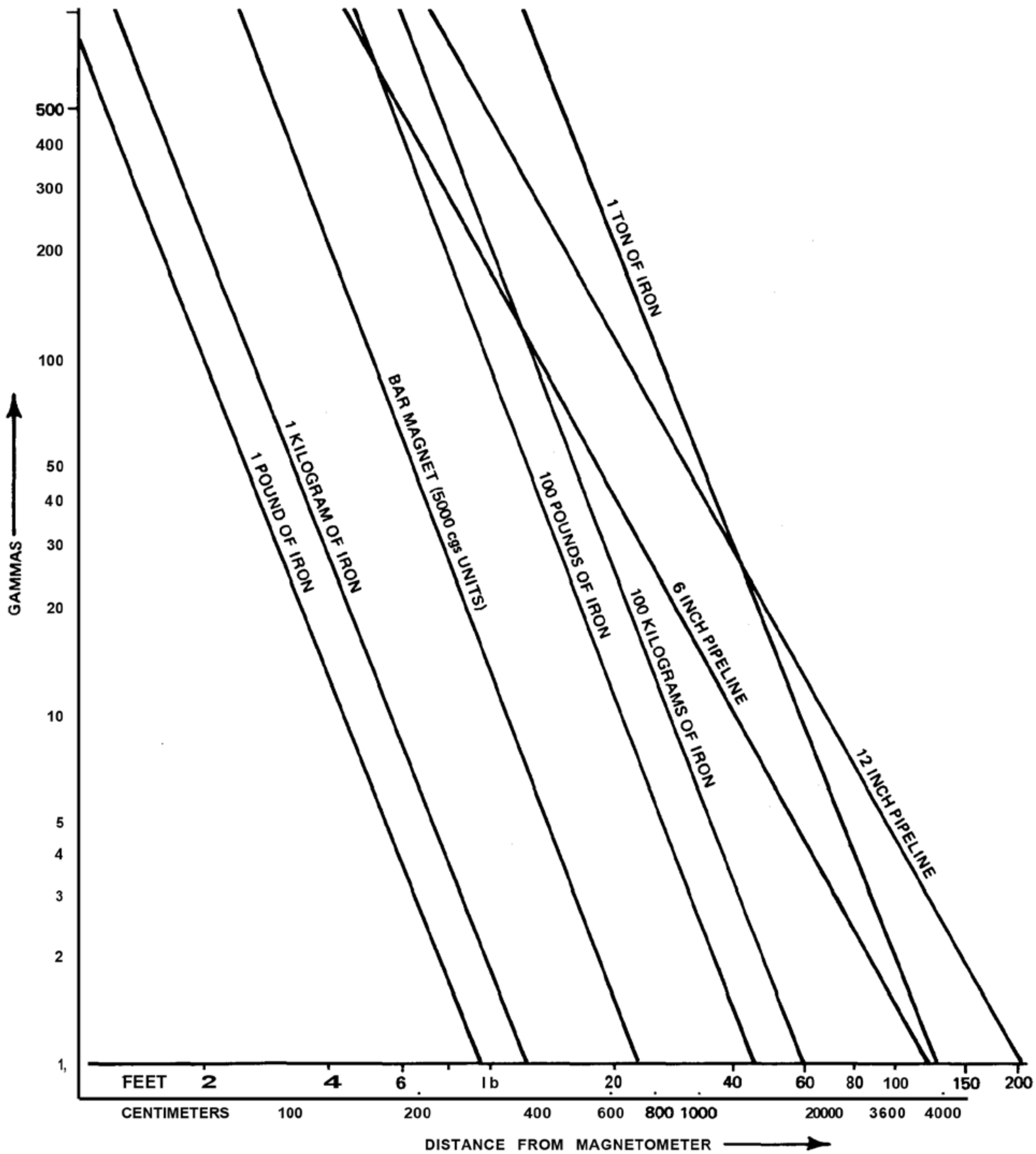

Figure 2.2. Nomogram for estimating anomalies from typical objects assuming dipole moment, M= 5 X 105 cgs/tom, i.e., k = 8 cgs). Estimates valid only within an order of magnitude (Breiner, 1999)

2.1.6 Shallow Penetrating Seismic Reflection Systems

Shallow penetrating, high resolution seismic systems image the shallow subsurface in order to characterize the shallow stratigraphy and identify potential geohazards in support of a variety of engineering studies (e.g., foundation design, cable burial risk assessment). Additionally, these high resolution systems are utilized in marine archaeological research through the interpretation of paleo-landforms which aid the reconstruction of past environments that are of potential archaeological interest.

For this study, we reviewed seismic data collected from 22 surveys on the Atlantic continental shelf. The surveys were conducted by various companies and the USGS. Several surveys were conducted within designated Wind Energy Areas in support of offshore wind development and others were conducted for sand resources investigations or scientific research. The following discussion is based on our evaluation of those survey data.

Shallow penetrating seismic systems transmit very high frequency sound waves, typically between 2 and 24 kHz, in order to provide sub-meter vertical resolution of the subsurface. Although equipment manufacturers indicate that signal penetration depth may be up 150 meters for systems, several factors in the Atlantic OCS limit collection of useful data collection to up to about 20 meters. Factors that limit the depth of mappable data collection include, but are not limited to, the water depth, reflection of a large portion of the signal at the seafloor, and signal attenuation.

In most surveys on the Atlantic OCS, subsurface reflections using these high-resolution systems rarely can be resolved below the seafloor multiple and therefore if the sub-bottom profiler is towed near the sea-surface, the system will be unable to image below twice the water depth (e.g., towing a Chirp system in 15 meters of water will provide, at best, imaging of the upper 15 meters of the subsurface).

Much of the seafloor in the Atlantic OCS Wind Energy Areas is comprised of sandy deposits. A large portion of the seismic energy is reflected from the sandy seafloor deposits as evidenced by the characteristic high-amplitude seafloor reflector observed in all of the surveys.

Another limitation of signal penetration when using these shallow penetration seismic systems is due to attenuation caused by the medium (i.e., sediment or rock) through which these seismic waves propagate. Unfortunately, the transmitted high frequencies are attenuated relatively quickly in the subsurface and signal penetration is limited typically to 20 meters or less, (Table 2.4). Generally, there is better signal penetration in fine-grained, interbedded sediments when compared to propagation in coarse-grained deposits and the presence of shallow gas can totally inhibit signal return. Table 2.5 summarizes notable geologic conditions that limit the signal penetration in the three geologic regions defined in Volume 1.

The three main categories of shallow penetration, high-resolution seismic systems used in marine surveying are pingers, parametric echosounders, and Chirp sub-bottom profilers. Transducer arrays (two-by-two, three-by-three, four-by-four or other), can be implemented to increase signal penetration. Transducer arrays are commonly found on larger survey vessels that work in deep water environments and are often hull-mounted; arrays can also be mobilized onto vessels. Table 2.4 summarizes the typical frequency ranges, vertical resolution and depths of signal penetration for these various shallow penetrating systems.

Pingers (such as the 3.5 kHz echosounder) emit a multi-cycle sinusoidal wave with a very narrow bandwidth centered around a single frequency. While these systems are extremely easy to use, these systems are difficult to use for engineering and archaeological studies due to their limited bandwidth and long pulse length providing poor quality images of the subsurface. Parametric sounders provide improvements over pingers in that two frequencies are emitted simultaneously and the interference of these two frequencies produces a secondary lower frequency that improves signal directivity and higher signal penetration using a small transducer.

Chirp systems obtain high resolution images of the shallow subsurface through the use of a long duration, frequency modulated "chirp" pulse that is swept over a full spectrum frequency range (e.g. 2-16 kHz), thus providing a broad bandwidth signal. Chirp system can transmit a variety of waveforms, that can be modified to improve penetration or eliminate sidelobe interference. Chirp systems are the most-common high resolution seismic system in use today and have been utilized in multiple Atlantic OCS geophysical surveys to aid the identification of paleo-landforms and reconstruct past shorelines and depositional processes to aid archaeological research. They have been successful in providing subsurface information in optimal conditions (e.g. paleo-channel infill), but their limited penetration often provides only a partial picture of the subsurface and therefore deeper penetration systems are often used in tandem to provide continuous mapping of seismic horizons and correlate discrete seismic reflections sporadically imaged with the Chirp system. The penetration of a Chirp signal can be enhanced by towing the system closer to the seafloor so that there is less signal loss in the water column prior to penetrating the seafloor and spatial resolution is improved due to a smaller portion of the seafloor being ensonified. Additionally, using lower frequencies or source arrays can increase the penetration of the signal.

Table 2.4. Typical Characteristics of Different High-Resolution Seismic Systems

Seismic Source	Frequency Range	Energy (Joules)	dB re 1 μPa (Representative examples)	Vertical Resolution	Typical Depth of Signal Penetration Atlantic OCS
Shallow Penetrating Systems					
Pingers	Typically 3.5 or 7 kHz	1 to 5	214 at 1 meter	5 to 20 cm	< 30 m in silt and clay 5 to 12 m in sand <3 m in gravel and sand
Parametric SBP (Echosounders)[1]	2 to 22 kHz		240 to 250 dB at 1 meter	5 to 15 cm	< 20m in soft, fine grained sediments 2 to 6 m in sand <2 m in gravel and sand

Seismic Source	Frequency Range	Energy (Joules)	dB re 1 μPa (Representative examples)	Vertical Resolution	Typical Depth of Signal Penetration Atlantic OCS
Chirp[2]	400 Hz to 24 kHz	1 to 10	212 at 1 meter peak (approximately at center frequency for 0.5-15 kHz)	2 cm to 1 m	< 20 m in silt and clay 2 to 8 m in sand <2 m in gravel and sand
Intermediate Penetrating Systems					
Single Plate Boomer	300 Hz to 6 kHz	100 to 600	212 at 1 meter at 200 J 215 at 1 meter at 300 J	10 cm to 1 m	25 m to 200 m
Double and Triple Plate Boomer		200 to 1000			30 m to 600 m
Sparker[3]	40 Hz to 1.5 kHz	200 to 16,000	216 at 1 meter at 500 J 222 at 1 meter at 1500 J	20 cm to 10 m	100 m to 1 km

[1]Unlike conventional echosounders that emit a constant waveform with a single frequency, parametric echosounders transmit two high-frequency signals that produce a lower frequency signal through interference of the two transmitted frequencies.

[2]Chirp systems transmit a frequency modulated (FM) pulse that provides a high-resolution, low noise image by correlating the reflected data with the transmitted pulse.

[3]Frequency of a sparker system is tip and depth dependent

Table 2.5. Notable Considerations for Geologic Conditions for Different High-Resolution Seismic Systems

Seismic Source	Typical Depth of Signal Penetration Atlantic OCS	Regional Geologic Zone as Described in Volume 1		
		New England	**Mid-Atlantic**	**South Atlantic**
Shallow Penetrating Systems				
Pingers	< 30 m in silt and clay 5 to 12 m in sand <3 m in gravel and sand	Surficial sand ridges are expected to limit signal penetration Sandy and gravelly glacial deposits may be present near the seafloor or exposed at the seafloor and are expected to limit signal penetration; pinger arrays may achieve moderate penetration	Surficial sand ridges are expected to limit signal penetration Gravel-rich deposits are anticipated to be localized and of limited extent	Surficial sand ridges are expected to limit signal penetration Shallow or exposed carbonate-rich deposits are expected to limit signal penetration for all systems
Pingers in 2x2, 3x3, or 4x4 Arrays	50 to 300% better penetration than single sensor			
Parametric SBP (Echosounders)[1]	< 20m in soft, fine grained sediments 2 to 6 m in sand <2 m in gravel and sand			
Chirp[2]	< 20 m in silt and clay 2 to 8 m in sand <2 m in gravel and sand			
Intermediate Penetrating Systems				
Single Plate Boomer	30 m to 200 m	Glacial deposits are expected to limit signal penetration; mappable signal penetration may be <30m	Mappable signal penetration may be <40m	Mappable signal penetration may be <40m Shallow carbonate-rich deposits are expected to limit signal penetration; inshore surveys have been unable to penetrate Pre-Quaternary carbonate rich strata
Double and Triple Plate Boomer	30 m to 600 m	Multi-plate boomer and sparker are anticipated to perform well		
Sparker	100 m to 1 km			

[1]Unlike conventional echosounders that emit a constant waveform with a single frequency, parametric echosounders transmit two high-frequency signals that produce a lower frequency signal through interference of the two transmitted frequencies.

[2]Chirp systems transmit a frequency modulated (FM) pulse that provides a high-resolution, low noise image by correlating the reflected data with the transmitted pulse.

2.1.7 Intermediate Penetrating Seismic Reflection Systems

Intermediate penetrating seismic systems are used to image subsurface stratigraphy from the seafloor to the foundation depth of interest. These systems can implement various seismic energy sources and receiver array configurations. The equipment and their configuration influences the data resolution and signal penetration depth. Selection of survey equipment and methodology (e.g. shot intervals, sampling rate, record length) are based primarily on the water depth, anticipated geologic conditions, signal penetration depth requirements, and data resolution needs.

Data quality depends on a large number of variables including sea state, positioning accuracy of source and streamers, shooting and recording controls, implementation of quality control during acquisition, and data processing methodology. Table 2.6 lists a summary of typical foundation embedment depths and water depth ranges. Actual embedment depths will depend on the ground conditions, foundation system, and desired foundation capacity.

Table 2.6. Typical Foundation Embedment Depth Ranges

Foundation Type	Gravity Based	Monopile	Jacket/Tripod	Suction Caisson	Floating Turbine Anchor
Water Depth Range	< 20 m	< 30 m	30 to 60 m	30 to 60 m	> 60 m
Embedment Depth Range	< 5 m	30 to 50 m	30 to 70 m	15 to 30 m	< 10 m
Bearing capacity foundation systems are primarily influenced by underlying materials that are within 3 to 5 diameters of the pile/caisson.					

Seismic Source

Seismic sources used for intermediate penetrating systems are typically selected to optimize the relationship between attaining the highest frequency content, achieving desired signal penetration depth, and providing a consistent signal signature during the course of the survey. Boomer and sparker sources are the two most commonly used sources for the offshore wind farm foundation surveys.

Boomer Source

The seismic signal in boomer systems is electromagnetically generated using a flat coil and metal plate below the coil (Edgerton and Hawyard, 1964). The plate is rapidly repelled from the coil using an eddy-current generated in the metal plate. The rapid pulling back of the plate by strong springs or rubber bands creates a cavitation in the water acting as the sound source. Discharge of a high-voltage capacitor bank through the coil generates the eddy-current in the metal plate and initiates the shot. Energy of the source depends on the capacitor bank, which for a single boomer plate can range from 100 to 1,000 joules (J). The frequency range of the boomer source is between 300 Hz to 20 kHz with decimeter scale resolution and the signal can penetrate tens to hundreds of meters. The boomer source signature is typically very consistent during the course of a survey and from survey to survey. The high resolution, good signal penetration depth, and repeatability of the source signature make the boomer a preferred sound source for engineering surveys.

Traditionally, boomers were used in a single plate mode for high resolution surveys that had shallow (<80 meter) penetration requirements. However, during the past two decades, there was an interest for using the boomer source due to its high frequency content and consistent source signature to modify it for achieving deeper signal penetration. Engineering surveys offshore California had a need for deep signal penetration to image fault traces while providing high resolution data to support engineering planning and design of tunnels, outfalls, bridges, power generating plants, and port facilities. As a result, boomer sources were modified to fire two or three plates simultaneously from a customized frames and sleds (personal communication, Subsea Systems, Inc.). Now boomer sources in double or triple-plate firing configurations are used on engineering surveys, including those for wind farms. A double-plate boomer was recently used to survey the Virginia Wind Energy Area (Fugro, 2013) and recorded over 400 ms (two-way travel time) of data which corresponds to approximately 350 meters below the seafloor.

Sparker Source

The sparker source has historically been used for surveys that required deeper signal penetration depth than the single plate boomer. The sparker functions similarly to a spark plug in an automobile engine. Discharge in a capacitor bank creates a spark between the positive and negative electrodes of the sparker (Allen, 1972). This spark vaporizes water between the electrodes and generates a pressure impulse. The physical design of the sparker influences the energy and shape of the sparker wavelet. The energy and shape of the sparker wavelet are also influenced by the capacitance and voltage of the high-voltage capacitor bank. Sparker sources are capable of generating shots with energy levels between 100 J and several thousands of joules.

The sparker signal can change over the course of a survey which will affect the character of the seismic data. Heat and usage of the capacitors lead to deterioration of the electrodes which affects the source signature. Periodically the capacitors need to be replaced however, recent technological improvements have reduced the rate of burnout. Also, lateral variations in the electrical conductivity of the water can affect the source signature (Bellefleur et al., 2006).

Table 2.4 lists the various intermediate penetration seismic sources, frequency content, and energy levels.

Receiver Arrays

Receiver arrays are either single channel or multichannel arrays. Receiver array configuration is a very important component that dictates seismic data resolution and signal penetration depth and improves ability to collect mappable data with targeted depth interval. “Mappable data” are defined herein as:

- Data with good signal-to-noise ratio

- Coherent events (primary reflections) that can be traced laterally along the entire record and correlated confidently between primary and tie lines,
- Seismic stratigraphic character can be observed in data, including the internal reflectors which provide valuable information used to interpret geologic nature (e.g. facies) of subsurface materials, and
- Wavelet should be processed to appear as a Ricker wavelet and deconvolved to zero phase to permit evaluation of reflection polarities and amplitudes.

Single channel arrays may either be comprised of 1 hydrophone or several hydrophones that are closely spaced and recorded as one group. An inherent limiting factor in using single channel arrays is that the water bottom multiple(s) may inhibit the usage of the data for interpreting subsurface conditions. Figure 2.3 presents a schematic of the water bottom multiple and how it interferes and can mask seismic reflection data. Based on our review of single channel seismic reflection data collected on the Atlantic OCS, those data meeting the definition of mappable data provided above, typically achieved 10 to 30 meters.

The water bottom multiple represents seismic energy that is reflected from the seafloor-water interface, travels upward through the water column and then is reflected downward from the air-water interface, and then reflects off the seafloor a second time as the first water bottom multiple and the reflection is recorded on the receiver array. Since the first water bottom multiple travels through the water column a second time, its arrival time is nearly two times later than the primary event of the initial energy reflected off the seafloor. Therefore, the interference of the first water bottom multiple occurs at approximately equal to the water depth below the seafloor. For example, at a site where the water is 20 meters deep, the first multiple would arrive approximately 20 meters below the seafloor event in the seismic data. Water bottom multiples can continue to reverberate in the water column and recorded in the seismic data (Figure 2.3). The water bottom multiple(s) cause destructive interference with upcoming reflected primary events from sub-seafloor interfaces and degrades their signal. Therefore, most primary event signals reflected from interfaces below the seafloor at a depth equal to or greater than the water depth are degraded or wiped out due to the multiples.

Single channel receiver arrays have other limitations that make it difficult to obtain good signal-to-noise ratios (SNR). Multichannel hydrophone arrays make more recordings of a single shot event that are stacked and migrated to improve the SNR. A single channel system does not have this ability and the result is an inherently lower SNR. This inherently limits a single channel system's ability to collect seismic data to the same depth as a multichannel system assuming they use the same energy source (e.g. 300 J single plate boomer). Single channel systems may not be capable of achieving the necessary penetration depth that provides mappable data for pile foundations in areas where it is difficult to achieve good signal penetration like glacial deposits in New England, carbonate deposits in the South Atlantic, or gassy Transgressive deposits.

Additionally, single channel receiver arrays do not have a long enough streamer to perform velocity analyses. Typically, a regional geophysical survey is performed before a geotechnical investigation is conducted. The geotechnical investigation may include borings with downhole compressional wave logging or seismic cone penetration tests that provide P-wave velocity data that can be used to convert seismic reflection data from travel time to depth. In the absence of downhole seismic profiles or seismic cone penetration test soundings, the velocity analysis performed on multichannel seismic data are the only sources of seismic velocity data available. Therefore, multichannel seismic velocity analysis becomes essential for converting seismic reflection data from time to depth and developing a ground model that can be used to plan geotechnical investigation and performing engineering analyses for foundation design.

Single channel data also have inherent signal processing limitations. Due to fewer channels of data collected and short streamer length, signal processing is limited in options for water bottom multiple suppression and muting noisy traces.

Advantages of collecting single channel data include the low cost of collection, simple processing techniques, the ability to utilize small vessels and quick deployment. The use of numerous, closely spaced hydrophones to form a single channel reduces spatial aliasing issues and allows for high sampling rates. The short distance between source and receiver means that high frequencies are easily recorded allowing thin beds to be resolved unlike the lower frequency data recorded at far offset channels on multichannel arrays. The combination of the acquisition/processing simplicity, use of small vessels, and the abundance of contractors on the Atlantic coast results in a lower cost per line kilometer for single channel seismic surveys when compared to multichannel seismic data collection. However, the use of a single channel leads to one trace per shotpoint and therefore if the recorded signal is noisy, there is potential that the data will unusable. Single channel systems are best suited for calm seas, in areas where only the shallow section needs to be imaged and where the water bottom multiple won't inhibit the imaging of the depth of interest.

Multichannel receiver arrays provide a means for working around the water bottom multiple challenge, allow more opportunities to improve signal-to-noise ratios during acquisition and signal processing, (e.g. through stacking, folding, etc.). Multichannel streamers consist of hydrophones or elements grouped together for form a channel. The hydrophones may be spaced 0.3 to 1m apart and grouped at defined intervals (e.g. 1.56-meter group interval [mgi]). The number of hydrophones per group may be 1 to 5 or more. The improved signal-to-noise ratio over single channel systems is approximated by the fold. For example, 24-channel systems collected at full fold (24) will result in a minimum signal-to-noise improvement of √24 (National Academy of Sciences, 1976).

The common mid-point (CMP) fold or multiplicity is a function of the group interval, the number of channels and the shot point interval. A higher CMP fold implies a higher signal-to-noise ratio (SNR) due to trace summation resulting from CMP stacking process.

$$\text{CMP fold} = \frac{\text{Number of channels} \times \text{Group Interval}}{2 \times \text{Shot Interval}}$$

Spacing of the hydrophones influence the resolution of the data. Closer spaced hydrophone arrays will be able to collect higher frequency content data and provide better resolution of the shallow subsurface than wider spaced hydrophone arrays. Ultra-high resolution multichannel surveys now utilize streamers with 1 to 2-meter group intervals.

Multichannel streamers used in engineering surveys in the US are commonly either at 1.56mgi or 3.125mgi.

The length of the streamer also influences the depth of investigation for the streamer and is approximately equal or the streamer length. The length should be at least 90 percent the targeted imaging depth. For example, if the seismic investigation target depth is 80 meters, then the streamer length would be about 72 meters long.

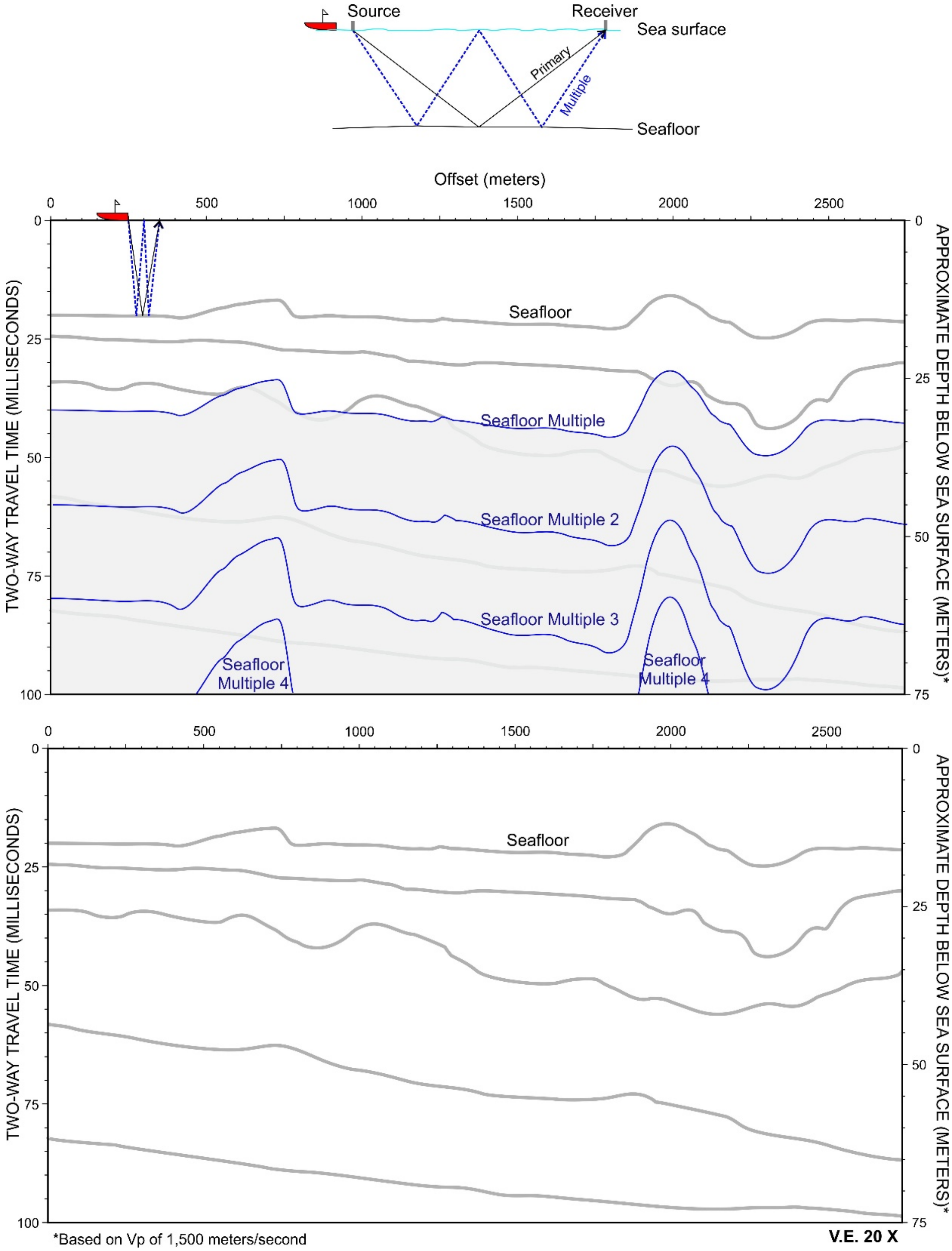

Figure 2.3. Schematic of water bottom multiples in seismic reflection data

Top image provides a schematic showing a ray path solution for a primary event reflecting off the seafloor and the first seafloor multiple. The middle image presents a schematic of how the seafloor multiple(s) occur in data and interfere or degrade other data. The lower image illustrates a concept of what data with just primary events would appear without water bottom multiples. Multichannel seismic reflection data provide opportunity to mitigate effects of water bottom multiples through the data acquisition and processing.

2.1.7.1 Seismic Data Processing

Seismic data processing is constantly evolving and as new methods and computational capabilities are developed. Most of the multichannel data processing procedures were developed for the oil and gas industry. Data processing methods and techniques should be selected based on the types of data collected (e.g. energy source and streamer configuration), water depths, geologic conditions, and targeted depth of interest. Multichannel data processing incorporates the follow steps.

Step 1. Trace Editing, Scaling and Filtering

The first step used in both processing flows, after loading the segy data into the processing workstation, is to filter and scale the data. Preliminary review of data traces to edit or "kill" bad traces is performed. An antialias filter is used as a band-pass filter to avoid aliasing in the time domain above the Nyquist frequency and to remove low-frequency streamer noise, like bulge waves and water wave motion. Filtering (e.g. Ormsby filter [trapezoid band-pass shape]) is applied to the data. Scaling is then applied in two parts: first to remove the geometrical spreading attenuation with a time varying exponential function, and second to equalize the average amplitudes of each trace in the data set, using an RMS scaling factor for a window of data with reasonable signal-to-noise ratio.

Step 2. Spiking Deconvolution

Spiking deconvolution is applied to shrink the original source wavelet down to an "ideal" zero-phase wavelet that is consistent from trace-to-trace and record to record. With infinite bandwidth, this ideal trace would be a delta function, or spike at the appropriate arrival time. For real band-limited data, a Ricker or similar symmetrical wavelet with minimal side-lobes is desired. Spiking deconvolution is used a defined operator length and then filtering is applied after deconvolution to eliminate high-frequency noise.

Step 3. Spatial Filter Design and Velocity Analysis

After the first trace processing and editing steps, frequency-wavenumber (FK) analysis is done on select shot records to design FK filters to attack spatial aliasing. Aliasing due to inadequate sampling in the spatial domain is often overlooked and may result in data artifacts from aliased high-frequency events that may appear as real reflection events. For marine data, where the velocity of sound in water is about 1,500 meters per second (5,000 feet per second), we can predict the frequencies where coherent noise traveling through the water past the streamer may become aliased. These frequencies are lower than much of the source energy, and so array forming in the streamer must be accomplished to attenuate noise traveling horizontally in the water column. Direct source to streamer wave propagation produces this coherent noise energy as does propeller noise in the water from the shooting vessel as well as from other ships passing through the area.

Velocity analysis Is performed to determine stacking velocities for subsurface reflection events. Processing software utilizes semblance and constant velocity stacked traces to aid in picking stacking velocities, as well as providing predictions of hyperbolic move-out plotted directly on offset gathers of seismic traces.

Step 4. Normal Move-out Correction and Stack

The deconvolved and filtered traces were sorted into the CMP order, spatially filtered and stacked to produce a CMP stack record section.

Step 5. Post-Stack Migration

Stacked data contain hyperbolic reflections and diffractions that need to be collapsed into proper spatial locations to further sharpen the image of subsurface reflection horizons and faults.

Step 6. Post-Migration Predictive Deconvolution

Because some reverberation or "ringing" of reflective horizons may appear, a post-migration predictive deconvolution can be applied to suppress the multiples. Predictive deconvolution is used to attenuate multiples; from the water bottom and from interbed reverberations.

During long duration seismic surveys, it would be desirable to perform preliminary data processing on board the vessel or at an onshore facility to monitor the quality of the data if the data can be efficiently transmitted at frequent interval

2.2 SURVEY APPROACHES AND SCHEDULES

2.2.1 Vessels

Selection of survey vessel are based on a variety of factors including:

- Suitability for type of survey,
- Size and duration of survey,
- 12-hour (daylight hours) or 24-hour operation,
- Distance from shore and water depth,
- Ability to control appropriate survey speeds and maintain course, and
- Vessel stability, deck space, and overall condition.

Survey vessels are either purpose built for surveying or can be vessels of opportunity (e.g. fishing trawlers, work boats, etc.). Advantages of using a local vessel of opportunity include:

- They may negate the need to mobilize a survey vessel from a long distance,
- Captain and crew may be familiar with the local sea state conditions and weather patterns, and
- Provide an opportunity to involve the local community.

Some of the disadvantages of using a local vessel of opportunity:

- Equipment set-up and configurations may have to be compromised and could affect quality,
- May not be as stable as a purpose built vessel and this could affect productivity and data quality,
- May not have ideal on-board facilities for data processing, and
- Vessel captain and crew may not be familiar with survey methodology and ability to stay on course and maintain the slow survey speeds may be difficult.

Survey vessels come in various sizes and should be selected based on suitability for the survey and working in anticipated sea states and weather conditions. Although data quality thresholds are usually affected before safe operation of a vessel with respect to sea states, the larger or more stable vessels can provide safer platforms for working, can stay at sea longer and during weather, and could continue collecting certain types of data (e.g. multibeam) if necessary. Shallow towed hydrophone streamers are typically the most sensitive survey equipment to sea states. Some advantages and disadvantages to various classes of survey vessels.

<u>Small Sized Vessels (15 to 20 meters in length)</u>

Advantages:

- Can access shallow water areas (e.g. shoals and inshore surveys),
- During good weather windows may be able to complete small surveys offshore, and
- Lowest day rate cost.

Disadvantages:

- Most sensitive to weather and sea state,
- Limited to 12-hour surveys,
- Cannot stay offshore,
- Limited space on board for crew, PSO's, and client representative(s), and
- May not be able to run all systems at once.

<u>Intermediate Sized Vessels (20 to 30 meters in length)</u>

Advantages:

- Can work offshore,
- Can stay offshore for a few days,

Disadvantages:

- More weather sensitive than large vessels,
- Cannot stay offshore for long periods of time,
- May not have adequate space for vessel crew, surveyors, data processors, PSO's, and client representatives.

Large Sized Vessels (>30 meters in length)

Advantages:

- Can work offshore and is most stable platform,
- Can stay offshore for long periods of time,
- 24-hour operations are possible.
- Have adequate space for vessel crew, surveyors, data processors, PSO's, and client representatives. Survey programs can require 25 to 35 people to be on board the vessel at one time.

Disadvantages:

- Most expensive day rate,
- May not be able to access shallow water,
- Limited availability of purpose-built vessels where wind energy areas are located. May need to be mobilized from Gulf of Mexico, Caribbean, or Europe.

Marine survey activities in the Atlantic OCS have the potential to impact marine resources. Many of the types of equipment described in this study utilize active acoustic sources that may affect marine animals if they are a close enough to the acoustic source when it is operating. The level of impact to the marine animal is related to the intensity of the acoustic signal, distance between acoustic source and animal, and type of animal and its sensitivity to the acoustic signal when it is encountered.

The intensity and decay of a transmitted acoustic signal (sound wave) is commonly described using the decibel scale where the change in intensity of the sound wave due to purely spreading loss from the source is given by the equation:

$$I_{dB}=10\log_{10}\frac{I_2}{I_1}$$

where I_{dB} is the intensity of the signal in decibels and I_1 and I_2 are the linear intensity measured at two locations. The equation above is used to describe signal strength such that a -10 dB drop in the intensity means a drop in the intensity by a factor of 10 given the logarithmic nature of the decibel scale. Therefore, a -20 dB reduction is a drop in the intensity by a factor of 100 and a -30 dB drop is a drop by a factor of 1000 (Evans, 1997; Hansen, 2011). An important parameter that helps characterize the seismic source and its impact on marine mammals is the Sound Pressure Level (SPL). The SPL, with units of decibels (dB), in water is defined:

$$\mathrm{SPL} = 20\log_{10}\frac{p}{p_{\mathrm{ref}}}$$

National Marine Fisheries Service (NMFS): Marine Mammal Protection Act

Level A Harassment: sound levels > 180 dB re 1 μPa (RMS)

Level B Harassment: sound levels > 160 dB re 1 μPa (RMS)

Table 2.7 provides a summary of typical decibel levels for various sound sources. BOEM's Final Programmatic Environmental Impact Statement for Proposed Geological and Geophysical Activities in Mid-Atlantic and South Atlantic Planning Areas (BOEM, 2014) provides a detailed discussion of the marine survey sound sources, marine wildlife, anticipate levels if impact on the wildlife, and recommended mitigation actions. Wind developers should ensure that appropriate permits are obtained for conducting marine surveys and allow time for procuring any required permits.

Table 2.7. Acoustic Sources Used in Renewable Energy Program High-Resolution Geophysical Surveys (BOEM, 2014 Volume 2 Table 1)

Sources	Frequency Range	Modeled Frequency in Draft PEIS, Appendix D	JASCO Modeled Frequency Max Threshold Radii for Level B Impulsive Harassment (rms SPL, 160 db ispoleth) (Draft PEIS Appendix D)	JASCO Observed Distance to SPL 160 dB isopleth (Martin et al. 2012)	JASCO Observed Distance to SPL 160 dB isopleth (Zykov and MacDonnell 2013)
Vessel Noise	Broadband	Not Modeled	Not Modeled	20 m to 120 dB (broadband)	< 150 m to 120 dB (broadband, filtered 10 Hz to 100 kHz)
Boomer	200 Hz – <14 kHz	200 Hz – 16 kHz	1 km - 2.1 km (<20m)	12 m [300 Hz – 14 kHz]	
Sub-bottom Profiler	500 Hz – 200 kHz	Knudsen Chirp 3260 3.5 kHz, 12 kHz, and 200 kHz Knudsen Chirp 3260 3.5 kHz; SL, assumed 210dB [note this is a multichannel sub-bottom profiling echosounder and not a chirp seismic used in deepwater applications]	350 m – 1 km [< 700 m] < 50 m		
Chirp	500 Hz – 24 kHz		Not Modeled	10m [<450m]	

Sources	Frequency Range	Modeled Frequency in Draft PEIS, Appendix D	JASCO Modeled Frequency Max Threshold Radii for Level B Impulsive Harassment (rms SPL, 160 db ispoleth) (Draft PEIS Appendix D)	JASCO Observed Distance to SPL 160 dB isopleth (Martin et al. 2012)	JASCO Observed Distance to SPL 160 dB isopleth (Zykov and MacDonnell 2013)
Side Scan Sonar	100 kHz – 900 kHz (some SSS exceed 900 kHz; application on the OCS is limited)	100 kHz / 400 kHz	500 – 650 m [<450m]		
Multibeam	70- 500 kHz (lower frequency MB available to 12 KHz but only for deepwater applications)	240 kHz	150m [<20m]	1m [260-400kHz]	
Swath	100-600 kHz		Not Modeled		<10-20 m [234 kHz]
Single Beam	3.5 kHz–540 kHz (typically >20 kHz)		Not Modeled	2m [70/200kHz]	

2.2.2 Line Spacing

One objective of implementing phased approaches in surveying is to use the initial survey to begin developing a geologic framework that can be used to inform the development process of the lease area and plan subsequent site investigation work. Line spacing will affect the resolution and detail of the ground model, ability to identify or define geologic features, and interconnectivity of various features (e.g. buried paleo-drainage networks). Projects in areas with complex geology may derive more benefit from closer spaced regional lines than areas with more uniform geologic conditions. Readers should refer to Virginia Wind Energy Geophysical Survey Phase 2 Study (Fugro, 2016) for a discussion of line spacing and orientation effects in interpreting buried features. An example of the sizes of geologic features and their interconnectivity that can be interpreted from regional surveys is provided in Figure 2.4.

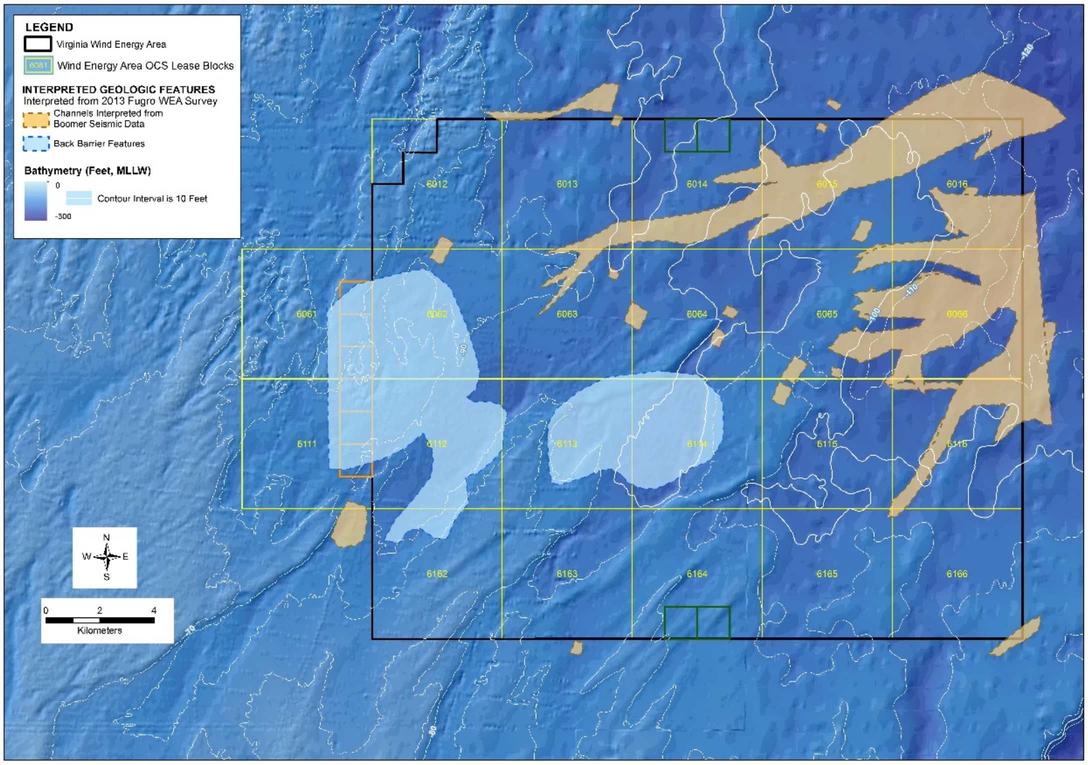

Figure 2.4. Example geologic features defined in a regional survey

Line spacing will influence the size of geologic features and their interconnectivity that can be resolved in surveys. Mapped geologic features shown in this Virginia wind energy area survey map, were interpreted from a regional survey that utilized a nominal line spacing of 1.5 by 3.5 km. Large buried paleochannel features (brown) were interpreted in the north, northeast, and eastern portions of the survey area. Two large back-barrier embayment features (light blue) were also interpreted from the data. The large features are about 1 to 4 kilometers wide and extending across several survey lines. Numerous other paleochannel features less than 1 km were identified in the data but their interconnectivity could not be interpreted. (Source: Fugro, 2013).

The buried features shown in Figure 2.4 were interpreted from the regional seismic survey. Those buried features are covered by younger marine deposits that exhibit a complex morphology. Inter-relationships between the seafloor morphology and subsurface conditions are important to understand when developing a ground model. Publically available data sets can aid in developing this framework, especially if those publically available data can fill gaps in the preliminary regional surveys. In the example shown in Figure 2.4, bathymetric data collected by NOAA and publically available, were used to develop a detailed regional seafloor model and aid the interpretation of the regional seismic data. Such valuable publically available data can be identified and synthesized into a database before surveys are conducted. This is one of the values that a desktop study provides at early stages of project development. Desktop studies are used to compile and synthesize available data that are used to develop a geologic framework. The geologic framework is used as a starting point to plan the geophysical and geotechnical investigations and begin the development of the ground model.

2.2.3 Integration of Temporally Different Data

If surveying is performed using a phased approach, then consideration for temporally sensitive data should be taken into account for the potential effect of merging data collected at different times. Dynamic processes can modify the seafloor and the magnitude of those effects may vary with respect to water depth, seafloor materials, and hydrodynamic conditions. The three most significantly affected types of data include bathymetric, side scan sonar, and magnetometer data.

Changes in the seafloor due to erosion, deposition, or movement of bedforms (e.g. sand waves) will affect the bathymetry. This could result in apparent seam artifacts where swaths from surveys conducted at different times meet each other. Migration of bedforms will result in an offset of the seam featured at the swath boundaries. However, if movement direction and rate of features can be interpreted two different bathymetric data sets, then this can provide valuable information used in evaluating potential sediment transport hazards (e.g. sand wave mobility hazards). If bathymetry data from two different surveys are combined, then edge or seam affects should be identified and described in order to avoid them being mistaken for real features.

Side scan sonar data can also be affected in a similar manner as bathymetric data. Features (e.g. sand wave crests) that have moved in between surveys will appear to be misaligned on side scan sonar data boundaries. However, if this process is captured in the two data sets, then this information may assist in evaluating bedform rates of change and movement direction.

Side scan sonar mosaics may have apparent seam artifacts when mosaicking sonar data collected by different sensors, using different acquisition settings (e.g. gain), or processed by different operators or using different software. Such artifacts should be identified and described in reporting to avoid mistaking for real features.

Since side scan sonar data are also used to identify shipwrecks and anthropogenic hazards, consideration should be taken into account for the length of time since the side scan sonar data were collected and when bottom disturbance activities will occur that could be sensitive to bottom obstructions (e.g. jacking up for geotechnical investigation or installation vessels).

Magnetometer data also have the potential to be affected if collected at different times and/or using different sensors. Gridding and contouring of magnetometer data collected using different sensors with different sensitivities and/or at different times will have seam effects if not addressed appropriately. Gridding and contouring of the residual magnetic field (deviation from the total and local field) should mitigate seam effects allow anomalies to be observed in merged data sets.

2.2.4 Survey Data Processing Bottlenecks

During large survey programs, it will be necessary to conduct data processing while the survey is ongoing to:

- Monitor and assess the quality of the data,
- Identify data gaps, and
- Identify data that need to be recollected.

In some cases, data interpretation may also be conducted during survey operations to support planning of other activities. For example, the survey vessel may also be used to conduct sediment grab sampling or biological surveys. Processing and interpretation of side scan sonar and/or multibeam data may be necessary in order to select sampling/camera locations.

Multibeam and seismic data represent two time and resource intensive data processing activities. During large programs it is common for processing to be performed on board the survey vessel. Initial checking and cleaning of the multibeam data can performed; final processing can also be performed on the vessel or deferred to the office.

Preliminary processing the seismic data usually is comprised of navigation checks and brute stacking. Some preliminary velocity analyses may be performed on board. If radio-telemetry capacity is adequate, data may be transmitted from the vessel to a shore-based office to conduct data processing. Final processing is commonly performed in an office. If the regional survey interpretation is being used to plan a geotechnical survey in the same season, then final processing and interpretation may need to be conducted while the survey is ongoing in order to have interpreted results available for use in planning. The final processing and interpretation can be conducted in a land based office.

2.3 ABBREVIATIONS

BS	Backscatter
A/B	Length-to-Width Ratio
CARIS	Computer Aided Resource Information System, part of Teledyne Technologies Inc.
CFR 585	Code of Federal Regulations Part 585
cgs	centimeter-gram-second
cm	Centimeter
CME	Coronal Mass Ejection
COP	Construction Operations Plan
CVA	Certified Verification Agent
D	Distance
dB	Decibel
DTS	Desktop Study
ESRI	Environmental Systems Research Institute
FM	Frequency Modulated
G&G	Geological and Geotechnical
GAP	General Activities Plan
GeoHab	Geological and biological Habitat mapping research group
GIS	Geographic Information System
GPS	Global Positioning System
HRG	High-Resolution Geophysical
Hz	Hertz
IHO	International Hydrographic Organization
J	Joules
k	magnetic susceptibility
kHz	kiloHertz
km	kilometer
lb	pound
m	meter

M	Dipole magnetic moment
MBES	Multibeam Echosounder
mgi	meter group interval
mm	millimeter
MMO	Marine Mammal Observer
NEPA	National Environmental Policy Act
NHPA	National Historic Preservation Act of 1966
nT	nanoTesla
O&G	Oil and Gas
psi	pounds per square inch
QPS	Quality Positioning Services BV software company
QTC	Quester Tangent Corporation
ROV	Remotely Operated Vehicle
RTK	Real-Time Kinematic satellite navigation
SAP	Site Assessment Plan
SBES	Single Beam Echosounder
SNR	Signal-to-Noise Ratio
SSS	Side Scan Sonar
UK	United Kingdom
UNB	University of New Brunswick
UNH	University of New Hampshire
US/U.S.	United States of America
UXO	Unexploded Ordnance
W	Weight
WEA	Wind Energy Area
ΔM	Change in magnetic field associated with a magnetic anomaly

2.4 REFERENCES

Allen, F.T. (1972) Some characteristics of marine sparker seismic data. Geophysics, vol. 37, pp. 462-470.

Bellefleur, G., Duchesne, M.J., Hunter, J., Long, B.F., and Lavoie, D. (2006) Comparison of single- and multichannel high-resolution seismic data for shallow stratigraphy mapping in St. Lawrence River estuary Quebec. Geological Survey of Canada, Current Research 2006-D2, 10 pp.

Breiner S. (1999), Applications manual for portable magnetometers, San Jose, California: Geometrics. 58 pp.

Bright, J., Carrier, B., Conlin, D., Danforth, W. Hoffman, W., King, J., Oakley, B., MacDonnell, J., Robinson, D., Schwab, W., and Zykov, M. (2013) Collaborative Archaeological Investigations and Sound Source Verifications within the Massachusetts Wind Energy Area. Final Report to the U.S. Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs. OCS Study BOEM 2013-221. 266 pp.

Bureau of Ocean Energy Management (BOEM) (2015a), Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585, Office of Renewable Energy Programs, July.

Bureau of Ocean Energy Management (BOEM) (2015b), Guidelines for Providing Archaeological and Historic Property Information Pursuant to 30 CFR Part 585, Office of Renewable Energy Programs, July.

Bureau of Ocean Energy Management (BOEM) (2014) Atlantic OCS Proposed Geological and Geophysical Activities, Mid-Atlantic and South Atlantic Planning Areas, Final Programmatic Environmental Impact Statement. BOEM 2014-001.

Camidge, K., Holt, P., Johns, C., Randall, L. and Schmidt, A. (2010) Developing Magnetometer Techniques to Identify Submerged Archaeological Sites Theoretical Study Report. Cornwall Council Historic Environments Projects, 121 pp.

Edgerton and Hawyard, (1964) The Boomer sonar source for seismic profiling. Journal of Geophysical Research, vol. 69, pp. 3033-3042.

Fugro Consultants (2016) Virginia Ocean Geophysical Survey, Phase II Analyses, Offshore Virginia Wind Energy Area. Prepared for the Commonwealth of Virginia, Department of Mines, Minerals, and Energy and the Bureau of Ocean Energy Management.

Fugro Consultants (2013) Regional Geophysical Survey and Interpretive Report, Virginia Wind Energy Area, Offshore Southeastern Virginia. Prepared for the Commonwealth of

Virginia, Department of Mines, Minerals, and Energy and the Bureau of Ocean Energy Management.

Gostnell, C. (2004) Efficacy of interferometric sonar of hydrographic surveying: Do interferometers warrant an in-depth examination? Report by Hydrographic Survey Division, Office of Coast Survey, National Ocean Service, National Oceanic and Atmospheric Administration.

Gostnell, C., Yoos, J., and Brodet, S. (2006) NOAA Test and Evaluation of Interferometric Sonar Technology. Report by Hydrographic Survey Division, Office of Coast Survey, National Oceanic Service, National Oceanic and Atmospheric Administration.

IMCA S 017 (2011) Guidance on vessel USBL Systems for use in offshore survey and positioning operations.

International Hydrographic Organization (2008) IHO Standards for Hydrographic Surveys, Special Publication No. 44, 5th ed., International Hydrographic Bureau, Monaco.

Lucieer, V., Roche, M., Degrendele, K., Malik, M. & Dolan, M., (2015) Chapter 3: Seafloor backscatter user needs and expectations. In Lurton, X.; Lamarche, G. (Eds.) (2015) Backscatter measurements by seafloor mapping sonars. Guidelines and Recommendations. pp 53-78.

Lurton, X. and Lamarche, G. (2015) Backscatter measurements by seafloor-mapping sonars; Guidelines and Recommendations. GeoHab Backscatter Working Group, May 2015.

Martin, B., J. MacDonnell, N. E. Chorney, and D. Zeddies. (2012) Sound source verification of Fugro Geotechnical Sources: Final report: Boomer, sub-bottom profiler, multibeam sonar, and the R/V Taku. JASCO.

Mitchell, T. and Smith, K. (2014) Investigations of Marine Geohazards for Coastal Infrastructure Projects. Sea Technology Magazine, March.

National Academy of Sciences (1976) Multichannel seismic reflection system needs of the U.S. Academic Community. Steering Committee of the Ocean Sciences Board, Assembly of Mathematical and Physical Sciences, National Research Council.

Plets, R., Dix, J., and Bates, R. (2013) Marine Geophysics Data Acquisition, Processsing and Interpretation: Guidance Notes. English Heritage, Swindon, UK, 48 pp.

Yilmaz, O. (2001), Seismic Data Analysis. Society of Exploration Geophysicists, Tulsa, Oklahoma, 2027 pp.

Zykov, M., and MacDonnell, J. (2013) Sound source characterizations for the collaborative baseline survey offshore Massachusetts Final report: Side-scan sonar, sub-bottom profiler, and the R/V Small Research Vessel experimental. JASCO.

FUGRO MARINE GEOSERVICES, INC.

VOLUME 3

GEOTECHNICAL INVESTIGATION BENEFITS AND RISKS

Study Title:

Geophysical and Geotechnical Investigation Methodology Assessment for Siting Renewable Energy Facilities on the Atlantic OCS

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3.1 GEOTECHNICAL SITE INVESTIGATION PLANS

Preliminary geotechnical site investigation plans are typically drafted based on desktop studies and / or geophysical data collected at the project site. Preparing these plans involves selecting: 1) vessels / platforms, 2) in-situ testing techniques, and 3) type of samplers. These selections should be based on the anticipated site conditions (e.g. stratigraphy, water depth, and geohazards), the needs of the project, and the applicability / limitations of the different available options. Other important selections made as part of the planning stage include the frequency of in-situ testing and sampling within the program, and an estimate of the anticipated / target depth of each exploration for different foundation systems. It is important to note that geotechnical site investigation plans should be constantly updated, whenever necessary, as more information about the project and site conditions are available. Hence, offshore geotechnical investigations are typically managed by a marine geotechnical engineer or a geologist with an extensive experience in the offshore industry.

3.1.1 Selection of Optimum Vessel/Platform for Offshore Investigations

There are several types of platforms that can be used to conduct offshore site investigations. Each vessel has its own set of advantages and disadvantages; two of the more common types are 1) dynamically positioned (DP) or anchored drilling vessels or 2) jack-up rigs. The selection of the optimal platform relies on many factors that in most cases are site-or project-specific. For example, 1) DP vessels cannot be used if the water depth is less than 30 meters, 2) DP vessels are typically much more expensive than standard vessels, but it takes less time for a DP vessel to position at a certain location compared to a standard one. Hence, the balance between cost and benefit plays a major role in selecting the suitable vessel. Table 3.1 presents various platforms used in offshore geotechnical investigations along with its advantages, disadvantages, and range of applicability.

Table 3.1. Applicability and limits of various geotechnical investigation platforms

Platform Type	Description	Notes
Dynamically positioned vessels (Figure 3.1)	-A vessel supplied with a dynamic positioning (DP) system that is computer controlled -The system is intended to maintain the position of the vessel by using its own propellers and thrusters. Station keeping to no more than 1% of water depth	-Suitable for water depths between 30 and 3,000+m (100 and 10,000+ft). -Required for water depths of 2,000 m (6,600 ft) and beyond. -Less sensitive to weather. -Fast set-up and moving between locations (a DP vessel might need approximately 30 to 45 minutes to collect information from the different sensors that measure the environmental loads, wind and current, to keep the vessel in place during the drilling operations). -Heave compensation units can work in sea states with up to 7 m (23 ft) heave. -Generally, much higher day rate cost than other vessels.
Jack-up platforms	-A specialized vessel that is supplied with	-Suitable for shallow waters up to approximately 40 m (130 ft). Randolph and Gourvenec, 2011 reported its viability up

Platform Type	Description	Notes
(Figure 3.2)	multiple vertical legs (usually 4 but sometimes 3). Once in position, the legs are lowered to elevate the vessel above water level. A large enough clearance (air gap) between the vessel and water level should be chosen which depends on the tides and wave heights.	to 120 m (400 ft) using lift boats. -Provides stable platform with no requirement for heave compensation for the drilling equipment. -It is rarely affected by weather once elevated and in operation. -It cannot be jacked-down or jacked-up in case of rough sea or major storms. This can cause significant delays and lower the productivity. -Can be very sensitive to laterally heterogeneous soil conditions since a sudden or excessive penetration of one of the legs compared to the others can cause serious incidents. This risk is mitigated by pre-loading the legs. For this reason, 4-legged platforms generally preferred to 3-legged. -Generally, need additional vessels for moving and supply.
Standard vessels (anchored; Figure 3.3)	-Any standard vessel can be used in offshore geotechnical investigation given it has a suitable size and capacity. In this case, dismountable rigs are generally deployed on these vessels to conduct the investigation.	-Suitable for water depths up to approximately 1,200 m (4,000 ft). -Standard vessels with moon-pool are generally the preferred option in this case. -Longer periods for anchoring and set-up compared with DP vessels. -Standard vessels may not have adequate freeboard protection which limits their operation in rough seas. -Requires at least 4-point anchor spread to remain in stable location.
Seafloor drill (Figure 3.4)	-These are specialized marine drill rigs that can be lowered to the mudline and remotely operated from the vessel deployment.	-Less sensitive to weather conditions and ability to operate in strong currents. -Reduced pipe handling. -Lower HSE risk. -Costly and specialized equipment that is difficult to acquire. -Limited number of systems available.

Figure 3.1. An example of a dynamically-positioned vessel (Fugro Explorer)
(Source: www.fugro.com)

Figure 3.2. Example of jack-up platforms (Fugro Excalibur and Deep Diver)
The jack-up platforms were used to conduct maintenance operations at the Arklow Bank Offshore Wind Farm, in the Irish Sea
(Source: www.fugro.com)

Figure 3.3. Example of a standard vessel used in offshore drilling
(Source: http://www.ryanmarine.com/)

Figure 3.4. Example of seafloor drill (Portable Remotely Operated Drill)
(Source: www.benthic.com/)

3.1.2 In-Situ Testing

This section is intended to give a brief introduction of the different in-situ tests that can be conducted offshore.

3.1.2.1 Cone Penetrometer Test (CPT)

Cone penetrometer tests (CPTs) are widely used for in-situ geotechnical characterization of ground conditions (ASTM D5778). CPTs involve the measurement of the resistance of ground to steady and continuous penetration of a cone penetrometer equipped with internal sensors. The cone sensors measure tip resistance, sleeve friction and pore pressure generated during the push. This allows for obtaining continuous profiles of the different soil properties when compared to the discrete nature of the various soil sampling techniques. The measurements can be used to evaluate the SBT (soil behavior type) of the subsurface sediments. Moreover, they can be used to estimate a wide variety of engineering parameters using industry-standard correlations (e.g. see Mayne, 2007 for more details).

CPTs can be problematic to advance in very dense sand, gravelly soil deposits, and cannot penetrate rock. They generally encounter shallow refusal in these materials and the instruments can be damaged if advanced in such deposits. On the other hand, the sensitivity of the CPT might not be enough to capture the subtle variations in material type or strength in the case where very soft fine-grained sediments are encountered. Parameters driven from data collected from weakly cemented carbonaceous or marl deposits in the South Atlantic might not be reliable.

CPT soundings are conducted in different modes when used for offshore site investigations, namely: seabed, downhole, and top push. Table 3.2 lists the different advantages and disadvantages of each system.

Seabed CPT. In the seabed CPT mode, the cone is pushed from the seafloor typically until reaches refusal, full length of the cone rods / coil, or target depth. This mode is frequently used since it provides a continuous profile of subsurface conditions and can be deployed using smaller vessels that can transit and set-up on the exploration location quickly. The lower cost associated with the smaller vessels used to deploy the seabed CPTs and efficiency of the exploration make this attractive tool in the investigation scheme. Depth of exploration is limited to the reaction force that the seabed frame and ballast provide or the length of the rods or coil. The larger end of the seabed CPT spectrum is comprised of units that provide 20 tons of reaction force. Smaller, lighter weight CPTs that can be deployed using smaller vessels, usually have smaller cone sizes, and are commonly coil based.

Smaller, lighter weight seabed CPTs are commonly used for export cable route investigations since they typically are used to explore the upper few meters. Larger, heavier seabed CPT systems (e.g. 20 ton units) are commonly used to investigation the turbine locations. Very dense sands, gravelly soils, very stiff clays, and some glacial tills may limit penetration depths of seabed CPTs. Hence, dense glacial deposits and shallow pre-Quaternary deposits in the New England region and the carbonaceous or marl deposits in the South Atlantic could limit penetration depths of some seabed CPT systems.

Downhole CPT. In the downhole CPT mode, the cone is pushed from the bottom of a borehole. Hence, downhole CPTs can be conducted at relatively large depths compared to the seabed mode. In essence, their probe limit is related to how far the borehole drill-string can be safely advanced. This also allows for pushing CPTs in soil profiles with hard and/or dense layers. While adopting this mode, CPT and drilling can be alternated which allows for collecting CPT data and samples that can be tested in the laboratory at the same borehole location; this is important for cross-correlation. In cases where the CPT soundings are needed up to the proposed depth, rather than up to refusal, seabed CPT is specified until refusal followed by downhole CPT till the predefined depth. One of the disadvantages of this mode is that its data is generally affected by drilling disturbance. While sampling and obtaining CPT data at the same location is sometimes useful, the discontinuity in CPT data might result in overlooking layers that could impact the design of the foundations.

Top Push CPT. CPT equipment developed for onshore applications can be used for nearshore projects given the availability of a suitable working platform and precautions are taken to prevent buckling of the rods during operations. This kind of system is known as top push (deck push) CPT systems. The water depth where this system is applicable is relatively limited and depends on the available equipment, environmental conditions (current, waves and wind speeds) among other conditions. In general, the applicability of this system is up to about 25 meters of water depth.

Table 3.2. Advantages and disadvantages of the various CPT systems

CPT System	Notes
Seabed	**<u>Advantages:</u>** -Easier and quicker operation compared to downhole system. -Can be easily relocated few feet in case of shallow refusal. **<u>Disadvantages:</u>** -Shallow refusal is possible if the surficial layers are dense / hard. **<u>Applications within the Atlantic OCS:</u>** -Risks associated with using this system are higher within the New England region due to the presence of glacial tills, glacial outwash, and moraines.
Downhole	**<u>Advantages:</u>** -Can reach large penetration depths -Advancement past hard / dense layers can be facilitated by drilling (referred to as “drill outs”) -Can be alternated with different in-situ tests (e.g. vane shear, piston, and tube samples) to obtain several data types from a single borehole. **<u>Disadvantages:</u>** -Slower production rate. -The sounding quality at the start of a CPT stroke is reduced due to soil disturbance from drilling **<u>Applications within the Atlantic OCS:</u>** -Risks associated with the system are typically lower that the seabed system especially within the northern Atlantic OCS. If shallow refusal is encountered, the system can be switched to drilling / coring mode to move past the obstruction (e.g. boulder, dense sand layer,…) then resume pushing the cone.
Top Push	**<u>Advantages:</u>** -Can make use of CPT rigs used onshore which can reduce the cost. **<u>Disadvantages:</u>** -This system can be used in limited water depths because of the possibility of buckling the rods. -Collecting CPT data offshore can be more challenging for contractors who predominantly have onshore experience. **<u>Applications within the Atlantic OCS:</u>**

CPT System	Notes
	-Would be particularly applicable to relatively shallow water depths. Hence, it might be used along export cable routes rather than at turbine locations.

There are several models of CPT equipment. Generally, each model is characterized by a maximum penetration depth and thrust force. Tip resistance (q_c), sleeve resistance (f_s), and pore water pressure (u) are the three most widely measured parameters. Other special parameters are measured by special CPT types and are used in a variety of geotechnical applications. Table 3.3 presents a list of the different types of cones and its applications.

Table 3.3. Different types of CPT tests used in practice

Type of CPT	Measurements	Notes*
Regular electric cone	q_c, f_s	-For most applications, the measurement of pore water pressure is standard. Hence, this CPT type is rarely used.
Piezocone Test	q_c, f_s, u	-The most popular cone type currently used in practice.
Piezocone test with dissipation	q_c, f_s, u	-As the cone advances into soil, it causes a change in pore pressure. This change can increase or decrease depending on the behavior of the soil deposit when sheared (contractive or dilative behaviors). In the case of this test, the cone penetration is stopped at specific depths. The change in pore water pressure is then measures versus time. This is used to back calculate the coefficient of consolidation and hydraulic conductivity (i.e. the dissipation characteristics). -In-situ dissipation test is time consuming especially for low permeability clay deposits. Hence, it is rarely conducted offshore.
Seismic Piezocone Test	q_c, f_s, u, V_s	-Is equipped with geophones to measure shear wave velocity profiles that can be used in dynamic analyses. -Seismic waves are imparted to the cone via external, seabed sound sources. -In seismically active areas, the measured velocity profiles can be used to assess liquefaction susceptibility and perform site response analyses. -For offshore applications within the Atlantic OCS, seismic CPT would be useful to measure the small strain shear modulus to be used in dynamic soil-structure interaction analyses.
Mini-cones	q_c, f_s	-Is characterized by a smaller cross sectional area than the regular CPT cones. -Pore water pressure is not commonly measured in this cone type. -Requires reduced force to penetrate into the different strata compared to the conventional size (10 cm^2). -The penetration rate of this cone type is typically double the standard penetration rate adopted in the rest of the cones. The change in penetration rate and the reduced cross sectional area should be accounted for if the data from this cone is used to develop design parameters. Hence, it is preferable to use these

Type of CPT	Measurements	Notes*
		cones in regions where prior geotechnical data is available (Danson, 2005). - It can detect very thin layers (i.e. higher resolution). A common example would be the detection of shells or shell beds. It can also detect thin sand layers within thick clay deposits which can have major implications on time rate of settlement in clay (Danson, 2005).
High Capacity Cones	q_c, f_s	-Typically double the capacity of regular cones (120 MPa versus 60 MPa). -Pore water pressure is not typically measured in this cone type. -It can be used to avoid refusal in dense sand deposits and is good for assessing max-outs in tip resistance.
CPT Stinger	-	CPT stinger is a long hydrodynamic dart that upon seabed impact will record dynamic cone penetration values. It then uses the reaction gained (around the perimeter) from embedment as a reaction to subsequently thrust an internal CPT for tens of meters below the initial penetration. The synthesized CPT plot is a combination of dynamic and static cone push results. Continuous data from seabed to 35 m (115-ft) can be acquired with this system.
Resistivity Piezocone Test	q_c, f_s, u, E_r	-Measures the electric resistivity profile versus depth which is used to investigate the corrosion potential for foundations and cables in contact with the soil -It can be used to localize potential contaminations within the soil deposit (see Campanella and Weemees, 1990)
Other types	Various	CPT cones can be modified to measure additional data / parameters. For example, adding heat probes to measure thermal conductivity of the soil.

Where: q_c = cone tip resistance, f_s = sleeve resistance, u = pore water pressure, V_s = shear wave velocity, and E_r = electric resistivity.
*Most of the information is based on Mayne (2007) and Lunne (2010).

3.1.2.2 PS Suspension Logging

PS suspension may be conducted after the drilling and sampling of a borehole. After completion of drilling, the borehole may be surveyed using a downhole geophysical technique. PS suspension logging is a technique used to measure the in-situ compressional (P) and shear (S) wave velocity profile of the subsurface. This velocity data profile is then used to determine dynamic soil properties including Poisson’s ratio, Young’s modulus and shear modulus. Additionally, the compressional wave profile data are commonly used to support time-to-depth conversion of seismic reflection data. Seismic reflection surveying is discussed in Volumes 2 and 4 of this study.

3.1.2.3 Ball Penetrometer Test (BPT) & T-bar Test (TBT)

Ball penetrometer tests (BPT) and T-bar tests (TBT) involve the in-situ measurement of the resistance of soil to continuous penetration at a steady slow rate of a cylindrical rod (Ball or T-Bar penetrometer, as applicable) positioned perpendicular to the lower end of push rods.

BPT / TBT soundings are particularly useful for strength profiling of relatively homogeneous very soft to soft clays and silts. Hence, its applicability within the Atlantic OCS is likely to be limited.

The procedure for conducting BPT / TBT soundings is similar to that of a CPT sounding. The cone penetrometer is unscrewed and replaced with the Ball / T-Bar penetrometer before deployment. TBT is difficult to perform within cased holes.

In addition to standard BPT / TBT soundings, cyclic testing can be performed during the seabed testing program as a means to classify the response of the soil to disturbance. A cyclic test consists of a number of downward and upward thrust cycles of the penetrometer at a certain depth.

3.1.2.4 Vane Shear Test

The in-situ vane shear test (VST) is widely used to measure the undrained shear strength of fine-grained deposits (ASTM D2573). The vane tool consists of a vane blade, electric motor to apply constant torque, a torque cell, and a vane carrier tool. The vane blade is advanced to the required depth (preferably adjacent to a previously conducted CPT sounding) and rotated at a constant rate. The measured torque is then correlated with undrained shear strength. The undrained shear strength from VST is generally expected to lie in between the values obtained from UU and CU triaxials because disturbance is expected to be minimal in the case of VST. After failure, the test can be rerun in the same material to measure the remolded strength; a residual value can also be measured by rotating the vane through consecutive 360 turns and recording the resistance. The main disadvantages of VST is that it provides discontinuous shear strength profiles and takes relatively more time to run when compared with CPT.

3.1.2.5 Pressuremeter Test

This in-situ test is generally associated with drilling boreholes since it consists of a flexible membrane that is inserted after a borehole is advanced. It is then inflated under equal pressure increments. The collected data is then used to estimate the pressuremeter modulus. This in-situ test was typically conducted in general accordance with ASTM D4719 that was recently withdrawn by ASTM without any subsequent replacement.

3.1.2.6 Dilatometer Test

The test consists of a blade that is equipped with an expandable steel membrane. Once the blade reaches a predefined depth, the membrane is inflated and the pressures needed to move the membrane by a preset amount is recorded. These numbers are then used to empirically estimate several soil properties that include: friction angle of coarse-grained deposits and undrained shear strength for fine-grained deposits. This in-situ test is conducted in general accordance with ASTM D6635. The strain range in this test is more limited when compared with the pressuremeter test. Deformation moduli can also be ascertained from this test.

3.1.2.7 Packer Test

A nitrogen Packer consists of two bladders separated by a set distance. The bladders are inflated with nitrogen to fill the confines of the borehole annulus. Water is then introduced within the space between the two bladders and the flow rate is related to the in-situ permeability (hydraulic conductivity). Typically grain size, fracture aperture and fracture frequency (RQD) control the measured permeability.

3.1.2.8 Thermal Conductivity

Thermal conductivity can be measured in-situ using a thermal conductivity probe (Danson, 2005).

3.1.2.9 Electrical Resistivity Test

Electrical resistivity of marine sediments is an important parameter used in the electrical design of cathodic protection of the foundation systems. Electrical resistivity can be measured in-situ using a seabed resistivity system (Danson, 2005). This system is applicable to water depths up to 2,000 m (6,500 ft). The electric resistivity measurements obtained from this system penetrate about 5 m (16 ft) below mudline. Electrical resistivity can be also measured using an electrical conductivity cone (Danson, 2005).

3.1.3 Drilling, Sampling, and Coring Techniques

3.1.3.1 Boreholes (Drilling / Coring)

Marine boreholes can be drilled using casing advancer or mud rotary wash systems depending on the expected stability of the sides of the borehole. In many cases, the drilling system is switched from casing advancer to mud rotary if a stiff fine grained layer is encountered. Rock coring is initiated once competent rock is encountered. Sampling of soils is sometimes alternated with downhole CPT to obtain samples for laboratory tests and CPT soundings at the same borehole location.

Several push (e.g. thin-walled, thick-walled Shelby tubes, and piston samplers), driven samplers (e.g. SPT split spoon), and rock coring techniques are typically used while drilling boreholes. The choice of the suitable sampler depends on the type of the layer (fine grained, coarse grained, or rock) and the nature of the layer (i.e. hard or soft). Push samplers are typically used to obtain relatively undisturbed samples from fine grained layers. Thicker wall tubes are used for stiffer soil layers, but thicker walls result in more disturbance to the soil sample compared to samplers with thinner walls. The push force is mostly provided by the wireline system or by pressurizing the drilling fluid / mud (Danson, 2005). Driven samples are typically obtained in coarse grained layers. Hence, these samples are for the most part considered disturbed. At shallow water depths, conventional SPT system can be used in offshore applications. In this case, it is important to note that the blow counts can be different than the standard blow counts obtained in onshore applications because of the additional energy losses seen in offshore boreholes. In deeper waters, the downhole wireline system is typically used to obtain driven samples. The downhole wireline system uses a 79.4 kg (175 lb) hammer dropped from 1.5 m (5 feet) which applies more energy than the standard SPT to be able to drive samples in deep water conditions. The blow counts in this case should not be directly used in empirical correlations to get design parameters since these correlations were developed using standard SPT blow counts. Rock coring devices can retrieve rock cores from 25 mm (1 in) to 150 mm (6 in) in diameter and 2 m (6 ft) to 6 m (18 ft) in length (Danson, 2005). Coring devices can be used to drill competent rock, cobbles, boulders, and stiff soil.

3.1.3.2 Piston Corer

Usually used to obtain high quality samples from surficial soil deposits. The length of the retrieved sample can be up to 30 m (90 ft). It can be deployed from a wide variety of vessels at practically any water depth. Hence, it should be an appropriate tool for application within the different regions of the Atlantic OCS.

3.1.3.3 Vibracorer

Instead of using gravity, vibracores use vibrations (heavily weighted oscillations) to penetrate through the soil layers. Hence, it can sample through dense sand, gravel and stiff clay layers. The retrieved samples are typically 3 to 8 meters in length. Due to the size and weight of the vibracore head assembly, it requires substantially sized vessels (Danson, 2005). It can be deployed up to a water depth of 1,000 m (3,000 ft). The vibrations used to penetrate the sampler induce disturbance to the soil samples. Hence, results of shear strength laboratory tests on these samples are not reliable.

3.1.3.4 Box Corer

Used to retrieve undisturbed block samples from surficial soil deposits. It is applicable for sampling soft fine grained sediments. The volume of the retrieved sample is about 25-30 liters (6.6-8.0 gallons). The retrieved samples are mainly used for environmental testing, ecosystem assessment, and characterization of the top 0.3 - 1.0 m (1 - 3 ft). It can be deployed in practically any water depth.

3.1.3.5 Grab Sampler

Available in many sizes and types. Hence, it can be deployed from a wide variety of vessels of different sizes. The retrieved samples are mainly used for environmental testing and ecosystem assessment. These samples are typically disturbed.

3.2 SAMPLING, TESTING, LOCATION, DEPTH AND NUMBER (STLDN)

Although not a universally accepted acronym, STLDN is easy to understand and provides a due-diligence thought process for a defensible geotechnical investigation program. The program must consider the question of how to acquire adequate geotechnical information that equates to the lowest acceptable risk to the project. If multiple wind turbines are planned in an area where complex geology is known to occur on the scale of a few tens of kilometers, then either 1) a set of explorations are assigned to each location to allow for design of individual foundation systems for each turbine or 2) a foundation system that would be suitable for a wide array of potential site conditions must be considered.

The geotechnical investigation program can be performed as a single or multiple phases over multiple years / seasons (see Volume I). In general, the geotechnical investigation schedule may look like the following:

a. Monopile or Jacket-Style foundation with piles

   i. One continuous seabed CPT, borehole (BH), or alternating downhole CPT / BH at each foundation location taken to 10 m (33 ft) below the hypothetical pile tip elevation. It is recommended that for 5% of the turbine locations, co-located seabed CPT and BH should be conducted.

ii. One deep boring at the center of the site and one along each side of the site.

iii. Additional borings based on geophysically-inferred variability.

iv. Additional CPTs for sample / testing correlation purposes.

v. Statistically-supported number of intermediary testing locations based on site variability.

b. Suction Caisson (for single bucket to multiple bucket support)

i. One BH with one co-located seabed CPT at each foundation location taken to 1.5 x caisson diameter below caisson design length or 10 m (33 ft) below whichever is greater.

ii. One deep boring at the center of the site and one along each side of the site.

iii. Additional testing locations based on geophysically-inferred variability.

c. Floating Foundations

i. Depending on the anchor system, typically 1-3 anchors spaced every 120° of spread distance. If piles or suction caissons are used as anchors, one BH or seabed CPT taken to 1.5 x pile / caisson diameter below its tip elevation or 10 m (33 ft), whichever is greater. If drag anchors are used, one BH or seabed CPT should be taken to 2 x the expected penetration depth of the anchor below sea floor. A single set of investigations is typically conducted at the center each anchor pattern. Depending on the variability inferred from the geophysical data collected, more than one set of investigations might be required for each anchor pattern.

ii. One CPT at the center of the anchoring array taken to the same depth for stratigraphic correlation purposes.

Of course, the main issue with the aforementioned programs is cost and time. Assuming a base-case of 100 wind turbines laid out in a square or rectangular pattern, the following table provides suggested guidance with respect to a phased geotechnical investigation program. This is based on a review of best practices and good engineering judgment. It is important to emphasize that these suggestions are generic. Hence, a marine geotechnical engineer should carefully assess each site and project-specific conditions to design an optimized program that include the number and type of explorations to be conducted in each phase of the investigation study (see Volume I for examples of site investigation plans). Final design must be in line with local regulations and approving authorities. Intermediary testing locations are those locations which are not located at foundation positions. CPT/BH should be taken at 100% of all the foundation locations but statistics of soils encountered in conjunction with geophysics results may support lowering this number, so long as the correlation is defensible.

Table 3.4. Geotechnical sampling and testing protocol for phased site investigations

Foundation	Test Types*	Testing Depth	Recommended Testing Schedule for Best Coverage
Piles	Seabed CPT, BH, or CPT / BH alternating	10 m below the tip elevation	**PRELIMINARY** 1 BH at each site corner and 1 BH along the edges of the site extents in the middle of the edge 1 CPT/BH in the middle of the site 1 CPT at the center of each quadrant for cross-correlation **FINAL (add these)** Statistically-supported number of intermediary testing locations based on geophysically-inferred variability *Single CPT/BH at 100% (MAX) of the foundation locations; percentage to be validated / amended (lowered) via stats variance values determined from general investigation results* CPTs are typically conducted before any other tests are undertaken
Suction Caissons	Seabed CPT co-located with BH	1.5 x Caisson OD below caisson design length or 10 m (33 ft) whichever is greater	**PRELIMINARY** 1 BH at each site corner and 1 BH along the edges of the site extents in the middle of the edge 1 BH in the middle of the site 1 CPT at the center of each quadrant for cross-correlation **FINAL (add these)** Statistically-supported number of intermediary testing locations based on geophysically-inferred variability *Single CPT/BH at 100% (MAX) of the foundation locations; percentage to be validated / amended (lowered) via stats variance values determined from general investigation results*

Foundation	Test Types*	Testing Depth	Recommended Testing Schedule for Best Coverage
			CPTs are typically conducted before any other tests are undertaken to define possible layers that may precipitate premature pile refusal
Floating Foundations	CPT, BH	1.5 x diameter below tip elevation if piles or caissons are used as anchors or 2 x the penetration depth if drag anchors are used	**PRELIMINARY + FINAL** 1 co-located BH / CPT in the middle of the anchor pattern. Additional co-located explorations might be needed depending on the geophysical data collected CPTs are typically conducted before any other tests are undertaken

*BH= Borehole

3.3 LABORATORY TESTING

Laboratory testing is an integral component of the design of offshore wind turbine foundations. The sophistication of laboratory tests and its applicability varies considerably. They can range from tests that can be easily and reliably conducted offshore in a few minutes while extracting samples from the seabed, to tests that require weeks to run and are conducted in highly-specialized onshore laboratories. In all cases, it is important to extract adequate samples to allow for an accurate characterization of the different soil properties that are relevant to the proposed foundation system. Part of this process is to maintain and preserve the separate samples in accordance with ASTM standards and other procedures listed in the contractual agreements. No matter how careful the preservation and transportation processes are, some samples may get damaged or become compromised during transportation. The testing results of these samples can be deemed unacceptable. Hence, it is a good practice to ensure collecting samples in excess to the number established by the preliminary laboratory testing program. This will ensure the availability of enough well-preserved samples for alternative or supplemental testing.

This section starts by introducing the concept of sample quality which is relevant to the laboratory tests subsequently presented. It then presents the various types of laboratory tests that are used to classify soils, measure consolidation and permeability characteristics, measure shear strength, and measure dynamic characteristics. The cyclic parameters relevant to the design of offshore foundation systems are highlighted towards the end of this section.

3.3.1 Sample Quality

Soil samples are generally described as either “disturbed” or “undisturbed” samples. The reality is that it is impossible to acquire a fully “undisturbed” sample, but it is a relative term that means that the sample is minimally disturbed to an acceptable limit.

Care must be taken to ensure intact or extruded samples are of the highest quality. Extruded samples should be sealed in air-tight bags, boxes or tubes using a combination of plastic wrap, tinfoil, wax and/or baggies. Samples may be stored in tubes maintained vertically and then placed in a refrigerated refer container for subsequent storage and transport. Samples may be stored at about seven (7) degrees Celsius (45 degrees Fahrenheit) with constant humidity, away from heat and excessive vibrations. Spatial orientation of the sample is important and generally samples are stored and shipped in a vertical position. In some cases, stiff clay soils may be transported in a horizontal position.

It has been widely acknowledged that sample disturbance might alter several parameters measured in the laboratory from its in-situ values. Hence, Lunne et al. (1997) investigated the effect of sample disturbance on multiple soil parameters using anisotropically-consolidated undrained triaxial and consolidation test results conducted on samples obtained using different samplers. They found that disturbance impacts multiple parameters including: volume change observed in the laboratory while consolidating the samples to the in-situ effective stresses, pre-consolidation stress, dilatancy parameter, coefficient of consolidation and constrained modulus.

Based on the findings of their study, Lunne et al. (1997) proposed using the ratio $\Delta e/e_0$ as a basis to estimate the quality of fine-grained soil samples where: Δe is the change in void ratio measured while reconsolidating the sample to its in-situ effective stresses and e_0 is the initial void ratio of the sample (see Lunne et al. 1997 for additional information). This assessment of sample quality should be subsequently used to approve or reject laboratory test results obtained from testing the different samples.

Obtaining coarse-grained samples with minimal disturbance is much more challenging than fine-grained samples. One approach to obtain such samples is to freeze the soil in-situ before sampling it. This approach is not widely used due to practical and economic considerations (Sivathayalan and Vaid, 2004). Yet this approach is used in important projects where testing of undisturbed coarse-grained samples is essential. Hofmann et al. (2000) described a methodology adopted to freeze loose sand deposits to obtain undisturbed samples.

In some cases, tube samples are X-rayed to assess the integrity of the samples before testing. This helps the laboratory manager or geotechnical engineer to select high quality specimens for testing. In addition to obvious discontinuities and potential disturbed sections, X-rays are used to locate inclusions (e.g. sand pockets, shell fragments, organic debris, voids from gas pockets, etc.). These inclusions can seriously compromise the laboratory test results. Testing samples with such inclusions can either yield unacceptable results or provide misleading results that do not represent the overall in-situ behavior of the soil deposits.

3.3.2 Classification Tests

3.3.2.1 Grain Size Distribution

Grain size distribution analyses are generally conducted in accordance to ASTM D422. The median particle diameter (D_{50}) for coarse-grained soils can be estimated from the typical gradation curve. D_{50} is an important parameter that can be used to estimate the interface friction angles between coarse-grained soils and the foundation systems (e.g. Jardine et al. 2005 and Lehane et al. 2005).

3.3.2.2 Atterberg Limits

Plastic and liquid limits, collectively termed the Atterberg limits, are considered among the most important test results used to describe characteristics of fine-grained materials. Both limits represent water contents at which the state of the soil changes. Namely, once water content exceeds the liquid limit, the soil behaves more like a liquid. On the other hand, soil behaves as a plastic solid if its water content falls between the plastic and liquid limits. Hence, water content and Atterberg Limits of a certain soil sample can provide the designer with a preliminary assessment of the behavior of the soil deposit. Moreover, many soil properties can be empirically estimated using Atterberg limits. Atterberg limits are generally measured in general accordance with ASTM D4318. One other important consideration is the liquid limit that can be correlated with soil compressibility which is useful for foundation settlement determinations in clayey materials.

3.3.2.3 Unit Weight

Unit weight is an important property of soil deposits that is mainly used to estimate the vertical stresses in the soil deposits. Unit weights of the soil sediments are determined by weighing specimens of known volumes. This simple test is performed in general accordance with ASTM D2937 or ASTM D7263.

3.3.2.4 Porosity / Void Ratio

Porosity is defined as the ratio between the volume of voids and the total volume of the soil sample. Void ratio is defined as the ratio between the volume of voids and the volume of solids. Hence, porosity and void ratio are used to measure the amount of voids within the soil structure. Both parameters are traditionally expressed in percentages and are widely used to obtain a preliminary idea about the behavior of the soil deposit. They give the geotechnical engineer a preliminary insight about the shear strength of the material and whether settlement is likely to play a major role in the design.

3.3.2.5 Relative Density

Relative density is a parameter used in practice to know the in-situ density value compared to the maximum and minimum possible densities of coarse-grained deposits. It can be calculated using void ratios, densities, or unit weights. This test is important because the engineering behavior of granular-soil deposits is highly affected by its relative density. This test is performed in general accordance with ASTM D4254.

3.3.3 Consolidation Tests

Over consolidation ratio (OCR), coefficient of consolidation (vertical and horizontal), hydraulic conductivity, compression index, recompression index, and secondary compression index are important parameters that can be measured from a typical consolidation test conducted on fine-grained materials. OCR, compression and recompression indices are used to estimate foundation settlement which is particularly relevant to gravity-based foundations and suction caissons. Secondary settlement (creep) can be estimated using the secondary compression index. OCR is used in calculating the capacity of driven piles in fine-grained sediments and settlement analyses of gravity-based foundations and suction caissons.

The generation of pore water pressure during the installation of driven piles and suction caissons facilitates its installation. The dissipation of pore water pressure results in a significant increase in skin friction capacity (Dutt and Ehlers 2009). This process is known as set-up. In some cases, the driving process of the piles stop or the installation of suction caissons is excessively slow. These scenarios would allow a considerable portion of the set-up to occur before the installation is completed. The increase in skin friction makes the installation challenging and sometimes not possible. Consolidation coefficients can be used to estimate the variation of excess pore water pressure with time. This information can be used to provide insight about the rate of set-up to prepare a construction plan that ensures that the installation can still be viable even given a certain amount of down time.

3.3.4 Hydraulic Conductivity Tests

Hydraulic conductivity can be measured in-situ (e.g. CPT) or in the laboratory (e.g. consolidation tests). It plays an important role in the design of the different foundations. It is also important to measure the hydraulic conductivity of soil deposits where export cables are installed using the horizontal directional drilling (HDD) technology.

3.3.5 Static Geotechnical Laboratory Tests

3.3.5.1 Ring Shear Tests

The interface friction angle between the foundation and the fine-grained sediments is an important parameter used in the design of the different foundation systems. Ring shear tests are used to measure the peak and ultimate interface friction angles between soil and the foundation materials. The expected relative movement between the foundation and the surrounding soil dictates whether the peak or the ultimate interface friction angle is to be used in design. ASTM D6467 and Jardine et al. (2005) present two slightly different procedures to run ring shear tests. The procedure by Jardine et al. (2005) includes a fast shearing stage before the slow drained shearing stage. The interface friction angles are measured in the later stage, while the fast shearing stage is intended to simulate driving the piles in fine-grained sediments. Hence, the procedure by Jardine et al. (2005) is more relevant to the design of piles. On the other hand, the ASTM D6467 procedure does not include a fast shearing stage. Hence, it is more relevant for foundations installed at a slower rate (e.g. suction caissons). It is worth noting that measuring the relative displacements at which peak and ultimate interface friction angles are expected is particularly important for the analysis and design of slender piles (Randolph and Gourvenec 2011).

3.3.5.2 Direct Shear Tests

Similar to ring shear tests, direct shear tests are used to measure interface friction angles within soil; the shear is soil to soil not soil to material. They can be used to measure friction angles for fine and coarse-grained soils. ASTM D3080 presents the standard procedure to run direct shear tests.

3.3.5.3 Unconsolidated Undrained (UU) Triaxial Compression Tests

Unconsolidated undrained (UU) triaxial tests are widely used to estimate the undrained shear strength of fine-grained sediments because they are a relatively easy and quick test to perform. UU triaxial tests are generally performed in general accordance with ASTM D2850. Due to sample disturbance, the shear strength obtained from UU triaxial tests tend to be lower than the undrained strength measured in-situ or by consolidated undrained triaxial tests. In spite of the limitations of this test, the American Petroleum Institute (API RP 2GEO, 2011) specifies that for piles driven through clay, the side friction should be taken to be less than or equal to the undrained shear strength determined by a UU triaxial test. Undrained shear strength measured using UU triaxial tests are generally used to calculate the empirical cone factor. This factor is used to obtain continuous undrained shear strength profiles from CPT data (e.g. Stark and Juhrend 1989). ε_{50} (strain at which 50% of the peak strength is achieved in the stress-strain curve) obtained from UU triaxial tests is generally used to develop lateral p-y curves.

Sensitivity is the ratio between the undrained shear strength of the intact sample to the undrained shear strength of the same material after being remolded. Measuring the sensitivity of the fine-grained sediments is important because remolding is likely to occur during the installation of the different types of foundations as well as eventually due to lateral cyclic loading during the life of the structure (Randolph and Gourvenec 2011). UU triaxial tests can be used to calculate the sensitivity of fine-grained sediments.

3.3.5.4 Consolidated Undrained (CU) Triaxial Compression Tests

Similar to UU triaxial tests, CU tests are used to estimate the undrained shear strength of the fine-grained sediments. A major difference between CU and UU triaxial tests is that samples are allowed to consolidate prior to shearing in the case of CU tests. The CU samples can be consolidated under either isotropic pressure (known as CIU, isotropically consolidated undrained triaxial) or anisotropic pressure (known as CAU, anisotropically consolidated undrained triaxial). In most cases, the samples are consolidated under the in-situ effective vertical stress or the preconsolidation pressure to replicate the in-situ conditions. Generally, this results in consolidated samples with void ratios smaller than the in-situ state, which in turn produces undrained shear strengths larger that in-situ measured shear strengths. Since the void ratio of the consolidated specimen changes with the chosen consolidation pressure, the undrained shear strength obtained from the CU triaxial tests increase with increasing confining pressure (void ratio decrease). This is another key difference between CU and UU triaxial tests since the shear strength is not a function of the confining pressure in UU triaxial tests. This test can be conducted on intact or remolded samples. CU triaxial tests are generally performed in general accordance with ASTM D4767.

In the case of CAU triaxial tests, the ratio between the horizontal and vertical consolidation stresses is generally set to equal to the in-situ coefficient of lateral earth pressure at-rest (k_0). K_0 can be estimated using CPT data. It is worth noting that the undrained shear strength obtained from CAU is lower than the strength from CIU if the same vertical consolidation stress is applied (Donaghe and Townsend 1978).

Three data points are generally needed to obtain a failure envelope. These points are generally obtained by consolidating the specimens at vertical effective stresses of 75%, 100%, and 150% of the in-situ vertical effective stress. In the laboratory, three individual samples can be tested at the three stress levels (multi-sample) or a single sample tested at the three stress levels (multistage). Both scenarios present advantages and disadvantages (Parry and Nadarajah 1973). Parry and Nadarajah (1973) conducted a laboratory investigation and concluded that results from multi-sample and multistage test procedures are similar for practical purposes. Hence, they recommended adopting the multistage procedure for soft lightly overconsolidated clays of low sensitivity.

3.3.5.5 Consolidated Drained (CD) Triaxial Compression Tests

Consolidated Drained (CD) triaxial compression tests are used to obtain drained shear strength parameters for coarse-grained soil deposits (i.e. effective friction angle and effective cohesion). In this test, soil is allowed to consolidate under a confining pressure. After consolidation is complete, the specimen is sheared under drained conditions. Hence, the specimen is allowed to change in volume during the consolidation and shearing stages, while excess pore water pressure should theoretically be equal to zero (or very close to zero). CD triaxial tests are generally performed in general accordance with ASTM D7181.

3.3.5.6 Direct Simple Shear (DSS) Tests

Direct simple shear (DSS) tests are consolidated undrained tests where the samples are allowed to consolidate under vertical effective stresses and sheared under undrained conditions. By allowing the sides of the apparatus to rotate, the shear strain is uniform across the whole sample. DSS tests are generally performed on fine-grained soils in accordance with ASTM D6528.

3.3.6 Dynamic Geotechnical Laboratory Tests

Offshore wind turbines are typically subjected to dynamic loading with a relatively wide range of frequencies and very large number of cycles (see Figure 3.1 in Andersen et al. 2013). These dynamic loading can be classified as follows:

1-Environmental dynamic loads: The loading condition controlling the design of offshore wind farms can be wind loads, current loads, wave loads, ice loads, or a combination of them depending on water depth and weather conditions at the project location (Schneider and Senders, 2010).

2-Internally generated dynamic loads: The motion of the blades results in dynamic loads that have two main excitation frequencies known as 1P (rotational frequency) and 3P (blade-passing frequency). Because the blades of the wind turbines rotate at different speeds, the two excitation frequencies are generally reported as ranges rather than two single values. The reader is referred to Bhattacharya et al. (2012) for additional details about these excitation frequencies. The motion of the blades imposes cyclic loading in the order of 1 billion cycles during lifetime of the turbines (Schneider and Senders, 2010).

The configuration and dimensions of the wind turbine system (i.e., the wind turbine and the foundation system combined) should be chosen such that its natural frequencies fall outside the ranges of the frequencies of the loads to avoid resonance. Because the dynamic properties of the soil surrounding the foundations alter the natural frequencies of the system, conducting cyclic laboratory soil testing became an integral component of the analysis and design of offshore wind turbines. An accurate characterization of the dynamic soil properties at the site is then used to conduct soil-structure interaction analyses to predict the behavior of the turbine system under extreme loading and the fatigue effects on its behavior.

The major / typical cyclic laboratory tests used in practice are as follows:

3.3.6.1 Resonant Column Tests

Resonant column tests are performed to determine elastic modulus, modulus degradation and damping ratio at small shear strain levels by applying torsional or flexural vibration. The test specimens can be either intact or remolded. Coarse grained samples are typically reconstituted by compaction in a mold to a specific density following the procedure proposed by Ladd (1978). The test is typically performed on specimens with a height to diameter ratio of approximately 2:1 under a fixed-free test arrangement. In this arrangement the test specimen is fully fixed at the bottom and an electrical oscillator applies torsional motion to the top. Resonant column tests are generally performed in accordance with ASTM D4015.

3.3.6.2 Cyclic Consolidated Undrained (CYCU) Triaxial Tests

CYCU triaxial tests are similar in most aspects to the static CU except for applying cyclic shear stresses under undrained conditions to simulate soil behavior under cyclic or seismic loading. Similar to the static CU triaxial tests, the applied consolidation stresses can either be anisotropic or isotropic. Several tests are generally required to investigate the soil response to different loading conditions and number of cycles. Similar to the static CU triaxial tests, CYCU can be performed in multi-samples or multistage within a single sample. In the multistage version, each sample is loaded under cycles with limited amplitudes for a finite number of cycles before increasing the amplitude and retesting the sample again. The number of cycles and its amplitude applied in the first and second stages should be chosen to be large enough to result in a measurable damping ratio, but small enough to prevent the failure of the samples until the last stage is achieved. During the final stage, the sample should be cycled until failure occurs. CYCU tests are generally conducted in general accordance with ASTM D5311.

3.3.6.3 Cyclic Direct Simple Shear (CYDSS) Tests

Cyclic direct simple shear (CYDSS) is similar in many aspects to the static DSS. CYDSS can be performed in multi-sample or multistage. If a multistage approach is adopted, each sample is consolidated under a single vertical stress value then cyclically sheared on multiple stages under stress controlled cycles with three different predetermined shear stresses for a specific number of cycles. As for the CYCU tests, it is important to carefully select the stress and the number of cycles such that the sample will not prematurely fail before the last stage (maximum shear stress value) is reached.

3.3.7 Other Laboratory Tests

3.3.7.1 Thixotropy tests

Thixotropy is defined as a process of softening caused by remolding, followed by a time dependent return to a higher strength state at the same water content and void ratio (Mitchell, 1993). A pure thixotropic material regains 100% of its original strength with time. Most natural clays are not pure thixotropic materials. Thixotropy is particularly important to estimate the increase in skin friction with time (set-up) especially for suction caissons, but also for driven piles.

Thixotropy tests consists of testing multiple remolded samples at different times to investigate the strength gain with time. Sample preparation and testing procedures are described in NORSOK G-001.

3.3.7.2 Thermal Conductivity Test

ASTM D5334 presents a standard test procedure used to measure the thermal conductivity of soils in the laboratory.

3.3.7.3 Electrical Resistivity Test

Electrical resistivity can be measured in the laboratory in general accordance to ASTM G187.

3.3.8 Cyclic Soil Parameters

Studying the dynamic response of structures imposes many challenges to the designer compared to simple static response. For example, stiffness alone is not enough to estimate the response of materials subjected to dynamic loading. In this case, damping ratio is an essential parameter to estimate as well (among other parameters). Shear modulus (the most important stiffness measurement for soils) and damping ratio for soils depend on many variables. It is particularly important to estimate how these two parameters change at the different strain levels to which the soil is subjected. The shear modulus is generally normalized by the maximum shear modulus of the soil that is measured at very low strains. The curves that represent the change in the normalized shear modulus and damping ratio with shear strain are known as degradation curves. Estimating the degradation curves of the different soils encountered at the turbine locations is an integral part of the cyclic / dynamic foundation design. Undrained cyclic shear strength and shear deformation characteristics are also needed to evaluate capacity under cyclic loads, cyclic displacements, permanent displacements (e.g., settlements) under cyclic loading for various stress paths (triaxial compression, triaxial extension, and direct simple shear modes).

Five cyclic soil parameters are needed to design foundations for offshore structures (Andersen 2004). These parameters can be obtained through contour diagrams that can be prepared using cyclic laboratory test results. The details of the different parameters along with examples on how to obtain each are presented by Andersen (2004). In summary:

Cyclic Shear Strength. The soil response can widely vary when subjected to dynamic/cyclic loads. In general, the cyclic shear strength depends on the number of equivalent loading cycles, the average stress applied to the soil, and the stress conditions applied on the soil element. Hence, these three parameters need to be identified to obtain relevant results from the cyclic laboratory tests. In practice, they are identified as follows:

- <u>Number of equivalent cycles</u>: Cyclic laboratory tests apply uniform cycles with the same amplitude and frequency which does not represent the actual loading conditions in the field (e.g. storm loads). Several procedures were proposed over the years to estimate the equivalent number of cycles that can mimic the projected loading patterns (e.g. storm events). Details about these different procedures are presented in Andersen (2015).
- <u>The average shear stress:</u> It represents the static stresses acting on the soil elements before the application of the dynamic loads.
- <u>The stress conditions:</u> It depends on the relative magnitude and orientation of the principal stresses on the soil elements. In general, direct simple shear tests, triaxial compression, or triaxial tension are used to mimic the stress conditions encountered in the different soil elements along the failure surface.

Cyclic Shear Modulus. Cyclic shear modulus can be directly calculated using the cyclic shear stress and its corresponding cyclic shear strain. Hence, it is implicitly a function of the equivalent number of cycles as well.

Damping. The area enclosed by the stress strain cyclic loops can be used to calculate the damping of the material. There are two types of damping 1) structural damping based on mode shapes and 2) material damping or a softening effect that transpires in the soil. Damping is also controlled by the normalized shear modulus and invariably increases with increasing strain.

Pore Pressure Generation and Permanent Shear Strain. Contour diagrams can be developed to estimate the average shear strains, the cyclic shear strains, and the pore pressure generated under dynamic loads for the different loading conditions. These loading conditions include different combinations of average shear stresses, cyclic shear stresses, and equivalent number of cycles.

3.4 DESIGN OF LABORATORY TESTING PROGRAMS

Every offshore renewables project is unique in terms of site conditions, nature of the wind turbine system and design loads. Hence, the implementation of a site-specific laboratory testing program is an important step in the success of the any offshore foundation system design. The best practice approach, given the availability of time and resources, would be to design the laboratory program based on three stages, as follows:

Initial Stage. This stage starts offshore during the drilling operations (field investigation program) and should be completed shortly after the investigation campaign is over. The tests assigned (often referred to LTAFs or laboratory test assignment forms) in this stage should include classification tests along with consolidation tests and unconsolidated undrained triaxial tests. This data is used to build a basic understanding of the properties of the marine sediments and start assembly of idealized soil profiles. The soil profiles also have a geotechnical parameter summary table assigned that summarizes the physical and behavioral characteristics of the foundation soils.

Preliminary Stage. The different static and dynamic strength tests should be assigned in this stage. The number of tests and the stresses adopted in each test can vary considerably between projects. This needs an advanced effort from the designer to assign the tests based on the preliminary site characterization while keeping in mind the parameters needed for the final design. Hence, prior experience is essential to the success of this preliminary laboratory testing stage.

Andersen (2015) presents a large set of correlations and charts that can be used to obtain preliminary estimates for the static and cyclic strength parameters of the different soil layers. These parameters can be used to conduct preliminary engineering analyses and design of the foundation system. The preliminary analyses can confirm the viability of the chosen foundation system and its dimensions. It will also guide the designer to select the depths where the various static and cyclic strength tests should be conducted. It can also be used to make more informed decisions on the average stresses, cyclic stresses and number of cycles to be applied on the different soil samples for each laboratory test.

Final Stage. The final laboratory design stage would allow the designer the opportunity to run additional tests to confirm and fill in the gaps left by the preliminary laboratory program if the designer might identify gaps, unacceptable results, or unanticipated behaviors from some of the laboratory tests. The results of these tests are generally used to finalize the details of the foundation design and address any concerns raised about the behavior of the system.

Unfortunately, time and budget could potentially limit the practical application of the aforementioned staged design of the laboratory testing program. In such case, prior experience of the designer in the area of the project plays an important role in reducing the timeline for the laboratory program without major implications on the quality of the results. It is imperative that selected testing regiments concentrate the allocated budgetary resources on tests that will provide critical design parameters and cover the full gamut of potential soil-foundation behavior.

The following sections will introduce the different advanced laboratory tests warranted for the different foundation systems. In no way should the information presented in the subsequent sections should be considered comprehensive. Rather, it is intended to be a generic framework that can assist geotechnical engineers in designing laboratory sample testing programs. As stated earlier, achieving an optimized testing program is an iterative process that requires experience and will depend on the project and site-specific characteristics.

3.4.1 Testing Program for Generic Site Characterization

Generic site characterization must include the synthesis of geophysical and geotechnical information in order to fully understand the ground model at the wind farm location. Geotechnical investigations cannot ascertain every possible deviation from a homogeneous subsurface ground model. However, the discretization of lateral and vertical changes in soil type, location and strength is possible. As stated in the previous section, the wind farm area will control the sample type (in-situ or laboratory), number, location and depth of each individual investigation or in-situ test. This is also constrained by the selected foundation system where design criteria such as base contact area, multiple / adjacent piles or imparted loads will govern the aforementioned components to a geotechnical sampling / testing schedule.

3.4.2 Testing Programs for Driven Piles

The analysis and design of offshore driven piles combines a wide variety of methods and approaches. This section presents the different design parameters required for each type of analysis. It is important to note that most of the information presented in this section is mainly applicable to siliceous sands and clays. Carbonate-based sands can behave considerably differently than siliceous sands. Hence, most of the described design methods and laboratory tests might not be applicable. Carbonate sands are addressed in further details by Le Tirant and Nauroy (1994).

Axial Pile Capacity. Axial pile capacity is typically calculated using the different methods described in API RP 2GEO (2011). These distinct methods are developed for siliceous sand and clays only. The API method is a simplified method that relies on relative density and soil classification to estimate the skin and end bearing design parameters for coarse-grained sediments. On the other hand, the API method uses the undrained shear strength obtained from UU triaxial and effective vertical stress (i.e. unit weights and idealized profiles) to estimate the design parameters in cohesive sediments. While UU triaxials are the only required test results for the API method, it is preferable to obtain CPT soundings to attain a continuous undrained shear strength profile with depth. It is important to note the CPT data does not directly measure soil shear strength; it is only done using correlations. It would also be preferable to run few CU triaxials since it is slightly less affected by sample disturbance compared to UU triaxials, so it can be used as a confirmation test to ensure that the results of UU triaxials are realistic. It is also important to note that CU triaxials tend to result in higher undrained shear strengths compared with UU triaxials (see the Static Geotechnical Laboratory Tests section for additional information).

API also presents another set of four axial pile design methods that are mainly based on CPT data. These methods are widely known as: ICP-05 (Jardine et al. 2005), UWA-05 (Lehane et al. 2005), Fugro-05 (Kolk et al. 2005), and NGI-05 (Clausen et al. 2005). Schneider et al.

(2008) presents a detailed investigation where the aforementioned four methods were compared.

In addition to the cone tip resistance, the ICP-05 method uses the interface friction angle between sand and the pile (δ_{cv}), the interface friction angle for clayey layers measured using the (δ_f), OCR, sensitivity, and vertical effective stresses. Hence, the different laboratory test results needed for the ICP-05 method will include: ring shear tests to measure δ_f, consolidation tests to measure OCR (CPT data can be used to obtain a continuous OCR curve along with the consolidation tests), tests used to measure the sensitivity of clays (e.g. UU triaxials, CU triaxials, in-situ vane shear, or fall cone test. CPT data can be used to obtain a continuous profile), and direct shear test to measure δ_{cv} (ICP-05 provided a curve that can also be used to estimate δ_{cv} as a function of D_{50}).

The UWA-05 and Fugro-05 methods are developed to estimate the axial pile capacity in sandy soil deposits. In addition to the cone tip resistance, the UWA-05 method uses the interface friction angle between sand and the pile (δ_{cv}). Hence, direct shear test can be conducted to measure δ_{cv}. UWA-05 also provides a curve that can be used to estimate δ_{cv} as a function of D_{50}. The UWA-05 curve is slightly different than the curve proposed by ICP-05.

The NGI-05 method is slightly different than the other three CPT-based axial design methods. It can be used to estimate the axial pile capacity in both sand and clay layers. In addition to the CPT tip resistance, it makes use of OCR (consolidation tests and CPT-based method), relative density, plasticity index, undrained shear strength (e.g. UU triaxial, CU triaxial, vane shear in-situ test, and CPT data).

Soil Resistance to Driving Curves. Wave equation analysis (drivability analysis) is generally conducted to investigate the viability of installing the pile to its design depth/elevation using a specific hammer. The skin and tip resistances expected during the driving process are important input parameters for the wave equation analysis. Due to the dynamic nature of the loading applied to the pile and soil during the driving process, the skin and tip resistances are expected to differ from the values obtained from conventional axial pile capacity methods. Several studies propose methodologies to develop skin and tip resistances that can be used in wave equation analyses to obtain blow counts that are comparable to field observations. The total resistance obtained from these methods is known as Soil Resistance to Driving (SRD) curves. The three most widely used methods to develop the SRD curves were proposed by Alm and Hamre (2001), Puech et al. (1990), and Stevens et al. (1982). These methods are applicable to sand and clay deposits and assume continuous driving without interruptions, and were derived based on field measurements for offshore pile driving. The capacity computed based on these methods better represents the soil resistance encountered during pile installation as opposed to the long term capacity computed using the API and CPT-based methods (discussed in the previous section). These SRD profiles generated from these methods together with soil damping are then used in conducting detailed pile drivability analyses.

The approach by Alm and Hamre (2001) makes use of the sleeve friction and tip resistance obtained from CPT tests. Moreover, the constant volume friction angle for sand layers is typically used which is generally measured using ring shear tests.

The methods proposed by Stevens et al. (1982) and Puech et al. (1990) are based on the API axial pile capacity method. The databases used in these studies were collected in the Arabian Gulf (very dense sands, hard clays, and mixed profiles of medium dense to very dense carbonate sands and very stiff to hard carbonate clays) and the Gulf of Guinea (typically hard clays, very dense sands, and rock), respectively. Both methods use OCR (over-consolidation ratio), interface friction angle between coarse-grained layers and the pile material, and undrained shear strength.

During driving, it is often necessary to interrupt driving operations in order to make pile add-ons or hammer changes. Such interruptions to driving operations usually last 6 to 8 hours. Delays on the order of several days may result from bad weather or equipment breakdown. During this time, many clays will gain strength as excess pore pressure dissipates and the soil particles reorient themselves. This phenomenon is commonly referred to as set-up (Section 2.5.2). A similar phenomenon may also occur in fine-grained granular deposits. After set-up has occurred, increased blow counts may be experienced while attempting to restart driving the piles. The soil resistance to driving may increase to the point of refusal. Therefore, the driving program should be scheduled so as to reduce the number and duration of delays. In cases where such delays are inevitable, the rate of excess pore water pressure dissipation and thixotropic effects should be evaluated. Hence, consolidation tests, hydraulic conductivity tests, and/or thixotropic tests are warranted in this case.

Axial and Lateral Load Transfer Curves (t-z, Q-z, and p-y curves). Axial and lateral movements of piles are important parameters that should be designed for. While these analyses can be conducted using detailed numerical modeling techniques, it is more often conducted using simplified approaches that use the axial and lateral load transfer curves.

The simplified axial load-pile movement analyses are usually performed using computer programs treat the pile as a series of discrete elements, represented by linear springs that are acted upon by nonlinear springs representing the soil. The curves representing the nonlinear soil response (modeled as a spring) at discreet depths are referred to as t-z and Q-z curves. These curves demonstrate the amount of axial deflection needed to fully mobilize the strength of the soil as it gets loaded. These t-z curves represent load deflection soil response along the pile shaft, whereas the Q-z curve represent load-deflection soil response at the pile tip. Input data for such programs include: 1) pile dimensions and material properties 2) load transfer characteristics of the soil surrounding the pile, and 3) the pile tip load-tip movement relationship. The lateral load transfer curves (p-y) are used in a similar manner to predict the load-deflection curves for piles subjected to lateral loads.

Several axial and lateral load transfer curves have been proposed over the years. API RP 2GEO (2011) presents procedures to build transfer curves for clay materials and siliceous sands. Wesselink et al. (1988) introduced a method to develop lateral (p-y) load transfer curves in carbonate sands. Depending on the methods chosen, different design parameters will be needed. Hence, the type of laboratory and in-situ testing required to develop the load transfer curves will vary. The methods presented in API RP 2GEO (2011) required measuring the following parameters: undrained shear strength of clays, angle of internal friction of sands, and the displacement at which the maximum adhesion or unit skin friction is mobilized. API RP 2GEO (2011) recommends some typical values for the latter parameter, but suggests measuring it if the pile stiffness is important in the design, which is likely the case for offshore wind turbine structures. Hence, direct shear tests can be run to estimate the distance at which the peak adhesion or peak unit skin friction is mobilized.

Axial and Lateral Capacity Degradation Due to Cyclic Loading. The effect of cyclic loading is particularly significant for piles in fine-grained, calcareous, and silt sediments when compared to medium and coarse-grained sediments (DNV, 1992). Puech, (2013) provide data and recommendations that can be used in the design of piles subjected to cyclic loads. Andersen et al. (2013) provides a comprehensive list of laboratory tests that may be run to measure the different parameters used in cyclic design of the different foundation types including piles. The reader is referred to that list for guidance concerning the laboratory tests that suits the project-specific needs.

3.4.3 Testing Programs for Gravity-Based Foundations

Gravity-based foundations can be analyzed using limiting equilibrium analysis (total or effective stress) or finite element modeling (DNV 1992). A typical laboratory testing program for a gravity-based foundation should include:

- Consolidation tests: Conducted on intact samples to measure OCR, compressibility, and permeability. Creep data might be needed as well. This info is used to calculate the total and differential settlements (DNV-OS-J101-p.147).
- Direct shear test (sand): To measure the monotonic failure shear stress (drained conditions). This is relevant to the horizontal sliding failure mode which is particularly important for cases where large lateral loads are expected.
- Simple shear test (silt and clay): To measure the undrained shear stress under monotonic loading (undrained conditions). This is relevant to the horizontal sliding failure mode.
- Compression and extension triaxial tests: Used to measure shear strengths along the failure surface below the gravity-based foundation.
- Two-way cyclic testing with post-cyclic monotonic loading: To measure the failure shear stresses under cyclic conditions and post-cyclic shear strength. These tests should be conducted under undrained conditions for clay sediments. The fines content in sand sediments or the hydraulic conductivity should be used to assess whether sand deposits would behave as a drained or undrained material.

3.4.4 Testing Programs for Suction Caissons

Geotechnical investigations should be designed such that any spatial heterogeneity within the footprint of the foundation system is captured and accounted for to avoid differential foundation settlement. Typically, testing programs for suction caissons must include:

- Grain size distribution analyses of granular materials: Zones of high resistance may result in premature refusal of the caisson during installation. A suction caisson moving from clay into sand while being installed may precipitate the loss of suction so it is vital that the grain size of granular materials be fully understood.
- Other classification tests: This includes soil unit weight, soil water content, and site layering to at least 30 m depth.

- Tests to measure shear strength of the different soil layers: Conducted on intact and remolded samples.
- Cyclic tests: These are important to ascertain the degradation in soil strength based on numerous repetitive loads. These can be imparted to the caisson by subsea currents (loop), wind loading or wave crashing at the foundation base.

  For the installation stage, the following laboratory tests are particularly important:

- Tests to measure shear strength of the different soil layers: This includes undrained shear strength for clays and sands with considerable amount of fine grained soils and effective friction angle for sands loaded under drained conditions.
- Permeability tests: It is critical to measure the coefficients of permeability of the different layers. This information is used in evaluating the suction pressure needed to install the caisson in place while avoiding the formation of piping channels around the caissons walls. Once piping channels are formed, additional insertion of the foundation under suction pressures will not generally be possible.

3.4.5 Testing Programs for Anchors

There is a wide variety of anchoring systems adopted by the oil and gas industry for offshore applications in moderate to deep waters. This section intends to introduce the various laboratory tests that are typically conducted to properly design the different anchors.

Piles Used as Anchors. Piles used as anchors are usually designed in a similar fashion as regular driven piles described in the previous section. Hence, most of the analyses and laboratory tests listed before are still applicable in this case. The major difference is that piles used as anchors are subjected to tensile and lateral loads (i.e. no compressive loading). Hence, the stresses applied in cyclic tests will be one-way.

Suction Caissons Used as Anchors. The DNV-RP-E303 manual describes in detail the analysis and design of suction caissons in clay sediments. No guidelines are currently available in the literature about suction caissons in sandy sediments, but there are several research papers that had been published in recent years to address this topic (e.g. Houlsby et al. 2005). The main laboratory tests that should be considered to design suction caissons are as follows (based on DNV-RP-E303):

- Direct simple shear (DSS) / triaxial compression / triaxial extension: Conducted on intact samples to measure its shear strength.
- Consolidation tests: Conducted on intact samples to measure OCR, compressibility, and permeability. Creep data might be needed as well.
- Cyclic DSS / cyclic triaxial compression / cyclic triaxial extension, with post-cyclic monotonic loading. To measure the cyclic shear strength for intact and remolded samples, and post-cyclic shear strength.
- In-situ vane shear/Fall cone test/UU triaxial/CU triaxial/any other available methods: To measure the undrained shear strength for intact and remolded samples. In-situ tests are preferred in estimating sensitivity.

  If site-specific set-up analyses are required/important, the following tests will be needed:

- Direct simple shear (DSS): Conducted on remolded samples to measure its shear strength.
- Consolidation tests: Conducted on remolded samples to measure permeability and the virgin constrained modulus (loading and reloading moduli).
- Thixotropy tests: Conducted on remolded samples to measure the thixotropic characteristics of fine-grained sediments.

Box Anchor. Box anchors are gravity-based foundations that are mainly subjected to lateral and tensile loads. These loads are supported by the weight of the foundation and the friction between the foundation and soil deposits. Hence, bearing capacity is less of a failure mechanism in this case as compared with the gravity-based foundations used in relatively shallow waters. The reader is referenced to Randolph and Gourvenec (2011) for additional details about this system. The main laboratory tests that should be considered to design box anchor foundations are as follows (based on Randolph and Gourvenec, 2011):

- Direct shear test (sand): To measure the monotonic failure shear stress (drained conditions). This is relevant to the horizontal sliding failure mode.
- Simple shear test (silt and clay): To measure the undrained shear stress under monotonic loading (undrained conditions). This is relevant to the horizontal sliding failure mode.
- One-way cyclic testing (with post-cyclic monotonic loading): To measure the failure shear stresses under cyclic conditions, and post-cyclic shear strength. These tests should be conducted under undrained conditions for clay sediments. The fines content in sand sediments or the hydraulic conductivity should be used to assess whether sand deposits would behave as a drained or undrained material.

Grillage and Berm Anchor. This system is addressed in details by Randolph and Gourvenec (2011). The typical laboratory tests required for this foundation system are:

- All laboratory tests required to design box anchors.
- Grain size distribution and Atterberg limits (fine-grained material): These laboratory tests are used to investigate the erosion potential (i.e. scour) of marine sediments.

Drag Anchors. Owing to uncertainty regarding the final location of drag anchors, a careful site characterization is vitally important. This is generally achieved by integrating geophysical surveys and geotechnical investigations to prepare detailed layering of the site. The number of boreholes should be decided on a case by case scenario. However, one borehole and/or CPT sounding per anchor location is generally desirable for sites where lateral variation of the stratigraphy is expected (DNV-RP-E301). One borehole and/or CPT sounding could be enough for each cluster of anchors if the soil profile shows little lateral variation in material type s or parameters. Undrained shear strength and consolidation characteristics of the remolded soil are particularly important if a detailed set-up analysis is to be conducted for the anchors (DNV-RP-E301). The laboratory tests that are typically needed to design drag anchors are as follows (based on Randolph and Gourvenec, 2011 and DNV-RP-E301):

- In-situ vane shear / Fall cone test / UU triaxial / CU triaxial / other methods: To measure the undrained shear strength for intact and remolded samples. In-situ tests are preferred for estimating sensitivity. Undrained shear strength should be measured for the different layers between mudline to the maximum possible penetration depth of the anchor.

- Consolidation tests: To estimate the coefficient of consolidation and OCR (over-consolidation ratio).
- Cyclic DSS (with post-cyclic monotonic loading): To measure the cyclic shear strength for design storm events, and post-cyclic shear strength.
- Thixotropy tests: Used to estimate soil strength regain / setup, over time.

3.4.6 Testing Programs Related to Geohazards

Table 3.5 presents a list of various laboratory tests to be conducted to get a handle of their geotechnical behavior; they are categorized based on geohazard presence.

Table 3.5. Different laboratory tests assigned to investigate the different geohazards

Geohazard	Laboratory Tests
Seabed mobility / Scour	-Grain size (D_{50} and D_{10}), Atterberg limits, unit weight, CD triaxial and/or direct shear (effective friction angle), macroscopic examination (mineralogy)
Slope Instability	-UU triaxial and/or CU triaxial (undrained shear strength – for undrained analyses) or CD triaxial and/or direct shear (effective friction angle – for drained analyses), Atterberg limits, unit weight
Filled Channels	-Atterberg limits, Consolidation tests, UU triaxial and/or CU triaxial (undrained shear strength), specific gravity, macroscopic examination (mineralogy)
Shallow Gas	-Chemical composition of fluid samples including gas concentration and composition
Liquefaction	-Cyclic CU triaxial tests and/or cyclic DSS

3.5 INTER-ARRAY AND EXPORT CABLES

Export cables are fairly light compared to pipelines and have a lower bending stiffness. Their inherent flexible nature allows for distortion from seabed movement. However, depending on the environmental constraints and planned cable route, they may be susceptible to damage from local fishing activities or dropped objects, during or after cable lay. Design items such as appropriate depth of cover or, in many circumstances burial depth, should be considered.

For soft clay or cohesive soils, the strength within the upper 0.5 m may be important in the design of the cable. Sites where the surface soils are highly variable can induce differential embedment depths along the cable route thereby imparting variable strain in the cable cross-section. If such conditions are anticipated, then a series of shallow seabed CPTs or T-Bar tests may be warranted to accurately characterize the shallow surface materials.

If homogeneous soils along the route are anticipated based on geophysical data, generally sampling and testing locations at 1 km (KP) intervals is warranted. However, the geophysical data should be used to route the cable thereby avoiding any obvious geohazards. Most offshore codes do not provide explicit direction regarding either the nature of the testing or the frequency of the testing locations. Nevertheless, interruption to power supplied by the wind farm may have socio-economic effects so planning, routing and potential cable burial are important elements in the design.

Testing such as resistivity, conductivity and sulfates / sulfides may be useful in understanding the chemical effects of the soil-cable armor interface. Thermal conductivity tests are also typically conducted for soil deposits along cable routes. If the cable is to be laid around seabed obstacles, then the soil-armor interface friction may play a role in the viability of the installation method. Cables cannot turn without the interface friction being high enough. Testing such as tilt table or interface shear may be warranted to understand the axial drained residual and lateral friction factors.

Burial depth, if considered, should be below the expected interface depth from vessel anchoring, fishing gear, iceberg keels (in areas of sea ice) or local seabed scour. Since scour is often related to seabed current and soil grain size, particle size distribution tests may be required to understand the scour potential along the length of the cable. More details on the scour propensity can be brought to light using CFD (computational fluid dynamics).

3.6 ELECTRICAL SERVICE PLATFORMS (ESPS)

Electrical service platforms for wind farms represent a collection point for infra-field cable to coalesce before the power is redistributed to shore. Depending on the layout of the wind farm, these structures may either be located within the confines of all the turbines or outside of the array. The predominate loading condition for these structures would be vertically downward. An example of a typical ESP foundation type would be a jacket with piles. These structures may be very heavy.

3.7 ADDITIONAL REMARKS

A few important conclusions can be gleaned from this work that and are listed below for the sake of clarity and convenience.

1. Geophysical equipment selection can significantly enhance the subsequent geotechnical investigation program. Geophysics should be used to assess risk by the advantageous placement of borings or in-situ tests in areas of critical geologic importance where anomalous readings are detected. If equipment is mobilized but is later deemed unsuitable for the encountered site conditions, the level of risk to acquiring high quality geotechnical information at the site, is compromised. For example, if the geotechnical drill vessel was only equipped with sampling devices for marine clays but encountered very dense sands at surface, this may compromise the investigation program. The corollary to this is if the geophysical survey did not consider the possible presence of gas in the soil and mobilized only Chirp sub-bottom profiler along with sidescan and multibeam systems, then the underlying gaseous soils may prove to undermine the integrity of the jack-up legs. The gas can decrease the underlying soil strength / bearing capacity of not only the rig, but also the future wind turbine foundation.
2. It is envisioned that at some point during the field geotechnical investigation and hopefully only after the geophysics has been collected, the data may reveal lateral and vertical continuity in subsurface geophysics. Should this occur, it is of vital importance that additional geotechnical investigation points be added to the campaign to correlate and support the results of the geophysics. For example, many shallow 2D seismic lines or profiles may have the same signature (appearance) but subtle contrasts in acoustic impedance (layer density x layer sound velocity) can translate to greater than anticipated variations in geotechnical properties.
3. Although the US wind industry is still young, there have been projects where developers have switched foundation types or loading conditions requiring the developer to mobilize equipment a second time to either drill deeper or collect different data types. As such, each offshore program may, as a first pass, conceptualize a hypothetical foundation type that may have been adopted on other proximal projects. Therefore, a main goal of the investigation should be to bolster or refute the initial foundation design concept. For example, monopiles may be presented as a viable foundation solution but geotechnical borings may reveal the presence of very dense materials where premature pile refusal is possible. In this instance, consideration should be given to either shorten the piles or to assess the use of suction caissons as an alternative.
4. Archeological considerations should be accounted for while planning for the testing locations, designing sampling protocols, and planning for sample handling and transportation techniques. This is particularly important if geological reconstructions indicated the presence of pre-inundated high probable paleo landforms. In this case, a qualified marine archaeologist and/or geo-archaeologist will decide whether or not to undertake chemical residue and palynological tests. If these tests are warranted, the geotechnical engineer of

record should work in conjunction with the marine archaeologist and/or geo-archaeologist to agree on the locations of intrusive sampling (e.g. vibracores). These samples can be used for the geotechnical as well as the paleolandform testing programs. Sample handling techniques should be agreed upon as well. For example, vibracores obtained for both testing programs should be handled with care to minimize sample disturbance until chemical residue and palynological tests are conducted.

3.8 GLOSSARY

fatigue: Pile fatigue usually occurs after multiple cycles of loading and can affect the strength of the steel, thereby reducing its life.

Soil fatigue can be described as a reduction in soil strength over repeated cycles that occur relatively slowly. However, high frequency cycles with high loads can actually increase the soil strength but generally only temporarily.

resonance: Resonance is the tendency of a mechanical system to respond at greater amplitude when the frequency of its oscillations matches the system's natural frequency of vibration (its resonance frequency or resonant frequency) than it does at other frequencies. This can lead to fatigue and subsequent failure, over time.

3.9 REFERENCES

Alm, T. and Hamre, L. (2001). "Soil Model for Pile Derivability Prediction Based on CPT Interpretations." *Proceedings of the 5th International Conference on Soil Mechanics and Geotechnical Engineering*.

American Petroleum Institute (2011). "Geotechnical and Foundation Design Considerations, ANSI/API," Recommended Practice 2GEO, First Edition, April 2011, API, Washington, D.C.

Andersen, K.H. (2004). "Cyclic Clay Data for Foundation Design of Structures Subjected to Wave Loading," Cyclic Behavior of Soils and Liquefaction Phenomena, Triantafyllidis, T (Ed.), London, UK: Taylor & Francis Group.

Andersen, K.H. (2015). "Cyclic Soil Parameters for Offshore Foundation Design," Frontiers in Offshore Geotechnics III, 2015 Taylor & Francis Group, London, ISBN: 978-1-138-02848-7.

Andersen, K.H., Puech, A. & Jardine, R. (2013). "Cyclic resistant geotechnical design and parameter selection for offshore engineering and other applications," XVIIIth ICSMGE, TC209 Workshop – Design for cyclic loading; piles and other foundations, Proc., Paris, 4 Sept. 2013.

ASTM D422, "Test Method for Particle-Size Analysis of Soils," ASTM International, West Conshohocken, PA, www.astm.org.

ASTM D2573-15, "Standard Test Method for Field Vane Shear Test in Saturated Fine-Grained Soils," ASTM International, West Conshohocken, PA, www.astm.org.

ASTM D2937-10, "Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method," ASTM International, West Conshohocken, PA, www.astm.org.

ASTM D3080-11, "Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions," ASTM International, West Conshohocken, PA, 2011, www.astm.org.

ASTM D4015-15, "Standard Test Method for Modulus and Damping of Soils by Fixed-Base Resonant Column Devices," ASTM International, West Conshohocken, PA, 2015, www.astm.org.

ASTM D4254-14, "Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density," ASTM International, West Conshohocken, PA, 2015, www.astm.org.

ASTM D4318, "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils," ASTM International, West Conshohocken, PA, 2015, www.astm.org.

ASTM D4767-11, "Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils," ASTM International, West Conshohocken, PA, 2011, www.astm.org.

ASTM D4719-07 (2007). "Standard Test Methods for Prebored Pressuremeter Testing in Soils," ASTM International, West Conshohocken, PA, www.astm.org.

ASTM D5311-13, "Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil," ASTM International, West Conshohocken, PA, 2015, www.astm.org.

ASTM D5334-14 (2014). "Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure," ASTM International, West Conshohocken, PA, www.astm.org.

ASTM D5778-12, "Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils," ASTM International, West Conshohocken, PA, 2011, www.astm.org.

ASTM D6467-13, "Standard Test Method for Torsional Ring Shear Test to Determine Drained Residual Shear Strength of Cohesive Soils," ASTM International, West Conshohocken, PA, 2013, www.astm.org.

ASTM D6528-07, "Standard Test Method for Consolidated Undrained Direct Simple Shear Testing of Cohesive Soils," ASTM International, West Conshohocken, PA, 2007, www.astm.org.

ASTM D6635-15 (2015). "Standard Test Method for Performing the Flat Plate Dilatometer," ASTM International, West Conshohocken, PA, www.astm.org.

ASTM D7181-11, "Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils," ASTM International, West Conshohocken, PA, 2011, www.astm.org.

ASTM D7263-09, "Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens," ASTM International, West Conshohocken, PA, 2011, www.astm.org.

ASTM G187 (2012). "Standard Test Method for Measurement of Soil Resistivity Using the Two-Electrode Soil Box Method," ASTM International, West Conshohocken, PA, www.astm.org.

Bhattacharya, S., Cox, J.A., Lombardi, D., and Muir Wood, D. (2012). "Dynamics of Offshore Wind Turbines Supported on Two Foundations," Proceedings of the Institution of Civil Engineers Geotechnical Engineering 166 April 2013 Issue GE2 Pages 159–169 http://dx.doi.org/10.1680/geng.11.00015 Paper 1100015.

Clausen, C.J.F., Aas, P.M., and Karlsrud, K. (2005). "Bearing capacity of driven piles in sand, the NGI approach." Proc., Int. Symp. on Frontiers in Offshore Geomechanics," ISFOG, Taylor & Francis, London, 677–681.

Danson, E. (Editor; 2005). "Geotechnical & Geophysical Investigations for Offshore and Nearshore Developments," International Society for Soil Mechanics and Geotechnical Engineering.

Det Norske Veritas (1992). "Classification Notes – No. 30.4: Foundations," dated February 1992.

Det Norske Veritas (2005). "DNV-RP-E303 – Geotechnical Design and Installation of Suction Anchors in Clay," dated October 2005.

Det Norske Veritas (2012). "DNV-RP-E301 – Design and Installation of Fluke Anchors," dated May 2012.

Det Norske Veritas (2013). “DNV-OS-J101 – Design of Offshore Wind Turbine Structures,” dated January 2013.

Donaghe, R.T., and Townsend, F.C. (1978). “Effects of Anisotropic Versus Isotropic Consolidation in Consolidated-Undrained Triaxial Compression Tests of Cohesive Soils,” Geotechnical Testing Journal, GTJODJ, Vol. 1, No. 4, Dec. 1978, pp. 173-189.

Dutt, R.N., and Ehlers, C.J. (2009). “Set-up of large diameter driven pipe piles in deepwater normally consolidated high plasticity clays,” Proc. ASME Int. Conference on Ocean, Offshore and Arctic Engineering, OMAE2009-79012, Honolulu.

Hofmann, B.A., Sego, D.C., and Robertson, P.K. (2000). “In Situ Ground Freezing to Obtain Undisturbed Samples of Loose Sand,” J. Geotech. Geoenviron. Eng., 126(11): 979-989.

Houlsby, G. T., Ibsen, L.B., and Byrne, B.W. (2005). “Suction Caissons for Wind Turbines,” Frontiers in Offshore Geotechnics: ISFOG 2005 – Gourvenec & Cassidy (eds), Taylor & Francis Group, London, ISBN 0 415 39063 X.

Jardine, R., Chow, F, Overy, R., and Standing, J (2005), “ICP Design Methods for Driven Piles in Sands and Clays”. Telford, London.

Kolk, H.J., Baaijens, A.E., and Senders, M. (2005). “Design criteria for pipe piles in silica sands.” Proc., Int. Symp. on Frontiers in Offshore Geomechanics,” ISFOG, Taylor & Francis, London, 711–716.

Ladd, R.S. (1978). “Preparing Test Specimens Using Undercompaction,” Geotechnical Testing Journal, GTJODJ, Vol. 1, No. 1, March 1978, pp. 16-23.

Le, T. P., & Nauroy, J.-F. (1994). “Foundations in carbonate soils,” Paris: Editions Technip.

Lehane, B. M., J. A. Schneider, and X. Xu. (2005). "The UWA-05 Method for Prediction of Axial Capacity of Driven Piles in Sand." ISFOG 2005: Frontiers in Offshore Geotechnics, 683-689.

Lunne T. Berre T. and Strandvik S. 1997. Sample disturbance on soft low plastic Norwegian clay, Proceeding of the International Symposium on Recent Developments in Soil and Pavement Mechanics, Rio de Janeiro, Brazil, 25-27.

Lunne, T. (2010). “Keynote Lecture 4: The CPT in offshore soil investigations – a historic perspective,” 2nd International Symposium on Cone Penetration Testing, May 9-11, Huntington Beach, California.

Mayne, P.W. (2007). “Final Report – Cone Penetration Testing State-of-Practice,” NCHRP Project 20-05; Task 37-14: Synthesis on Cone Penetration Test (February 2007).

Mitchell, J.K. (1993), “Fundamentals of Soil Behaviour”, 2nd edition, John Wiley & Sons, New York. Section 11.4 Causes of Sensitivity pp 201-202 - Thixotropic hardening.

NORSOK G-001. “Marine Soil Investigations,” Standards Norway.

Parry, R.H.G., and Nadarajah, V. (1973). “Multistage Triaxial Testing of Lightly Overconsolidated Clays,” Journal of Testing and Evaluation, JTEVA, Vol. 1, No. 5, Sept. 1973, pp. 374-381.

Pierre Le Tirant, P., and Nauroy J-P (Editors; 1994). “Foundations in Carbonate Sands,” Paris: Editions Technip. Translated from the French by Nissim Marshall, technical advisor Martin Fahey.

Puech, A. (Editor; 2013). “Design for Cyclic Loading: Piles and Other Foundations,” ISSMGE Technical Committee TC 209 – Offshore Geotechnics.

Puech, A., Poulet, D., Boisard, P. (1990). “A Procedure to Evaluate Pile Drivability in the Difficult Soil Conditions of the Southern Part of the Gulf of Guinea.” *22nd Annual OTC*, Houston, TX.

Randolph, M., and Gourvenec, S. (2011). “Offshore Geotechnical Engineering,” Spon Press, 520 pages.

Schneider, J.A., and Senders, M. (2010). “Foundation Design: A Comparison of Oil and Gas Platforms with Offshore Wind Turbines,” Marine Technology Society Journal, 44: pp 32-51.

Schneider, J.A., Xu, X., and Lehane, B.M. (2008). “Database Assessment of CPT-Based Design Methods for Axial Capacity of Driven Piles in Siliceous Sands,” J. Geotech. Geoenviron. Eng., Vol. 134, No. 9, pp:1227-1244.

Stark, T.D. and J.E. Juhrend (1989). “Undrained Shear Strength from Cone Penetration Tests,” Proceedings of 12th Intl. Conf. of Soil Mechanics and Foundation Engrg. (SMFE), Brazil, Vol. 2, 1989, pp. 327-330.

Stevens, R.S., Wiltsie, E.A., and Turton, T. H. (1982). “Evaluating Pile Drivability for Hard Clay, Very Dense Sand, and Rock.” *14th Annual OTC*, Houston, TX.

Sivathayalan, S. and Vaid, Y.P. (2004). “Evaluation of Static Liquefaction Potential Using Undisturbed Sand Specimen,” 13thWorld Conference on Earthquake Engineering Vancouver, B.C., Canada, August 1-6, 2004, Paper No. 2939.

Wesselink, B.D., Murff, J.D., Randolph, M.F., Nunez, I.L., and Hyden, A.M. (1988). “Analysis of Centrifuge Model Test Data from Laterally Loaded Piles in Calcareous Sand,” In Jewell and Andrews (eds), Proc. of Engineering for Calcareous sediments: 261-270. Balkema, Rotterdam.

FUGRO MARINE GEOSERVICES, INC.

VOLUME 4

BEST PRACTICE RECOMMENDATIONS FOR GEOPHYSICAL SURVEYS

Study Title:

Geophysical and Geotechnical Investigation Methodology Assessment for Siting Renewable Energy Facilities on the Atlantic OCS

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4.1 INTRODUCTION

This volume is written to address best practice recommendations for geophysical investigations based on site conditions and facility design requirements. Best practice recommendations are tailored to address the variety of ground conditions and water depths expected to be encountered within the Atlantic OCS. Volume 1 of this study provides a description of the anticipated geologic and bathymetric conditions within the Atlantic OCS. Geologic conditions may vary from carbonates in the south to interbedded and channel infill deposits in the mid-Atlantic through to glacial till, gravels, cobbles/boulders and very dense sands in the north. Water depths in the Atlantic Wind Energy Areas varies from approximately 5 to 70 meters. However, wind farms can be installed in water deeper than 70 meters using floating turbine technology.

The following guidance documents provide the base requirements for marine surveying. Additional risks and methods for mitigating those risks are described in Volume 2 of this study.

- Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585, BOEM, July 2015
- Guidelines for Providing Archaeological and Historic Property Information, Pursuant to 30 CFR Part 585, BOEM, July 2015
- Guidelines for Submission of Spatial Data for Atlantic Offshore Renewable Energy Development Site Characterization Surveys, BOEM, February 2013

4.2 MARINE SURVEYS IN THE PROJECT DEVELOPMENT PROCESS

Marine surveys in the Atlantic OCS will often provide the first project-specific data that define the physical environment for an offshore wind farm development. Therefore, high quality marine survey data offer an opportunity to mitigate risk related to ground conditions. Conversely, poor quality marine survey data can result in mis-characterization of ground conditions which:

- Introduces risk to the project schedule,
- Leads to less-informed selection of geotechnical exploration locations,
- May result in over- or under-conservatism in design,
- Result in encountering unexpected ground conditions during construction, and/or
- Ground conditions or geohazards not adequately addressed in design may result in unplanned for costs to mitigate or remediate problems during operation of the facility.

Marine archaeological resource surveys are required to investigate a site for potential archaeological resources before the seafloor is disturbed due to geotechnical exploration, anchoring, or spud-can legs, it is important to collect data of high quality to facilitate archaeological resource evaluation. Poor quality data could result in an inconclusive archeological resource evaluation that prevents approval of conducting seafloor disturbance activities in an area or may require the data to be re-collected. Such issues could result in delays of the follow-on geotechnical investigation and added costs of re-collecting data or standby costs stemming from delayed geotechnical investigation. Therefore, collecting high quality data is important for successfully performing an archaeological resource assessment and reducing the potential for project delays.

It is best practice to conduct a marine survey prior to a geotechnical investigation. The marine survey data should be used to develop a geologic framework, also referred to as a ground model, of the site (Figure 4.1). The initial ground model is used to inform and plan the geotechnical investigation and support conceptual engineering analyses. The initial ground model should be used to select the types of geotechnical explorations, exploration depths, and types and frequencies of geotechnical sampling, in situ testing, and laboratory testing.

Figure 4.1. Using marine survey data to develop initial ground model
Marine survey data are the first project-specific data used to define ground conditions

that become available for a wind farm facility. Survey data are used to develop a geologic framework and the first version of a site's ground model. The ground model can be segregated into soil provinces or zones that are used to plan geotechnical investigations, initiate conceptual engineering analyses, and plan development of the site. The Virginia Wind Energy Area ground model shown above was developed based on a regional survey (Fugro, 2013).

Volume 2 provides an overview of the various marine survey equipment and how the data they are used to collect and process are using in the wind development process. Volume 2 also described various challenges and risks associated with using that equipment in the Atlantic OCS.

We note that commercial lease areas are large and may not be developed in one single phase of construction. Some portions of the lease area may not be developed at all. Phased development strategies and whether to develop some areas are based, in part, on construction and operations costs that are influenced to varying degrees by ground conditions and geohazards. The following text provides several examples of how marine surveys can be used to identify and mitigate hazards or risk. It may be desirable to avoid constructing turbines and cables in bouldery zones or areas with large, mobile sand waves. Installation of piled foundations in bouldery zones may result in damaged piles or require relief drilling if boulders are encountered. Standby costs incurred while waiting for a relief drill to mobilize to the site can be considerable. Mobile sand wave fields can result in unburying of cables or be indicative of strong currents that can lead to development of significant scour at wind turbines that is costly to monitor and mitigate. Understanding where those hazards are on a site at an early stage will allow for mitigation if they can be avoided or through engineering design. Marine surveys help identify where favorable or unfavorable ground conditions for certain foundation concepts may exist. Interbedded deposits or gravelly deposits can be problematic for installation of some foundation types, such as suction caissons.

An understanding of those site conditions can be gained using regional preliminary surveys and be instrumental in planning the phases of development. Identifying problematic areas using regional surveys that will not be developed will help reduce unnecessary survey costs. Although there are clearly benefits of conducting marine surveys using phased approaches, there are also risks or challenges. For example, integrating data sets that are sensitive to temporal variations can prove challenging. UXO surveys are one of the that data types that are most to this issue. The state of the practice for UXO surveying is collect UXO data during one survey and not to integrate data sets collected during different survey seasons.

The following sections discuss various best practices for different surveying methods in the context of anticipated geology and water depth ranges. BOEM's G&G and marine archaeology guidance documents (2015a and 2015b, respectively) provide recommendations for survey specifications. The following best practice recommendations supplements the survey specifications provided in BOEM's guidance documents and provides additional recommendations with respect to water depth, geologic conditions, and marine facility.

4.3 BATHYMETRY

Bathymetric surveys should be conducted using swath bathymetry systems and provide full coverage of the wind farm and along the cable corridors. BOEM's G&G and marine archaeology guidance documents (BOEM, 2015a and 2015b) provide line spacing and vertical/horizontal accuracy requirements. Bathymetric surveys should meet IHO Special Order survey standards for water depths less than 40 meters and 1a survey standards for water deeper than 40 meters (IHO, 2008). Table 2.1 in Volume 2 of this study summarizes the total horizontal and vertical uncertainties for the range of water depths anticipated to be encountered in the Atlantic OCS WEAs.

In order to ensure that the bathymetry survey equipment types, configuration, settings, and survey methodology will collect data that adhere to the minimum accuracy standards, appropriate calibrations and quality control measurements should be conducted. Documentation of those tests and their results should be included with data transmittals or associated reports.

Vessel offsets between position, IMU, and sensors should be performed using a tape measure or surveyed using a total station. A patch test calibration should be conducted to derive the mounting offsets between the sonar head and motion reference unit. The patch test should be run at varying speeds, headings, and overlaps into coincidence. Patch tests are employed to correct the data for navigation timing, pitch, roll, and azimuth offsets between the transducer and the Inertial Measurement Unit (IMU).

A Performance Test should be conducted to evaluate the quality and confidence of the bathymetric data being collected. The Performance Test is used to determine the swath width that for the tested bathymetric system at survey site. Total Propagation of Uncertainty should be calculated to determine the beam angle limit required to meet the vertical accuracy specifications. Total Propagation of Uncertainty computations take into consideration the navigation system, IMU, echosounder parameters, vessel speed, and sound velocity measurements when calculating the accuracy of the soundings.

4.3.1 Recommended Bathymetric Systems

4.3.1.1 Water Depth and Survey Objective

As discussed in Volume 2, swath bathymetric data can be acquired using either true beam-forming systems or interferometric systems. Volume 2 provides a description of how each system operates and their benefits and limitations. Some notable differences between the two systems that should be considered when determining which system to use are that beam-forming systems typically yield denser data and interferometric systems collect wider swaths of data. Therefore, as water depths increase, the interferometric systems have more difficulty achieving accuracy requirements. Interferometric systems may be used in bathymetric surveys for water depths less than about 30 meters as long as they can achieve the survey accuracy requirements. Beam-forming systems also function very well in less than 30 meters of water. In water depths greater than 30 meters, it is recommended that beam-forming systems are used. Results from Performance Tests and Total Propagation of Uncertainty should ultimately be used to determine if a bathymetric system meets the accuracy requirements for a survey area.

For condition assessment surveys during operation of a wind farm that are used to monitor scour hole development around a turbine, condition of scour protection, or cable burial condition, it is recommended that beam-forming systems be used. Owing to the higher data density of a beam-forming system, they are recommended for accurately defining sloping ground (e.g. scour pit or cable trench scar) and demonstrate a better ability to define details of small features (e.g. scour protection, exposed cables, etc.; refer to Volume 2).

4.3.1.2 Northern Atlantic OCS

The surficial geologic conditions in this region indicate that there is the potential for glacial deposits and their derivatives to be present on the seafloor. Those glacial deposits include moraine deposits that contain cobbles and boulders and glacial outwash plain deposits that may also contain boulders and cobbles. Boulders represents significant potential hazards for installation of wind turbine foundations. Boulders, cobbles, and gravel-rich deposits present challenging conditions for installation of cables. Additionally, Cretaceous units are inferred to outcrop in the New York Bight region and it is uncertain whether those units exhibit rock- or soil-like engineering properties.

Therefore, it is recommended to utilize very high-resolution systems capable of detecting and identifying boulders and rock outcrops (for the New York Bight). Examples of such systems are 256 beam, 0.5-degree separation angle, that operate at 200 to 400 kHz. Dual-head sensors can be used to increase the data density in deep water (e.g. deeper than 40 meters). Developers should consider the minimum size of boulder that would be deemed a hazard and then select a bathymetric system specification (based on sounding per square meter) that would be able to detect that sized object.

Backscatter intensity data should also be collected. Volume 2 presents a description of the backscatter intensity data, how it is collected, processed and interpreted. The backscatter intensity data will aid inaccurately interpreting hard bottom areas, gravel/cobble areas, and locations of boulders.

4.3.1.3 Mid-Atlantic OCS

The Mid-Atlantic OCS seafloor is characterized as exhibiting ridge-and-swale topography and predominantly consists of sandy deposits with localized regions of gravel or fine-grained deposits. Gravel deposits exposed on the seafloor are inferred to be of fluvial in origin and may include up to cobble-sized clasts in some areas. They are not anticipated to include boulder-sized clasts. Mobile seabed conditions (sand waves and sand ridges) are one of the primary geohazards that bathymetric data are used to characterize. Bathymetric systems and survey methodology should be capable of confidently resolving the crests of dune-scale bedforms.

4.3.1.4 South Atlantic OCS

The South Atlantic seafloor conditions are similar to the Mid-Atlantic (e.g. ridge-and-swale topography and dynamic bedforms) with the exception that carbonate deposits may also be present. It is recommended that backscatter intensity data be collected and used to interpret the presence of carbonate deposits exposed at the seafloor.

4.4 SIDE SCAN SONAR

Side scan sonar data are collected to create an acoustic picture of the seafloor by measuring the amplitude of the backscattered return signals. The collected data are rendered in a way that provides a photo-like image of the seafloor. Side scan sonar data are used to interpret seafloor conditions, sediment type, anthropogenic features, archaeological objects, and potential geohazards (e.g. boulders, sand waves, pock marks, etc.). Volume 2 provides additional information on the information contained in the data, how side scan data are acquired, processed and interpreted. BOEM's G&G and marine archaeology survey guidance documents (BOEM, 2015a and 2015b) provide the survey specifications, tow fish altitude requirements, sonar frequencies, and positioning requirements. Those side scan sonar specifications are considered to be in line with the standard practice for the industry.

As noted, side scan sonar data are also used to interpret seafloor conditions (e.g. sediment type, boulder zones, rock outcrops, hard bottom areas, etc.). Grab samples should be collected to provide ground-truthing and aid in interpreting seafloor sediment type and features. Grab sample locations should be selected based on review of the side scan sonar data and locations should be selected in order to ground truth characteristic reflectivity areas. It is recommended that at least one grab sample should be collected every 3 to 4 square kilometers. Grab sample frequencies should be increased or decreased based on uniformity or heterogeneity of seafloor.

The Atlantic OCS is subject to a strong thermocline in some areas. USBLs can be affected by a strong thermocline. Survey plans should take into consideration the potential presence of a strong thermocline and select a USBL system set-up that will not be adversely affected by the thermocline. It is noted that an acoustic velocity model updated frequently during the survey using sound velocity casts maybe required to adjust the USBL set-up.

Integration of side scan sonar collected during different survey seasons will likely result in data artifacts and seam effects due to natural processes when creating a mosaic that integrates both data sets. The data artifacts (e.g. tonal differences at the seam) can be reduced if the same side scan system and data processing software are used. However, as long as the side scan sonar data have the required overlap as required in the BOEM guidance documents (BOEM, 2015a and 2015b), then the artifacts should not hinder the interpretation of the data if the individual line files are reviewed (as opposed to solely relying on the mosaic). Natural processes, such as migration of bedforms (e.g. sand waves), can also result in apparent artifacts in the form of misaligned features when two temporally different data sets are merged. However, this information provides value in aiding the interpretation of the mobility rate and direction of the bedforms and actually support sand wave hazard assessments. Reporting should clearly document the misaligned features provide an assessment of the bedform or sea floor changes (e.g. distance, direction, rate, and size of bedform).

4.5 MAGNETOMETER

BOEM (2015a and 2015b) indicates that for HRG surveys in water depths of 100 meters or less, a magnetometer should be deployed to detect ferrous objects or other magnetically susceptible materials, composed of iron, iron alloys such as steel, cobalt and/or nickel. BOEM's

G&G and marine archaeology survey guidance documents (BOEM, 2015a and 2015b) provide line spacing, tow fish altitude, sensor specifications, acquisition, interpretation, and reporting requirements. Three distinct line spacing requirements are defined by the objective of the individual survey. For project siting surveys, line spacing for hazard assessment should have primary lines running 150 meters or less and tie lines positioned at most, 500 meters apart. For surveying along a transmission route, line spacing should run along the centerline with parallel lines located every 150 meters on either side of the centerline route optimally covering the entire region affected by installation activities. At least three equidistant tie-lines should be positioned along the survey corridor at most 500 meters apart from one another. The line spacing for both the project siting and transmission route survey are similar in separation distance and vary mainly by the orientation of the lines. The 150 m by 500 m line spacing for these two survey categories will likely be sufficient to identify any pipeline or cable crossings and very large ferromagnetic objects that could be detrimental to construction. Archaeological surveys require tighter line spacing, with primarily lines spaced no more than 30 meters apart and perpendicular tie-lines spaced 150 meter apart. In the case on UXO surveys in the areas of prior military conflict, line spacing is typically 4 meters or less.

Volume 2 of this study discusses various methods of quality assurance and quality control measures that should be implemented during the surveys. Volume 2 also provides a description of data processing and interpretation techniques. We note that it is advantageous to cross check and correlate interpreted magnetic anomalies inferred to be geologically related to sub-bottom seismic reflection data. In the Atlantic OCS, fluvial gravel deposits derived from the Appalachian Mountains often contain abundant heavy minerals and the gravelly deposits often create a magnetic anomaly trend that correlates to former drainage. Correlating the anomalies to fluvial features in seismic data could aid the identifying gravel bodies that may be problematic to cable or wind turbine foundation (e.g. suction caisson) installations.

4.5.1 UXO Magnetometer Surveys

The first step in UXO hazard assessments is to conduct a desktop study to evaluate the potential for encountering a UXO during construction of the wind farm. The desktop study will evaluate what types of UXOs may be encountered in a specific wind farm area. A UXO expert can then work with the developer to determine what the minimum size of UXO should be searched for and then develop a mitigation plan. The minimum size UXO will aid in designing a UXO survey (e.g. sensor type, line spacing, and sensor tow altitude).

Prior to conducting a UXO magnetometer survey, the acquisition company will run a test somewhat equivalent to a bathymetric patch test (known as an acceptance or verification test) where an object of known weight and dimension is lowered to the seafloor and survey lines running in four distinct directions (e.g., north-south, east-west, south-north and west-east) will pass over the object. This acceptance test is used to verify positioning, repeatability (similar size and shape of the object) and determine the influence of background noise on the detectability of the anomaly. In some cases, the result of the acceptance test has been used to setup the survey's specifications, such as line spacing, altitude limits and anomaly detection cutoff.

The ability to detect a ferromagnetic object on or beneath the seafloor, given a specific magnetometer type, is largely a function of:

1. the dimensions and weight of the magnetically susceptible object,

2. the distance between the sensor and the object (which can be optimized by positioning the magnetometer as close to the seafloor as possible),

3. the object's orientation in relation to the sensor's orientation,

4. the presence of background noise and

5. the spacing between adjacent survey tracklines.

BOEM (2015a and 2015b) require continuous monitoring of the position and altitude of the magnetometer. Echosounders or altimeters are usually provided (or optional) for marine magnetometers. Presently, BOEM requires that the magnetometer sensor be towed no more than 6 meters above the seafloor for G&G and marine archaeology surveys to ensure that large magnetically susceptible objects are resolved. For UXO surveys, the sensor is typically towed at 2 to 3 meters above the seafloor.

The specification of line spacing (and altimeter specifications) should be determined by the size of the object of interest because the intensity of the magnetic field caused by a ferromagnetic material decreases with the cube of the distance to the object. Volume 2 of this study provides an example of how to calculate line spacing based on target UXO detection size. Volume 2 also provides a discussion of data processing and interpretation techniques.

4.6 SHALLOW PENETRATING SEISMIC REFLECTION SYSTEMS

Shallow penetrating, high resolution seismic systems image the shallow subsurface in order to characterize the shallow stratigraphy and identify potential geohazards in support of a variety of engineering studies (e.g., foundation design, cable burial risk assessment). Additionally, these high resolution systems are utilized in marine archaeological research through the interpretation of paleo-landforms which aid the reconstruction of past environments that are of potential archaeological interest.

As discussed in Volume 2 of this study, Chirp sub-bottom systems with operating frequencies between 2 and 24 kHz have been historically used for Atlantic OCS surveys. However, those systems have achieved limited signal penetration in the sandy deposits of the Atlantic OCS. Signal penetration in sandy deposits of Northern Atlantic and beneath sand ridges of the Mid- and Southern Atlantic are typically less than 3 meters and often do not penetrate below gravelly deposits. Table 2-4 (Volume 2) summarizes the typical frequency ranges, vertical resolution and depths of signal penetration for these various shallow penetrating systems. Table 2-5 (Volume 2) summarizes geologic conditions on the Atlantic OCS and how they affect seismic signal penetration.

Three methods to overcome the limited signal penetration of the Chirp sub-bottom systems are discussed in Volume 2. The first method includes using a sub-bottom profiler that utilizes a lower frequency for the source. Some systems that use a frequency range of 500 Hz to 12 kHz have demonstrated better signal penetration, albeit at a slightly lower resolution, than their counterparts that use a 2 to 24 kHz range. A second method would be to use an array of transducers. Such arrays (4x4, 3x3, or 2x2) have been used in deep water surveys and would be expected to achieve better signal penetration. A third method to increase signal penetration is to tow the system close to the seafloor to limit the amount of frequency attenuation in the water column.

Another method for imaging the shallow subsurface is to utilize multichannel streamer arrays with tight group intervals. Multichannel streamer arrays with 1 to 1.56mgi have demonstrated their data can overlap with sub-bottom systems.

4.6.1 Northern Atlantic OCS

Glacial outwash deposits in the Northern Atlantic will prove difficult to achieve signal penetration unless using one of the methods described above. Sub-bottom data in the Northern Atlantic should be reviewed closely and parabolic diffractions that may represent boulders should be interpreted. The sub-bottom systems are expected to achieve little to no signal penetration in the New York Bight where Cretaceous units may be exposed at the seafloor.

4.6.2 Mid-Atlantic OCS

The Mid-Atlantic OCS seafloor is characterized as exhibiting ridge-and-swale topography and predominantly consists of sandy deposits with localized regions of gravel or fine-grained deposits. Gravel deposits exposed on the seafloor are inferred to be of fluvial in origin and may include up to cobble-sized clasts in some areas. The methods described above should be implemented in order to achieve useful shallow seismic data beneath sand ridges and gravel deposits.

4.6.3 South Atlantic OCS

The South Atlantic seafloor conditions are similar to the Mid-Atlantic (e.g. ridge-and-swale topography and dynamic bedforms) with the exception that carbonate deposits may also be present. Sub-bottom data is expected to achieve little to no signal penetration where carbonates are exposed or near the seafloor. Similar to the sand ridges in the Mid-Atlantic, one of the methods described above will be required to achieve useful signal penetration beneath the sand ridges.

4.7 INTERMEDIATE PENETRATING SEISMIC REFLECTION SYSTEMS

Intermediate penetrating seismic systems are used to image subsurface stratigraphy from the seafloor to the foundation depth of interest (Tables 2-4 and 2-5 of Volume 2). These systems can implement various seismic energy sources and receiver array configurations. The equipment and their configuration influences the data resolution and signal penetration depth. Selection of survey equipment and methodology (e.g. shot intervals, sampling rate, record length) are based primarily on the water depth, anticipated geologic conditions, signal penetration depth requirements, and data resolution needs.

These data represent an important component to the engineering planning and design and planning of overall site investigation for the following reasons. A regional seismic survey in the Atlantic OCS will most often be the first subsurface data available for a wind farm. The regional survey is used to develop the first version of the ground model as illustration in Figure 4.1. The ground model should be used to plan the initial phase of the geotechnical investigation. Additionally, the first version of the ground model can be used to begin bracketing a range of soil conditions and begin identifying problematic or favorable conditions for various foundation concepts.

Although the design level seismic survey will provide primary and tie lines through each wind turbine position, not all wind turbine positions are anticipated to have geotechnical data to the full foundation depth. The seismic data will be relied upon to extrapolate and interpolate ground conditions for turbines where the geotechnical data do not extend to the full foundation depth.

Therefore, the seismic data will play a significant role in the site investigation planning, engineering analysis and foundation designs for a wind farm. The engineering team's ability to mitigate risk related to ground conditions by reducing uncertainty of the subsurface conditions relies very much on the data quality.

Data quality depends on a large number of variables including sea state, positioning accuracy of source and streamers, shooting and recording controls, implementation of quality control during acquisition, and data processing methodology. Table 2-6 (Volume 2) lists a summary of typical foundation embedment depths and water depth ranges. Actual foundation embedment depths will depend on the ground conditions, foundation system, and desired foundation capacity.

4.7.1 Seismic Source

Seismic sources used for intermediate penetrating systems are typically selected to optimize the relationship between attaining the highest frequency content, achieving desired signal penetration depth, and providing a consistent signal signature during the course of the survey. Boomer and sparker sources are the two most commonly used sources for the offshore wind farm foundation surveys. Volume 2 provides a description of the boomer and sparker sources, their benefits and limitations.

Based on anticipated hard ground conditions in the Northern Atlantic related to glacial and Cretaceous deposits and potentially shallow carbonates in the Southern Atlantic, it is recommended that a boomer system in a double or triple-plate configuration or a sparker source is used. A boomer (single- or double-plate configuration) or sparker source is anticipated to be adequate for achieving 80 to 100 meters of signal penetration in the Mid-Atlantic.

4.7.2 Receiver Arrays

Receiver arrays are either single channel or multichannel arrays. Receiver array configuration is a very important component that dictates seismic data resolution and signal penetration depth and improves ability to collect mappable data with targeted depth interval. "Mappable data" are defined herein as:

- Data with good signal-to-noise ratio

- Coherent events (primary reflections) that can be traced laterally along the entire record and correlated confidently between primary and tie lines,
- Seismic stratigraphic character can be observed in data, including the internal reflectors which provide valuable information used to interpret geologic nature (e.g. facies) of subsurface materials, and
- Wavelet should be processed to appear as a Ricker wavelet and deconvolved to zero phase to permit evaluation of reflection polarities and amplitudes.

Single channel arrays may either be comprised of 1 hydrophone or several hydrophones that are closely spaced and recorded as one group. As discussed in Volume 2, single channel systems have inherent limitations. Those systems are prone to water bottom multiple artifacts that result in unmappable data below a depth equivalent to the water depth. Therefore, where signal penetration requirements exceed the water depth, single channel systems should not be used. Refer to Table 2-6 (Volume 2) typical wind turbine foundation depths.

Another inherent limitation for single channel arrays, is they are limited to signal attenuation. Signal attenuation occurs due to geometric spreading (as a function of $1/R^2$ where R = distance), scattering off of points sources, and refraction and seismic wave conversion at interfaces. Geometric spreading is one of the primary sources of attenuation. Multichannel seismic arrays mitigate the attenuation issue by common mid-point stacking and trace summation as described in Volume 2. Therefore, in water depths greater than about 30 meters, multichannel arrays should be used instead of single channel arrays to mitigate signal loss due to attenuation.

Multichannel receiver arrays provide a means for working around the water bottom multiple challenge, allow more opportunities to improve signal-to-noise ratios during acquisition and signal processing, (e.g. through stacking, folding, etc.). Multichannel streamers consist of hydrophones or elements grouped together to form a channel. The hydrophones may be spaced 0.3 to 1m apart and grouped at defined intervals (e.g. 1.56-meter group interval [mgi]). The number of hydrophones per group may be 1 to 5 or more. The improved signal-to-noise ratio over single channel systems is approximated by the fold. For example, 24-channel systems collected at full fold (24) will result in a minimum signal-to-noise improvement of $\sqrt{24}$ (National Academy of Sciences, 1976).

The common mid-point (CMP) fold or multiplicity is a function of the group interval, the number of channels and the shot point interval. A higher CMP fold implies a higher signal-to-noise ratio (SNR) due to trace summation resulting from CMP stacking process.

$$\text{CMP fold} = \frac{\text{Number of channels} \times \text{Group Interval}}{2 \times \text{Shot Interval}}$$

Spacing of the hydrophones influence the resolution of the data. Closer spaced hydrophone arrays will be able to collect higher frequency content data and provide better resolution of the shallow subsurface than wider spaced hydrophone arrays. Ultra-high resolution multichannel surveys now utilize streamers with 1 to 2-meter group intervals.

Multichannel streamers used in engineering surveys in the US are commonly either at 1.56mgi or 3.125mgi.

For offshore wind farm surveys, the recommended current best practices are for short group intervals: 1mgi, 1.56mgi, or 2mgi. The 1mgi and 2mgi streamers have been used recently in Europe while the 1.56mgi streamers have been used in the US. Surveys have also successfully combined shorter with wider group intervals (e.g. front section utilizing 1mgi and aft section utilizing 2mgi or front section utilizing 1.56mgi and aft section utilizing 3.125mgi). Shot intervals should allow for full fold collection of the data.

The length of the streamer also influences the depth investigation for the streamer and the relationship are approximately equal or the streamer length should be about 90 percent the targeted imaging depth. For example, if the seismic investigation target depth is 80 meters, then the streamer length would be about 70 meters long.

4.8 ABBREVIATIONS

BS	Backscatter
CARIS	Computer Aided Resource Information System, part of Teledyne Technologies Inc.
CFR 585	Code of Federal Regulations Part 585
cgs	centimeter-gram-second
cm	Centimeter
COP	Construction Operations Plan
dB	Decibel
DTS	Desktop Study
FM	Frequency Modulated
G&G	Geological and Geotechnical
GPS	Global Positioning System
HRG	High-Resolution Geophysical
Hz	Hertz
IHO	International Hydrographic Organization
J	Joules
kHz	kiloHertz
km	kilometer
lb	pound
m	meter
M	Dipole magnetic moment
MBES	Multibeam Echosounder
mgi	meter group interval
mm	millimeter
NHPA	National Historic Preservation Act of 1966
nT	nanoTesla
psi	pounds per square inch
RTK	Real-Time Kinematic satellite navigation
SBES	Single Beam Echosounder

SNR	Signal-to-Noise Ratio
SSS	Side Scan Sonar
US/U.S.	United States of America
UXO	Unexploded Ordnance
WEA	Wind Energy Area

4.9 REFERENCES

Allen, F.T. (1972) Some characteristics of marine sparker seismic data. Geophysics, vol. 37, pp. 462-470.

Breiner S. (1999), Applications manual for portable magnetometers, San Jose, California: Geometrics. 58 pp.

Bureau of Ocean Energy Management (BOEM) (2015a), Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585, Office of Renewable Energy Programs, July.

Bureau of Ocean Energy Management (BOEM) (2015b), Guidelines for Providing Archaeological and Historic Property Information Pursuant to 30 CFR Part 585, Office of Renewable Energy Programs, July.

Bureau of Ocean Energy Management (BOEM) (2014) Atlantic OCS Proposed Geological and Geophysical Activities, Mid-Atlantic and South Atlantic Planning Areas, Final Programmatic Environmental Impact Statement. BOEM 2014-001.

Camidge, K., Holt, P., Johns, C., Randall, L. and Schmidt, A. (2010) Developing Magnetometer Techniques to Identify Submerged Archaeological Sites Theoretical Study Report. Cornwall Council Historic Environments Projects, 121 pp.

International Hydrographic Organization (2008) IHO Standards for Hydrographic Surveys, Special Publication No. 44, 5th ed., International Hydrographic Bureau, Monaco.

National Academy of Sciences (1976) Multichannel seismic reflection system needs of the U.S. Academic Community. Steering Committee of the Ocean Sciences Board, Assembly of Mathematical and Physical Sciences, National Research Council.

FUGRO MARINE GEOSERVICES, INC.

VOLUME 5

BEST PRACTICE RECOMMENDATIONS FOR GEOTECHNICAL INVESTIGATIONS

Study Title:

Geophysical and Geotechnical Investigation Methodology Assessment for Siting Renewable Energy Facilities on the Atlantic OCS

Table of Contents

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5.1 INTRODUCTION

This volume is written to address best practice recommendations for geotechnical investigations based on site conditions and facility design requirements. It also provides a summary of the differences between marine and onshore site investigations. Best practice recommendations are tailored to address the myriad of soil conditions expected to be encountered within the Atlantic OCS. The soil conditions may vary from carbonates in the south to interbedded and channel infill deposits in the mid-Atlantic through to glacial till, gravels, cobbles and very dense sands in the north. Geotechnical drilling equipment must be capable of working in shallow water, the wave-breaking zone, and deeper water up to several tens of meters. Such equipment will be exposed to strong currents, high waves and gusty winds.

Cone penetration equipment should be capable of measuring tip, sleeve and pore pressure. High capacity cones may be warranted in areas where very dense sands and gravel deposits are expected to be encountered. Any array of geotechnical in-situ testing and sampling tools must be capable of both shallow and deep probes, must be designed to handle high reaction forces and must be mobilized with suitable spares should data quality issues arise. Suitable systems should include a combination of CPT, SPT, thick and thin-walled Shelby Tubes, split spoons, vibracores and coring barrels, in case rock is encountered. Piston cores and box cores may run into difficulty with sample recovery. However, grab samplers may be used to sample the surface materials for benthic habitat studies. Offshore labs should be equipped to measure clay shear strength, assess fines contents, water content and bulk density. All of these parameters can aide in the selection of suitable onshore laboratory assignments to fully characterize the site soils.

Dynamic soil behavior is a very important aspect of best practices for offshore wind farms. The soil behavior under dynamic loading can vary widely depending on the number of cycles, the rate of loading, magnitude of loading, the foundation type and the size of the wind turbine. Research has shown that typical offshore wind farms foundations may experience a broad range in shear strain and that this range is best handled by in-situ testing, advanced dynamic testing or a combination of both.

5.2 MARINE (OFFSHORE) VERSUS ONSHORE SITE EXPLORATIONS

Marine investigations can be conducted in a wide variety of environments; these can be categorized as follows:

- **Protected (shallow) waters.** This environment is typically found in harbors, lakes, and bays. Water depth is typically a few feet to several tens of feet. Site investigations in such environments are typically simple and do not require a lot of experience nor specialized approaches. This environment will not be encountered within offshore wind farm areas to be developed within the Atlantic OCS.

- **Shallow coastal waters.** Water depth in this environment can range from few feet to several tens of feet. In this case, tides and surf (shape and size of breaking waves) conditions are important. While this environment is not of a concern while conducting site investigations at the proposed turbine locations, it will be relevant for site investigation along the alignment of the export cables. This environment is considered to be the second most challenging environment for site investigations after the deep water environment.

- **Continental shelf.** Water depth in this environment ranges between few tens of feet to about 300 ft (100 m). Most of the offshore wind turbines within the Atlantic OCS will be located within the confines of this marine environment.

- **Deep water.** Water depth in this environment is typically beyond 100 m (300 ft). It is considered to be the most challenging marine environment to conduct site investigations. Hence, it typically requires specialized equipment, large vessels, and crews with extensive experience.

Each of the aforementioned environments imposes a different set of challenges on the site investigation. Hence, the level of experience and type of equipment selected for site investigations depends on the marine environment where the project is located. Yet, conditions within these environments (collectively referenced to as marine geotechnics) can differ significantly from the conditions onshore. These differences lead to many changes in the way site investigation is conducted. These differences can be separated into the following categories:

- **Type of loads.** Cyclic and uplift loading is encountered more often in the marine environment than onshore. This results in a more significant emphasis on obtaining relatively undisturbed samples for cyclic laboratory testing and tests to measure site-specific pile to soil skin friction.

- **Drilling systems.** Drilling systems used in marine site investigations typically include: larger pipes, larger and heavier systems, higher capacity for the pumps, higher applied torque and greater degree of control compared to their counterparts used for onshore operations.

- **Type and size of foundation systems.** Some of the foundation systems used within the marine environment are not adopted onshore. For example, large monopiles with diameters reaching up to 6 m (18 ft). Another example is suction caissons. The usage of these foundation systems offshore necessitates the ability to acquire more soil samples and in-situ testing data that extend to large depths in order to conduct suitable design. Hence, specialized marine investigation techniques were developed to fulfill these needs. For example, downhole wireline hammers are used to deliver enough energy to the split-spoon sampler in deep waters.
- **Site investigation cost.** Marine site investigations are typically much more expensive compared with onshore investigations mainly due to the need of specialized equipment and vessels from which the equipment is deployed. Hence, it is crucial that the planned site investigation is conducted properly and carefully from the first trial. Any problems associated with data quality and sample integrity during the first campaign, can result in financial and time penalties until a second investigation campaign is planned and executed. On the other hand, if sampling issues arise while drilling onshore, usually they are easy to fix since the equipment is readily accessible. This represents a major difference between marine and onshore site investigations. Moreover, offshore investigations are more susceptible to environmental constraints, are limited by weather windows which inflate the cost of conducting marine investigations.
- **Logistics associated with site investigation.** Marine site investigations usually require a complex suite of specialized equipment that is typically shipped around the world. This imposes several logistical challenges in order to ensure the availability of all required equipment on-site and on-time. Due to the high cost associated with marine site investigations, the operations typically run on a 24/7 mode. This imposes another set of challenges that is not typically of concern in onshore investigations. Logistics associated with a site investigation relies heavily on the site location and its environmental and subsurface conditions. Careful assessment of site conditions is crucial for a successful marine site investigation campaign. It is typical practice to have an on-site geotechnical laboratory to obtain nearly real time geotechnical characterization (e.g. water contents, Atterberg limits, fines contents, and UU triaxials) of the different strata to adjust / modify the exploration program as needed, on site. This is essential to ensure that the collected data and investigation depths fulfill the design requirements of the foundations. It also reduces the chances of disturbing the samples since they are directly tested after retrieval with no transportation operations. On the other hand, having an offshore laboratory is an additional logistical challenge that needs to be accounted for during the planning and execution phases of the site investigation program.
- **Health, safety, and environment (HSE) considerations.** Risks, consequences, and cost of injuries or environmental damage can be significant in marine site investigations compared to its counterpart onshore. This results in the need for

substantial insurance coverages that add to the overall cost of the marine site investigations.

- **Importance of geology.** The characteristics of marine deposits and marine environments dictate the possible presence of geohazards that are not typically encountered onshore during onshore investigations. Examples of these geohazards include gassy sediments, paleo channels, very soft to soft near surface sediments that can extend to considerable depths, albeit, these sediments are not anticipated to be encountered within the Atlantic OCS boundaries.

Based on the discussion presented above, it can be concluded that marine site investigations have many similarities but just as many differences with onshore investigations. These differences should be carefully evaluated especially when onshore based contractors and equipment are planned to be used for marine investigations. The typical characteristics of onshore and marine site investigations are summarized in the following sections.

5.2.1 Onshore Site Investigations

Onshore geotechnical investigations range in depth from just a few meters to many tens of meters. Additionally, test pits can be conducted onshore so a clear visual inspection of the layering can be made above the water table. Moving between boreholes is fairly simple and does not usually take much time. For rock, typical core diameter can be in the range of 2.0 - 7.5 cm (1 - 3 in). Various drill bits can be mobilized to core rock formations of variable strength and structure. Many onshore investigations adopt the use of hollow stem augers. These invariable bring to surface disturbed samples which are not contained within a tube. Recovering samples from the drill string is typically a simple and relatively fast process. SPT hammers used on land are of standard energy. The correlations between blow count and relative density are very well understood. Cone penetration tests are used onshore to compliment the results of the SPT; they also are suitable for uncovering subtle variations in strength that are not detectible using discretized SPT alone. Sample preservation is more easily addressed onshore since the samples can be transported away from the site almost immediately after the test is finished.

5.2.2 Marine (Offshore) Site Investigations

Marine geotechnical investigations also range in depth from just a few meters to many tens of meters. Grab samples coupled with box coring can help defining the variability within the shallow surficial soils but these may be limited in penetration depth by the presence of dense sands. More time is required to move between exploration locations. For rock, typical core diameter can be in the range of 2.0 - 12.5 cm (1 - 6 in). Various drill bits can be mobilized to core rock formations of variable strength and structure. Sampling in sands is very different from that in clays. Sand samples are always disturbed, however, clay samples can be fairly undisturbed so long as the most appropriate (thin or thick walled) Shelby Tube is selected. Tripping up and down the drill string also consumes more time when retrieving samples compared to the onshore counterpart. Hammering SPT samples is different offshore than onshore because more dissipation of energy occurs while the hammer travels through the soil column. Hence, in many cases a downhole wireline system is used (see Volume 3). If a standard SPT setup is deployed, it is important to note that the blow counts in that case are not equivalent to the standard blow counts obtained onshore. In any case, the standard SPT correlations are not applicable to blow counts collected offshore before correcting them to equivalent standard blow counts. CPTs provide a better discretization of the strata as compared to SPT. In offshore investigations, high capacity cones with tip resistances of up to 120 MPa can be mobilized should very dense sands be encountered. However, high capacity cones are not fitted with pore pressure sensors. Over the years, the offshore industry created a full suite of tools generally not available for onshore projects. This includes, but is not limited to, T-Bar, BAT-Probe, Dolphin Vane and Jumbo Piston Corer. Offshore sample storage can become problematic since days and weeks can pass before the samples can be transported onshore. Hence, climatically-controlled reefers are usually required to store the samples while offshore (as per ASTM guidance).

Sample quality is controlled by the method of sample extraction as well as ambient soil type. Samplers used in the bottom of boreholes can be initiated via hydraulic pushing or hammering. Cohesive soils generally are easier to sample whereas granular, wet materials, can slide out of the sample tube. Very soft clay, however, can flow out of sample tubes as well. Therefore, there is a limit where sampling is no longer viable and it must be complemented via in-situ testing devices. This precludes the fact that sensitive tools (e.g. BPT and TBP) must be deployed to test materials that are very soft (in consistency) or very loose (in relative density). Sampling in granular material most often takes the form of split spoons, heavy-walled samplers or sometimes cryogenic freezing. Soft clays are best sampled with piston cores where the added suction keeps the sample intact inside the tube. Thin walled samplers are best suited to softer materials whereas thicker-walled samplers are best suited to harder clays.

Core catchers are small hemispherical-shaped devices that can be added to the end of the Shelby Tubes or split spoons to ensure granular or soft cohesive samples do not flow out of the tube, upon retrieval. Sometimes, additional plastic bags can be added to the periphery of the core catcher; these provided an added barrier through which the soil can't migrate during retrieval.

High quality samples can be taken even in deep water environments but the sampling process must be controlled at every step of the way. Sharpened Shelby Tubes, thin-walled samplers and hydraulically-driven sampling systems can all increase the potential to retrieve undisturbed samples. Sometimes higher quality samples can be acquired if adopting longer sample tubes. Even if the end material is disturbed, a full, lab-quality specimen should be intact on the inside of the tube. X-ray tests are sometimes used on tube samples to check the sample for internal damage / disturbance. The reader is referred to Section 3.1 in Volume 3 for additional information on sample quality.

5.3 BEST PRACTICES RECOMMENDATIONS FOR GEOTECHNICAL INVESTIGATIONS

There is a wide variety of in-situ instruments and techniques that can be mobilized in order to conduct viable marine geotechnical investigations. The viability of using different tools depends on the limitations of each tool as well as the site-specific characteristics. Atlantic OCS is a frontier region where limited geotechnical data has been collected. Hence, in many cases, the geotechnical investigation program will be prepared based on the understanding of the geologic history of the site (as determined from regional and local desktop studies) as well as preliminary / first-pass geophysical surveys. Depending on the amount of information available to the project team, multiple plans that use various sets of equipment can be prepared to ensure the success of the investigation campaign. Obviously, this comes at a financial cost. For example, investigation techniques within old drainage pathways (rivers) that were subsequently infilled with relatively soft / loose transgressive material would be different than the techniques adopted in purely glacial deposits.

This section intends to shed the light on the best practices that are adopted to select the suitable in-situ testing and sampling equipment / techniques that are suitable for the job.

5.3.1 Northern Atlantic OCS

It is envisaged that the risks associated with conducting geotechnical site investigations within the Northern Atlantic OCS lies mainly in encountering boulders and cobbles within the glacial deposits as well as the probability of encountering dense to very dense sands.

The availability of high capacity cones (up to 120 MPa) to the site investigation team is warranted if considering a robust CPT program. It is important to note that standard offshore drilling vessel-based CPTs usually have a 3 m and 1.5 m stroke length for standard cones and high capacity cones, respectively. Since pore water pressure is not typically measured by high capacity cones, the use of standard cones (up to 60 MPa) up to refusal would be preferred; the operator could then switch to a high capacity cone. Moreover, pore pressure generation in sands is usually not that important nor generally observed in many circumstances. Even with high capacity cones, refusal would be possible before reaching the planned penetration depth. Hence, it is important to prepare provisions for drill outs in case of shallow, premature refusal. It is standard practice to limit the number of drill outs allowed per CPT sounding. If the maximum number of drill outs is reached: 1) the seabed CPT might be shifted over a few feet and reattempted or 2) it is also common practice to switch to drilling and sampling operations when shallow refusal of seabed CPT is encountered. The depth of the refusal in most cases dictates the path to follow. For example, if this depth is below the point of fixity of the pile, switching to drilling and sampling would be the preferable approach over shifting over with a CPT reattempt. It is always good practice to determine, via physical sample, what material within the borehole has led to the CPT refusal.

Consideration should be given for the potential to encounter rock. For example, mobilization of a core barrel system will afford the drilling contractor the option of coring should rock or very dense materials be encountered.

Other items for contemplation include the hypothetical recovery in very dense sands. Very dense sands are notoriously associated with poor recovery. Usually, a few attempts are needed and the time required to acquire suitable sample volume can be increased. Correlations relating cone tip resistance to in-situ relative density begin to diverge when appreciable fines content is present. As such, complimentary index tests in association with MIN/MAX (these are two standard tests to estimate the maximum and minimum densities of soils. In the United States, they are typically conducted in accordance to ASTM D4253 and ASTM D4254. They are typically used along with estimated in-situ relative density derived from CPT data to estimate the in-situ density of granular soils), direct shear (DS) or CD tests are required to determine the internal angle of friction. However, the MIN/MAX test requires at least 35 pounds of sample for reliable relative density assessment. MIN/MAX tests will give relative density whereas DS and CD measure PHI angle directly. MIN/MAX relative density is then used to determine PHI angle through known geotechnical relationships.

The anticipated high degree of variability in the soil properties within the Northern Atlantic OCS imposes additional risks on the marine site investigations. This variability should be carefully assessed during the planning phase by procuring all necessary equipment that could be potentially used when different site conditions are anticipated.

5.3.2 Mid-Atlantic OCS

Dense sands, surficial clays and interlayered soils are expected to occur within this region. The sporadic presence of Pleistocene gravels is also anticipated. This could elevate the risk associated with advancing CPT tests. Moreover, variable / interlayered material where gravels and dense sands may overly clayey deposits sometime result in the desaturation of pore pressure element; if this occurs, the cone will have to be replaced or reconditioned. Buried channels may have softer materials as infill; depth extent and lateral continuity are all characteristics that must be carefully delineated based on careful integration of geophysical data with geotechnical data. If the percentage of marine shell fragments is significant, this may result in high initial peak strength but with low residual strength. Clays are expected to be of low to moderate plasticity and slightly to highly over-consolidated. The presence of sand or silt seams may act as preferential failure surfaces that may not be indicative of the overall clay mass strength.

It is important that the testing regiments covers the different failure modes / envelopes anticipated for the various loading conditions. Inter-mixed gravels and sand atop clayey materials can also lead to pore pressure cavitation responses in the CPTs in addition to desaturation of pore pressure elements. Shallow refusal of CPTs may occur if very dense sands are encountered. Therefore, the unsupported length of CPT rod may be an issue with jack-up rig based / top push investigations. If clay infill is pervasive in channel deposits, then the ability to undertake vane shear tests within the borehole would benefit the assessment of shear strength.

Geotechnical programs in this region should consider 1) an adequate supply of spare cones, 2) mobilizing high capacity cones, 3) thin and thick-walled Shelby Tubes, 4) the ability to advance CPT and take samples within a borehole via an alternating sequence would also be useful. The investigation may benefit from conducting a CPT prior to subsequent sampling so as to obtain a picture of the underlying stratigraphy.

5.3.3 Southern Atlantic OCS

Soil deposits within the Southern Atlantic OCS are expected to contain a variable amount of carbonate content, along with typical sand and clay. Hence, it would be prudent to expect that some sort of cementation of the particles will be present in this region which might result in shallow refusal of seabed CPT soundings. Low sleeve friction values are sometimes a hallmark of calcareous materials. It is also important to note that the typical charts that are used to correlate soils behavioral type are not really applicable since carbonate materials tend to behave differently than siliceous materials. Hence, obtaining high quality push / core samples would be essential to optimize the design parameters for the non-traditional strata that could be encountered. Having an adequate supply of HCL on the drill platform will aide in the identification / presence of such materials since calcareous soils effervesce in the presence of HCL. A standard suite of cones, vibracores and boreholes should suffice for this region. However, the ability to acquire drill cores should also be considered since limestone or calcareous cemented sands may be present.

5.4 DYNAMIC SOIL PROPERTIES

Magnitude, predominant frequency, and repeatability of dynamic loads acting on wind turbines can vary considerably and are crucially important in offshore foundation engineering. Examples of these characteristics include, cyclic loads induced by the motion of the blades, wave/storm loads, and seismic motions. Cyclic / dynamic loads can result in post-load degradation of axial and lateral capacity and / or increase in lateral permanent deformations depending on the various foundation system. Moreover, these loads can alter the fundamental frequency of the offshore wind turbine system beyond the target frequency range; this can be a detriment to the structure itself.

Hence, measuring the dynamic soil properties and investigating the effects of dynamic loads on the offshore wind turbine system is an integral part of the design process. It is widely known that wind turbines can experience millions of loading cycles throughout their design life; this property has huge implications for foundation performance and reliability and must be assessed with advanced testing methods.

In order to ascertain the effects on the foundation system, several in-situ and laboratory testing techniques can be used to measure the dynamic properties of the surrounding soils. In-situ techniques include downhole PS (P-wave and S-wave) logging and Seismic CPT (Shear wave velocity versus depth using multiple geophones). With these methods, various seismic wave velocities can be ascertained which when used in combination with other tests can help define the density, acoustic impedance and velocity profile through the soil column.

Laboratory testing on the other hand includes cyclic DSS, cyclic triaxial tests, and resonant column tests. These specific dynamic tests simulate soil behavior under cyclic or seismic loading conditions with the option of understanding this behavior under multiple loading stages. Resonant column tests help determine the soil's elastic modulus, modulus degradation and damping ratio at small stain levels by applying torsional or flexural vibration. Cyclic triaxial tests can be modified to include bender elements or LVDTs to measure small strain response in the middle of the sample. It is worth noting that these laboratory tests can either be stress or strain controlled.

As shown in Figure 5.1, various in-situ and laboratory testing techniques have different ranges of strains within which they are applicable. Resonant column, bender element, and small strain LVDTs can be used to measure the dynamic properties at small strains while cyclic laboratory tests can measure the dynamic properties at larger strains. The range of strain level applicable to the design of the foundations for offshore wind turbines depends on many factors. These factors include: the adopted foundation system (type and dimension), in-situ soil conditions, and environmental loads. Hence, it is particularly important to carefully assess the project-specific information (geophysics, soil type, etc.) to select the type of in-situ and laboratory tests applicable for design. In many situations, a wide range of strains will be of interest which will necessitate combining data from multiple laboratory and in-situ testing techniques. It is beyond the scope of this document to relate, on a one-to-one basis, what specific test regiments will be required for an array of foundation systems.

Table 7.1 from Anderson et al. (2013) relates foundation type to soil type to applicable cyclic tests and highlights the necessary input parameters for design. This table provides reasonable guidance regarding the range in tests required to assess 1) soil frictional characteristics, 2) monotonic loading paths, 3) cyclic performance as well as 4) consolidation properties.

In order to correctly run cyclic laboratory tests, various parameters must first be assigned. This include:

- The average and cyclic shear stresses imposed on the sample while running the tests (for stress controlled tests) or the average and cyclic shear strain (for strain controlled tests). These stresses / strains should be carefully selected based on the expected operating conditions of the wind turbine.

- Frequency of applying cycles; this depends on the nature of dynamic loading applied to the wind turbine.

- Failure criteria; this includes the maximum number of cycles, and/or reaching a maximum strain / stress level.

In the presence of a substantial amount of cyclic test results, multiple curves can be developed to capture the behavior of the material under a wide variety of cyclic testing conditions. The curves prepared for the Drammen clay (Andersen, 1991, Andersen, 2009, and Andersen et al., 1980) are a well-known example in the literature. This work includes curves that can be used to estimate the number of cycles that leads to failure for a given combination of stresses (average shear stress, cyclic shear stress, and undrained shear strength of the material). This is the main premise of cyclic testing; the designer would like to know how many cycles leads to strength reduction. If the in-situ material is comparable to the Drammen clay, a designer might choose to run a reasonable number of cyclic tests and compare the results with the curves of the Drammen clay. If the in-situ material is not comparable to that clay, the designer may at his/her discretion investigate the behavior of the foundation system under cyclic/dynamic loads.

The cyclic data can be used in multiple ways to investigate the behavior of the foundation system under cyclic loads. This unusually requires the use of numerical analyses (finite elements or finite difference), analytical models, or a combination of both. Currently, these design approaches are not standardized and the designer needs an extensive amount of experience to effectively design for long-term behavior of the different foundation systems. Research based studies and joint industry projects (JIPs) could help advance the state of the art/practice and help reach some level of standardization to ensure the safety of such valuable infrastructure. For example, the SOLCYP joint industry project provided some insight about axial and lateral design of piles under cyclic loading (Puech, 2013 and Garnier, 2013).

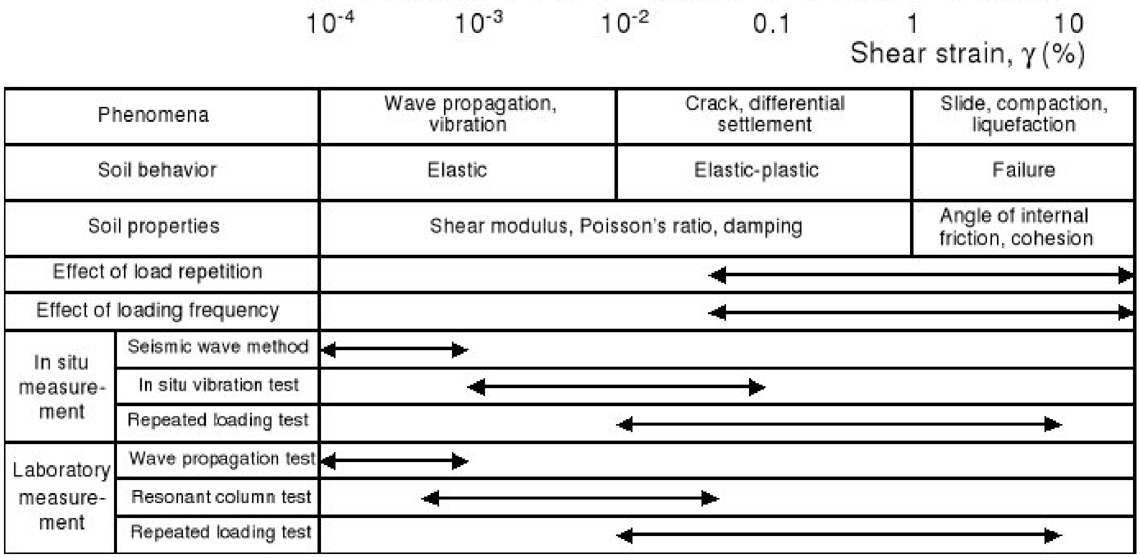

Figure 5.1. A typical shear modulus degradation curve showing the strain levels for different applications, in-situ tests, and laboratory tests

Source: Modified from Sawangsuriya, 2012 (after Atkinson and Sallfors 1991, Mair 1993; Ishihara, 1996; Sawangsuriya et al. 2005).

Once the various dynamic / cyclic tests have been undertaken, the designer will now have a window into how the number of loading cycles affects the foundation over the design life. Millions of cycles can weaken the soil, reduce the foundation stiffness, increase material and structural damping (especially with tall and slender structures), increase the amount of lateral and / or vertical displacement and increase the propensity for structure/system/soil fatigue to occur.

It is important to note that no specific test will provide the entire picture and that multiple cyclic tests should be used in combination to define the structure's performance loading regime. In addition, some soils get stiffer with increasing number of cycles; this phenomenon is not lost on designers since it has implications for the correct assessment of structural fatigue. Stiffer systems under a very large number of cycles can fatigue more quickly.

5.5 REFERENCES

ASTM D4253, Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table, ASTM International, West Conshohocken, PA, 2016, www.astm.org

ASTM D4254, Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density, ASTM International, West Conshohocken, PA, 2016, www.astm.org

Andersen, K.H. (1991), "Foundation Design of Offshore Gravity Structures", in O'Reilly, M.P. and Brown, S.F. (Eds.), Cyclic Loading of Soils: from Theory to Design, Blackie, Glasgow, pp. 122-173.

Andersen, K.H. (2009), "Bearing Capacity under Cyclic Loading - Offshore, along the Coast, and on Land. The 21st Bjerrum Lecture presented in Oslo, 23 November 2007", Canadian Geotechnical Journal, Vol. 46, No. 5, pp. 513-535.

Andersen, K.H., Pool, J.H., Brown, S.F. and Rosenbrand, W.F. (1980), "Cyclic and Static Laboratory Tests on Drammen Clay", Journal of the Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers, Vol. 106, No. GT5, pp. 499-529.

Andersen, K.H., Puech, A.A., and Jardine, R.J. (2013). "Advances in Lateral Cyclic Pile Design: Contribution of the SOLCYP Project," Proceedings of TC 2009 Workshop 18th ICSMGE, Paris, 4 September 2013

Atkinson, J. H. and Sallfors, G. (1991). "Experimental determination of stress-strain-time characteristics in laboratory and in situ tests" Proceedings of the 10th European Conference on Soil Mechanics and Foundation Engineering, Florence, Italy, 915-956.

Campanella, R.G., and Weemees, I. (1990). "Development and Use of an Electrical Resistivity Cone for Groundwater Contamination Studies," Canadian Geotechnical Journal, 1990, 27(5): 557-567

Garnier (2013). "Advances in Lateral Cyclic Pile Design: Contribution of the SOLCYP Project," Proceedings of TC 2009 Workshop 18th ICSMGE, Paris, 4 September 2013

Mair, R. J. (1993). "Developments in Geotechnical Engineering Research: Application to Tunnels and Deep Excavations," Unwin Memorial Lecture 1992, Proceedings of the Institution of Civil Engineers-Civil Engineering, Vol. 97, No. 1, pp. 27-41.

Mayne, P.W. (2007). "Final Report – Cone Penetration Testing State-of-Practice," NCHRP Project 20-05; Task 37-14: Synthesis on Cone Penetration Test (February 2007)

Olsen, R. S. and Mitchell, J. K. 1995. "CPT stress normalization and prediction of soil classification." Proc., Int. Symp. on Cone Penetration Testing, CPT 95, Linkoping, Sweden, 257–262.

Puech (2013). “Advances in Axial Cyclic Pile Design: Contribution of the SOLCYP Project,” Proceedings of TC 2009 Workshop 18th ICSMGE, Paris, 4 September 2013

Robertson, P. K. (1990). “Soil Classification using the Cone Penetration Test.” Canadian Geotechnical Journal, 27(1), 151-158.

Sawangsuriya (2012). "Wave Propagation Methods for Determining Stiffness of Geomaterials,” Wave Processes in Classical and New Solids, book edited by Pasquale Giovine, ISBN 978-953-51-0821-4,

Sawangsuriya, A., Bosscher, P. J., and Edil, T. B. (2005). “Alternative testing techniques for modulus of pavement bases and subgrades.” Proceedings of the 13th Annual Great Lakes Geotechnical and Geoenvironmental Engineering Conference, Geotechnical Applications for Transportation Infrastructure, ASCE, Geotechnical Practice Publication, No.3, Milwaukee, WI, 108-121.

Schneider, J.A, Randoph, M.F., Mayne, P.W., and Ramsey, N.R. (2008). “Analysis of Factors Influencing Soil Classification using Normalized Peizocone Tip Resistance and Pore Pressure Parameters.” Journal of Geotechnical and Geoenvironmental Engineering, 134(11), 1569-1586.

FUGRO MARINE GEOSERVICES, INC.

VOLUME 6

GEOPHYSICAL AND GEOTECHNICAL GUIDEBOOK

Study Title:

Geophysical and Geotechnical Investigation Methodology Assessment for Siting Renewable Energy Facilities on the Atlantic OCS

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6.1 INTRODUCTION

The objective of this guidebook is to present and describe equipment that may be used in geotechnical and geophysical site investigations for offshore wind farm developments on the Atlantic OCS. Geotechnical and geophysical equipment should be selected based on the anticipated physical environment (e.g. water depth and geologic conditions), types of data required to support the study, and reliability or robustness of the equipment. Volume 1 of this study presents the anticipated physical conditions in the Atlantic OCS. Volumes 2 through 5 present various types of equipment and site investigation methodologies that can be used for the different regions of the Atlantic OCS and for various wind farm projects. Volume 6 (current volume) presents a catalog of the various equipment, photographs of the equipment and additional equipment specifications.

Our compilation of this guidebook was made possible through the insight gained from newly acquired data within federally-designated WEAs on the Atlantic OCS. This was done by comparing data collected for offshore wind energy development in other parts of the world and by utilizing previously collected data along the Atlantic Margin to understand the adequacy of various research methods. This ensures that proper instrumentation guidance is available for development of offshore renewable energy in the US.

The scope of this portion of the larger BOEM G&G Best Practices study is to present a guidebook with specifications and expected results of geophysical and geotechnical equipment based on site conditions (sediment type, water depth, etc.) encountered near federally identified WEAs on the Atlantic OCS. As required by BOEM, this equipment guidebook has been compiled by researching technical specifications (i.e. “Spec Sheets”) from the various, manufacturers of widely available G&G instrumentation. However, the text refrains from making reference to trade names in order to ensure that no company receives endorsement from the publication of this document. For some instruments, there are a limited number of manufacturers (e.g. marine magnetometers) and therefore, the technical specifications presented are indicative of a single manufacturer even though their name does not appear in the document.

Research on geotechnical equipment includes analysis of the various drilling, sampling and in-situ testing instruments and methods for use in offshore renewable energy development. Where applicable, the working water depth ranges, sediment sample depth ranges, various methods of sampling and any other relevant information have been mentioned. The geophysical equipment analysis concentrates on those instruments used for measuring bathymetry, characterizing the seafloor through sonar imaging (i.e. side scan sonar and multibeam backscatter), identification of magnetic anomalies and the acquisition of seismic reflection data. For each system listed, where applicable, anticipated resolutions, penetration depths, swath widths, sampling rates and other limiting factors specific to each of these geophysical systems is presented.

6.2 GEOTECHNICAL EXPLORATION VESSELS

Offshore geotechnical drilling is one of the most challenging operations in offshore engineering, since vessels and crew must face the worst environments; these include extreme weather conditions, extended durations while at sea, rough sea conditions in terms of significant wave period and swell. This environment provides impetus for the industry to research and design innovative drilling and sampling techniques in order to maintain the highest possible quality of the recovered soil material.

Drilling in open seas and deep water is more commonly related to activities of the oil and gas industry. Geotechnical drilling is required for the design of platform foundations, subsea pipelines and tethered anchoring systems, just to name a few. Years of experienced garnered from the O&G industry can be directly applied to those shallow water investigations within the Atlantic OCS. Robust drilling systems and proven platforms (drill vessel, jack-up, lift barge or anchored vessel) are a requirement to understand the subsurface conditions within the Atlantic OCS.

The major challenge during offshore site investigation is the station-keeping of the vessel. Waves and wind tend to move vessel in all directions. Anchors and/or dynamic positioning (DP) systems are used to reduce the lateral movement of the vessels during the different operations. On the other hand, the vertical heave of the vessel as waves pass by is usually addressed with a drill-string heave compensated system that allows the vessel to move up and down around the drill string which is hard-tied to the seafloor via a heavy seabed frame. Due to the aforementioned reasons, specialized vessels might be needed for some projects. The different classes/types of site investigation platforms include:

Dynamically positioned vessels. In order to stay on position, drilling vessels or drillships must be equipped with a DP system, which includes GPS, an array of satellite receivers in conjunction with seafloor-mounted acoustic beacons and thrusters to keep the vessel on location with minimal lateral offset. Figure 6.1 shows an example of a DP vessel.

Standard vessels (anchored). Typical anchored systems generally rely on a four-point-anchor spread. However, sometimes the use of anchor lines is not an appropriate method to keep the vessel on position due to the prevailing wind and associated variable ocean currents and waves that constantly impart multidirectional loads on the vessel. Figure 6.2 shows an example of a standard (anchored) vessel.

Jack-up platforms/Lift boats. Once jacked-up on location the drilling platforms are stable in place and less susceptible to inclement seas and weather than floating vessels. Jack-up platforms positioned on the U.S. coast are currently limited to shallow water (<20 meter) working depths. Specialized jack-ups or lift boats that can work in deeper water depths are located in the Gulf of Mexico or Europe. Jack-ups/lift boats are flat-bottomed and do not weather rough sea states as well as drilling ships. As a result, they are susceptible to delays in moving between locations if the sea state exceeds the vessel's threshold. Figure 6.3 shows an example of a jack-up platform.

Seafloor drills. Are specialized marine drill rigs that can be lowered to the mudline and remotely operated from the vessel deployment. It is less sensitive to weather conditions and has the ability to operate in strong currents. On the other hand, it is costly to acquire and operate because it is highly specialized.

Figure 6.1. An example of a dynamically-positioned vessel (Fugro Explorer)
(Source: www.fugro.com)

Figure 6.2. Example of a standard vessel used in offshore drilling
(Source: http://www.ryanmarine.com/)

Figure 6.3. Example of jack-up platforms (Fugro Excalibur and Deep Diver)
The jack-up platforms were used to conduct many of the initial geotechnical site investigations in Europe. During the early stages of the European industry some of the jack-ups even installed wind turbines until larger, purpose-built installation vessels became available. Today, some of those jack-ups service wind turbines as shown in the photograph. (Source: www.fugro.com)

Figure 6.4. Example of seafloor drill (Portable Remotely Operated Drill)

(Source: www.benthic.com/)

6.3 GEOTECHNICAL EQUIPMENT

6.3.1 Cone Penetrometer Testing

The Cone Penetration Test (CPT), the piezocone (CPTu), and the seismic cone (SCPT) are very versatile tools used as complimentary testing techniques to the drilling operations in order to have a better understanding of the ground conditions for engineering design.

The advantages and disadvantages of this *in-situ* testing have been discussed in more detail within Volume 3 of this report.

Table 6.1. Different types of CPT tests used in practice

Type of CPT	Measurements	Notes*
Regular electric cone	q_c, f_s	-For most applications, the measurement of pore water pressure is standard. Hence, this CPT type is rarely used.
Piezocone Test	q_c, f_s, u	-The most popular cone type currently used in practice.
Piezocone test with dissipation	q_c, f_s, u	-As the cone advances into soil, it causes a change in pore pressure. This change can increase or decrease depending on the behavior of the soil deposit when sheared (contractive or dilative behaviors). In the case of this test, the cone penetration is stopped at specific depths. The change in pore water pressure is then measured versus time. This is used to back calculate the coefficient of consolidation and hydraulic conductivity (i.e. the dissipation characteristics). -In-situ dissipation test is time consuming especially for low permeability clay deposits. Hence, it is rarely conducted offshore.
Seismic Piezocone Test	q_c, f_s, u, V_s	-Is equipped with geophones to measure shear wave velocity profiles that can be used in dynamic analyses. -Seismic waves are imparted to the cone via external, seabed sound sources. -In seismically active areas, the measured velocity profiles can be used to assess liquefaction susceptibility and perform site response analyses. -For offshore applications within the Atlantic OCS, seismic CPT would be useful to measure the small strain shear modulus to be used in dynamic soil-structure interaction analyses.
Mini-cones	q_c, f_s	-Is characterized by a smaller cross sectional area than the regular CPT cones. -Pore water pressure is not commonly measured in this cone type. -Requires reduced force to penetrate into the different strata compared to the conventional size (10 cm^2). -The penetration rate of this cone type is typically double the standard penetration rate adopted in the rest of the cones. The change in penetration rate and the reduced cross sectional area should be accounted in data processing. Especially if the data from this cone is to be used to develop geotechnical design parameters. Hence, it is preferable to use these cones in regions where prior geotechnical data is available (Danson, 2005). - It can detect very thin layers (i.e., higher resolution). A common example

Type of CPT	Measurements	Notes*
		would be the detection of shells or shell beds. It can also detect thin sand layers within thick clay deposits which can have major implications on time rate of settlement in clay (Danson, 2005).
High Capacity Cones	q_c, f_s	-Typically double the capacity of regular cones (120 MPa versus 60 MPa). -Pore water pressure is not typically measured in this cone type. -It can be used to avoid refusal in dense sand deposits and is good for assessing max-outs in tip resistance.
CPT Stinger	-	CPT stinger is a long hydrodynamic dart that upon seabed impact will record dynamic cone penetration values. It then uses the reaction gained (around the perimeter) from embedment as a reaction to subsequently thrust an internal CPT for tens of meters below the initial penetration. The synthesized CPT plot is a combination of dynamic and static cone push results. Continuous data from seabed to 35 m (115-ft) can be acquired with this system.
Resistivity Piezocone Test	q_c, f_s, u, E_r	-Measures the electric resistivity profile versus depth which is used to investigate the corrosion potential for foundations and cables in contact with the soil -It can be used to localize potential contaminations within the soil deposit (see Campanella and Weemees, 1990)
Other types	Various	CPT cones can be modified to measure additional data / parameters. For example, adding heat probes to measure thermal conductivity of the soil.

Where: q_c = cone tip resistance, f_s = sleeve resistance, u = pore water pressure, V_s = shear wave velocity, and E_r = electric resistivity.
*Most of the information is based on Mayne (2007) and Lunne (2010).

The equipment consists of cone penetrometers, which range in size from 2 cm^2 to 40 cm^2, but the most commonly adopted cones used in the industry are the 10 cm^2 and 15 cm^2 probes. The size of the selected cone depends of the soil strength and consistency expected at the site. Additional requirements such as cone accuracy and layer detection may also constrain the cone choice.

Cone penetrometers measure the tip resistance (q_c) and sleeve resistance (f_s), due the measurement obtained from the gauge load cells. The piezocone can measure pore water pressure, where the measurements depend on the location of the filter. The filters can be located on the cone face (u_1 location), behind the cone (u_2 or shoulder location) or behind the friction sleeve (u_3) (Lunne, 1997). The location of the filter is not standardized but the most common one used most often recommended is the u_2 cone.

From the measured parameters, one can obtain derived factors as the alpha (α) factor, cone tip resistance (q_c), net cone tip resistance (q_n) and friction ratio (R_f)

The alpha factor reflects the influence of the water pressure on the cone. The total cone resistance is the cone resistance corrected for the water pressure at the tip of the cone and the cone construction. The net cone resistance is the cone resistance corrected for the hydrostatic pressure, excess pore pressure, in-situ ground pressure and cone construction. The friction ratio is the local sleeve friction measured at a certain depth divided by the calculated average cone resistance at the same depth. Table 6.1 presents the various types of cone penetration tests that are currently available to provide an assessment of soil characterization. It is important to note that the cone does not “classify” the soil per say, rather provides an estimate on the soil behavioral type (SBT) which can be correlated with soil classifications.

During the protrusion of the CPT into soil, the engineer/technician should verify the verticality, reference measurements of the cone, rate of penetration, interval of the readings, and depth measurements in order to ensure the test has been conducted in accordance with the standard. Cone premature refusal can occur depending on the mobilized equipment selection and metrics such as verticality, penetration rate and excessive rod friction can all hinder advancement of the cone tip.

The standard rate of penetration, in accordance with the International Society of Soil Mechanics and Geotechnical Engineering – International Reference Test Procedure (ISSMGE - IRTP) indicates that the of penetration should be 20 mm / sec with a variance not greater than ± 2 mm /sec.

6.3.1.1 Seabed CPT Systems

The functionality of the Seabed CPT system had been explained in detail in Volume 3 of this report. Originally, the equipment consisted of two vertical hydraulic cylinders pushing cone rods, and then were subsequently replaced by four uninterrupted turning wheels that reduce the operational time. With this system, investigations can be conducted to a maximum water depth between 3,000 to 3,500 meters, and in favorable conditions, can achieve up to 40 to 50 meters of penetration. Table 6.2 presents various types of currently available Seabed CPT equipment with associated specifications and capabilities.

Figure 6.5 also shows the Roson 40, which is one of the more common Seabed CPT systems used for offshore geotechnical investigations. All the systems listed below are suitable for investigations within the Atlantic OCS. However, the mode of deployment and measurement limits differentiates the systems as listed. It is also important to understand that cone selection must be based not only on the expected geotechnical conditions but is constrained by the deployment system characteristics (i.e. available reaction thrust, autonomous or real-time viewing of cone parameters and ambient water depth).

Many of the systems are stand-alone in nature and require a method of deployment to get to the seafloor. Usually, a single-arm davit or tugger-winch in combination with an aft-mounted hydraulically actuated A-Frame are used to deploy the seabed CPT. These configurations require deployment over the side of the vessel or over the vessel's transom. Care should be taken to ensure the lifting line does not encroach upon the vessel screws or thrusters. Moreover, USBL systems are usually mounted to the CPT so that a rough position of the equipment is known prior to touchdown on the seabed.

Table 6.2. Various seabed CPT equipment

Equipment	Pushing Force (kN)	Water Depth (m)	Max CPT Penetration below mudline (m)	Cone Area (cm^2)	Continuous CPT Push?	Coiled Rod?	Notes
Shallow Penetrating CPTs Typically Used for Cable Alignment							
SEASCOUT	10-35-50*	3000	10&25	5 & 10	Yes	Yes	Light weight (1 or 3.5 tons underwater) * The thruster unit generates a maximum of 50 kN of thrust, however is reduced to 35 kN in the standard ballast condition of the reaction frame
Searobin	25	2500	2	5, 10 & 15	Yes	No	-
Smartsurf	25	2500	3	10 &15	Yes	No	-
Neptune	10&35	3000-5000	10&20	2, 5 &10	Yes	Yes	-
Penfeld	40	6000	30	-	Yes	Yes	36 mm diameter rod is coiled around a 2.20 m diameter drum

Equipment	Pushing Force (kN)	Water Depth (m)	Max CPT Penetration below mudline (m)	Cone Area (cm^2)	Continuous CPT Push?	Coiled Rod?	Notes
Deeper Penetrating CPTs Typically Used for Wind Turbine Foundations							
ROSON	50,100&100	1500 (max)	50	-	Yes	-	-
Deep Water (DW) ROSON	100&200	4000 (max)	50	-	Yes	-	-
SEACALF	50,100&200	2500	40	10, 15 & Vane shear	No	No	-
GeoScope	200	-	50	-	No	No	-
GeoCeptor	100	-	-	-	Yes	No	CPT and up to 6 m vibracore

Figure 6.5. Roson 40 seabed CPT.
(Source: MG3, http://www.mg3.co.uk/)

6.3.1.2 Downhole CPT systems

The functionality of the Downhole CPT system, has been explained in detail in the Volume 3 of this report. This system uses a wireline system that allows the surface vessel to perform the test consecutively or intermittently throughout the borehole at any depth, down to 1,500 m below seabed. Table 6.3 presents the different types of Downhole CPT equipment, with main properties and capabilities.

Table 6.3. Downhole CPT system equipment

Equipment	Pushing Force (kN)	Water Depth (m)	Max CPT Stroke (m)	Cone Area (cm^2)	Notes
WISON APB-Classic	-	550(max),	-	-	Can be used for Seabed CPT and Vane shear testing
WISON APB-1000	-	500-1000	-	-	Can be used for Seabed CPT and Vane shear testing
WISON APB-3000	-	3000(max)	-	-	Can be used for Seabed CPT and Vane shear testing
WISON **MKIII/MKIV**	90	650	3 or 1.5	5, 10, & 15	Can be used for Seabed CPT and Vane shear testing
WISON EP	100	3000	3 or 1.5	5, 10, & 15	-
WISON **XP**	90	1500	1.5	5 & 10	Can be used for Seabed CPT and Vane shear testing
Dolphin	80	3000	-	-	CPT, Vane shear, piston and tube samples

6.3.1.3 Top Push CPT Systems

CPT equipment typically used for onshore applications can be used for nearshore projects given the availability of a suitable working platform in conjunction with realistic precautions to prevent buckling of the rods during operations. This kind of system is known as top push (deck push) CPT systems. The water depth where this system is applicable is relatively limited and depends on the available equipment, environmental conditions (current, waves and wind speeds) among other conditions. In general, the applicability of this system is up to about 25 meters of water depth.

6.3.2 Geotechnical Offshore Drilling

The main objective of drilling and coring is to accurately quantify ground conditions by: 1) Drilling a hole (typically vertical) with minimum disturbance to the ground, 2) retrieving different types of soil and rock samples that depend on the nature of the sediments and the nature of the project, and 3) performing *in situ* tests to directly measure physical properties at distinct intervals.

Offshore drilling imposes a set of additional challenges when compared with onshore (land-based) drilling operations. This includes 1) continuous movement of the vessel in the vertical and horizontal direction as waves hit the vessel (this is not applicable when jack-up platforms are used). Offshore drilling requires using heave-compensation systems to prevent the movement of the drilling rods and casings from moving with the vessel; 2) positioning and moving the vessel between target locations can be a challenging process. For example, jacking down a jack-up rig can be delayed by days if the weather conditions are not favorable; 3) Mudline is typically few meters to hundreds of meters below sea-level. Hence, accurate depth control measurements should be conducted to track the depth interval of the various samples; 4) Water depth is variable with tides and storms can impact the drilling activities to a point where they can be interrupted for days and in some cases the drilling locations are abandoned and the vessel is forced to get back to port; and 5) stabilizing holes using mud mixtures is more challenging offshore and typically requires a lot of experience and a thorough understanding of the ground conditions.

Offshore drilling and coring operations can be conducted by mobile drill rigs. These drill rigs are designed to be simple to transport and mounted on various jack-up platforms, boats, or barges. They are typically designed to accommodate an array of coring and drilling systems including alternating drilling and downhole CPT systems. In some circumstances, typical land-based drill rigs used for onshore projects can be adapted for offshore drilling, especially for shallow waters. If the drill rig operators lack work experience in offshore environments, the site investigation can be negatively affected. Hence, offshore drilling operations in deep water (> 50 m) requires specialized drilling rigs with tailor-made seabed frames.

6.3.2.1 Offshore Drilling Equipment

Offshore drilling operation depends on the water depth, the required penetration and the ambient seabed material. Selection of fit-for-purpose equipment does not guarantee that adequate sample will be recovered for testing purposes. Moreover, good sample quality highly depends on the experience of the personal and their familiarity with the equipment especially if drilling in environments where drilling has never been performed.

Table 6.4 presents as reference the recommended equipment to be used depending on the water depth and the required penetration to be drilled from the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE).

Table 6.4. Water depth and penetration capabilities drilling, sampling and coring systems[1]

Equipment Description	Maximum Water Depth, (m)*	Penetration, (m)*
Drilling Mode-Based Sampling		
Push Sampler	Suitable for Atlantic OCS WEA water depth ranges	1 to 2 m
Percussion Sampler		0.5 to 0.6 m
Soil Corer		1 to 3 m
Christensen Core Barrel (hollow, double-tubed core barrel that permits switch out of Shelby tubes to rock coring activities…N-size to H size rock cores can be achieved)		0.5 to 1 m
Rock Corer		2 to 3 m
PROD™ seabed drilling/coring	20 m to 2,000 m	2 to 100 m
Shallow Subsurface Sampling Methods		
Basic Gravity Core	Unlimited**	1 to 8 m
Box Core	Unlimited**	0.3 to 0.5 m
Grab Sampler (mechanical)	Unlimited**	0.1 to 0.5 m
Grab Sampler (hydraulic)	200 m	0.3 to 0.5 m
Piston Core	Unlimited**	3 to 30 m
Vibracore	200 m	3 to 8 m

*These figures should be used for general guidance only.
** Water depths are limited by the deployment winch and handling capabilities.

If the drilling vessel capabilities are not well suited to the site environment, remote controlled robotic seafloor drilling techniques can be employed. This system is principal deployed on vessels lowering the equipment using an umbilical cable. This umbilical cable consists of several copper conductors for electrical power, optical fibers or electrical conductors

[1] Geotechnical & Geophysical Investigations for Offshore and Nearshore Development, (2005), International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE)

for control signals, system monitoring and video data (Bar-Cohen, Y., Zachy, K., 2009). Such systems have the capacity to add drill string on the fly, collect and preserve samples while drilling and in some cases can undertake CPT profiling from the same platform.

6.3.2.2 Wet Rotary Drilling Techniques

Commonly used offshore drilling techniques reside within the category of conventional open-hole wet rotary techniques, where the use of drilling fluid as seawater, salt/fresh water gel or bentonite are typically deployed to expel drill cuttings to the seafloor while working to keep the hole open so that good quality samples can be retrieved.

It's very important to employ an experienced driller that can monitor, identify and indicate the volume of mud required to keep the hole open and secured since drilling success depends on the soils conditions encountered, the change in mud pressure, and the sampling technique tabled. The increase in drilling pressure can indicate the presence of cohesive material such as silt and or clay, and low drilling pressure may be indicative of cohesionless material such as sand and gravel; this also could be an indication that the hole has collapsed. Pump readings and rate of drill fluid return are highly contingent upon the sampling technique and system selected.

Normally, for offshore drilling operations in shallow water the use of seawater could be used in shallow borings where cohesive material is encountered. Normally, salt / fresh water can be mixed with bentonite gel, to try and expel the cuttings to the seabed keeping the integrity of the hole intact. Although methane gas may be an issue during certain drilling operations, the mud consistency (viscosity) can be varied to make the mud heavier. It is very important to use a proper mud mix, since consistency can affect the rotation of the drilling pipes. Improper mud consistency can result in stuck drilling pipe, inadequate expulsion of drill cuttings to the seabed and/or incorrect operation of downhole tools.

Other indicators that the mud mixture may be inadequate include the presence of cuttings in the sample tube or inhibited borehole depth advancement. In such situations, the shift engineer and driller must collaborate to remedy the mud mixture to advance the hole and retrieve clean samples.

Mud rotary drilling operations commonly uses three types of drill bits. These include 1) Drag Bits, 2) Roller Cone Bits, and 3) Diamond Bits. Selection depends on the expected ground conditions and the experience of the driller. In practice, drag bits are typically used for most soils whereas roller bits are suitable for rock or soil with boulders.

6.3.2.3 Soil Samplers

- **Push Samplers.** Push samplers are used to obtain high quality, relatively undisturbed samples and is applicable to almost all soil conditions including soft to very stiff clay or loose sands. Thin-walled tubes are applicable to almost all soil conditions except hard clays; dense sands and well-cemented sands are better sampled with thick-walled tubes or may require percussion sampling or soil coring. Push tubes are typically either 51 mm or 76 mm in diameter, about 1 m in length, and 2 to 4.5 mm in wall thickness. The push force is either obtained through a wireline system or a pressurized fluid inside the drill string which is administered at depth via a hydraulic umbilical.

Downhole thin wall piston samplers are widely used to collect high quality undisturbed soil samples specifically in clay. Piston samplers are similar to thin-walled samplers except that they are equipped with an internal piston that creates a vacuum inside the sampler as it is withdrawn from the soil. The piston included in the sampler will a) reduce losses of samples by providing an efficient airtight seal in the tube during withdrawal due to the suction pressure generated on top of the sample and b) reduce disturbance as the sample is being extracted. Although piston samplers may be deployed to sample different soil types, they are most proper to collect undisturbed samples of soft clay materials. Hence, they are not considered the first choice to collect soil samples within the Atlantic OCS.

Percussion (Driven) Samplers. Several driven samplers are typically used in offshore applications. This includes:

- **Wireline:** Is typically used to sample in sandy materials or materials that push tubes cannot be advanced into. The samples obtained from the wireline sampler are disturbed. Thin and thick-walled tubes can be used depending on the relative density of the strata. The tubes are driven using a downhole wireline hammer. Since the wireline hammer is dropped through the water column, considerably higher energy losses are observed during the free-fall of the wireline hammer compared with the standard SPT hammer. For this reason, wireline hammers are typically heavier than the standard SPT hammers used in onshore applications and its drop height is also larger than the typical SPT drop height. It is worth noting that the blowcounts obtained from the wireline system is not equivalent to the standard SPT blowcounts obtained from land-based SPT hammers/samplers. Nevertheless, these blowcounts give a general idea about the relative density of the different layers. It can also be modified to obtain an equivalent SPT blowcounts that can be used in the empirical equations and charts that are typically used for onshore applications/designs.

- **SPT Samplers:** The land-based classical SPT sampler have limited applicability in offshore projects especially within the water depth ranges where offshore wind farms within the Atlantic OCS are planned. As water depth increases, the unsupported length of the rods will equally increase. Hence, buckling of the rods is inevitable at considerable depths. This problem can be avoided by inserting the rods inside casings that supports it from lateral buckling. Nevertheless, the viability of this solution is also limited by the water depth. Hence, this system is not considered appropriate for site investigations for offshore wind farms within the Atlantic OCS. The SPT data may be affected on tests done in deep water by the energy losses. This is the reason why wire-line downhole hammers are adopted.

- **Downhole SPT:** In this system, the hammer is installed in a sealed chamber that is lowered down in the borehole at the time of testing. The weight of the hammer and drop height of this system is equivalent to the land-based SPT system. The sealed chamber is filled with air which makes this system a replica of the land-based SPT system. Hence, the blowcounts obtained from system are equivalent to the standard SPT blowcounts. This system combines the advantages of the wireline and standard SPT systems.

- **Modified California:** This sampler is also known as Mod-Cal. The outer and inner diameters of the small version of this sampler are 6.35cm and 4.76 cm. The diameters of the larger version of that sampler are 7.62 and 6.1 cm. The sample liner can be comprised of a single liner or 1-inch rings. An advantage of using this sampler is that samples can be easily transferred into direct shear laboratory testing equipment and can be used to measure soil unit weight on sandy samples that don't stay intact when extruded.

6.3.2.4 Rock Coring Techniques

Underwater rock coring systems are normally used to recover core samples, where the coring tube must be completely static to have a high quality rock sample. The coring system consists of a core barrel covered by a temporary casing system to stabilize the hole and the drilling system. The normal core barrels used consist of the simple tube, double tube and triple tubes, and uses a wire-line system to extract the core sample tubes.

In a single tube sampler, the core barrel of the sampler rotates, providing a rock sample of poor quality owing to the disturbance or any kind of erosion that can be produced with the mix of the mud fluid during the drilling, normally this core barrel is used during the beginning of the coring operations. Within the double tube core samplers, the tube sampler does not rotate with the core barrel and the sample is not in contact with the drilling mud fluid, but this can manifest as a problem during the extraction of the sample, where mechanical fractures or weakness zones can manifest themselves. The triple core tube samplers differ from the double tube core barrels since they present a static liner that protects the sample during the extraction. The triple tube sample is the preferred method and can maintain the quality of the sample. The third tube can usually be plastic or aluminum, which makes for easy extraction of the sample from the core barrel. These techniques are normally used in shallow water depths, because for offshore purpose these systems must be adapted to the drilling sampling system used on the vessels.

The main objective during rock coring operations is to obtain the maximum total core recovery (TCR). That is why the driller with the engineer/technician may use the best core drilling technique depending of the material that had been encountered. In order to accomplish this objective one must take in consideration multiple variable including: type of core bit to be used, speeding of the core barrel during drilling, quantity of mud to be used (if it's required), and length of the runs of the core barrel.

The speed of the core barrel ranges between 50 to 1,500 rpm. It generally increases while drilling through a rock with medium to high RQD, and the weathering of the rock is slightly weathered to fresh, without fractured zones. While drilling in a fractured zone, it's recommended to decrease the speed of the core barrel. The recovery is typically lower in such zones, and also limits the length of the core run.

Typically, the core runs are ranged between 1.5 m to 3.0 m when we are in a competent rock with a high RQD and slightly weathered to fresh, and when the rock is moderately to intensely fractured and very weathered its recommended to drill shorter lengths of core run, sometimes it's necessary make runs less than 1.0 m.

6.3.2.5 Rock Samplers:

Rock samplers are different coring systems that utilize different diameter core barrels. Table 6.5 presents the coring systems most widely used in the geotechnical drilling industry. In the US, the HQ system is the most widely used when rock characteristics (e.g. rock quality designation factor, discontinuity information, rock strength, and rock mass characterization) are important. NQ systems are sometimes used on the rock characteristics are not a critical parameter for design. Geobor-S system is widely used in Europe and collects are larger diameter core than PQ, HQ, and NQ. The larger diameter core is helpful when coring carbonates with dissolution features (e.g. vugs) and capturing poor quality rock (e.g. the weathering profile beneath soil overburden or fractured intervals). A common approach to drilling is to use Geobor-S to advance through the soil overburden and weathered interval and then switch to HQ or NQ when moderately weathered rock is encountered.

Table 6.5. Different wire-line coring tubes

Size	Hole (outside) diameter (mm)	Core (inside) diameter (mm)
NQ	**75.7**	**47.6**
HQ	**96**	**63.5**
PQ	**122.6**	**85**
Geobor-S (Note that the Geobor-S system can be used for drilling and sampling in soil-like materials)	**146**	**102**

For the offshore drilling, depending on diameter size of the downhole system, one of these coring sample systems could be used.

6.3.3 Vibracores

Vibracores are widely used nearshore and offshore to sample relatively shallow sediments. Vibracores are commonly used to cable route studies and investigations at wind turbine foundations. Vibracores can also be used evaluate the potential for paleosol development in support marine archaeological studies. In this system, a variable high frequency vibration is applied to the top of the corer to penetrate it through surficial sediments. These vibrations typically allow for high penetration rates. Vibracores are viable for most soil conditions, but with variable penetration depths. They can typically be used in 100 meters of water or deeper and can be deployed using A-Frames from the stern of a vessel.

Vibracore specifications can vary considerably (e.g. maximum penetration below mudline, maximum water depth, weight of the equipment, and power source of the vibration). This makes it important to select a suitable vibracore based on site-specific conditions and the target depth of penetration. Some of the most widely used vibracores include pneumatic, electric, mini, and portable. The length of the recovered cores typically ranges from 1.5 to 9.0 meters. The different equipment can operate in water depths that range between 15 and 600 meters. The weight of the systems can vary considerable and typically range between 75 and 1,900 kilograms. The different systems are generally viable for fine grained sediments and sand. More recently, heavier and more powerful systems had been adopted to obtain samples from gravelly zones. The weight of such systems can be in the order of 3 metric tons (in air). Some can also penetrate through gravel layers. Vibracoring is typically less effective in very dense or cemented sands.

6.3.4 Piston corers

In this system, a piston is added above the sample to apply suction pressure (vacuum) on the top of the sample in an attempt to increase the recovery of the samples and reduce disturbance as the sample if being extracted from the seabed. Piston corers are mostly suitable for soft fine grained deposits and employ the use of a plastic liner that is first inserted into the steel core barrel prior to deployment. Hence, although this system may be deployed for broad spectrum surficial soil collection, it is not considered the first choice to collect soil samples within the Atlantic OCS. The system setup is typically lowered from the vessel through an A-Frame from the stern of the vessel or moon-pool. Once the system includes the piston and a balance weight connected to a trigger arm. The balance weight is assembled preceding the piston in such a way so that it touches the seafloor while the piston is still within the water column. Once the weight touches the seafloor, the arm is triggered and the piston is released to free-fall under its own weight in the water column and penetrate into surficial sediments. The sampler is driven by gravity and many hundreds of pounds of steel can be affixed to the top of the sampler to provide the driving force. The piston is then retrieved on the vessel for extraction and classification (see Figure 6.6). The most widely used piston corers in practice are the Kullenberg and STACOR piston corers.

6.3.4.1 Kullenberg Piston Corer

Introduced around 1947 as an improvement over the regular gravity type samplers. Many improvements were applied to the original Kullenberg piston corer over the years (see Lunne and Long, 2006 for additional details). Giant/Jumbo piston corer, and CALYPSO are some examples of improved versions of the original Kullenberg piston corer (Lunne and Long, 2006). Depending on the nature of the soil deposits, the sample length obtained using these corers can be up to 42 m (140 ft). The typical sample diameter is about 11 cm (4.5 in).

6.3.4.2 STACOR (Stationary Piston) Corer

Details about this corer are presented in Montargès et al. (1983, 1987) and Fäy et al (1985, 1988). It has been used in water depths up to 5,800 m (19,000 ft) and recovered up to 34 m (112 ft) of materials below mudline (Lunne and Long, 2006). The core pipe length goes up to 35 m (115 ft). A 125 mm (5 in) outer diameter plastic liner inside a 170 mm (7 in) outer diameter steel pipe are typically used. The diameter of the soil sample is typically 105 mm (4 in).

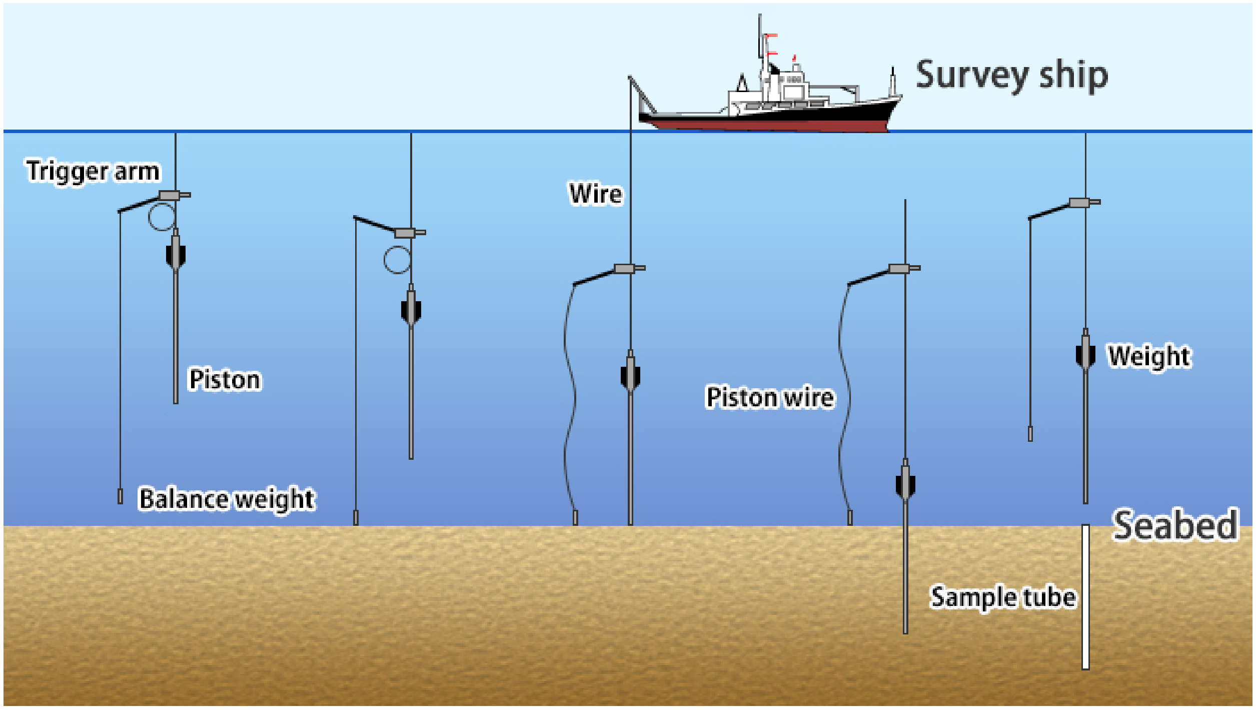


Figure 6.6. Schematic diagram of the deployment of piston sampler[2]

6.3.5 Box Samplers

Box samplers / corers are typically large volume, mechanical excavating devices that operate to obtain high quality, undisturbed "block" samples. After the box penetration is complete, the base of the box is closed by a spade or clamshell to extract the soil block. During offshore operations, it is typical practice to use two boxes in an alternating fashion to ensure the continuation of the operation of retrieving samples. The penetration and subsequently the retrieved soil sample is typically limited. Hence, this test is mainly intended to collect information regarding surficial strata. The depth of penetration is typically very limited in sandy soils. Box samplers can be used in soft soil environments to retrieve < 1 meter of sample.

Since the retrieved samples are relatively undisturbed, in-situ shear strength tests (e.g. torvane) are typically run on these samples to get an indication of the strength of the surficial materials. Index tests are routinely run on these samples to properly classify the soil and understand their behavior. This information is then used to assess transportation of surficial

[2] Ocean Engineering Corporation website at http://www.ocean-eng.com/english/businessguide1/

sediments. It is also used in conjunction with side scan sonar data to map the extent of the different surficial strata within the area of interest. Moreover, box samples can be used for benthic habitat mapping surveys. The area of box samples typically varies between 0.05 and 0.30 m^2 and its penetration can be between 0.3 and 1.0 m. The mass of the box sampler system can be in the order of 1.5 tons.

6.3.6 Grab Samplers

Grab samples are used to retrieve soil samples from surficial strata. The average rate of retrieving these samples is 3 to 4 samplers per hour and is typically viable to water depths up to 200 meters. As opposed to box samples, grab samples are highly disturbed (Figure 6.7). Hence, assessing shear strength of surficial sediments is not possible on grab samples. The reminder of the tests mentioned in the box samples are typically valid for the grab samples. Many grab samplers with different sizes, configurations, and weight are used in practice. The suitable grab sampler depends on the surficial soil conditions and the required size of the retrieved samples. The technical specifications of some of the widely used grab samplers in practice are listed below (in no specific order). The information regarding the manufacturer and model of the samplers was intentionally excluded from the table. The provided list is no way comprehensive, but gives a general overview of the some of the equipment available.

Table 6.6. Technical specifications of some grab samplers widely used in practice

Grab Sampler #	Approximate Weight (kg) [empty/full]	Volume (liters)	Area [mm x mm]	Penetration depth (mm)	Notes
Petite Ponar Grab Sampler	6.8 / 14.0 or 12 / 19	2.4	152 x 152	70	-Lightweight which allows for deployments without cranes -It is mainly intended for benthic habitat mapping -versatile for different types of bottoms including sand, gravel, and clay
Standard Ponar Grab Sampler	23 / 34	8.2	229 x 229	90	-Cranes are used to deploy this system -It is typically used for benthic habitat mapping -Versatile for different types of bottoms including sand, gravel, and clay
Van Veen Grab Sampler	18 / 98 or 30 / 180	24 or 60	360 x 280 or 700 x 360	250	-Designed to grab large samples from soft sediment layers.
Ekman Bottom Grab Sampler	6.8 / 14 to 15 / 47	3.5 to 11.9	150 x 150 or 230 x 230	150 to 300	-Designed to grab samples from soft strata including muck and peat.

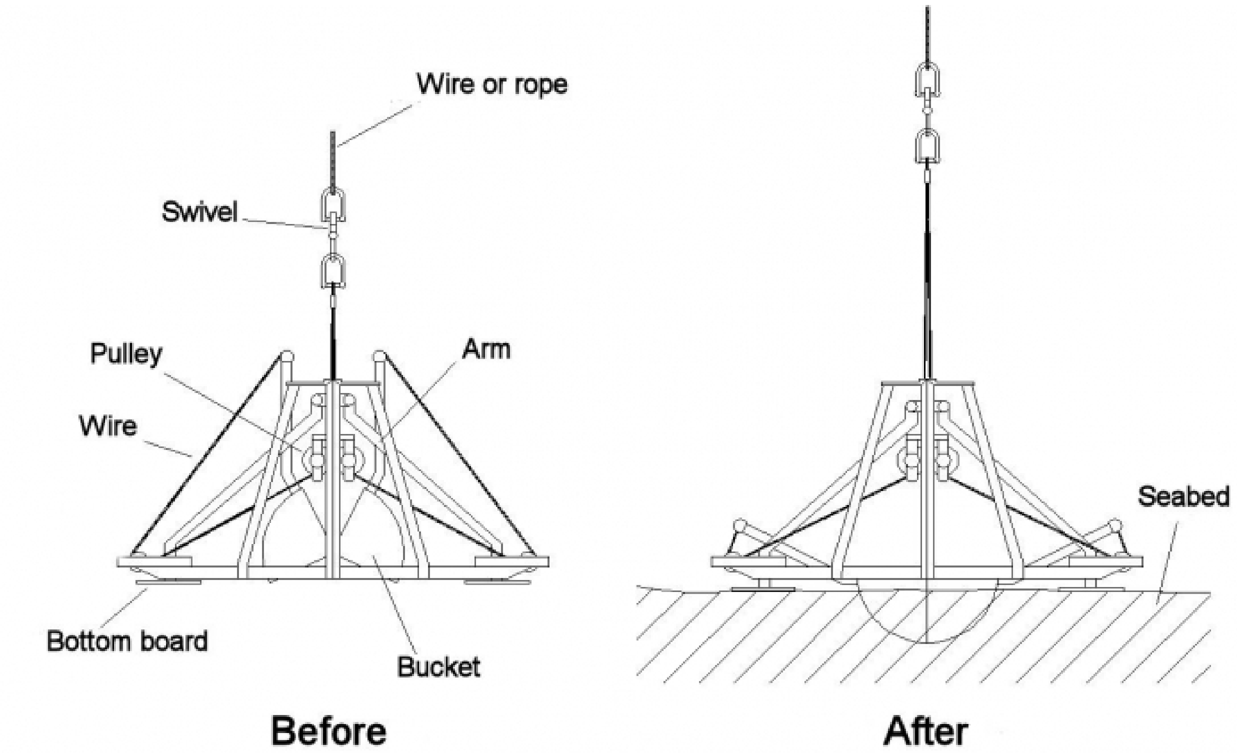


Figure 6.7. Schematic diagram of grab sampler before closing the bucket to capture the sample (left) and after grabbing the sample from seafloor (right)

(Source: Ocean Engineering Corporation website at:

http://www.ocean-eng.com/english/ownedequipment/detail.php?id=13)

6.3.7 Additional Remarks

Sampling and testing offshore requires an understanding of the available equipment and the associated limitations. In-situ testing can either be conducted down-hole through a vessel's moonpool or over the side. In-situ sampling, depending on the system, can be run from similar platforms. Drilling systems can take many forms but most provide a conduit to the subsurface through which samples and testing equipment can be inserted. When drill bits churn through the seabed, cuttings are generated. These cuttings must be brought back to surface. Hole stability comes from drill mud which can range from onion-based guar-gum with low weight to bentonite with barite as a heavy additive to lift the cuttings to surface and maintain hole stability. Holes in sands are less stable than holes in cohesive materials.

It is important to note that the amount of geotechnical data typically collected from in-situ as well as laboratory testing conducted for offshore projects is typically more substantial compared with the data collected for onshore-based projects. It is typical practice to combine in-situ data and laboratory test results in comprehensive borehole logs (see example shown in figure below). The borehole logs should typically include: CPT data (e.g., tip resistance, skin friction, excess pore pressure, undrained shear strength, among other parameters derived from CPT data), laboratory test results (including unit weights, moisture contents, Atterberg limits), in-situ shear strength tests (including torvane, pocket pens, mini-vanes), dynamic soil properties if

P-S logging data was collected (including S and P-wave velocities, shear modulus, and Poisson's ratio), material descriptions, sampler symbols.

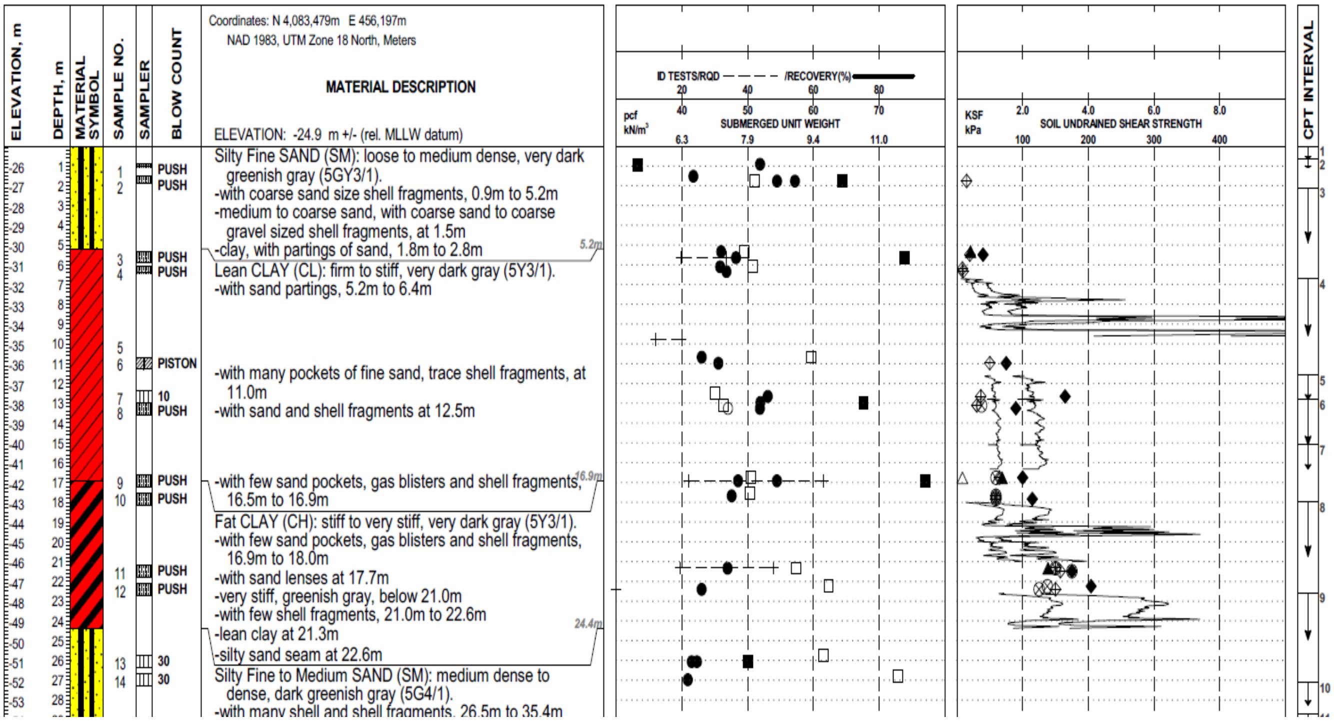


Figure 6.8. Example of a borehole log for offshore projects

6.4 GEOPHYSICAL EQUIPMENT

6.4.1 General Overview of Geophysical Systems

In high-resolution geophysical surveys, there are five main types of systems used by the geoscientist to characterize the seafloor and shallow subsurface, identify geohazards, and aid the archaeologist in identifying paleo-landscapes and anthropogenic objects found at or near the seafloor (Table 6.7). Surveys are typically conducted by deploying all systems simultaneously or can be run during separate surveys. If systems are separated and run in two or more passes, then complementary systems such as sub-bottom profilers and intermediate depth penetrating seismic reflection systems should be run at the same time to ensure they are collocated. Figure 6.9 presents an example equipment deployment configuration with all systems run simultaneously during a HRG survey.

Table 6.7. Typical high-resolution geophysical survey systems

Sensor System	G&G Site Characterization Survey (BOEM, 2015a)	Marine Archaeology Survey (BOEM, 2015b)	Primary Applications
Bathymetric	X	X	Measure water depth; interpret seafloor morphologic features (e.g. sand waves), boulders, and objects
Side Scan Sonar	X	X	Collect acoustic picture of seafloor used to interpret seafloor conditions (e.g. hard bottom areas, sand waves, etc.) and objects (e.g. shipwrecks or archaeologic features of interest)
Magnetometer	X	X	Detection of ferromagnetic materials on seafloor or shallowly buried (e.g. shipwreck)
Sub-Bottom Profiler	X	X	Interpreting very shallow stratigraphy, paleo-landforms, buried paleo-channels, gas bearing subsurface sediments
Seismic Reflection System	X		Interpreting stratigraphy, detection of faults, gas bearing subsurface sediments

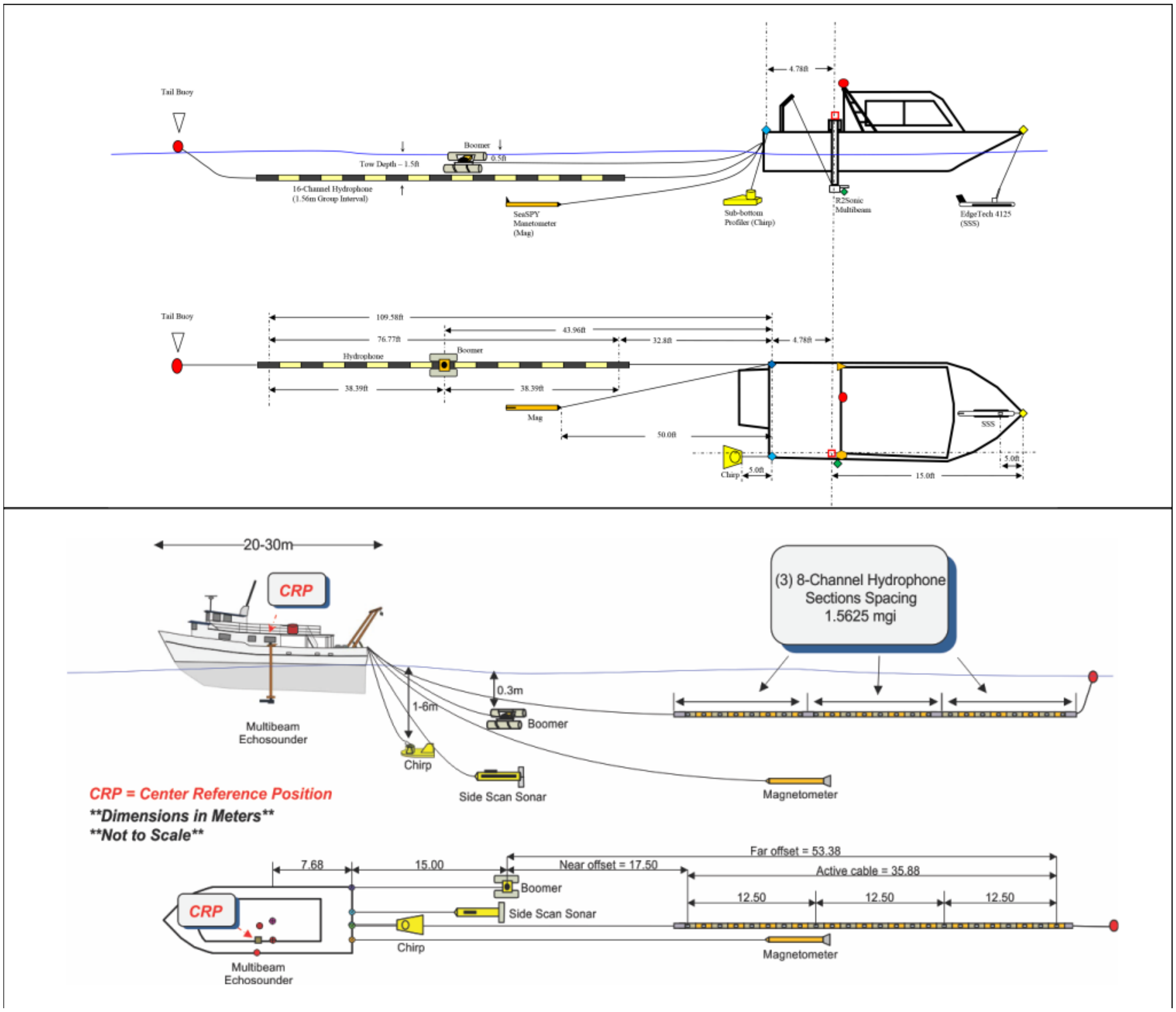


Figure 6.9. Example HRG survey configuration.

6.4.2 Bathymetric

Bathymetry data are collected to measure the water depth and used to develop informative seafloor elevation models. Seafloor elevation models are used to evaluate seafloor morphology (e.g. presence of sand waves), seabed conditions, potential anthropogenic hazards, and geohazards. Refer to Figure 6.10 for an example of seafloor morphology depicted using multibeam data.

Using swath bathymetry to obtain full bathymetric data coverage is encouraged in the G&G Guidance document and is considered to be the state of the practice in European offshore wind farms and internationally in large marine infrastructure projects. Swath bathymetry can be collected using either a multibeam echosounder or an interferometric system.

BOEM recommends that bathymetric surveys meet IHO Special Order requirements for water depths up to 40 meters and Order 1a requirements for water deeper than 40 meters (IHO, 2008). BOEM also recommends the use of system that can produce gridded data with resolution of at least 0.5 meter in water depths shallower than 50 meters and 1 meter or better than 2 percent of water depth resolution in water depths beyond 50 meters. Table 6.8 summarizes the horizontal and vertical accuracy requirements for bathymetric surveys.

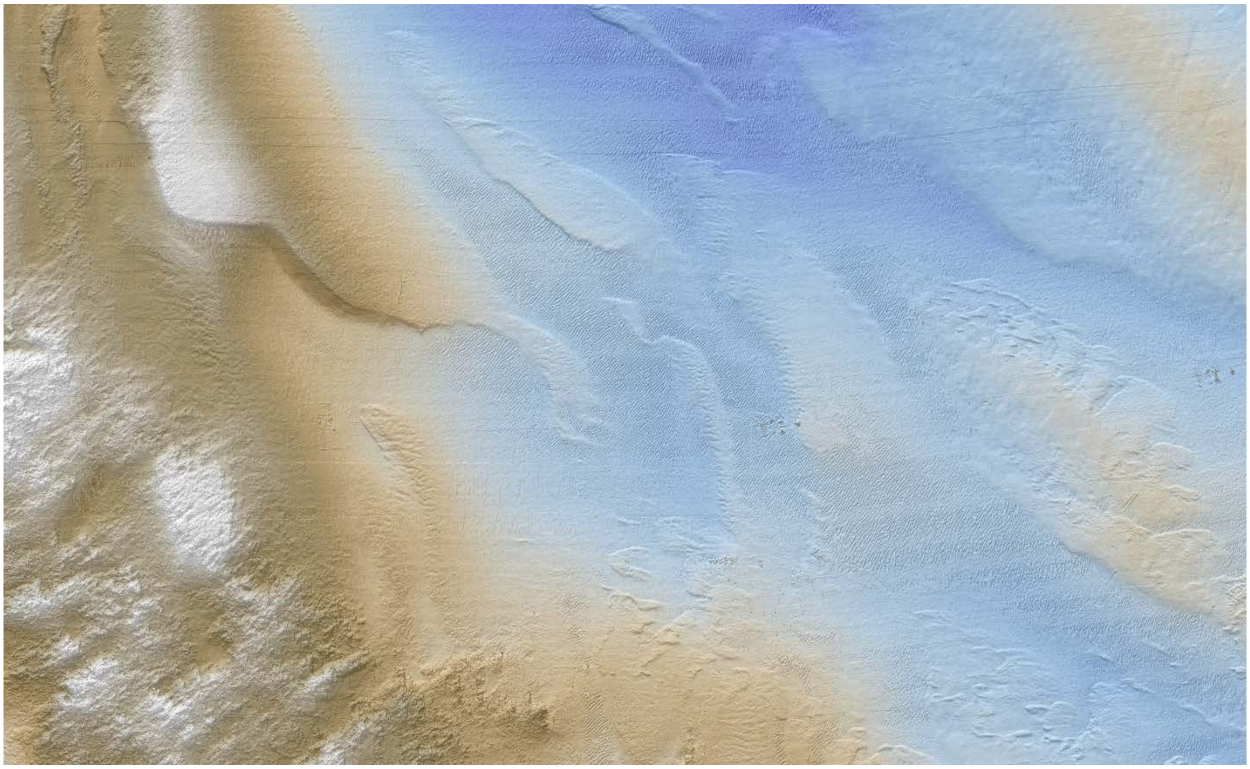


Figure 6.10. Multibeam data example from Block Island Wind Farm.

Data were collected using a beam-forming system as part of BOEM's RODEO Study by Fugro.

Table 6.8. Calculated bathymetry survey standards at varying water depths*

Water Depth (m)	IHO Order	Maximum Allowable THU[1] (m) 95% Confidence level	Maximum Allowable TVU[2] (±m) 95% Confidence level	Minimum Required Feature Detection (m)[3]	Gridded Data Resolution (m)
Less than 6	Special Order	2.00	0.25 (approximately)	1.0	0.5
10	Special Order	2.00	0.26	1.0	0.5
15	Special Order	2.00	0.27	1.0	0.5
20	Special Order	2.00	0.29	1.0	0.5
25	Special Order	2.00	0.31	1.0	0.5
30	Special Order	2.00	0.34	1.0	0.5
35	Special Order	2.00	0.36	1.0	0.5
40	Special Order	2.00	0.39	1.0	0.5
45	Order 1A	7.25	0.77	4.5	0.5
50	Order 1A	7.50	0.82	5.0	1.0
55	Order 1A	7.75	0.87	5.5	1.1
60	Order 1A	8.00	0.93	6.0	1.2
65	Order 1A	8.25	0.98	6.5	1.3
70	Order 1A	8.50	1.04	7.0	1.4
75	Order 1A	8.75	1.10	7.5	1.5
80	Order 1A	9.00	1.15	8.0	1.6
85	Order 1A	9.25	1.21	8.5	1.7
90	Order 1A	9.50	1.27	9.0	1.8
95	Order 1A	9.75	1.33	9.5	1.9
100	Order 1A	10.00	1.39	10.0	2.0

*Calculations based on recommendations of BOEM (2015a) with reference to IHO (2008) standards.

[1]**Total Horizontal Uncertainty**: The contributions of both the systematic and random components of uncertainty affecting the positioning of a sounding or feature. Assuming a normal distribution of error about the true value for this 2-D quantity, a 95% confidence level is defined as 2.45 x standard deviation. For IHO Special Order specifications, the THU is 2 meters and for IHO Order 1a, the THU is equal to 5 meters +5% of the depth.

[2]**Total Vertical Uncertainty**: The contributions of both the systematic and random components of uncertainty of the reduced depths (the observed depths after corrections related to the survey, post processing and adjustment to a vertical datum). Assuming a normal distribution of error about the true value for this 1-D quantity, a 95% confidence level is defined as 1.96 x standard deviation. Since there are both constant and depth dependent uncertainties that affect the uncertainty of depth, the maximum allowable TVU is calculated using two parameters (a and b) along with the water depth (d). The parameter "a" represents the constant uncertainty and the coefficient "b" is the uncertainty which varies with depth. TVU for a specific depth is equal to $\pm\sqrt{(a^2+(b \cdot d))}$. For IHO Special Order specifications, the TVU is calculated using a = 0.25 meters and b = 0.0075 and for IHO Order 1a, the TVU is calculated using a = 0.5 meters and b = 0.013.

[3]**Feature detection:** For IHO Special Order specifications, the required feature detection is 1 meter and refers to a cubic feature that has equal sides. For IHO Order 1a, beyond a depth of 40 meters, the feature detection requirement (in meter cubes) is equal to a value of 10% of the depth.

Accuracy of the bathymetric survey data is related to several components including the type of sensor, inertial motion unit (IMU), positioning system, and sound velocity model. For beam-forming sensors, the resolution largely depends on the number of beams used, beam separation angle, frequency of acoustic energy, and update rates. Beam-forming systems typically are available in 0.5, 1.0, and 1.5-degree beam separation angles. Higher density data are achieved with closer-spaced the angles. For water depths up to approximately 30 meters, 400 kHz data can be used to achieve IHO Special Order requirements. For water depths greater than 30 meters, 200 kHz data are preferred in order to meet IHO requirements. Swath widths can be approximately 3 to 5 times the water depth and meet IHO Special Order requirements.

Interferometric systems were developed for use in collecting swath bathymetry in shallow water environments. Interferometric systems use phase differencing between arrival times at a receiver array to calculate the beam's direction and depth. Interferometric systems also provide co-registered side scan sonar imagery with bathymetry as opposed to the backscatter available with multibeam systems and higher resolution sonar imagery is achievable using longer transducer arrays. Swath widths can be approximately 6 to 12 times the water depth and meet IHO Special Order requirements. Interferometric data are used in water depths shallower than 20 meters.

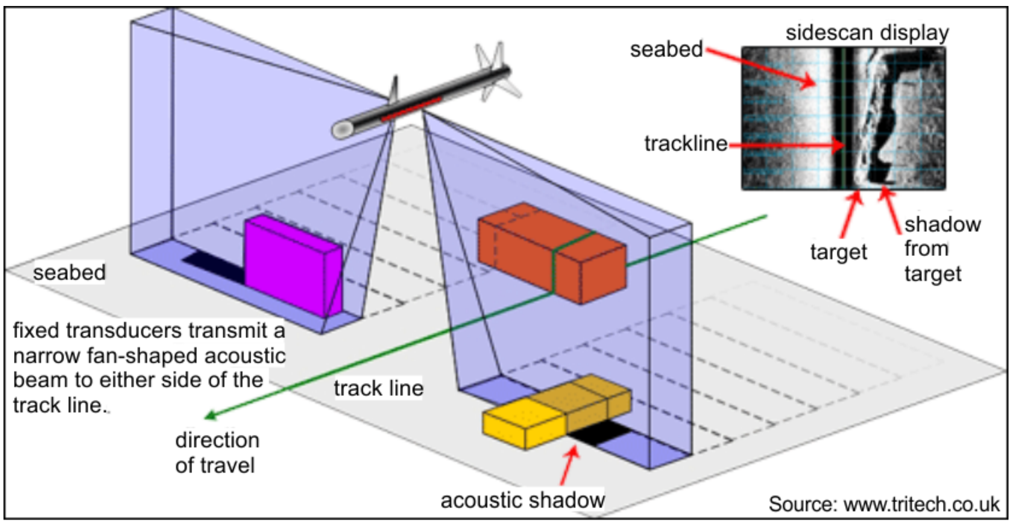
Performance tests should be conducted before surveying to evaluate and determine the bathymetric system (beam-forming or interferometric) settings required to achieve the quality and accuracy standards referenced in BOEM's guidance documents (BOEM 2015a and 2015b). BOEM's guidance documents refer to IHO surveying standards (IHO, 2008) for bathymetric surveying. Table 6.8 summarizes the horizontal and vertical accuracy requirements. A performance test is used to evaluate the bathymetric system's performance and determine the swath angle for a site's temperature, salinity, and bottom conditions. Performance test procedures can be found in the USACE Hydrographic Survey Manual (USACE, 2004) or CARIS (2009).

6.4.3 Side Scan Sonar

Side scan sonar data are used to create an acoustic picture of the seafloor by measuring the amplitude of the backscattered return signals (Figure 6.11). The collected data are rendered in a way that provides a photo-like image of the seafloor. Dark and light colors in the imagery represent areas of varying acoustic reflectivity and absorption. In general, harder bottoms (gravel and sand) will have higher reflectivity than softer bottoms (silt and clay). The angle of the seafloor can also influence the amplitude of the reflectivity. Areas with a seafloor slope (e.g. sand wave flank) that provides an angle closer to a normal angle of incidence (90 degrees) will reflect more sonar energy than a flatter seafloor that results in a more oblique angle to incoming sonar energy. Side scan sonar data are used to locate objects such as shipwrecks, archaeological objects, anthropogenic objects (e.g. pipelines, UXO's, etc.), and geohazards (e.g. sand waves, boulders, etc.).

For archaeological surveys, BOEM requires using a side scan that is capable of operating at a 500-kHz frequency or greater. For G&G site characterization surveys, BOEM recommends using a system with operational ranges of 200 to 600 kHz frequency. Additionally, BOEM's guidance documents recommends towing a side scan above the seafloor at a distance that is 10 to 20 percent of the range of the instrument. Table 6.9 provides a summary of fish tow heights based on the frequencies for various side scan sonars.

All frequencies from 100 to 1,000 kHz provide adequate coverage at a 30-meter line spacing (which would require a 60 meter ensonified distance), yet only frequencies of 400 kHz and lower would provide adequate coverage at a 150-meter line spacing. This limits 100% overlap for the 150-meter line spacing to ~20 meter or greater water depth, otherwise there would be less overlap.



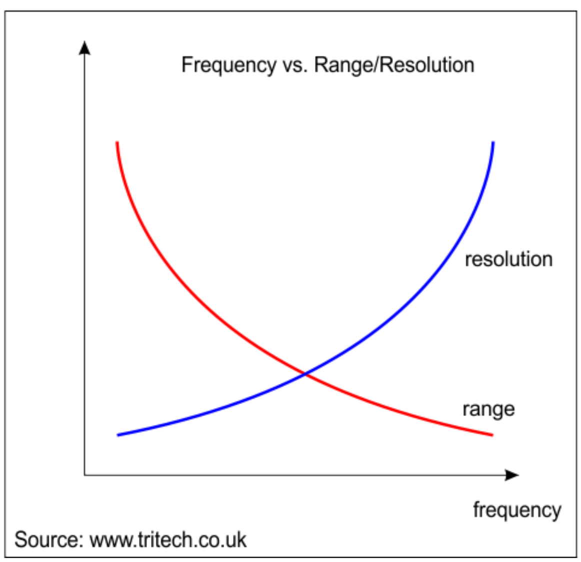


Figure 6.11. Side scan sonar schematic

Table 6.9. Typical characteristics of different side scan sonar systems

Frequency (kHz)	Wavelength (cm)	Approximate range (m)	Tow height above seafloor (m)[1]	Across-track ensonified distance (m)[2]	Horizontal beam width (degrees)[3]	Pulse length (μsec)[4]
100	1.50	600	60 to 120	1200	0.05	Approximately 11.5
200	0.75	300	30 to 60	600	0.09	
300	0.50	200	20 to 40	400	0.14	
400	0.38	150	15 to 30	300	0.19	
500	0.30	120	12 to 24	240	0.24	
600	0.25	100	10 to 20	200	0.29	
700	0.21	85	8.5 to 17	170	0.34	
800	0.19	75	7.5 to 15	150	0.39	
900	0.17	65	6.5 to 13	130	0.44	
1,000	0.15	60	6 to 12	120	0.49	

[1]Calculated range is based on BOEM's (2015a) recommendations that the tow height is 10 to 20% of the range.

[2]Calculation based on a flat seafloor and is approximate for a tow height of 10% of the range.

[3]Calculation for maximum range is based on BOEM's (2015a) recommendations that along-track resolution is 0.5 meters.

[4]Pulse length calculation is at maximum grazing angle on a flat seafloor based on BOEM's (2015a) recommendations that across-track resolution is 0.5 meters. Across-track resolution is also dependent on ping rate and vessel speed that will need to be adjusted to provide a 0.5 meter across-track resolution.

6.4.4 Magnetometer Survey

Magnetometer surveys are conducted to locate ferromagnetic objects on the seafloor or shallowly buried below the seafloor. The ferromagnetic objects could be related to shipwrecks, pipelines, unexploded ordnance, or anthropogenic sources. Figure 6.12 presents photographs of various magnetometers and gradiometers. A magnetometer survey is required by BOEM as part of the marine archaeological surveys in sites where water depths are 100 meters or less. BOEM's guidance document (BOEM 2015a) recommends the following for magnetometer surreys:

- Overhauser or optically pumped systems are preferred,
- Magnetometer sensitivity should be 1.0 gamma (1.0 nano-Tesla) or less,
- Background noise level should not exceed a total of 3.0 gamma peak-to-peak,
- Data sampling rate should be greater than 4.0 Hz,
- Magnetometer altitude should not exceed 6 meters above the seafloor,
- An altimeter should be used to ensure the proper height of the magnetometer in the water column,
- Magnetometer data should be recorded on a digital medium,
- Survey line, time, position, altitude, and speed should be annotated on all output data.

The magnetic field is a vector, with both a magnitude and a direction. Fluxgate magnetometers measure both the direction and magnitude of the Earth's magnetic field but because their use requires very accurate positioning/heading, cesium-vapor and Overhauser magnetometers, which measure only the total magnetic field, are the most common magnetometers employed in marine surveying. The Overhauser magnetometer is a type of proton-precession magnetometer capable of near-continuous output with a high sensitivity. When compared to the cesium-vapor (optically pumped) magnetometer, the Overhauser magnetometer is less sensitive and has a lower sampling rate. Therefore, to meet the archaeological survey requirements of BOEM (2015b), typically only the cesium vapor magnetometer will satisfy the need to sample at rates greater than 4.0 Hz (Table 6.10).

Table 6.10. Typical characteristics of marine magnetometers

Operating Principle	Sensitivity	Sample Rate	Heading Error
Overhauser System	0.01 to 0.02 nT/√Hz RMS	0.1 to 4 Hz	None
Optically Pumped Systems (e.g., Cesium-Vapor)	<0.004 nT/√Hz RMS	Up to 40 Hz	<1 nT over entire 360° spins

Sources:
[1]www.geometrics.com/geometrics-products/geometrics-magnetometers/g-882-marine-magnetometer/
[2]ftp://geom.geometrics.com/pub/mag/DataSheets/G-882TVG_DataSheet.pdf
[3]www.marinemagnetics.com/wordpress/wp-content/themes/marine/brochures/SeaQuest_2012_2.pdf
[4]www.marinemagnetics.com/products/seaspy/seaspy-options
[5]www.geometrics.com/files/images/862rbs_2013.pdf
[6]www.marinemagnetics.com/wordpress/wp-content/themes/marine/brochures/MM_Brochure_Sentinel.pdf

Figure 6.12. Example magnetometers and gradiometers

6.4.5 Shallow Penetrating Seismic Sources

Shallow penetrating, high resolution seismic systems image the shallow subsurface in order to characterize the shallow stratigraphy and identify potential geohazards in support of a variety of engineering studies (e.g., foundation design, cable burial risk assessment). Additionally, these high resolution systems are utilized in marine archaeological research through the interpretation of paleo-landforms which aid the reconstruction of past environments that are of potential archaeological interest.

The three main categories of shallow penetration, high-resolution seismic systems used in marine surveying are pingers, parametric echosounders, and Chirp sub-bottom profilers. Transducer arrays (two-by-two, three-by-three, four-by-four or other), can be implemented to increase signal penetration. Transducer arrays are commonly found on larger survey vessels that work in deep water environments and are often hull-mounted; arrays can also be mobilized onto vessels. Table 6.11 summarizes the typical frequency ranges, vertical resolution and depths of signal penetration for these various shallow penetrating systems.

Pingers (such as the 3.5 kHz echosounder) emit a multi-cycle sinusoidal wave with a very narrow bandwidth centered around a single frequency. While these systems are extremely easy to use, these systems are difficult to use for engineering and archaeological studies due to their limited bandwidth and long pulse length providing poor quality images of the subsurface. Parametric sounders provide improvements over pingers in that two frequencies are emitted simultaneously and the interference of these two frequencies produces a secondary lower frequency that improves signal directivity and higher signal penetration using a small transducer.

Chirp systems obtain high resolution images of the shallow subsurface through the use of a long duration, frequency modulated “chirp” pulse that is swept over a full spectrum frequency range (e.g. 2-16 kHz), thus providing a broad bandwidth signal (Figure 6.13. Chirp sub-bottom profiler. Chirp systems can transmit a variety of waveforms, that can be modified to improve penetration or eliminate sidelobe interference. Chirp systems are the most-common high resolution seismic system in use today and has been utilized in multiple Atlantic OCS geophysical surveys to aid the identification of paleo-landforms and reconstruct past shorelines and depositional processes to aid archaeological research. They have been successful in providing information subsurface information in optimal conditions (e.g. paleo-channel infill), but their limited penetration often provides only a partial picture of the subsurface and therefore deeper penetration systems are often used in tandem to provide continuous mapping of seismic horizons and correlate discrete seismic reflections sporadically imaged with the Chirp system.

For certain Chirp systems, the use of lower frequencies (e.g., 0.5 -12 kHz) has shown remarkable improvement in the depth of penetration when compared to higher frequency systems (e.g., 2 - 16 kHz). Since one of the largest technical challenges facing developers in the Atlantic is dealing with imaging below surficial coarse-grained deposits such as sand ridges and moraines, the use of lower frequency Chirp systems can add great benefit to the developer. These lower frequency Chirp systems typically have higher power outputs (often an order of magnitude greater) than their higher frequency counterparts and reports from manufacturers indicate that penetration in coarse sand increases up to 5 times (i.e., 6 m for 2-15 kHz systems compared to 30 m for 1-5 kHz systems) and soft clay penetration increases up to 3 times (i.e., 80 m for 2-15 kHz systems compared to 250 m for 1-5 kHz systems). The main trade-off between the increased depth of penetration is the decrease in vertical resolution (approximately 6 cm for 2-15 kHz systems and 20 cm for 1-5 kHz systems).

Table 6.11. Typical characteristics of shallow depth penetrating seismic source

Seismic Source	Frequency Range	Energy (Joules)	dB re 1 µPa (Representative examples)	Vertical Resolution	Typical Depth of Signal Penetration Atlantic OCS
Pingers	Typically, 3.5 or 7 kHz	1 to 5	214 at 1 meter	5 to 20 cm	< 30 m in silt and clay 5 to 12 m in sand < 3 m in gravel and sand
Parametric SBP (Echosounders)[1]	2 to 22 kHz		240 to 250 dB at 1 meter	5 to 15 cm	< 20 m in soft, fine grained sediments 2 to 6 m in sand < 2 m in gravel and sand
Chirp[2] Note: Manufacturers report significant improvement in penetration depth using lower frequency Chirp systems (see Section 6.4.5)	400 Hz to 24 kHz	1 to 10	212 at 1meter peak (approximately at center frequency for 0.5-15 kHz)	2 cm to 1 m	< 20 m in silt and clay 2 to 8 m in sand < 2 m in gravel and sand

[1]Unlike conventional echosounders that emit a constant waveform with a single frequency, parametric echosounders transmit two high-frequency signals that produce a lower frequency signal through interference of the two transmitted frequencies.

[2]Chirp systems transmit a frequency modulated (FM) pulse that provides a high-resolution, low noise image by correlating the reflected data with the transmitted pulse.

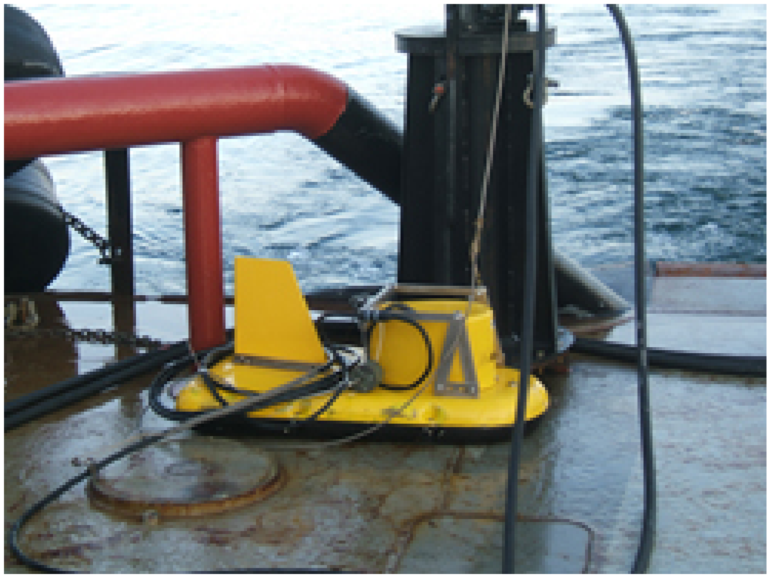
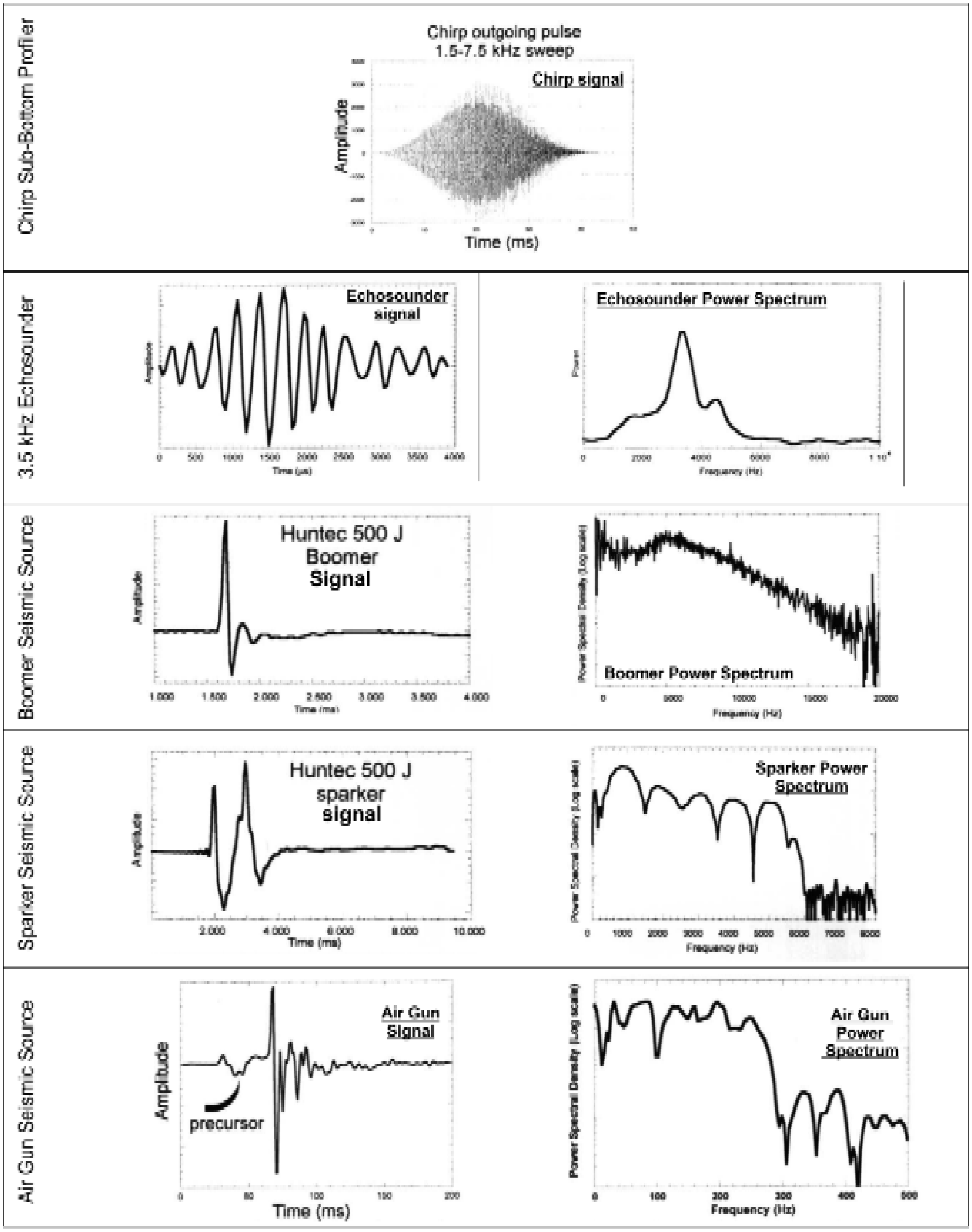


Figure 6.13. Chirp sub-bottom profiler

6.4.6 Intermediate Depth Penetrating Seismic Sources

Seismic sources used for intermediate penetrating systems are typically selected to optimize the relationship between attaining the highest frequency content, achieving desired signal penetration depth, and providing a consistent signal signature during the course of the survey. Boomer and sparker sources are the two most commonly used sources for the offshore wind farm foundation surveys. Figure 6.14 presents examples of various seismic source signatures.



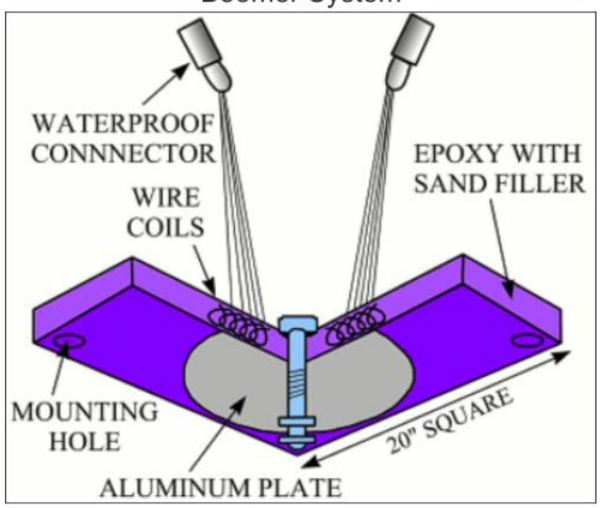
Source: Mosher and Simpkin (1999)

Figure 6.14. Example seismic source signatures

6.4.6.1 Boomer Source

The seismic signal in boomer systems is electromagnetically generated using a flat coil and metal plate below the coil (Figure 6.15; Edgerton and Hawyard, 1964). The plate is rapidly repelled from the coil using an eddy-current generated in the metal plate. The rapid pulling back of the plate by strong springs or rubber bands creates a cavitation in the water acting as the sound source. Discharge of a high-voltage capacitor bank through the coil generates the eddy-current in the metal plate and initiates the shot. Energy of the source depends on the capacitor bank, which for a single boomer plate can range from 100 to 1,000 joules (J). The frequency range of the boomer source is between 300 Hz to 20 kHz with decimeter scale resolution and the signal can penetrate tens to hundreds of meters. The boomer source signature is typically very consistent during the course of a survey and from survey to survey. The high resolution, good signal penetration depth, and repeatability of the source signature make the boomer a preferred sound source for engineering surveys.

Boomer System



Source: Woods Hole Coastal and Marine Science Center
After: Kramer et al. (1980)

Figure 6.15. Boomer source schematic in cross section view

Traditionally, boomers were used in a single plate mode for high resolution surveys that had shallow (<80 meter) penetration requirements. However, during the past two decades, there was an interest for using the boomer source due to its high frequency content and consistent source signature to modify it for achieving deeper signal penetration. Engineering surveys offshore California had a need for deep signal penetration to image fault traces while providing high resolution data to support engineering planning and design of tunnels, outfalls, bridges, power generating plants, and port facilities. As a result, boomer sources were modified to fire two or three plates simultaneously from a customized frames and sleds (personal communication, Subsea Systems, Inc.). Now boomer sources in double or triple-plate firing configurations are used on engineering surveys, including those for wind farms (Figure 6.16).

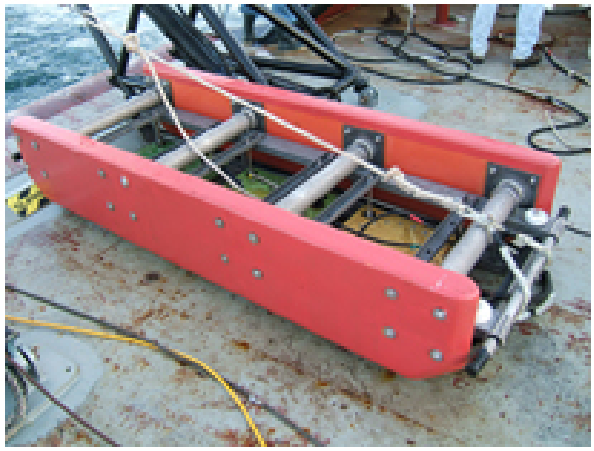


Figure 6.16. Triple-plate boomer source
(Courtesy of Subsea Systems, Inc.)

6.4.6.2 Sparker Source

The sparker source has historically been used for surveys that required deeper signal penetration depth than the single plate boomer. The sparker functions similarly to a spark plug in an automobile engine. Discharge in a capacitor bank creates a spark between the positive and negative electrodes of the sparker (Figure 6.17; Allen, 1972). This spark vaporizes water between the electrodes and generates a pressure impulse. The physical design of the sparker influences the energy and shape of the sparker wavelet. The energy and shape of the sparker wavelet are also influenced by the capacitance and voltage of the high-voltage capacitor bank (Figure 6.14). Sparker sources are capable of generating shots with energy levels between 100 J and several thousands of joules.

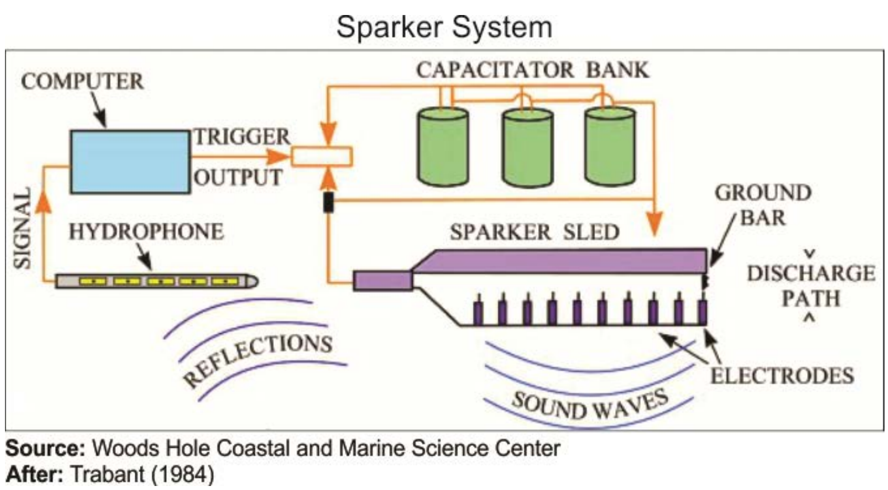


Figure 6.17. Sparker source schematic

The sparker signal can change over the course of a survey which will affect the character of the seismic data. Heat and usage of the capacitors lead to deterioration of the electrodes which affects the source signature. Periodically the capacitors need to be replaced however, recent technological improvements have reduced the rate of burnout. Also, lateral variations in the electrical conductivity of the water can affect the source signature (Bellefleur et al., 2006).

Table 6.12 lists the various intermediate penetration seismic sources, frequency content, and energy levels.

Table 6.12. Typical characteristics of intermediate depth penetrating seismic sources

Seismic Source	Frequency Range	Energy (Joules)	dB re 1 μPa (Representative examples)	Vertical Resolution	Typical Depth of Signal Penetration Atlantic OCS
Single Plate Boomer	300 Hz to 6 kHz	100 to 600	212 at 1 meter at 200 J	10 cm to 1 m	25 m to 200 m
Double and Triple Plate Boomer		200 to 1000	215 at 1 meter at 300 J		30 m to 600 m
Sparker[3]	40 Hz to 1.5 kHz	200 to 16,000	216 at 1 meter at 500 J 222 at 1 meter at 1500 J	20 cm to 10 m	100 m to 1 km

[3]Frequency of a sparker system is tip and depth dependent

6.4.7 Receiver Arrays

In HRG seismic surveys, the seismic energy that is reflected from interfaces with seismic impedance contrasts are recorded by the receiver array. Receiver arrays are either single channel or multichannel arrays.

Single channel arrays may either be comprised of 1 hydrophone or several hydrophones that are closely spaced and recorded as one group.

Multichannel receiver arrays are comprised of multiple channels spaced equidistance apart in a streamer. Each channel consists of hydrophones or elements grouped together to form one channel. The hydrophones may be spaced 0.3 to 1m apart and grouped at defined intervals (e.g. 1.56-meter group interval [mgi]). The number of hydrophones per group may be 1 to 5 or more. The improved signal-to-noise ratio over single channel systems is approximated by the fold. For example, 24-channel systems collected at full fold (24) will result in a minimum signal-to-noise improvement of √24 (National Academy of Sciences, 1976).

The common mid-point (CMP) fold or multiplicity is a function of the group interval, the number of channels and the shot point interval. A higher CMP fold implies a higher signal-to-noise ratio (SNR) due to trace summation resulting from CMP stacking process.

Spacing of the hydrophones influence the resolution of the data. Closer spaced hydrophone arrays will be able to collect higher frequency content data and provide better resolution of the shallow subsurface than wider spaced hydrophone arrays. Ultra-high resolution multichannel surveys now utilize streamers with 1 to 2-meter group intervals. Multichannel streamers used in engineering surveys in the US are commonly either at 1.56mgi or 3.125mgi.

The length of the streamer also influences the depth investigation for the streamer and the relationship are approximately equal or the streamer length should be about 90 percent the targeted imaging depth. For example, if the seismic investigation target depth is 80 meters, then the streamer length would be about 72 meters long.

Streamers used in surveys today are digital streamers. Digital streamers are an improvement over analog streamers and new developments like Ethernet connections allow for:

- higher sampling rates, and
- smaller streamers that can be more easily deployed by hand or small winches.

Also, multichannel streamers are now available as liquid or solid filled. Solid-filled streamers are a more recent development and are reportedly quieter than the liquid filled streamers.

Table 6.13. Typical characteristics of high-resolution seismic streamers

Number of channels	Typical group intervals (m)	Number of elements per channel	Element spacing	Active Section Length
Single-Channel	-	1 to 48	0.1 to 0.6 m	< 15 m
Multi-Channel (16 to 160)	0.5, 1, 1.56, 3.125	1 to 16	0.3 to 0.5 m	< 100 m

6.4.8 Vessels

Geophysical survey vessels can be divided into three general classes based on their size, duration of stay offshore, and number of personnel they can accommodate. Table 6.14 summarizes the three classes of survey vessels. Although it is true that the smallest vessel is most sensitive to weather and sea state, the limited sea states for the intermediate and large vessels is usually dictated by the most weather sensitive system.

The multichannel streamers are typically towed at 0.3 to 0.5 meter below the water surface and are most susceptible to sea state conditions. The side scan sonar is typically the second most sensitive system. Waves that cause the vessel to rock or roll can cause the side scan sonar tow line to jerk and create jumps in the data.

Smaller vessels can perform short duration surveys (e.g. a marine archaeology survey for a floating lidar buoy deployment) and inshore surveys. Intermediate size vessels can work offshore for several days and perform 12 or 24-hr operations. Space restrictions may not permit onboard data processing and or restrict surveying to 12-hour, daylight only operations to reduce crew, geoscientists, and PSO's. Large vessels can work offshore for several weeks and accommodate 30 or more personnel.

Table 6.14. Typical geophysical vessel characteristics

Vessel Size	Length (meters)	Operation	Ability to remain offshore	Day Rate (Relative Cost)	Shallow Water Surveying	Weather Sensitivity
Small	15 to 20	12-hours per day (daylight)	Daily berth requirements	$	Yes	High
Intermediate	20 to 30	12-24 hours per day	Remain offshore for days	$$	Possibly	Moderate
Large	Over 30	24 hours per day	Remain offshore for weeks	$$$	Typically, greater than 10 meters water depth	Low

Figure 6.18. Small survey vessel
The survey vessel shown above is a 50-foot long, catamaran style vessel purpose-built for surveys (courtesy of Zephyr Marine)

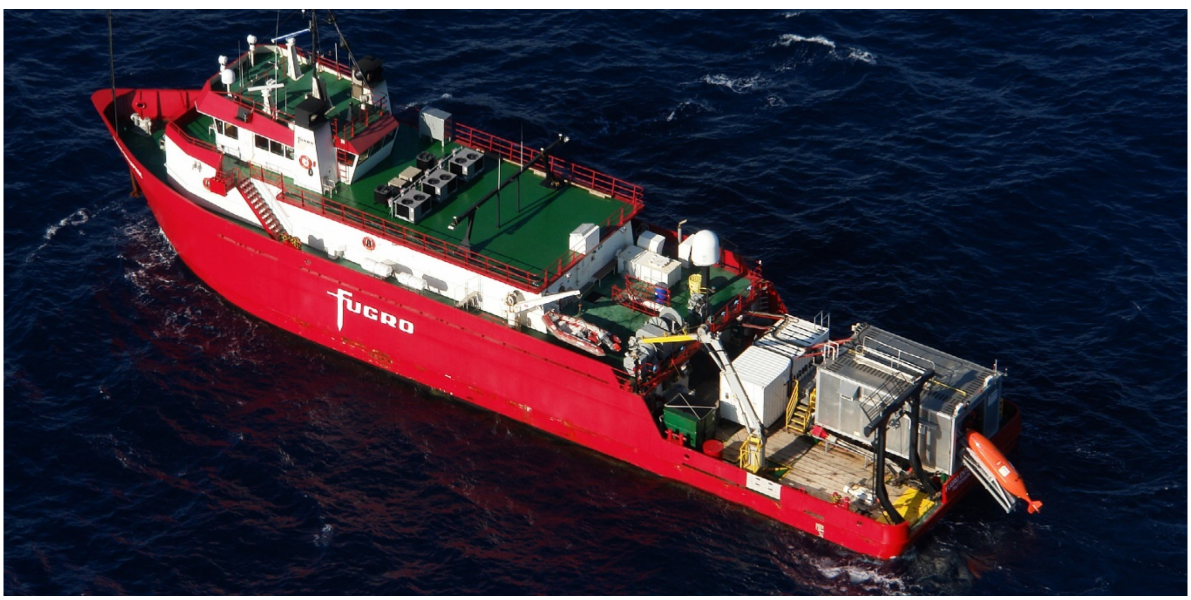


Figure 6.19. Large survey vessel
The survey vessel shown above is 170-feet long and can conduct 24-hour operations with data processing staff on board. (courtesy of Fugro)

6.5 REFERENCES

Bar-Cohen, Y., Zacny, K., Drilling in Extreme Environments, Penetration and Sampling on Earth and other Planets, 2009 Wiley-VCH Verlag GmbH & Co. KGaA Weinheim, Chapter 5

Bureau of Ocean Energy Management (BOEM) (2015a), Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585, Office of Renewable Energy Programs, July.

Bureau of Ocean Energy Management (BOEM) (2015b), Guidelines for Providing Archaeological and Historic Property Information Pursuant to 30 CFR Part 585, Office of Renewable Energy Programs, July.

Campanella, R.G., and Weemees, I (1990). "Development and use of an electrical resistivity cone for groundwater contamination studies," Canadian Geotechnical Journal, 1990, 27(5): 557-567

Danson, E. (Editor; 2005). "Geotechnical & Geophysical Investigations for Offshore and Nearshore Developments," International Society for Soil Mechanics and Geotechnical Engineering.

Fäy, J.B., Le Tirant, P. and Montargès, R. (1988). "Advanced equipment for geotechnical surveys," Proc., 2nd Latin American Congress on Hydrocarbons, Rio de Janeiro, Brazil.

Fäy, J.B., Montargès, R., Le Tirant, P. and Brucy, F. (1985). "Use of the PAM self-boring pressuremeter and the STACOR large sized fixed piston corer for deep seabed surveying," Proc. Int. Conf, Offshore Site Investigation, Society for Underwater Technology, London, March 13-14, 187 - 199.

Fugro Consultants, Inc. (2013), Regional geophysical survey and interpretive report: Virginia Wind Energy Area offshore southeastern Virginia, prepared for U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, OCS Study BOEM 2013-220, November.

GeoSwath Product Information Bulletin, (GeoAcoustics 2002). Covers acoustic propagation principles, transmit beamforming, receive beamforming, multiple receive arrays, and phase comparison principles, advantages, and limitations.

Geotechnical & Geophysical Investigations for Offshore and Nearshore Development, (2005), International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE),

IHO Manual on Hydrography. (IHO 2005). Details amplitude, phase detection, and interferometric techniques, including total propagated uncertainties of collected multibeam data.

Kramer, F.S., Peterson, R.A. and Walter, W.C., eds., 1980, Seismic Energy Sources 1968 Handbook. United Geophysical Corporation, p. 50.

Lunne, T., (2010). “The CPT in offshore soil investigations – a historic perspective”, 2nd International Symposium on Cone Penetration Testing, Huntington Beach, CA, USA, May 2010, Table 5.1

Lunne, T., Robertson, P., Powell, J.J.M., (1997). “Cone Penetration Testing in Geotechnical Practice”, Blackie Academic & Professional

Lunne, T., and Long, M. (2006). “Review of long seabed samplers and criteria for new sampler design,” Marine Geology, 226: 145-165.

Mayne, P.W., (2007). “Cone Penetration Testing, A Synthesis of Highway Practice”, NCHRP Synthesis 368

Montargès, R., Fäy, J.B. and Le Tirant, P., (1987). “Soil reconnaissance at great water depth,” Proc. of 4th Int. Deep Offshore Technology.

Montargès, R., Le Tirant, P., Wannesson, J., Valéry, P., and Berthon, J.L., (1983). “Large-size stationary-piston corer,” Proc. 2nd 2 Int. Deep Offshore Technology Conference, Malta, 17-19 October, 1, 63 - 74.

Mosher, D.C. and P.G. Simpkin, 1999, Status and Trends of Marine High-Resolution Seismic Reflection Profiling: Data Acquisition, Geoscience Canada, V. 26 (4), p. 13.

Multibeam Sonar Theory of Operation, (L-3 SeaBeam 2000). Comprehensive multibeam signal processing techniques. Details various beamforming methods used in multibeam systems.

R2Sonic Broadband Multibeam Echosounders Operation Manual V3.0, (R2Sonic 2010). Basic general underwater acoustic principles, amplitude and phase detection theory, especially broadband multibeam systems.

Sylwester, R.E., 1983, CRC Handbook of Geophysical Exploration at Sea, Richard Geyer and J. Robert Moore (Eds.), CRC Press Inc., Boca Raton, FL, p. 109.

Trabant, P.K. (1984), Applied High-Resolution Geophysical Methods, International Human Resources Development Corporation: Boston, MA, USA.

U.S. Army Corps of Engineers, 2004, Chapter 11: Acoustic multibeam survey systems for deep-draft navigation projects, in Engineering and Design - Hydrographic Surveying, US Army Corps of Engineers, Maryland, USA, EM 1110-2-1003 Change 1, 44 p.

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under US administration.

The Bureau of Ocean Energy Management

As a bureau of the Department of the Interior, the Bureau of Ocean Energy (BOEM) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS) in an environmentally sound and safe manner.