ANNEX V
Mooring & Anchors Research Projects

CONTENTS

V.1 SUMMARY OF PROJECTS

This section of the report provides a summary of each of the project groupings, namely Wave and Current Energy Generating Devices, Hurricane Effects on Mooring Capabilities, Hurricane Hindcast Data, and Anchors.

V.1.1 WAVE AND CURRENT ENERGY GENERATING DEVICES

Two (2) TA&R projects have been conducted into the progress of wave and current energy generating devices, and the subsequent need for the development of suitable standards. These projects are TA&R Projects No. 629 and 628, and are summarized below. Detailed summaries of these projects are provided in a later section of this Annex.

V.1.1.1 Assess the Design and Inspection Criteria and Standards for Wave and Current Energy Generating Devices

The objective of this project was to provide a description of wave and current energy generating device systems and subsystems and provide a functional taxonomy. To identify criteria pertinent to the design, construction, installation, maintenance and operations of these systems, and review the criteria to determine applicability, adequacy, and suitability. Also, to identify existing codes and standards that can be applied to these devices; conduct a regulatory gap analysis; and recommend regulatory initiatives or approaches for addressing identified deficiencies.

It was found that the existing regulations do not specify the requirements of the various criteria for wave and current energy generating devices. At present the International Electrotechnical Commission (IEC) is conducting research into the development of specific standards for this emerging industry, and it was recommended that the MMS does not add any missing criteria to the existing standards until after the completion of this work.

V.1.1.2 Assess the Design/Inspection Criteria/Standards for Wave and/or Current Energy Generating Devices

The aim of this project was to perform a gap analysis to determine the possible requirement of modifications that should be made to engineering specifications and regulatory standards to enable the placement of wave and current energy devices within the outer continental shelf (OCS) without compromising safety and performance guidelines.

The report found that the designs of wave and current energy conversion devices suitable for OCS implementation are uncertain at present, and that energy conversion requires a system for which a set of suitable standards needs to be developed. It is recommended that the MMS should take the lead in developing a Memorandum of Understanding with the Federal Energy Regulatory Commission (FERC) to promote relationships to (a) maximize the efficiency of wave and current energy conversion facility inspection and monitoring, (b) minimize overlap, (c) ensure consistent policy, (d) help advance the emerging marine energy industry, and (e) support and strengthen federal renewable energy initiatives.

V.1.2 ANCHORS

Two (2) TA&R projects have been conducted into the development of anchors for the Gulf of Mexico, and the development of anchor codes of practice. These projects are Project 575 which reports on the development of torpedo pile anchors, and Project 437 which summarizes developments of the standards for drag-in and push-in plate anchors. Both reports are summarized below. Detailed summaries of these projects are provided in a later section of this Annex.

V.1.2.1 Torpedo Piles for Gulf of Mexico Applications

The project consisted of four phases. The first phase consisted of a thorough review of the literature about torpedo piles and other seafloor penetrator experiments. The second phase consisted of developing a set of design models to predict the penetration and the capacity of torpedo piles as a function of seafloor velocity, pile geometry and soil shear strength. The third phase consisted of conducting a series of 1:30 model torpedo pile experiments at The University of Texas at Austin using their large soil bed facilities. The final phase involved performing a limited number of offshore field tests.

The work of this study further developed mathematical models for torpedo piles design capacity to incorporate soil interactions, adding to the previous experience and knowledge of Petrobras and the University of Western Australia. Work in this area is still ongoing with full scale testing planned. Figure VI.1 shows a typical torpedo pile geometry that has been successfully deployed by Petrobras in the Campos Basin in offshore Brazil.

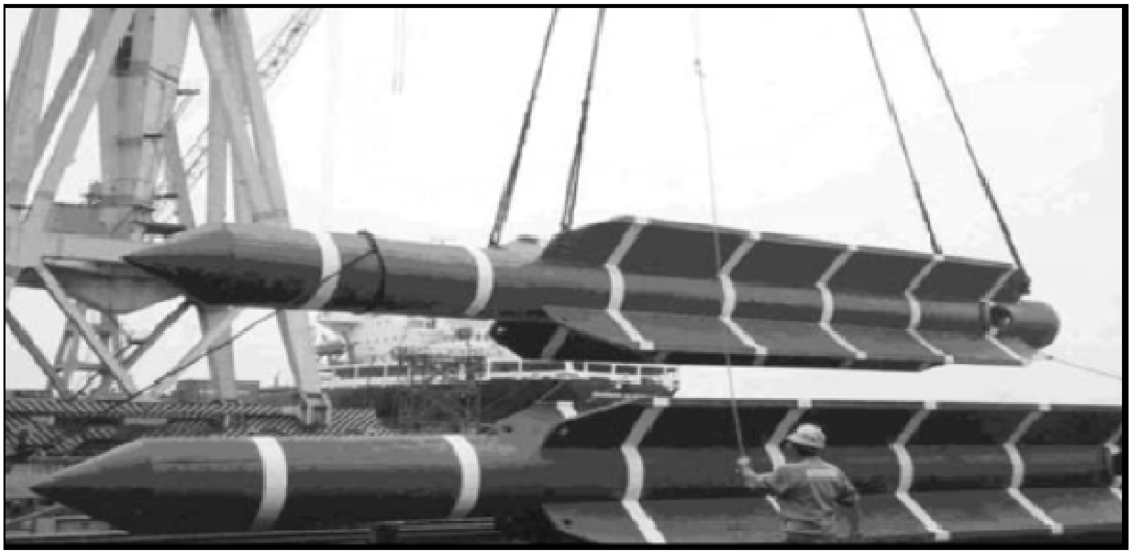

Figure V.1: Typical Torpedo Pile Geometries as used by Petrobras in the Campos Basin

V.1.2.2 Reliability Analysis of Deepwater Anchors

During the last 5 years push-in plate anchors have emerged as a potential alternative to more popular drag-in anchors. This report developed the standards to enable better clarification and definition of the design safety factors required for plate anchors, and improved the understanding of the mathematical modeling of these anchors. Calibration of the standards against twelve (12) test cases showed some variability over the scope of the code, and highlighted the need for further investigation to utilize more test data to allow for future development of the standard.

V.2 WAVE AND CURRENT ENERGY GENERATING DEVICES

V.2.1 PROJECT NO. 629 – ASSESS THE DESIGN AND INSPECTION CRITERIA AND STANDARDS FOR WAVE AND CURRENT ENERGY GENERATING DEVICES

V.2.1.1 Introduction

V.2.1.1.1 Background

A 2007 report by the Electric Power Research Institute (EPRI) states that U.S. wave and current resources have the potential to meet 10% of the nation's electric power demand [17]. The marine hydrokinetic industry is in a nascent state and includes new technologies that must be evaluated to determine if existing standards are adequate to ensure safety of personnel and the environment.

Examples of potential renewable energy projects include, but are not limited to: wind energy, wave energy, ocean current energy, solar energy, and hydrogen production. Under this new authority, MMS published final rulings in April 2009 [20] intended to encourage orderly, safe, and environmentally responsible development of renewable energy resources and alternate use of facilities on the Outer Continental Shelf (OCS).

V.2.1.1.2 Technical Scope

Given that the MMS has a specific responsibility under the Energy Policy Act [18] it was necessary to undertake this study to assess the existing standards and identify any gaps in these standards.

V.2.1.1.3 Study Limitations

Based on an initial review of existing codes and standards developed for the offshore energy industry, and new codes and standards being developed in Europe specifically for these new technologies, a range of documents, thought to be most applicable, were selected for review. This is a subjective approach, and as such may omit some documents which may be pertinent.

V.2.1.2 Project Conclusions

V.2.1.2.1 Key Conclusions and Results

The main conclusions of the report are:

- Of the 31 different standards only a handful provide substantive guidance on any given criterion, and many either do not address a particular criterion or provide substantive guidance beyond stating that the criterion should be addressed;
- Existing standards do not specify requirements for the various criteria. As an example, the standards do not state what return period the wave and current energy generating devices should be designed for, only that loading information must be submitted.
- Substantive guidance for operation, inspection maintenance, and repair activities is largely lacking for floating platforms (e.g., wave energy absorbers, submerged current turbine nacelles), electrical cables, and auxiliary systems;
- While there is considerable guidance for periodic and special surveys after construction of closed (or type certified) offshore buoys, installations, and vessels, these requirements are specific to the classification organization such as ABS, DNV, or GL (Germanischer Lloyd);
- It is anticipated that detailed survey requirements will be developed and modified based on long-term operational experience across tens to hundreds of floating platforms.

V.2.1.2.2 OSER Goals

The combination of an increasing energy market and depletion of natural gas and oil reserves in the U.S. has resulted in renewed interest in developing renewable sources of energy, including the conversion of ocean waves and currents into usable forms of energy. The ocean is an appealing source of renewable energy because of its high power density, meaning it can potentially produce large amounts of electricity. However, current standards for the marine hydrokinetic industry are not adequate to ensure safety of personnel and the environment. This is in-line with the OSER goals of independent verification of emerging technologies in terms of reliability, operational safety and environmental protection.

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V.2.1.2.3 Recommendations

It is recommended that the MMS do not add missing criteria to existing standards until the work of the IEC TC-114 [19] is completed to ensure consistency with international standards. The IEC TC-114 is a technical committee which aims to address:

- System definition.
- Performance measurement of wave, tidal and water current energy converters.
- Resource assessment requirements, design and survivability.
- Safety requirements.
- Power quality.
- Manufacturing and factory testing.
- Evaluation and mitigation of environmental impact.

V.2.1.3 Current State of Knowledge

There are no existing U.S. regulatory criteria governing wave and current energy devices with submittals contained in MMS 285 and FERC Pilot Plant licenses, currently the only existing regulations in the U.S. governing wave and current energy devices.

V.2.2 PROJECT NO. 628 – ASSESS THE DESIGN/ INSPECTION CRITERIA/ STANDARDS FOR WAVE AND/OR CURRENT ENERGY GENERATING DEVICES

V.2.2.1 Introduction

V.2.2.1.1 Background

The Minerals Management Service (MMS) seeks to advance the development of the alternative energy regulatory process pertaining specifically to wave- and current-energy conversion on the Outer Continental Shelf (OCS). This report assesses the design and inspection criteria and standards for wave and current energy-generating devices.

V.2.2.1.2 Technical Scope

The main objectives of the report were to:

- Review the current technologies for wave and current energy conversion devices, offshore electrical transmission and interface, offshore facilities, anchoring and mooring systems, and offshore facilities management;
- Review engineering standards relevant to the design, development, implementation, test, operation, and decommissioning of wave and current energy conversion devices on the OCS;
- Review existing inspection and monitoring approaches and technologies for wave and current energy conversion devices and ancillaries, and outline safety and regulatory concerns of the current engineering standards for these systems;
- Determine modifications to engineering specifications and regulatory standards needed from gap analysis, to enable the implementation of wave and current energy conversion equipment on the U.S. OCS without compromising safety or performance;
- Recommend research initiatives to enhance the safe and effective regulation of wave and current energy conversion equipment devices and ancillary equipment;
- Provide comments to the MMS Potential Incident of Non Compliance (PINC) list to reflect the results of research and evaluation.

V.2.2.1.3 Study Limitations

This study focused on evaluating existing conversion devices by conducting a wide ranging literature review of information available in the public domain, as well as consultations with all perceived major stakeholders in this technology development. However, given the large variations in approaches [21] and the competitiveness of this emerging industry, it is perhaps conceivable that some aspects may have been omitted.

V.2.2.2 Project Conclusions

V.2.2.2.1 Key Conclusions and Results

In summary the report found:

- **Energy conversion devices** The designs of wave and current energy conversion devices suitable for OCS implementation are quite uncertain at this juncture. Variations in the device designs suggest it is problematic to ensure compliance with installation, operation, maintenance, and decommissioning specifications;

- **Energy conversions systems** Viable alternative energy conversion requires a system, and may include control systems, transmission equipment, and grid interconnection apparatus, as well as shore-based support industry;
- **Electrical transmission** Electrical transmission is emerging as a pivotal issue in the success of offshore wave and current energy conversion. The cost of subsea transmission cable and installation (estimated at $5 million per mile) will significantly limit development on the OCS unless new technologies and methods for manufacturing and installation are developed. Additionally, at present the interface of wave and current devices to the subsea transmission network presents some technical challenges;
- **Engineering standards** Only a few engineering standards have been specifically written for wave and current facilities, equipment, and operations. Due to the dramatic variance of technologies being considered for marine energy conversion some standards lack relevance. As a result many developers have a low awareness of the standards, and may avoid them. To avoid confusion and to increase compliance, one set of standards should be applied to the global wave and current industry;
- **Impact of existing oil and gas industry** Areas of overlap between renewable energy conversion and existing oil and gas industries do exist and can be exploited. However, specific standards for the renewable energy industry should be developed;
- **Desirable sites** In addition to adequate wave activity and/or flow velocity, suitable sites for wave and current energy conversion will have one or more of the following conditions: a deregulated power market, high electrical kilowatt hour rates, limited electrical power availability from traditional means, strong renewable energy incentives, and/or an existing electrical infrastructure;
- **Regulations** Properly developed regulations can advance the industry by providing a guide from start-up to end of life for energy conversion equipment, systems and facilities.

V.2.2.2.2 OSER Goals

For both wave- and current-driven energy systems, a wide range of technology presently exists to harness this renewable resource for the generation of electricity. Despite the array of technologies available, no definitive designs have emerged. In addition, current standards for the marine hydrokinetic industry are not adequate to ensure safety of personnel and the environment. This effort is in-line with the OSER goals of independent verification of emerging technologies in terms of reliability, operational safety and environmental protection.

V.2.2.2.3 Recommendations

The following recommendations are made:

- **Inspection and monitoring** Wave and current energy generation primarily will be remotely controlled and monitored, with inspection of this industry be performed in a consistent manner;
- **Collaboration with FERC** MMS should take the lead in developing a Memorandum of Understanding with the Federal Energy Regulatory Commission (FERC) to promote relationships to (a) maximize the efficiency of wave and current energy conversion facility inspection and monitoring, (b) minimize overlap, (c) ensure consistent policy, (d) help advance the emerging marine energy industry, and (e) support and strengthen federal renewable energy initiatives;
- **Scientific and technical committees** MMS should develop and join scientific and technical committees specific to the ocean energy industry, to represent and directly engage in interagency and international efforts. MMS should take the lead role in this;
- **International involvement** Increase U.S. involvement in international activities of the ocean energy industry. This will facilitate the growth of energy conversion, which will help ensure that U.S. regulations are consistent with participants globally.
- **OCS development** An impartial assessment of ocean energy resources on the OCS would benefit the advancement of offshore wave and current energy conversion development.

V.2.2.3 Current State of Knowledge

As most familiar with the industry would acknowledge, wave and current energy conversion is a nascent industry with many stakeholders, many technologies, and many uncertainties. A distinction must be made between *site developers* and *technology developers*, and within these groups, the technical, financial, and managerial capabilities of the various players should be ascertained.

V.3 ANCHORS

V.3.1 PROJECT NO. 575 – TORPEDO PILES FOR GULF OF MEXICO APPLICATIONS

V.3.1.1 Introduction

V.3.1.1.1 Background

Torpedo piles are steel, torpedo-shaped objects that are installed as projectiles penetrating the sea floor under velocity. They are a potentially viable alternative for anchoring both mobile drilling units as well as permanent facilities and have been deployed successfully in offshore Brazil. However, they have not yet been used in the Gulf of Mexico. The goal of this project was to improve understanding about how torpedo piles behave during installation and pull-out by conducting 1:30 scale model tests in normally consolidated beds of kaolinite typical of that found in the GOM.

V.3.1.1.2 Technical Scope

The goal of this study was to provide a fundamental understanding of how torpedo piles behave in normally consolidated clay during installation and pull-out under rapid loading conditions (representing a storm load). Specific objectives were:

- Measure how the final penetration depth of a torpedo pile varies with the velocity at the mudline, the weight and geometry of the torpedo pile, and the undrained shear strength of the clay;
- Measure how the pull-out capacity for rapid loading varies with the penetration depth, the set-up time between installation and pull-out, the angle of loading, and the un-drained shear strength of the soil; and
- Compare measured behavior with predictive models of behavior.

V.3.1.1.3 Study Limitations

- The kaolinite clay used in the model tests outlined in the report is not directly representative of typical marine clay, in that it displays little thixotropy (strength increase with time at a constant water content). However, this effect on soil disturbance may be less pronounced in clays where the strength continues to increase with time with constant water content, which is typical of marine clay in the Gulf of Mexico.

- Possible soil disturbance related to a hydrodynamic drag effect at the tip of the torpedo pile, may be dependent on scale, thus leading to possible differences in soil interactions with a full-scale torpedo pile where the penetration velocity and the diameter are larger.

V.3.1.2 Project Conclusions

V.3.1.2.1 Key Conclusions and Results

In summary the results are:

- The embedment depth of a torpedo pile increases as the drop height and the weight of the pile increase. A simple model of soil resistance during penetration that accounts for remolding and rate effects on the un-drained shear strength is able to predict the embedment depth accurately (generally within +/- 10 percent of the measured value);
- The axial pull-out capacity, under un-drained loading after set-up, increases with the embedment depth, the un-drained shear strength of the soil, and the weight of the torpedo pile. The soil immediately adjacent to the shaft in the model test developed in this report was reconstituted at a higher moisture content during penetration; with the predicted capacity matching the measured capacity when an empirical side shear transfer factor, α, value of 0.5 is used in the prediction model. This zone of reconstituted soil is localized, and may not affect the mobilized side shear on the fins of a torpedo pile.
- The lateral pull-out capacity under un-drained loading after set-up is predicted well by a simple model that assumes the pile rotates as a rigid body in undisturbed soil.

V.3.1.2.2 OSER Goals

The goal of this study was to improve understanding about how torpedo piles behave during installation and pull-out by conducting scale model tests. The results indicated that torpedo piles have the potential to provide a practical alternative for offshore anchors in temporary or permanent mooring systems. This effort is in-line with the OSER goals of independent verification of emerging technologies in terms of reliability, operational safety and environmental protection.

V.3.1.2.3 Recommendations

It is recommended that further work is conducted, to include performing additional model tests with different pile geometries (such as fins), different pile diameters and lengths, different soil conditions (such as a soil with a different sensitivity or thixotropic behavior) and different loading conditions (such as sustained loads). In addition, field-scale testing of installation and pull-out with a small torpedo piles (perhaps 1/3 to 1/2 of full scale) are believed to be of future benefit.

V.3.1.3 Current State of Knowledge

Petrobras has successfully used in excess of 90 torpedo piles since 2002 [22] to anchor flexible risers in the Campos Basin. The pull out capacities immediately after deployment were shown to be 1.5 times the air weight of the torpedo, increasing to 3 to 4 times after ten days of set-up time. However, no information about the soil conditions has been published with these results. Further scaled model analysis for torpedo designs has been performed at the COFS at the University of Western Australia [23], modeling the impact velocities. The work in this current TA&R study has further developed mathematical models for torpedo piles to incorporate soil interactions. However, the work is still ongoing with recommendations for further work on full scale tests in the field [24].

V.3.2 PROJECT NO. 437 – RELIABILITY ANALYSIS OF DEEPWATER PLATE ANCHORS

V.3.2.1 Introduction

V.3.2.1.1 Background

During the last 10 years, the offshore energy industry has shown an increasing interest in drag-in anchors so there is a need to calibrate safety factors for these anchors. Drag-in anchors continued to be first choice, but push-in plate anchors emerged as a potential alternative 5 years ago, especially by Petrobras in Brazil.

V.3.2.1.2 Technical Scope

The objectives of the report were to:

- Perform a reliability analysis of drag-in type plate anchors utilizing the experience from previous projects;
- Incorporate push-in type plate anchors into the reliability analysis utilizing the similarities between the pullout resistance of the drag-in and push-in types of plate anchor, but account for the differences in anchor specific installation effects on pullout resistance;
- Use reliability analysis in the calibration of a simplified design code for both types of plate anchors;
- Quantify partial safety factors for use in the DNV recommended practice No. RP-E302 for design and installation of drag-in plate anchors;
- Quantify partial safety factors for use in the design of push-in type plate anchors as related to a tentative and simplified code for such anchors.

V.3.2.1.3 Study Limitations

The reliability analysis disregards the anchor installation effects, which are anchor type specific. Such effects are addressed separately and become part of the overall design issues, which emphasizes the important inter-relationship between design and installation of plate anchors.

V.3.2.2 Project Conclusions

V.3.2.2.1 Key Conclusions and Results

The main conclusions of the report are:

- The characteristic anchor resistance calculation has been changed from the current two partial safety format to a single partial safety format as given in DNV RP-E302 [25];
- The change to a single partial safety format is due to the cycling loading effect not being of significance to warrant a specific safety factor, and that the cyclic shear strength rather than the intact shear strength should be used as the characteristic strength when designing offshore foundations governed by wave loading;
- Reliability analysis was applied to twelve test cases from which parameters which could be modeled as stochastic variables were chosen [26];
- For two layer soil profiles it is found more appropriate to model the uncertainty in the intact undrained shear strength by using a Coefficient of Variation (CoV);

- Calibration of the achieved failure probabilities showed some variability over the scope of the code as represented by the 12 test cases, showing the need for the refinement of the DNV RP E302 code or a reduction in its scope to obtain a more uniform safety level.

V.3.2.2.2 OSER Goals

A reliability analysis of plate anchors was performed with the objective to calibrate the partial safety factors of a simplified design code applicable to both drag-in type and push-in type plate anchors. This effort is in-line with the OSER goals of independent verification of emerging technologies in terms of reliability, operational safety and environmental protection.

V.3.2.2.3 Recommendations

The following recommendations are made:

- To obtain a more uniform safety level the DNV RP E302 code format should either be refined, or the scope of the code should be reduced;
- Improvement of the code can also be obtained if the characteristic soil strength is greater defined from its present value equal to the mean to some lower-tail quartile;
- Improvement in the calibration and robustness of the code can be obtained by adding more test cases, such as environmental conditions and water depths;
- Follow up work should focus more on the interpretation of the results with the objective to learn more about what causes the variability in the achieved failure probabilities by thorough investigation of each test case.

V.3.2.3 Current State of Knowledge

The conclusions and findings of this report resulted in the Recommended Practice being updated [27], which is the current RP used by the industry. However, further work recommendations made by the report will likely result in further future updates of the standard.

V.4 REFERENCES

17. Bedard, R., EPRI, "Overview of Wave and Current Energy: Resource, Technology and Business Issues", OTC Paper No. 19094-MS, 2007.

18. Energy Policy act of 2005, "An act to ensure jobs for our future with secure, affordable, and reliable energy", HR6, 2005.

19. IEC, "Marine Energy – Wave, tidal and other water current converters", TC-114.

20. MMS, "Renewable Energy and Alternate Uses of Existing Facilities on the Outer Continental Shelf: Final Rule: Environmental Assessment", April 2009.

21. Englander, D., and Bradord, T., "Forecasting the Future of Ocean Power", GreenTech Media, October 2008.

22. Medeiros Jr., C. J., "Low cost anchor system for flexible risers in deep water," Offshore Technology Conference, Houston, May, 2002, Paper No. OTC 14151.

23. O'Loughlin, C. D., Randolph, M. F., Richardson, M., "Experimental and theoretical studies of deep penetrating anchors," Offshore Technology Conference, Houston, May, 2004, Paper No. OTC 16841.

24. Torpedo Piles JIP, "Model Torpedo Pile Tests in Kaolinite Test Beds", Principal Investigator Gilbert, R. B, March 2008.

25. DNV Recommended Practice RP-E302, "Design and Installation of Drag-in Plate Anchors in Clay", April 2000.

26. Ronald, Knut O., Dahlberg, Rune, Horte, Torfinn and Strom, "Reliability analysis of deepwater plate anchors", DNV Report No. 2001-1482 (JIP Technical Report No. TR1), Rev 02, February 2002.

27. DNV Recommended Practice RP-E302, "Design and Installation of Drag-in Plate Anchors in Clay", December 2002.