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An Expert Panel Review of Geotechnical Site Investigation Regulations and Current Industry State of Practice

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Abstract

The paper describes a joint industry project (JIP) conducted to provide an independent review of the current Bureau of Safety and Environmental Enforcement (BSEE) regulations and the American Petroleum Institute (API) standards (including their historical development). The main objective of the JIP was to make recommendations for improving industry's state-of-practice including revising regulations as needed to reflect the best methods for conducting deepwater geotechnical investigations.

The study provides a careful review of all regulations applicable to an integrated site investigation required for the foundation design of a permanent floating production system. A panel of experts in offshore geotechnical engineering was assembled to obtain their technical guidance for defining the most appropriate work scope for an offshore geotechnical investigation for a permanently moored production system.

The study describes the progress that has been made in site investigation technology (continuous sampling and *insitu* testing methods) and interpretation of the data since the regulations were initially published. The study also discusses how the current regulations should be interpreted in light of these recent advancements, as applied to the foundation design of suction piles, plate anchors, or driven piles.

The expert panel also recommended revising the regulatory text to ensure that best field practices and sound engineering design principles can be employed when designing foundations to be safe and accomplish their intended purpose. The major benefit of the revised regulatory text is avoiding ambiguity between regulators and practicing geotechnical engineers as to what constitutes best practices for conducting a deepwater integrated site investigation.

Introduction

On December 27, 2001, the Minerals Management Service (MMS) published amended requirements in the Federal Register (30 CFR 250) to address the design of Floating Production Systems (FPSs). The purpose was to incorporate into their regulations a body of industry standards pertaining to FPSs so that system designers would know what is acceptable. Instead of writing their own standards, MMS determined that it would be most efficient and provide the highest level of expertise to the regulatory process if they incorporated the American Petroleum Institute (API) standards.

In recent years, practicing geotechnical engineers working on deepwater offshore projects worldwide have found that establishing the scope of an offshore site investigation is often difficult. The difficulty lies in the ambiguity in the regulations leading to a lack of consensus among regulators, certified verification authorities (CVAs), and practicing geotechnical engineers as to requirements for conducting site investigations for deepwater projects.

Since the new requirements (30 CFR 250) were published over a decade ago, the practice of conducting deepwater site investigations has dramatically improved. Today, high quality, digital geophysical data is routinely acquired very efficiently with an Autonomous Underwater Vehicle (AUV). The suite of data such as swath-bathymetry, sub-bottom profiles, and side-scan sonar imagery can be interpreted and mapped to provide a clear 3D picture of the seafloor and subsurface geologic/sediment conditions. More innovative site investigation methods have been developed for obtaining large diameter continuous samples (Jumbo Piston Core - JPC), performing continuous cone penetration test (CPT) soundings and combining these data with the geophysical survey data into an integrated geologic/geotechnical model.

This paper reports the findings of a JIP performed by a panel of expert geotechnical engineers. The panel consisted of the authors of this paper. The senior author managed the project on behalf of the participating companies. The purpose of the JIP was to conduct an independent review of the current BSEE and API regulations (including their historical development) and make recommendations for improving industry's state-of-practice by changing the regulations to reflect improved methods for conducting deepwater site investigations. The study objective was to assemble their technical guidance for planning the most appropriate work scope for offshore geophysical survey and subsequent geotechnical investigation for a permanently moored production platform in the Gulf of Mexico and other offshore regions.

Regulatory Background

An understanding of the chronology of applicable regulations is important to understand how the initial regulations evolved to their present state. The MMS[1] published a proposed rule in the Federal Register (66 FR 66851-66865) on December 27, 2001, to amend subpart I of 30 CFR Part 250 – Platforms and Structures. Their proposed rule was designed to streamline the permitting process for FPSs.

By incorporating the API standards into the MMS regulations, they dictated that each company would comply with the requirements in the API documents that included the CVA review and hazards analyses. Eight API standards were initially incorporated into the regulations, and the one that most directly addressed deepwater facility siting is API RP 2SK[2], (Recommended Practice for Planning, Designing and Analysis of Station Keeping Systems for Floating Structures).

During the commentary phase and prior to the final publication of Section 250.915a, Shell and the Offshore Operators Committee (OOC) commented on the site investigation requirements as follows:

1. Spatial variability of soil properties on the continental shelf is much more of an issue than for deepwater sites. For jackets on the shelf, maximum distance between borings of 500 ft. is reasonable for deterministic designs with conventional safety factors. However, it is possible to have cases where multiple borings are spaced farther apart, but the uncertainty at the platform site may be explicitly quantified and specific safety factors developed accordingly.
2. In lieu of the prescriptive requirement as proposed, the wording from ISO/DIS 19901-4 could be adopted:

> *Geotechnical and Foundations Design Considerations. Results of previous integrated geoscience studies and experience at the site may enable the design and installation of additional structures without additional investigation. The onsite studies should extend throughout the depth and areal extent of soils that will affect or be affected by installation of the foundation elements. The number and depth of borings and extent of soil testing will depend on the soil variability in the vicinity of the site, environmental design conditions (e.g. earthquake loading and slope instability) to be considered in the foundation design, the structure type and geometry, and the definition of geological hazards and constraints.*

American Bureau of Shipping (ABS) also submitted the following comment concerning proposed Sec. 250.915:

> *It will be very helpful to the offshore industry to clarify requirements as to the maximum distance of the soil boring from the foundation piles and number of borings. It would also be helpful to clarify if the borings can be replaced by other means of taking soil samples such as CPT or by a combination of geotechnical investigation and geophysical survey.*

The MMS published their response to the industry comments as follows:

> *MMS does not agree with OOC, Shell, and ABS. None of their proposals is as stringent as what MMS has proposed, i.e., site-specific borings within 500 feet of the proposed foundation pile. In the deepwater areas of the OCS, particularly in the GOM, there are slope and abyssal areas that are much more geologically active than the relatively shallow and familiar areas of the OCS. There are highly active slumping and faulting zones in deepwater areas that exhibit stratigraphic shallow water flows and mud volcanoes. MMS does not believe that floating production systems in these areas should be anchored without site-specific soil boring information.*
>
> *… The policy currently outlined in Sec. 250.141 of our regulations promote the use of alternative technology or innovative practices that are not specified or otherwise covered under our regulations. Such technologies and practices may be tried on a case-by-case basis, so long as they "provide a level of safety and environmental protection that equals or surpasses current MMS requirements."*
>
> *… Thus, if a lessee or operator believes that for a proposed platform on a specific site it can use alternate means to assure secure foundations for the facility or its anchoring systems, it can present its evidence to the MMS Regional Supervisor under the provisions of Sec. 250.141.*

OOC and Shell also commented on the proposed Section 250.915 b concerning the requirement for deepwater floating platforms utilizing catenary or taut-leg moorings. This requirement states that borings must be taken at the most heavily loaded anchor location and at anchor points approximately 120 and 240 degrees around the anchor pattern from that boring, and as necessary to establish a suitable soil profile.

OOC and Shell commented on this section as follow:

> *… Recognizing that deepwater developments with moored floaters and many subsea wells may cover a very large lateral extent (with the layout in a constant state of flux), an alternative site investigation strategy would be to base geotechnical data collection locations on the prevailing geology rather than specific facility locations. An integrated geotechnical/geology study of the development area is required for this methodology ``i.e., stratigraphy must be known at any specific foundation location and uncertainties quantified. Specific safety factors may be developed accordingly.*

The MMS again responded to these industry comments with the following response:

> *Again, MMS disagrees with OOC and Shell for the same reasons as discussed in the preceding issue concerning the maximum distance from a foundation pile to a soil boring. If a lessee or operator believes that for a proposed platform on a specific site it should use a different boring pattern, or alternate means to assure a secure anchoring pattern for a floating facility, it can present its arguments for a different boring pattern, or alternate method to the MMS Regional Supervisor under the provisions of Sec. 250.141.*

Sections 250.915 a and b are the site investigation requirements that are causing the ambiguity that now exists among regulators, CVAs, and practicing geotechnical engineers as to what constitutes best practices for conducting a deepwater integrated site investigation. These sections are prescriptive in nature and do not take into consideration the site geology and the influence of site variability upon the required scope of the geotechnical investigation. Because of this, API changed their standards to help practicing engineers set the final scope of an offshore site investigation.

Revisions to 30CFR Part 250 and API RP 2SK

The MMS recognized the rapid technological changes that were occurring in deepwater oil and gas operations, so 30 CFR Part 250[3] was amended in 2005 to include Section 250.906 describing what must be done for approval of the proposed site around the platform. The section was amended to include Subsection a - that describes the broad requirements for the shallow hazards surveys and Subsection b - that describes the testing program for the subsurface survey.

The key sentences in Subsection b indicate that the testing program must investigate the stratigraphic and engineering properties that may affect the foundation system. The revised section b described the testing program in a broader context indicating that in situ testing, boring and sampling methods were all acceptable to define the important soil and rock strata within the foundation zone. These additions were made to allow the significant advances of in situ testing and long coring developed during this period to be used to improve the quality and efficiency of conducting a deepwater geotechnical investigation.

During this transition period, the API committee decided that API RP 2SK should be updated and asked its Geotechnical Resource Group to update Appendix E (Pile and Plate Anchor Design and Installation). The third edition dated October 2005 with an addendum dated May 2008 presents a very detailed description of the foundation design requirements including the soil investigation objectives. The standard specifically states that the type of foundation and the geologic conditions as defined from a high quality geophysical survey should guide the scope of the geotechnical investigation. For the first time the RP confirmed the importance of performing an integrated study *"to develop the scope of work for the vertical and horizontal extent of the final geotechnical investigation (i.e., number, depth, and location of soil borings and/or insitu tests such as PCPTs) and to aid in the interpretation of the acquired geotechnical data."*

Appendix E of RP 2SK provides detailed descriptions of all aspects of foundation design and the critical soil parameters that need to be determined from the geotechnical investigation. Some key statements included in Appendix E relating to the need for soil borings as compared to long cores or in situ testing are as follows:

> *Should the designer choose to rely on soil sampling and laboratory testing instead of insitu testing during design, the designer should be aware that the measured properties of soil samples retrieved from deep waters may be different from insitu values.*
>
> *Insitu testing may allow a more reliable estimate of soil parameters and alleviate issues with sample disturbance.*
>
> *Coring with 'jumbo' or 'long' coring devices has also been shown to provide shear strength equivalent to those obtained by rotary drilling methods.*

The experienced geotechnical engineers who wrote and later updated RP 2SK clearly intended that the geotechnical engineer serving on a project would apply his/her judgment in specifying the site investigation method that best serves the project. The use of insitu testing and long coring are expressly allowed as viable altenatives to a rotary boring. The expert panel believes that the original term "boring" has taken on a broader meaning in the last decade to include all of these options. The engineer's job is to develop designs that are safe and cost effective. The opinion of the expert panel is that it is inappropriate to rigidly adhere to an outdated definition of the term "boring" that contributes to neither objective. Further, the panel believes that this is entirely consistent with the intent of 30 CFR 250 as was originally written to apply the recommendations in RP 2SK.

State of Practice – Offshore Site Investigations

Technological improvements over the last decade have dramatically changed the way geophysical surveys and geotechnical investigations are conducted. In earlier years these two independent efforts were conducted to satisfy regulatory requirements for exploration and production permitting. Thus, the geophysical and geotechnical data were seldom integrated and not used in a mutually supportive way to fully understand the subsurface geologic conditions and variability in sediment properties in a cost effective manner.

The integration of geophysical and geotechnical data has resulted in a significant advancement in the understanding of geological processes, solutions to geological constraints, and the interpretation of geotechnical parameters. The application of an integrated geoscience methodology combines the geophysical data, a model for the geological process used to explain the geophysical data, and the geotechnical data itself to develop the soil properties required to understand potential geological constraints and for foundation design. Using this process also defines the type and resolution of geophysical and geotechnical data required to undertake an integrated geoscience study (i.e., considers the entire process when planning every data acquisition activity).

The large area covered by most deepwater floating production developments requires an integrated study to be performed in a logical sequence of phases. By conducting the work in phases (see Figure 1) as described by Campbell et al.[4, 5], all data needed to define the potential subsurface variability and geohazard risks can be confidently acquired. The current state of practice is well suited to provide a clear picture of the geologic variability and sediment properties throughout the project area.

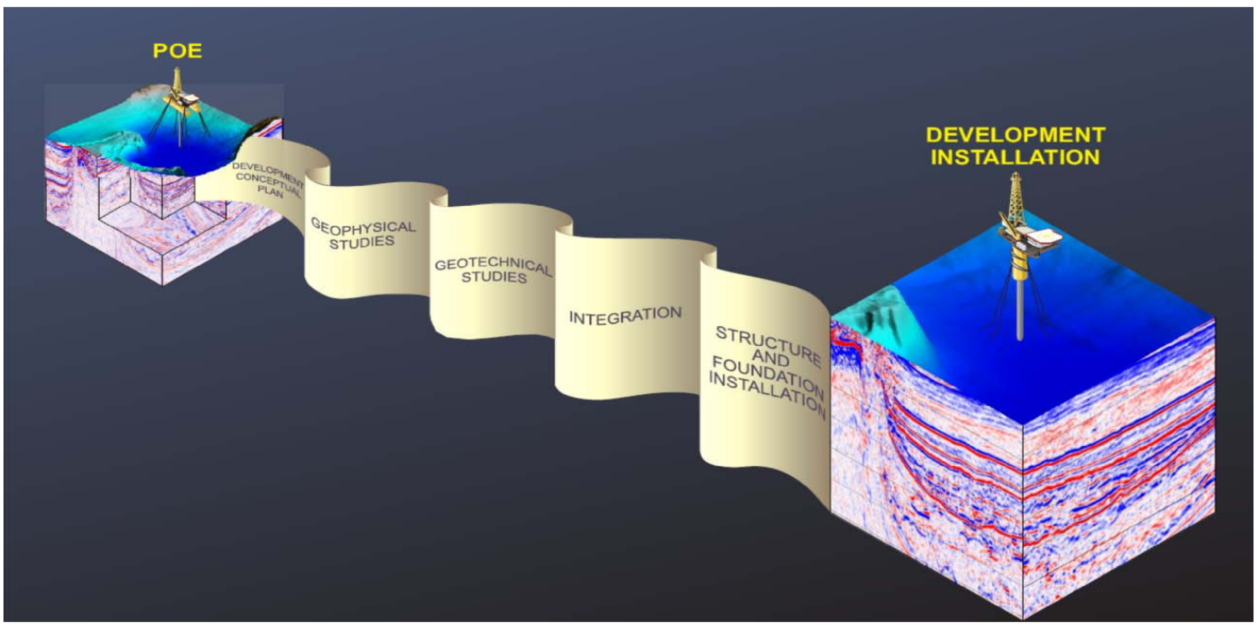

Figure 1. Phases of deepwater integrated study

Over fifty years ago, Dr. Ralph Peck (1962)[6] emphasized the importance of performing an integrated study. He pointed out that we must understand the natural processes that created a soil deposit if we want to appreciate its inherent variability. He believed that we must approach all geotechnical engineering problems from a geological point of view. This early pioneer stressed that the disciplines of geology and geotechnical engineering are mutually dependent to achieve a reliable site characterization. He believed that geology should play an essential role in the design process and should guide all data acquisition activities.

The following sections will describe the methods for conducting geophysical surveys and geotechnical site investigations that have evolved to our current state of practice. The sections will describe advances in equipment and the resulting benefits in the quality and resolution of the data for interpreting stratigraphic section and correlating the relevant soil properties.

Role of Geophysical Survey

The critical role that the (shallow hazards) geophysical survey plays in defining site conditions during an integrated geoscience study has been clearly explained in RP 2SK and Section 250.906 of 30 CFR 250. The geophysical (acoustic-profiling) survey provides the basis for defining the subsurface conditions, the complexity of geo-constraints, and the required scope of the geotechnical investigation.

The objective is to develop a comprehensive understanding of the geologic setting in which the foundations that moor the permanent floating production platform will be installed. An extensive geophysical database allows one to make an accurate assessment of the risks posed by various seafloor and subsurface conditions. Thus, the geotechnical investigation can be carefully planned to investigate those features so identified. Regional geologic data used in conjunction with the high-resolution geophysical survey assures that the findings of the "subsurface investigation" are consistent.

As stated in RP 2SK, the site specific, high-resolution geophysical information will define the conditions existing at and near the surface of the seafloor, that is

> *The survey should include the mapping and description of all seafloor and sub-bottom features that may affect the foundation system. Such features may include: seafloor contours, seabed slope angles, shallow stratigraphy, position of bottom shapes…*

In other words the geologic model will confirm the degree to which uniform soil stratigraphy exists, and for example, whether geotechnical data at a single site within each anchor cluster might be adequate for design of individual anchors within that cluster. Conversely, highly variable soil conditions would mean that a more detailed geotechnical investigation is needed to understand spatial soil variability throughout the anchor cluster. In other words the final scope of the geotechnical investigation is highly dependent upon the variability in geologic conditions, the details and nature of the proposed foundation, and ultimately, the judgment of the geologist and geotechnical engineer.

Deepwater geophysical surveys prior to 2000 were performed with a fish that was towed behind the vessel with a long umbilical with lengths up to 10,000 ft (Prior et al.)[7]. The tow-fish was equipped with a suite of geophysical sensors capable of acquiring high-resolution data such as swath bathymetry, sub-bottom profiles, and side-scan sonar imagery. Survey speeds were slow generally ranging between 2.0 to 2.5 knots. In addition, extensive time (four to six hours) was required in making the turn at the end of each track line owing to the length of the umbilical.

The inefficiencies of performing geophysical surveys with a deepwater tow-fish system prompted industry to pursue an improved system (i.e., Autonomous Underwater Vehicle – AUV) as described by Bingham et al.[8.] Over the last decade the AUV has become the workhorse for conducting deepwater geophysical surveys due to its many technical and commercial benefits.

Today AUV systems are routinely used and the advances in equipment design have dramatically improved the quality and resolution of the geophysical data. The advances have improved the science from simply recognizing stratigraphic horizons to the ability to recognize the stratigraphic sequences, interpret their depositional history, and distinguish unconformities and reconstruction of the transgressional-regressional history of the area. The end result is that the geologic model can be defined with sufficient confidence that seafloor conditions, geologic processes, and subsurface conditions impacting facility placement and foundation design are understood throughout the entire project area.

The improved methods for conducting a geophysical survey provide an important benefit in that the scope of the geotechnical investigation can be more carefully planned to properly define the potential subsurface variability throughout the project area. Thus, the risks associated with foundation placement, performance, and installations are clearly understood.

After the geologic model has been defined the scope of the geotechnical investigation can be planned to investigate: (1) site strength profiles, (2) spatial soil variability, (3) validation of the past, current, and future geologic processes, and (4) the presence of any excess pore pressures. The challenge is to define each of these design constraints in sufficient detail to understand their potential impact on proposed anchors and foundations. The following section will describe the improvements in geotechnical site investigations that have occurred over the last ten to fifteen years.

State of Geotechnical Site Investigation Practice

During the planning process, full use of geophysical data and geologic interpretations is needed to select the preferred sampling and insitu testing equipment. Of course the type of foundation, the type of sediments, and the type and location of anchors and foundations must be known to make sure that required engineering properties are obtained.

Conventional Rotary Boring.

A conventional soil boring has been the primary method used to acquire geotechnical data since the first borings were drilled in the Gulf of Mexico in 1946. The borehole is advanced by rotary drilling methods as described by McClelland[9] and downhole samples are acquired using a wireline sampler lowered down the bore of the drillpipe used to advance the borehole. The technology is very mature and the equipment has been continuously upgraded until present to improve sample quality and allow operations in deeper water.

Unfortunately, there are a number of drilling, sampling, and testing procedures as described by Young et al.[10] that can have deleterious effects upon our measurements of the undrained shear strength, one of the most important geotechnical parameters. Some of these deleterious effects may include: (1) boat motion and movement of the drill-pipe, (2) care exercised during the drilling operations, (3) type of sampling procedures, (4) stress relief during sample recovery, (5) sample extrusion process, (6) sample handling, packaging and transportation, (7) sample storage, (8) laboratory testing procedures, and (9) unusual geologic or physio-chemical properties of the sediments. All these factors can have an impact on sample quality and may introduce some error in the reported values of undrained shear strength. These factors are particularly significant in deepwater investigations. For this reason, all personnel involved with any of the drilling and sampling operations must exercise extreme care to minimize these effects.

Recognition of the potential negative impacts of these field operational and laboratory procedures led the offshore geotechnical industry to put more emphasis on insitu testing in the early 70s. The following sections will describe many of the innovative insitu testing methods that have been introduced to overcome the many problems associated with traditional drilling, sampling, and testing methods.

Insitu Testing Methods.

A wide variety of insitu testing methods have evolved over the last the forty years that now can be used in the difficult deepwater operating environment. The piezo-cone penetrometer test (PCPT)[11] and vane shear test (VST)[12] have seen many innovative developments that have dramatically improved the operational reliability of the equipment.

Vane Shear Test.

The first use in 1970 of the VST from a floating vessel took place with a system called the Remote Vane as described by Doyle et al.[13]. The system was operated in a downhole mode and obtained high quality measurements of the undrained strength of the soft, sensitive Mississippi Delta clay. Traditional sampling and laboratory testing methods had resulted in excessive disturbance in these materials.

Since this initial use, many improvements have been made with the equipment as described by Peterson et al.[14] including the battery, electronics control, and remote memory module. Other operational improvements now allow the equipment to be used reliably in both a seabed and downhole mode in water depths up to 10,000 ft. Today the VST is used more infrequently during deepwater geotechnical investigations due to the long time required to make an individual measurement.

Piezo-Cone Penetrometer Test.

The PCPT was initially employed in the early 70s in the North Sea. The Seacalf[15] system was introduced in 1972 and consisted of a seafloor platform capable of performing continuous cone soundings down to 120 ft below the seafloor in normally consolidated clays. Fugro introduced the Wison[16] in 1972 and and McClelland Engineers introduced the Stingray[17] system in 1975 that could perform PCPT soundings in a downhole mode.

A number of different innovations have been introduced over the last two decades that have improved the PCPT equipment as described by Peterson el al. (1986) that now allow high quality data to be reliably obtained in water depths up to 10,000 ft. Standards[18,19] have been written that allow the PCPT data to be properly measured and interpreted. For example standardized procedures are available that allow geotechnical engineers to use the point resistance, sleeve friction, and dynamic pore pressure measurements to classify soil types and to interpret various physical and engineering properties. As a result, the practice of performing PCPT soundings on deepwater projects has become a routine and reliable method of measuring sediment properties for foundation design.

One key advantage of using the PCPT system over the insitu VST tool and/or a conventional soil boring is that it provides a continuous profile of data thus improving our understanding of the variation in soil properties and stratigraphy throughout each sediment layer. This detailed definition of soil properties is not possible with data acquired in a traditional soil boring or with a single VST measurement with samples/tests taken at say 10 to 20-ft increments.

Operational Considerations.

The size and type of vessel required for a site investigation depends upon water depth, planned depth of the foundations, and the methods used for insitu testing and sample acquisition. The procedures for sampling and insitu testing below the seafloor are generally divided into two broad categories: (1) seabed mode – where the rig or sampling equipment is placed on or activated near the seabed, and (2) downhole mode – where the sampling or testing is conducted through the bore of the drillpipe at the bottom of an open borehole.

The vessel used for the equipment in a seabed mode is typically much smaller and much more economical since an onboard drilling rig and dynamic positioning are generally not required. The downhole mode requires a much larger purpose-built geotechnical drillship as shown in Figure 2 that requires absolute dynamic positioning (DP 2) to keep the vessel sufficiently stationary while drilling and sampling operations are underway for periods up to 4 to 5 days. The drillship as described by Ehlers and Lobley[20] requires a special built drill rig positioned over a moonpool while the drill-pipe must be heave compensated to limit movement as the vessel heaves under each swell. Costly heave compensation is essential to assure good sample quality and minimize the impact on the insitu testing results. The larger vessel with all the specialized equipment means the day rate for the drill vessel is much greater than the smaller vessel used for seabed mode operations.

Figure 2. Geotechnical drillship

The vessel type and mode of sampling and insitu testing must also be carefully matched to the required data coverage (number and type of sampling and insitu testing sites) of the site investigation. For example the time to drill and sample a boring in the downhole mode requires numerous days since all operations must be conducted down the bore of the drillpipe using wireline operations. In the downhole mode, each 3-ft long sample or a single insitu PCPT test may take 3 to 4 hours. In comparison, a continuous CPT sounding can be performed from the seafloor to 140-ft penetration in the same time that it would take to acquire the single sample with the more expensive drillship. The end result is that many more sites can be investigated when sampling and testing in the seabed mode than working with the drillship in the downhole mode.

Later sections will describe recent innovative methods and their benefits for mitigating foundation risk. These methods are important for addressing operators and regulators common goal of acquiring appropriate quantity, quality, and type of subsurface data to achieve a reliable foundation design.

Recent Innovative Deepwater Site Investigation Methods.

Significant advances of insitu testing and long coring equipment have been developed over the last decade that can improve the quality and efficiency of conducting a deepwater geotechnical investigation.

Long Core Sampling.

Large diameter drop cores such as the Jumbo Piston Core (JPC) shown in Figure 3 and STACOR[21] are relatively recent innovations. These devices are well suited for normally consolidated clays and allow continuous large diameter piston cores to be taken to depths of about 60 to 70 ft. Extensive field testing (Young et al.[22] and Wong et al.[23]) has established that the quality of samples from these cores is as good as or better than that from drilled borings. The long cores have many technical benefits that include: (1) continuous cores provide a visual image of variations in soil properties, (2) a core can be continuously logged with a Multi-Sensor Logging System (MSCL), and (3) a core provides an opportunity for continuous correlation of the data results with high resolution sub-bottom profiling data. In addition samples from long cores can provide the same test data that borehole samples can. The disadvantage is the depth limitation, i.e. they may have limited depth range in strong soils.

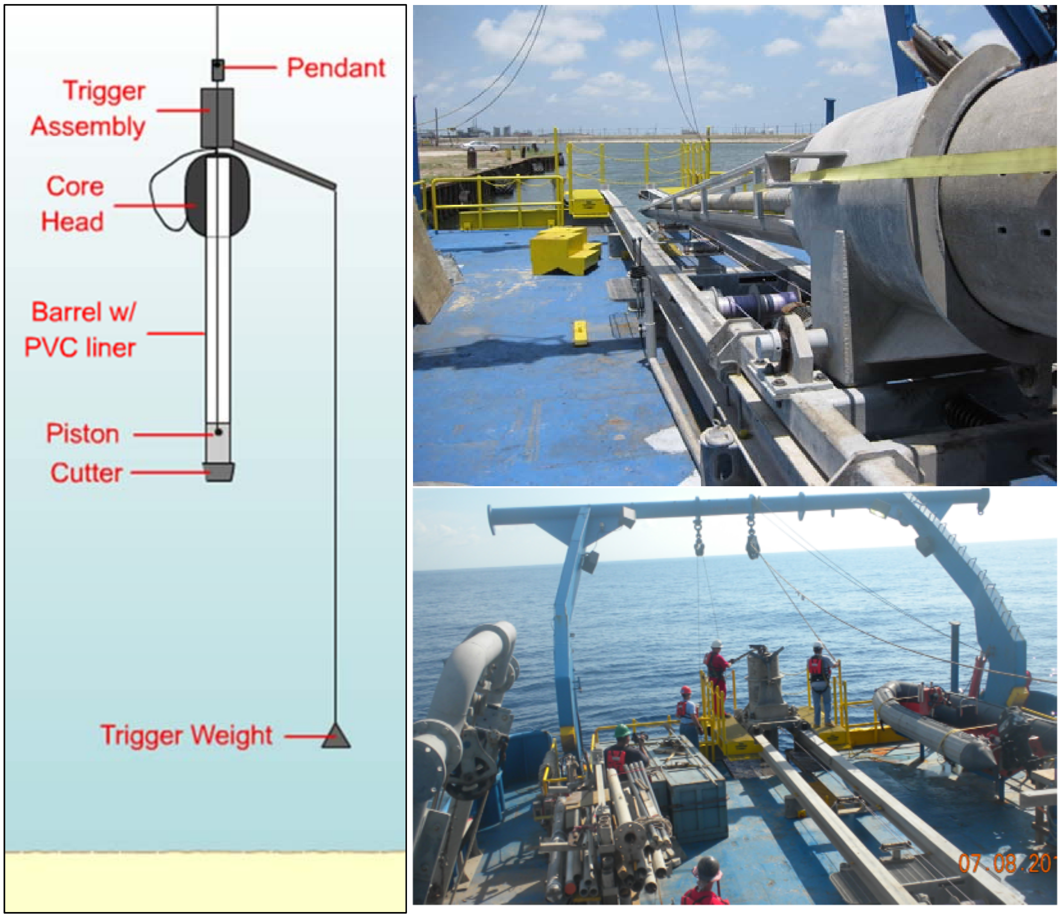

Figure 3. Jumbo piston core operation and layout

There are clearly situations where rotary borings are needed. Examples include very stiff soils or for deep piles where the combination of cone penetrometers and long corers cannot penetrate to the requisite depths. However, in other situations, such as foundations of limited depth in normally consolidated profiles, insitu testing and/or long coring may alone be perfectly adequate.

Continuous PCPT Testing.

PCPT testing provides continuous sounding of point resistance, side friction, and pore pressure response throughout the interval tested. There are now well-accepted calibrations based on comprehensive field testing that relate the measurements to undrained shear strength as well as to soil type. A new innovative system called the “CPT-Stinger” that allows CPT testing to overlap and extend below the bottom of a long core (Young et al.)[24] has recently been developed and used on a large number of site investigation (see Figure 4). This system allows PCPT soundings to depths up to 145 ft below the seafloor without the requirement for a PCPT seafloor platform. The CPT does not provide a sample for laboratory testing; hence rotary borings or long cores are desired adjacent to the CPT location to provide samples to measure strength and other engineering properties of the sediments and for CPT calibration.

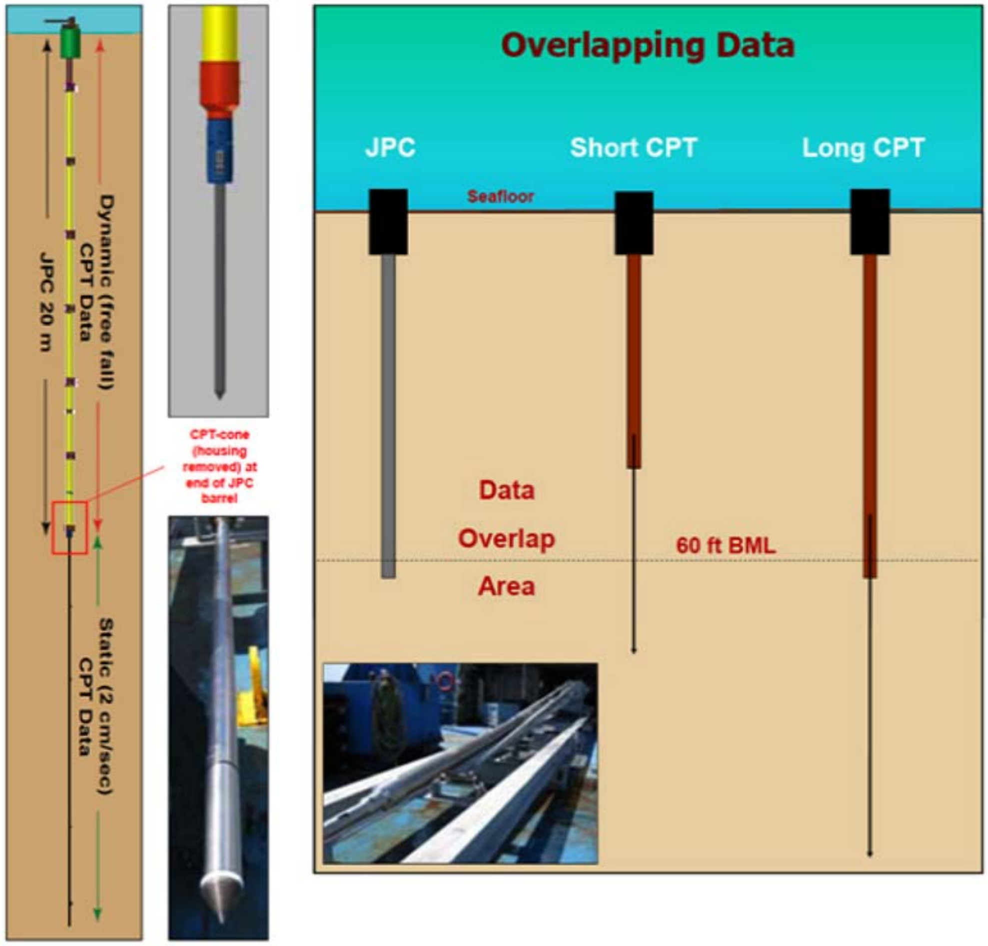

Figure 4. Overview of CPT-Stinger system

Seabeded Drilling, Sampling, and Testing Systems.

A number of self-contained seabed systems have been developed in the last decade that avoid the difficulties of working from a drillship and the inefficiencies of using a wireline for sampling and testing operations. As described by Carter et al.[25], the Portable Remotely Operated Drill (PROD) is a seabed system that has the capability to take piston samples and perform CPTs in the same borehole (See Figure 5).

Figure 5. Portable remotely operated drill (PROD)

The Rovdrill as described by Spencer[26] is a seabed sampling and insitu testing system that uses an ROV as shown in Figure 6. The ROV provides electrical and hydraulic power, telemetry, and high definition video and operator interface to the operator control room onboard the vessel. The Seabed CPT system as described by Boggess and Robertson[27] is another seabed system that uses telemetry and robotic components to perform the insitu testing operations. These seabed systems improve operational efficiency and reduce vessel time. Working from the seabed eliminates delays associated with operating a wireline tool down more than 1 to 2 km of drillpipe.

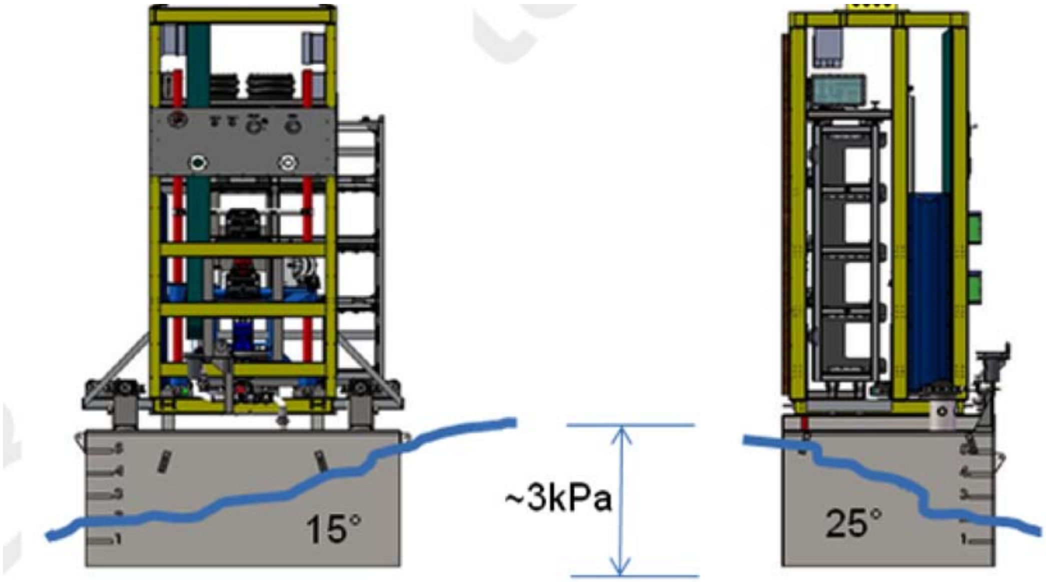

Figure 6. Rovdrill 3 seabed sampling and insitu testing system

Risk and Reliability Assessment

The regulatory goal of “assuring secure foundations” is measured by the level of risk or reliability that is achieved. Evaluating the risks of foundation failure and the options for mitigating the risks is key in planning and designing an offshore development. Because of the potentially high cost of a failure, the offshore energy industry has been leaders in understanding the risk in design and the decision making process associated with reducing the risks to acceptable levels.

Over the last decade, the methods for making a reliability-based design have matured and case studies have shown the success of using this approach. Appropriate risk is never zero risk, and excessive conservatism can be as onerous as excessive risk. According to Gilbert et al.[28] an acceptable level of reliability can be achieved by a combination of design information to reduce uncertainty in the foundation performance and design conservatism to limit the effect of uncertainty on the performance of the design.

One of the most important considerations in planning a site investigation is determining the amount of geotechnical data that is warranted. One must ask whether additional data beyond that conventionally acquired would justify the cost of acquiring the data. Of course this decision will hinge on the geologic conditions and the potential variability in sediment properties that may exist within the area or at a specific site. Maximizing the value of information entails finding the optimal combination of design information and conservatism, such that the combination will minimize the total expected cost.

Reliability analyses as described by Gilbert et al.[29] were performed to establish the value of various geophysical and geotechnical investigation methods in reducing the uncertainty in foundation design. For example, reliability analyses allows the engineer to compare the value of obtaining a continuous JPC core and CPT sounding with drilling a boring sampled at discrete intervals.

Case Studies

A number of case studies were analyzed to quantify the uncertainty in soil properties caused by limited sample locations and the different site investigation methods. The results show that uncertainty associated with conventional soil borings can often be reduced by: (1) relying upon high-resolution geophysical data at the site, (2) increasing the number of continuous samples (JPC/borings) or insitu tests performed within the planned area of foundations, and (3) correlating the geophysical and geotechnical data to understand the geologic depositional environment.

Several published papers illustrate the use of an integrated geoscience study in developing design parameters, e.g., Doyle[30], Campbell et al.[31], Jeanjean et al.[32], and Newlin[33]. Due to length limitations only one case study will be discussed. We have selected the Mad Dog Development located in Green Canyon, Block 782. Mad Dog includes a SPAR platform located in 1,348 ft of water positioned about 365 ft away from the edge of the Sigsbee Escarpment as shown in Figure 7 and Figure 8.

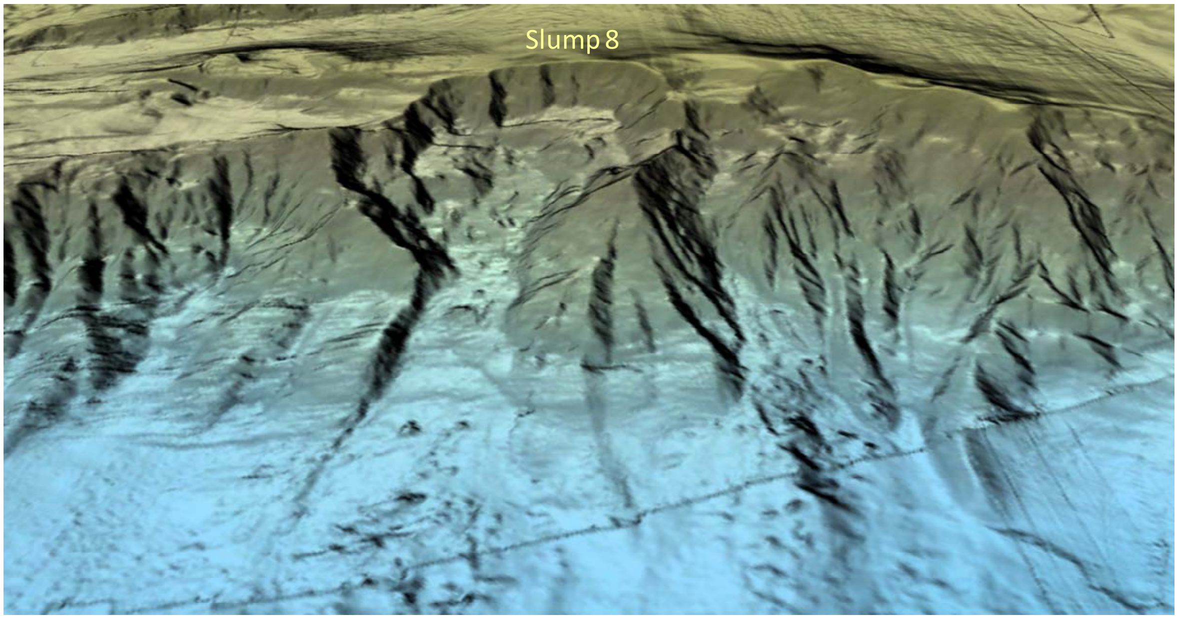

Figure 7. Sigsbee Escarpment – Slump 8 at Mad Dog SPAR development

The suction caisson anchors for this system vary in diameter from 18 to 25 ft and embedded length from 47 to 85 ft. The mooring spread includes three anchor clusters as shown in the Figure 8 with three suction caissons in Anchor Cluster 1 and four suction piles in Clusters 2 and 3. Cluster 2 is located within a major slump (submarine landslide) named Slump 8.

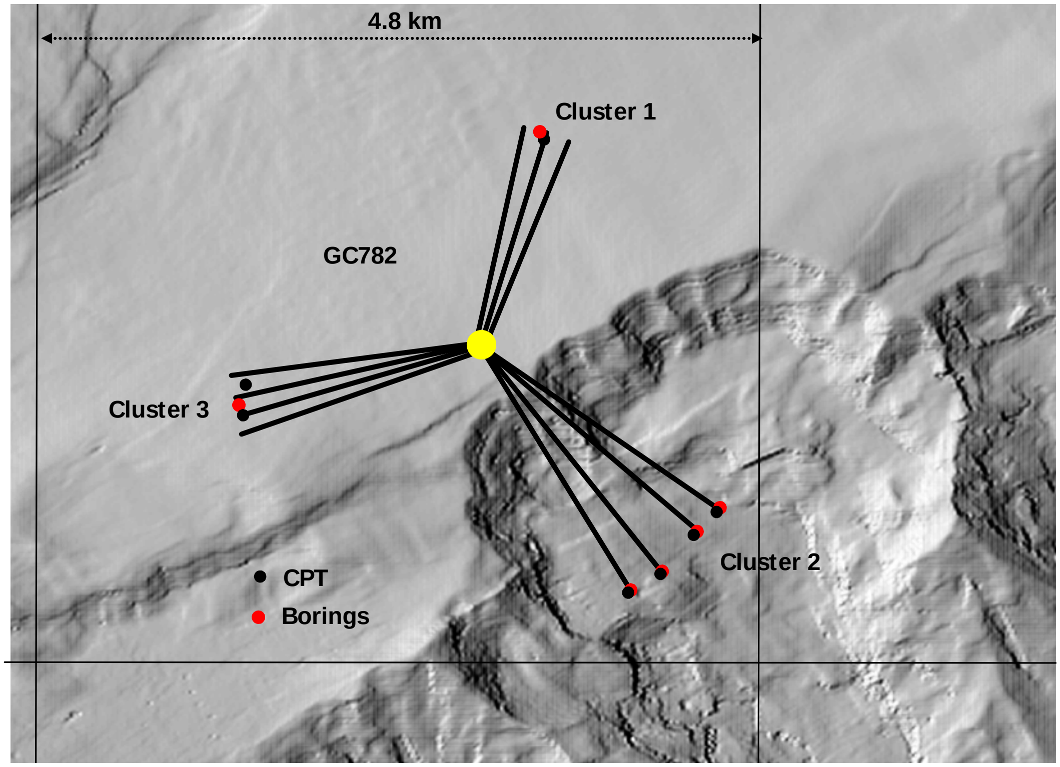

Figure 8. Mad Dog SPAR morring spread with 11 suction caissons

The soils in Slump 8 are highly variable since they were deposited as part of massive debris flows as shown in Figure 9. The soils in the debris flow deposits consist of interbedded zones of soft debris flow material, silt and sand layers, and stiff debris flow blocks (see Figure 10). On the contrary Clusters 1 and 3 were located where very uniform and continuous sediment layers exist as shown in Figure 11.

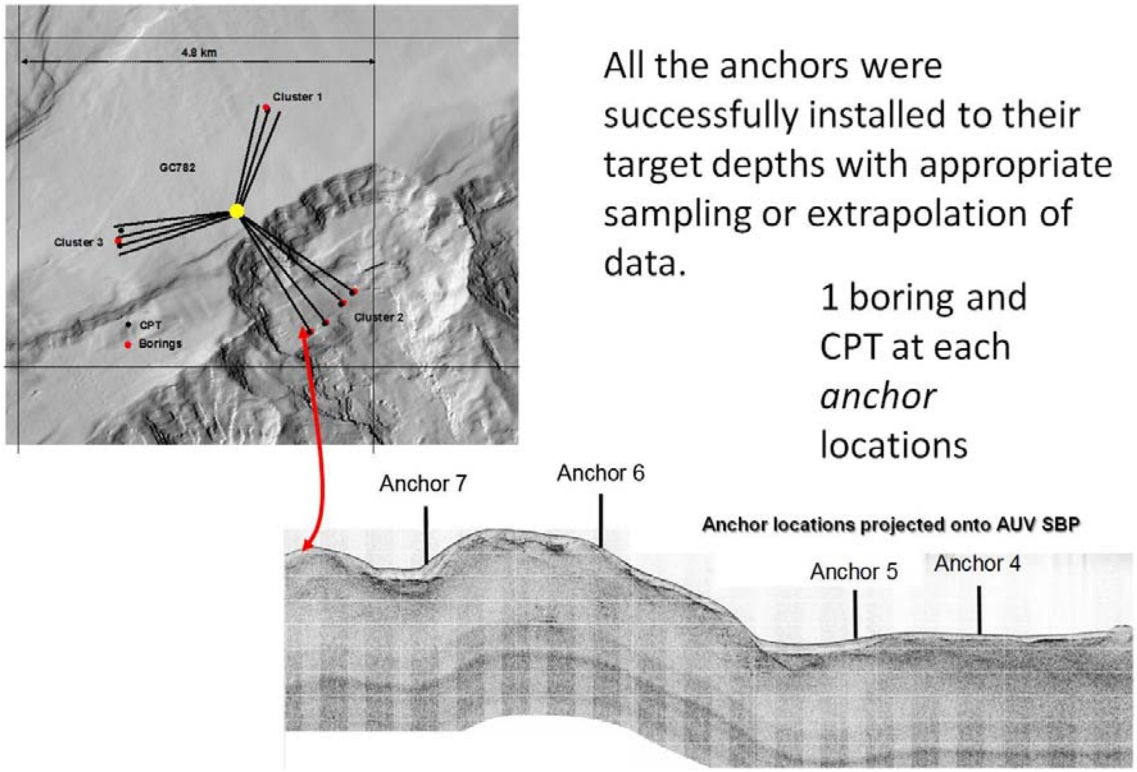

Figure 9. Mad Dog Slump 8 geotechnical work scope

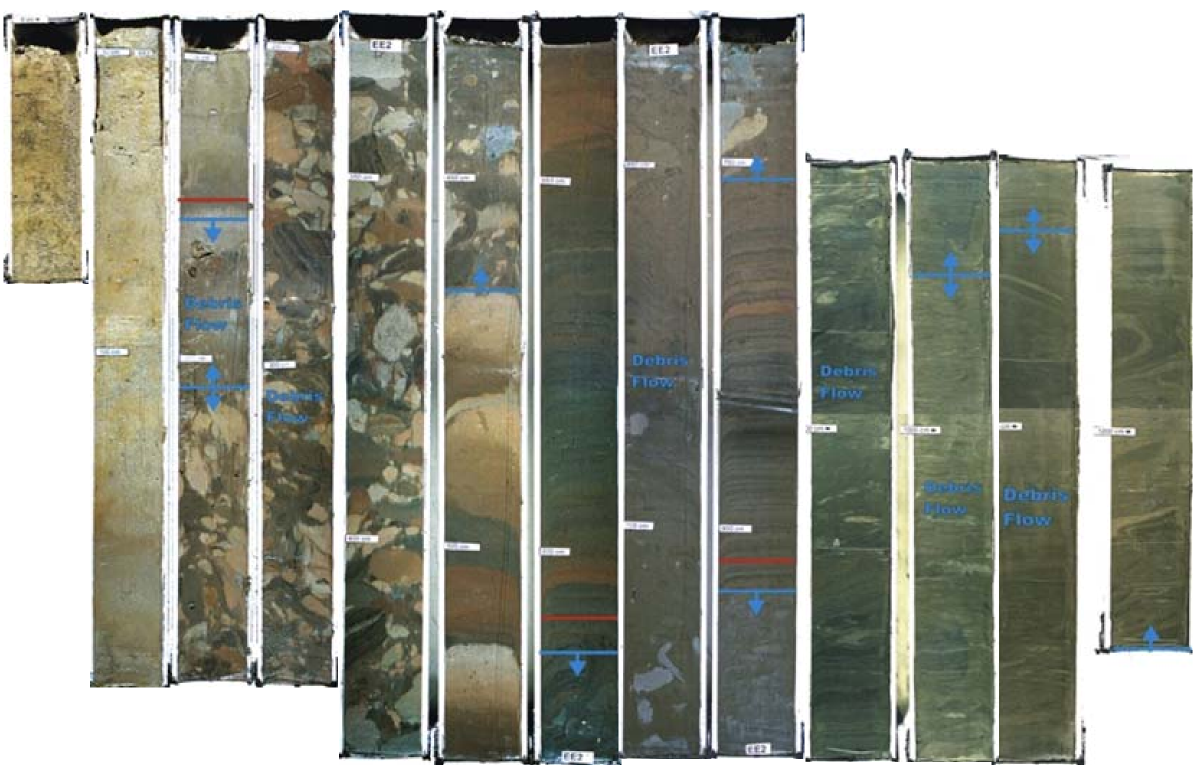

Figure 10. Debris flow deposits in slump core

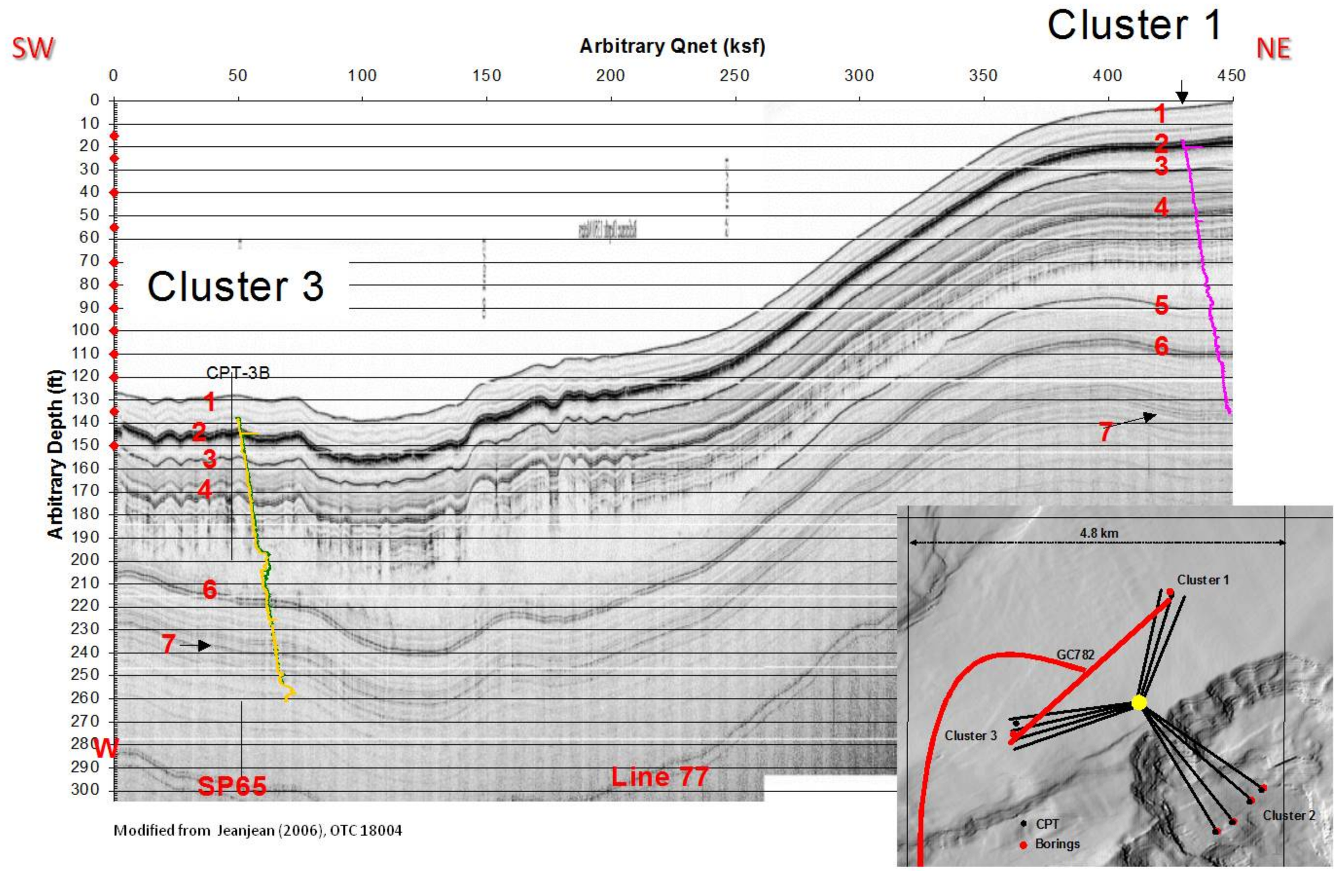

Figure 11. Subbottom profile data showing uniform soil stratigraphy between Clusters 3 and 1

This example clearly shows that three soil borings as specified in CFR 250 would provide inadequate geotechnical data to design the suction piles. This example provides an opportunity to discuss the epistemic and aleatory uncertainty of the data throughout the project area. Epistemic uncertainties are defined as uncertainty due to lack of knowledge that can be reduced but not eliminated with additional data (Christian[34]). Aleatory uncertainties are due to the random nature of the phenomenon; thus, more data will not reduce this uncertainty.

Geologic processes can give rise to sediments ranging from layered to chaotic conditions. Understanding the depositional process is the most important factor for interpreting the engineering properties throughout the foundation site. Epistemic uncertainty can be reduced when we further investigate the spatial distribution of soil properties by acquiring additional geotechnical data. Random errors in testing or sample disturbance create much of the aleatory uncertainty. When the geophysical data are integrated with the geotechnical data one can develop a better understanding of the epistemic versus aleatory uncertainties and the range of soil strength profiles applicable for foundation design.

A paper by Jeanjean et al.[35] describes the details of the site investigation performed for the eleven suction caissons used at Mad Dog. By using the high-resolution geophysical data to guide site selection and investigation methods, the final site investigation met its intended purpose of providing reliable strength profiles for design. The predicted and observed installation behavior of the eleven suction caissons as described by Schroeder et al.[36] confirms that the scope of the site investigation described below provided a reliable description of subsurface conditions. Clusters 1 and 3 are located above the escarpment where uniform soil stratigraphy exists as shown by the sub-bottom profile line in Figure 11. The profile does reveal a thin debris flow layer with soil strengths only slightly stronger than the uniform bedded soils located below and above the layer as shown in Figure 12. The site investigation at Cluster 1 included only one boring and one CPT whereas a single boring and two CPTs were performed at Cluster 3.

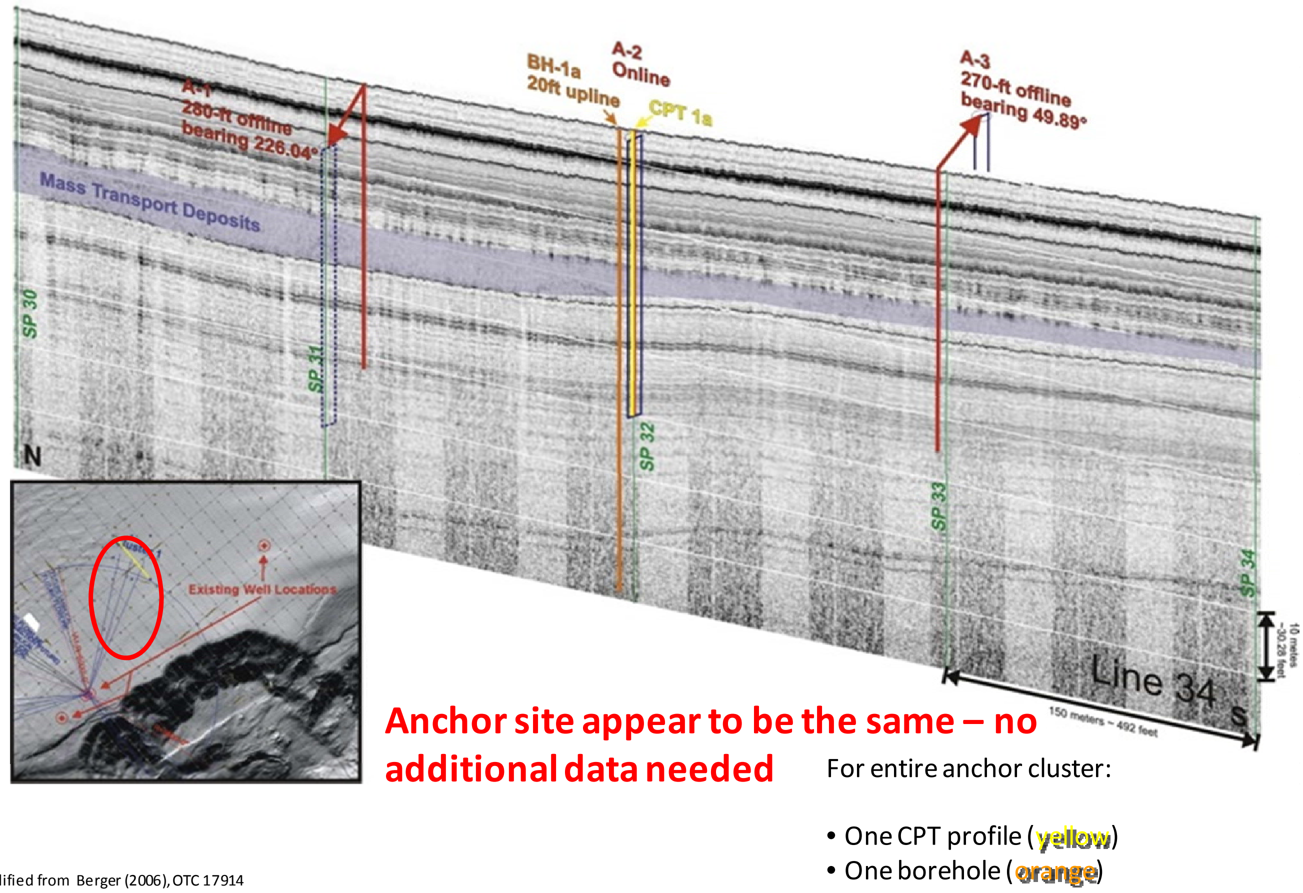

Figure 12. Subsurface fence diagram of data locations at Cluster 1

Cluster 2 is located within Slump 8 where the sub-bottom profiler data show that no correlation of soil stratigraphy can be made between any of the four anchor sites as shown in Figure 9. Thus, the field investigation included a boring and a companion CPT at each of the four anchor sites. Figure 13 shows a comparison of all the CPT data at all seven CPT sites. The point resistance data (q_{net}) for all seven CPT sites show the wide variation in the measured data within Slump 8 where the four anchors in Cluster 2 are located. The three CPTs obtained for Cluster 1 and 3 (CPT1-A, CPT3-A and CPT3-B) confirm the very uniform and horizontal parallel bedding that exists above the escarpment. In this case a single CPT within each anchor cluster would have provided all the information that would be required to cover foundation design requirements.

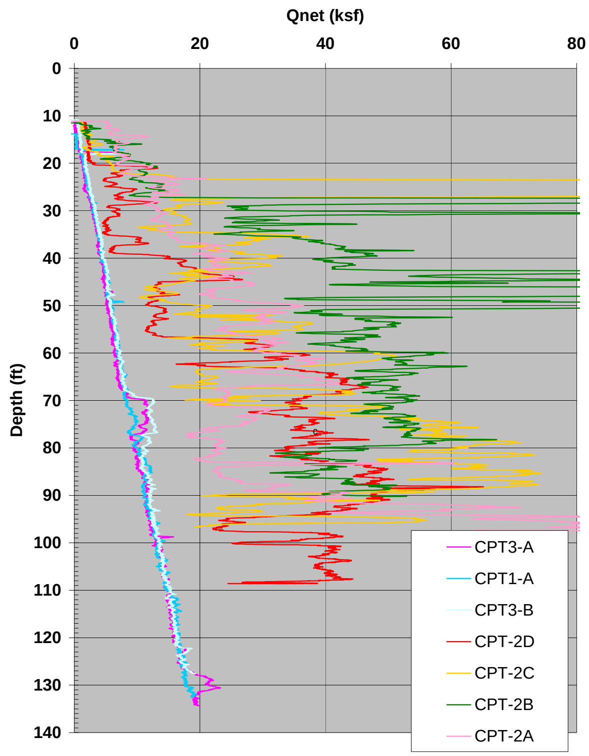

Figure 13. CPT site variability for all anchor clusters

The Mad Dog case study clearly demonstrates that the site investigation plan should be based upon the geologic variability as revealed in the high-resolution sub-bottom profiler data. Thus, the prescriptive requirements specified in CFR 250 will often not properly address the potential site variability. For example these requirements may be overly prescriptive (e.g., Clusters 1 and 3) or insufficient (e.g., Cluster 2) depending on the site geology. API RP 2SK clearly underscores the critical role that the (shallow hazards) geophysical survey plays in defining site conditions during an integrated geoscience study.

There are a number of other deepwater developments that also strongly support the approach that the site investigation teams need flexibility in setting the scope so that the judgment of experienced engineers, a critical element, continues to play its proper role in foundation design practice. The reliability of this methodology is described in other papers, e.g., Clukey, et al.[37], illustrating the need for flexibility in site investigation scope needed to investigate various levels of uncertainty.

New Regulatory Text

After reviewing all the regulations and reviewing the state of practice, the expert panel concludes that the existing ambiguity in the present language of 30 CFR 250 can only be corrected by rewriting them. The panel recommends that the new regulations should make the following modifications:

1. Change “foundation borehole,” “soil boring,” and “boring” to “geotechnical investigation” wherever used. It is preferable that “geotechnical investigation” refers to rotary borings, pushed samplers, drop cores, cone penetrometer tests, and other techniques that are available or may become available that will provide the parameters required for foundation design/or to understand geologic processes such as slope stability.
2. Eliminate all reference to specific distances and locations for geotechnical field investigation. Instead, the text should require an integrated geoscience study for all deepwater investigations to determine the scope of the geotechnical field investigation including the locations of the sites to be investigated.

The 30 CFR 250 was originally written to encourage innovation in practice, but the explicit references to location and distances relative to foundation site stated in two of the sections have led in the opposite direction. The ambiguity between regulators and practicing geotechnical engineers in interpreting the regulations requires that changes in the regulation language be implemented to provide the practicing engineer more flexibility. It is the opinion of the authors that there is no “one size fits all” designation with regard to the complex art of site investigation. What is adequate for one site may be inadequate for some and unnecessary for others.

Conclusions

This paper highlights the need for flexibility in designing site investigations so that the site plan and equipment can be tailored to the geologic conditions. A good example of this is the fact that long coring and CPT testing in conjunction with geophysical surveys can be legitimate alternatives to rotary borings for geotechnical investigations for many applications. A chronology is presented of the evolution of applicable requirements included in 30 CFR 250 that have led to the current state of confusion regarding offshore site investigation. The regulatory framework in Section 250.906 of 30 CFR 250 as further described in API RP 2SK clearly underscores the critical role that the (shallow hazards) geophysical survey plays in defining site conditions during an integrated geoscience study. The geophysical (acoustic-profiling) survey provides the basis for defining the subsurface conditions, the complexity of geo-constraints, and the required scope of the geotechnical investigation.

API RP 2SK highlights the progress that has been made in site investigation technology and interpretation over the last decade and provides insight as to how these methods evolved to their present state. The geotechnical engineer now has an outstanding set of tools for developing parameters for a myriad of geologic conditions and he/she can confidently and economically design anchors and foundations around the world. This document emphasizes the importance of allowing flexibility in design requirements so that the judgment of experienced engineers, a critical element, continues to play its proper role in geotechnical design practice.

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