FUGRO ATLANTIC

SEABED SCOUR CONSIDERATIONS FOR OFFSHORE WIND DEVELOPMENT ON THE ATLANTIC OCS

Prepared for:
Bureau of Ocean Energy Management,
Regulation and Enforcement

February 2011
Fugro Project No. 3707.001

This report has been reviewed by the Bureau of Ocean Energy Management, Regulation and Enforcement and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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February 3, 2011
Project No. 3707.001

Bureau of Ocean Energy Management, Regulation and Enforcement,
U.S. Department of the Interior
BOERME Engineering & Research Branch
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Attention: Ms. Lori Medley

Subject: **Seabed Scour Considerations for Offshore Wind Energy Development in the Atlantic OCS**

Dear Ms. Medley:

On behalf of the Fugro group of companies and the Center for Coastal Physical Oceanography at Old Dominion University, we are pleased to submit our report for the Technology Assessment and Research (TA&R) 656 - Seabed Scour Consideration study.

The report contains information intended to help the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) raise the awareness of how seabed scour can affect the siting, design, installation, and operations of an offshore wind farm on the Atlantic outer continental shelf (OCS). It includes information describing why scour is an important consideration for an offshore wind farm, what factors can contribute to scour, how the severity of sediment mobility depends on the interrelationship between the ocean bottom and the seafloor interface, and how the installation of offshore wind structures and cables can alter the dynamic equilibrium among the many factors that contribute to the dynamic morphology of the seafloor. In addition, the report describes lessons learned from offshore wind development in Europe, and provides our recommendations for the investigations appropriate for design-phase evaluations and for post-installation monitoring.

The report also includes two appendices that provide example evaluations of how local variations in the factors affecting sediment mobility and scour can be micro-zoned within an offshore wind farm (OWF) development area. Appendix A provides an example for the Northern Atlantic OCS. Appendix B provides an example for the Mid-Atlantic OCS. The locations for the examples have been chosen based on availability of data to illustrate variations in the severity of anticipated sediment mobility. Scour should be anticipated to vary within a commercial OWF development area, and that by extension, site-specific evaluation of such conditions and hazards should be a component of offshore wind energy development siting evaluations.

TA&R Study 656 was authorized by MMS Contract M10PC00069, dated January 4, 2010. The contract award was based on Fugro's proposal dated September 18, 2009 in response to MMS' request for proposal, dated August 21, 2009. The proposal followed Fugro's June 19, 2009 White Paper submittal in response to MMS Solicitation No. M09RS00071, dated May 14, 2009. The Seabed Scour Consideration TA&R topic was Topic No. 2 of the referenced MMS solicitation.

A draft of this report was provided to BOEMRE, and the comments received have been considered when finalizing the report. We appreciate the opportunity to be of service to the BOEMRE.

Sincerely,

FUGRO ATLANTIC

Kevin R. Smith
Senior Engineering Geologist

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Vice President

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EXECUTIVE SUMMARY

PROJECT BACKGROUND AND DESCRIPTION

Offshore wind in the U.S. is initially anticipated to be developed on the Atlantic OCS offshore the Mid-Atlantic and Northern Atlantic coast. This is a *Frontier Area* where there has not been historical offshore energy development. It is also an area where high sediment transport occurs and the seafloor is often composed of sediments that are scour susceptible. The initial offshore wind farms (OWF) are anticipated to include a number of locations where scour may be significant.

The Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), as part of their Technology Assessment & Research (TA&R) for offshore renewable energy research (REnR), awarded TA&R Project 656 to evaluate Seabed Scour Considerations for offshore wind energy development on the Atlantic OCS. The objective of this study is to: 1) review oceanographic and seabed data from the Atlantic OCS, 2) review readily available information from European OWF projects, and 3) describe how OWF structure and cable installation may affect scour susceptibility of the seabed. This report, which documents the results of TA&R project 656, is intended to help increase the awareness that scour is an important technical consideration for the development of offshore wind resources.

SEDIMENT TRANSPORT IN THE ATLANTIC OCS

The Atlantic OCS is an area of dynamic ocean conditions and complex seafloor geomorphology. It is the interrelationship between the bottom currents (produced by the various oceanographic conditions) and the seabed and seafloor sediments that: 1) produces the seafloor geomorphology and 2) creates the potential for erosion, transport, and redeposition of the seafloor sediments. That interrelationship varies both spatially and temporally. Subtle changes in the seafloor have been documented during minor storms, while large storms can produce significant changes in the seafloor due to erosion, transport, and redeposition of the seafloor sediments.

For normal conditions - those that occur during normal cycles of tides and typically storms that occur many times per year - the sediment transport (i.e. erosion, transport, and redeposition) in an area will evolve to a condition of dynamic equilibrium. All areas of the OCS, however, are subjected to periodic larger storms and other ocean forces of varying severity, directions, character, and return periods that unbalance the dynamic equilibrium of the ocean-seafloor system. When the changes to the seafloor due to those events are modest, the former dynamic equilibrium may be re-established with time. The amount of time required to re-establish the former equilibrium conditions depends on the severity of the changes produced by the larger storm. If the severity and magnitude of the event-driven changes are extreme, the long-term dynamic equilibrium of the ocean system may be changed.

SCOUR POTENTIAL AT AN OFFSHORE WIND FARM

The dynamic equilibrium among the ocean currents, seabed conditions, and seafloor sediments is complex. Small changes in any of the conditions can affect the equilibrium and re-establishment of the equilibrium after comparatively rare events. Moreover, certain seafloor sediment types (e.g. sand) can respond to hydrodynamic changes in time scales of an hour or less. Conversely, for cohesive sediments significant topographic changes may require months or years to occur. The introduction of OWF structures can significantly alter the rates and magnitudes of seafloor changes. OWF structures and OWF installation activities can: 1) locally increase the bed stresses due to bottom currents, 2) reduce the resistance of the seafloor sediments to scour, and 3) unbalance the dynamic equilibrium at the ocean-seafloor interface.

This can increase the potential for sediment mobility and cause scour around the structures and along cable routes. The changes in the ocean-seafloor dynamics are created by: 1) introducing obstructions (wind turbine substructures) that create localized areas of increased bottom currents and 2) disturbing the sediment (and increasing its scour susceptibility) during the structure and associated cable installation. Both the obstructions produced by the structures and the disturbance created during the wind farm construction alter the dynamic equilibrium at the ocean-seafloor interface, and increase the potential for sediment erosion, transport and redeposition.

Thus, the potential for scour around the structures or along the cable routes is anticipated to be an important technical consideration for offshore wind development in the Atlantic OCS. The variation of scour will depend on the following factors and the interrelationship among these factors: 1) seabed current velocities, 2) seabed conditions (e.g. sand waves), 3) seabed sediment type and conditions, and 4) degree of seabed disturbance caused by: a) inner-array cable installation, b) turbine substructure and foundation, and/or c) construction vessel anchors and barge legs.

EUROPEAN EXPERIENCE

Experience offshore Europe has documented scour around the turbine substructures and in areas disturbed by inner-array cable installation. The amount of scour has commonly been observed to vary temporally and spatially within the area encompassed by the wind farm. The most problematic conditions produced by the scour have often been at the J-tube where the OWF cables enter and exit the base of wind turbine substructure. This is also the location where mitigating scour has proven to be the most challenging and problematic. Elsewhere, the mobility of the seafloor sediments and sand waves has re-exposed previously buried cables.

If left unattended, scour around a wind turbine substructure can reduce the foundation capacity, soften the load-deformation characteristics of the foundation and sub-structure, and change the fundamental period of vibration of the foundation and sub-structure. When scour undermines the cables at the base of the J-tube, this can cause the cables to strum, which in turn can cause abrasion of the cable on the J-tube. If not mitigated, this condition can lead to a fault in the cable and the loss of energy transmission from the OWF or a portion of the OWF.

DESIGN STUDIES

Scour potential is related to oceanographic and seabed conditions and how the installation of OWF structures and cables will alter the natural environment. Thus, the design of an OWF, and the consideration of scour hazards and mitigation requires the input from and use of information from several disciplines. An integrated approach to that effort is encouraged as part of the OWF siting, design, and installation planning.

Two examples of mapping to predict how the combination of the different oceanographic and seabed conditions collectively lead to different degrees of scour susceptibility in an OWF-size are of the Atlantic OCS are included as appendices to this report. Appropriate consideration of scour potential will require high quality seabed charting using both multi-beam, echo-sounder (MBES) hydrographic systems and side scan sonar (SSS) data collection.

SCOUR AVOIDANCE, PROTECTION AND MITIGATION

The potential for scour to develop within an OWF is significant. The occurrence of conditions that produce scour and their frequency will be a significant consideration for the design of future WTs and OWF developments. The potential for scour, and the depths and size of the scour depressions around the foundations will determine whether scour avoidance or protection will be required.

There are various options available for avoiding, protecting against, or mitigating scour problems. Because there are many variables that affect scour susceptibility and these variables can be different in different parts of an OWF, it is possible that a combination of avoidance and protection may be appropriate for many OWFs. Also the approach to avoidance and protection should consider the future difficulties associated with mitigating scour once it begins to occur. This is illustrated by several of the case histories of European experience.

POST-INSTALLATION MONITORING AND INSTRUMENTATION

Site-specific measurements of the bottom current velocities and scour depths will provide important information for: 1) verifying that the scour assumptions during design have not been exceeded, 2) verifying that any scour avoidance or protection measures are effective, and 3) generating data that will reduce unnecessary conservatism or unrecognized risk at future OWFs. Our recommendations for oceanographic instrumentation and post-installation MBES hydrographic surveys are included in the report.

CONCLUSIONS AND RECOMMENDATIONS

Seabed scour is anticipated to be a potential hazard to offshore wind development in many areas of the Atlantic OCS. Scour potential is related to oceanographic and seabed conditions and how the installation of OWF structures and cables will alter the natural environment. Thus, the evaluation of scour hazards and mitigation requires the input from and use of information from several disciplines. An integrated approach to that effort and detailed evaluation is required as part of OWF siting and design.

The seafloor topography is complex in many areas of the Atlantic OCS. The complexity of the seafloor topography is due to both geologic processes that occurred as the sea level rose following the last ice-age and the dynamic nature of the currents on the ocean bottom. Lesser-scale sand waves and ripples as well as larger-scale ridges, banks and swales are often present on the seafloor. Subtle changes in the seafloor have been documented on the Atlantic shelf during minor storms, while large storms can produce significant changes in the seafloor due to erosion, transport and redeposition of the seafloor sediments. High quality, multibeam bathymetry data are required to define the seafloor topography and monitor changes of the topography.

To locate structures so as to minimize potential scour requires detailed evaluation of the potential for scour due to the bottom currents that occur due to normal conditions and due to different types of storm conditions. These considerations will include both probability of occurrence and potential severity of scour. Because storms can produce bottom currents that flow in different directions depending on the location of the storm and the wind circulation and wave patterns created by the storm, it will be necessary to obtain site-specific measurements to plan the site layout and plan the project-specific scour protection and mitigation measures.

The development of scour avoidance and mitigation should be evaluated and chosen based on project- and site-specific conditions and evaluations. Post installation monitoring and measurements will be required to validate or modify a project’s scour avoidance and mitigation approach. As project data are developed and as industry experience is gained, an adaptive approach should be used define requirements for future measurement and monitoring.

1.0 INTRODUCTION

TA&R PROGRAM FOR OFFSHORE RENEWABLE ENERGY DEVELOPMENT

The authority to manage the resources of the U.S. Outer Continental Shelf (OCS) was vested to the Minerals Management Service (MMS; renamed the Bureau of Ocean Energy Management, Regulation and Enforcement [BOEMRE]) by 43USC§1331. That authority historically has included the responsibility for leasing and regulation of the OCS for Oil and Gas (O&G) energy developments. By §1337(p)(1)(c), this responsibility was explicitly extended to include renewable energy developments on the OCS.

Whereas, the BOEMRE has a long history regulating O&G development on the OCS, the locations of the active O&G developments are typically in the Gulf of Mexico (GoM) and, to a lesser extent, offshore southern California and Alaska. In contrast, many of the areas of anticipated renewable energy operations are in areas that have not been historically developed for O&G.

While many of the technical and development requirements associated with renewables will be similar to those for O&G development, there are several important differences between offshore wind developments (both turbine structures and cabling connections) and typical O&G developments and structures. In recognition of those differences, the BOEMRE via their Technology Assessment and Research (TA&R) Program solicited (on May 14, 2009) white papers on five topics of interest to BOEMRE relative to renewable energy research.

BACKGROUND FOR TA&R SEABED SCOUR STUDY

Offshore wind in the U.S. is initially anticipated to be developed on the Atlantic OCS offshore the Mid-Atlantic and Northern Atlantic coast. The initial offshore wind development areas are often areas of high sediment transport, and many areas of the seafloor are composed of sediments that are scour susceptible. For example, Acoustic Doppler Current Profiler (ADCP) measurements (Atkinson, 2010) and underwater glider measurements have documented sediment re-suspension offshore Wallops Island and southern New Jersey, respectively. These are areas of potential offshore wind development.

The development of offshore wind energy is anticipated to increase seabed scour because of: 1) structures that introduce obstructions that create localized areas of increased currents and 2) disturbance of the sediment during wind-turbine support structure and inner-array cable installation.

Experience offshore Europe has documented scour around the turbine substructures and in areas disturbed by inner-array cable installation. The amount of scour has commonly been observed to vary temporally and spatially within the area encompassed by the wind farm. The variation of scour appears to depend on the following factors and the interrelationship among these factors: 1) seabed current velocities, 2) seabed conditions (e.g. sand waves), 3) seabed sediment type and conditions, and 4) degree of seabed disturbance caused by: a) inner-cable installation methods, b) turbine substructures and foundations, and/or c) construction vessel anchors and barge legs.

To date, research of scour issues related to OWF projects has focused more on scour processes around wind-turbine foundations than due to cable installation. Although scour and sediment transport problems related to cables have been recognized as a need for future research in Europe, little information is available about the topic. Moreover, since no OWFs have been constructed on the U.S. OCS, information regarding scour and sediment transport hazards must be extrapolated from European experience, limited oceanographic studies and marine surveys on the Atlantic OCS, O&G development elsewhere on the OCS, and waterfront projects along the U.S. east coast.

THE ATLANTIC OCS

The Atlantic OCS, where energy development is regulated by the BOEMRE, extends from the U.S./Canadian border to offshore the Florida Keys, and from 3 nautical miles (Nm) offshore and outward. The primary focus of this report is relative to developing the initial offshore wind projects on the Atlantic OCS. While the considerations discussed herein have broader application, they are primarily focused within the context of the oceanographic, seafloor, and subsurface conditions present offshore the Atlantic coast.

As described in this report, the interrelationship between the bottom currents produced by the various oceanographic processes and conditions, and the seafloor conditions and materials, produce the seafloor geomorphology and create the potential for sediment mobility. The installation of a structure can unbalance the dynamic equilibrium at the ocean - seafloor interface. This can increase the potential for sediment mobility and cause scour around the structure.

For the purpose of the discussions in this report, the Atlantic OCS is divided into three areas: 1) the Northern (or New England) Atlantic, 2) the Mid-Atlantic, and 3) the Southern Atlantic. The divisions we make for this report are shown on Figures 1-1 through 1-3. We note that these divisions may be slightly different from that defined based on only oceanographic or only geologic and geomorphologic considerations.

Oceanographic Conditions

The eastern seaboard of the U.S. and the adjacent Atlantic OCS is an area of dynamic ocean conditions. The conditions and their significance for offshore wind development vary spatially (as well as temporally). For example, the exposure to tropical storms is greatest in the Southern Atlantic. To the north of Cape Hatteras, exposure, severity, and duration of tropically storms generally decrease with increasing latitude. While exposure to tropical storms in the Mid- and Northern Atlantic is less than in the GoM, it is important to recognize that the exposure to tropical storms in the Atlantic regions is beyond the offshore wind experience provided by the initial development of offshore wind in northern Europe.

Conversely, the significance and magnitude of tides and tidal currents increases with latitude. Thus, the significance of tidally generated hydraulic forces is greatest in the Northern Atlantic. This implies that the potential for scour may be more tide-driven than storm driven in much of the Northern Atlantic OCS. In contrast, storm-generated bottom forces are anticipated to be the predominant factor relative to scour in most of the Mid- and Southern Atlantic OCS.

Seafloor Characteristics

Except for offshore northern New England, the bathymetry on the continental shelf offshore the Atlantic coast is relatively uniform regionally. However, the bathymetry also commonly includes significant local topography. Often the variation of water depth in a 3 Nm by 3 Nm OCS block is greater than the regional variations across multiple OCS blocks. The local topographic variations, or seafloor morphology, often are due to both: 1) the presence of relict geologic features associated with the glacial sea level low stands and subsequent post-glacial period sea level transgression, and 2) active erosion and deposition due to tidal and/or storm currents.

Subsurface Conditions

The geology and subsurface conditions beneath the Atlantic OCS have been significantly influenced by geologic processes during repeated cycles of glacial advance and retreat, and resulting cycles of sea level fall and rise.

Offshore the Northern Atlantic coast, the glaciers advanced across portions of the inner shelf. Figures 1-1 and 1-2 include the probable southern limit of the last glacial maximum. In those areas, the shallow subsurface conditions and seafloor materials can include glacial deposits and rock. The subsurface materials beneath the seafloor off the New England coast can include different types of materials, which in descending sequence, can include some or all of the following: 1) recent, soft clays and loose sands, 2) various types of marine and fluvial marine sediments that can vary considerably in thickness, layering and lateral extent, 3) various types of glacial deposits that can vary considerably in thickness, layering and lateral extent, and 4) rock. In some areas, the marine and fluvial deposits can be interlayered within the glacial deposits.

The seafloor and subsurface sediments farther offshore the Northern Atlantic coast and off the mid and Southern Atlantic coast typically are composed of alluvial, estuarine, and marine deposits. The subsurface conditions in those areas of the Atlantic OCS will be composed of layered marine and fluvial sediments. Globally, sands should exceed clay. But locally where relict drainages (formed during sea level low stands) were flooded and in-filled (as sea level rose), a substantial thickness of clay may be encountered. Buried shoreline deposits and back-bay estuary deposits also are present in some areas.

Frontier Area Considerations

Because project-specific data, design-level studies, and a historical record of structure installation and performance are generally lacking, the BOEMRE considers the Atlantic OCS to be a *Frontier Area*. That definition and the lack of historical energy development have specific significance relative to the development of energy resources in the Atlantic OCS.

Because there has not been historical development of the energy resources in the Atlantic OCS, there is no historical record of how structures and energy developments have performed. In contrast, there are thousands of structures and developments, and decades of experience relative to developing and using design practices, installation methods, and structure performance for the GoM OCS (and to a lesser extent in the southern Pacific OCS and in some parts of the Alaskan OCS). Since a comparative historical record is not available for the Atlantic OCS, the ability to apply lessons learned from what has been successful, and what has not, is not available for siting, design, installation, and performance of offshore energy development on the Atlantic OCS.

Not surprisingly, there is a comparative lack of project-detail, engineering data and studies that define the oceanographic, seafloor, and subsurface conditions in the Atlantic OCS (relative to areas offshore the U.S. and in other areas of the world where there has been historical offshore energy development [whether that development be offshore wind, offshore O&G, or other offshore energy development]). Fortunately, a number of high-quality scientific, research, and academic studies (together with project-level studies for a few energy development projects, and a moderate number of pipeline and cable route projects) provide a framework that can be drawn from. Nevertheless, the site-specific knowledge of the oceanographic, seafloor, and subsurface conditions as they apply to designing and installing large foundations and extensive networks of cables, such as required for an offshore wind turbine, is limited.

The implication to the BOEMRE is that the initial offshore energy projects on the Atlantic OCS should be carefully evaluated and thoroughly investigated. One of the fundamental lessons learned during the initial offshore wind projects in Europe was that the oceanographic, seafloor, and subsurface conditions and their inherent variations were sometimes not well defined or were not defined in a timely manner during the early phases of some projects. The lack of detailed appreciation of the variations of those conditions, and how those conditions and their variations adversely affected the development of some offshore wind projects, is a lesson that the BOEMRE recognizes and hopes to avoid as offshore wind resources are developed on the OCS.

STUDY OBJECTIVE

The objective of this study is to: 1) review readily available information from European OWF projects, 2) review oceanographic and seabed data from the Atlantic OCS, and 3) describe how OWF structure and cable installation may affect scour susceptibility of the seabed. The research has focused on: 1) how differences in ocean and seabed conditions can affect scour in the undeveloped offshore environment, and 2) how the introduction of structures and cable-installation disturbance can further modify (increase) the scour susceptibility of the seabed.

The objective of the TA&R 656 Study has been to provide a document for BOEMRE's use that will increase the awareness of seafloor scour as an area of importance for the planning and installation of offshore wind developments. The study report is written to help BOEMRE educate potential wind developers, and their project teams, relative to the importance of evaluating scour potential and scour, and to further their understanding of the:

- Factors that affect scour and scour susceptibility,
- Requirements for site studies to include data collection that is important to this evaluation,
- Potential need for scour protection as part of their project design, and
- Requirements for monitoring and provisions for possible scour mitigation options in their project operational plans.

Based on information reviewed during the study, this report describes factors that affect scour and scour susceptibility and provides descriptions of data collection for site studies to help evaluate scour and sediment transport hazards for future OWF projects. This report also describes the importance of evaluating scour potential and effects during planning, design, installation, and monitoring of wind farm developments.

ADMINISTRATIVE DETAILS

Study Authorization

TA&R Study 656 was authorized by MMS Contract M10PC00069, dated January 4, 2010. The contract award was based on Fugro's proposal dated September 18, 2009 in response to MMS' request for proposal, dated August 21, 2009. The proposal followed Fugro's June 19, 2009 white-paper response to MMS Solicitation No. M09RS00071, dated May 14, 2009. The Seabed Scour Consideration TA&R topic was Topic No. 2 of the referenced MMS solicitation.

Study Participants

Fugro's designated point of contact for the TA&R study has been Tom McNeilan, the general manager of Fugro Atlantic in Norfolk, VA. The principal investigators for the study were Kevin Smith, senior engineering geologist at Fugro Atlantic, and Dr. Jose Blanco, research scientist at the Center for Coastal Physical Oceanography at Old Dominion University (ODU) in Norfolk, VA. Their work has been supported by various members of Fugro Atlantic's staff, including Mr. James Fisher, Dr. Mohamed Mekkawy, and Mr. Craig Butler. The work completed for this study has benefited from the input and review provided by: Drs. Larry Atkinson and Don Swift, professors emeritus at ODU, Dr. Jean-Francisco Vanden Berghe, general manager of Fugro S.A. in Belgium, and Tony Hodgson, of Fugro Geoconsulting in the U.K. who is Fugro's European offshore renewables services coordinator.

REPORT ORGANIZATION

The main text of this Seabed Scour Consideration report includes the following topics:

- Section 1.0 - Introduction
- Section 2.0 - Offshore Wind Farm Components, which describes the typical components associated with offshore wind developments
- Section 3.0 - Sediment Transport and Scour
- Section 4.0 - Sediment Transport and Scour Considerations for Offshore Wind Development
- Section 5.0 - European Offshore Wind Observations and Lessons Learned
- Section 6.0 - Scour Susceptibility Evaluations for Two Hypothetical OWFs
- Section 7.0 - Recommendations for Design Studies and Post-Installation Monitoring
- Section 8.0 - Scour Avoidance, Protection and Mitigation
- Section 9.0 - References

Pertinent tables are included within the text. Figures are included at the end of the text.

The report also includes three appendices. Appendices A and B provide examples of how variations of ocean conditions, seafloor conditions, and seafloor sediments are anticipated to provide different magnitudes of scour severity within a hypothetical OWF development. Appendix A provides an example for the Northern Atlantic OCS, while Appendix B provides a comparable example for the Mid-Atlantic OCS. Appendix C contains shear-stress equations.

2.0 OFFSHORE WIND FARM COMPONENTS

OFFSHORE WIND TURBINES

Components

Offshore wind turbines are typically large structures supported by monopiles, jackets, or gravity base foundations. The structures include the following primary components, from top to foundation:

- Blades,
- Nacelle,
- Tower,
- Transition Piece,
- Substructures, and
- Foundation.

For a monopile or gravity base structure, the substructure and foundation are combined. Figure 2-1 illustrates the different structural elements of a typical (non-floating) offshore wind turbine.

The size and type of structure is dependent on: 1) the elevation of the nacelles, 2) turbine/nacelle size, 3) length of blades, 4) wind speed, 5) water depth, 6) foundation conditions, as well as other factors. The nacelle elevation and blade length typically increase in proportion to the turbine size (i.e. nameplate capacity), as shown on Figure 2-2. Regardless of nacelle size or foundation type, wind turbines are tall, slender structures, whose structural slenderness ratio (height/plan dimension), loads, and performance are much different from that of a typical continental shelf O&G platform. The height/slenderness ratio of the structure increases as the turbine size increases and water depth increases. In addition, the height/slenderness ratio of a wind turbine with a monopile substructure will exceed that of a wind turbine with a gravity base or jacket substructure.

Wind turbines are inherently flexible structures. The vibrational periods of the nacelle and blades must be compatible (i.e. not in resonance) with the period of the tower, substructure, and foundation. If scour develops around the base of the structure (particularly a monopile foundation), the unsupported length of the substructure will increase and its fundamental period of vibration will increase. Hence, scour has the potential to change the structural performance of the system, as well as the load-deformation and factor of safety of the foundation.

In addition to those vibrational design considerations, the design and performance of a wind-turbine structure must accommodate the many cycles of load application inherent to the operation of the wind turbine. The number of cycles of operating loads for a wind turbine exceeds the number of cycles of load for a bridge or plane. Thus, the design of the wind turbine must accommodate both the maximum cyclic loads from design storms, and the many cycles of lower dynamic loads created by the operation of the machine.

Substructures

Four types of substructures have typically been used for fixed offshore wind turbines in Europe. Those substructure types are: gravity base, monopile, tripod, and jacket structures (Figure 2-3). The typical sizes of the foundation element for those substructures in Europe have been:

- Gravity Base Substructure - 15- to 22-meter (~50- to 70-foot) base diameter,
- Monopile Substructure - 4.5- to 6-meter (~15- to 20-foot) pile diameter,
- Tripod Substructure - three, 1.8- to 2.5-meter (~6- to 8-foot) diameter piles, and
- Jacket Substructure - four, 1.8- to 2.5-meter (~6- to 8-foot) diameter piles.

The monopiles and piles that support tripod and jacket structures typically penetrate 30 to 40 meters (~100 to 130 feet) below the seafloor.

To date in Europe, the typical water depth ranges for the four different types of foundations have been as follows:

- Gravity Base Substructure - 2- to 10-meter (~7- to 30-foot) water depth,
- Monopile Substructure - 2- to 25-meter (~7- to 80-foot) water depth,
- Tripod Substructure - 2- to 30-meter (~7- to 100-foot) water depth, and
- Jacket Substructure - 6- to 40-meter (~20- to 130-foot) water depth.

As offshore wind development moves into deeper water, additional structure combinations and substructure/foundation elements are anticipated. Those could eventually include floating wind turbines. Consideration of those potential future evolutionary wind-turbine structures is beyond the scope of the current study.

ELECTRICAL SUBSTATION PLATFORMS

Most commercial OWFs currently planned on the U.S. OCS will include at least one electrical substation platform (ESP). The exceptions to that generality are small pilot OWF projects, typically located near the coast, with a few to possibly few tens of wind turbines.

The ESP substructure is typically a four- or six-leg, pile-supported jacket structure. The design of the substructure and its foundation piles, its performance, installation, and typical dimensions are comparable to that of a typical offshore O&G platform.

STRUCTURE INSTALLATION CONSIDERATIONS

Installation of the OWF structures is typically accomplished with large jack-up rigs, although floating barges and installation vessels are also a possibility. Jack-ups are elevated on legs which are jacked down into the seafloor. The depressions left by legs, termed spud can depressions, can be large and deep. When floating vessels are used, they may be either anchored on a multi-point anchor spread or dynamically-positioned at the location. Anchors for the installation vessels will be large, and can disturb the seafloor.

During construction, various other barges, vessels, and/or jack-ups will deliver equipment to the site. In addition, it has been common practice that the wind-turbine foundations, substructures, and transition pieces are installed with one vessel, while the towers, nacelles, and blades are installed later using a different vessel.

In addition to installation, the normal operational and maintenance cycle for an offshore wind turbine will require periodic servicing of the nacelle and blades. This also will require positioning of a jack-up, anchored vessel or dynamically-positioned vessel adjacent to the structure.

All of these installation and maintenance activities can disturb and alter the seabed in the immediate vicinity of the structure, and where the cables enter and exit from the structure.

CABLE REQUIREMENTS

Offshore wind farms include two general types of cables to collect the electricity and transfer it to the onshore grid. Inner-array cables connect the wind turbines and will usually connect to an electrical substation platform (ESP). An export cable(s) will transfer the electricity from the ESP to the onshore grid connection.

Inner-Array Cables

The infield cables connect the turbines into arrays and connect the various arrays together. The operating voltage for the inner-array cables is typically 33 kilovolts (kV). The inner-array cables enter and exit the wind-turbine support structure through a J-tube (Figure 2-4) immediately above the seafloor. J-tubes are semi-rigid or flexihose tubes that the cables use to enter the turbine structure. The J-tubes also may protect the cable from abrasion as the cable penetrates through the turbine's scour protection. . Cables between wind turbines are relatively short (typically 1,500 to 3,000 feet]) but could be up to 12,000 feet) between wind turbine and the offshore ESP.

Export Cables

Export cables transmit electrical power generated by the offshore wind farm to an appropriate connection point on the electrical grid. This is typically onshore from the shoreline or cable landfall, but can also be to an offshore backbone grid cable.

Due to the anticipated distance offshore that wind farms are being considered to be constructed in federal waters, an offshore power substation will likely be required. Inner-array cables will be collected at the offshore substation where a step-up transformer(s) will boost the voltage and transmit the electricity to shore via a high-voltage (generally 115 or 132kV) cable. Alternatively, three or four 33-kV cables may be used instead of one high voltage (e.g. 115 or 132-kV) cable, but the latter is generally more economical when considering the cost per installed kilometer. Depending on the length of the export cable, an offshore ESP may not be required to step up the voltage for 33-kV cables.

CABLE BURIAL REQUIREMENTS

The primary purpose of burying cables is to protect them from fishing, anchoring activities, and current abrasion. Studies indicate that nearly 70 percent of submarine cable faults from 1958 to 2008 are due to fishing incidents (IPCP, 2009). Bottom-fishing activities are common on the Mid-Atlantic continental shelf. Damage typically is caused by vessels accidentally dragging anchors as a measure to slow down or hold position during inclement weather. Nearly 60 percent of all cable faults occur in water depths less than 200 meters (~650 feet). Table 2-1 presents a summary of cable faults from 1958 through 2006 based primarily on telecommunication cable and O&G industry data.

There are several reported incidents where cables have been damaged or were unburied and reburial was required. Several wind farm projects in Europe experienced incidents where the cables were damaged, including: Arklow Bank (inner-array cable), Horns Rev 1 (end row due to dragging anchor), Burbo Bank (inner-array due to backhoe dredger), Barrow (export cable due to loop on cable), and Princess Amalie (export cable), (BERR, 2008 and Slengesol, 2010).

Table 2-1. Sources of Cable Faults from 1958 to 2006

Cause	Percentage
Fishing	67
Anchors	8
Current Abrasion	5
Dredging	2
Other (e.g. natural events like submarine landslides or turbidity flows triggered by earthquakes)	18

Note these statistics are predominantly from telecommunication cables, not OWF power cables.
Sources: ICPC (2009) and Wood and Carter (2008).

The standard practice for mitigating these types of hazards is to bury the cable using plows or jet-trenching methods. The depth of cable burial is typically determined during a cable burial assessment. Depth required for protection is a function of the threat to the cable (or force with which the threat applies to the seabed) and the resistance (density or strength) of the seabed materials. Table 2-2 provides general burial depths for different types of threats and for various types of seabed materials. Types of seabed materials and their engineering properties (e.g. density and strength) are determined during the geotechnical site investigations.

Table 2-2. General Cable Burial Depths for Varying Seabed Conditions and Threats

Threat	Hard Ground (clay > 1.5 ksf, rock), ft	Soft-firm soils (sand, gravel, clay 0.5 to 1.5 ksf), ft	Very Soft - soft soils (mud, silt , clay 0.04 to 0.5 ksf), ft
Fishing (trawl boards, beam trawls, scallop dredges)	<1.3	1.6	>1.6
Hydraulic dredges	<1.3	2.0	N/A
Slow net fishing anchors	N/A	6.6	>6.6
Ship's anchors - up to 10,000t DWT (50% of world fleet)	<5	~ 7	24
Ship's anchors - up to 100,000t DWT (95% of world fleet)	<7	9.5	30

Source: BERR (2008)

CABLE INSTALLATION TECHNIQUES

Methods of Burial

OWF cables historically have been installed using either jet-trenching or plowing techniques. Although both are still used today, jet-trenching is becoming more common for several reasons. Most notably this method can achieve burial depth almost immediately at the onset of trenching.

In contrast, plowing requires a transition distance of about 150 feet at the start of a plowing run to reach the target burial depth and a shorter distance for tapering upward at the end of the plowing run on the approach to the next turbine. Therefore, the cable may not be buried at the target depth or may require divers to bury the cable within the transition zone. This is generally not a significant issue for jet-trenching tools, although they typically do not get closer than 30 to 50 feet of the turbine. Another factor is that jet-trenches can conduct multiple passes to achieve burial depth and plows generally utilize only one pass. That can make it difficult to achieve target burial depth with a plow in stiff or dense soils. Another reason jet-trenchers are often favored is that they (if using a tracked machine or remotely operated vehicle [ROV]) offer more directionality control than vessel-towed plows.

Jet-Trenching

Jet-trenchers utilize high-pressured water jets to fluidize soil as the machine traverses along the cable route. Typically, the cable is initially laid on the seabed and a jet-system injects high-speed water into the seabed. The cable descends into a temporary trench incised by the jetting swords and is subsequently buried as the eroded sediments deposit back inside the trench. Figure 2-5 presents: 1) a schematic drawing of a jet-trenching machine in operation and 2) an image from a jet-trenching laboratory study which shows the fluidization process. Figure 2-6 presents the key mechanisms that occur during jet-trenching process. The following description of the mechanisms is based primarily on work by Vanden Bergh et al. (2008), who studied the mechanisms of jet-trenching using physical experiments. During trenching, two types of processes occur:

1. Longitudinal Processes. Longitudinal processes involve the erosion and entrainment of sediment from the trench floor and side wall by a jet-induced current that transports the sediment backwards. After flowing along the bed in the shooting flow regime, the jet-induced current undergoes an internal hydraulic jump across which the flow thickens and decelerates before depositing the sediment grains farther away to backfill the incised trench.
2. Lateral Processes. Lateral processes include erosion by the breaching and collapse of the trench side walls. This will occur to a greater extent in looser sediments and those with lower fines contents. Overspill occurs beyond the internal hydraulic jump once the upper boundary of the turbid current exceeds the trench wall. Once the turbid water rises above the trench wall, the plume expands laterally, and some sediment will redeposit outside the trench. The amount of sediment that deposits outside the trench will largely depend on the sediment particle sizes, velocity of the ocean bottom current, and duration the sediments are in suspension. Ultimately, the lateral overspill results in a lower volume of sediment being redeposited in the trench body than was initially present and will create a depression in the seabed along the trench.

The effects of the jet-trenching process include the following (Figure 2-6):

- A slight depression (trench scar) forms along the trench since not all sediment deposits back inside the trench.
- Modification of the condition of the seafloor and sediment characteristics, which results in an increase in the sediment's susceptibility to erosion and transport. The changes are produced by several factors, including:
    - The sediments that deposit inside the trench are in a looser or weaker state than the undisturbed sediments. This reduces their resistance to currents and forces that cause scour.
    - Disturbance of any biologic film that may exist at the ocean-seafloor interface. This also reduces natural conditions that can resist sediment transport.
    - Sediments that deposit back in the trench may have a lesser fines content than the undisturbed sediments. This is because as sediments are suspended, larger particles will settle out faster than the smaller particles. Thus, proportionately more fines are carried away from the trench. A decrease in the fines content reduces the cohesion of the sediment and, thus, its resistance to scour.
- Overspill occurs as some of the fluidized sediments deposit outside the trench. These sediments may form a small levee. Some suspended sediments may be transported away from the trench due to currents. The amount of the sediment transported away depends on the jetting pressure and volume, sediment size, duration in suspension, and velocity of the bottom currents.

Trench geometry will depend upon several factors including the depth of burial and cohesion of the sediments, among other factors. Most trenches form a trapezoidal cross-section. The ratio between the top and bottom widths will decrease as the percent fines or cohesion of the sediments increases. In general, a trench constructed in loose, clean sand (low fines content) will have a wider top than will a trench in clayey sand sediments (high fines content). Trenches in firm to stiff clayey soils may have near-vertical sidewalls.

For sandy marine sediments in Nantucket Sound, Applied Science Associates estimated that the trench created by a cable installed to a depth of 8 feet by jetting would be 6 feet wide at the top and 2 feet wide at the bottom (Galagan et al., 2003). They estimated that 70 percent of the sediments would remain in the trench and 30 percent would be distributed in the overlying water column during trenching. The Galagan et al. (2003) modeling predicted that sediment would be redeposited within 200 feet of the trench with a maximum depositional depth of about 1 inch.

Plowing

Plows have been used historically in the telecommunications industry and on some wind farm projects. Typical plows used in soil conditions are either conventional narrow-share plows or advanced cable plows (which include modular cable plows). The conventional narrow-share plow is a passive tool that uses a plow share to cut a wedge of soil as it is towed or pulled from a vessel or barge. The wedge of soil is lifted by the shape of the plow share as it is pulled. The cable is fed through the pathway in the machine, and the wedge of soil falls back into the trench and buries the cable. Sometimes a burial plow is required to be pulled along to provide additional burial work. Maximum burial depth of these types of plows is typically 5 to 7 feet.

Advanced plows have been designed to achieve burial depths of up to about 10 feet. Most are equipped with water jets that fluidize sediments at the leading edge. Those without water jets use a plow share with a unique geometry.

Trenching in Rock or Stiff Soil

Cable installation in rock or soil that is too stiff or dense for jet-trenching or cable plows usually require the use of rock-ripping plows, vibrating-share plows, chain excavators, or rock saws. Rock outcrops are limited to nearshore and shoreline areas in the New England states. Glacial tills (hard clayey sediments) are present north of the last glacial maximum extent (Figures 1-1 and 1-2).

3.0 SEDIMENT TRANSPORT AND SCOUR

INTRODUCTION

The Atlantic OCS is an area of dynamic ocean conditions and complex seafloor geomorphology. The interrelationship between the bottom currents produced by the various oceanographic conditions, and the seabed and seafloor sediments, produces the seafloor geomorphology and creates the potential for erosion, transport, and redeposition of the seafloor sediments. That interrelationship varies both spatially and temporally. Subtle changes in the seafloor have been documented during minor storms, while large storms can produce significant changes in the seafloor due to erosion, transport, and redeposition of the seafloor sediments.

For normal conditions - those that occur during normal cycles of tides and typically storms that occur many times per year - the sediment transport (i.e. erosion, transport, and redeposition) in an area will evolve to a condition of dynamic equilibrium. In some areas, that dynamic equilibrium will create a condition where the seafloor sediments do not erode, move, or accrete during normal conditions. In some areas where the seafloor sediments are stable, biological activity will create a film on the sediments that increases the sediments' resistance to disturbance by hydrodynamic forces.

In other areas, the dynamic equilibrium will produce conditions where the sediments shift in response to tides or hydrodynamic stresses produced by typical storms. Sediment movement or mobility that occurs in response to the normal variations of the ocean conditions can occur at various spatial scales and different temporal scales. The changes are produced by the repeated cycles of tides, the monthly cycle of tides, the changes between seasons, etc. Those types of sediment movement can be thought of as systems-driven sediment mobility. Movement of the bottom sediment in a tidal inlet during regular flood and ebb tides, changes in the sediment movement that occur in tidal systems through the lunar cycle or due to annual peak tides, and the movement of a sand bank seaward during the winter storm season and landward during the relative quiescence of summer are examples of system-driven sediment mobility.

All areas of the OCS are subjected to periodic extreme storm events of varying severity, directions, character, and return period. The extreme events have the potential to produce hydrodynamic forces and bottom currents that exceed the magnitudes of the forces and currents that have produced conditions of dynamic equilibrium. This temporarily increases the possibility of sediment erosion, transport, and redeposition. When such event-driven forces and currents change the seafloor water depth, topography, or sediment distribution, the former dynamic equilibrium conditions will be (at least temporarily) unbalanced.

When the changes to the seafloor are modest, the former dynamic equilibrium may be re-established with time, provided the length of time required to re-establish the former dynamic equilibrium is less than the time until another extreme event. If the severity and magnitude of the event-driven changes are extreme, the long-term dynamic equilibrium of the ocean system may be changed. The creation of a new pass through a barrier island or the closure of an existing pass through a barrier island by a hurricane is an example of such long-term changes to the system.

Movement of a formerly stable seafloor is also likely to disturb any bio-film on the seafloor. This will temporarily increase the susceptibility of the sediments to subsequent erosion, transport, and redeposition.

The introduction of offshore wind structures and cables changes the dynamic equilibrium of the ocean-seafloor interface. This can increase the potential for sediment mobility and cause scour around the structure. The changes in the ocean-seafloor dynamics are created by: 1) introducing obstructions (monopiles or jacket-structures) that create localized areas of increased bottom currents, and 2) disturbing the sediment and increasing its scour susceptibility.

SEDIMENT TRANSPORT PROCESSES

Sediment transport processes in the marine environment have important implications for the installation and maintenance of OWF substructures. Figure 3-1 shows a simplified sketch that illustrates marine sediment transport processes. Seafloor sediments can be mobilized due to wave and/or currents, and either: 1) move along the seafloor, or 2) be suspended in the water column. Whether the sediment is transported along the seabed (bedload transport) or in the water column (suspended transport) depends upon characteristics of the flow and the seabed sediments.

Figure 3-2 shows 14 months of ADCP measurements obtained offshore Wallops Island, Virginia (Atkinson, 2010). The 14 months of data show about four dozen periods when the measured velocities are at least 1.2 times the estimated velocity required to suspend sediment in the water column, and eight periods when the measured velocities are more than twice the estimated velocity required to suspend sediment in the water column.

Sediment transport is a function of the interrelation between the water and seafloor. The main factors that affect marine sediment transport can be broadly grouped as follows:

- **Hydrodynamic Forcing.** The types, characteristics, and directions of fluid flow and currents in a marine environment can include: 1) current flow (tidal-, wind-, wave-, or density-driven), 2) wave flow (i.e. wave orbital velocity as created by surface waves), or 3) a combination of the two. For most areas in the Atlantic OCS, it will be the combination of both current and wave flows that create the hydrodynamic forces that produce sediment mobility. Those forces will vary due to location and time. Often the direction and orientation of the hydraulic flow will vary within a site and as a function of the many met-ocean conditions that create the forces.
- **Water Depth and Seabed Characteristics.** The water depth, seafloor conditions, and water properties all affect the velocity of the flow across the water-seafloor interface. Thus, the flow velocities (and resulting driving forces that cause movement of the seafloor sediments) depend on many factors including water depth, local variation of water depth, bottom roughness, water density and kinematic viscosity, and seafloor slope gradient.
- **Sediment Characteristics.** The resistance of the seafloor sediments to movement due to the hydraulic flow along the water - seafloor interface depends on the type and condition of the bottom sediments. Sediment type, the characteristic sediment size (e.g. D_{50}, D_{30}, D_{90}), fines content, and the sediment condition or density are all factors that affect the resistance of the sediment to transport. Different methods for calculating sediment transport are used for different sediment types (e.g. sand vs. cohesive sediments).

Many of those factors vary with time and due to met-ocean conditions. Thus, sediment transport processes are dynamic. That dynamic process creates the morphodynamics of the seabed, and its changes over time (Soulsby, 1997). The dynamic equilibrium among the factors produces the seafloor geomorphology in an area. The changes in that equilibrium change the seafloor geomorphology. Introduction of structures and modification of the seafloor due to foundation and cable installation change the balance of the dynamic equilibrium among the many variables.

Environments can be characterized as mainly depositional or erosional. If the environment is erosional, it can be defined as being either: wave-dominated or tidal current-dominated, depending on the hydrodynamics. This is an important distinction because: 1) the methods commonly used to predict sediment transport and scour differentiate between wave, current, or combined flows, and 2) the short-term and long-term morphodynamics may be quite different for these two flow regimes. The morphodynamics and ultimately sediment transport and scour susceptibility can vary spatial across an OWF site and temporally as the seabed morphology evolves. Any of those variables can change the hydrodynamic flow.

Spatial variability can be significant over an area the size of a wind farm footprint (refer to Section 5; e.g. Scroby Sands [Figure 5-1a through 5-1f] and as illustrated in Appendices A and B). The temporal changes related to seabed morphodynamics (e.g. shifting sand banks or encroachment of a sand wave on an OWF structure) can occur quickly in highly dynamic environments. In addition, significant inter-annual variation of the oceanographic conditions and by extension the bottom currents and bottom shear stresses have been documented in the Atlantic OCS. Understanding the spatial and temporal variability is critical to mitigate sediment transport and scour hazards.

The primary factors that define marine sediment transport are described below. The subsequent section of this report discusses how OWF development can affect the dynamic equilibrium among the factors and cause scour. In particular, this study focuses on processes related to OWF cables. The discussions are by necessity simplified, and are not meant to be an exhaustive dissertation of the meteorological and oceanographic environment and its dynamics. Readers interested in a more scientific discussion of sediment transport issues and scour behavior around piled foundations are referred to Breusers et al. (1977), Sumer and Fredsøe (2002), Richardson and Davis (1977), Shepard (2003), Whitehouse (1998), Soulsby (1998), USACE (2008).

HYDRODYNAMIC FLOW CHARACTERISTICS

Bottom currents are generated from tides, wave circulation, and mixed forcing conditions. Understanding and characterizing the forcing mechanisms is based on site measurements. When such data are not available (or are not of adequate duration - as noted significant inter-annual variation of the oceanographic conditions and by extension the bottom currents and bottom shear stresses have been documented in the Atlantic OCS.), hind-cast models are used to predict the hydrodynamic environment and forcing mechanisms.

Several different current flows occur on the Atlantic OCS. These include tidal currents, wind-driven currents, and density-driven currents. The prominent regional currents that have been documented along the Mid-Atlantic shelf include:

- Semidiurnal tidal currents that are mainly directed east-west;
- Regional coastal currents (e.g. Middle Atlantic Bight coastal current) that are forced by alongshore wind stress, buoyancy produced by river discharge, and bottom stress produced by the shallow bathymetry;
- Down-shelf (equatorial-directed) geostrophic current flow caused by downwelling from winds driving onshore surface Ekman transport; these winds tend to accelerate the southward flow of buoyant outflows and to compress plume waters against the coast;
- Northward (poleward-directed) geostrophic current flow caused by upwelling from favorable winds driving offshore surface Ekman transport; these winds counter buoyancy-driven southward flow and tend to spread buoyant waters offshore; strong upwelling winds can reverse the coastal current and transport buoyant waters northward.

Often the driving forces produce different currents flowing in different directions within the water column. The Wallops Island, Virginia ADCP data (Figure 3-3) provide an example of data showing three different layers within the water column with different flow directions.

Flows observed in shallow marine environments are frequently combinations of currents and waves. Currents, with timescale variations of hours or days, are principally tidal, wind-driven, or related to larger-scale patterns of ocean circulation. Wave-generated oscillatory flows, with periods on the order of seconds to tens of seconds, are produced by surface gravity waves, though lower-frequency internal waves also can be present.

Sediments can be eroded and/or transported by currents (whether tidal currents, density-driven circulation currents, wind-driven circulation), oscillatory wave motion, and/or a combination of both flow types. Anticipating and understanding whether waves or currents are the dominant mechanism is important as is how combinations of the two mechanisms may create bottom currents. Several references (e.g. Soulsby, 1998, Sumer and Fredsøe, 2002, Appendix C of this report) provide relationships that are used to derive bottom current velocities and bed shear stresses due to waves, currents, and mixed flow conditions.

The combined effect of waves and currents does not always yield higher bottom stresses than are created by either waves or currents alone. When the flow directions due to waves and currents are not parallel or at slightly oblique angles, then the combined flow effect can lead to bottom current velocities that are lower than those derived from one component alone. This is illustrated in the hypothetical Atlantic OCS "demonstration evaluations" presented in Appendices A and B.

When evaluating bottom shear stress conditions, it is important to consider the mean, maximum, and extreme-event flow conditions. The mean, mean + 1 standard deviation, and mean + 2 standard deviations flow conditions are useful in defining the conditions of normal dynamic equilibrium as well as long-term sediment transport and scour effects. The maximum or extreme events will define event-driven conditions. Both dynamic equilibrium and event-driven conditions need to be evaluated to understand the potential for scour and its significance for offshore wind development. For example, under steady current conditions, scour around pile-founded structures can reach equilibrium within 1 hour. However, on the wave dominated Mid-Atlantic OCS, storms that occur 1 to 3 times a year are believed to be the dominant mechanism for sediment transport on the continental shelf (Swift, 2010). Thus both normal and extreme conditions must be evaluated.

Factors other than the type of forcing mechanism also influence flow conditions. These factors include water depth, fluid density, salinity, and temperature. Figure 3-4 illustrates how variations in several of these properties may affect critical bed shear stresses. Although variations in the fluid properties are important in understanding the flow behavior within the water column, their consequence is much less than other factors related to seabed conditions and sediment properties. Thus, those fluid-property factors are considered to be parameters of secondary importance relative to sediment mobility and potential seabed scour at an OWF.

During the design phase of a project it is customary to develop design criteria for the wind, wave, and current conditions in the project area. The evaluations include statistical evaluations to define the probability of occurrence (often expressed as probability of exceedance) of wave height (both significant and maximum wave height defined over an interval of time [such as by hour]), wave period, and the current profile in the water column. Those evaluations define variations throughout the year (or by season). In addition, design criteria for extreme events, defined by different return periods, are also required. For an OWF development, those evaluations need to consider spatial differences relative to the probability of occurrence of the different design parameters.

Because there has not been historical energy development or structures installed in the Atlantic OCS, most of the initial evaluations for OWF on the Atlantic OCS will, by necessity, rely on hind-cast evaluations from regional, scientific measurement systems and/or site-specific data of limited duration. This is in contrast to the GoM OCS where decades of site-specific measurements are available from thousands of structures throughout much of the GoM. As noted previously, this is one of the reasons the BOEMRE defines the Atlantic OCS as a *Frontier Area*. It also is a reason that the met-ocean evaluations for the design of OW structures will need to carefully recognize and consider the uncertainty associated with potential inter-annual variations of conditions when using site-specific data of only limited duration.

WATER DEPTH

Water depth is a profoundly important variable that defines the variations in the forcing mechanisms, and how bottom current velocities vary within an OWF-size project area. In addition to regional variations of water depth across the continental shelf, other local variations are of significant importance. In general, velocities will decrease as flow passes from a shallower water column into deeper water, or increase as the water column decreases. Figure 3-5 illustrates how flow lines will constrict over a seabed rise, which reduces the height of the water column.

Those local variations occur due to evolution of the shelf as sea level repeatedly transgressed and regressed across the site in response to the advance and retreat of glaciers. That geologic history has produced numerous topographic ridges and swales in many areas of the Atlantic OCS (Figure 3-6). In some areas, the local variation of water depth within a 3-nautical-mile (Nm) by 3-Nm OCS block can be 25 to 30 feet. In comparison, the regional gradient of the seafloor slope can be on the order of 0.05 to 0.1 percent, which means that the local water depth variations can be more than the water depth variation due to the regional slope across 4 to 7 Nm of the shelf.

In addition, the water depth can vary temporally in response to natural or human-induced processes that can locally raise and/or lower the seafloor. The evolution and shifting of a sand ridge or tidal bank, and the migration of sand waves are examples of natural change that can raise or lower the seafloor within an OWF area or at an OWF structure. Depressions along a cable-lay trench and a scour pit around a turbine foundation are examples of human-induced changes in water depth.

SEABED CONDITIONS AND MORPHOLOGY

The interaction of the flow and currents at the bottom of the water column, and the stresses transferred to the seafloor sediments depends on the characteristics of the seabed. The seabed characteristics that influence the bottom shear stress created by the flow across the seafloor are the:

- Seafloor relief that accelerates or decelerates the flow and current velocity, and can cause eddies or channelize flow; and
- Bottom roughness that creates friction and drag.

Variations in the seafloor relief (local water depth variations) and seabed roughness are partially a function of the seabed geomorphology. Variations in the seafloor morphology affect the shear stress transferred to the seafloor sediments and their propensity to transport. It is the interrelationship between the ocean conditions and the seabed that creates the seabed geomorphology, and this affects sediment mobility, but the mobility of the seafloor sediments also affects the seabed geomorphology. This illustrates the dynamic character of the ocean-seafloor interface.

Exceedance diagrams are used to show the bottom shear stress induced by waves or currents. Those diagrams plot total bottom shear stress exceedance as a percentage of time. According to Whitehouse (1998), the generated bottom shear stress needs to exceed the critical erosion threshold (required to induce sediment movement of the seafloor sediment grain size) at least 10 percent of the time (i.e., 10-percent exceedance) to cause long-term sediment transport. For example, if the mean annual current meets the 10-percent exceedance criteria for a given particle size, it is probable that currents will be capable of mobilizing those sediments.

When stresses induced by ocean-bottom currents are capable of transporting sediments by entrainment, bedload, or suspension, the seabed will respond morphodynamically and develop bedforms in response to flow conditions. These changes may occur quickly (within one tidal cycle or during a single storm) or over longer periods (years, decades, hundreds, or thousands of years). Seafloor morphology and bedforms demonstrate the interrelationship between current velocity, particle size, and bedform. Figures 3-7a and 3-7b present two relationship diagrams.

It is not uncommon to see different types and sizes of bedform across an OWF site or within smaller areas of an OWF. The Scroby Sands OWF (refer to Section 5) provides a dramatic example of a dynamic site with various bedforms that have been formed by natural processes and been induced or modified by the presence of OWF structures. Figures 5-1a through 5-1d present bathymetry data that reveal ripples and dunes of various scales superimposed on a sand bank and scour wakes caused by current flow around turbines.

In many areas, the Atlantic OCS seafloor also includes different sizes and types of geomorphic features. Frequently, smaller-scale features are super-imposed on larger-scale features. This implies that the smaller features can be modified by lesser events, smaller currents and lower bed shear stresses, while larger events producing stronger currents and higher bed stresses are required to modify the larger features.

Figure 3-8 provides an example from the Mid-Atlantic where 0.5-foot-high sand ripples, about 3 feet apart and larger 4-foot-meter-high sand waves spaced at 800 feet apart overly the topographic variation produced by a 4-Nm-long by 1-Nm-wide, 18-foor-high ridge. In some, but not all of the area, the sand ripples overlie the larger sand waves. Figure 3-9 shows side scan sonar results that document the obliteration of the small sand ripples during a relatively small storm. This suggests that these small sand ripples are mobile during normal conditions of dynamic equilibrium, are obliterated by currents produced by rather modest storms, and then reform as the dynamic equilibrium is re-established following the minor storms.

Mapping of the seafloor geomorphology and bedforms provides an opportunity to differentiate seabed conditions (and often anticipate differences in seafloor sediments) across a project area. Figure 3-7a and 3-7b show examples of different bedforms and their significance relative to sediment transport evaluations.

The concepts of micro-zoning an OWF based on seafloor morphology, sediment type, and water depth to differentiate areas of commonality are described and applied to two hypothetical OWF areas in Appendices A and B.

SEDIMENT CHARACTERISTICS

Granular Sediments

Sediment type and condition are the third set of variables that define sediment mobility and scour potential. The resistance of sediment to erosion and transport depends on the type, grain size, and condition of the sediment. Those factors establish the threshold shear stress that must be exceeded for a particle of sediment to be eroded and transported. Those factors also define the flow velocity required to maintain a particle in suspension. For granular sediments, larger (and heavier) particles are more resistant to erosion (require a higher bed shear stress to erode) and require a larger velocity to remain in suspension (since they drop out of suspension more quickly as the flow velocity decreases). Those fundamental principles together with how the flow velocity decreases or increases in response to increases or decreases in water depth (Figure 3-5) explain variations in grain sizes associated with different morphologic features within an area. Figure 3-8b shows an example of such variation in grain size for a site in the Mid-Atlantic OCS.

Particle size, fines content (collectively, the percentage of silt and clay-sized particles), and sediment density are important when determining the erosion threshold for sediments. Particle or grain size distribution of sediments is usually presented as a cumulative curve showing the percentage by mass of grains smaller than a diameter (d). Sediment is often characterized by its median sieve diameter, d_{50} (the diameter for which 50 percent of the grains by mass is finer) and by the uniformity or gradation of the sediment. An increase in the d_{50} value indicates an increase in the mean grain size of the sediment and the weight of the average size of the sediment (for a spherical grain, the weight increases at a rate equal to

8 times the grain size diameter). Since it requires a greater force to dislodge a heavier grain than a lighter grain of sediment, the threshold shear stress (required to mobilize a sediment) increases as the grain size increases (see Figure 3-4). Similarly, higher current velocities are required to transport heaver grains than lighter grains. Appendix C provides a description of how the d_{50} value is used to estimate sediment transport thresholds and scour.

The fines content of a granular sediment is an important parameter to consider when evaluating scour susceptibility. Increasing amounts of fine-grained sediment (silt and clay), increase the threshold shear stress by increasing the inter-particle forces. The equations for calculating bottom shear stresses in non-cohesive (sandy) sediments are based on clean sands (very low fines content). This is important to note because for mixed sediments, it has been shown (Mitchener and Torfs, 1996; Panagiotopoulos et al., 1997), that cohesive sediments generally increase the erosion threshold of sandy deposits. This can occur with as little as 3-percent cohesive sediments mixed in the sand. Furthermore, when sandy sediments have a fines content of only 10 percent, the individual sand particles will be subjected to cohesive forces of the fines. Appendix C provides relationships that can be used to estimate the threshold shear stress for non-cohesive sediments.

Cohesive Sediments

Scour potential in cohesive sediments (composed of clay and silt) depends largely on the state of consolidation of the fine-grained sediments. In general, the scour potential in cohesive sediments decreases with: 1) an increase in sediment plasticity, 2) a decrease in sediment water content, 3) an increase in sediment strength, and 4) an increase in the degree of sediment consolidation. Scour rates in cohesive sediments are generally significantly lower than for non-cohesive sediments. For descriptions of scour procedures in cohesive sediments, refer to Mitchener and Whitehouse (1996) or Whitehouse et al. (2000).

Bed Roughness

Another factor related in part to particle size (d_{50}) is the bed length roughness factor (z_o). The bed roughness factor is used to determine the drag coefficient (C_D) and the grain related bed shear stress. Refer to Appendix C for equations used to define this relationship. Figure 3-10 presents a general relationship between bottom roughness and bed shear stress. As the roughness of the bottom increases, so does the resulting bed shear stress (see table on Figure 3-10). This is logical since a flat, smooth bed will produce less friction than a rough bed with ripples/sand waves. The same effect is true when comparing clay beds (lower roughness) to sand beds (greater roughness).

SUMMARY COMMENTS

The preceding discussion is meant to establish the many factors, and interrelationship among many of the factors, that cause and define sediment erosion, transport, and redeposition processes on the seafloor of the OCS. Variation of the factors within an area sized to accommodate an OWF is to be expected. The dynamic equilibrium among the ocean currents, seabed conditions, and seafloor sediments is complex. Small changes in any of the conditions can affect the equilibrium and re-establishment of the equilibrium after rare event-driven conditions. OWF structures and OWF installation activities can both locally increase the bed stresses due to bottom current and reduce the resistance of the seafloor sediments to scour, as described in the following section of this report.

4.0 OFFSHORE WIND DEVELOPMENT EFFECTS ON SEDIMENT TRANSPORT

HOW OFFSHORE WIND STRUCTURES AND THEIR INSTALLATION CAN AFFECT SEDIMENT MOBILITY

The dynamic equilibrium among the ocean currents, seabed conditions, and seafloor sediments is complex. Small changes in any of the conditions can affect the equilibrium and the time required to re-establish equilibrium after comparatively rare events. OWF structures and OWF installation activities can: 1) locally increase the bed stresses due to bottom currents, 2) reduce the resistance of the seafloor sediments to scour, and 3) unbalance the dynamic equilibrium at the ocean-seafloor interface.

This can increase the potential for sediment mobility and cause scour around structures and along cable routes. The changes in the ocean-seafloor dynamics are created by: 1) introducing obstructions (wind turbine substructures) that create localized areas of increased bottom currents, and 2) disturbing the sediment (and increasing its scour susceptibility) during structure and cable installation. Both the obstructions produced by the structures and the disturbance created during the wind farm construction alter the dynamic equilibrium at the ocean-seafloor interface, and increase the potential for sediment erosion, transport, and redeposition.

Thus, the potential for scour around the structures or along the cable routes is anticipated to be an important technical consideration for offshore wind development on the Atlantic OCS. The variation of scour will depend on the following factors and the interrelationship among these factors: 1) seabed current velocities, 2) seabed conditions (e.g. sand waves), 3) seabed sediment type and conditions, and 4) degree of seabed disturbance caused by: a) inner-array cable installation, b) turbine substructure and foundation, and/or c) construction vessel anchors and barge legs.

SIGNIFICANCE OF SCOUR FOR OWF DEVELOPMENT

Sediment transport processes in the marine environment have important implications for installing and maintaining OWF substructures. Scour is directly related to the sediment transport processes in the OWF area, which as noted, potentially will be affected by the installation of the OWF structures and cables. If not recognized, avoided, or mitigated, these conditions can become problematic, or even detrimental, to the stability of OWF turbines. Significant scour around the turbines also can lead to spanning of inner-array or export cables.

The entrance/exit of the cables to and from the J-tube at the base of the turbine support structure is an area of particular importance. If the seabed (or protection) beneath the cables is eroded, the cables will span. Hydrodynamic forces can then cause vibrations in the spanning cables. This strumming of the cables can cause chafing at the end of the J-tube. The chafing can then damage the cable's outer-protective armoring. In the extreme, this can cause a short in the cable and loss of the energy transmission from a portion of the OWF, or from the entirety of the OWF if the short occurs in the export cable.

Understanding these processes is required to anticipate and predict the possibility, potential extent, and depth of scour. The recognition of scour potential needs to be considered in the design of the turbine structure foundations, cable entrances and exits at the structure, and cable burial. Therefore, investigating the sediment transport dynamics at an OWF site is an important component of both: 1) design-phase site investigations and evaluation, and 2) post-construction monitoring programs.

OBSTRUCTIONS CREATED BY WIND TURBINE STRUCTURES

Conceptual Framework

Scour occurs when the sediment is eroded from the seafloor in response to the forcing by waves and currents as modified by the presence of a structure. The presence of a structure that modifies fluid flow is what differentiates scour from erosion. However, the changes in the seafloor over time (known as morphodynamics) is important when considering scour at a structure, since these changes are ongoing even without the human-induced effect of the structure.

The presence of a substructure or pile modifies the ambient flow around the obstruction, thus inducing scour. The characteristics of the disturbance to the ambient flow depend on the shape and size of the structure and its orientation with respect to the flow direction. For example, larger structures block more of the flow than slender structures and produce a different turbulent flow. It is this turbulence that causes scour around a structure.

Furthermore, scour can be local or general. Local scour occurs over the immediate area around a single pile, whereas general scour is the lowering of the seafloor over a wide area due to hydrodynamic process, as discussed previously. Both have the potential to develop quickly.

Permanent and Temporary Obstructions

Obstructions produced by an offshore wind farm include permanent obstructions produced by the wind-turbine substructures and the electrical substation structure. In addition, the presence of jack-up rigs during installation and maintenance/servicing activities introduces temporary obstructions that can further complicate the dynamics at the ocean-seabed interface. In addition, the proximity of an installation (or maintenance) jack-up can create a condition where the combined effect of the permanent structure and temporary structure amplify the effect of either structure by itself.

Scour around Structures

The obstruction produced by a circular pile causes the flow pattern to undergo considerable changes. A horseshoe vortex develops on the upstream side of the pile. Typically, flow approaching a monopile has low pressure near the seafloor, which increases in magnitude with distance above the seafloor. This pressure gradient causes rotation of the incoming flow, creating a vortex. The acceleration of flow together with the creation of the vortex causes removal of sediment from around the structure. As the flow separates around the monopile, a spiral vortex is created, which trails into a vortex flow pattern on the downstream side of the pile. Depending on the flow velocities, the vortex flow pattern on the downstream of the monopole may create a zone of deposition (Figure 4-1). The location of (or offset between the monopole and) the zone of deposition will depend on the velocity of the flow. The vortex flow on the downstream side of the pile can produce scour wakes.

Figures 5-1a and 5-1b show significant scour wakes that developed at Scroby Sands OWF. The scour wakes extend up to 900 feet beyond the pile and traverse several inner-array cables (Figure 5-1b), and begin to encroach upon some of the adjacent turbines.

In current-dominated environments, research has shown that the vortex is highly dependent on the ratio of the bed boundary-layer thickness normalized by the pile diameter (δ/D) and Reynolds number (Reδ) of the bed boundary. For a small δ/D, the bed boundary layer might not separate and, thus, no vortex will be created. The pressure gradient must be strong enough to separate the bed boundary layer and create a horseshoe vortex. Similar to the effect of δ/D, the boundary layer separation may not occur for small Reδ values. According to Sumer and Fredsøe (2002), the boundary layer will exhibit more resistance to separation in the case of a low Reδ; and therefore, a small vortex will be created. Other factors that influence the horseshoe vortex are the pile cross-sectional area and orientation, which are directly related to the magnitude of the pressure gradient.

In wave-dominated environments, the Keulegan-Carpenter (KC) number is another factor that must be accounted for in the scour mechanism. A function of orbital velocity, wave period, and pile diameter, KC controls the creation of the horseshoe vortex. For small KC values (KC<6.0), the flow orbital motion is small relative to the pile diameter. Therefore, bed boundary separation may not occur and a vortex may not form.

Sumer and Fredsøe (2002), and Whitehouse (1998) provide additional information on scour around foundations.

Consequence of Scour on Foundation Performance and Cables

If left unattended, scour around a wind turbine substructure can reduce the foundation capacity, soften the load-deformation characteristics of the foundation and substructure, and change the fundamental period of vibration of the foundation and substructure. Because a wind turbine is a slender structure subjected to dynamic loads, the performance of the blades - nacelle - tower - substructure - foundation system is sensitive to the dynamics of the system and the periods of vibration of the different components of the system. Changes in the vibration period of one component can change the overall dynamic response of the entire system.

One of the most problematic conditions produced by scour around a structure has been its effect where the cables enter and exit the base of a wind-turbine substructure at the J-tube. When scour undermines the cables at the base of the J-tube, this can cause the cables to strum, which in turn can cause abrasion of the cable on the J-tube. If not mitigated, this condition can lead to a fault in the cable and the loss of energy transmission from the OWF or a portion of the OWF.

The scour related to these types of structures has been observed to cause spanning under a cable and increase the scour rate of cable trench backfill materials. Mitigating scour and providing protection to cables around existing structures is sometimes challenging when considering: 1) the logistics of setting spuds and working around cables, 2) the potential for damaging the foundation's protective coating (when rock strikes or abrades against the foundation), and 3) the inefficiency and need for repetitive repairs if rock settles into the seabed.

CABLE INSTALLATION CONSIDERATIONS

Effects on Seabed and Sediment

Jet-trenchers utilize high-pressured water jets to fluidize soil as the machine traverses along the cable route, described in Section 2. Jet-trenching (or plowing) may influence scour susceptibility by: 1) disturbing any bio-film on the seafloor, 2) loosening the sediment, 3) reducing the fines content of the sediment, 4) creating micro-topography along the cable route, and 5) modifying the seafloor roughness.

By disturbing any bio-film that has developed at the ocean-seabed interface, the resistance of the sediments within the disturbed zone will be less than the in situ sediments prior to the cable installation. Possibly more important, the seabed roughness will be increased in the disturbed trench zone. Preferential erosion may occur (or occur at lower current velocities) within the rougher trenched seabed than in the smoother seabed area outside the trench zone. Figure 3-10 illustrates the relationship between bottom roughness and bed shear stress. Figure 4-2 (Inset B) provides and illustration of how a difference in roughness can lead to preferential erosion or winnowing of smaller particles. Although the illustrations in Figure 4-2 have been used to discuss potential erosion processes in a flow parallel to a trench, Inset B illustration also applies to the processes discussed in this paragraph.

As jetting fluidizes the sediments, it causes sediments to be suspended. Some of the fines (silt- and clay-sized particles) will be removed from the sediment that falls back into the trench as currents will disproportionately transport the suspended fines outside of the trench footprint to be deposited elsewhere. The amount of fines swept from the sediment that falls back into the trench (or adjacent to the trench) will depend on the bottom current velocity. Dredging industry experience suggests that 5 to 10 percent of the fines will be lost. The reduction in fines content will reduce the cohesion and resistance to erosion.

In addition, the disturbance of the sediment during jet-trenching will produce a backfill in the trench with a lower density than was present prior to cable installation. This also will reduce the sediment's resistance to erosion.

The cutting of the trench can produce small levee deposits along the sides of the trench, a depression along the trench alignment, and/or a mound along the trench alignment. All of these factors will increase the micro-topography along the cable alignment. The implications will depend in part on the orientation of the cable alignment relative to the existing bottom topography. For example the micro-topography from jet-trenching will have different effects depending on whether the cable route is: 1) parallel, 2) perpendicular, or 3) obtuse to the trend of the existing slope. Each of those orientations will have different effects on the bottom current-seabed dynamics. Regardless, the micro-topography created by cable installation will modify the seabed and increase the seabed roughness.

The direction of hydrodynamic flow (bottom currents) relative to the orientation of the cable trench determines how the micro-topography created by cable burial will affect sediment transport and the potential for scour. Figures 4-2 and 4-3 illustrate the difference between when the flow direction is parallel to the cable trench (Figure 4-2) and when the flow direction is perpendicular to the cable trench (Figure 4-3). Each of these orientations (as well as different flow orientation obtuse to the cable alignment) creates somewhat different modifications to the flow regime at the ocean-seabed interface.

The roughness of the seabed generally will be increased by: 1) destruction of any bio-film on seabed, 2) the loss of fines, and 3) the micro-topography created by the installation process. Since friction at the water-seabed interface increases with increases in the seabed roughness, cable installation will generally increase the friction on the interface, and thus increase the seabed shear stress caused by a specific bottom-current velocity. This implies an increased potential for inducing sediment erosion. Thus, cable installation increases seabed mobility in multiple ways.

Temporal Considerations

It is logical to expect that time will reduce, if not eliminate, many of the seabed modifications created by the cable installation process. Various European experiences (refer to Section 5) provide some perspective relative to the length of time that seabed modifications caused by cable installation will last. That experience suggests that the length of time a trench scar will remain present depends primarily on sedimentation and sediment transport rates. In areas of high sediment transport and sedimentation, cable trenches can be infilled and no scar visible within a few weeks of the trenching. At some wind farm sites, trench scars can still be locally observed more than 1 year after cable installation (e.g. Barrow [BOWind, 2008].

PASSING SAND WAVES

Sediment transport, such as the passing of sand waves, can pose a significant natural threat to OWF structures and cables. Migration of large bedforms (e.g. sand waves or dunes) or shifting of sand ridges, sand banks, and shoals in response to changes in sediment supply and flow regime can create conditions that alter local erosion or accretion processes. Moreover, migrating sand waves can expose cables that were previously buried within the body of the sand wave. Migration of large bedforms can: 1) significantly accelerate scour rates and magnitudes, 2) conversely reduce scour rates, or 3) reverse scour by infilling scour holes.

Sand waves can be very dynamic. Various sizes of sand wave are present in different areas of the Mid-Atlantic OCS where OWFs may be developed. For example, sand waves up to 14 feet tall have been identified at the proposed Cape Wind OWF site (MMS, 2009). Sand waves have been documented to migrate at rates of about 150 feet per year in dynamic environments. Periodic multibeam echosounder (MBES) hydrographic surveys can be used to estimate their rates and direction of migration. Monitoring these types of bedforms within an OWF is prudent for protection of cables and structures.

Migrating sand waves have the potential to expose cables buried during installation. Figure 4-4 presents a schematic of how this can occur. The lower image in Figure 4-4 shows a field of sand waves approaching several turbines and the inner array cable. If a cable is installed to a target burial depth that is less than the height of the sand waves that move across the cable route, the cable likely will be exposed as the sand wave migrates and the trough of the sand wave reaches the former position of the crest. The potential hazard from fishing or anchoring activities will be increased as the cable burial depth is reduced. In the extreme, if the cable is exposed on the seabed it may be subjected to excessive abrasion from vibration or strumming by currents and waves. Abrasion has been the source of about 5 percent of cable faults since 1955.

Based on our project experience, we describe a situation where a migrating sand wave first mitigated scour for a wind turbine and inner-array cable and then later created a condition of extreme scour. In the upper image on Figure 4-5 the sand wave is mitigating the scour at the turbine by: 1) shielding the turbine from waves by dissipating the wave energy as the wave base encounters the sand wave, 2) shields the turbine from the stronger ebb tidal current, and 3) provides a source of sediment as particles are transported in that direction. Extreme scour in this scenario is initiated when the sand wave reaches the monopile (not shown on Figure 4-5) and the sand wave reduces the height of the water column by 50 percent. This causes the current flow lines to constrict and current velocity to increase over the crest of the sand wave (refer to Figure 3-5). In addition, turbulent flow is induced, which increases the wake vortex flow around the monopile beyond what would occur in deeper water before the sand wave passed. After the sand wave passes by the monopile, extreme scour continues to develop because: 1) the sand wave is no longer present to buffer (attenuate) the waves, 2) the monopile is now exposed to the full force of the dominant tidal current in the ebb direction, 3) the dominant sediment supply (sand wave) is no longer available, and 4) the general elevation of the seafloor has been lowered due to general scour. The extreme scour in this scenario could lead to extensive cable spanning around the monopile and potentially adversely affect the performance the monopile.

SCOUR PROTECTION EFFECTS

The presence of scour protection may induce secondary scour. For example, rock placed for scour protection around a turbine can cause turbulent flow at the edge of the rock that is capable of eroding the sediments. As the scour hole begins to develop, rock can fall laterally into the scour hole. This may lead to a falling apron of rock. The scour hole can grow large enough that the cables entering/exiting the turbine may eventually span the scour hole. The spanned cable is susceptible to vibration and strumming in the current, which may lead to accelerated abrasion at the contact points.

Also, scour protection placed as protection of a cable can be the cause secondary scour that may evolve into a hazard. If rock is placed on the cable, the secondary scour can cause the rock to fall into scour holes as described in the preceding paragraph. If concrete mats are used for protection, they may also be susceptible to secondary scour problems. Figure 5-1e shows a section of an export cable that appears to have scour protection placed on top. Significant scour holes have developed on the down-current side of the cable. If the holes become large and deep enough to undermine the cable or scour protection, then the added weight of the scour protection may put the cable under tension and increase abrasion rates if vibration or strumming is occurring.

Spud depressions from installation or service vessels can create difficulty for installing cables. This was reported to have occurred at Kentish Flats (BOWind, 2008) (see Figure 5-2 for example of spud depressions). If scour develops in one of the depression adjacent to the cable trench, it is possible that it could lead to exposure of the cable or reduced burial protection. Note how scour developed laterally at Kentish Flats in the southern spud depression at turbine F3 in Figure 5-2.

5.0 OBSERVATIONS AND LESSONS LEARNED FROM EUROPE

HISTORY OF OWF DEVELOPMENT IN EUROPE

The first demonstration OWFs in Europe were installed in the 1990s. These initial demonstration OWFs were installed offshore Denmark, the Netherlands, and Sweden within a few kilometers of shore, in water depths of a few meters, and included a limited number of relatively small wind turbines (less than 1 megawatt [MW] capacity per wind turbine). The total installed capacity at the end of the 1990s was about 40 MW.

In the early 2000s, the industry moved to larger wind turbines (several MW per wind turbine) and began to include larger OWF with more wind turbines farther from shore and in deeper waters. By about 2006, an additional 720 MW of capacity was in place offshore Denmark, the Netherlands, Sweden, the U.K., and Ireland (plus two one-wind-turbine demonstration projects offshore Germany). Development during this period included four projects of 30 MW and two projects between 70 and 80 MW capacity. With the exception of Horns Rev 1, off Denmark, all of these projects were within 10 km (~5 Nm) of the coast. During the 7 years from 2000 through 2006, the maximum water depth increased from about 10 meters to 20 meters (~30 to 70 feet).

Starting in about 2007 and continuing through 2010, the capacity of installed offshore wind energy delivered to the grid has grown by an average of about 50 percent per year. Projects have grown and OWFs have been installed offshore additional countries. These projects included at least five projects 20 to 30 km (~11 to 16 Nm) offshore and six projects in more than 20 meters (65-ft) water depth.

By the end of 2009, the total installed generating capacity of offshore wind in Europe was nearly 2,000 MW, including 12 projects with 90 MW or greater capacity. An additional 1,000 MW of capacity was anticipated to be connected to the grid in 2010.

OPPORTUNTITIES FOR LESSONS LEARNED

Collectively, the European experience provides opportunities to learn from the experiences - both positive and negative - on these projects. For some projects there is considerable information in publicly-available documents, particularly for the initial Round 1 projects in the U.K. Availability of public information for projects in other countries is less accessible. In addition to the publicly-available information, we have drawn from Fugro's experiences and contributions to many of the European projects during our review of European experience.

From this review we have selected projects with citable experience that illustrates the significance of sediment mobility and scour relative to offshore wind structures and cables. These projects collectively illustrate many of what we consider to be the salient observations from which to draw lessons learned. Figures showing examples from Europe are indexed by project, as follows:

- Figures 5-1a, -1b, through -1e provide examples from the Scroby Sands OWF.
- Figure 5-2 provides examples from the Kentish Flats OWF, and
- Figure 5-3 provides example seabed material type influence on scour at the Barrow OWF.

SCOUR AND EARLY OWF DEVELOPMENTS

As previously noted, many of the early European OWF developments are located close to shore and in shallow water (shallower than 10 meters [~30 feet]). Nearshore, shallow-water locations were initially considered favorable to reduce cabling and turbine costs by: 1) reducing the length of export cable, thus reducing voltage reduction due to frictional loss during transmission, and 2) increasing the accessibility of the sites for the existing fleet of construction and support vessels. These sites, however, are in dynamic oceanographic environments and prone to sediment transport and scour related hazards. Although scour may have been acknowledged to a certain degree during the planning and design of these early wind farms, the magnitude of impact and effort required to monitor and mitigate scour during the operation of the wind farm sometimes was not fully appreciated.

As a result of the early scour experience, the potential for scour is being carefully vetted during the site-selection phase for most subsequent European OWF projects, especially for shallow-water sites like sand banks. In some cases, deeper water sites are being selected over shallow-water sites for future development due to a lower potential for scour.

Due to the large number of scour problems experienced by early developments, a number of research studies were undertaken to evaluate scour. Most of those studies (e.g. Whitehouse et al., 2008; DEFRA, 2008; den Boon et al., 2004) focused on scouring related to turbine foundations. However, many of the case studies and lessons learned from early projects recommend that scour hazards related to OWF cabling also should be the focus of future research.

SCOUR AND SEDIMENT TRANSPORT RELATED HAZARDS OBSERVED IN EUROPE

Based on the review of available information and our experience on OWF projects, the following sediment transport and scour related problems that affect OWF cables have been experienced.

Scour around Turbine Foundations

Scour at the turbine foundations is one of the most common and well-documented OWF scour-related issue. The lateral extent and depth of the scour pit depends primarily on the diameter of the pile, bottom current velocity, and seabed material. Scour pits observed around monopiles have been as deep as 10 meters (~30 feet) and have extended more than 30 meters (~100 feet) outward from the pile face. Cases of extreme scour can exceed these numbers.

Secondary scour has occurred at the edge of the scour protection. For example, the presence of rock armor can induce turbulent flow at the edge of the rock thus inducing scour. A scour pit may develop and the rock may fall into the adjacent pit. This process may continue, and develop a falling apron of rock. If left unabated, the scour pit may become so large that the cables may span over the pit.

Cables that span the scour pit adjacent to the turbine or secondary scour pits at the edge of scour protection may experience excessive vibration or strumming from currents. The vibration and strumming may lead to accelerated abrasion where the cable is in contact with the seafloor, scour protection, or within the J-tube.

Mitigating scour around the turbine once it has developed has several technical and logistical challenges. Logistically, it can be difficult to position the vessel close enough to conduct the work without accidentally damaging the existing cables. A turbine may have one or two inner-array cables or possibly three cables (two inner-array and an export cable) connected to it. When placing rock, care must be taken to ensure not to damage the cables during placement and also provide protection from point contacts between the newly placed rock and cable. This sometimes requires that a protection shield (liner) be placed around the cable. If concrete blankets or frond mats are being used, this usually requires a diver to be involved with the installation.

If scour continues to develop and undermine the cable, consideration of the weight of the concrete blanket or frond mat draped on the cable may lead to an increased hazard by adding weight. The added weight increases frictional forces on the cable at the contact with the seabed or J-tube bell and put the cable under tension.

Another example of how the combination of turbines and trenching effects can modify scour susceptibility is illustrated in the following example.

Figure 5-2 presents an example of where the turbines are inferred to be the primary cause of scour and are increasing scour of the cable trench backfill materials in the vicinity of the turbines. Figure 5-2 shows bathymetry survey results from the 2005 and 2007 scour monitoring surveys. Spud can depressions from the primary wind turbine installation vessel are readily observable (the series of 6 circular depressions southwest of the turbines that are about 20 to 30 meters [~65 to 100 feet] in diameter). The 2007 survey documents alteration of the seabed topography by new spud depressions from a smaller jack-up rig.

Apparent scouring along the inner-array cable is not evident in 2005, but is evident in 2007. In addition to the scour development along the cable alignment, the scour appears be deeper by about 0.5 m (~2 ft) and becoming wider around the turbines in the 2007 survey. Conversely, the spud can depressions from the installation vessel appear to be infilling (~0.5 m [~ 1.5 ft] between 2005 and 2007).

We postulate that:

- Spud depressions from the main installation vessel are expanding but infilling because the sediments from the side walls of the pit are being mobilized and moving downslope with assistance from gravitational forces and infilling the pit.
- The presence of the wind turbine foundation is inducing localized scour around and causing the scour to grow deeper and wider (more than twice the diameter at F3 in 2007 than 2005). Otherwise we would expect the depressions to behave (e.g. infilling) like the spud depressions. This suggests that the vortex flows created by the flow around the piled foundation are acting to continue the scour process. The vortex flows are likely removing the trenched backfill. Since the trench backfill is in a looser state than the surrounding undisturbed sediment, this is causing preferential erosion of the trench backfill materials.
- Further evidence that the vortex flows (e.g. lee-wake vortex flows) created by currents flowing around the piles are inducing the scour is inferred from the dissipation to nil of the trench scour within 15 to 25 meters (~50 to 80 feet) from the turbine. If the trench scouring is not related to pile-induced vortex flow, we would expect to observe scour along the trench in between the turbines. The only trench scour observed between turbines F2 and F3 and turbines F3 and F4 is that shown on the Figure 5-2.

Sediment Transport by Natural Processes

Migrating sand waves and lowering of the seabed by natural processes is another process that has exposed cables on the seafloor. The crests of sand banks, ridges, or shoals may shift over the course of a few years, tens of years, or longer. Sand waves can be highly mobile. We have observed sand waves that migrate at rates of 50 to 60 meters (~160 to 200 feet) per year at OWF sites. Exposed cables may be prone to strumming by currents, which may lead to excessive abrasion of the outer-cable armor and reduce protection from fishing and anchoring hazards. Figure 5-1f shows the crest of the sand bank shifting within one year at Scroby Sands OWF. Such shifts can actually lead to infilling of scour pits as shown in Figure 5-1f. Conversely, shifting features such as a ridge or bank crest, or sand waves superimposed on larger features can influence local scour conditions. Figures 3-5 and 4-5 illustrate how shifting bedforms can alter local flow conditions.

Unexpected Seabed Conditions

Cable installation work that encountered unexpectedly hard seabed conditions sometimes did not achieve the target burial depths. As a result, the burial protection was reduced. In some cases, this required scour protection to be placed that was not initially planned. Figure 5-1d presents an example of a section of the export cable at Scroby Sands OWF where this occurred. Cable protection is inferred to have been added at a later date. Appropriate burial assessment can help mitigate the potential for this condition.

Secondary Scour from Cable Scour Protection

If cable scour protection is used, secondary scour may occur. Figure 5-2 presents a section of the export cable route that has scour protection placed because the cable did not achieve the target burial depth due to a hard seabed. Significant scour is developing on the down-current side of the protection. Monitoring of this area will be required and future remedial work may be required if the conditions continue to deteriorate. If rock armor is placed, the rock armor may sink into the seabed and require reapplication of rock. Secondary scour effects and hydrodynamic loading may induce settlement and loss of rock protection.

Spud Can Depressions

During installation or servicing work at an OWF, the vessels can leave depressions in the seabed. The depressions result from a combination of compression of the seabed materials under the weight of the vessel and scour that occurred while the vessel's spuds were in position. The spud can depressions can make it difficult for cable installations. Spud can depressions can infill quickly or remain for several years. Conversely, spud can depressions can continue to develop scour and if adjacent to a trench, the scour may breach and increase scour rates of the looser, trench backfill material. The middle images of Figure 5-2 illustrate an example where scour grew laterally and breached a natural depression, and began to preferentially develop forming an elliptical pattern.

Seabed Materials

Seabed materials can vary across an OWF site and therefore, so can scour potential. Figure 5-3 presents examples that show where no noticeable scour has developed at in glacial till, but scour has developed in silty sand sediments. As noted in this text, fines content in sand can reduce scour potential. However, the lower image on Figure 5-3 shows that scour can occur in silty sands with 15 to 50 percent fines.

Unknown Causes

Several cases were reported where cables became exposed on the seafloor along inner cable arrays or export cable routes. Scour monitoring surveys using swath bathymetry and side scan sonar methods were used to identify the exposed cable. The exposed cables were subsequently re-buried. The cause of the exposure is unknown because either it was not reported or data (e.g. multibeam and side scan sonar) were not available for review to infer the cause. The causes are likely related to natural processes that lowered the seabed or preferential erosion of the looser, trench backfill materials.

LOOKING FORWARD WITH INSIGHT FROM EUROPE

Several key points can be taken away from European experiences and the lessons learned based on the data reviewed. The following lessons learned and recommendations are echoed throughout the European project experiences.

- Understanding scour susceptibility is important for OWF and cable routes.
- Cable burial assessments are a critical component of design studies. However, areas of unexpectedly hard seabeds were a common problem that limited as-laid burial depths.
- Swath bathymetry (multibeam or interferometric [e.g. GeoSwath system]) is a requirement for: 1) understanding the morphology (e.g. identifying sand waves and assessing migration rates) and 2) monitoring scour.
- Side scan sonar is effective for identifying exposed cables on the seafloor
- Scour monitoring survey schedules typically follow this general schedule:
    - Preconstruction survey.
    - As-laid survey to determine burial depth and provide baseline post-trenching condition survey used to assess the change of conditions through a comparison of subsequent surveys.
    - Scour monitoring surveys occur two times a year for a minimum of three years after construction.
    - Scour monitoring surveys should be conducted after significant storms.
    - Scour monitoring surveys are comprised of swath bathymetry and side scan sonar.

ANTICIPATED DIFFERENCES BETWEEN EUROPEAN AND U.S. OWF DEVELOPMENTS

Although several similarities (e.g. foundation types, seabed materials, etc.) may exist between existing European and future U.S. OWFs, the differences between the two environments may be significant. Many of the future U.S. OWFs are planned to be in deeper water than the existing European OWFs. Bottom flow conditions and current velocities in the deeper U.S. OWF sites may be lower than the shallower European OWFs. Therefore, some of the processes discussed in this report may appear to be more significant factors in forming scour in the U.S. than in the European sites. Sediment transport rates are so high in some of the shallow European sites (e.g. Scroby Sands) that the movement of the large bedforms drowns out the expression of other processes (e.g. contribution of bed roughness [z_o], channelized flow in where current and trench depressions are parallel) that may be pronounced in the deeper U.S. OWF waters. However, some planned U.S. OWF wind developments (e.g. Cape Wind) and export cable routes will be in comparable water depths, although other differences may exist (e.g. hydrodynamic conditions).

6.0 SCOUR SUSCEPTIBILITY EVALUATIONS FOR TWO HYPOTHETICAL OWFS

BACKGROUND

One component and objective of TA&R 656 Study was to develop example scour susceptibility evaluations for hypothetical commercial OWFs at two sites on the Atlantic OCS - one in the Northern Atlantic OCS and one in the Mid-Atlantic OCS. This portion of the *Seabed Scour Considerations* study is meant to illustrate how the factors (discussed throughout this report) that affect scour can be expected to vary in an OWF-sized area. The sites have been chosen to include conditions that may be somewhat representative of the various conditions that will be present in many potential OWF areas on the Atlantic OCS.

The choice of one area in the Northern Atlantic and one area in the Mid-Atlantic recognized that: 1) the areas in the Northern Atlantic will likely be more affected by tidal currents than the areas farther to the south, and 2) the seabed conditions and seafloor sediments offshore New England may include effects of glaciation whereas those effects are not present farther to the south. The choice of the second example location in the Mid-Atlantic was based on the expectation that offshore wind development in the Mid-Atlantic would start in advance of offshore wind development in the Southern Atlantic.

Once the two areas were chosen, we have:

- Macro-zoned (or micro-zoned in areas where data allow more detailed differentiation) areas of comparable seafloor sediment type and condition, bathymetry, seafloor geomorphology (differentiated by morphologic features indicative of active sediment transport from those that are not indicative of active sediment transport), and localized seafloor slope.
- Calculated (using established methodologies) threshold velocities for sediment re-suspension and transport based on undisturbed, in situ conditions for the different

zones of comparable seafloor sediment type and condition, bathymetry, seafloor geomorphology and localized seafloor slope.

- Compared those estimates with published and unpublished bottom current data and prior research observations to establish an initial assessment of the scour susceptibility of the seafloor in an undisturbed condition.

CHOICE OF AREAS

Area Sizes

To illustrate the variations in scour susceptibility that might be present in an OWF-size area, we assumed that the OWF would be a commercial-scale wind farm with a 20- to 25-square-mile footprint. We also assumed several different potential export cable routes.

Availability of Priority Types of Data

During the initial period of the study, the Fugro team collected, and evaluated the availability of, various data required to define the characteristics of the seabed and seafloor sediments. That effort was focused toward identifying candidate areas where those data provided insight to the local variations of the conditions, rather than just the regional character of the conditions.

Relative to the physical conditions of the seafloor and seabed, we focused toward identifying areas where we could:

- Obtain high-quality data to map the seafloor bathymetry, by obtaining and reprocessing digital NOAA or USGS multibeam echosounder (MBES) data. Reprocessing the MBES data was to obtain more detailed portrayal of the localized seafloor features than can be provided by the commonly available regional bathymetry data.
- Calculate the local seafloor slope gradient using the reprocessed MBES data, and differentiate areas of comparable seafloor geomorphology, including small-scale seabed topography and morphology.
- Obtain side scan sonar data to map spatial extents of various sediment types and identify bedforms (e.g. ripples, dunes, etc.).
- Estimate seabed sediment grain size using published and unpublished seafloor sediment maps and sediment type data to establish a site-specific model of sediment type distribution.

In addition to evaluations of the available data for defining the physical condition of the seafloor and seabed, we also evaluated the availability of met-ocean data that could be used to define the forcing mechanisms, magnitudes, and directions of bottom currents, and their spatial and temporal variability. That evaluation was based on publicly available oceanographic data on the Atlantic OCS from offshore southern New England to Cape Hatteras, North Carolina. In addition, special attention was placed on the perspective provided by 14 months of unpublished ADCP data in about 100-ft water depth offshore Wallops Island, Virginia.

Other Considerations

In addition to choosing an area in the Northern Atlantic and an area in the Mid-Atlantic, we also endeavored to choose the two "demonstration" areas to illustrate differences between

- Water depths
- Seafloor morphology
- An area where an OWF development would be unconstrained by cultural features and an area where the rectangular OWF area was not feasible due to cultural conflicts (navigation channels)

CHOSEN AREAS AND EVALUATION RESULTS

The areas chosen to illustrate the interrelationships among the various physical and environmental oceanography considerations and the implications for scour susceptibility are shown on Figure 6-1 and include:

- Round Island Sound, approximately 5 to 15 Nm south-southwest of Sakonnet Point, Rhode Island, and
- Approximately 7 to 12 Nm, south-southeast of Ocean City, New Jersey

Results and maps created to evaluate the scour susceptibility for the two demonstration sites are provided in Appendix A - Rhode Island and Appendix B - New Jersey. Those appendices also include additional description of: 1) the data, 2) the process used to create GIS layers, and 3) micro-zoning the hypothetical demonstration OWF project areas.

OBSERVATIONS AND COMMENTS

The preliminary, regional scour susceptibility evaluations for the two hypothetical OWFs and associated export cable routes illustrate the expected variability of scour hazards in areas where the bathymetric, oceanographic, hydrodynamic flow, and seabed conditions (topography and materials) are complex. Those variations are due to many of the technical factors (e.g. characteristic sediment size, induced bottom shear stress, etc.) and their implications that have been discussed previously within this report.

At both of the hypothetical OWF sites, the regional analyses suggest that it may be possible to locate structures and route cables so as to reduce (but not eliminate) the potential severity of scour. This illustrates the importance of conducting appropriately-scoped and detailed scour evaluation analyses early in the project planning and development process. While the regional analyses in Appendices A and B provide useful information for planning, more detailed analyses based on site-specific measurements are advisable for: 1) optimizing structure siting and route selection, and 2) planning and designing scour monitoring and mitigation programs for the specific OWF structures and cable routes.

There is a high degree of inter-annual variability in the oceanographic data in both areas. It will be prudent to recognize such potential variations in oceanographic conditions when using short-term, site-specific oceanographic measurements at proposed OWF sites. Otherwise, it will be difficult to understand whether the limited duration, site-specific measurements are representative of a period of quiescence, extreme, or normal oceanographic conditions.

Key Observations Common to Both Sites

The evaluations at both sites suggest that the potential for scour will be variable across the wind farm footprint and export cable routes. Water depth and seafloor sediment types are key factors that influence scour potential at both demonstration sites. Since an OWF requires minimum turbine spacings along and between rows of wind turbines, it probably will be difficult to site all structures in areas of lesser scour severity. In contrast, there may be more latitude in cable route selection so as to reduce scour potential along the selected cable routes.

Rhode Island Demonstration Site

The Rhode Island site is a complex site with variable water depths and seafloor sediment types. Also, hydrodynamic conditions are complex due to large topographic variation in the region and presence of islands.

The available oceanographic data, in the region, suggest a high degree of variability of bottom current velocities. This is attributed to the complex seafloor topography, presence of islands and their interaction with tidal currents, and the variable wave climate. In addition, the seabed morphology and variable water depth indicate that the erosion threshold stresses also are highly variable across the area. Site-specific measurements will be critical for assessing hydrodynamic conditions at a site in this region. Selection of appropriate locations for site-specific measurements (e.g. current profiles) should be made within the context of the variability intrinsic to the area.

The site is characterized by deeper water channels with fine-grained seafloor sediments, shallower water areas with sandy sediments, and localized areas with sand waves. A shipping channel divides the OWF into northern and southern areas.

Sand waves and sandy seafloor sediments are present throughout much of the northern area and about one-third of the southern area. In those areas, the seabed morphology and sediment types are inferred to be prone to sand wave migration and a relatively high scour hazard around structures.

Although the southern area contains deeper water channels where sediment transport appears to be less than in the shallower water areas with sand waves, the disturbance of the seafloor associated with cable burial and structure installation will increase the potential for scour.

Two export cable routes were selected for evaluation to illustrate the differences in potential scour along different routes, as described below:

- The northern "red" cable route is shorter but crosses an area of sand waves that are a potential hazard. Migrating sand waves can potentially result in exposure of cables on the seafloor, which may cause: 1) abrasion due to strumming on the seafloor and 2) an increased susceptibility to fishing and anchoring hazards, as discussed in Section 4 (Figure 4-4).
- The southern "green" cable route passes through the deeper water channel with fine-grained sediments and avoids areas of sand waves. Cable burial will increase bed roughness and reduce erosion resistance in finer-grained sediments. As noted elsewhere in the report, this increases the potential for scour (Figure 3-10 and Inset B of Figure 4-2).

While the shorter northern "red" route is in shallower water, it has a much higher potential for scour than the longer "green" route in deeper water. The long-term implications and costs associated with different scour potential and severity may to some degree offset the lesser costs of the shorter route through shallower water.

New Jersey Demonstration Site

The New Jersey site is located in a wave- and storm-dominated ocean environment and the seabed is characterized by ridge-and-swale topography. The seafloor sediments are predominantly fine- and medium-grained sand with minor amounts of gravel, silt, and clay. The New Jersey site is in shallower water than the Rhode Island site.

The calculated bottom shear stresses indicate that the threshold for sediment transport is typically exceeded to 25 to 75% of the time in the western half of the study area. In contrast, in some of the eastern half of the site (with the exception of the sand ridges) the percent exceedance was lower (<25%).

The ridge crests are inferred to experience the highest bed shear stresses, which is consistent with the information presented in this report (Figures 3-5, 3-8a, and 3-9). Therefore, structures and cables near the ridge crests are inferred to be exposed to higher scour potential and sediment transport hazards than locations off the ridge crests. The ridge crests in the OWF will most likely be areas that require scour protection and be the focus of future scour monitoring during operation.

Three export cable routes were evaluated. The western route crosses four sand ridges where high bed shear stresses are to be expected. The central cable route avoids most of the sand ridge crests, while the eastern cable route was chosen to avoid crossing the crests of any sand ridges. The inferred scour potential is lowest for the eastern route.

7.0 PRE-DESIGN INVESTIGATIONS AND POST-INSTALLATION MONITORING

PRE-DESIGN INVESTIGATIONS AND EVALUATIONS

Scour potential is related to oceanographic and seabed conditions and how the installation of OWF structures and cables will alter the natural environment. Thus, the design of an OWF, and the consideration of scour hazards and mitigation requires the input from and use of information from several disciplines. An integrated approach to that effort is encouraged. Various elements and recommendations for the investigations and evaluations that should be conducted as part of the OWF siting, design, and installation planning are discussed below.

Oceanographic Evaluations and Design Criteria Development

We anticipate the design of many of the initial OWFs will rely heavily on hind-cast of regional data and/or hydrodynamic modeling to develop design criteria for tides, waves, and currents. Because of the comparative scarcity of data (as compared to the GoM OCS), the initial OWF designs should thoroughly evaluate uncertainty of the wave and current conditions, and how such uncertainty can affect risk. With future OWF development and structure installation, the regional data will be supplemented with increasing amounts of area-specific data and data that document local variations of the oceanographic conditions within an OWF-size area.

Oceanographic design analyses should consider and evaluate spatial variations across the OWF area. Discussions included in the main text of this report describe how seabed morphology responds to the hydrodynamic regime. The variability within the scale of an OWF of the seabed's morphology, which also reflects variability in flow conditions, is illustrated on several figures provided in the main text, and in Appendices A and B. When planning for the collection of oceanographic site measurements, it will be logical to place instrumentation on or at the meteorological tower. However, over-reliance on only those data should be avoided, as other areas in the planned OWF area may experience stronger currents and thus have a greater potential for scour hazards. Thus, it may be necessary to conduct site measurements at additional locations, other than the meteorological tower, to evaluate the highest-risk areas. Insight to spatial variability and identification of the highest-risk areas can be gained during the desk studies. Particularly if appropriate data are available as illustrated in Appendices A and B of this report, and/or from bathymetric and side scan sonar (SSS) surveys.

Design evaluations also should consider how temporal variations can affect currents in the water columns. Inter-annual variations can be significant off the Atlantic coast. Those evaluations should consider the potential that storms may locally alter the water depth in some portions of an OWF area. Oceanographic (waves and currents) data collection for a minimum of 1 year is recommended. Since directionality is important for understanding the combined effect of waves and currents, measurement of directionality should be a part of the data collection program.

Site Hydrographic and Geophysical Surveys

Although the BOEMRE has yet to issue Notices to Lessees (NTLs) for geophysical survey and geotechnical investigations for OWF development on the Atlantic OCS, it is possible to anticipate what some of those requirements will include based on: 1) BOEMRE *Guidelines for Geological and Geophysical Site-Surveys for Meteorological Towers and Other Seafloor Founded Structures and Devices on the OCS* (BOEMRE, 2009), 2) NTLs for O&G development in other OCS areas, and 3) codes and guidelines for geophysical surveys and geotechnical investigations for OWF development offshore different European countries.

For hydrographic surveys, the referenced BOEMRE guidelines and NTLs have not historically required collection of multibeam echosounder (MBES) or swath hydrographic data. As described previously, those methods are uniformly required throughout Europe for both design-phase and post-installation surveys. In addition, availability of such full-coverage hydrographic data is crucial and necessary for mapping the seabed geomorphology, anticipating sediment mobility, assessing sand wave migration rates, designing for scour, and monitoring to document the development (or not) of scour.

When MBES or swath data are processed, the data should be processed to obtain the highest-resolution (smallest bin size) bathymetry data that the accuracy and precision of the raw data measurements allow. This will provide the highest detail documentation of the seafloor conditions and geomorphology for scour assessments. That level of resolution may exceed de facto specifications and standards for the data acquisition. This is appropriate to allow comparison with data from future surveys to identify and measure small changes in seabed elevation due to sediment erosion, transport, and accretion. In current practice, it is not uncommon for processors to use larger bin sizes (e.g. 5-meter bin instead of a 1-meter bin) to make data files smaller and easier for transferring and to reduce editing efforts of contours. European industry and scour research papers have identified this as an issue that has limited the ability to effectively use MBES and swath bathymetry in scour monitoring and assessments.

Side scan sonar (SSS) data collection also is required by the referenced BOEMRE guidelines and NTLs, and in Europe. Those data provide a second view of the seabed morphology (as well as potential artifacts that are proud of the seafloor). SSS data are capable of imaging smaller bedforms and features than are possible with MBES. Also, SSS data can be used to interpret the seabed sediment types and map their spatial distribution. Ground-truthing the interpretation with sediment samples and grain size testing is a critical component of the scour assessment for a wind farm. When combined with high-quality MBES data, it is possible to better locate the SSS by correlating SSS features to the same features on the MBES data.

Seabed Sediment Sampling and Subsurface Investigation

The geotechnical investigation for a typical OWF will include both preliminary and final (site-specific) exploration. Preliminary investigations typically include borings at some percentage of the anticipated wind-turbine locations, vibracore and/or shallow-penetration cone penetration test (CPT) soundings at widely spaced intervals along the potential export cable routes, and seismic reflection surveys. Those preliminary investigations may be conducted either coincident with or following the hydrographic and geophysical survey data collection described previously.

During the subsequent design-phase investigation, borings and/or deep CPT soundings are typically conducted at a larger frequency of wind-turbine locations; and borings, vibracores, and/or shallow CPTs are conducted at closer intervals along the export cable route(s) and potential at locations along some inner-array cable alignments.

In addition to those subsurface investigations, seafloor samples should be collected at appropriate locations for the following purposes: 1) to define how the sediment type and grain size vary across the OWF and with water depth, 2) to define the sediment classification and grain size of various seafloor geomorphic features imaged on the hydrographic and SSS data, and 3) to ground-truth the relationship between seafloor sediment grain size and seafloor reflectivity as shown on the SSS and MBES backscatter data. Figure 7-1 illustrates the successful ground-truthing of sediment grain size and SSS reflectivity.

In addition, seismic reflection and geotechnical data are used to interpret the thickness of the surficial and subsurface layers. Appropriate testing should be conducted to correlate sediment type and grain size characteristics for sub-seafloor sediment layers that may be mobile. The thickness and grain size characteristics of the stratigraphic layers are used to evaluate and predict potential scour depth. Moreover, a thorough understanding of a site's physical and geological characteristics is important for understanding the fluid dynamic data and provide context for assessing the reasonableness of scour predictions.

INSTALLATION AND POST-INSTALLATION MONITORING

The potential for scour to develop within an OWF is significant. The occurrence of conditions that produce scour and their frequency will be a significant consideration for the design of future wind turbines and OWF developments. The potential for scour, and the depths and size of the scour depressions around the foundations will determine whether scour mitigation will be required for the future wind-turbine foundations. Thus, site measurements of the current velocities and scour depths will provide important information for: 1) verifying that the scour assumptions conducted during design have not been exceeded and 2) generating data that will reduce unnecessary conservatism or unrecognized risk in the future OWF.

Post-installation monitoring typically include requirements for baseline and periodic monitoring. The requirements may include surveying of the seafloor and measurement of currents. We recommend that post-installation monitoring programs adopt an adaptive approach. At OWF sites where scour hazards are relatively benign, the monitoring may be limited to representative areas. In contrast, where scour hazards are considered severe, the monitoring program should be more substantial. The monitoring program can be modified to include more or less frequent or more or less locations, as deemed appropriate, based on the initial monitoring results. The following monitoring approach is recommended for the initial Mid-Atlantic OWFs projects.

Post-Lay Cable Burial Survey

Following the installation of the cables, burial surveys should be performed to estimate the as-laid cable burial depths. Cable burial depth surveys are typically conducted using remotely operated vehicles (ROV) and tone detection systems. Figure 5-4 presents the results of a typical survey from a European OWF.

An MBES bathymetric survey should be performed concurrently with the burial depth survey to measure the seabed elevation immediately following the cable installation. This survey can be compared to the pre-lay and design-phase surveys. Subsequent MBES surveys can be compared to the as-laid burial depth and MBES surveys to monitor changes in cable burial depth.

If excessive or unexpected scour is observed it may be necessary to conduct another cable burial survey using an ROV.

Side Scan Sonar Survey

As part of the post-lay monitoring, side scan sonar surveys are commonly performed to monitor for exposed cables. Sonar surveying can be conducted at the same time as MBES hydrographic surveys.

Multibeam Hydrographic Survey Data Collection

Repetitive MBES surveys are appropriate to document the development (or not) of scour around OWF structures and along the cable routes. Some of those surveys should include full coverage of the entire OWF area, while the surveyed area during other surveys can be limited to the specific structure locations and cable routes.

The structure- and route-specific surveys are to document changes in seafloor and development of scour around the structures and along the cable routes, while the larger area surveys are to document changes in and movement of the geomorphic features in the project area. The definition of those details should be defined on a project-specific basis and should consider: the anticipated variations of conditions within the OWF area, the anticipated severity of scour, the amount and significance of sediment mobility defined by prior surveys at the site, the severity of storms since the prior surveys, whether (or not) this is the initial OWF in the project area, etc. Therefore, an adaptive approach with respect to data collection and evaluation is needed that considers these different factors.

Initially, MBES data collection is recommended at the following intervals:

- No more than 1 month prior to the start of OWF installation activities (to document baseline conditions for future comparison);
- If the OWF installation activities extend beyond one season of construction, supplemental MBES surveys of areas with construction should be conducted at the end of and prior to the beginning of each construction season;

- Following completion of the OWF installation activities, MBES surveys should be conducted:
    - o In the late fall, if the installation is completed prior to late summer:
    - o Following the first winter after installation, if the installation is completed in late fall, and
- In the late fall and early spring for 3 years after OWF construction.

Those dates should be supplemented or expedited after the occurrence of extreme storms. An evaluation should be performed to determine what level of event should trigger a survey. Examples of trigger criteria are as provided below:

- Following the passage of a tropical depression within 50 Nm of the site, or a hurricane passage within 100 Nm of the site; and
- Following a major nor'easter event that produces wave conditions equal to or greater than that for a 5-year return period storm.

Timing and frequency of the MBES surveys should be reviewed based on the data obtained during the first three years following the OWF operations. The appropriateness of the above schedule also should be reviewed (potentially decreased) based on relevant project experiences and data with future surveying adapted to site-specific conditions.

As knowledge is gained in an area and at an OWF, it may be possible to select representative areas for future long-term monitoring. This adaptive approach to reduce the monitoring as knowledge, understanding, and a historical record has been used in Europe.

Structure-Mounted Instrumentation

The collection of tide, wave, current, and seafloor elevation data is recommended as part of OWF development. The numbers of instrumented structures and their locations should be a project-specific evaluation based on the expected variations of conditions and scour susceptibility in the OWF. The instrumentation should be placed on structures dispersed throughout the OWF with priority given to placement of instruments on some of the initial installed substructures.

Tides, and wave height and period can be monitored using a total pressure sensor attached to the wind-turbine substructure.

The collection of current velocity data is appropriate to more accurately characterize the hydrodynamic conditions in an OWF area, and to compare actual currents with design criteria based on predicted currents from hind-cast analyses. An Acoustic Doppler Current Profiler (ADCP) is recommended to measure current velocity through the entire water column. ADCPs transmit sound at a constant frequency into the water column and receive the reflected sound (echoes) from particles suspended in the water. The frequency shift between the transmitted sound and echoes is used to compute velocities of the particles and, by inference, the current velocity.

Sonar altimeters can be used to measure the distance to seafloor and, therefore, the depth of scour. Altimeter(s) can be attached to the wind-turbine substructures. Sonar altimeters on multiple sides of a monopile offer the advantage of detecting changes in scour depth and location as a function of changes in the flow conditions at the site. If scour reaches a threshold depth, a MBES bathymetry survey can be initiated to measure the scour depression at the structure or along a cable route.

8.0 SCOUR AVOIDANCE, PROTECTION, AND MITIGATION

Several options are available for avoiding, protecting against, or mitigating scour problems. Options discussed as avoidance measures include techniques that are conducted in advance of or as part of the offshore wind structure installation and cable-lay activities. Options discussed as mitigation measures include protection activities that can either be conducted as part of the original installation or be used as mitigation after scour has developed.

Because many variables affect scour susceptibility and these variables can be different in different parts of an OWF, it is possible that a combination of avoidance and mitigation methods may be appropriate for many OWFs. Whereas the strategy in some areas of the OWF may rely primarily on avoidance, in other areas mitigation and protection may be necessary. At some OWFs, the type and level of protection may vary within the OWF.

Also the approach to protection could depend on the future difficulties associated with installation of mitigation after scour develops. Work conducted adjacent to the wind-turbine substructure must be carefully planned so as not to affect the inner-array cables. The difficulty of working adjacent to the wind-turbine substructure can be complicated by the presence of scour depressions around the substructure.

SCOUR AVOIDANCE MEASURES

Avoidance of Areas Prone to High Sediment Transport

Because scour susceptibility varies within an area the size of an OWF, it is possible to site structures and select cable routes so as to minimize or reduce the potential for scour to affect the OWF. For example, avoidance of active sediment transport areas, such as sand wave fields, can be accomplished during the siting and planning phase of a project. Although there is limited flexibility in routing of the inner-array cables, since positions of wind turbines are relatively fixed, there is more latitude when selecting the export cable route. This is illustrated in the two project examples provided in Appendices A and B. While it often may not be possible to completely avoid areas of potential scour, it may be possible to avoid the areas with the highest potential for scour and the areas where scour may be most severe.

Cable Burial

Burial is the standard practice for mitigating potential damage to cables. Burying cables provides protection from fishing activities, anchoring, current abrasion, and in some cases, exposure to the effects of sediment mobility. Typical burial depth is about 7 feet for OWFs but newer trenching technology is able to bury cables up to 10 to 12 feet. Burial of the cables beneath the seafloor may protect the cables from scour, but as described previously, the disturbance created by cable installation can increase the potential for scour.

Pre-Dredging Route Corridor to Allow Deeper Cable Burial

Sand waves can be large. Where sand waves are greater than about 7 feet tall, cables are at risk to be exposed even if the cables were originally buried. For example, where a cable is buried 7 feet below the crest of a 10-foot tall sand wave, the cable will be subsequently exposed when the trough of the sand wave passes over the location where the cable was originally buried 7 feet beneath the crest of the sand wave..

In areas with mobile sand waves, burial of the cable beneath the mobile sediments may require pre-sweeping or dredging a corridor through the mobile sand waves to allow trenching equipment to install the cable below a lower elevation. Depending on the sediment transport rates, cable installation may need to occur immediately following the pre-sweeping in order to avoid infilling the dredged corridor.

Horizontal Directional Drilled Shoreline Crossing

Export cables will need to cross the shoreline to connect to the onshore power grid. The nearshore area is commonly an area of high energy and high scour potential. It is common in today's marine construction practice to install cables and pipelines several tens of feet below the seabed through the nearshore and shoreline area using horizontal directional drilling (HDD) techniques. HDD techniques are also commonly employed in order to reduce environmental impacts to the shore crossing section of the alignment. HDD entry/exit points into the subsurface are typically seaward of the where waves begin to break and commonly 500 to 1,500 feet landward of the shoreline.

SCOUR PROTECTION AND MITIGATION MEASURES

Rock Protection

Rock placement has been frequently used to compensate for scour or to protect around the base of wind-turbine foundation. This method of protection against or mitigation of scour also has been commonly used below and around J-tubes and other connections to the wind-turbine substructure.

Rock placement around wind-turbine foundations has been used at many European wind farms. Results have been mixed. As additional storms pass over the site, the underlying sediments may liquefy due to hydrodynamic loads and the rock can sink into the underlying sand. The loss of rock can be reduced by using multiple layers of rock with different gradations in order to build a graded rock filter layer.

Since scour is expected around the edges of a graded rock layer, the lateral extent of the rock layer must be wide enough to maintain an unaffected rock protection region around the monopile itself. In addition, scour at the edge of the rocked area can undermine the rock and cause the rock to shift away from the monopile. This can then allow any filter material placed beneath the rock to be eroded from around the monopile and increase the localized scour around the pile. To reduce the potential for undermining at the edge of the rock protection, sites are sometimes pre-dredged so that the top of the rock is flush with the surrounding seafloor, which reduces the turbulent flow at the edge of the rock.

The secondary scour at the edges of the rock apron has led to the spanning of cables at some European OWFs. Another effect observed in rock dumps is that as the rock falls into the secondary scour pits or settles due to the hydrodynamic loading, gaps between the rock can lead to erosion of underlying filter material (if installed) and to accelerated deterioration of the rock armor protection.

In areas with sand waves, the rock is used to partially stabilize the seabed after laying and burying the cable. The conceptual intent is that as the crest of the sand wave migrates, the rock berm will settle downward onto the cable as the sand wave trough migrates into the former crest position. The concept is that although some spreading and lowering of the rock berm will occur, the rock berm will remain as cover and provide protection to the cable. Eventually, accretion will bury the rock and cable until the passage of the next sand wave trough re-exposes the rock.

Placement of rock as a mitigation measure should recognize the potential to: 1) damage the protective coatings on the wind-turbine substructure, and 2) create chafing of the cables if they abrade against that rock.

Rock Bags

Placement of bagged rock into the scour depression has been more successful than unbagged rock. The bags, which are filled with crushed or river-run rock, are composed of a woven geotextile. Bagged rock units are flexible and can adapt to the shape of irregular scour depressions. The rock size will be determined based on analyses and design criteria for the threshold motion at the surface of the rock layer. The bag enclosure and its mesh size are designed to prevent loss of the gradation of rock enclosed within the bag. As compared to loose rock, bagged rock better resists rock movement due to high flow velocities and piping of the underlying finer bed material.

Articulated Concrete Mats

Articulated concrete mats, with or without fronds, are designed to protect the underlying seafloor from loss of material as currents pass the structure. By doing so, concrete mats protect the seafloor material from erosion. Routine investigations and surveying must be performed to ensure that the edges of the mat are not undermined by secondary scour.

This method is commonly used at locations where one cable crosses another cable. When inner-array or export cables must cross an existing cable, one concrete mat is placed over the existing cable to provide separation and cover between that existing cable and the overlying OWF cable. A second concrete mat may then be placed on top of OWF cable for protection.

Frond Mats

One alternative to concrete mats is concrete mats with fronds. Once placed, fronds act as sea-grass, which improves scour prevention. Fronds have been shown to add drag and wave dissipation, reducing the current velocity so that particles of material are deposited onto the mats. When successful, this creates an underwater sand bar around the area to be mitigated. The added weight from the deposited material further increases the stability of the mat. Typically, fronds are built from chemically inert materials that do not break down in seawater. This technique has been used at the base of turbine foundations where scour has led to spanning of cables.

Grout Bags

Grout bags can be applied in a manner similar to concrete mats or bagged rock, but are typically used on a smaller scale. Divers are commonly used to install and stabilize grout bags. Grout bags can be either prefilled or deployed on site and filled using a diver and pumping spread from a vessel.

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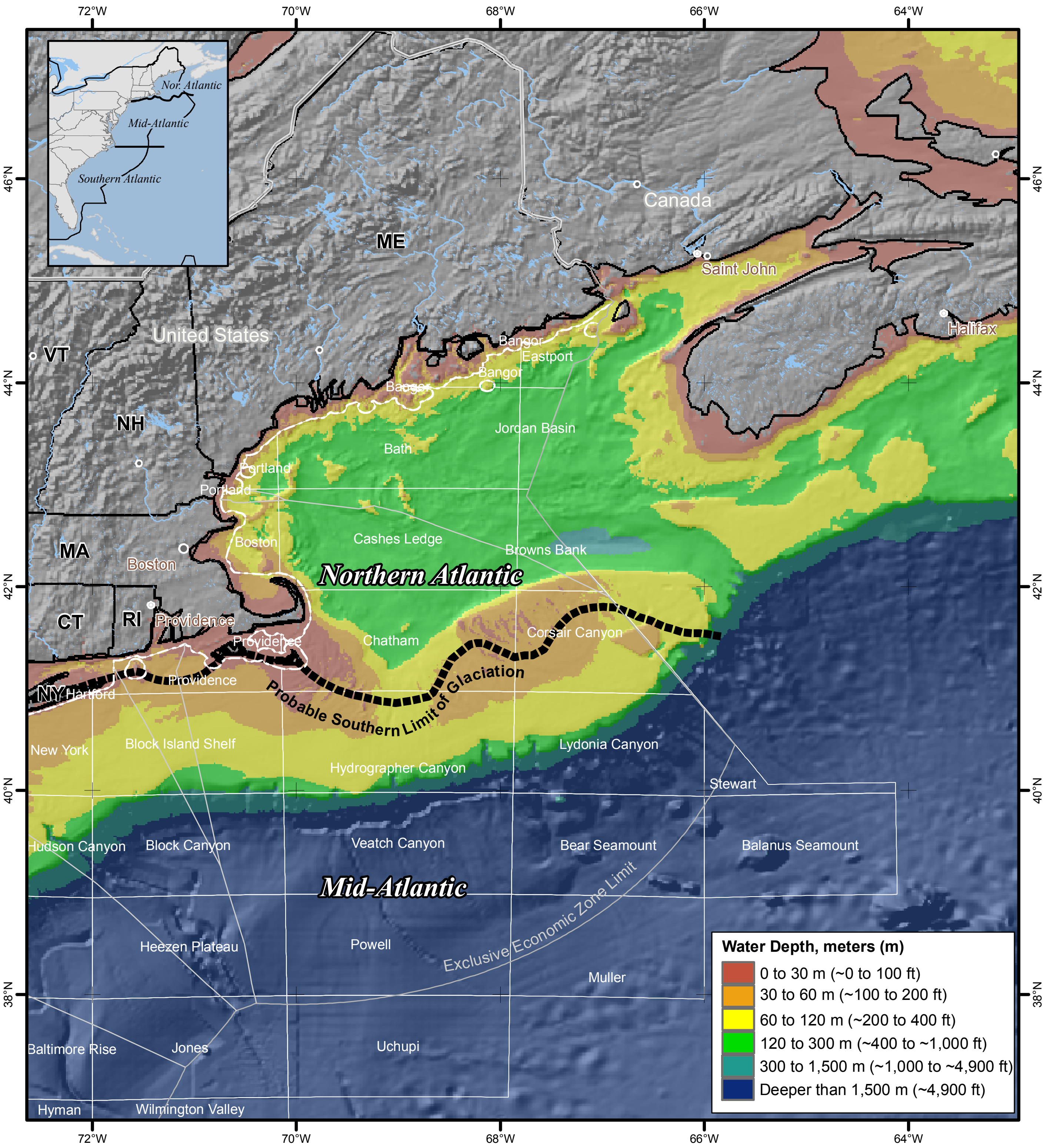
FIGURES

Bureau of Ocean Energy Management, Regulation and Enforcement
Technology Assessment & Research Program Project #656



Sources: NOAA, BOEMRE

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km

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NORTHERN ATLANTIC OCEAN CONTINENTAL SHELF

TA&R Project #656
Seabed Scour Considerations

FIGURE 1-1

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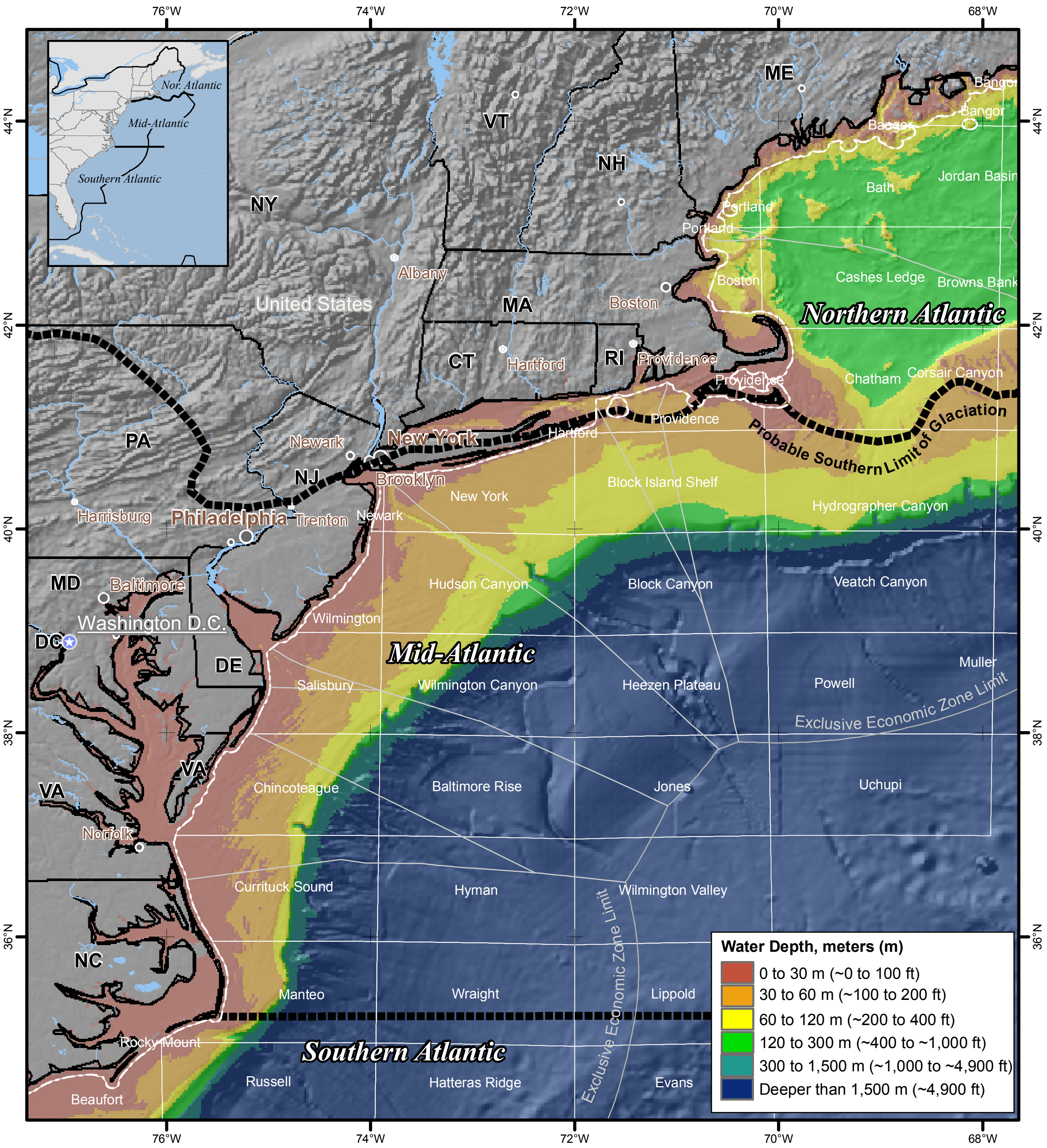

Sources: NOAA, BOEMRE

MID-ATLANTIC OCEAN CONTINENTAL SHELF

TA&R Project #656

Seabed Scour Considerations

FIGURE 1-2

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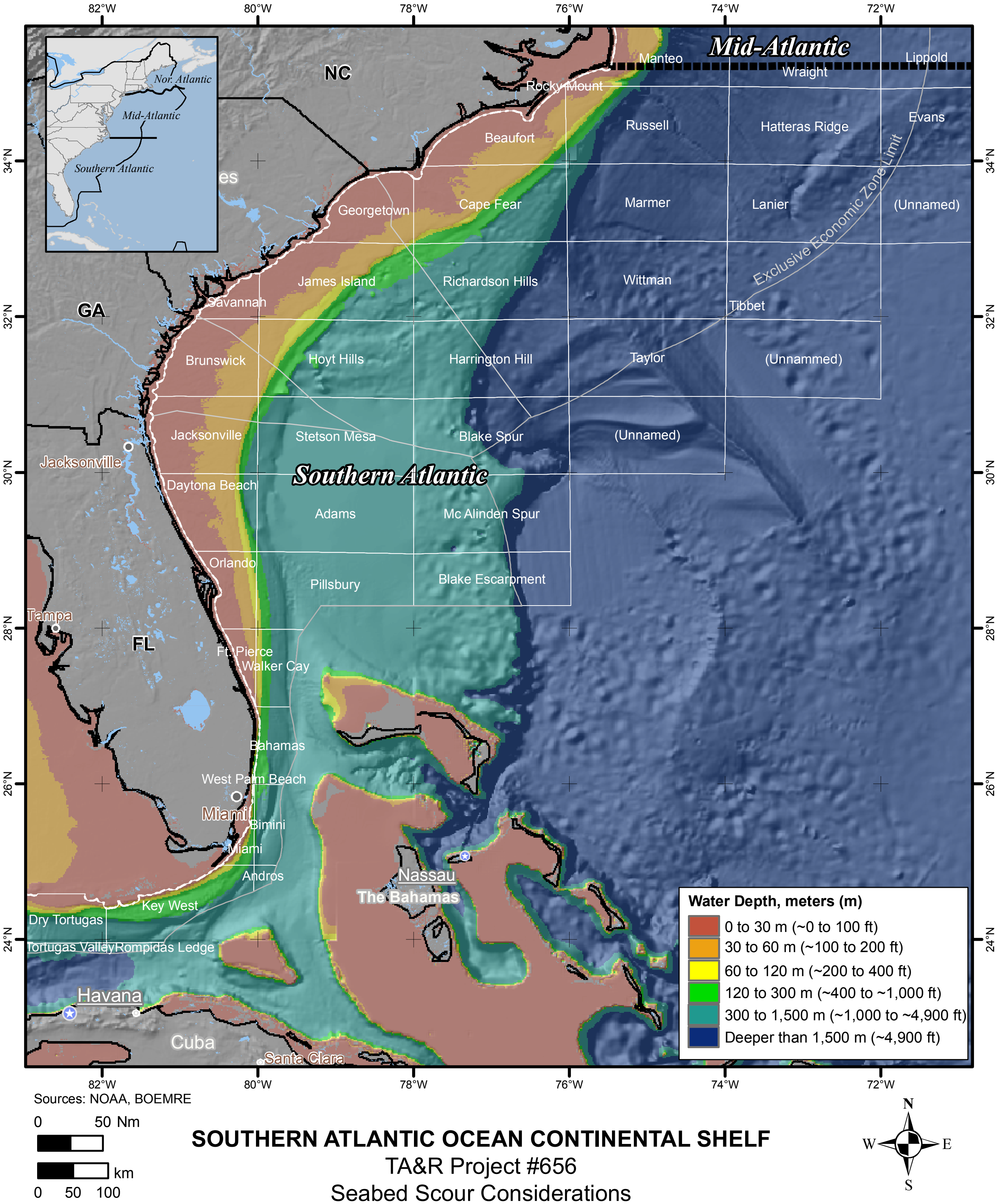

SOUTHERN ATLANTIC OCEAN CONTINENTAL SHELF

TA&R Project #656

Seabed Scour Considerations

FIGURE 1-3

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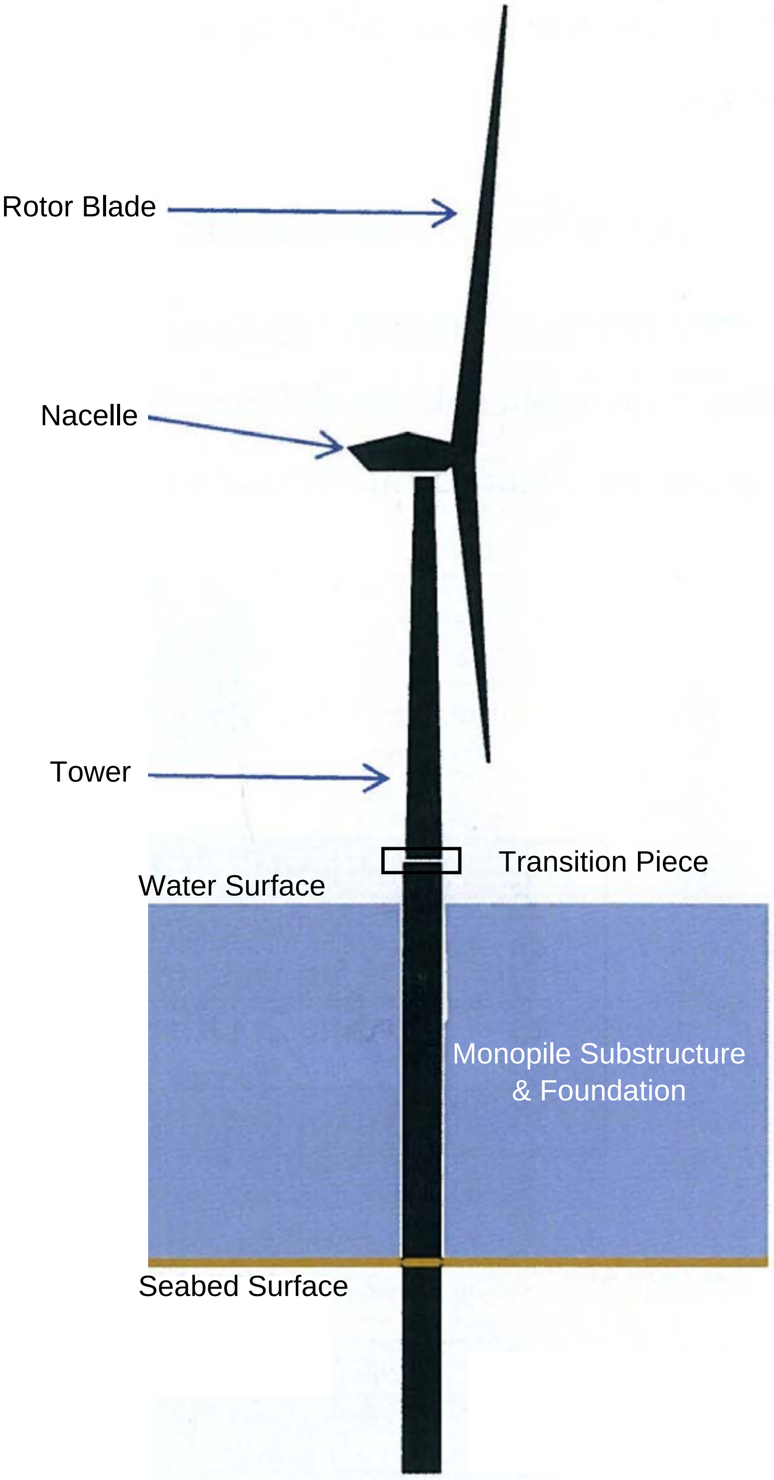


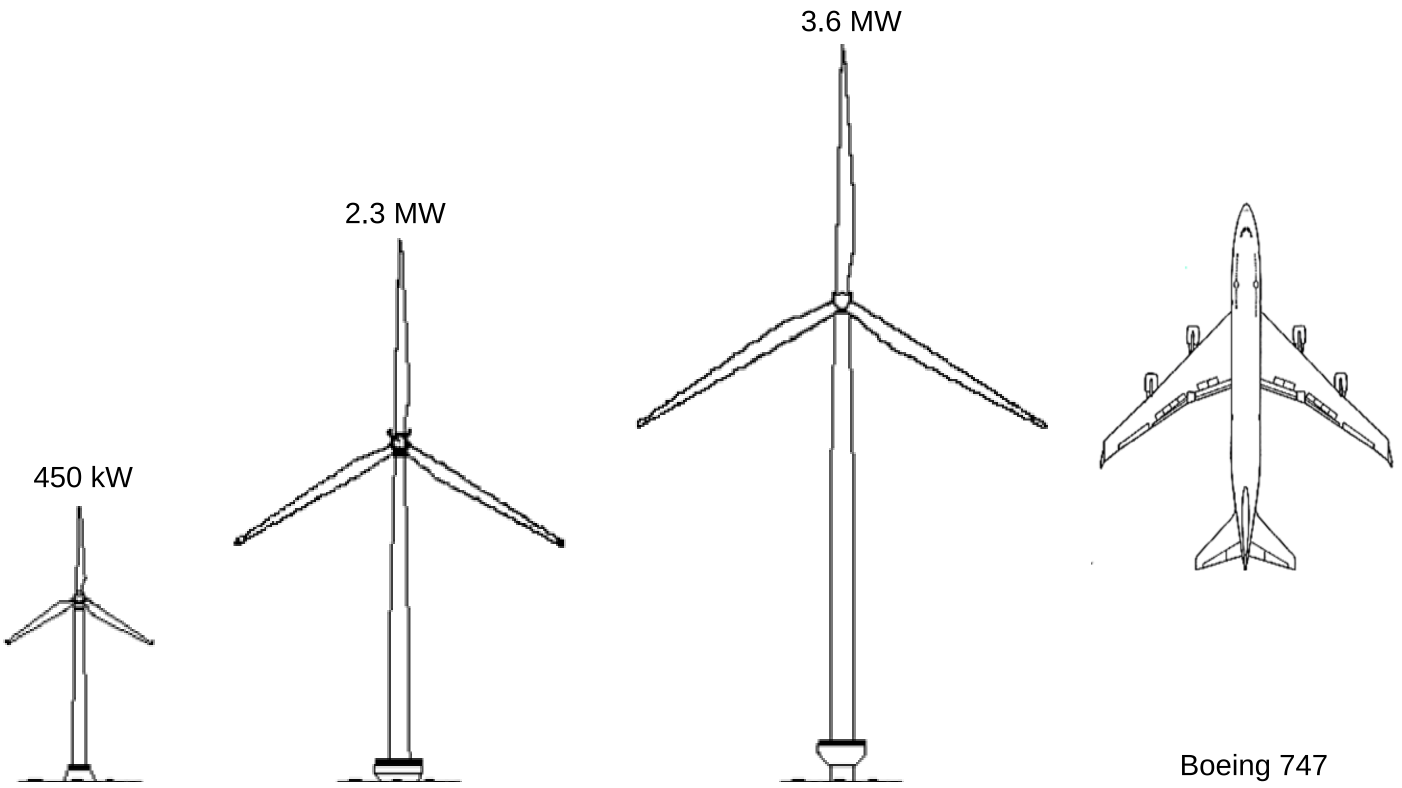
Figure modified from MMI Engineering, Inc (2009).

TYPICAL COMPONENTS OF AN OFFSHORE WIND TURBINE STRUCTURE

TA&R Project #656

Seabed Scour Considerations

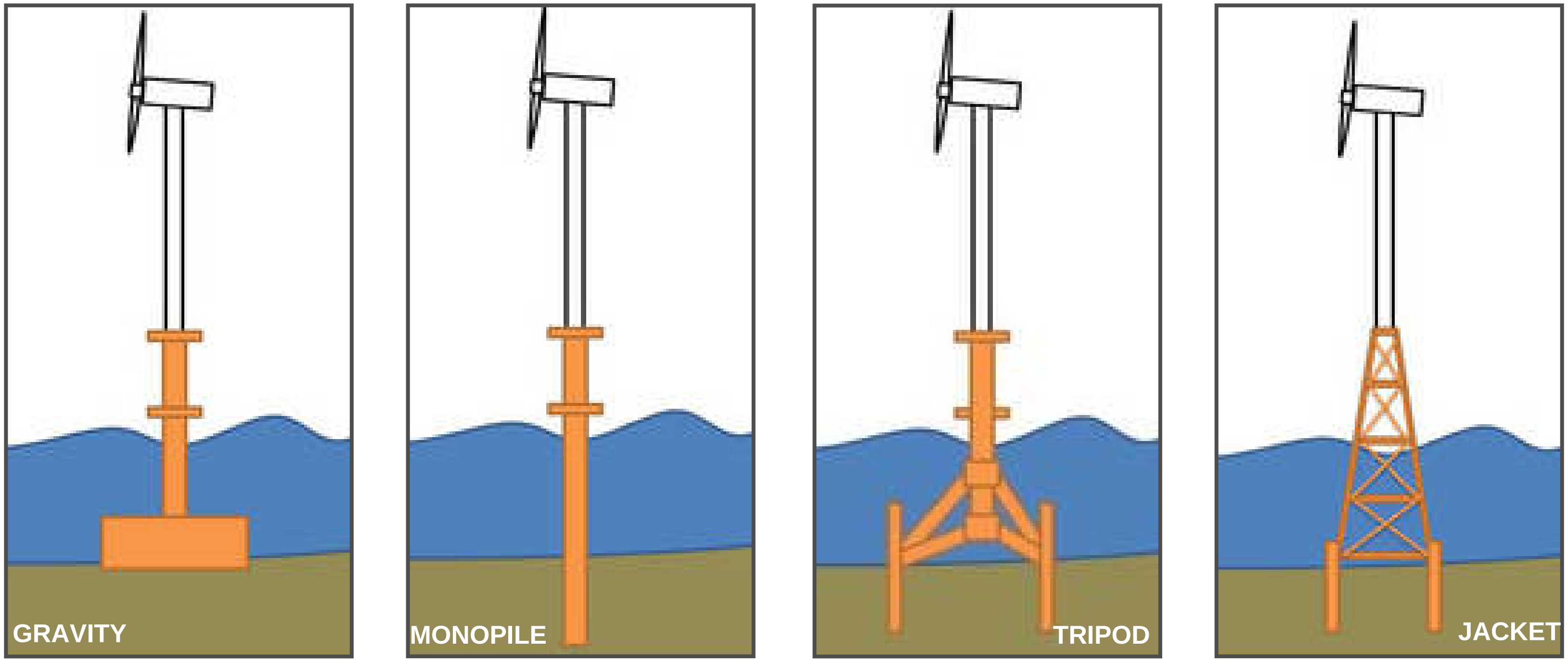
FIGURE 2-1



Depicted above are some of the typical sizes for offshore wind turbines based on amount of power generation. A Boeing 747 airplane is shown to give a general idea of the scale for these structures. Although not to scale the images are proportionally comparable. (Modified from Todd Wynn, 2010)

TYPICAL SIZES OF OFFSHORE WIND TURBINES
TA&R Project #656
Seabed Scour Considerations

FIGURE 2-2

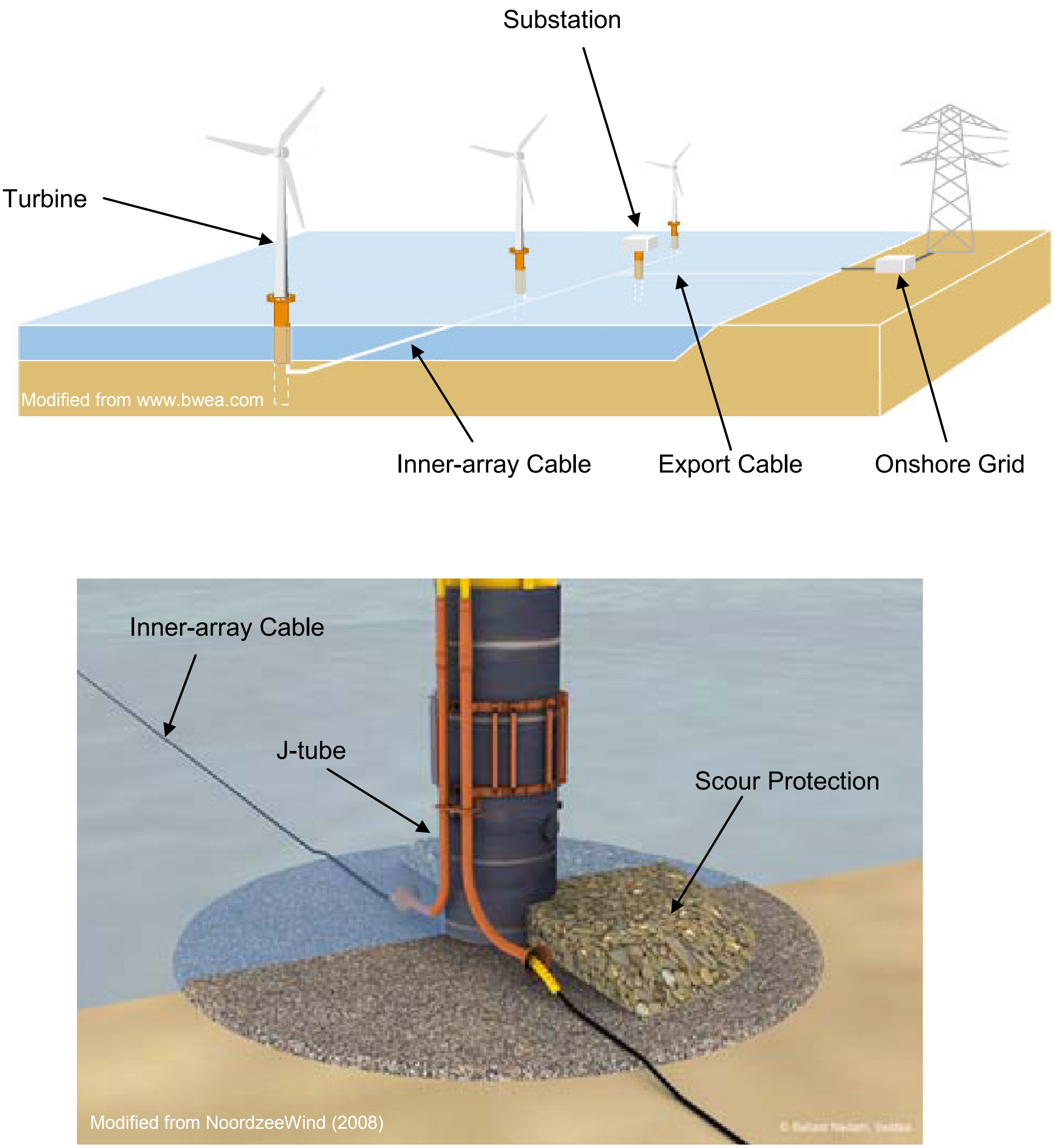


Depicted above are various types of offshore wind turbine substructures. In Europe, the typical types of substructures used for fixed offshore wind turbines are the gravity, monopile, tripod, and jacket foundations. These substructure types have typically been installed for the following water depths: less than 10 meters (~30 feet) for a gravity foundation, less than 25 meters (~80 feet) for a monopile foundation, less than 30 meters (~100 feet) for a tripod foundation, and 6 to 40 meters (~20 to 130 feet) for a jacket structure.

Note: Illustrations are not to scale.

TYPICAL OFFSHORE WIND TURBINE SUBSTRUCTURES
TA&R Project #656
Seabed Scour Considerations

FIGURE 2-3

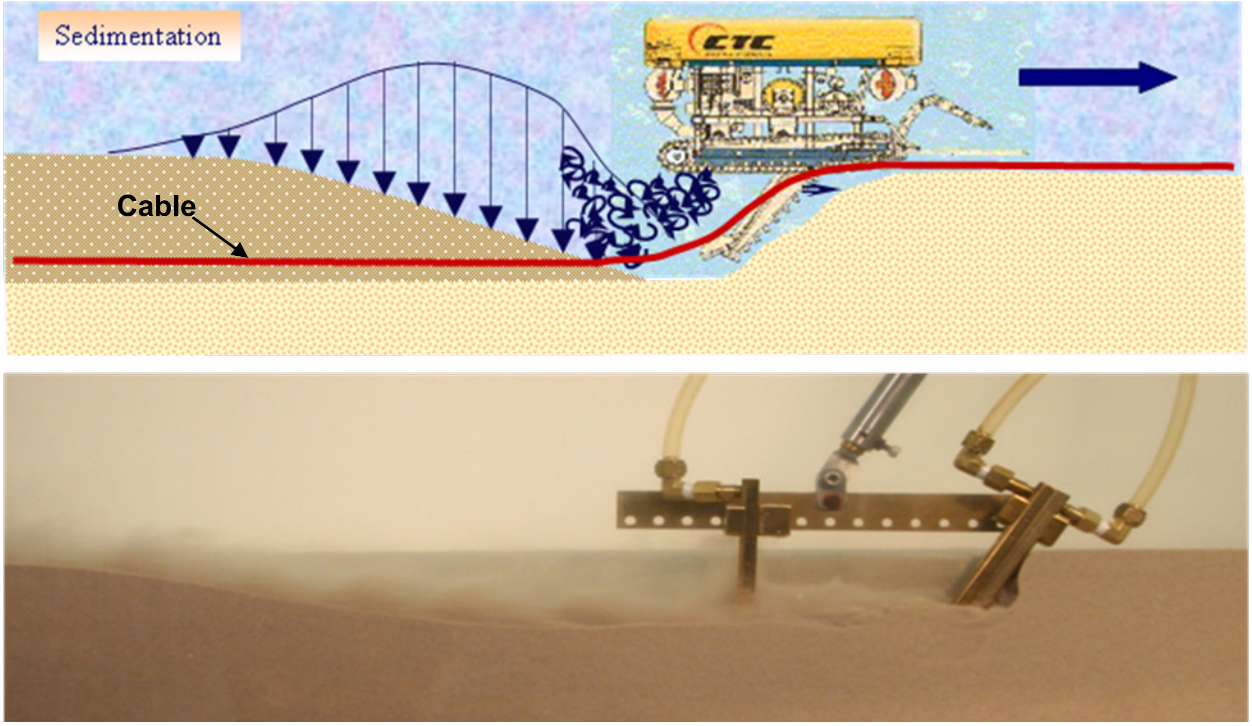


Modified from www.bwea.com

Modified from NoordzeeWind (2008)

OFFSHORE WIND FARM COMPONENTS
TA&R Project #656
Seabed Scour Considerations

FIGURE 2-4



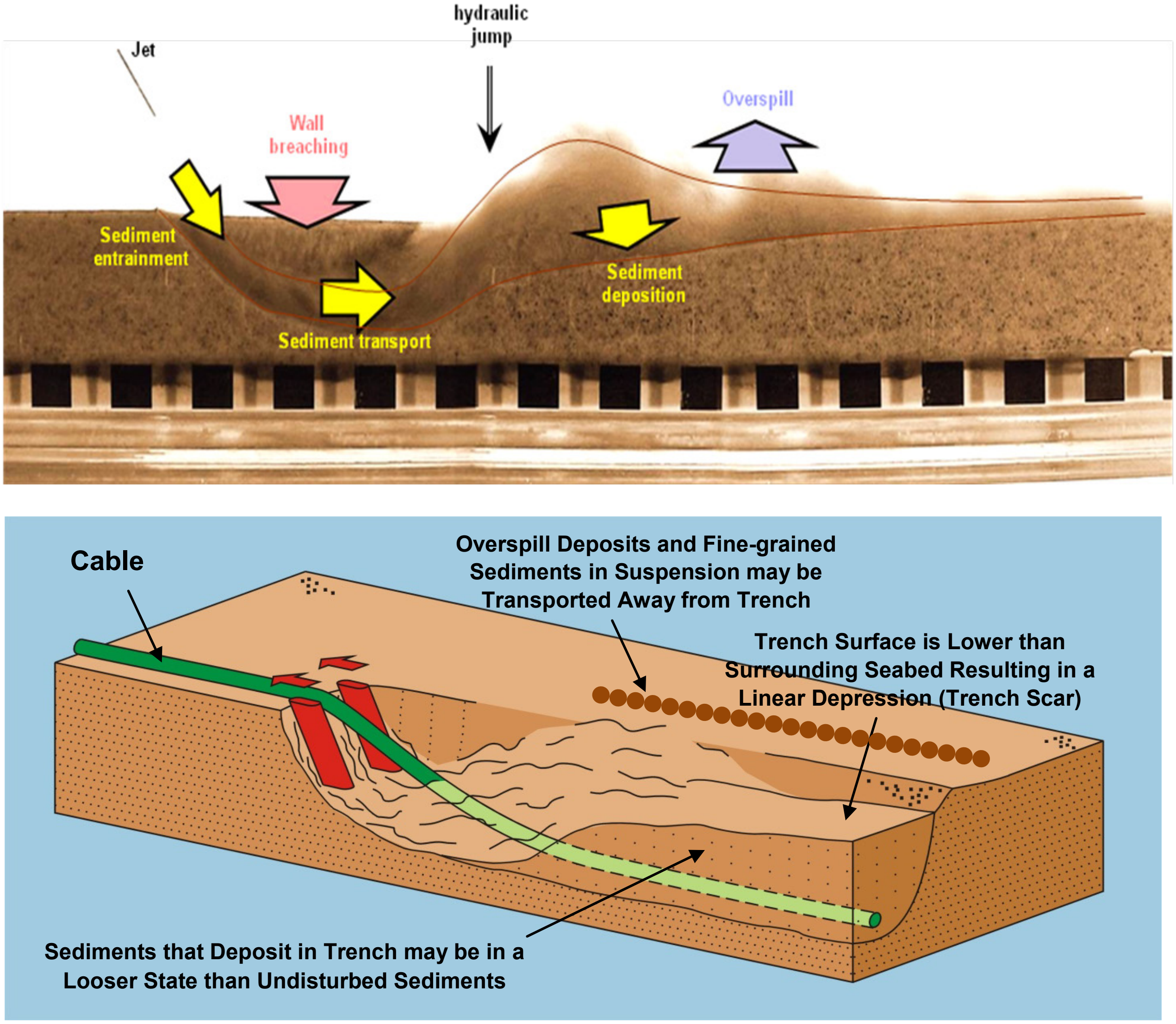
The upper image presents a schematic drawing of a jet-trencher in operation. As a machine moves along the cable route, pressured jets fluidize the sediments and transport the sediments backwards and upwards. The cable is laid into the fluidized trench and is subsequently buried by the sediments entrained by the fluid and sediments in suspension. The lower image presents a still image from video collected during a laboratory research study. Entrained and suspended sediments are readily observable in the photograph. Images modified from Vanden Berghe et al. (2008).

JET-TRENCHING SCHEMATIC AND LABORATORY TEST PHOTOGRAPH

TA&R Project #656

Seabed Scour Considerations

FIGURE 2-5



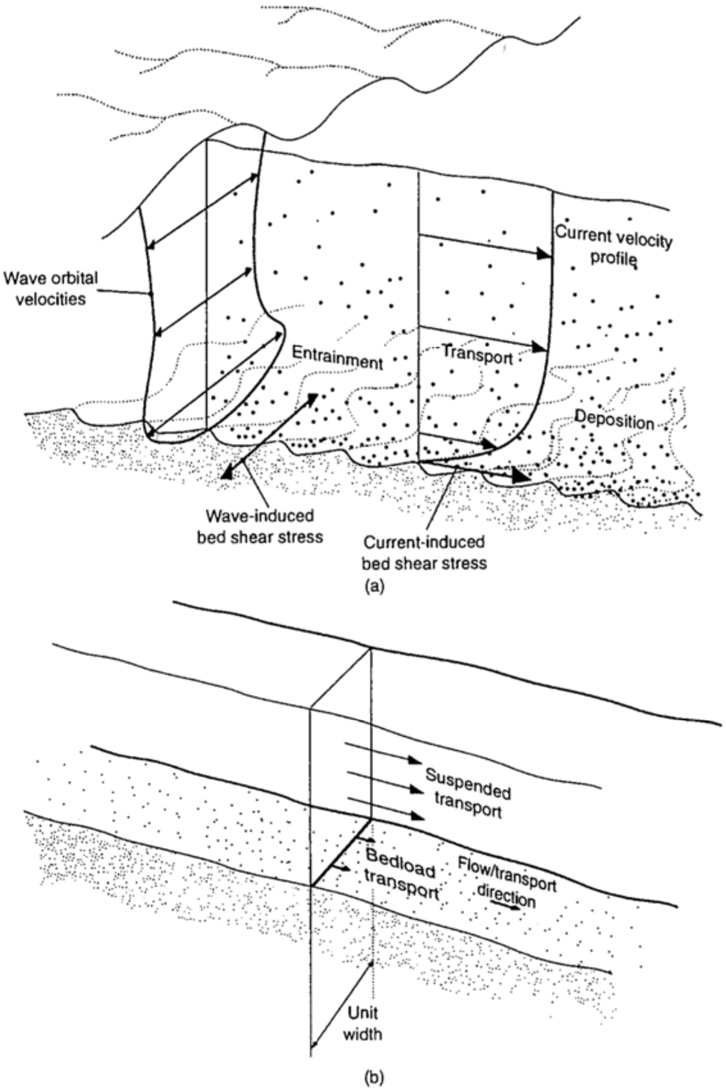
The upper image identifies the processes that occur during jet-trenching. Erosion, sediment entrainment and transport, deposition, breaching, and overspill are the key mechanisms. The lower image presents a schematic drawing of the trenching process and results. Images modified from Vanden Berghe et al. (2008).

JET-TRENCHING MECHANISMS AND EFFECTS

TA&R Project #656

Seabed Scour Considerations

FIGURE 2-6



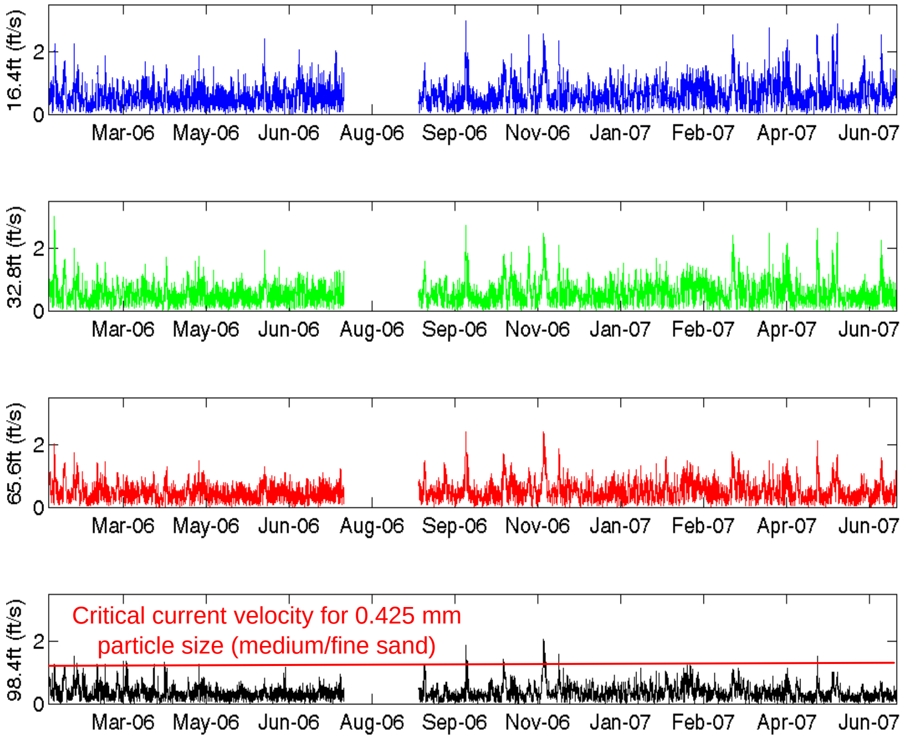
(a) Diagram showing the marine sediment transport components, i.e., waves or currents. (b) Types of sediment transport – bedload transport and suspended transport. From Soulsby (1997)

MARINE SEDIMENT TRANSPORT PROCESSES

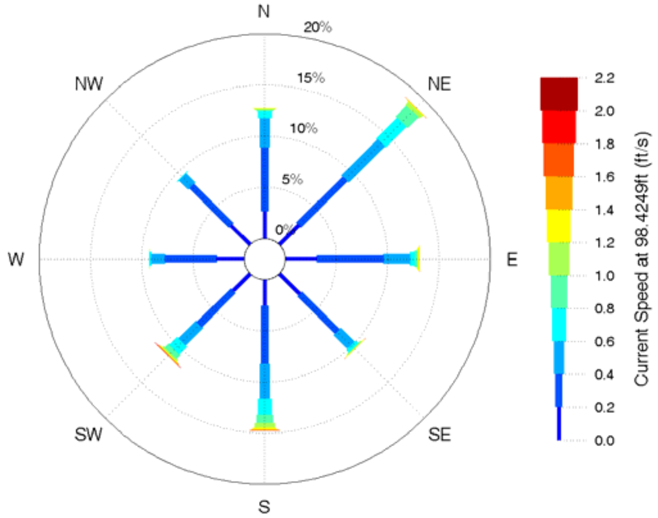
TA&R Project #656

Seabed Scour Considerations

FIGURE 3-1



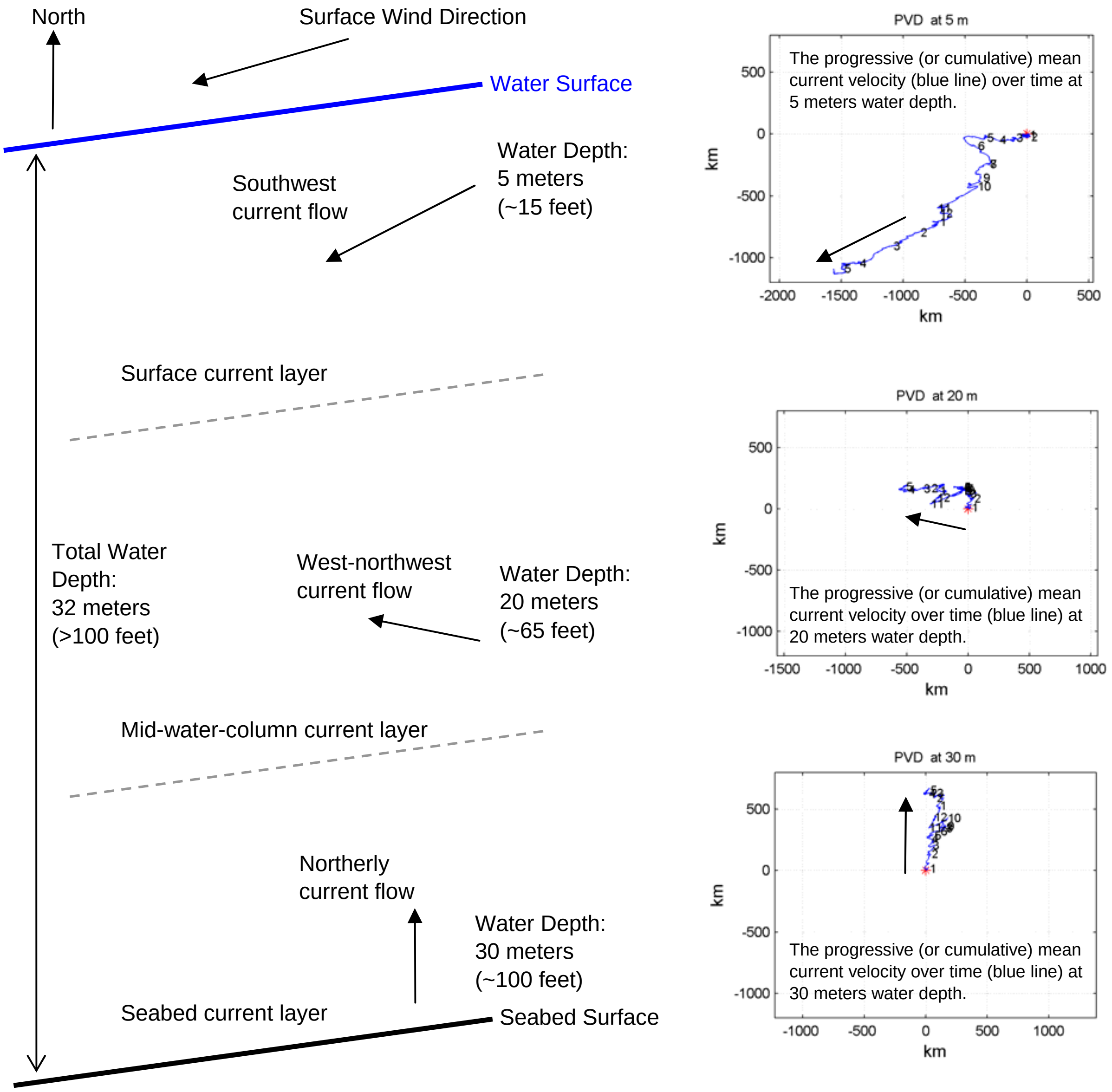
Rose Diagram of Bottom Current Velocity



The top image shows ADCP time series bottom current velocity data collected by Old Dominion University, offshore Wallops Island, Virginia. The current velocities shown are for approximate water depths (from top to bottom) of 16.4 feet, 32,8 feet, 65.6 feet, and 98.4 feet below the water surface. These data represent 14 months of current data over two deployment periods (January 2006 to July 2006 and October 2006 to June 2007, respectively). The calculated critical current velocity (Soulsby, 1997), i.e., the velocity that initiates sediment transport, shown by the red line demonstrates that sediment transport will occur during periods of higher bottom current velocities for medium/fine sand grain sizes. The bottom image shows a rose diagram of bottom current velocity direction based on the same dataset. The direction indicated is the direction in which the flow is moving. This diagram demonstrates that current direction and magnitude vary throughout the year.

ADCP CURRENT DATA
Offshore Wallops Island, Virginia
TA&R Project #656
Seabed Scour Considerations

FIGURE 3-2

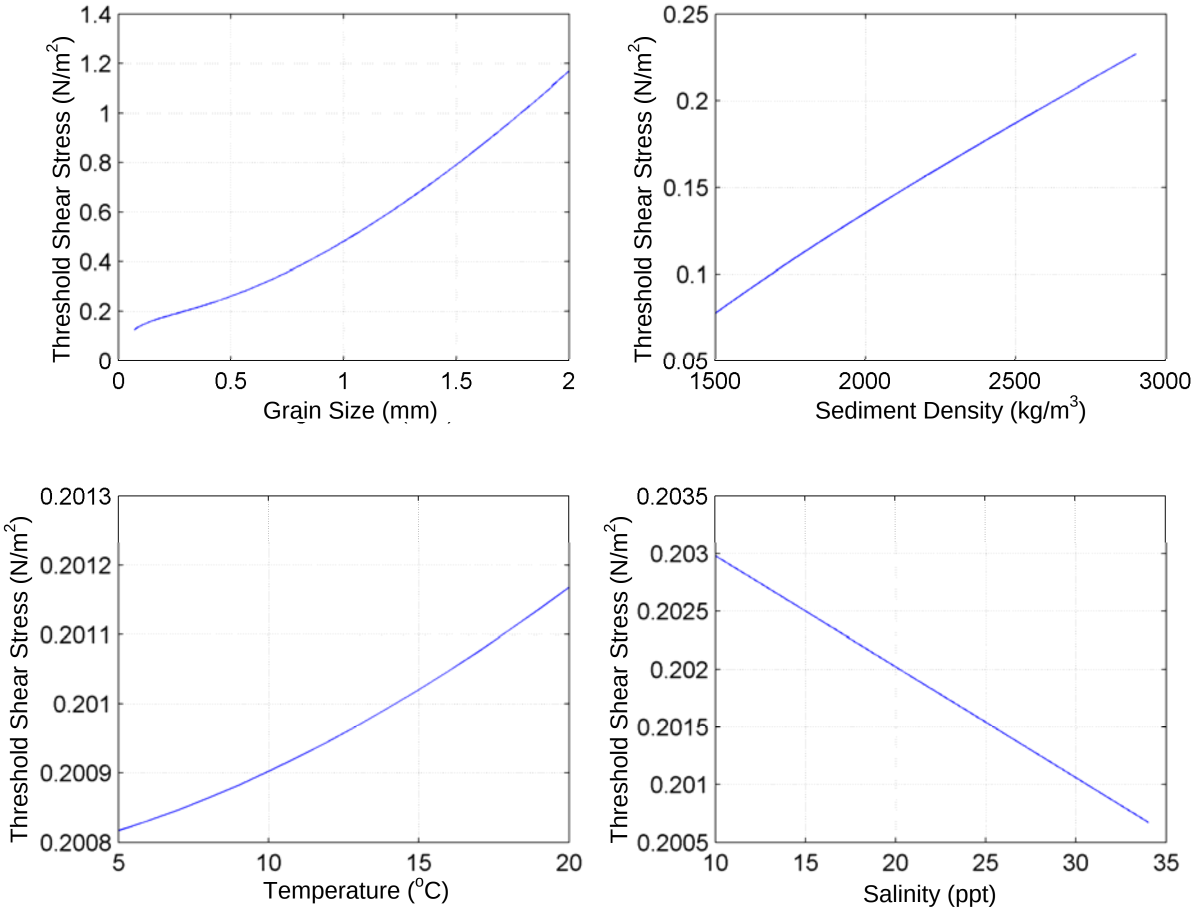


Note: Diagram is not to scale.

The schematic diagram on the left illustrates the variation in current direction from the water surface to the seabed from ADCP current velocity data collected by Old Dominion University offshore Wallops Island, Virginia. The current data are shown on the right as progressive vector diagrams (PVDs) at different water depths. The PVDs represent the cumulative velocity vectors of the daily mean current velocity over a period of several days, which is shown by the blue line. The arrow shows the overall trend in the cumulative current velocity. The data show that the surface current direction is towards the southwest, whereas the bottom current direction is towards the north. The mid-water-column current direction is west-northwest. Often the surface current direction is with the surface wind direction, which is depicted in the schematic diagram on the left.

CURRENT DIRECTION VARIATION WITH WATER DEPTH
Offshore Wallops Island, Virginia
TA&R Project #656
Seabed Scour Considerations

FIGURE 3-3



The above parametric analysis plots show the variation in threshold shear stress for grain size (top left), sediment density (top right), water temperature (bottom left), water salinity (bottom right). Temperature and salinity are used to determine the density of water and the kinematic viscosity, which are used with grain size and sediment density to calculate the threshold shear stress (refer to Appendix C). These parametric analyses show that changes in grain size or sediment density significantly affect the calculated threshold shear stress, whereas changes in the water temperature and salinity have less of an effect.

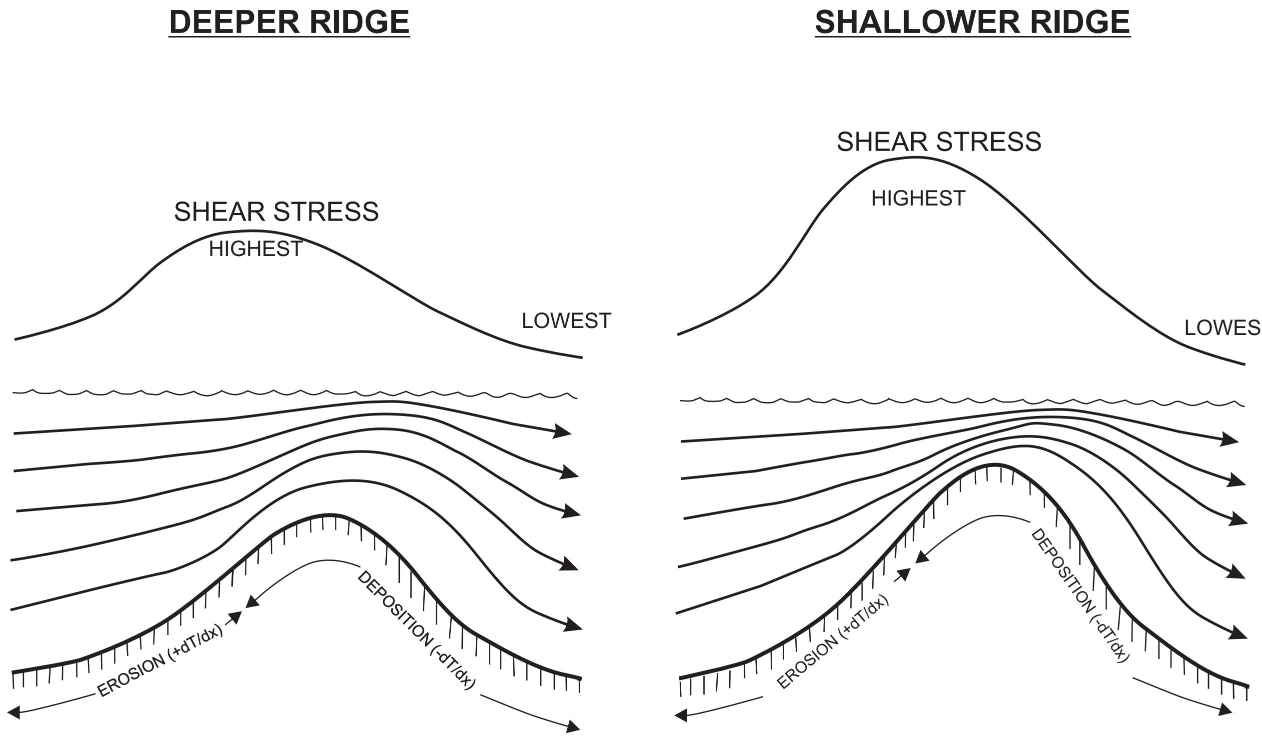
Conversion: 1 N/m^2 = 0.020885 lb/ft^2

THRESHOLD BED SHEAR STRESS PARAMETERS

TA&R Project #656

Seabed Scour Considerations

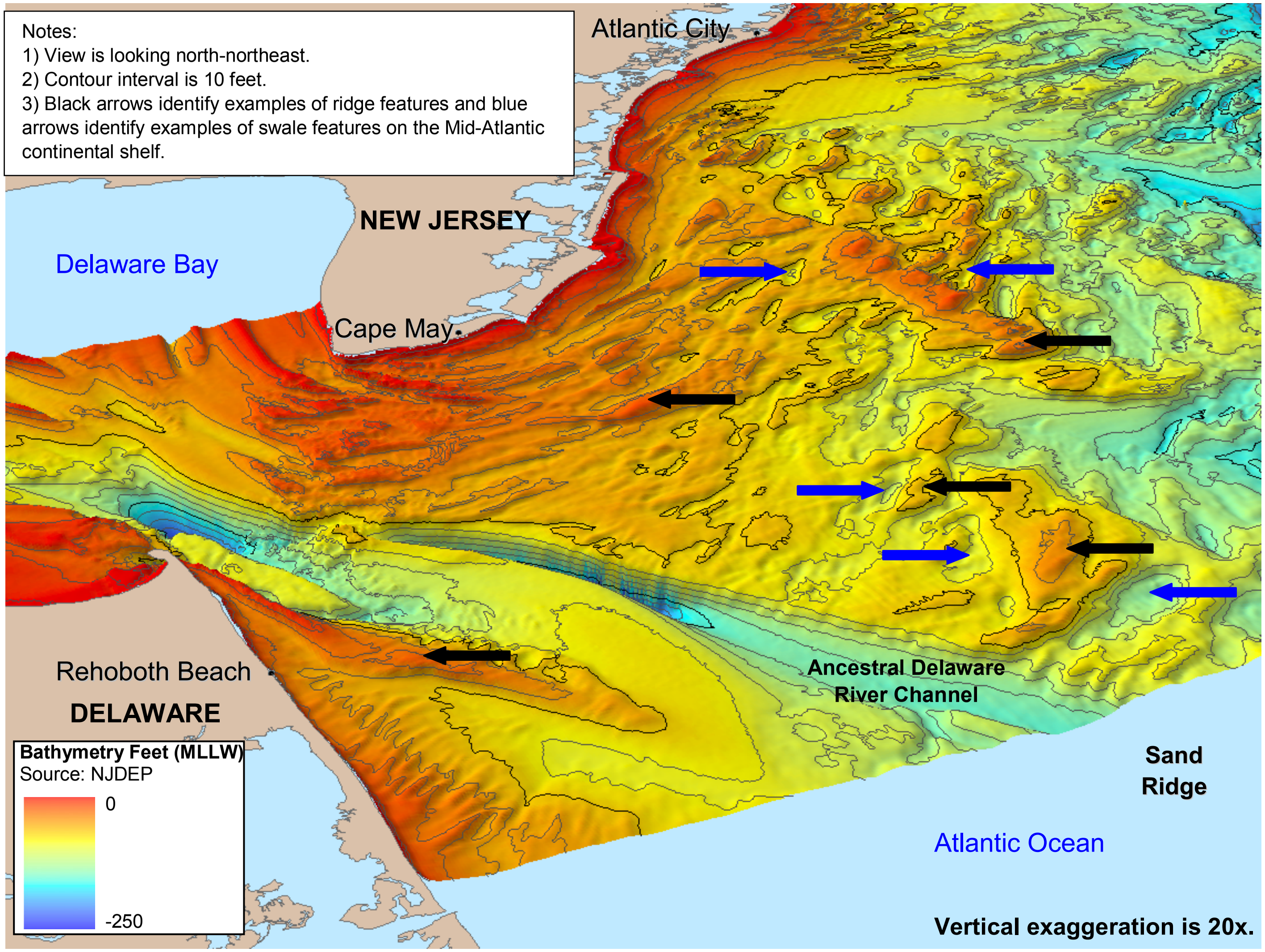
FIGURE 3-4



This schematic diagram depicts current flow lines over a sand ridge, shoal, or bank for two different water depths. The scenario on the left shows the current flow lines over a deeper ridge, shoal, or bank as compared to the shallower ridge scenario on the right. The current flow lines are more constricted in the scenario on the right (shallower ridge). This represents accelerated flow through a smaller column of water. The result is higher shear stress being generated over the ridge. For the deeper ridge scenario, on the left, flow lines are less constricted and the generated shear stress over this ridge is less. This condition reflects changes that may occur as a sand wave (or dune) migrates along a sand ridge (or shoal) and creates localized higher current flow or as accretion on the crest of a sand ridge, bank, or shoal causes it to grow taller creating localized higher current flow. Conversely, as the sand ridge, shoal, or bank lowers, thus increasing the water depth, the velocity and shear stress will be expected to decrease. Such a change could dramatically affect scour around a monopile if constructed on top of the sand ridge, shoal, or bank. Modified from Swift and Field (1981).

VARIATION IN WATER DEPTH AND SHEAR STRESS
TA&R Project #656
Outer Continental Shelf, United States

FIGURE 3-5



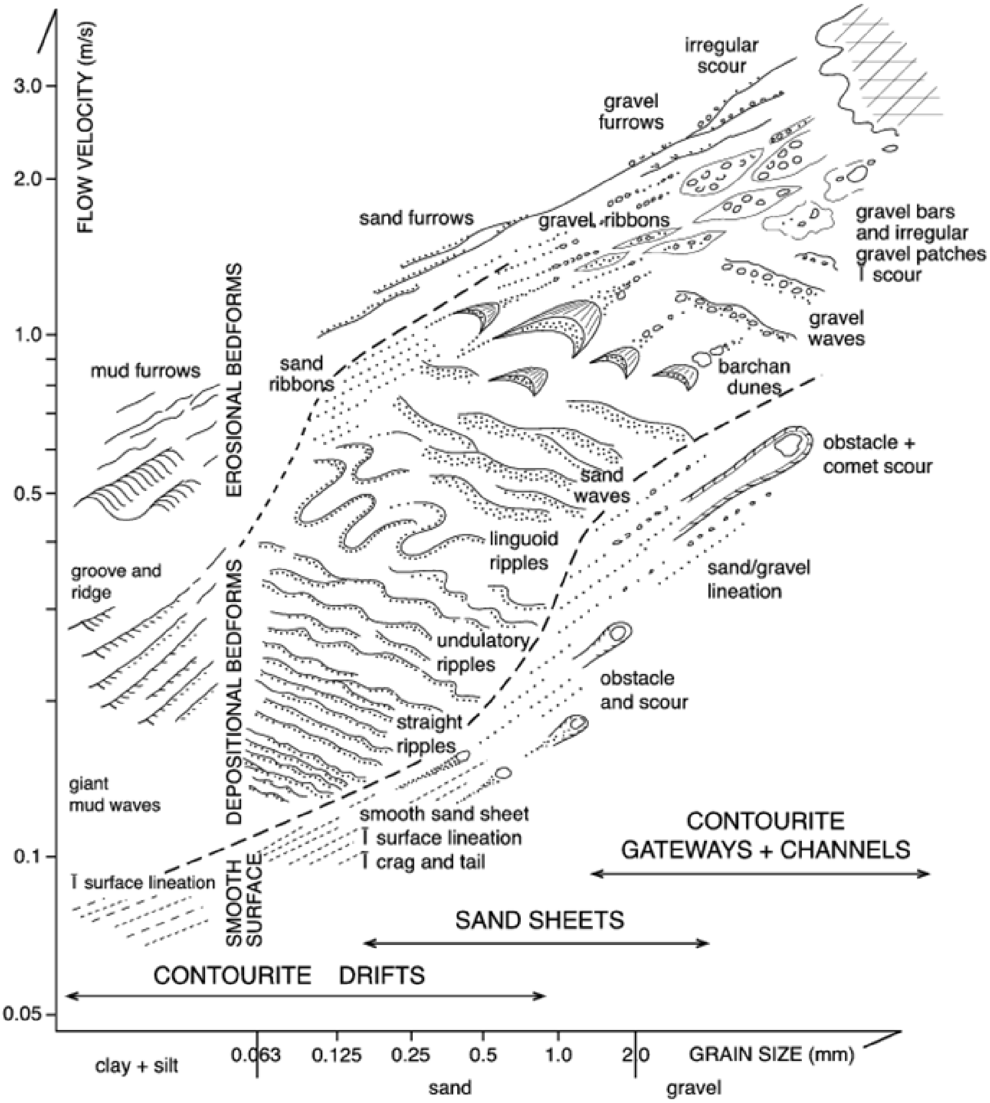
Notes:
1) View is looking north-northeast.
2) Contour interval is 10 feet.
3) Black arrows identify examples of ridge features and blue arrows identify examples of swale features on the Mid-Atlantic continental shelf.

Vertical exaggeration is 20x.

THREE-DIMENSIONAL RENDERING OF MID-ATLANTIC RIDGE AND SWALE FEATURES

TA&R Project #656

Seabed Scour Considerations



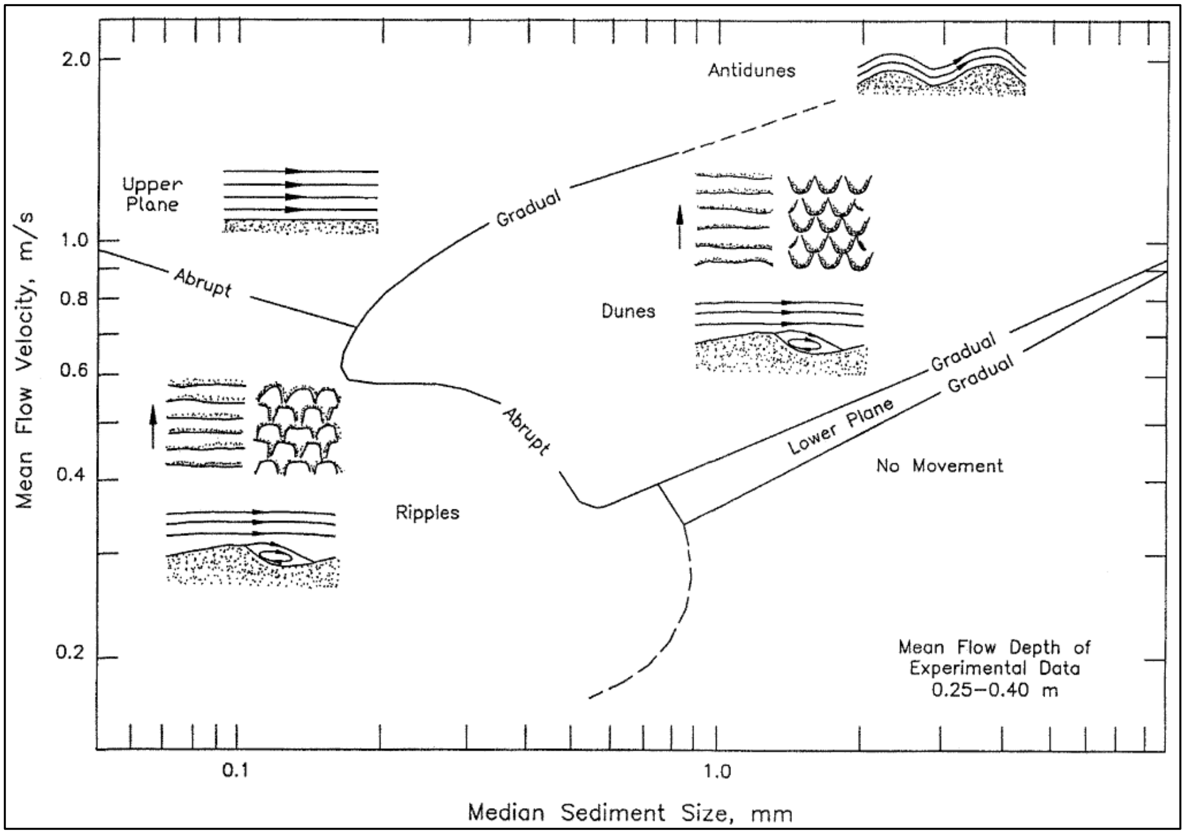
The illustration above represents a bedform-velocity matrix that demonstrates the relationship between flow velocity and grain size with respect to bedform formation (from Stow et al, 2009). Flow velocity and grain size are principle parameters that control the development of forms (as well as water depth, fluid density, sediment density, bed roughness, etc). If grain size and flow velocity data are available, bedform type and approximate dimensions can be estimated using this matrix. Furthermore, if bathymetry data are available that allow bedforms to be measured, grain size data can be used to estimate flow velocity.

This matrix was developed for deep-water bottom current environments based on field observations. However, it is analogous to bedform distributions in shallow marine current environments and can be applied to approximate the parameters described above.

Conversion: 1 meter/second (m/s) = 3.28084 feet/second (ft/s)
1 m = 3.28084 ft

RELATIONSHIP OF BEDFORMS TO
GRAIN SIZE AND FLOW VELOCITY
TA&R Project #656
Seabed Scour Considerations

FIGURE 3-7a



The illustration above shows zones of bedform formation as determined by mean flow velocity and median grain size data (D_{50}) (modified from Ashley, 1990). As with Figure 3-7a, flow velocity and grain size are crucial parameters for determining bedform type and dimensions. However, this plot shows that the transition from one bedform to another may either be gradational or abrupt.

Data used to develop this plot are from various laboratory studies.

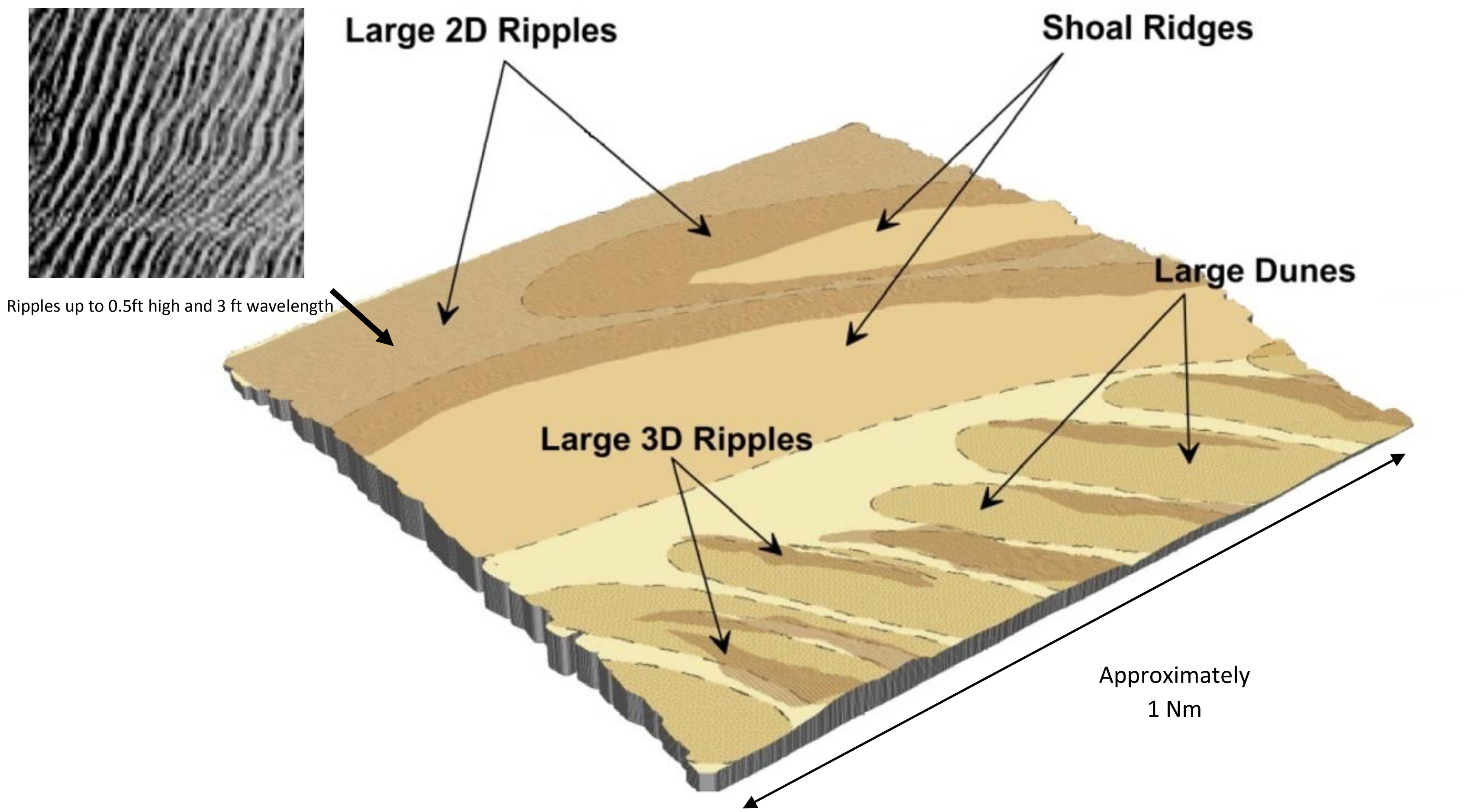
Conversion: 1 m/s = 3.28084 ft/s
1 m = 3.28084 ft

RELATIONSHIP OF BEDFORMS TO GRAIN SIZE AND FLOW VELOCITY

TA&R Project #656

Seabed Scour Considerations

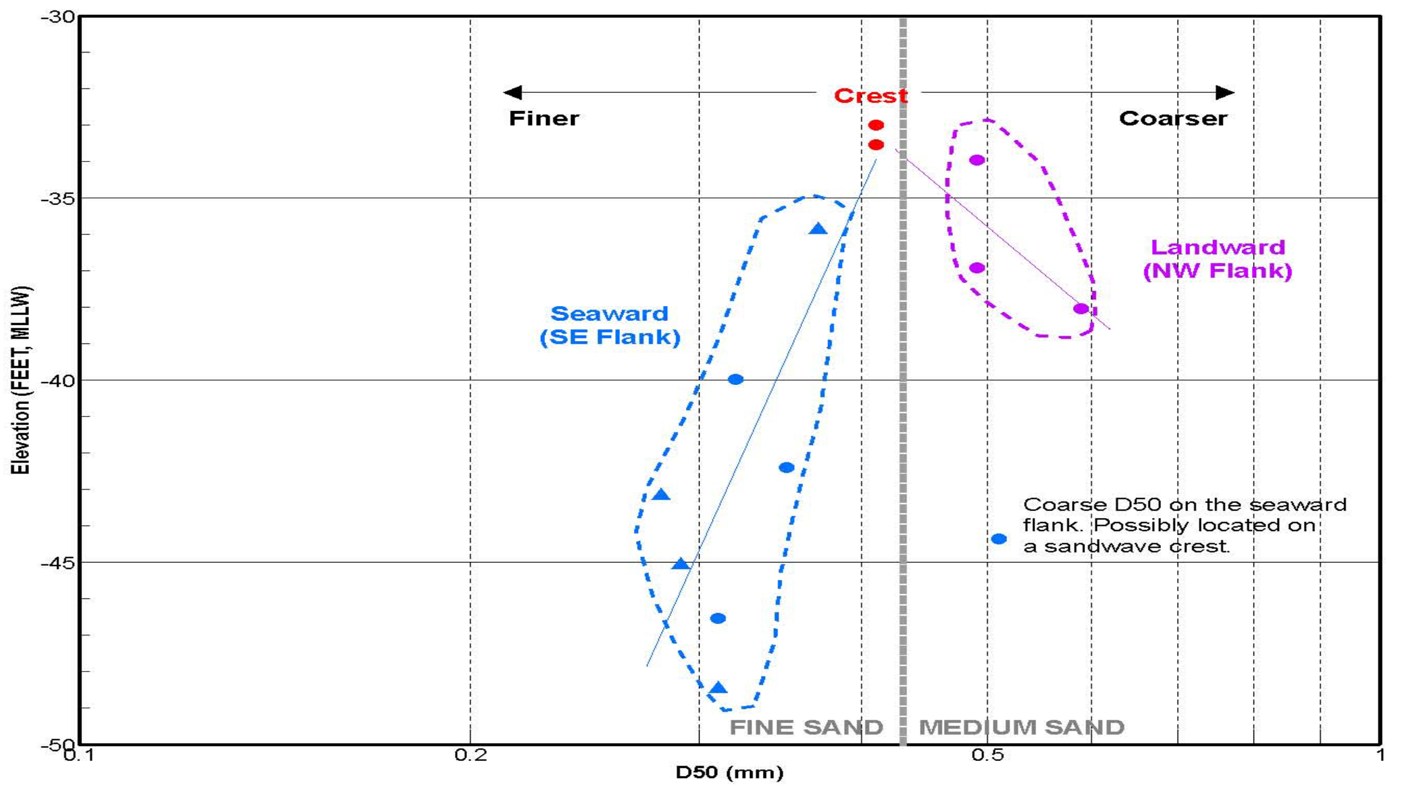
FIGURE 3-7b



Three bedforms if different scales are identified in this image. They are sand ridges, large dunes and ripples of both straight (2D) and discontinuous (3D) types. Each bedform represents flows of different direction, velocity, and duration. Bedforms were interpreted from multibeam bathymetry and side scan sonar data. The dune crests are on the order of 900 ft apart, are approximately 5 ft high, and the steeper, right-hand-side flanks indicate migration to the right in response to currents from the left. The reflectivity of side scan sonar data and grain size data suggest that the ridge crest flank to the top of the page is coarse than the flank on the bottom side of the page. This is consistent with other sand ridge studies that conclude that downwelling currents from nor'easter type storms flowing from top to bottom (cross ridge) of the page are responsible for this sediment distribution. The 2D ripple crests are symmetrical in shape and are suggestive of wave dominated bottom flow. The 3D ripples indicate areas of higher flow velocities than the 2D ripple covered areas. This condition is common on sand ridges in the Mid-Atlantic from Maryland to New Jersey and reflects the complex hydrodynamic

BEDFORMS SUPERIMPOSED ON A SAND RIDGE
TA&R Project #656
Seabed Scour Considerations

FIGURE 3-8a



Sediment grain size of samples collected across seafloor ridge shown on Figure 3-8a. All samples are poorly-graded (well-sorted) with exception of outlier on seaward flank of ridge which is (to a slight extent) more broadly graded.

SEDIMENT GRAIN SIZE ACROSS SEAFLOOR RIDGE
TA&R Project #656
Seabed Scour Considerations

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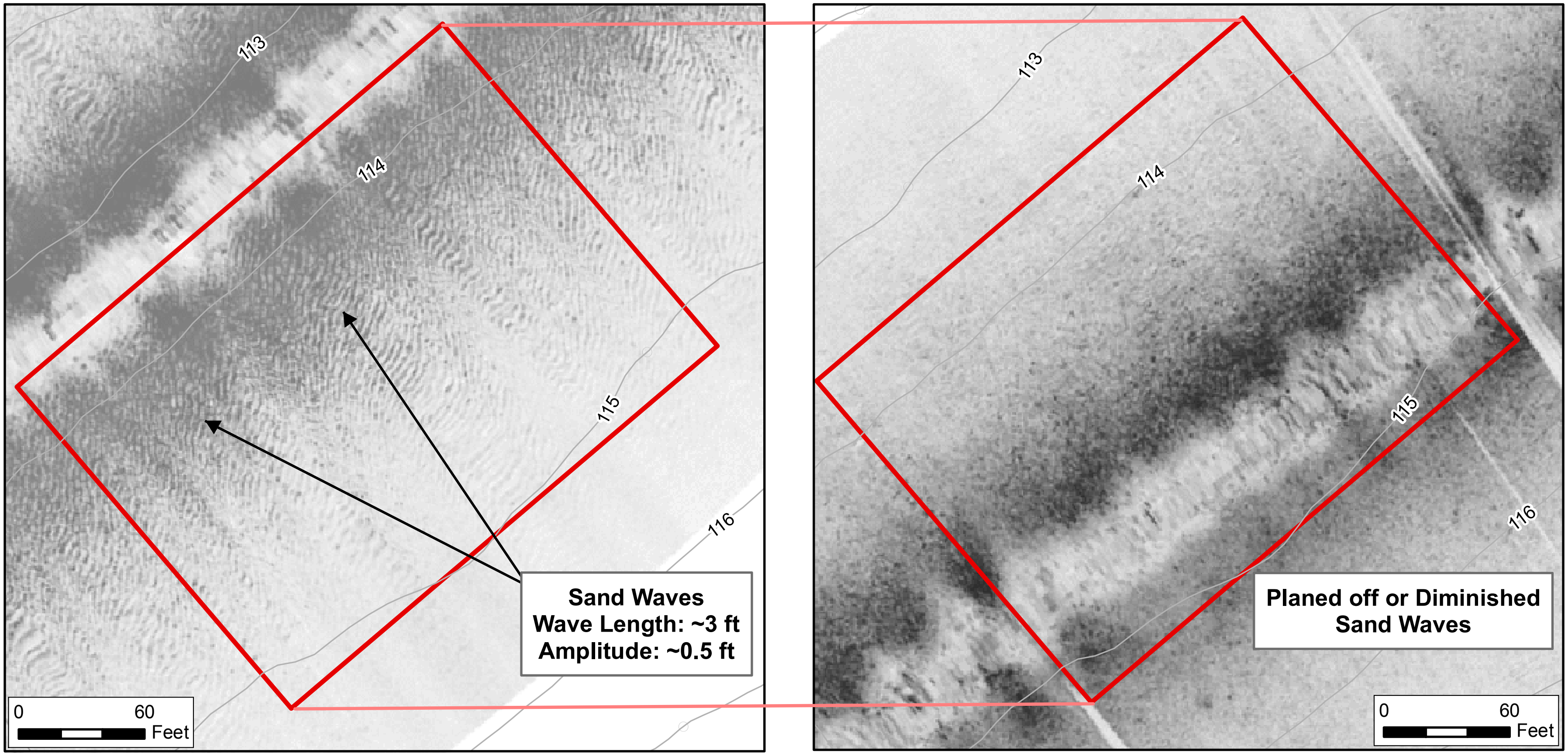


Pre-Storm Seafloor Conditions, Survey Line 113, October 30

No surveying was performed on October 31 due to storm-generated strong wind and rough sea-state conditions.

The side scan sonar image on the left (Line 113) shows the seafloor conditions prior to the storm event and the side scan sonar image on the right (Line 115) shows the seafloor conditions after the storm event.

The red rectangle defines the same extent in both images.

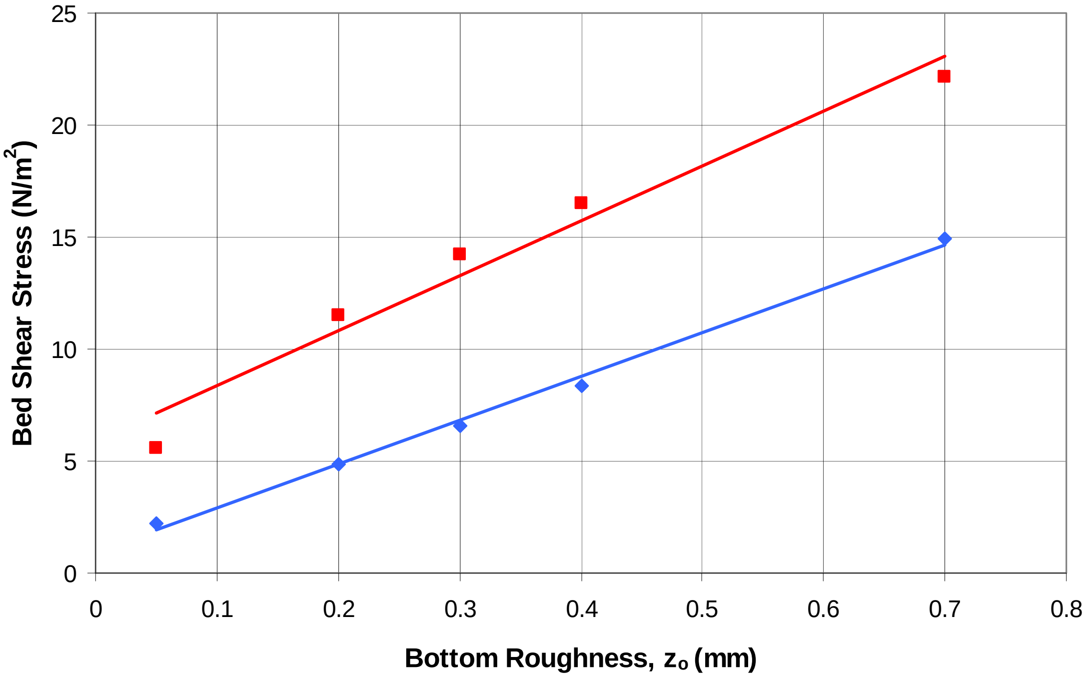
Post-Storm Seafloor Conditions, Survey Line 115, November 1

The image on the left shows bedforms (sand waves) that are absent or diminished in the right image. It is postulated that the storm event produced strong bottom flow and turbulance which induced sediment transport and modified bedforms on the seafloor.

This site is located 15 to 20 nautical miles offshore the Mid-Atlantic coast.

EVIDENCE OF SEDIMENT TRANSPORT
IN SIDE SCAN SONAR DATA
TA&R Project #656
Seabed Scour Considerations

FIGURE 3-9



This simplified plot shows the influence of bottom roughness on the calculated bed shear stress for waves (red) and currents (blue) for a given range of bottom roughness. The bottom roughness values are based on data in Soulsby (1997), which are shown in the table below. The general trend of the data shows that as bottom roughness increases, bed shear stress also increases. This increase in bed shear stress is due to more frictional force acting on the sea bed as a result of increasing the bottom roughness.

Note that this plot is for demonstrational purposes only to show the general trend of increasing bed shear stress with increasing bottom roughness. This should not be used to determine bed shear stress for a particular bottom roughness value since bed shear stress is a function of several variables. The equations used for calculating bed shear stress are described in Appendix C.

Sediment Type	**Bottom Roughness, z_o (mm)**
Silt/Sand	0.05
“Mud”	0.2
Sand with shell	0.3
Unrippled sand	0.4
Mud with sand	0.7
Gravel	3*
Rippled sand	6*

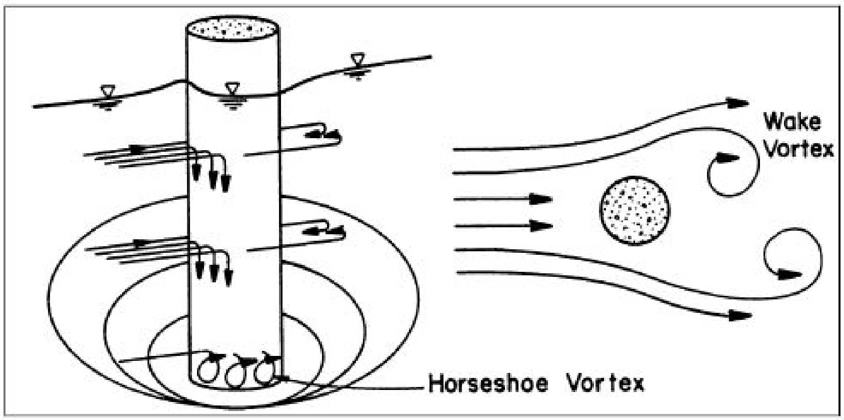
Note: * symbol indicates that the bottom roughness values are not shown in the plot above. This is because calculating bed shear stress using these values for bottom roughness results in bed shear stress values orders of magnitude higher than the scale above.

Conversion: 1 N/m^2 = 0.020885 lb/ft^2

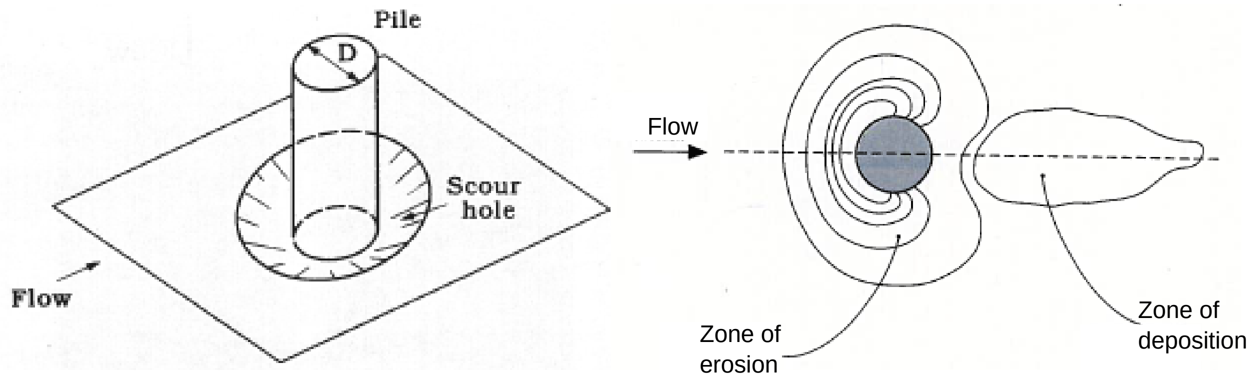
INFLUENCE OF BOTTOM ROUGHNESS ON BED SHEAR STRESS

TA&R Project #656
Seabed Scour Considerations

FIGURE 3-10



According to Sumer and Fredsøe (2002), the key element in the scour process is the horseshoe vortex. This vortex can erode a significant amount of sediment away from the vicinity of the pile. As shown above, the horseshoe vortex is a result of flow encountering the pile and being directed downward into the seafloor causing a rotation of the flow. The turbulent flow then moves around the pile and decelerates (wake vortex) until it stabilizes with the surrounding flow. (Image from Idaho Transportation Department, 2004)



As a result of the turbulent flow around the base of the pile, a truncated cone-shaped scour hole will form (left). In the up-flow direction, the scour hole is more or less equal to the angle of internal friction, whereas in the down-flow direction, the slope is flatter. The characteristic scour pattern (right) is deep scour in the direction of the flow, and a shallow, broad scour on the lee-side. Often an area of deposition is observed as the flow velocity decreases and sediments settle. The location of the zone of deposition will depend upon the flow velocity. The distance from the pile to the zone of deposition will increase in proportion to the difference between the turbulent wake flow in this zone and the flow velocity required to induce scour. The overall depth and lateral extent of this scour hole will depend on the diameter (D) of the pile, sediment characteristics (grain size, sediment gradation), and flow velocity (direction with respect to the pile and magnitude). [Images from Sumer and Fredsøe, 2002 (left), and Whitehouse, 1998 (right)]

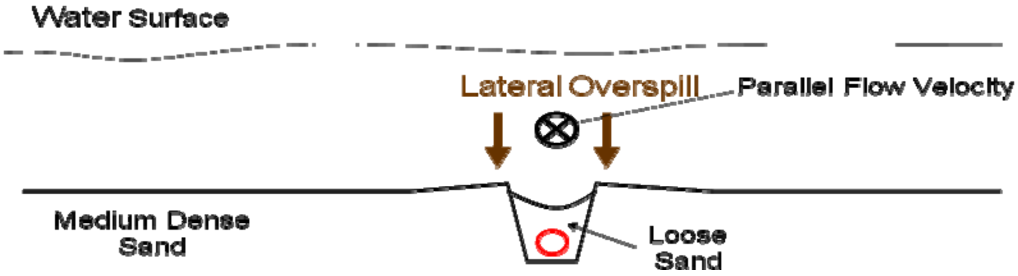
Note: Diagrams are not to scale.

SCHEMATIC DIAGRAM OF SCOUR AT A MONOPILE

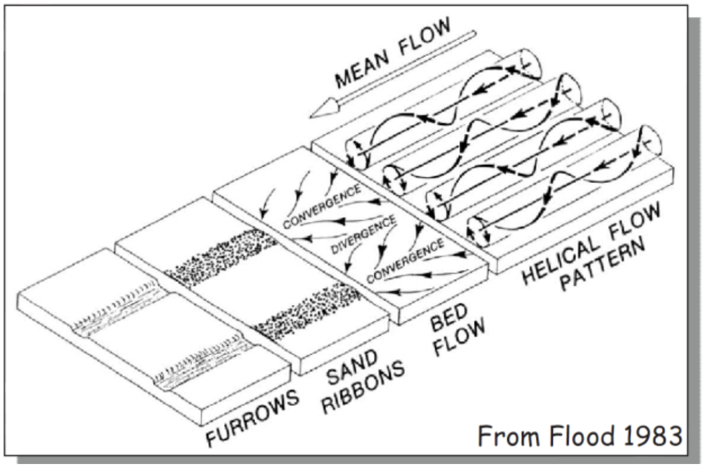
TA&R Project #656

Seabed Scour Considerations

FIGURE 4-1

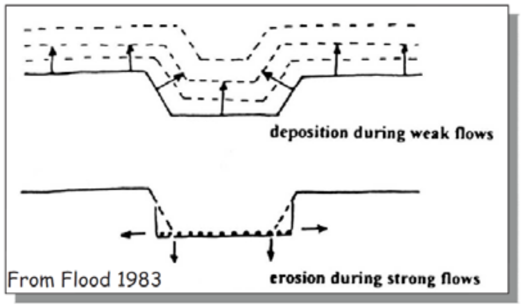


Inset A. The condition depicted above represents a current that flows parallel to a linear trench depression. During the jet-trenching process, fluidized sediments deposit back in the trench in a looser state than the undisturbed sediments. Some of the fluidized sediments will deposit outside the trench as overspill deposits leaving a backfill sediment volume that is less than the volume of the undisturbed trench body. The result is looser sediments infilling the trench which has a slight topographic depression. It is possible the currents flowing parallel could lead to further development or maintenance of the depression in a fashion similar to furrow development and maintenance.



From Flood 1983

Inset B. Development of furrows (long, linear depressions on the seafloor) occurs when concentrated flow transports the finer-grained particles and leave coarser grained (sand ribbons in the image above) sediments. This process is referred to as winnowing. The resulting condition is a localized seabed with a rougher bed (e.g. higher z_o) than the surrounding seabed. This increased roughness leads to localized turbulent flow that continues to erode sediments and eventually develop furrows. Once a furrow is developed, the bedform geometry and distribution of bed-roughness distribution create a secondary stationary circulation current the maintains the furrow and continues to develop it during high-velocity flows.



From Flood 1983

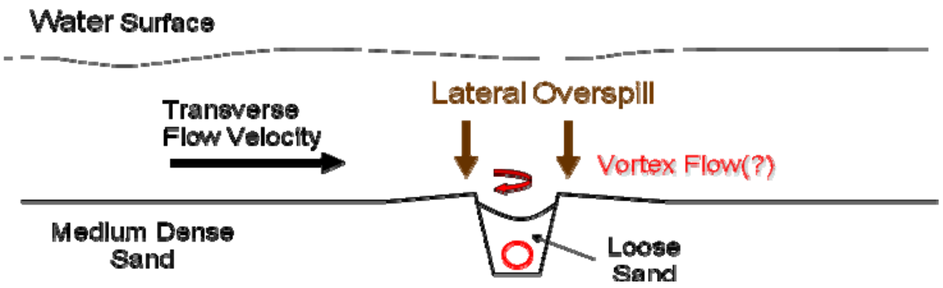
Inset C. Flood (1983) suggests that deposition will narrow the furrow during weak flow and erosion will widen the furrow during strong flows.

FLOW PARALLEL TO TRENCH

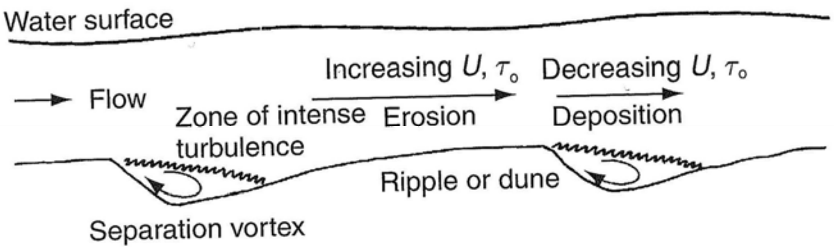
TA&R Project #656

Seabed Scour Considerations

FIGURE 4-2

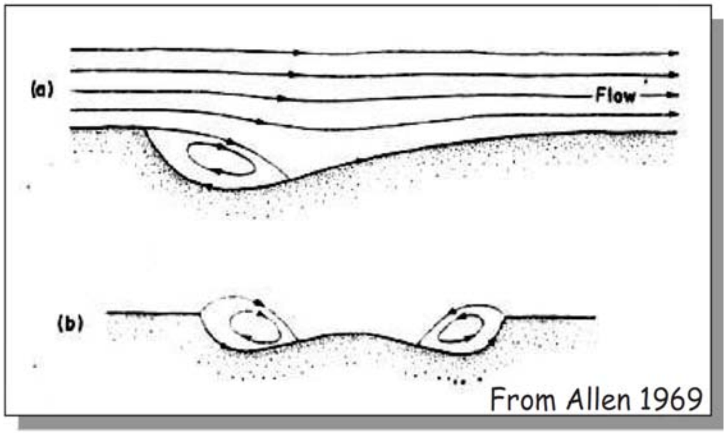


Inset A. The condition depicted above represents a current that flows transversely across a linear trench depression. During the jet-trenching process, fluidized sediments deposit back in the trench in a looser state than the undisturbed sediments. Some of the fluidized sediments will deposit outside the trench as overspill deposits leaving a backfill sediment volume that is less than the volume of the undisturbed trench body. The result is looser sediments infilling the trench which has a slight topographic depression.



U= flow velocity
τ_o = bed shear stress

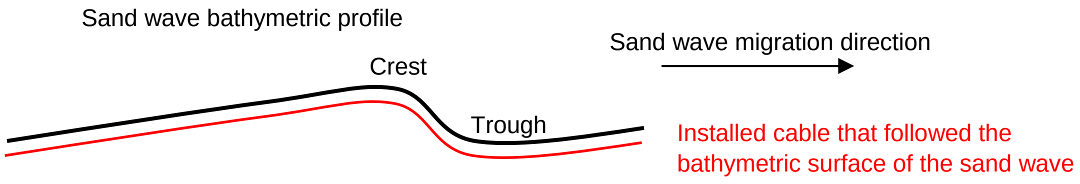
Inset B. This inset depicts a current flowing across ripples or dunes. As the current passes from the crest of the ripple or dune and over the trough portion where the water depth is greater, the flow velocity will decrease and deposition will occur. Modified from Bridge and Demicco (2008)



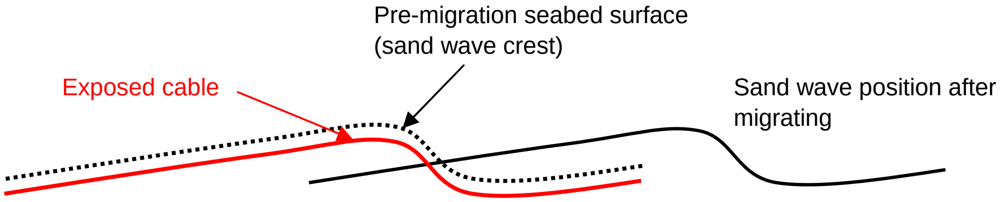
Inset C. This inset depicts current flow lines that separate and form vortex type flows in the depression (similar to the scenario above). Allen (1969) infers that this mechanism is capable of scouring the bed and forming depressions. His work is based on studies in cohesive materials and is adopted by many as the mechanism for forming scour holes that ultimately lead to furrows in the Gulf of Mexico. Modified by Allen (1969).

FLOW PERPENDICULAR TO TRENCH
TA&R Project #656
Seabed Scour Considerations

FIGURE 4-3



(a) Initial installation of an inter-array or export cable over a sand wave with a wave height of 2 to 3 meters (~7 to 10 feet). Cable burial depth is approximately 2 meters (~7 feet). Note that the diagram is not to scale.

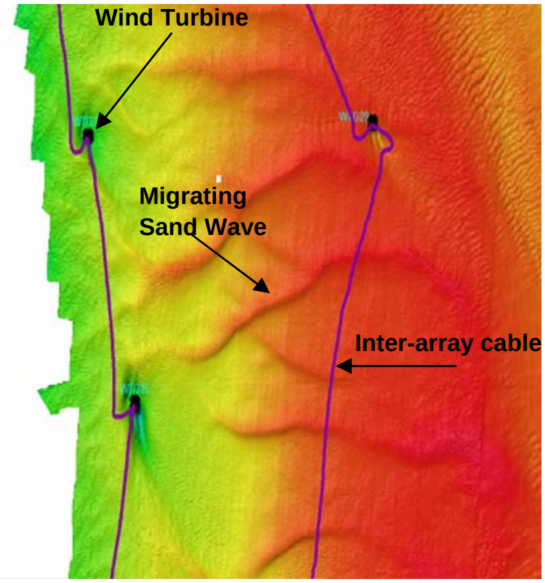


(b) After sand wave migration, the section of the cable installed in the sand wave crest is now exposed in the sand wave trough. Note that the diagram is not to scale.

(c) The image on the right shows and example from an OWF, offshore Europe, where sand waves are migrating through the OWF and over the inter-array cables.

Potential hazards to cables in this situation are:

1) Cable suspension which could put the cables under tension or be supported by only two contact points
2) Unprotected cables which are vulnerable to fishing activities or ship anchoring
3) Exposed cables could experience vibratory movement (strumming) along the sea bed causing abrasion



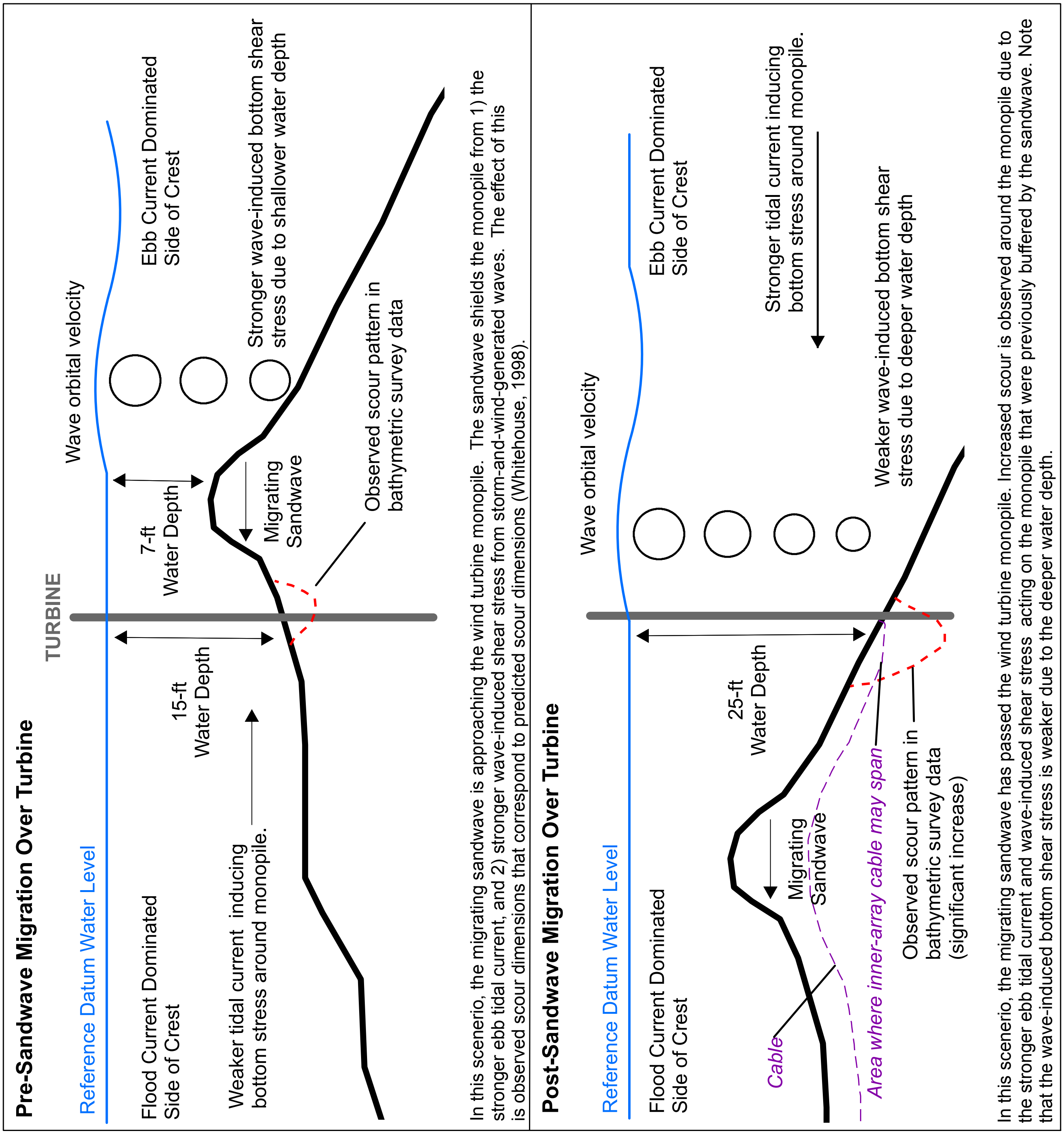
Modified from EON UK (2006)

POTENTIAL HAZARDS TO CABLES IN MOBILE SAND WAVE AREAS

TA&R Project #656
Seabed Scour Considerations

FIGURE 4-4

N:\Projects\3707_MMS\Outputs\Final_Report_Jan2011\mxd\Fig-4-5_Hydrodynamic_Flow_Profile.mxd, 01/20/11, jfisher


Pre-Sandwave Migration Over Turbine

In this scenerio, the migrating sandwave is approaching the wind turbine monopile. The sandwave shields the monopile from 1) the stronger ebb tidal current, and 2) stronger wave-induced shear stress from storm-and-wind-generated waves. The effect of this is observed scour dimensions that correspond to predicted scour dimensions (Whitehouse, 1998).

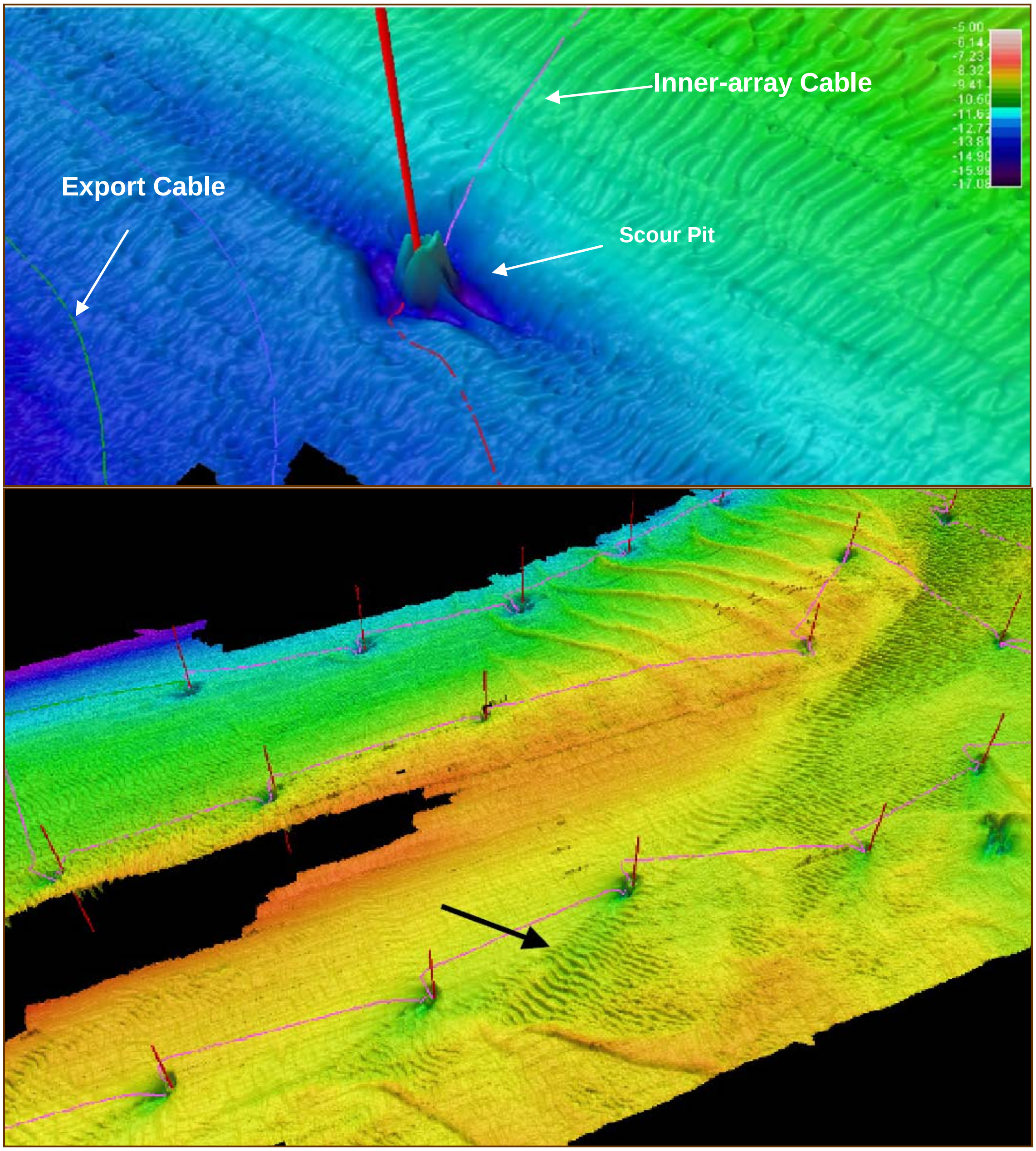
Post-Sandwave Migration Over Turbine

In this scenerio, the migrating sandwave has passed the wind turbine monopile. Increased scour is observed around the monopile due to the stronger ebb tidal current and wave-induced shear stress acting on the monopile that were previously buffered by the sandwave. Note that the wave-induced bottom shear stress is weaker due to the deeper water depth.

HYDRODYNAMIC FLOW PROFILES

TA&R Project #656
Seabed Scour Considerations

FIGURE 4-5



The upper image shows an inner-array cable connecting to a wind turbine. Note the large scour pit formed around the base of the wind turbine. The mass at the base of the turbine suggests that scour protection is present and the scour pit has formed around the edge of the scour protection. It is likely that the cable is spanning across the scour pit. The lower image shows an oblique view of a three-dimensional rendering of the multibeam bathymetry data and wind farm. The turbines (red sticks) and inter-array cable (pink line) are also shown. The bedforms indicate that the hydrodynamic flow regime is variable across the site. Dominant tidal flow is from right to left in the image. Note large sand waves in central area, ripples in the right-hand third, relatively featureless in middle third (ripples are not visible at this scale), and larger, long period sand waves in bottom third. The black arrow points to scour wakes created by the dominant tidal flow from right to left. Modified from CEFAS (2006).

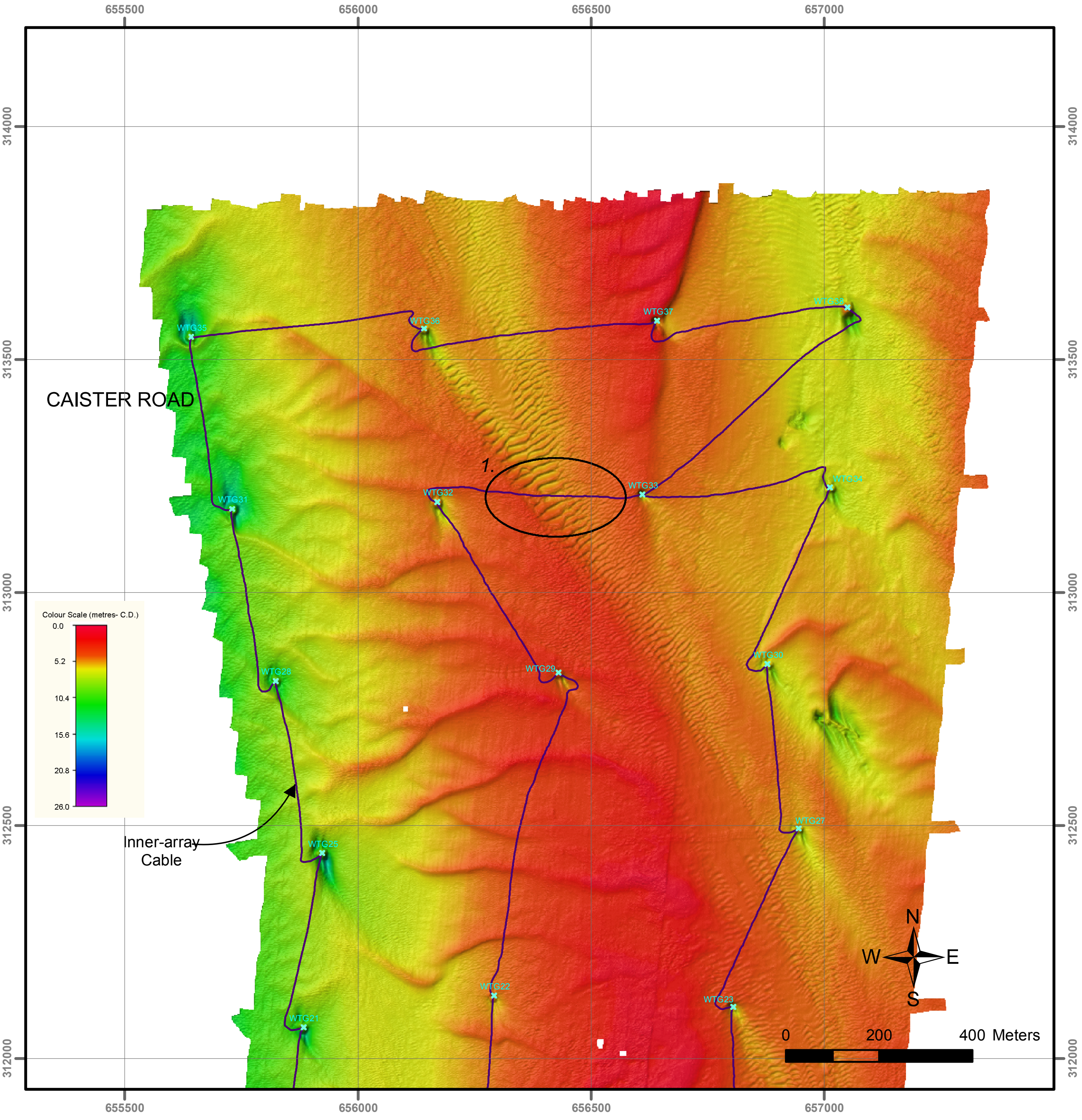
SCROBY SANDS WIND FARM

3D Oblique View of Bathymetry

TA&R Project #656

Seabed Scour Considerations

FIGURE 5-1a



1. Scour wake from turbine
encroached upon inner-array cable

Survey by E.ON UK plc (2006)
C.D. (Chart Datum) is 2.85 below MSL
Coordinate Grid: OSGB(36)

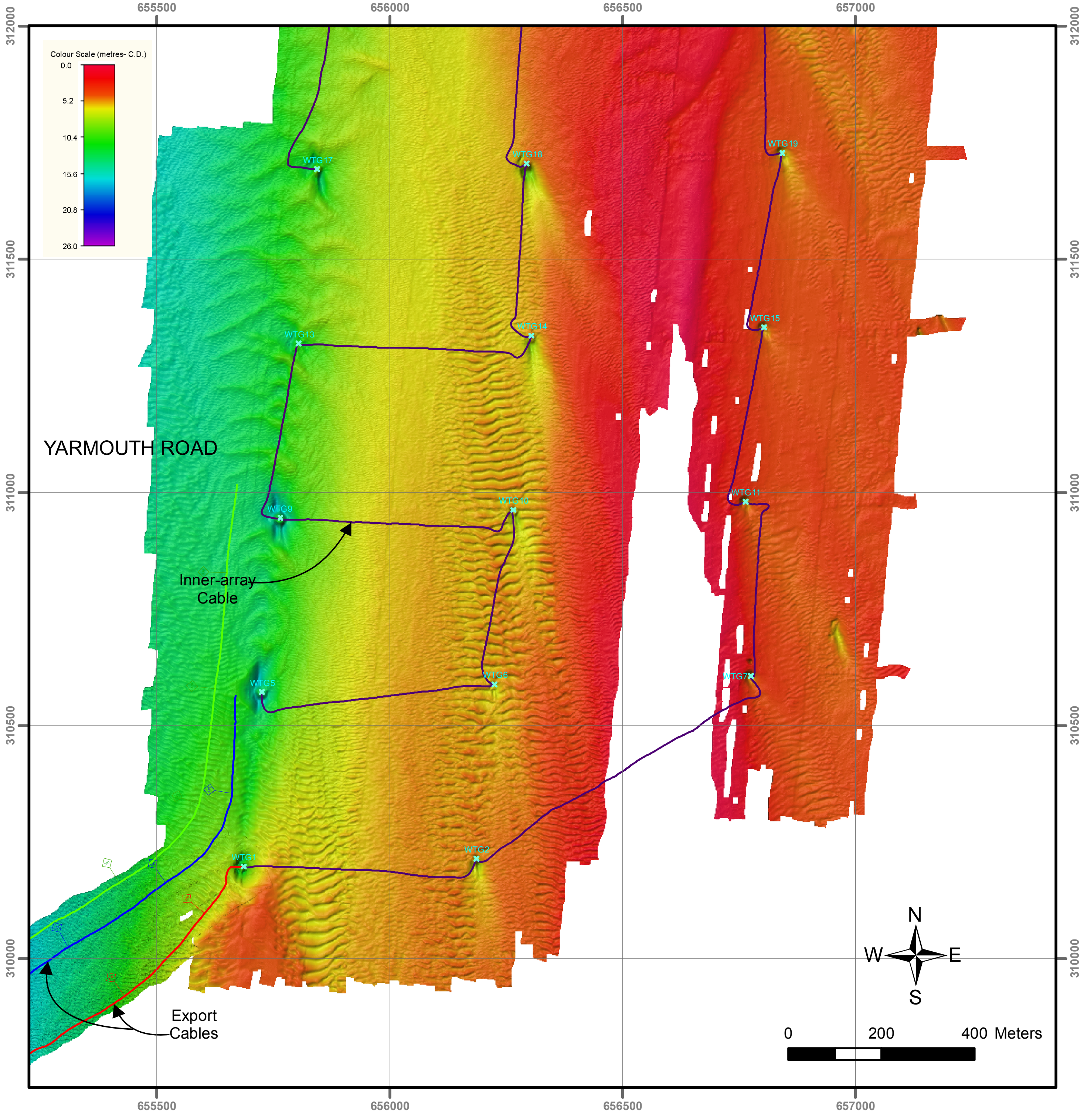
SCROBY SANDS WIND FARM
Northern Section
TA&R Project #656
Seabed Scour Considerations

LEGEND

WTG35 × Turbine Location

FIGURE 5-1b

N:\Projects\3707_MMS\Outputs\Draft_Report_Nov2010\mxd\Fig-5-1b_Scroby_Bathymetry.mxd, 12/06/10, ksmith



Survey by E.ON UK plc (2006)
C.D. (Chart Datum) is 2.85 below MSL
Coordinate Grid: OSGB(36)

SCROBY SANDS WIND FARM
Southern Section

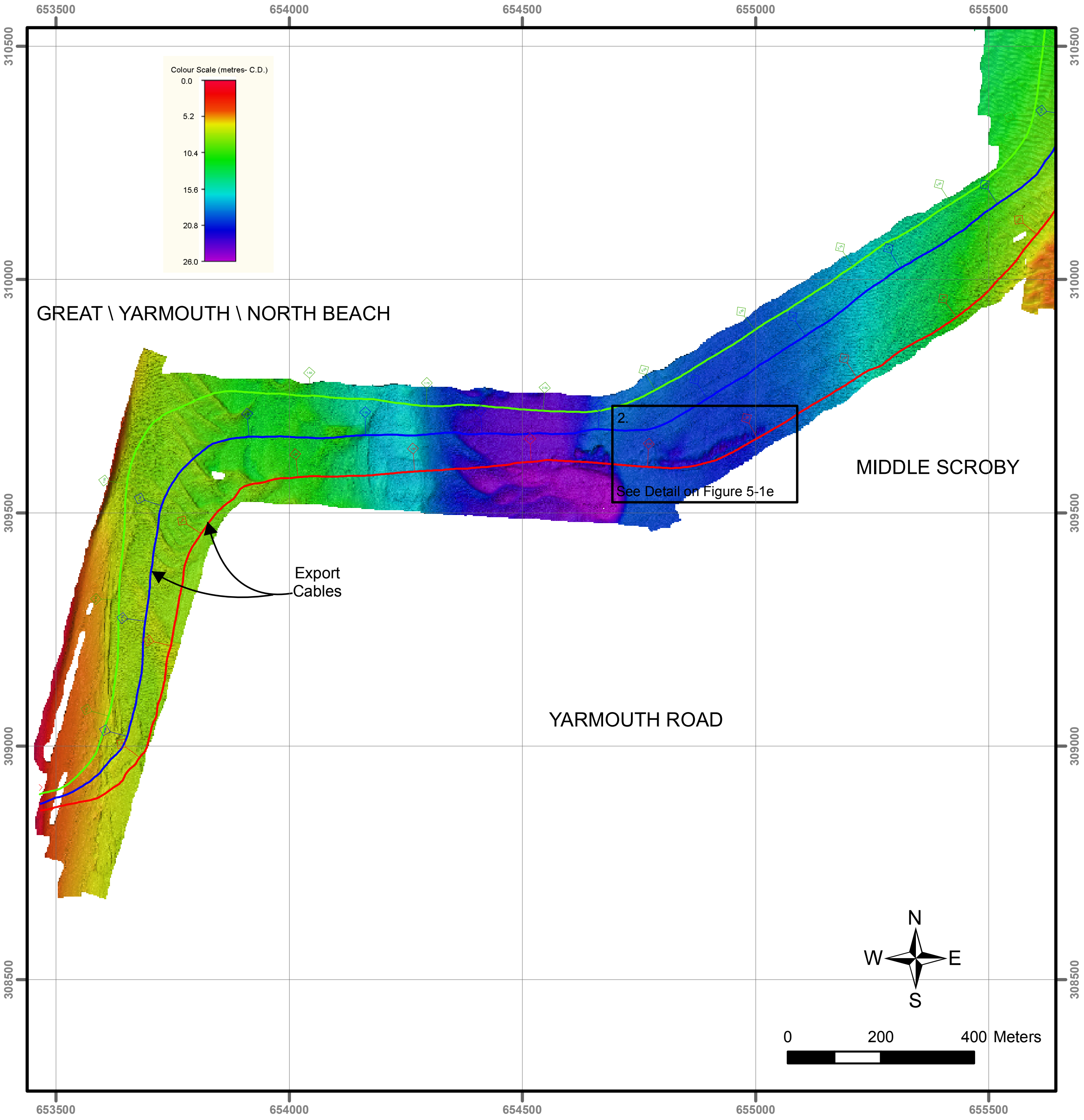
TA&R Project #656
Seabed Scour Considerations

LEGEND

WTG35 ✕ Turbine Location

FIGURE 5-1c

N:\Projects\3707_MMS\Outputs\Draft_Report_Nov2010\mxd\Fig-5-1c_Scroby_Bathymetry.mxd, 12/06/10, ksmith



N:\Projects\3707_MMS\Outputs\Working\mxd\Fig-5D_Scroby_Bathymetry.mxd, 12/03/10, kstevens

2. Apparent scour protection with noticable sediment disturbace. See Figure 5-1e for detailed plan and profile view.

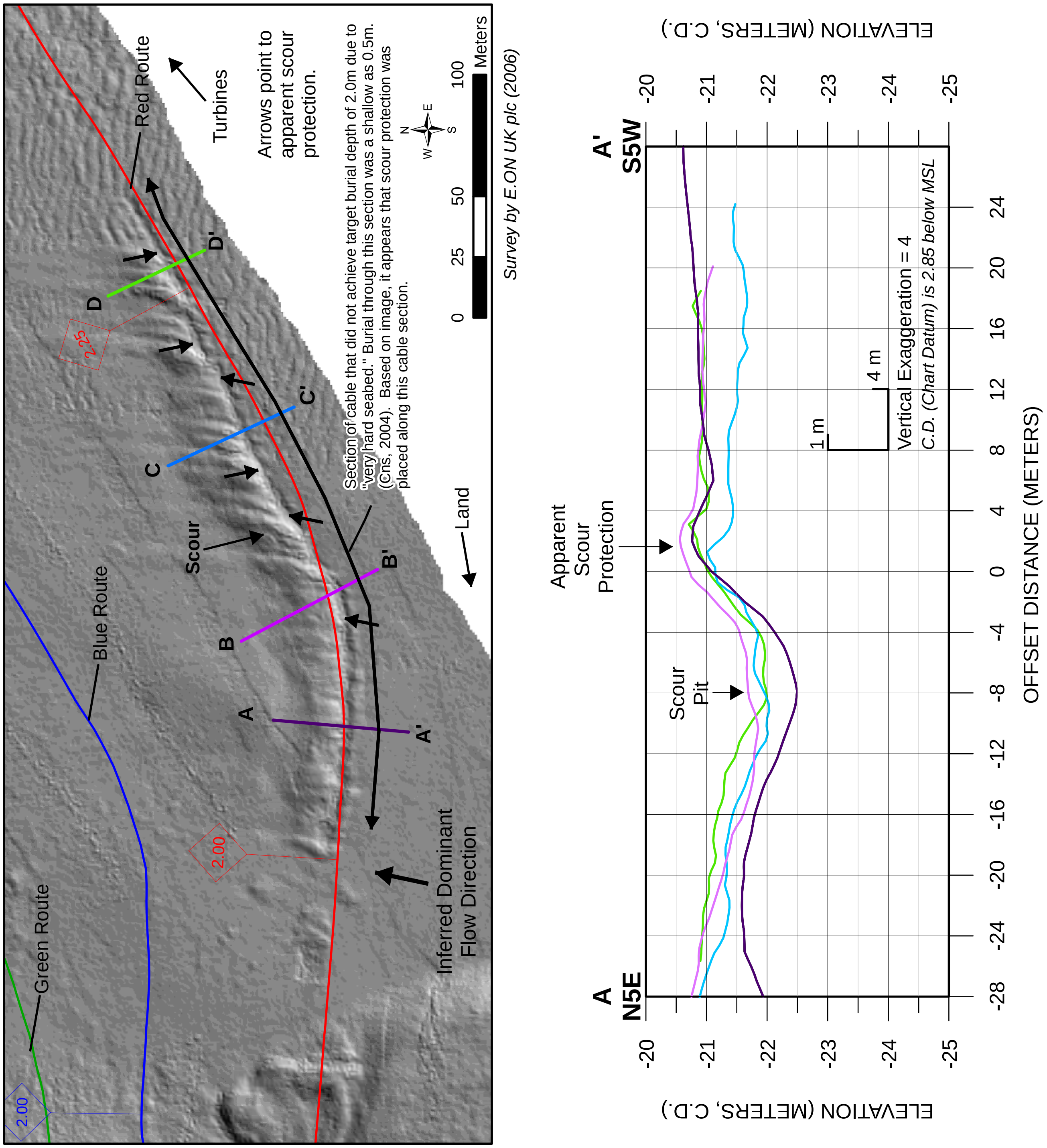
Survey by E.ON UK plc (2006)
C.D. (Chart Datum) is 2.85 below MSL
Coordinate Grid: OSGB(36)

SCROBY SANDS WIND FARM
Export Cable
TA&R Project #656
Seabed Scour Considerations

LEGEND

WTG35
× Turbine Location

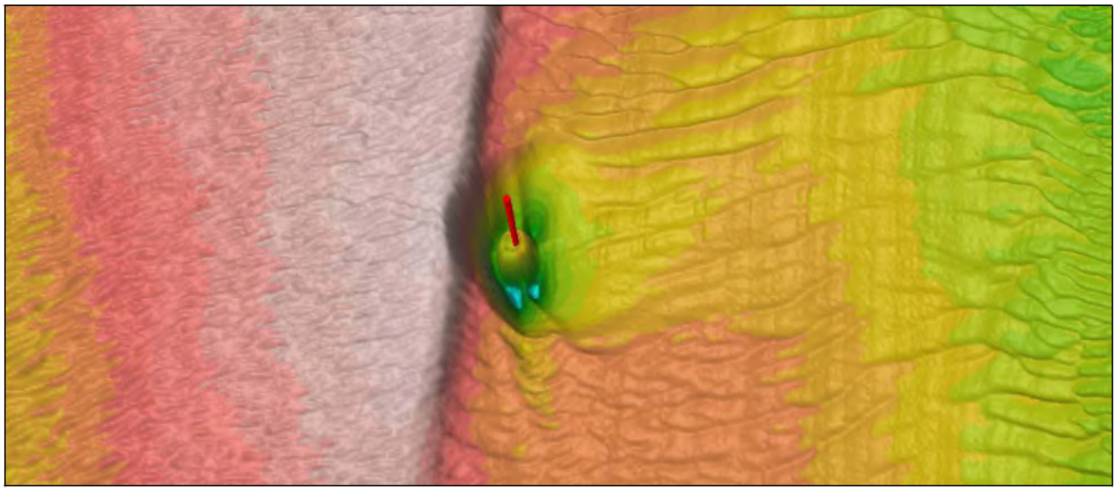
FIGURE 5-1d



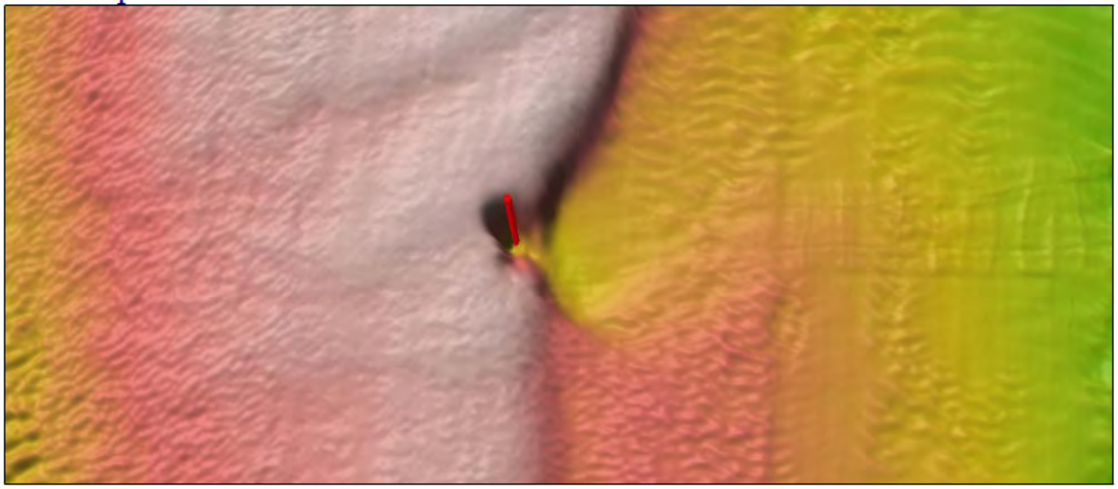
SCROBY SANDS WIND FARM
Export Cable Route
TA&R Project #656
Seabed Scour Considerations

FIGURE 5-1e

N:\Projects\3707_MMS\Outputs\Working\mxd\Fig-5E_Scroby_CableRoute_Profile.mxd, 12/03/10, kstevens



a. April 2006

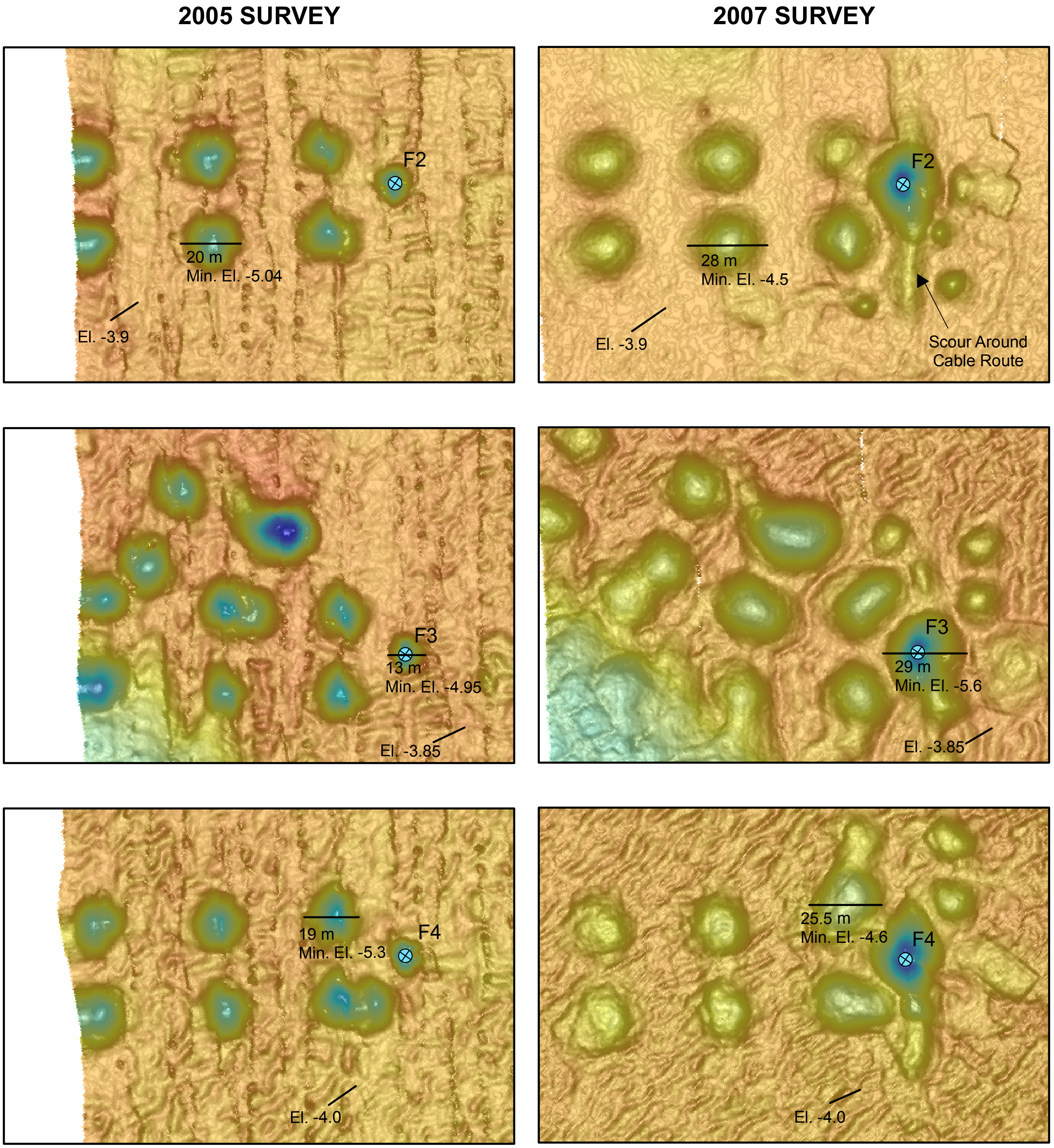


b. November 2006

The bathymetry data in the images above show the shift of the sand bank crest between April and November in 2006 at WTG-37. Movement of large bedforms can infill scour pits or provide additional cable burial protection. Conversey as discussed elsewhere in this report, movement of large bedforms can expose buried cables and modify local flow conditions that can increase or decrease scour. Modified from CEFAS (2008).

SCROBY SANDS WIND FARM
Shifting of Bank Crest
TA&R Project #656
Seabed Scour Considerations

FIGURE 5-1f



Survey by Emu Ltd. (2005/2007)

LEGEND

⊕ Turbine Location

Elevation (meters, C.D.)
C.D. (Chart Datum) is 2.85 m below MSL

High : -3.4

Low : -6.22

SPUD DEPRESSIONS AND SCOUR AT KENTISH FLATS WIND FARM

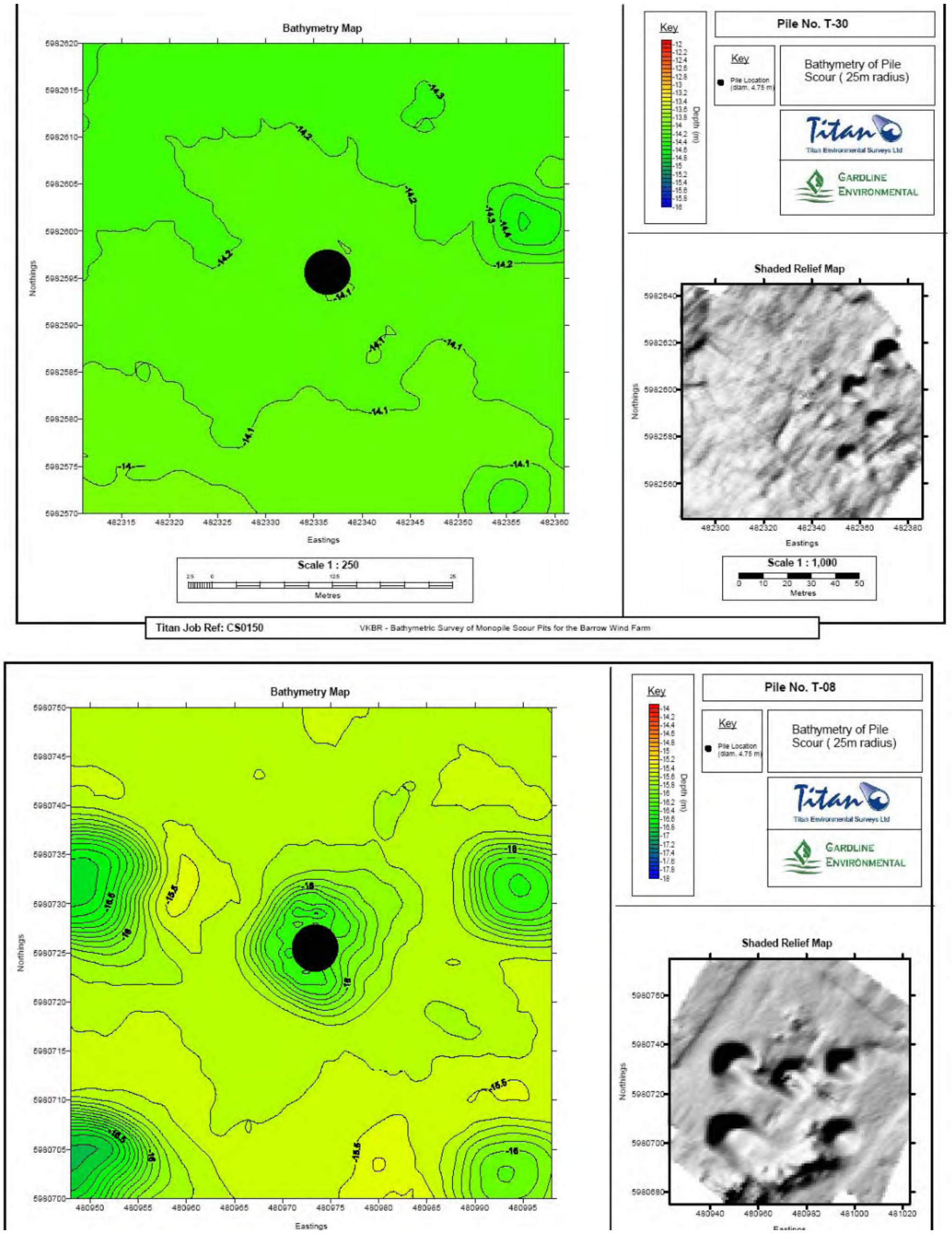
Post-construction Surveys
TA&R Project #656
Seabed Scour Considerations

W N E S

0 25 50 Meters

FIGURE 5-2

N:\Projects\3707_MMS\Outputs\Final_Report_Jan2011\mxd\Fig-5-2_KentishFlat_ScourExamples.mxd, 01/20/11, jfisher



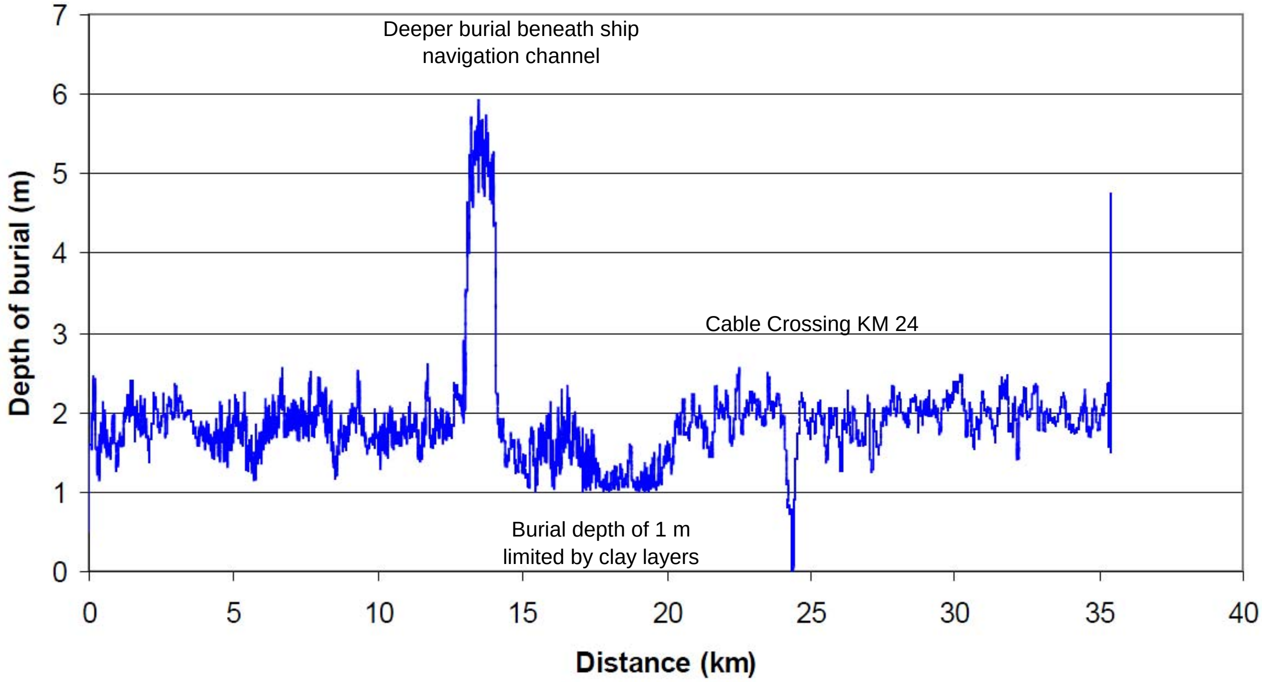
Scour is influenced by the seabed materials. No visible scour has developed in the upper image where the seabed is comprised of glacial till. However the spud depressions from the jack-up are still present. In contrast, scour has developed in the silty sand seabed sediments shown in the lower image. Modified from CEFAS (2008).

BARROW WIND FARM
Scour Influenced by Seabed Materials

TA&R Project #656

Seabed Scour Considerations

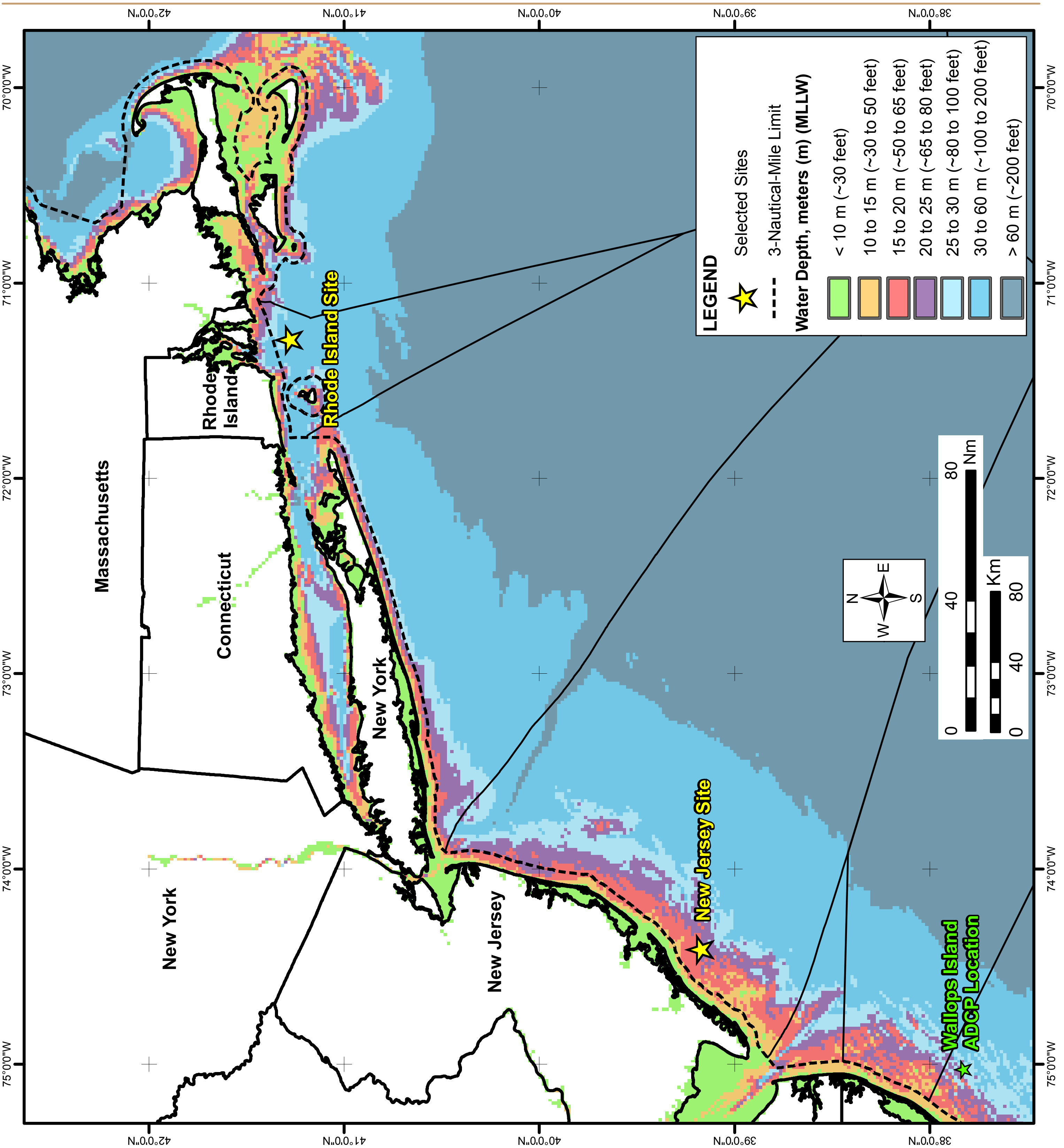
FIGURE 5-3



Cable burial survey indicates cable buried typical about 2 meters (~ 7 feet) except where limited to 1 meter (~3 feet) by clay layers and beneath a shipping channel and telecommunications cable crossing. Modified from C-Power (2009).

THORTON BANK WIND FARM
Cable Burial Survey
TA&R Project #656
Seabed Scour Considerations

FIGURE 5-4

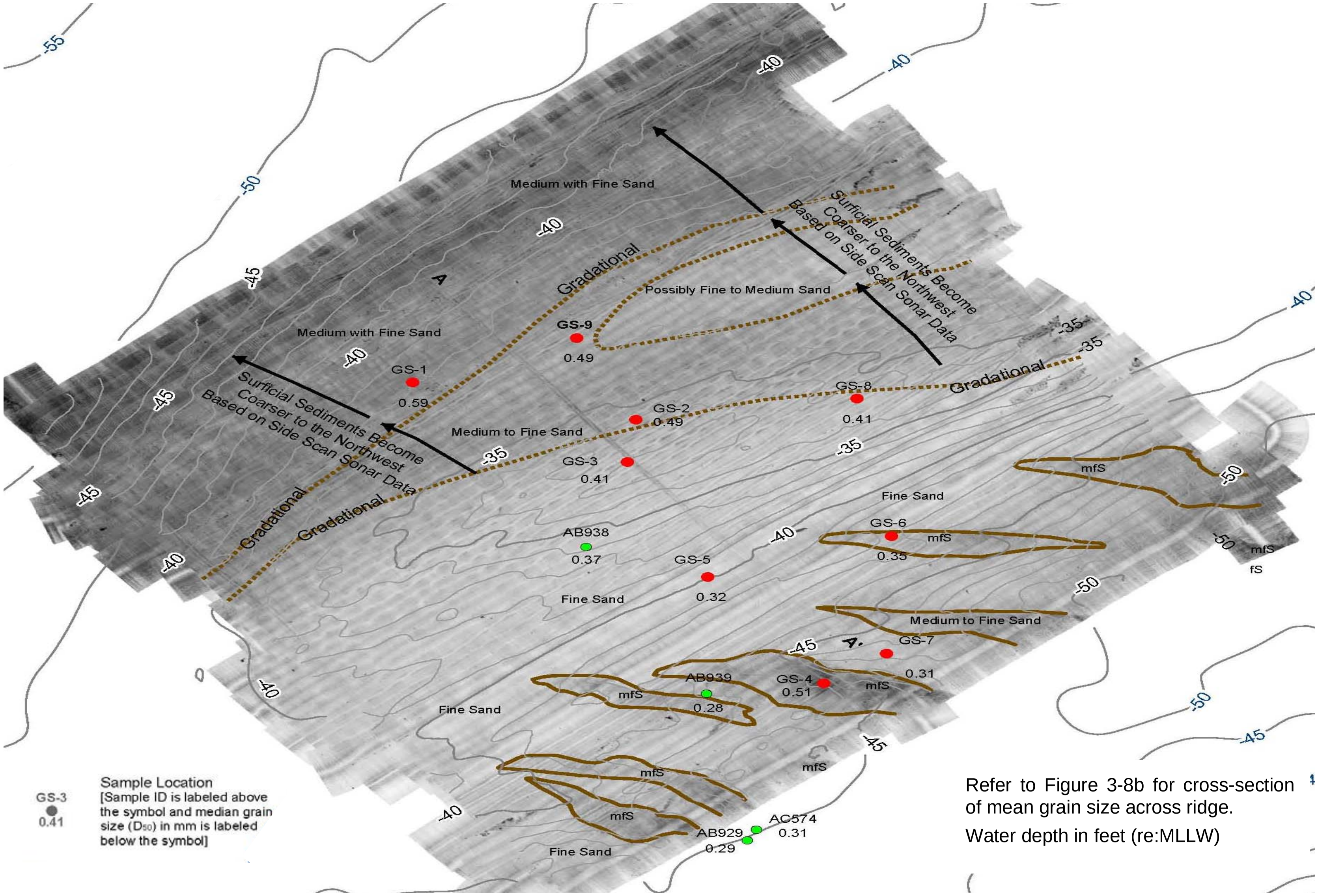


N:\Projects\3707_MMS\Outputs\Final_Report_Jan2011\mxd\Fig-6-1_Site_Locations.mxd, 01/11/11, jfisher

Coordinate Grid: Latitude/Longitude, WGS84

SITE LOCATIONS
TA&R Project #656
Seabed Scour Considerations

FIGURE 6-1



Refer to Figure 3-8b for cross-section of mean grain size across ridge.

Water depth in feet (re:MLLW)

ZONATION OF SIDE SCAN SONAR REFLECTIVITY
Based on Sediment Grain Size
TA&R Project #656
Seabed Scour Considerations

APPENDIX A
RHODE ISLAND SOUND SITE EVALUATION

APPENDIX A CONTENTS

FIGURES

APPENDIX A
RHODE ISLAND SOUND SITE EVALUATION

INTRODUCTION

Two sites were selected for demonstration site evaluations on the Atlantic continental shelf: Offshore Rhode Island in the Round Island Sound in the North Atlantic and offshore New Jersey on the open Mid-Atlantic continental shelf (Figure A-1). These sites were selected for the following reasons:

- Data were available to perform site specific scour analyses. This includes bathymetry, side scan sonar, sediment grain size data, and current and wave data.
- These sites are different in terms of the hydrodynamic flow regime and geologic conditions, and are generally representative of the broad range in conditions that Offshore Wind Farm (OWF) developers could experience on the Atlantic continental shelf.
- Both sites are in areas under consideration for potential OWF development.

The offshore Rhode Island site is within Rhode Island Sound, which separates the Narragansett Bay system from the open Atlantic Ocean shelf, and is bounded by Block Island Sound to the west and Buzzard's Bay and Vineyard Sound to the east. This region is defined as microtidal with a mean tidal range of about 2.5 to 3 feet (FitzGerald et al., 2002). The Rhode Island Sound has a similar flow regime to that of the Mid-Atlantic continental shelf environment due to its proximity to the open shelf, but also shows seabed features that are tidally-influenced such as sand waves (Morton, 1972; FitzGerald et al., 2002, McMullen, 2007a).

The complex hydrodynamic flow regime in the Rhode Island Sound requires investigating the interrelationship of several variables to assess and predict scour. Data and information required to assess scour includes:

- Wind, wave, current, and tidal data (including direction) for developing bottom flow conditions;
- Water depth;
- Seafloor topography and morphology; and
- Seafloor sediment characteristics.

Several public domain resources were available to obtain the required information to assess scour. Surface-wave data were available through the National Data Buoy Center (NDBC). Current data were available from bottom-mounted Acoustic Doppler Current Profilers (ADCPs) used as part of the Front-Resolving Observation Network with Telemetry (FRONT) project. For waves, hourly statistics were analyzed for significant wave height, dominant (or peak) wave period, and mean wave direction for buoy 44025 over the time period 1991 to 2009. For currents, data from four bottom-mounted 600-kHz ADCPs (SP01-Wm, FA01-W, WI02-W, and SP02-Wm) were analyzed over the period from March 2001 through June 2002. Wave and current data were analyzed by Dr. Jose Blanco from the Center of Coastal Physical Oceanography at Old Dominion University.

Multibeam bathymetry and side scan sonar survey data were available from several National Oceanic and Atmospheric Administration (NOAA) surveys. The processed survey data were downloaded and reprocessed to a finer resolution, and then incorporated in Fugro's geographical information system (GIS) system for analysis.

Surficial sediment data were available through several U.S. Geological Survey (USGS) databases. The USGS usSEABED database (Reid, et al., 2005) includes a variety of information about sediment texture, composition, seafloor features, and sediment grain size data derived from laboratory investigations. The USGS East Coast Sediment Analysis database (Hastings, 2000) is a collection of data on sediment grain size that includes sediment gradation laboratory test data. USGS Open-File Report 03-001 (Poppe et al., 2003a-d) contains GIS compilation of surficial sediment data from several sources, specifically for the New England region.

Additional GIS data were available through the Rhode Island Ocean Special Area Management Plan (OSAMP) research (URI EDC, 2008). The GIS data included marine boundaries, utilities, transportation routes, water depth, etc., that are useful for locating areas suitable for OWF development, offshore Rhode Island.

SITE CHARACTERIZATION

Site Location

The OSAMP research (URI EDC, 2008) included a Tier 1 analysis that defined restricted areas and no-build zones for offshore Rhode Island. Results from that analysis were used to site and define the hypothetical OWF footprint boundaries for the Rhode Island Sound site (Figure A-2). This analysis considered regulated cable and navigation areas on NOAA nautical charts, distance buffers for coastal areas and airport fly zones, and water depth to define areas suitable for development. The defined OWF footprint is comparable in size to other OWFs being considered in the U.S. The water depth in the hypothetical site is 100 to 130 feet and the site is divided into two parts to avoid the navigation lanes. The export cable routes were chosen to avoid restricted areas and to converge at the coast in a location where several submarine cables meet.

Bathymetry

Figure A-3 shows the regional and detailed bathymetry for the Rhode Island Sound. A dashed line in the figure delineates the boundary between the two data sets. The detailed bathymetry is from multibeam data and encompasses most of the demonstration site. The regional data is from soundings that span several decades and the soundings are widely spaced (100s to 1000s of feet apart). The multibeam data have significantly closer data point spacing than the regional data and therefore can resolve smaller features. The multibeam data are able to resolve bedforms (e.g. sand waves) that were used to identify sediment transport hazard areas (e.g. sand wave fields).

Block Island Sound and Rhode Island Sound are separated by an approximately 4 Nautical mile (Nm) submarine ridge that extends north from Block Island. A second ridge protrudes about 5 Nm south from Point Judith and terminates abruptly. A series of isolated bathymetric highs continue along that trend into the OWF area. A large channel south of the site runs from the open shelf of the Atlantic towards the Vineyard Sound.

The southern section of the OWF generally is within a bathymetric low. Most of the area is relatively flat, smooth and featureless, and has a maximum water depth of approximately 135 feet. Several highs are present in the central and eastern portion of the southern section. The northern section of the OWF is on a bathymetric high that is relatively broad, composed of sedimentary features (e.g. sand waves), and has a maximum water depth of approximately 100 feet. Sand waves observed in side scan sonar data (McMullen et al., 2007a-b; McMullen et al., 2009) trend north-south indicating an east-west flow direction and have wavelengths ranging from about 30 to 100 feet.

Subsurface Geology of Rhode Island Sound

The general subsurface geology of Rhode Island Sound is as follows (McMaster, 1960; McMaster et al., 1968; Knebel et al., 1982; Needell et al., 1983; Needell and Lewis, 1984; McMullen et al., 2007a, b). Bedrock consists of south-southeasterly dipping igneous and metamorphic basement rocks. These units are overlain by a seaward-dipping unconformity and Cretaceous age coastal-plain strata. Pleistocene glacial drift deposits and/or Holocene fluvial and transgressional sediments represent the near-subsurface and surficial units.

In terms of geological influences on the surficial sediments and bathymetry, glacial and post-glacial events have had the greatest influence in the area of interest (Figure A-4). Bathymetric lows in the southern section of the OWF generally correspond to post-glacial stream channels that are infilled with fine-grained sediments. These channels were mapped using high-resolution seismic reflection methods (Needell et al., 1983) and represent melt water drainages. Two moraines traverse the Rhode Island Sound as indicated by submarine ridges and extensive areas of gravel deposits. Surficial sediments in these areas are diverse (i.e., fine-grained sediments to boulders) and represent reworked glacial drift deposits, including moraine, outwash, and glaciolactustrine deposits (McMullen et al., 2007a, b). In adjacent Block Island Sound, bottom sediments are predominantly sand derived from reworked glacial deposits (Savard, 1966), which is analogous to areas outside of the ridges in Rhode Island Sound.

Surficial Seabed Sediments

Figure A-5 shows the sediment mapping for the Rhode Island Sound site area. Surficial sediment classifications from sampled locations are shown along with grain size data for samples locations where available (Hastings, 2000; Poppe et al., 2003a-d; Reid, et al., 2005).

Surficial sediments within the bathymetric lows (blue areas) are generally described as "mud" and have grain sizes characteristic of silts or clays (0.02 to 0.05 millimeters [mm]) in the deeper portions of the area, and of fine sand (0.10 mm) elsewhere. In the side scan sonar data, these areas have low backscatter, which indicates finer-grained sediments. These surficial sediments are interpreted as silty fine sand/sandy silt/sandy clay with a characteristic grain size of 0.10 mm (light blue), and silt or clay with minimal sand and a characteristic grain size of 0.05 mm in the deep areas.

Surficial sediments on the submarine ridges (light red areas) are generally described as gravelly sands to gravel, with a few samples described as mud. Those surficial sediments within those areas are interpreted as gravelly sands with a characteristic grain size of 0.50 mm due to the gravel component. No laboratory data are available for consideration when assigning the characteristic grain size.

Areas adjacent to ridges (yellow areas) in deeper water are described as silty sand or silt. Although no laboratory data were available to show a characteristic grain size, these surficial sediments are interpreted as silty sand to sand with a characteristic grain size of 0.29 mm.

In the northern section of the OWF (orange area), surficial sediments are described as fine to medium sand. One laboratory test sample within this area had a median grain size (D50) of 0.29 mm. Sand waves that trend north-south were observed in the side scan sonar data in the western part of this section. These surficial sediments are interpreted as poorly graded sand with a characteristic grain size of 0.29 mm.

On the eastern part of the southern OWF section (orange area), sand waves are observed in the side scan sonar data on the bathymetric high. No samples or laboratory data are found within this area. Based on the area's similarity to the northern section, the surficial sediments are interpreted as poorly-graded sand with a characteristic grain size of 0.29 mm.

Two export cable routes were considered. The Option 1 export cable route extends mostly within the bathymetric low areas that are interpreted as silty fine sand/sandy silt (characteristic grain size of 0.10 mm) with silt or clay in the deep areas (characteristic grain size of 0.05 mm). The Option 2 export cable route starts on a bathymetric high interpreted to consist of poorly-graded sand (0.29 mm characteristic grain size) and migrating sand waves. As both routes progress toward the shore, the surficial sediments change to silty sand (characteristic grain size of 0.29 mm), and then to a gravelly sand (characteristic grain size of 0.50 mm). The shallow zone near the coast is interpreted as gravel to gravelly sands with a characteristic grain size of 0.50 mm, but may include areas of rock outcrop.

SCOUR POTENTIAL ANALYSIS

Interpreted Sedimentary Environments

Bed shear stress for waves and/or currents, and threshold shear stress for the characteristic sediment grain sizes were calculated following the methodology in Soulsby (1997), as described in Appendix C. Exceedance diagrams are produced by plotting the percentage of bed shear stress exceedance versus shear stress. This is useful because, according to Whitehouse (1998), long-term sediment transport is likely to occur if the generated bed shear stress exceeds the threshold shear stress for particular sediment grain size at least 10 percent of the time.

Figure A-6a and Figure A-6b show the bed shear stress exceedance diagrams for waves and currents, respectively. Figure A-6c shows the summary of all-year wave, current, and combined wave and current bed shear stress. The bottom shear stress exceedance diagrams suggest the following:

- The calculated bed shear stress due to waves (Figure A-6a) for the sandy silt, silty sand, and fine sand grain sizes exceeds 10 percent only for the months of September, February, and March. The calculated bed shear stress shows variation throughout the year with the higher shear stresses typically occurring during the late summer through winter months. The mean wave bed shear stress is in the exceedance range of approximately 18 to 25 percent for the fine grain sizes that are characteristic of the OWF footprint.
- The calculated bed shear stresses due to currents (Figure A-6b) for the sandy silt, silty sand, and fine sand grain sizes exceeds 10 percent for only the month of July. The calculated bed shear stress shows less variation throughout the year when compared to the wave bottom shear stress. The mean current bed shear stress is in the exceedance range of approximately 2 to 12 percent for the fine grain sizes which are characteristic of the OWF footprint.
- The summary exceedance diagram for waves, currents, and combined currents and waves (Figure A-6c) shows that the all-year mean flow for waves is above the 10-percent exceedance level for all characteristic grain sizes within the OWF (i.e. 0.10 mm, 0.29 mm, and 0.50 mm). However, the mean combined wave and current flow only exceeds 10 percent for the fine sand sediment sizes and not the 0.50 mm grain size. This is because the combined wave and current mean flow is less than the all-year mean wave flow, due to the wave and current flows not being co-directional. The mean current flow only exceeds 10 percent for the very fine sand grain sizes.

The assessment of sediment transport within the potential OWF based on the bed shear stress data is shown in Figure A-7. Areas with surficial sediments consisting of silty sands to sands (characteristic grain size of 0.29 mm) are considered to be highly mobile due to waves and/or currents. This interpretation is consistent with observation of sand waves within parts of these areas. The reworked ridge deposits mapped as gravelly sands (characteristic grain size of 0.50 mm) are considered mobile due to wave-only flow conditions.

Areas within the bathymetric lows that consist of fine-grained or silty/clayey sand areas are interpreted to be depositional environments. The fine-grained sediments are most likely mobile under extreme wave-induced bed shear stress (i.e. storm events), but are inferred to be immobile under mean flow conditions. This is partly due to the cohesive effect of fine-grained sediments increasing the threshold shear stress.

Sediments in the nearshore area are considered to be very mobile, since this area includes the surf zone where breaking waves are common. Surficial sediment samples within this region are commonly described as gravels or rock (Poppe et al., 2003b), which may be either gravel lag deposits or exposed shallow bedrock due to increased sand sediment transport.

Scour Susceptibility Assessment

Figure A-8 shows the scour susceptibility for the Rhode Island Sound OWF. The scour susceptibility of OWF structures is summarized as follows:

- Wind turbine structures in shallower water depths (bathymetric highs) are anticipated to have higher scour potential. Based on the calculated shear stress data, the surficial sediments within those areas are mobile. The introduction of an OWF monopile structure will increase flow velocities promoting scour.
- Wind turbine structures in deeper water depths (bathymetric lows) are anticipated to have lower scour potential. Those areas are inferred to be within depositional environments where sediments are accumulating. Therefore, even though the introduction of a monopile will further increase the flow velocity and promote scour, it is inferred that developed scour will be limited, or even infilled, by the accumulating sediments during periods of decreased flow.
- Trenched areas for the export cable route Option 1 are anticipated to have a lower scour potential in areas interpreted to be depositional environments and a higher scour potential in the nearshore/surf zone area. For the lower scour potential areas, it is inferred that sediments will accumulate and homogenize the seabed after trenching.
- However, the Option 1 export cable route through these depositional (lower scour potential) areas may exhibit scour and expose the cable. The potential for scour to occur is as follows: 1) the initial loss of fine-grained sediments due to jet-trenching may significantly decrease the threshold shear stress of the trenched sediments versus the surrounding in situ sediments, causing them to have a higher scour potential. 2) The trenched areas may have irregular topography that is not homogenized by accumulating sediments, which may cause a significant increase in bottom roughness. Increasing the bottom roughness increases bottom friction and bottom shear stress, which promotes scour.
- Trenched areas for export cable route Option 2 also have higher and lower scour potential areas similar to Option 1. However, the higher scour potential areas on the bathymetric highs represent a scour hazard due to migrating sand waves. A cable buried within a sand wave crest may be exposed in the sand wave trough after migration if the cable burial depth is less than the sand wave height (7 feet) burial depth within a sand wave crest height of 10 feet means the cable has a 3-foot height above the sand wave trough once migration occurs[.

ASSUMPTIONS AND LIMITATIONS

The following are the assumptions and limitations for the OWF scour susceptibility analysis:

- For the calculation of bed shear stress, we assumed that environmental conditions are constant for the site (e.g. steady current flow) and the seafloor is relatively flat and featureless. Furthermore, we assumed that sediments are clean sands (i.e. cohesionless).

- We assumed that the bathymetric low areas that consist of fine-grained (or finer) sediments represent depositional environments. Further investigation is needed to collect current bottom velocity data within these areas to assess the long-term sediment transport potential.
- ADCP current-meter data from the FRONT database were located in the vicinity of Rhode Island Sound and at a water depth of about 110 feet. These current data are assumed representative of this site. However, having no current data within the OWF site is a limitation in the analysis because variation in the current velocity is likely to be observed between the bathymetric high and low areas, as well as along the export cable routes.
- Surficial sediment data available through the USGS databases allowed for regional mapping within the Round Island Sound and the regional application of limited median grain size data, but was limited in terms of OWF site-specific mapping. Site-specific mapping and grain size data within the OWF footprint, and for the export cable routes, are needed to more accurately determine characteristic sediment grain size and fines content of surficial sediments. Fine-grained sediments or sands mixed with fine-grained sediments are likely to have a higher threshold shear stress when compared to clean sands (Mitchener et al., 1996), which would increase the surficial sediments' resistance to scour.
- Mapping of morphological features (e.g. sand waves) was based on the available side scan sonar and bathymetry data, which were limited around the OWF footprint and export cable routes. Areas where these data were lacking were assessed based on the limited grain size data and were often assumed to be without seabed features. This limit in morphological mapping likely underestimates the extent of seabed features, meaning the potential scour hazards to OWF substructures also may be underestimated.

In spite of these assumptions and limitations, the analyses performed for this site demonstrate the application of wave and current data, sediment data, and bathymetry data for assessing scour, and also the importance of collecting site-specific data to define potential scour hazards to OWF substructures.

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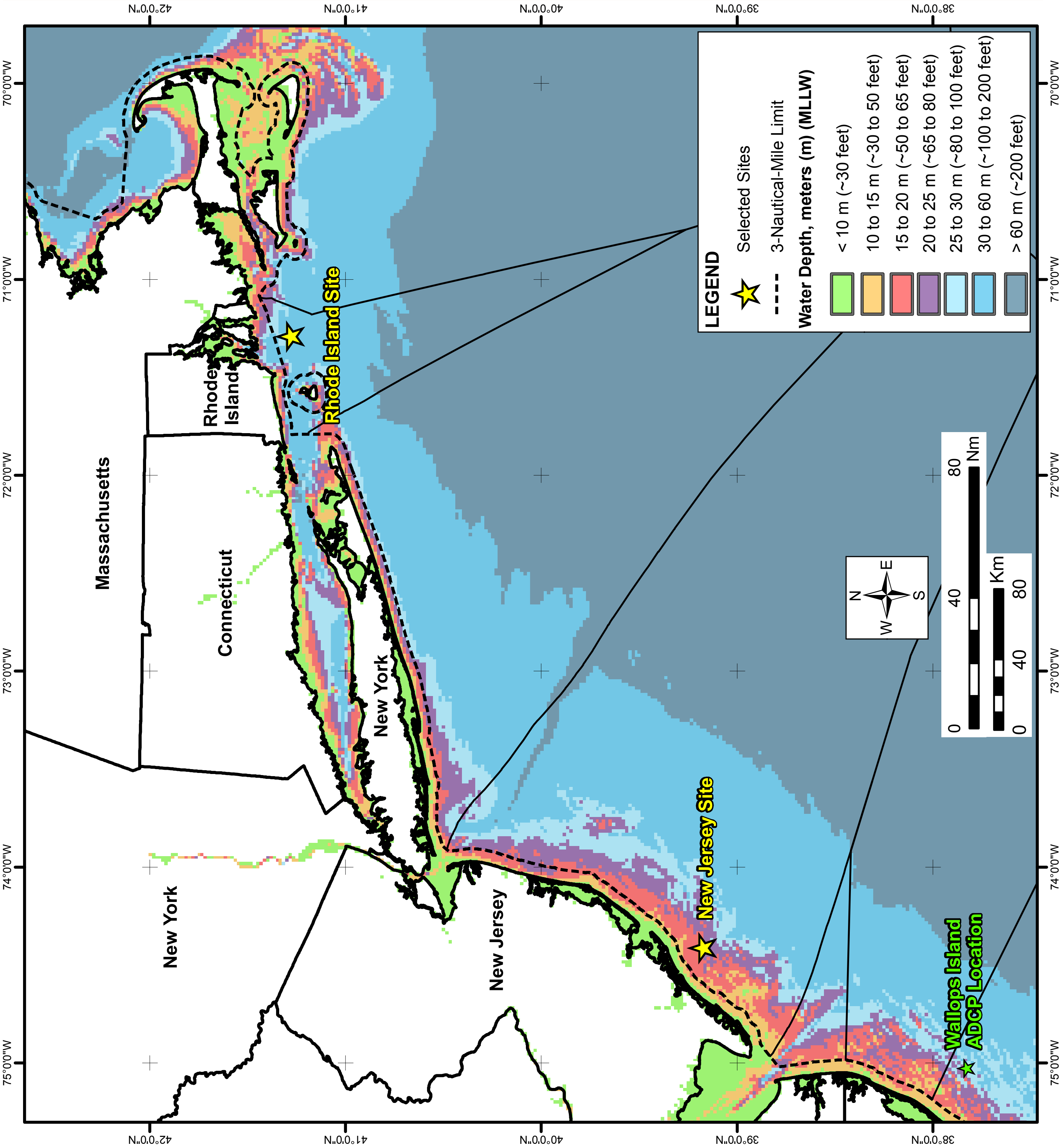
Appendix A
Figures



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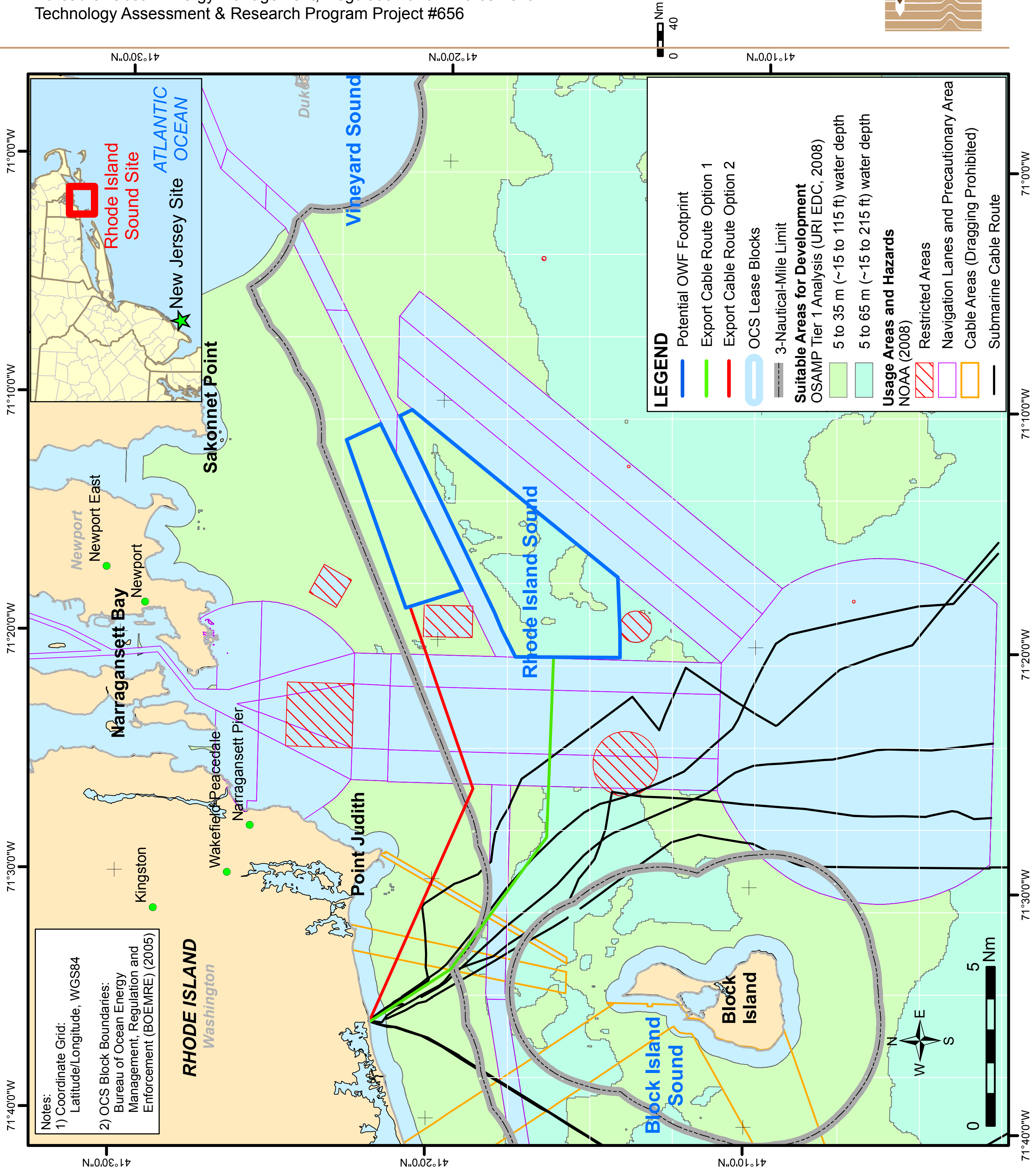
Coordinate Grid: Latitude/Longitude, WGS84

SITE LOCATIONS
TA&R Project #656
Seabed Scour Considerations

FIGURE A-1



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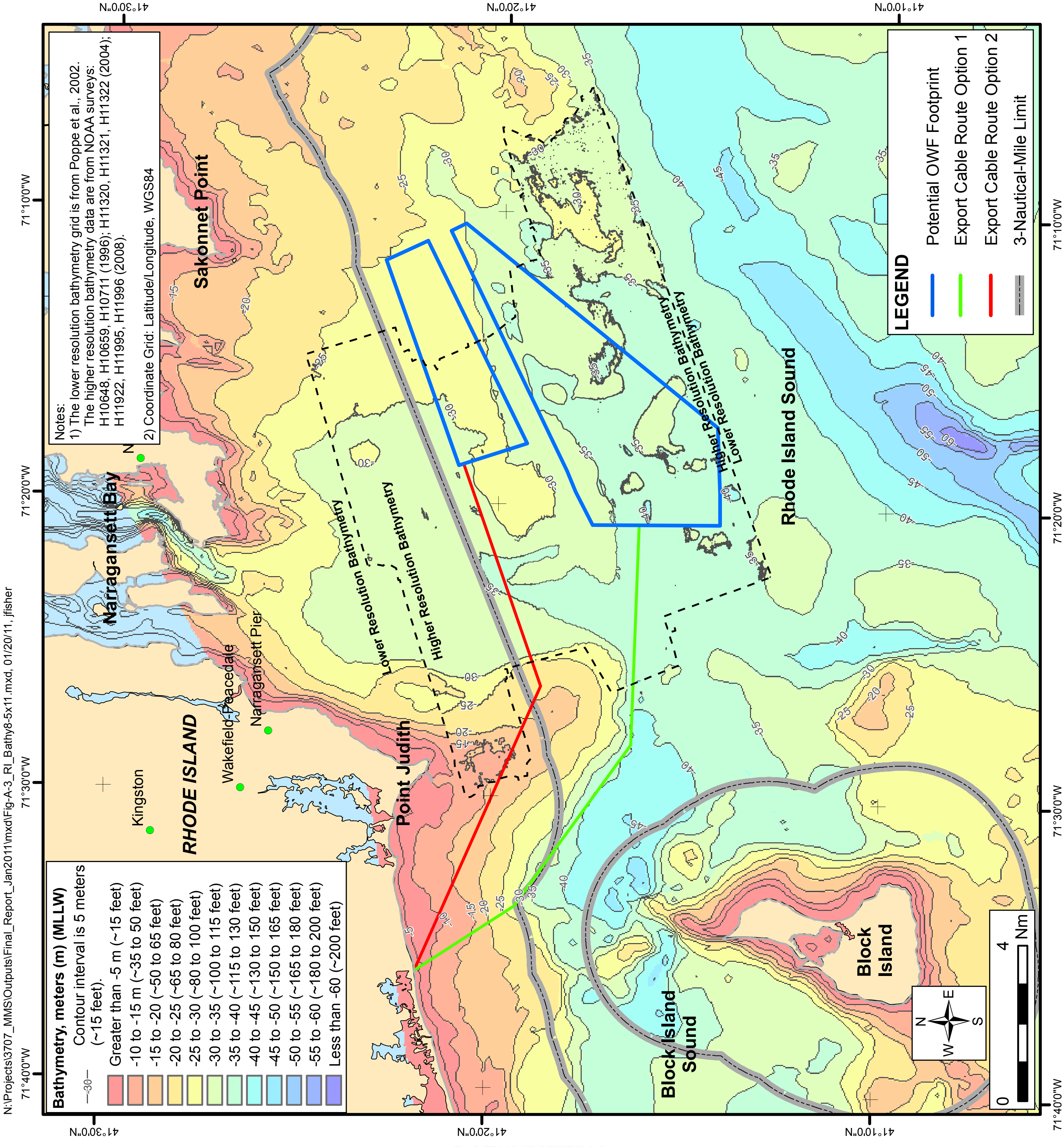
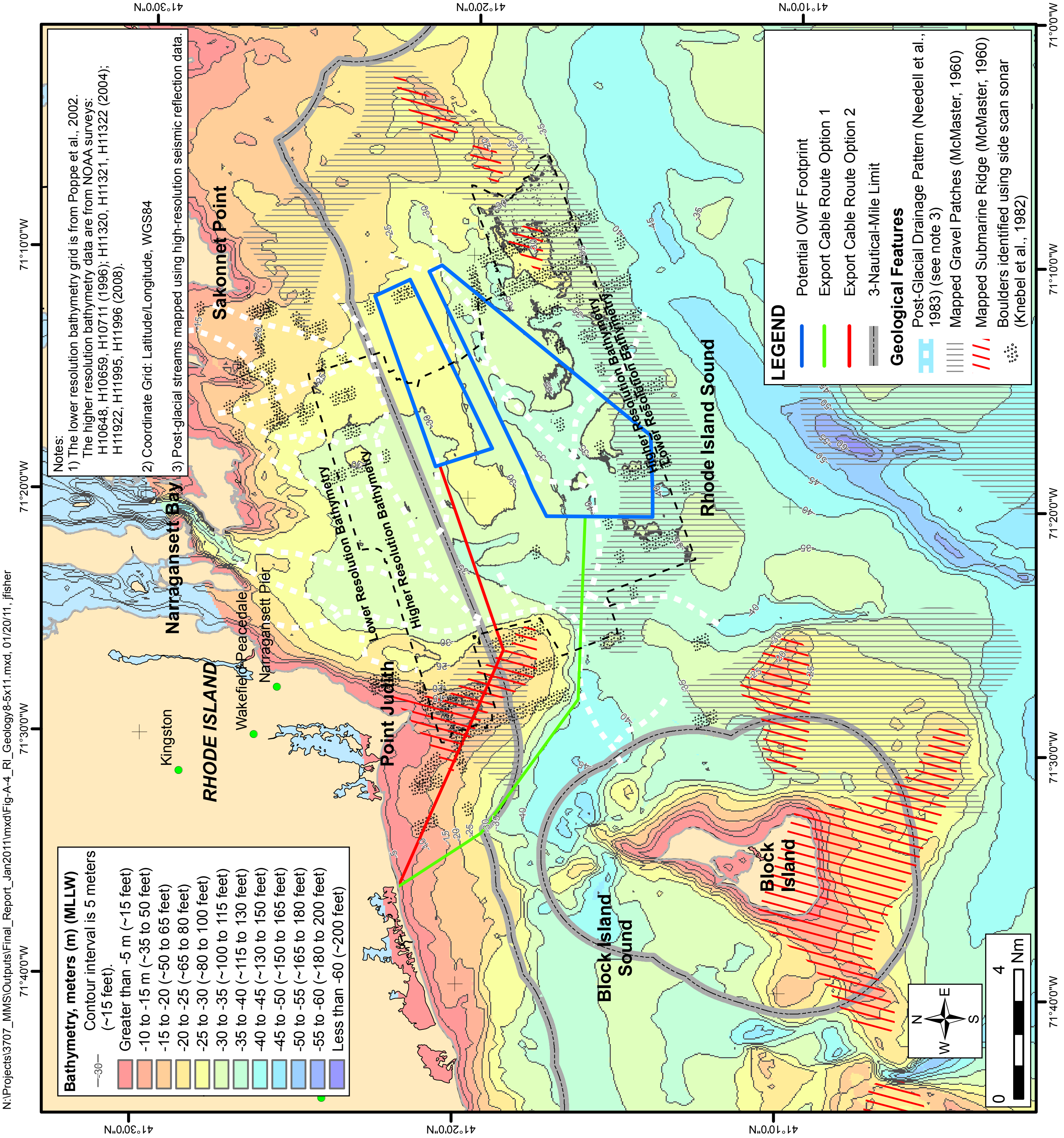
LOCATION AND SITING CRITERIA
Rhode Island Site
TA&R Project #656
Seabed Scour Considerations

FIGURE A-2



BATHYMETRY
Rhode Island Site
TA&R Project #656
Seabed Scour Considerations

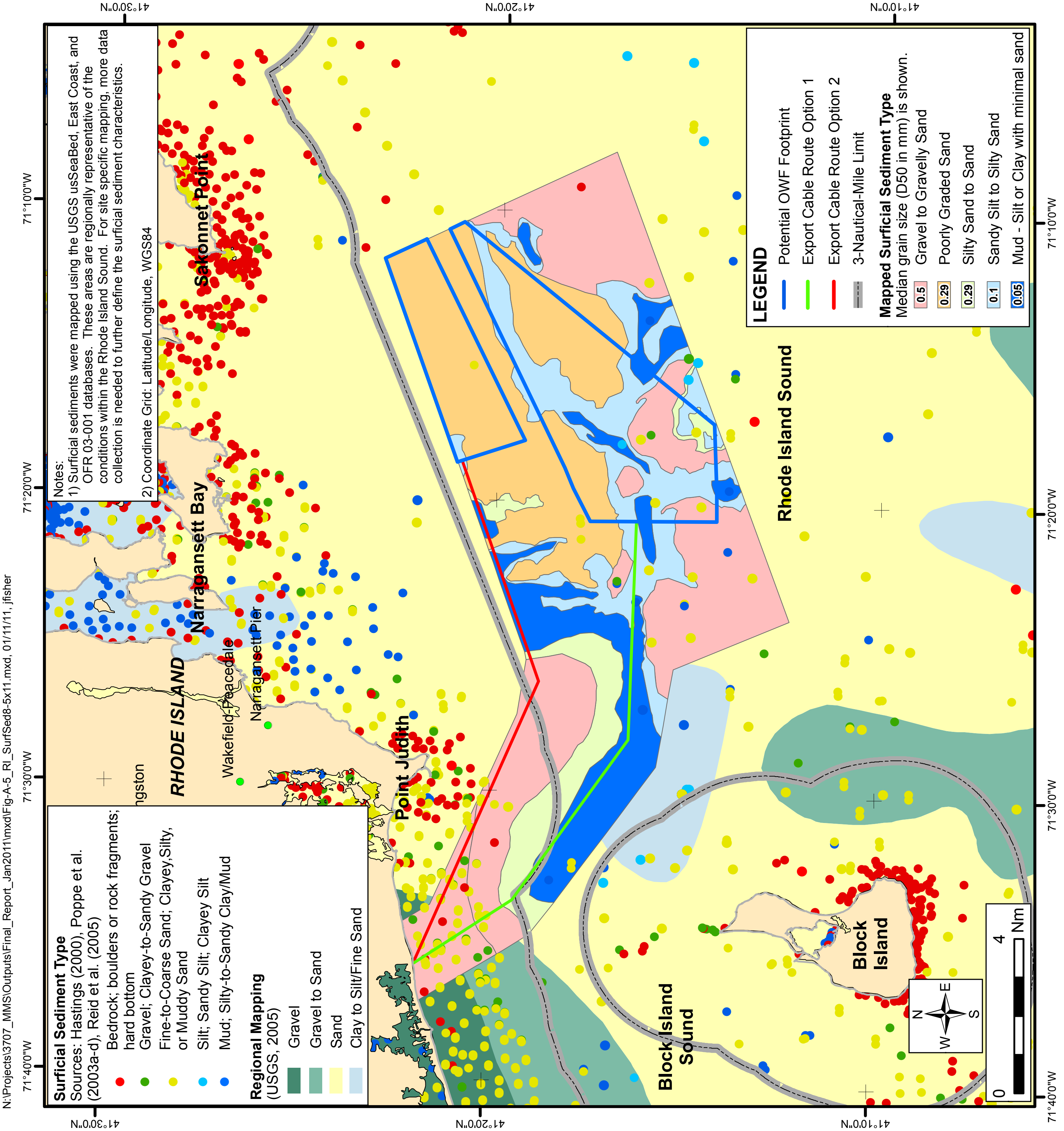
FIGURE A-3



GEOLOGICAL FEATURES

Rhode Island Site
TA&R Project #656
Seabed Scour Considerations

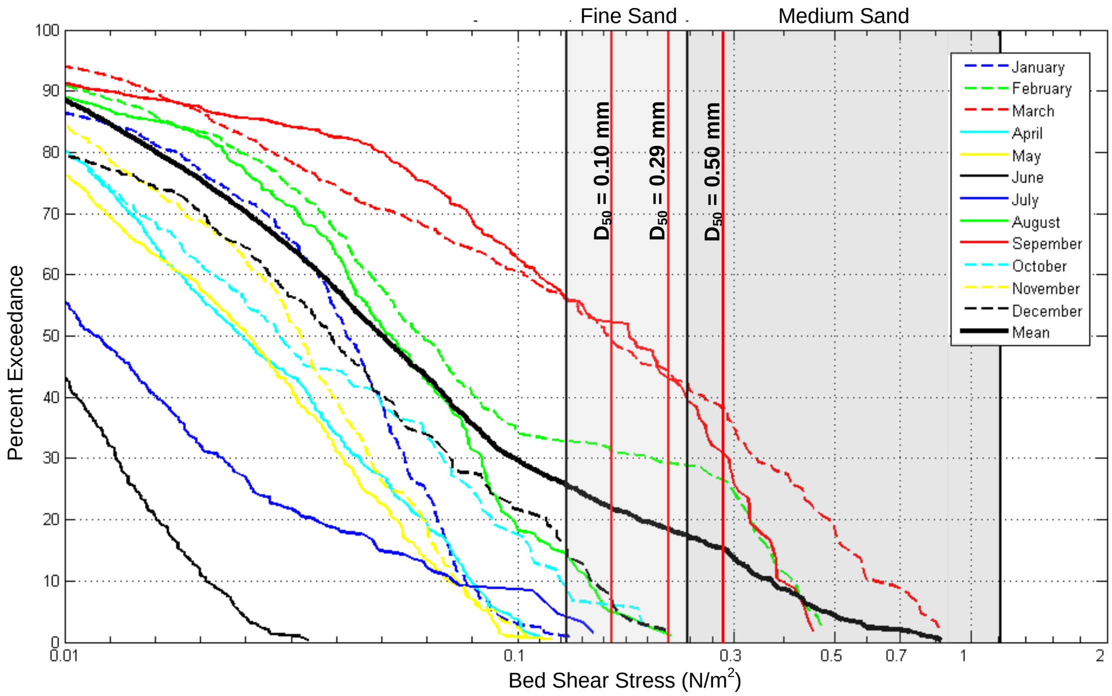
FIGURE A-4



Notes:
1) Surficial sediments were mapped using the USGS usSeaBed, East Coast, and OFR 03-001 databases. These areas are regionally representative of the conditions within the Rhode Island Sound. For site specific mapping, more data collection is needed to further define the surficial sediment characteristics.
2) Coordinate Grid: Latitude/Longitude, WGS84

SURFICIAL SEDIMENTS
Rhode Island Site
TA&R Project #656
Seabed Scour Considerations

FIGURE A-5



This plot represents the exceedance diagram showing bed shear stress for waves. The shear stress values are calculated from data based on NDBC buoy 44025 (latitude 36.611 degrees north and longitude 74.836 degrees west).

This analysis was performed for an approximate water depth of 30 meters (~100 feet) (re: MLLW), which is representative of the OWF footprint. The threshold shear stress values corresponding to the characteristic grain size values (0.10 mm, 0.29 mm, and 0.50 mm) within the OWF are denoted by the red lines. The shaded areas represent the threshold shear stress ranges for the fine sand (lighter gray shaded area) and medium sand (darker gray shaded area) grain sizes.

The bottom shear stress generated by waves is highly variable throughout a year, with the fall/winter months generally showing higher bottom shear stress than the spring/summer months. The threshold shear stresses for the medium sand and fine sand grain sizes (i.e. 0.10 mm, 0.29 mm, and 0.50 mm) are exceeded more than 10 percent of the time for the months of September, February, and March, as well as for the all-year mean condition.

Note: Grain size classification is based on the Unified Soil Classification System (USCS).

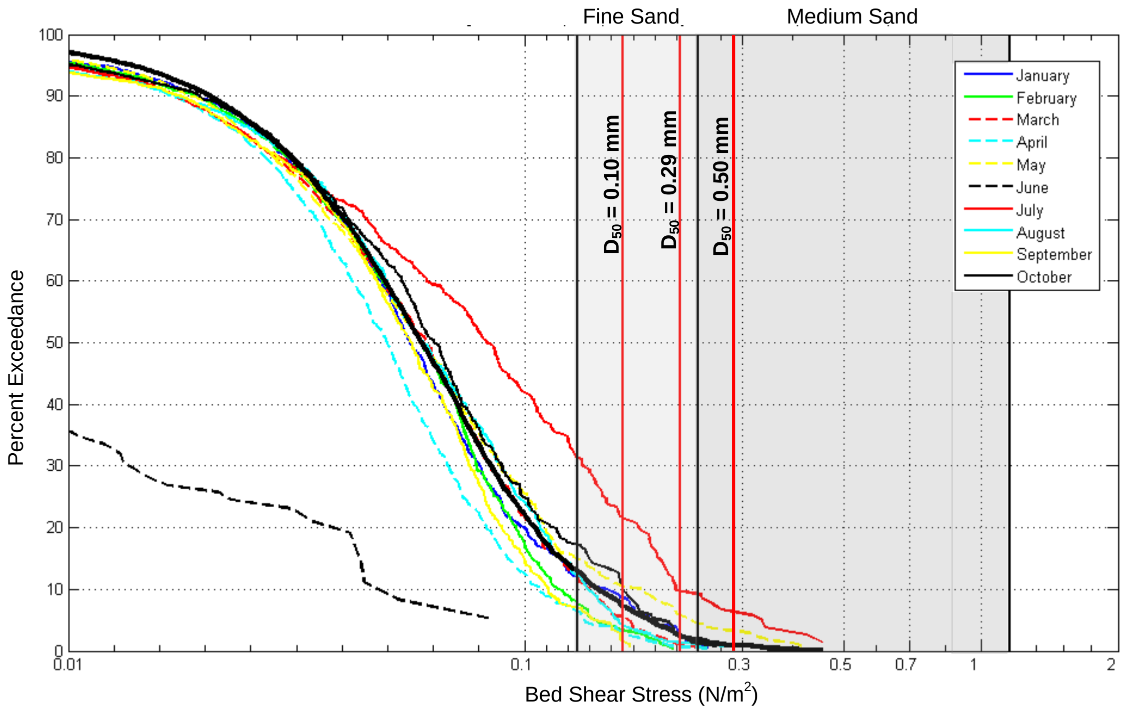
WAVE-INDUCED BED SHEAR STRESS PERCENTAGE EXCEEDANCE PLOT

Rhode Island Site

TA&R Project #656

Seabed Scour Considerations

FIGURE A-6a



This plot represents the summary exceedance diagram showing bed shear stress for currents. The shear stress values are calculated from ADCP current data part of the FRONT project database.

This analysis was performed for an approximate water depth of 30 meters (~100 feet) (re: MLLW), which is representative of the entire OWF footprint. The threshold shear stress values corresponding to the characteristic grain size values (i.e. 0.10 mm, 0.29 mm, and 0.50 mm) within the OWF are denoted by the red lines. The shaded areas represent the threshold shear stress ranges for the fine sand (lighter gray shaded area) and medium sand (darker gray shaded area) grain sizes.

The bed shear stress generated by currents shows less variation and is significantly lower than by the bottom shear stress generated by waves (Figure A-6a). The threshold shear stresses for the fine sand grain sizes (0.10 mm and 0.29 mm) are over 10 percent exceedance for the month of July only, with the threshold shear stress for the medium sand grain size (0.50 mm) not over 10 percent exceedance during any month.

Note: Grain size classification is based on the Unified Soil Classification System (USCS).

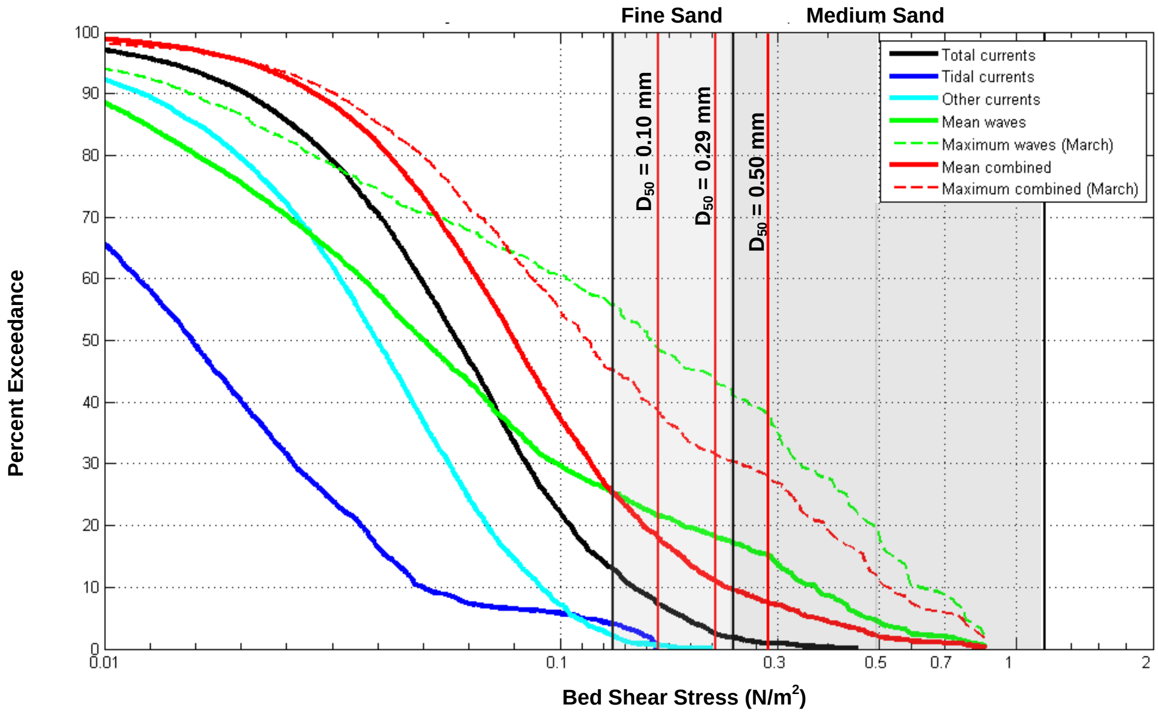
CURRENT-INDUCED BED SHEAR STRESS PERCENTAGE EXCEEDANCE PLOT

Rhode Island Site

TA&R Project #656

Seabed Scour Considerations

FIGURE A-6b



This plot represents the summary exceedance diagram showing bed shear stress for currents, waves, and combined wave and current conditions. For currents, the mean conditions are shown for total currents, tidal currents, and all other currents (e.g. density-driven currents, geostrophic currents, etc.). The combined wave and current flow is based on the total current flow and the all-year mean wave flow. The maximum wave and maximum combined flow represents the maximum induced shear stress observed during the year (i.e. the month of March) (refer to Figure A-6a).

This analysis was performed for an approximate water depth of 30 meters (~100 feet) (re: MLLW), which is representative of the entire OWF footprint. The threshold shear stress values corresponding to the characteristic grain size values (i.e. 0.10 mm, 0.29 mm, and 0.50 mm) within the OWF are denoted by the red lines. The shaded areas represent the threshold shear stress ranges for the fine sand (lighter gray shaded area) and medium sand (darker gray shaded area) grain sizes.

The all-year mean bed shear stress for waves is above 10 percent exceedance for the threshold shear stress corresponding to the fine sand and medium sand grain sizes. However, the combined wave and current flow is only above 10 percent exceedance for the threshold shear stress corresponding to the fine sand grain sizes. This is likely due to the wave and current flow not being co-directional and possibly opposing each other. The current all-year mean is above 10 percent exceedance for the threshold shear stresses corresponding to very fine sand grain sizes and not for the characteristic grain sizes within the OWF footprint.

Note: Grain size classification is based on the Unified Soil Classification System (USCS).

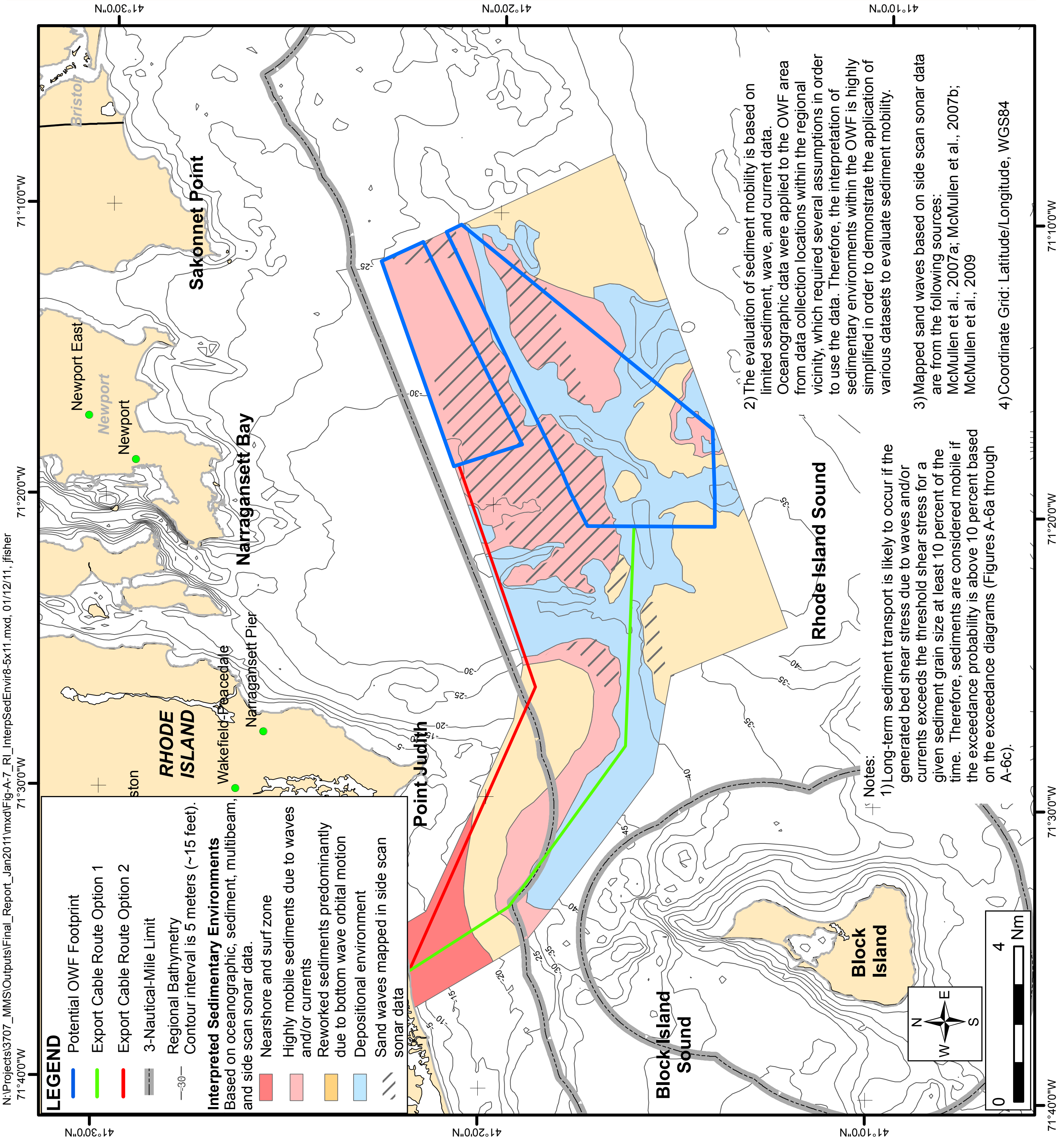
SUMMARY BED SHEAR STRESS PERCENTAGE EXCEEDANCE PLOT

Rhode Island Site

TA&R Project #656

Seabed Scour Considerations

FIGURE A-6c



Notes:

1) Long-term sediment transport is likely to occur if the generated bed shear stress due to waves and/or currents exceeds the threshold shear stress for a given sediment grain size at least 10 percent of the time. Therefore, sediments are considered mobile if the exceedance probability is above 10 percent based on the exceedance diagrams (Figures A-6a through A-6c).

2) The evaluation of sediment mobility is based on limited sediment, wave, and current data. Oceanographic data were applied to the OWF area from data collection locations within the regional vicinity, which required several assumptions in order to use the data. Therefore, the interpretation of sedimentary environments within the OWF is highly simplified in order to demonstrate the application of various datasets to evaluate sediment mobility.

3) Mapped sand waves based on side scan sonar data are from the following sources: McMullen et al., 2007a; McMullen et al., 2007b; McMullen et al., 2009

4) Coordinate Grid: Latitude/Longitude, WGS84

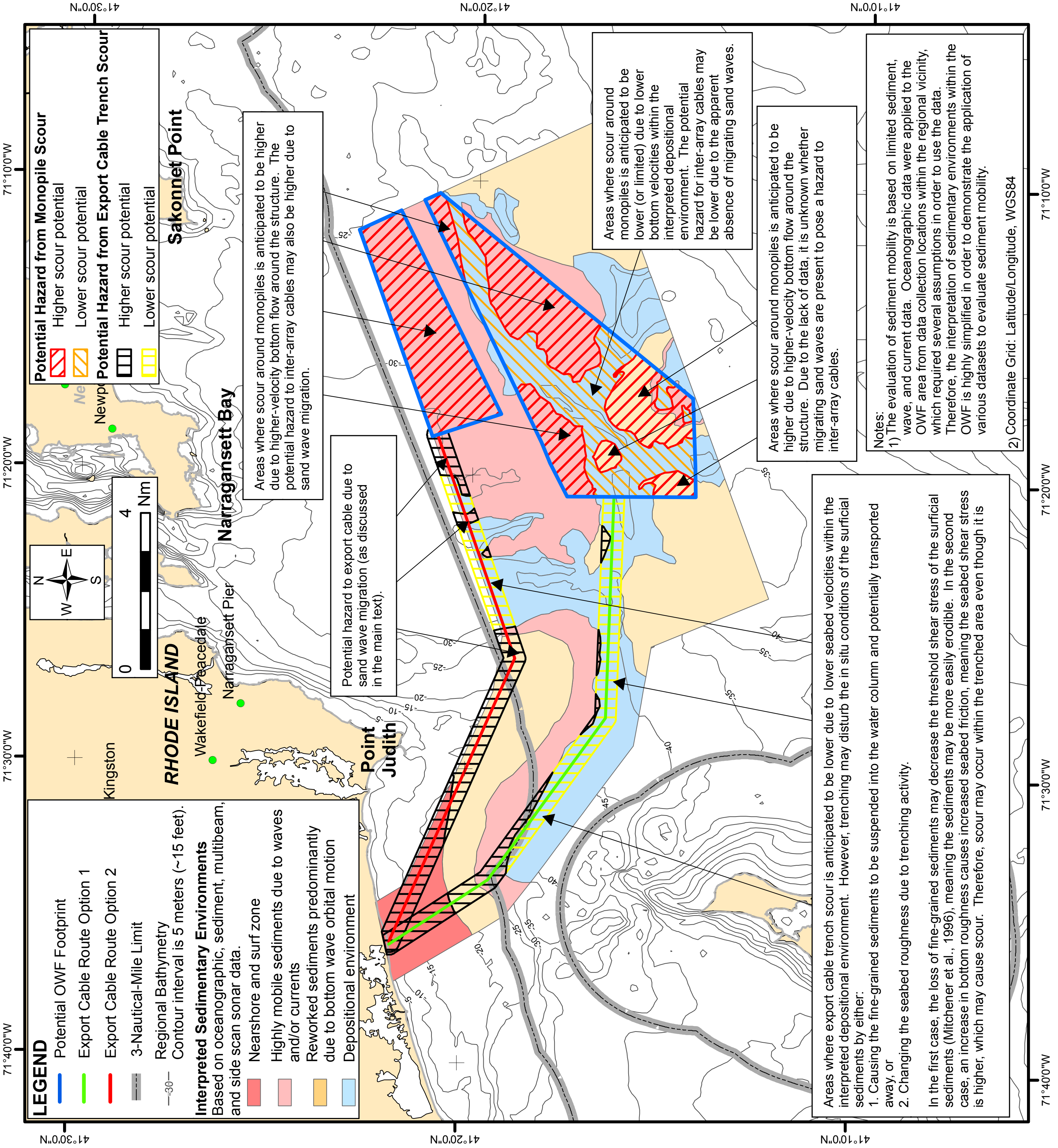
INTERPRETED SEDIMENTARY ENVIRONMENTS

Rhode Island Site

TA&R Project #656

Seabed Scour Considerations

FIGURE A-7



Areas where scour around monopiles is anticipated to be higher due to higher-velocity bottom flow around the structure. The potential hazard to inter-array cables may also be higher due to sand wave migration.

Areas where scour around monopiles is anticipated to be lower (or limited) due to lower bottom velocities within the interpreted depositional environment. The potential hazard for inter-array cables may be lower due to the apparent absence of migrating sand waves.

Areas where scour around monopiles is anticipated to be higher due to higher-velocity bottom flow around the structure. Due to the lack of data, it is unknown whether migrating sand waves are present to pose a hazard to inter-array cables.

Potential hazard to export cable due to sand wave migration (as discussed in the main text).

Areas where export cable trench scour is anticipated to be lower due to lower seabed velocities within the interpreted depositional environment. However, trenching may disturb the in situ conditions of the surficial sediments by either:
1. Causing the fine-grained sediments to be suspended into the water column and potentially transported away, or
2. Changing the seabed roughness due to trenching activity.

In the first case, the loss of fine-grained sediments may decrease the threshold shear stress of the surficial sediments (Mitchener et al., 1996), meaning the sediments may be more easily erodible. In the second case, an increase in bottom roughness causes increased seabed friction, meaning the seabed shear stress is higher, which may cause scour. Therefore, scour may occur within the trenched area even though it is

Notes:
1) The evaluation of sediment mobility is based on limited sediment, wave, and current data. Oceanographic data were applied to the OWF area from data collection locations within the regional vicinity, which required several assumptions in order to use the data. Therefore, the interpretation of sedimentary environments within the OWF is highly simplified in order to demonstrate the application of various datasets to evaluate sediment mobility.

2) Coordinate Grid: Latitude/Longitude, WGS84

OWF SCOUR SUSCEPTIBILITY

Rhode Island Site
TA&R Project #656
Seabed Scour Considerations

FIGURE A-8

APPENDIX B
NEW JERSEY SITE EVALUATION

APPENDIX B CONTENTS

FIGURES

APPENDIX B
NEW JERSEY SITE EVALUATION

INTRODUCTION

Two sites were selected for demonstration site evaluations on the Atlantic continental shelf: Offshore Rhode Island in the Round Island Sound and offshore New Jersey on the open continental shelf (Figure A-1). This demonstration study evaluates the scour susceptibility for a hypothetical wind farm project in a region where wind farms are currently being planned. This evaluation utilizes real data that were readily available at the time of the study. Due to time and budgetary restrictions, limited available data, the study had to make several assumptions, perform simplified and generalized analyses, and evaluate limited scenarios. However, the study provides valuable insight into how scour evaluations can be incorporated into early planning and design stages and provides insight into oceanographic and potential sediment transport related issues for OWF development in this region.

These sites were selected for the following reasons:

- Data were available to perform site specific scour analyses. This includes bathymetry, side scan sonar, sediment grain size data, and current and wave data.
- These sites are different in terms of the hydrodynamic flow regime and geologic conditions, and are generally representative of the broad range in conditions that Offshore Wind Farm (OWF) developers could experience on the Atlantic continental shelf.
- Both sites are in areas under consideration for potential OWF development.

The offshore New Jersey site is located on the Mid-Atlantic continental shelf approximately 10 nautical miles (Nm) south of Atlantic City, New Jersey and approximately 10 Nm offshore. In June of 2009, the Federal Government issued four exploratory leases, the first of their kind ever issued by the Federal Government, to Bluewater Wind New Jersey Energy, LLC; Fishermen's Energy of New Jersey, LLC; and Deepwater Wind, LLC. Three of the leases are for offshore wind development sites located offshore New Jersey in the vicinity of the demonstration study location. The leases were developed under an Interim Policy, and authorize data gathering activities, allowing for the construction of meteorological towers on the Outer Continental Shelf from 6 to 18 Nm offshore to collect site-specific data on wind speed, intensity, and direction.

The complex hydrodynamic flow regime in Mid-Atlantic requires investigating the interrelationship of several variables to assess and predict scour. Data and information minimally required to assess scour includes:

- Wind, wave, current, and tidal data (including direction) for developing bottom flow conditions;
- Water depth;

- Seafloor topography and morphology; and
- Seafloor sediment characteristics.

During this study, we used available data to:

- Characterize flow forcing conditions,
- Characterize seabed sediments and map their spatial extent, and
- Evaluate potential scour susceptibility spatially across an OWF site.

Several public-domain resources were available to obtain the required information to assess scour. Surface-wave data were available through the National Data Buoy Center (NDBC). Current data were available from bottom-mounted Acoustic Doppler Current Profilers (ADCPs) deployed by Old Dominion University offshore northern Virginia and the USGS in the Hudson Shelf Valley offshore northern New Jersey. Wave and current data were analyzed by Dr. Jose Blanco from the Center of Coastal Physical Oceanography at Old Dominion University.

Multibeam bathymetry and side scan sonar survey data were available from several National Oceanic and Atmospheric Administration (NOAA) surveys. The processed survey data were downloaded and reprocessed to a finer resolution, and then incorporated in Fugro's geographical information system (GIS) system for analysis.

Surficial sediment data were available through several U.S. Geological Survey (USGS) databases. The USGS usSEABED database (Reid, et al., 2005) includes a variety of information about sediment texture, composition, seafloor features, and sediment grain size data derived from laboratory investigations. The USGS East Coast Sediment Analysis database (Hastings, 2000) is a collection of data on sediment grain size that includes sediment gradation laboratory test data. USGS Open-File Report 03-001 (Poppe et al., 2003a-d) contains GIS compilation of surficial sediment data from several sources. The usSEABED data represent a compilation of exploration performed over the last several decades by various entities.

SITE CHARACTERIZATION

The OWF site is located approximately 10 Nm south of Atlantic City, New Jersey and approximately 10 Nm offshore. The site is located southwest of the Great Egg shelf valley (Figure B-1 and B-2). The footprint of the site is notionally 3 Nm wide by 9 Nm long (approximately the size of a 350 megawatt [MW] wind farm).

Bathymetry

The water depth within the wind farm footprint is generally between 35 and 70 feet (MLLW) deep. Water depth varies locally by 30 to 35 feet across the site. The Great Egg shelf valley is a flat-bottomed, featureless valley oriented northwest-southeast and borders the hypothetical OWF area to northeast. Water depth in the shelf valley adjacent to the OWF is between 60 and 70 feet (MLLW) deep.

Seafloor Morphology

The inner and mid-continental shelf areas off the Mid-Atlantic coastline are comprised of ridges and swales that have a northeasterly trend (Figures B-1 and B-2). The sand ridges typically exhibit relief of 15 to 25 feet, are between 0.5- and 1.5-Nm wide, and may extend for a distance of 5 to 15 Nm. The ridges are postulated to be shoreface deposits abandoned as the shoreline transgressed during the last rise in sea level (Swift et al., 1973). As discussed by Snedden and others (1999), ridge shape and morphology are inferred to be a function of the hydrodynamic environment with ridges evolving over time until dynamic equilibrium is reached with the hydrodynamic environment.

Smaller scale bedforms are commonly superimposed on the larger ridges and swales. Dunes, sand waves, and sand ripples of varying size are common throughout the area and form in response to flow conditions. It is not uncommon to observe bedforms in an area that form in response to two or more flow conditions (e.g. downwelling currents from the north during nor'easters, currents from the south in response to tropical storms, ripples from oscillatory wave currents).

Within the hypothetical OWF footprint, several sand ridges are present. The insets on Figures B-2 and B-3 provide a detailed view of the prominent ridges. The shallowest water depths in the hypothetical OWF footprint are on this ridge and the sand ridge to its southwest are approximately 35 feet deep (MLLW).

Several scales of bedforms are present in this wind farm and reflect seafloor responses to flow conditions of different types, directions, velocity, and duration. The side scan sonar data in Figure B-3 includes a detailed view of a sand ridge in the center inset and three scales of bed waves in the upper inset. Superimposed on the sand ridges are ripples and dunes. The upper inset includes two-dimensional (2D), symmetrical ripples created from oscillatory wave currents, and two scales of dunes that formed in response to currents or combinations of waves and currents. Ripples are present throughout most of the hypothetical OWF area and dunes appear to splay off the crests of the sand ridges. The bedforms suggest that the seafloor is a dynamic environment.

Surficial Seabed Sediments

Seabed sediments were characterized using a combination of: 1) grain size data from surface grab samples, 2) soil descriptions from grab samples, and 3) reflectivity from side scan sonar data (Figure B-4). The sediment data, side scan sonar, and bathymetric data were used to map seafloor sediment type (Figure B-5).

According to the available data, seafloor sediments within the hypothetical OWF area are predominantly comprised of medium- and coarse-grained sand with lesser percentages of fine-grained sand. A few small patches of gravelly sediments are present in the swales between the ridges. These are likely pre-Holocene sediments deposited during the last glacial sea level low stand or relict beach deposits. In general, based on sonar reflectivity, the landward flanks of the ridges are coarser-grained than the seaward flanks. This is consistent with conclusions from other studies and sediment transport models for the region. Storms that set up downwelling currents pass over the sand ridges from north to south and transport the fine-grained sediments from the landward flank to the seaward flank resulting in a winnowing effect. Reflectivity contrasts are greater on the nearshore ridges than on those farther offshore, which suggests this effect is more pronounced due to stronger currents closer to shore.

Grain size data were then used to define a "characteristic" grain size for each sediment type. We note that limitations exist regarding the grain size data and using it for the scour analyses. Notable limitations and considerations are:

- Equations used to calculate the threshold shear stress for mobilizing sediments use the median grain size (d_{50}) value (refer to Appendix C). The sediment database did not always include the d_{50} value and, therefore, one had to be assumed.
- Surface samples were obtained over several decades. Sediment types may differ during the time the side scan sonar was collected and when the grab samples were collected. We noted several areas where grain size description differed from what the reflectivity character of the sonar data suggests.

The characteristic grain size data were used to calculate the threshold bed shear stress described in a later section of this appendix. The following list provides the characteristic grain size assigned to the mapped sediment type:

- Coarse Sand and Gravel: > 5.6 mm
- Coarse Sand: 1.8 mm
- Medium and Coarse / Medium to Coarse Sand: 1.0 mm
- Medium Sand: 0.35 mm
- Fine Sand: 0.15 mm
- Silt with Fine Sand: 0.008 mm

OCEANOGRAPHIC CONDITIONS

Bottom-current flows observed in shallow marine environments are frequently combinations of currents and waves. Currents, with timescale variations of hours or days, are principally tidal, wind-driven, or related to larger-scale patterns of ocean circulation. Wave-generated oscillatory flows, with periods on the order of seconds to tens of seconds, are produced by surface gravity waves, though lower-frequency internal waves also can be present.

Sediments can be eroded and/or transported by currents (whether tidal currents, density-driven circulation currents, wind-driven circulation), oscillatory wave motion, and/or a combination of both flow types. Erosion processes may be problematic for offshore wind farm cables if scour removes burial protection or undermines the cable creating a span over a scour pit. Moreover, sediment transport can cause large bedforms to migrate and expose a cable on the seafloor. Conversely, sediment transport can provide additional burial protection if accretion is occurring. Therefore, scour produced by sediment transport is considered to be a primary geologic hazard for structures in the study area.

The Mid-Atlantic continental shelf is considered a storm-dominated environment. According to Swift (2010), sand waves and sand ridges are modified due to large storms that occur on a frequency of one to three times each year. These large storm events often produce forerunner waves with long wave periods (e.g. 15 seconds) that produce strong oscillatory bottom flow and induce sediment suspension and/or transport.

However, this does not imply that currents are insignificant. A seaward-directed bottom current is produced by storms as water pushes toward the coast causes downwelling resulting in a bottom flow in the opposite direction from which the storm waves are directed. It is postulated that such bottom currents transport sediments suspended by the storms and is the mechanism of long-term sand ridge evolution and migration.

The mechanisms that cause sediment transport are also the mechanisms that potentially cause scour. Therefore, the complete characterization of the wave and current hydrodynamic flow regimes is necessary to identify the mechanisms mobilizing sediments that may cause scour.

Current Regime

Several different current flows occur on the Mid-Atlantic shelf. These include tidal currents, wind-driven currents, and density-driven currents. The prominent regional currents that have been documented in the Mid-Atlantic include:

- Semidiurnal tidal currents that are mainly directed east-west with the flood current being stronger than the ebb current;
- The Middle Atlantic Bight coastal current that is forced by alongshore wind stress, buoyancy produced by river discharge, and bottom stress produced by the shallow bathymetry;
- Down-shelf (equatorial-directed) geostrophic current flow caused by downwelling from winds driving onshore surface Ekman transport; these winds tend to accelerate the southward flow of buoyant outflows and to compress plume waters against the coast;
- Northward (poleward-directed) geostrophic current flow caused by upwelling from favorable winds driving offshore surface Ekman transport; these winds counter buoyancy-driven southward flow and tend to spread buoyant waters offshore; strong upwelling winds can reverse the coastal current and transport buoyant waters northward.

Geostrophic bottom currents form by downwelling from winds driving onshore surface Ekman transport. This current flow is the inferred mechanism of sand ridge migration due to the transport of suspended sediments from large storms. It is also important to note that current variability is responsive to wind stress on the synoptic scale (i.e. 2 to 10 days).

Current Analysis

The current regime was estimated (by Dr. Jose Blanco of Old Dominion University) using the time-series data recorded by a bottom-mounted Acoustic Doppler Current Profiler (ADCP). This ADCP unit, known as COBY 5, was deployed 15 miles offshore of Wallops Island, Virginia, at 37.833° north latitude and 75.029° west longitude, in approximately 32 meters water depth (re: MLLW) (Figure A-1). The COBY 5 dataset contains more than one year (436 days) of current data collected during two deployment periods: the first from January 28, 2006 through July 25, 2006, and the second from October 8, 2006 through June 23, 2007. Together, the 436 days of recording represent one of the largest ADCP records available from the Mid-Atlantic shelf. These data were analyzed to characterize the current conditions in this region of the Mid-Atlantic continental shelf. The data for COBY 5 were used to produce exceedance diagrams to assess potential long-term sediment mobility.

The COBY dataset was augmented using data collected in northern New Jersey during December 1999 to April 2000 and April -to June 2006 (Butman et al., 2003, USGS, 2010). The objectives of the studies were to understand transport of sediments and contaminants in the Hudson Shelf Valley. Data were collected using tripods equipped with 4-axis Benthic Acoustic Stress Sensors (BASS) at 1.0 meters above the bottom were installed. Data from station A1 located at latitude N40.390 degrees and longitude W73.785 degrees, at a bottom depth of 40m, and sampled every hour were used in the analysis.

The current data were reduced to monthly and annual averages which were used to estimate bottom shear stresses. Bottom shear stresses were then used in the scour susceptibility evaluation described later in this appendix.

Wave Regime

The Mid-Atlantic shelf is a storm-dominated environment. The wave regime exhibits a high degree of seasonal variation with the summer months showing calmer conditions than the remainder of the year. The late summer and early fall time includes the effects of occasional tropical storms that move into the area from the south. These storms are infrequent in the Mid-Atlantic, especially when compared to the number of occurrences of comparable storms in the Gulf of Mexico. The late fall through early spring time period is subject to winter nor'easter storms that form off the Mid-Atlantic from Virginia to the New England states. These storms generate extreme wave conditions that can be sustained for several days.

Wave Analysis

Surface-wave observations collected in buoys near the study area were selected from the National Data Buoy Center (NDBC). Considering that there is no wave data at the study site for the same period as the currents measurements, for the analysis here we used the data from New Jersey buoy NDBC 44025 (35.611 N; -75.836 W). The information were obtained for the period 1991-2009, hourly statistics of significant wave height (H_s), dominant (or peak) wave period (T_p), and mean wave direction corresponding to energy of the dominant period (D_{mw})

were available. There are some gaps in the wave record and no attempt was made to fill these gaps.

Representative near-bottom wave-orbital velocities (u_{br}) caused by surface waves were computed at selected depths from the wave observations using a parametric spectral method described by Wiberg and Sherwood (2008) and assuming the Donelan spectra. This parametric method uses an assumed wave spectrum shape defined by H_s and T_p and calculates u_{br}, the amplitude of a monochromatic wave with the same variance as the full spectrum (Wiberg and Sherwood, 2008).

The wave data were reduced to monthly and annual averages which were used to estimate bottom shear stresses. Bottom shear stresses were then used in the scour susceptibility evaluation described later in this appendix.

SCOUR POTENTIAL ANALYSIS

Bed shear stress for waves and/or currents, and threshold shear stress for the characteristic sediment grain sizes were calculated following the methodology in Soulsby (1998) as described in Appendix C. Exceedance diagrams are produced by plotting the percentage of bed shear stress exceedance versus shear stress. This is useful because, according to Whitehouse (1998), long-term sediment transport is likely to occur if the generated bed shear stress exceeds the threshold shear stress for particular sediment grain size at least 10 percent of the time.

Figures B-6a through B-6d show the bed shear stress exceedance diagrams for waves and currents. The bed shear stresses were calculated for three water depths (10 m [35 ft], 15 m [50 ft], and 20 m [65 ft]). Bed shear stresses were also calculated for monthly averages, annual average, currents only, waves only, and combined conditions. The bottom shear stress exceedance diagrams suggest the following:

- The calculated bed shear stresses due to currents (Figure B-6a) for 0.15 mm diameter fine sand grain sizes exceeds 10 percent for all months evaluated except for March and April. The only month it exceeded 10 percent for 0.35 mm diameter medium sand is January and May. January, July, and April experienced the highest percent exceedance for the fine and medium grained sand.
- The calculated bed shear stress due to waves (Figure A-6b) experienced the highest percent exceedance at the shallowest water (10m depth) and during the winter and early spring months (November through May).
- The combined flow effect (red line in lower graphs) shows a decrease in percent exceedance for the more severe events (e.g. larger shear stresses) than for waves alone. The reduction is a directionality effect; when wave and current flows are at a high angle (not parallel to each other), they will reduce each other's effect.

- Percent exceedances for medium sand (0.35 mm) were as great as 80 percent at 10 m in November. That means that 80 percent of the time in November, bottom currents were capable to transporting medium sand of 0.35 mm.

Scour Susceptibility Assessment

The New Jersey site appears to be more dynamic as a whole than the Rhode Island site. We note the seafloor sediments are mobile across most of the site during most of the year in contrast to Rhode Island, which has "deposition" environments. Ripples and dunes observed throughout most of the side scan sonar data support this. Therefore, we characterize scour susceptibility based on sediment transport activity.

We used the exceedance curves shown in Figures B-6a through B-6d and the sediment mapping presented on Figure B-5 to characterize predicted sediment transport rates. We assign higher scour potential to areas with higher sediment transport rates. Figure B-7 presents the sediment transport rates and classes of scour potential.

Figure B-7 shows the scour susceptibility for mean annual conditions. The scour susceptibility of OWF structures is summarized as follows:

- The highest potential scour areas are located on the crests of the two shallowest sand ridges. OWF structures construction on top of the shoals may experience the greatest degree of scour.
- Threshold bed shear stresses will be exceeded more often for the western half of the OWF than for the eastern half. This reflects shallower water conditions in the western half.
- Figure presents the mean annual condition. Percent exceedances would increase in the eastern half from the <10-percent exceedance class to the 10-percent to 25-percent exceedance class if using the monthly average for November.

We considered three export cable routes options, as described below:

- The western route passes through high sediment transport rate areas. Those areas likely have abundant sand waves. Therefore, hazard related to scour and sand transport processes (e.g. migrating sand wave) may be highest for this route.
- The central route is routed to avoid several small areas of high sediment transport rates. The relief of the seafloor along this route may not be optimal compared to the eastern route which is flatter.
- The eastern cable is routed through a flatter area and avoids high sediment transport areas except for the nearshore area. This flatter route may be longer than the other routes.

Summary:

- Discrete or extreme events should also be considered in scour evaluations. Scour can develop quickly in non-cohesive sediments. Physical experiments under constant flow conditions indicate that scour can reach equilibrium in less than an hour. Discrete events (e.g. nor'easter storm) can potentially cause significant scour.
- An evaluation of the installation costs (based on cable length, seabed conditions, etc.), scour and sediment transport related hazards, and risk should be carefully vetted when planning a wind farm. Proactive planning in the early stages can effectively mitigate hazards and reduce risks. Evaluating scour and sediment transport hazards can help in selecting locations for offshore substations and export cable routes, thus reducing risk.

ASSUMPTIONS AND LIMITATIONS

The following are the assumptions and limitations for the OWF scour susceptibility analysis:

- For the calculation of bed shear stress, it is assumed that environmental conditions are constant for the site (e.g. steady current flow) and the seafloor is relatively flat and featureless. Furthermore, it is assumed that sediments are clean sands (i.e. cohesionless).
- Surficial sediment data available through the USGS databases allowed for regional mapping within the study area and the regional application of limited median grain size data, but was limited in terms of OWF site-specific mapping. Site-specific mapping and grain size data within the OWF footprint, and for the export cable routes, are needed to more accurately determine characteristic sediment grain size and fines content of surficial sediments. Fine-grained sediments or sands mixed with fine-grained sediments are likely to have a higher threshold shear stress when compared to clean sands (Mitchener et al., 1996), which would increase the surficial sediments' resistance to scour.

Despite these assumptions and limitations, the analyses performed for this site demonstrate the application of wave and current data, sediment data, and bathymetry data for assessing scour, and the importance of collecting site-specific data to define potential scour hazards to OWF substructures.

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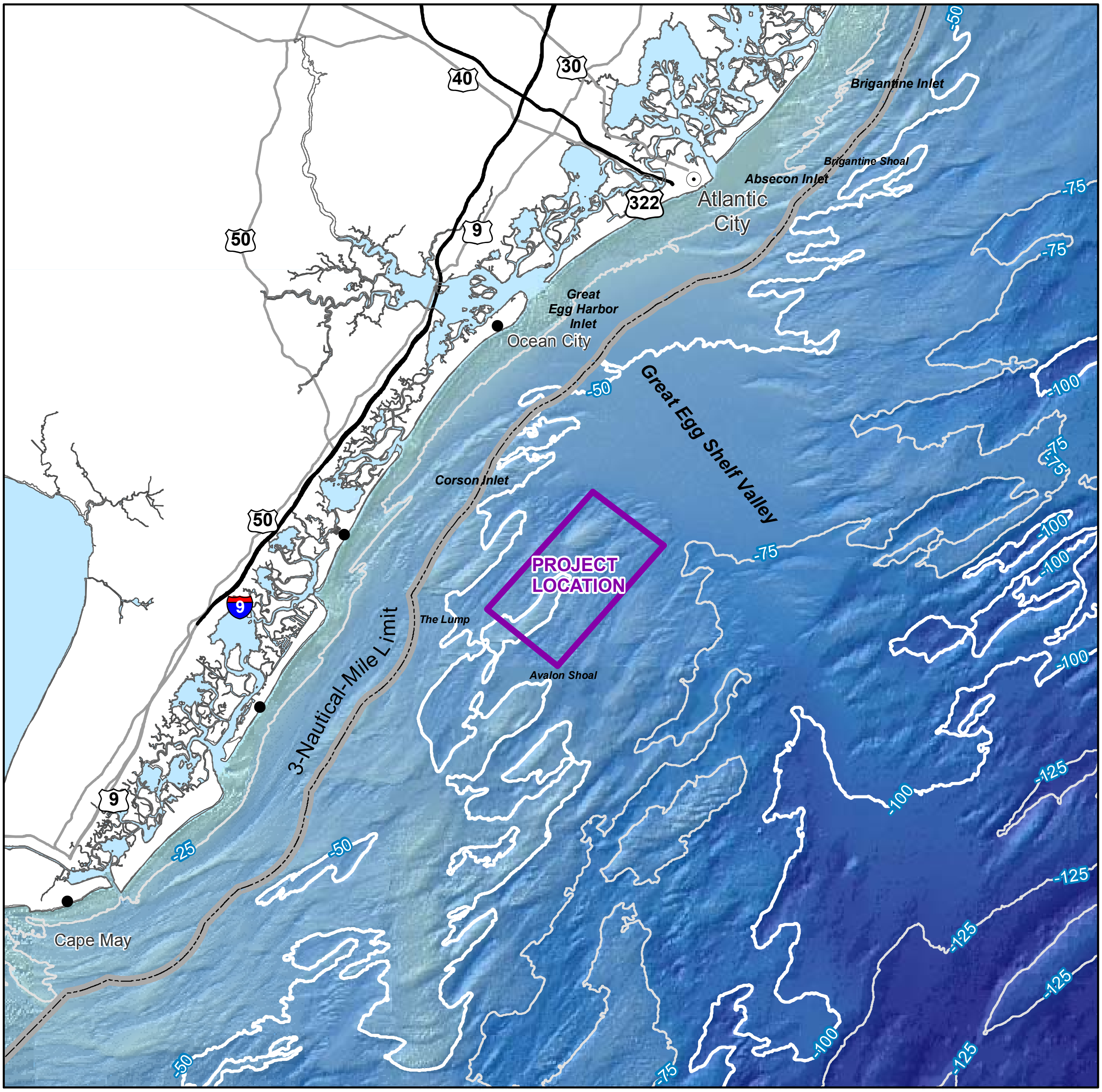
Appendix B
Figures



Source: NJDEP, NOAA

Legend

Bathymetric Contours (MLLW)

- 25 Foot Contour Interval
- 50 Foot Contour Interval

Bathymetry - Feet (MLLW)

0

-225

PROJECT LOCATION
New Jersey Demonstration Site
TA&R Project #656
Seabed Scour Considerations

0 2 4 Nm

0 8 km

N W E S

FIGURE B-1

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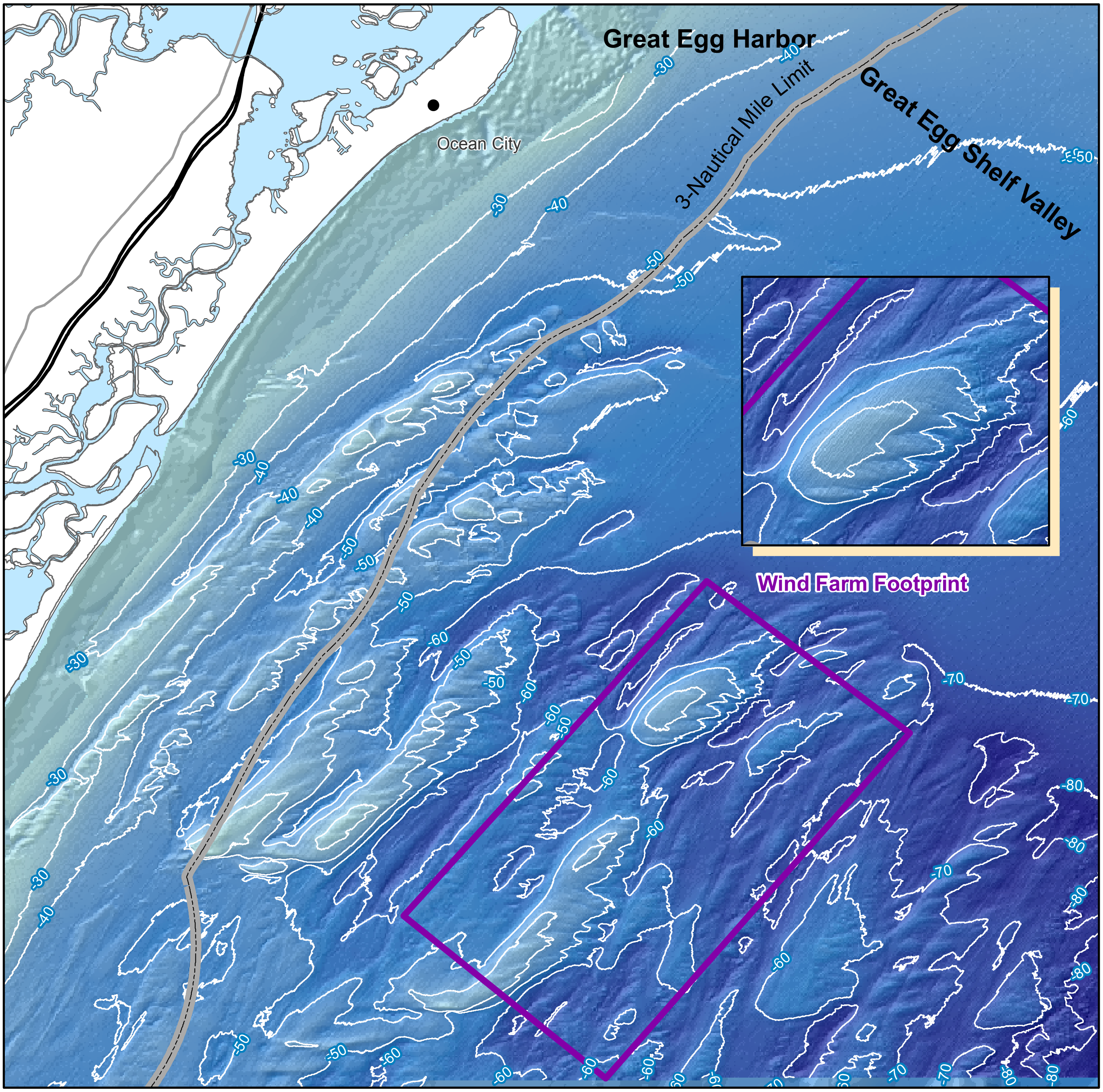

Source: NJDEP, NOAA

Legend

Bathymetric Contours (MLLW)

▤ 10 Foot Contour Interval

Bathymetry - Feet (MLLW)

0

-225

BATHYMETRY
New Jersey Demonstration Site

TA&R Project #656
Seabed Scour Considerations

0 1 2 Nm
0 4 km
N W E S

FIGURE B-2

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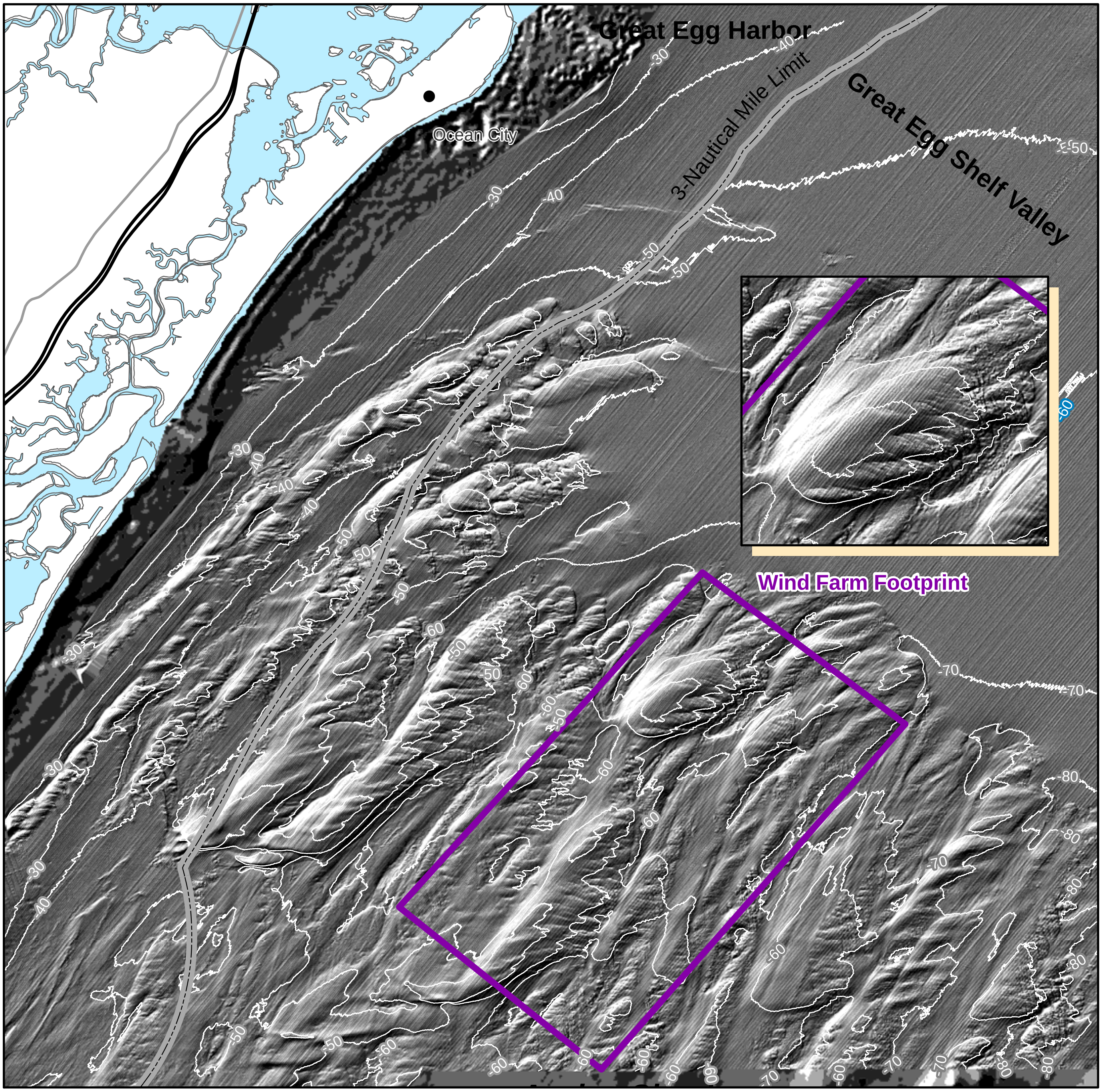

Source: NJDEP, NOAA

Legend

Bathymetric Contours (MLLW)

▬ 10 Foot Contour Interval

HILLSHADE
New Jersey Demonstration Site

TA&R Project #656
Seabed Scour Considerations

0 1 2 Nm
0 4 km
N E S W

FIGURE B-3

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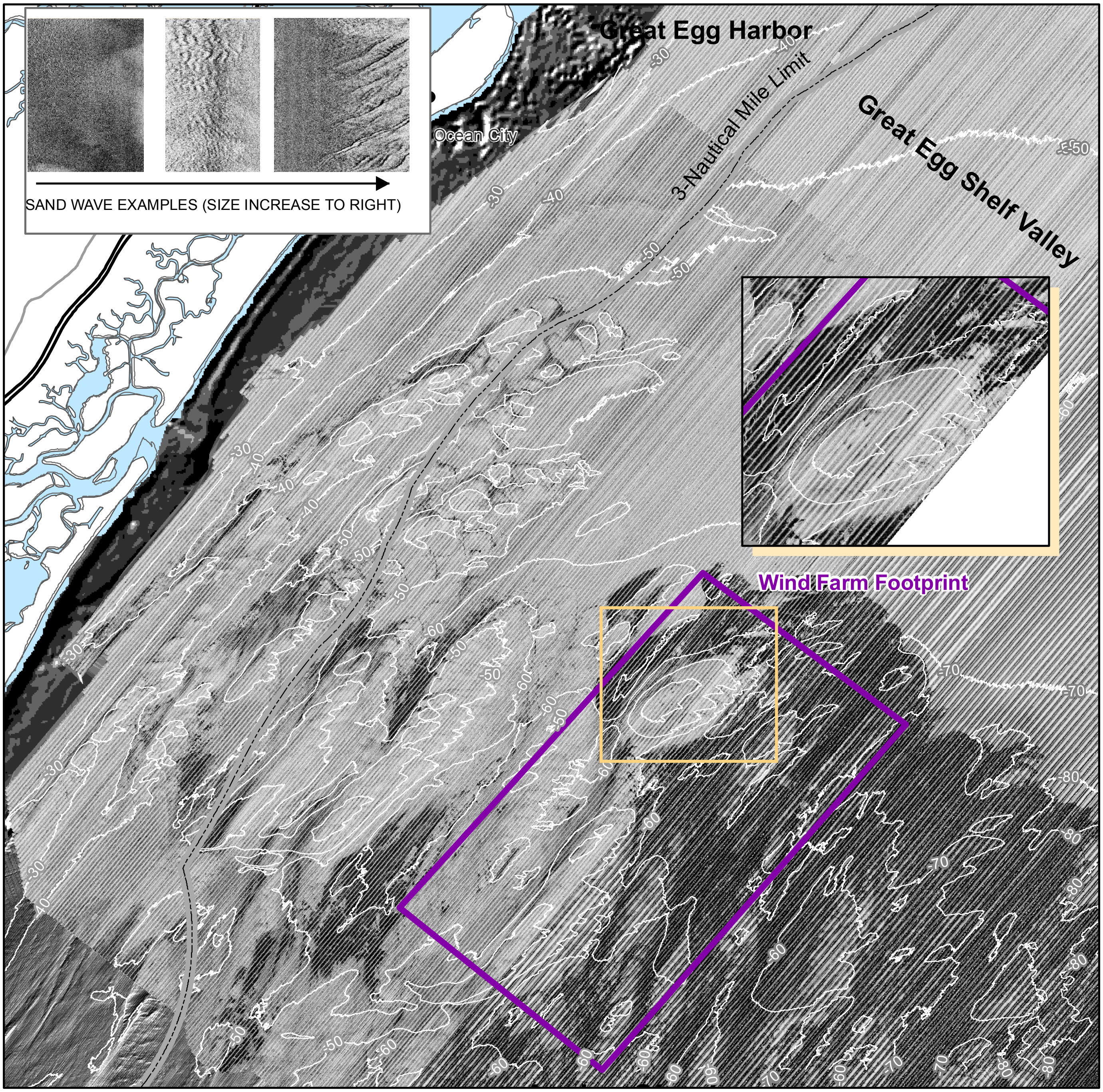


Source: NJDEP, NOAA

Legend

Bathymetric Contours (MLLW)

▬ 10 Foot Contour Interval

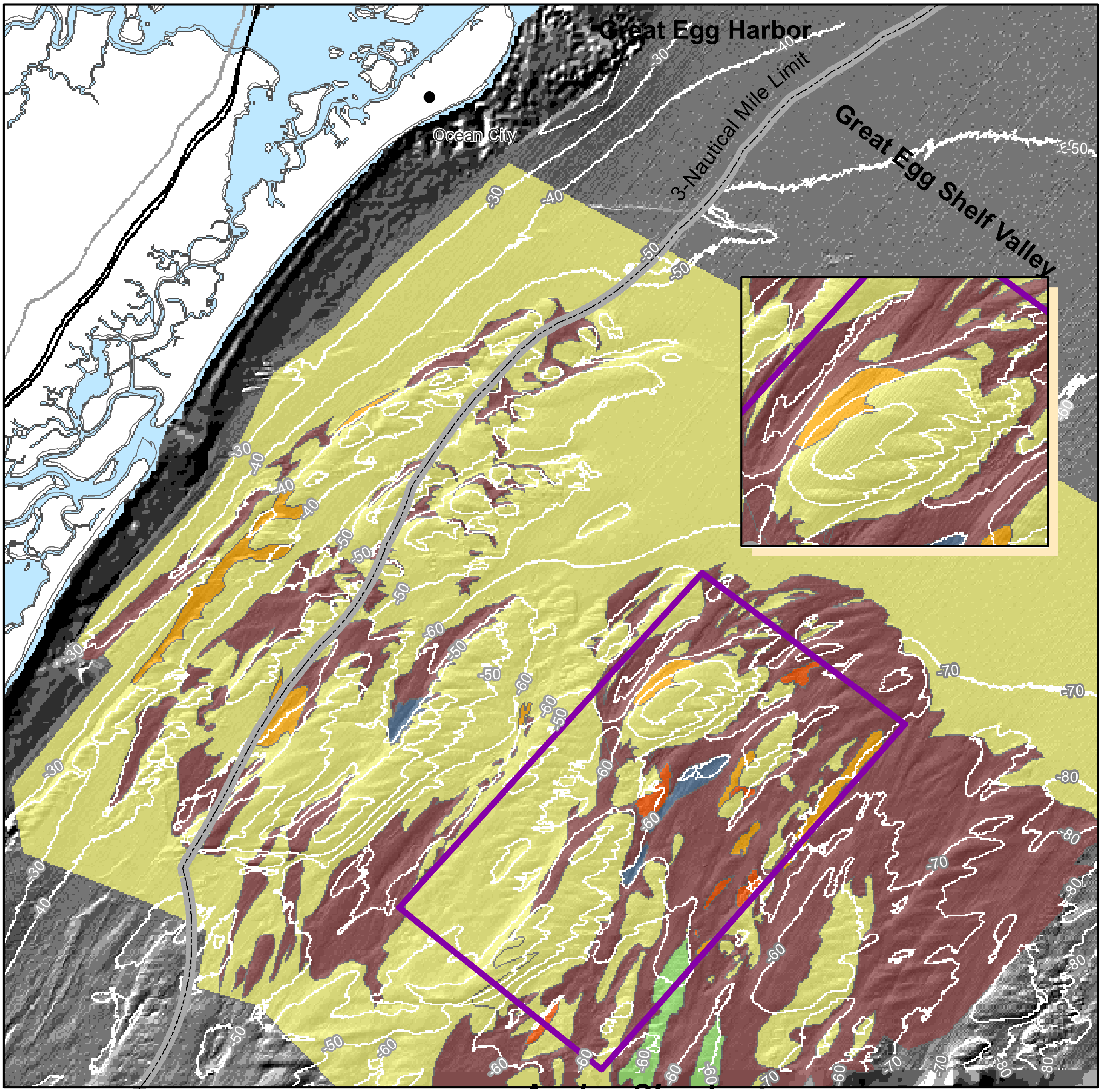
SIDE SCAN SONAR MOSAIC
New Jersey Demonstration Site

TA&R Project #656
Seabed Scour Considerations

0 1 2 Nm
0 4 km
N W E S

FIGURE B-4

N:\Projects\3707_MMS\Outputs\Draft_Report_Nov2010\mxd\Fig-B-3_Hillshade.mxd, 12/05/10, ksmith



Source: NJDEP, NOAA

Legend

Bathymetric Contours (MLLW)

10 Foot Contour Interval

🟦	Coarse Sand and Gravel
🟫	Coarse Sand
🟧	Medium and Coarse Sand
🟨	Medium to Coarse Sand
🟨	Medium Sand
🟩	Silt with Fine Sand

INTERPRETED SEABED SEDIMENTS
New Jersey Demonstration Site

TA&R Project #656
Seabed Scour Considerations

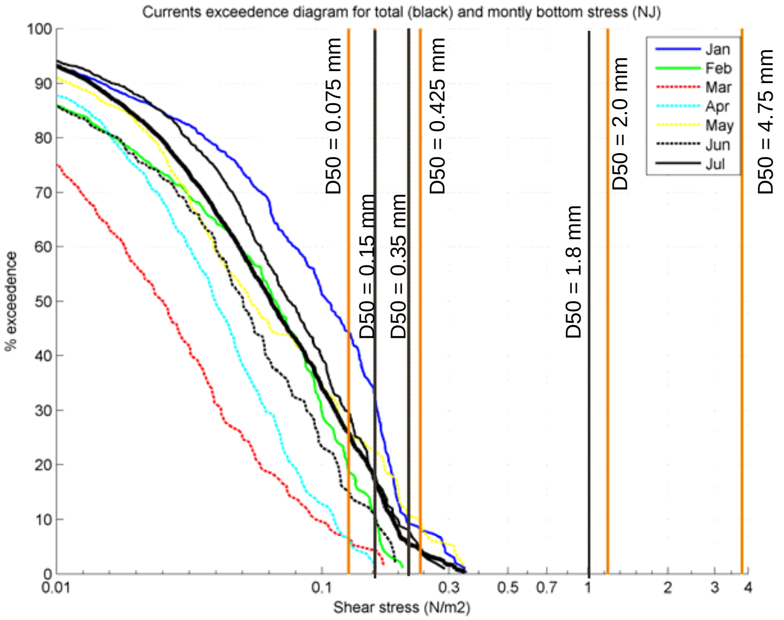
0 1 2 Nm

0 4 km

N
W E
S

FIGURE B-5

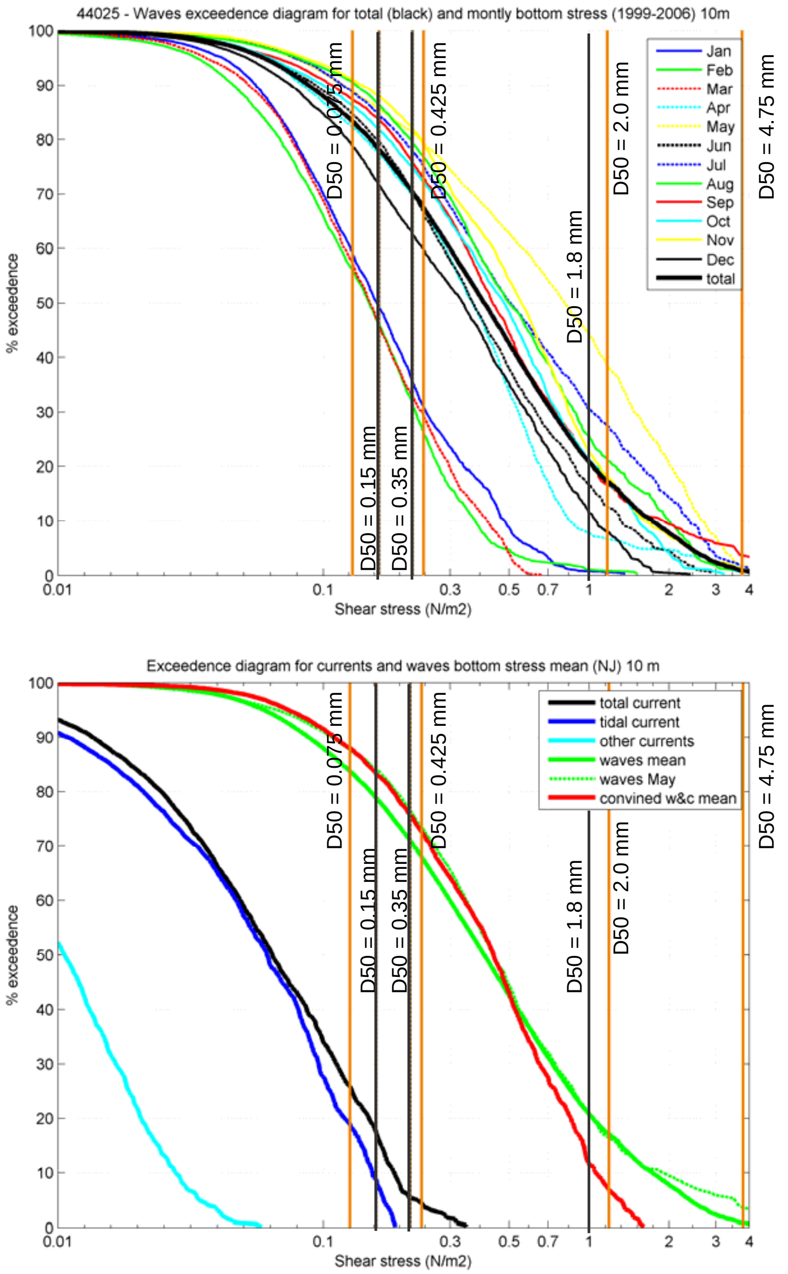
N:\Projects\3707_MMS\Outputs\Draft_Report_Nov2010\mxd\Fig-B-4_SSS.mxd, 12/05/10, ksmith



This plot represents the exceedance diagram showing bed shear stress for total currents. The shear stress values are calculated from current data collected in the Hudson Valley Shelf (USGS, 2010), which are representative of the New Jersey site. The threshold shear stress values corresponding to the characteristic grain size values (0.15 mm, 0.35 mm, and 1.8 mm) within the OWF are shown. Grain size classification is based on the Unified Soil Classification System (USCS).

PERCENT EXCEEDENCE CURVES
New Jersey Demonstration Site
TA&R Project #656
Seabed Scour Considerations

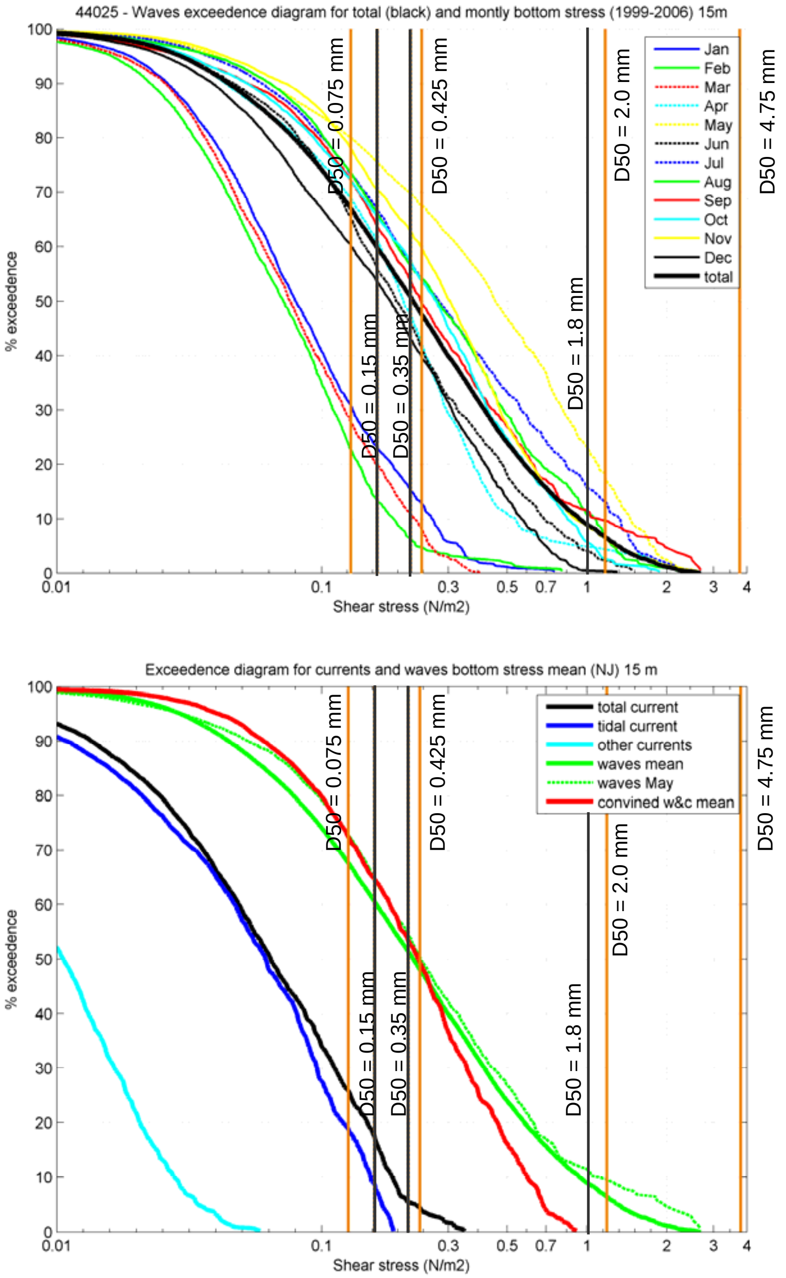
FIGURE B-6a



These plots represent the exceedance diagrams showing bed shear stress for waves (top) and total currents and waves (bottom). The shear stress values are calculated from wave data are based on NDBC Buoy 44025. These analyses were performed for an approximate water depth of 10 meters (~30 feet) (re: MLLW). The threshold shear stress values corresponding to the characteristic grain size values within the OWF are shown (0.15 mm, 0.35 mm, and 1.8 mm). Grain size classification is based on the Unified Soil Classification System (USCS).

PERCENT EXCEEDENCE CURVES
New Jersey Demonstration Site
TA&R Project #656
Seabed Scour Considerations

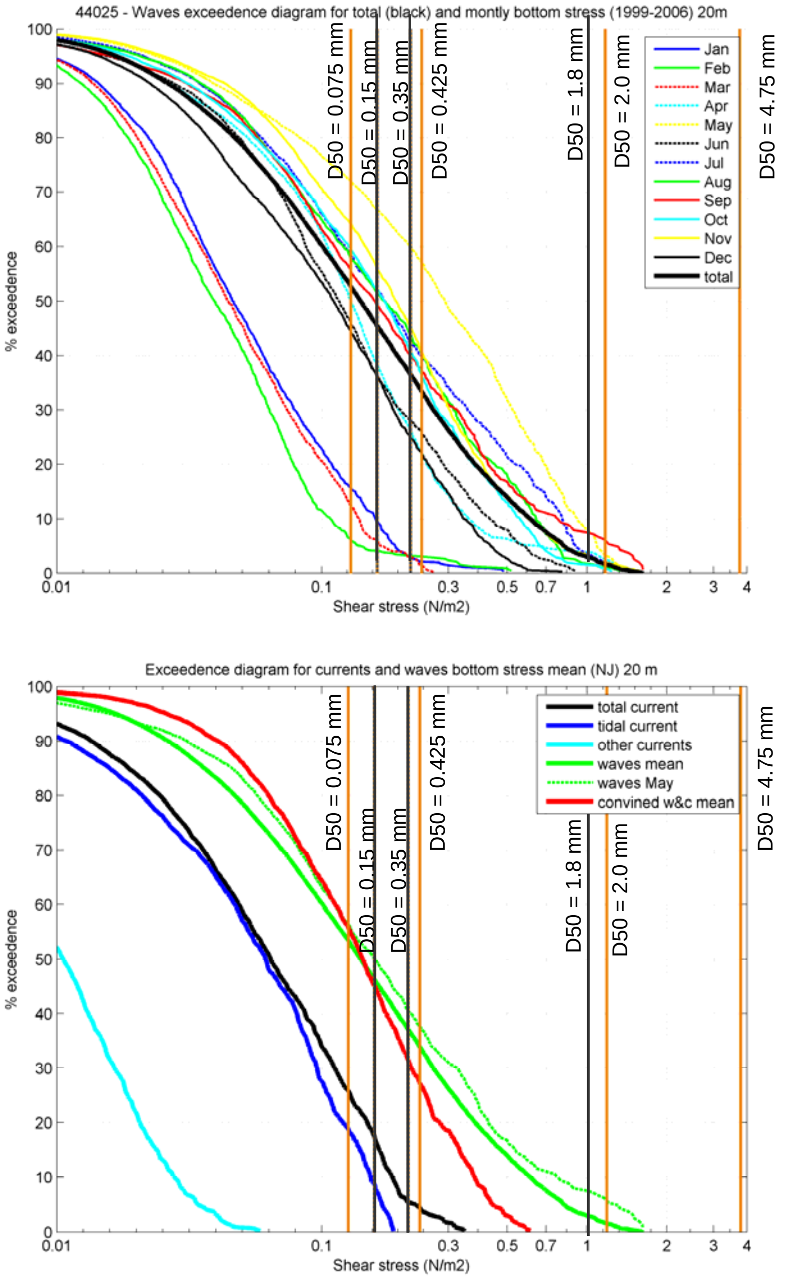
FIGURE B-6b



These plots represent the exceedance diagrams showing bed shear stress for waves (top) and total currents and waves (bottom). The shear stress values are calculated from wave data are based on NDBC Buoy 44025. These analyses were performed for an approximate water depth of 15 meters (~50 feet) (re: MLLW). The threshold shear stress values corresponding to the characteristic grain size values within the OWF are shown (0.15 mm, 0.35 mm, and 1.8 mm). Grain size classification is based on the Unified Soil Classification System (USCS).

PERCENT EXCEEDENCE CURVES
New Jersey Demonstration Site
TA&R Project #656
Seabed Scour Considerations

FIGURE B-6c



These plots represent the exceedance diagrams showing bed shear stress for waves (top) and total currents and waves (bottom). The shear stress values are calculated from wave data are based on NDBC Buoy 44025. These analyses were performed for an approximate water depth of 20 meters (~65 feet) (re: MLLW). The threshold shear stress values corresponding to the characteristic grain size values within the OWF are shown (0.15 mm, 0.35 mm, and 1.8 mm). Grain size classification is based on the Unified Soil Classification System (USCS).

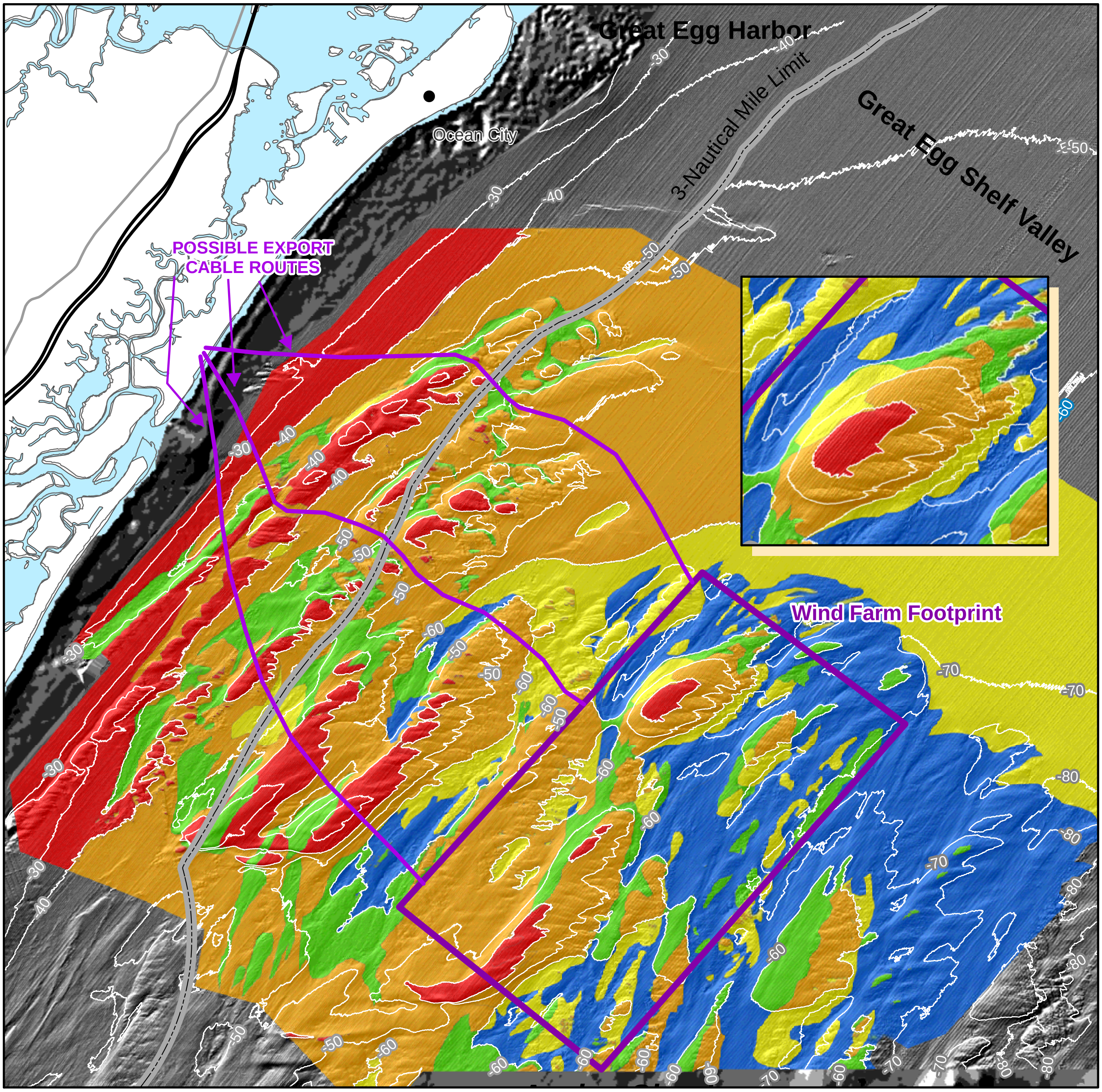
PERCENT EXCEEDENCE CURVES

New Jersey Demonstration Site

TA&R Project #656

Seabed Scour Considerations

FIGURE B-6d



Source: NJDEP, NOAA

Legend

Bathymetric Contours (MLLW)

10 Foot Contour Interval

% Exceedance of Bed Shear Stress	Sediment Transport Rate	Scour Potential
🟥 >75%	High	High
🟧 50%-75%	Moderate-High	Moderate-High
🟨 25%-50%	Moderate	Moderate
🟩 10%-25%	Moderate-Low	Moderate-Low
🟦 <10%	Low	Low

SCOUR SUSCEPTIBILITY
MEAN ANNUAL FLOW CONDITIONS
New Jersey Demonstration Site

TA&R Project #656
Seabed Scour Considerations

0 1 2 Nm
0 4 km

FIGURE B-7

N:\Projects\3707_MMS\Outputs\Draft_Report_Nov2010\mxd\Fig-B-7_ScourSusceptibility.mxd, 12/05/10, ksmith

APPENDIX C
SHEAR STRESS EXCEEDANCE METHODOLOGY

APPENDIX C CONTENTS

APPENDIX C
SHEAR STRESS EXCEEDANCE METHODOLOGY

INTRODUCTION

This section describes the analytical methods used to estimate the bed shear stress due to wave, current, combined hydrodynamic flow regimes, and threshold shear stress for the characteristic grain sizes identified within the study areas. Plotting the percentage of shear stress exceedance versus shear stress produces an exceedance diagram. Long-term sediment transport is likely to occur if the generated bed shear stress exceeds the threshold shear stress for particular sediment grain size at least 10 percent of the time (i.e. 10-percent exceedance) (Whitehouse, 1998). Therefore, exceedance diagrams are useful to assess long-term sediment transport for a particular sediment grain size based on the calculated threshold shear stress for that sediment.

The methodology described herein is based on equations given in Soulsby (1997) and Wiberg and Sherwood (2008). Whitehouse (1998) includes a summary of the equations found in Soulsby (1997) as applied to scour analyses.

WAVE FLOW REGIME

The calculation of wave-related bed shear stress (τ_W) is given by:

$$\tau_W = 0.5\rho f_W \cup_W^2$$

where ρ is the fluid density, f_W is the dimensionless wave friction factor, and U_W is the amplitude of the bottom orbital velocity due to the wave motion.

Based on the method given by Soulsby (1997), the dimensionless wave friction factor in rough, turbulent flow is given by:

$$f_W = 1.39\left(\frac{A}{z_O}\right)^{-0.52} \quad \text{and} \quad A = \frac{\cup_W T_P}{2\pi}$$

where A is the amplitude of the orbital wave motion at the seafloor, T_p is the peak period, and z_O is the hydraulic roughness length (calculation is given above).

The calculation for the wave orbital velocity is based on one of the following assumptions: 1) The wave is small-amplitude and monochromatic (single frequency) which allows the linear wave theory to predict the bottom orbital velocity (U_W); or 2) a spectrum of wave frequencies and wave heights are used to calculate the representative bottom orbital velocity (U_{br}) based on these spectrum.

For a small-amplitude, monochromatic waves, the bottom orbital velocity is given by the following:

$$U_w = \frac{\pi H_s}{T} \frac{1}{\sinh(kh)}$$

where H_s is the significant wave height, T is the wave period, h is the water depth, and k is the wave number.

Hence the bottom orbital velocity is directly proportional to the wave height and inversely to the water depth.

The spectral wave analysis and calculation of the representative bottom orbital velocity (U_{br}) is complex. A detailed description of one method is given in Wiberg and Sherwood (2008). That methodology was used to calculate the representative bottom orbital velocity used to determine the wave-related bed shear stress as presented in the shear stress exceedance diagrams.

CURRENT FLOW REGIME

The grain related bed shear stress due to a steady current (τ_C) is calculated by:

$$\tau_C = \rho C_D \mathrm{U}^2$$

where ρ is the fluid density, C_D is the dimensionless drag coefficient for the depth-averaged current speed U.

The dimensionless drag coefficient is given by:

$$C_D = \left[\frac{0.40}{\left(\ln\left(\frac{h}{z_O} \right) - 1 \right)} \right]^2$$

where h is the mean water depth and z_O is the hydraulic roughness length.

To calculate the bed shear stress for currents, the hydraulic roughness length (z_O) is given by:

$$z_O = \frac{2.5 d_{50}}{30}$$

where d_{50} is the mean grain size. These calculations assume that the depth-averaged current velocity, U, is given.

COMBINED WAVE AND CURRENT FLOW REGIME

The approach for calculating the mean and maximum bed shear stress, as given in Soulsby (1997), due to the interaction of waves and currents is as follows. To calculate the maximum bed shear stress, the mean is first calculated by:

$$\frac{\tau_m}{\tau_C} = 1 + 1.2\left(\frac{\tau_W}{\tau_C + \tau_W}\right)^{3.2}$$

where τ_W is the wave related bed shear stress, τ_C is the current bed shear stress, and τ_m is the mean bed shear stress.

The maximum bed shear stress is calculated by vector addition of τ_m and τ_W to give the magnitude of the shear stress vector:

$$\tau_{\max} = \left[(\tau_m + \tau_W \cos\phi)^2 + (\tau_W \sin\phi)^2\right]^{0.5}$$

where Φ is the angle (°) between the wave and current bed shear stresses.

THRESHOLD SHEAR STRESS CALCULATIONS

The threshold shear stress (τ_o), which after exceeded sediments are mobilized, is determined by solving the following equation:

$$\theta = \frac{\tau_O}{(\rho_S - \rho) g d_{50}}$$

where ρ_s is the sediment density, ρ is the fluid density, g is the acceleration due to gravity, d_{50} is the mean sediment grain size, and θ is the Shields parameter.

The Shield parameter is given by:

$$\theta = \frac{0.30}{1 + 1.2D_*} + 0.55\left[1 - \exp(-0.20D_*)\right] \text{ with } D_* = d_{50}\left(\frac{(s-1)g}{\upsilon^2}\right)^{1/3}$$

where s is the density ratio (ρ_s / ρ) and v is the kinematic viscosity of the fluid.

The threshold shear stress value (τ_o) is compared to the current, wave, and/or combined bed shear stress values (on the exceedance curves) to estimate the long-term mobility of marine sands.

SUMMARY OF INPUT PARAMETERS

The following parameters are needed to calculate the bed shear stress for the different flow regimes:

- Water depth (h) and water density (ρ);
- Mean grain size d_{50} of the seafloor sediment;
- Wave characteristics including significant wave height (H_s), wave period (T) or peak period (T_p), and wave number (k);
- The monochromatic (U_W) or spectral representative (U_{br}) bottom orbital velocity;
- The depth-averaged current velocity ($\bar{U}$); and
- Angle between mean current flow and mean wave direction (ϕ).

ASSUMPTIONS AND LIMITATIONS

The following are the assumptions used in calculating the bed shear stress, as well as the limitations of these methods.

- All environmental conditions are assumed to be constant (e.g., steady current flow) and the seafloor is flat and relatively featureless.
- If unknown, the flow directions for waves and currents under combined conditions are assumed to be co-directional.
- The choice of a suitable wave theory is determined by water depth, wave height and period. These calculations assume that sinusoidal wave theory is applicable. The applicability of this theory can be checked by calculating the Ursell parameter as described by Sumer and Fredsøe (2002).
- The equations given in Soulsby (1997) assume that the sediments are cohesionless (i.e. clean sand with little to no cohesive sediments). This represents a conservative estimate of sediment mobility if cohesive sediments are present due to the fact that cohesive sediments will increase the threshold shear stress of sandy sediments (Mitchener et al., 1996). The inability to reliably calculate the threshold shear stress when considering cohesive sediments is a limitation to the method.

It is important to recognize that Soulsby (1997) provides a guide that is intended to be a practical approach to sediment transport evaluations. Soulsby (1997) notes in the preface that he made simplifications and assumptions to bridge the gap from academic research, which is published in unfamiliar language in journals and proceedings that are sometimes difficult to comprehend, to a practical method that can be used. In keeping with Soulsby's spirit, we have attempted to keep the information understandable to the non-technical audience while addressing technical issues.

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